Laboratory for Earthquake Engineering
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Dynamic Soil-Structure Interaction: Historical Development and Modern Practice

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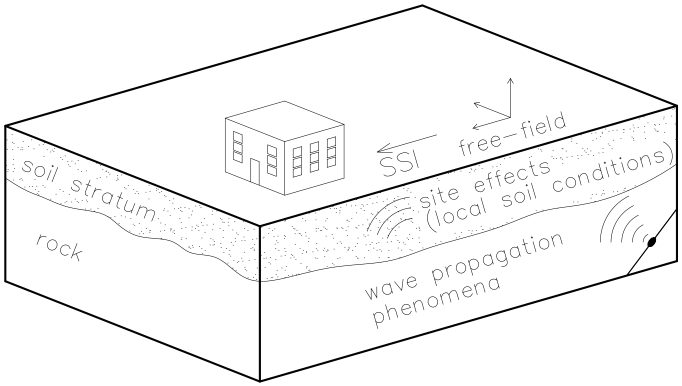
Assessment of Seismic Loads

seismic movement in the free field depends on:

- phenomena related to the source (i.e. earthquake magnitude, fault mechanism)



- wave propagation phenomena

- phenomena related to local soil conditions (i.e., soil layers, soft soil amplification, slopes, landslides)

Assessment of Seismic Loads

Source phenomena

Wave propagation phenomena

Site effects

free-field motion

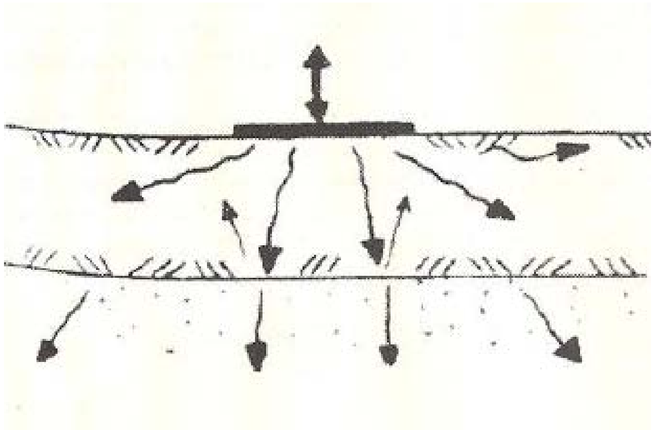
(absence of structure)

The Soil-Structure Interaction (SSI) takes into consideration :

Structure and foundation

Most Important Effects of SSI

1. Response significantly different from fixed-base assumption.
2. Soil damping (radiation damping and hysteretic soil damping).



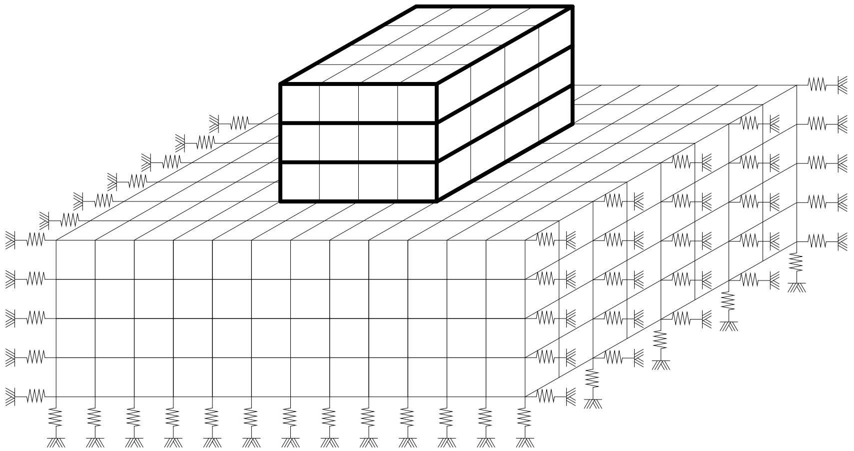
3. Particularly important for relatively “stiff” structures founded on "soft" soil.

Methods of SSI consideration

A. Direct methods

Simultaneously modeling of structure, foundation and soil. Suitable to study of not-linear behavior. Common methods:

- Finite Element Method
- Boundary Element Method



B. Substructure methods

Suitable for elastic analysis. Commonly adopted by seismic regulations.
Kinematic soil-structure interaction
Inertial soil-structure interaction

Types of Interaction

A. Kinematic interaction

Kinematic interaction refers to the modification of ground motion relatively to the free-field motion because of the presence of a foundation (averaging of variable ground motions across the foundation slab, wave scattering, and embedment effects).

Parameters :

- **Size and shape of foundation**
- **Depth of foundation**

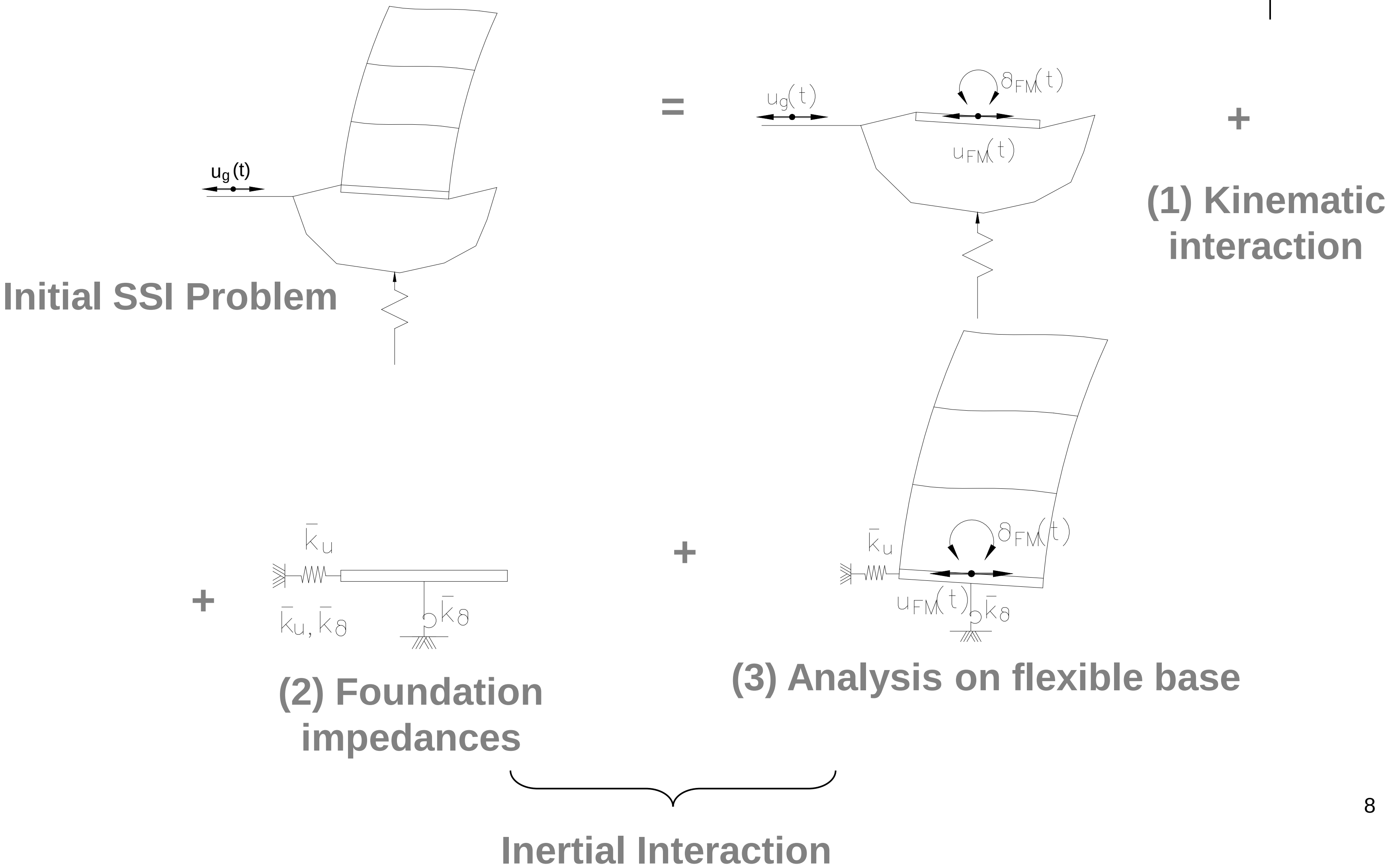
Consideration of kinematic interaction means modification of free-field ground motion to the Foundation Input Motion (FIM), that is the motion imposed at the base of foundations.

Types of Interaction

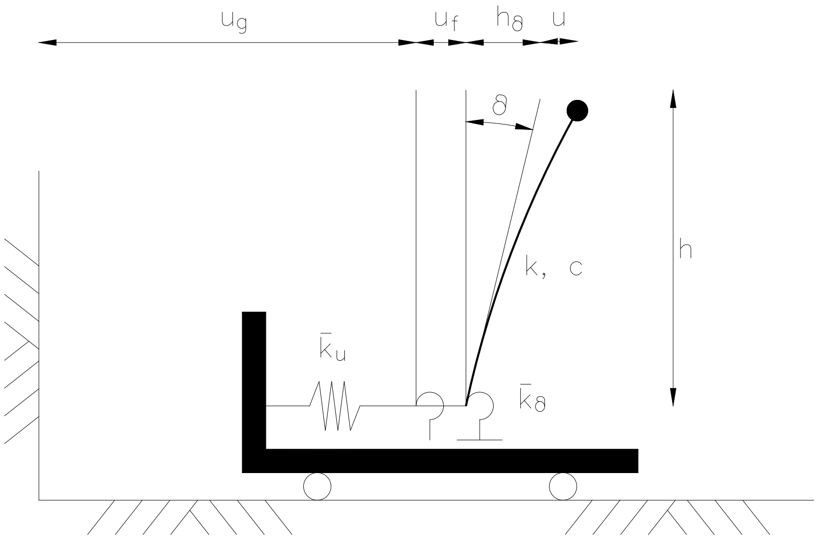
B. Inertial interaction

Inertial interaction effects include inertia characteristics, stiffness and damping of structure and soil, as these parameters affect the overall response of the soil-foundation-structure system under the seismic excitation at the interface between foundation and soil.

Substructure method for SSI



Basic equations – Inertial SSI



Oscillator model for analysis of inertial interaction under lateral excitation.

$$\begin{bmatrix} V \\ M \end{bmatrix} = \begin{bmatrix} \bar{k}_u & 0 \\ 0 & \bar{k}_\theta \end{bmatrix} \begin{bmatrix} u_f \\ \theta \end{bmatrix}$$

Basic equations – Inertial SSI (cont'd)

The impedance function for the i_{th} degree-of-freedom are expressed in a complex form as follows

$$\bar{k}_i = k_i(\alpha_o, \nu) + i \cdot \omega \cdot c_i(\alpha_o, \nu)$$

ω: frequency of the excitation

v: Poisson's ratio for the soil

α_o: dimensionless parameter expressed as $a_o = \omega \cdot r / V_s$, where r=foundation radious, V_s= shear wave velocity

Basic equations – Inertial SSI (cont'd)

The real part of the stiffness and damping of the translational and rotational springs and dashpots are expressed by:

$$k_u = \alpha_u K_u, k_\theta = \alpha_\theta K_\theta$$

$$c_u = \beta_u \frac{K_u r_1}{V_S}, c_\theta = \beta_\theta \frac{K_\theta r_2}{V_S}$$

where

K_u, K_θ, static translational and rotational stiffness, and

α_u, β_u, α_θ, β_θ nondimensional parameters that express the frequency dependence of the impedance terms.

Foundation radii are computed separately for translational and rotational deformation modes to match the area (A_f) and moment of inertia (I_f) of the actual foundation:

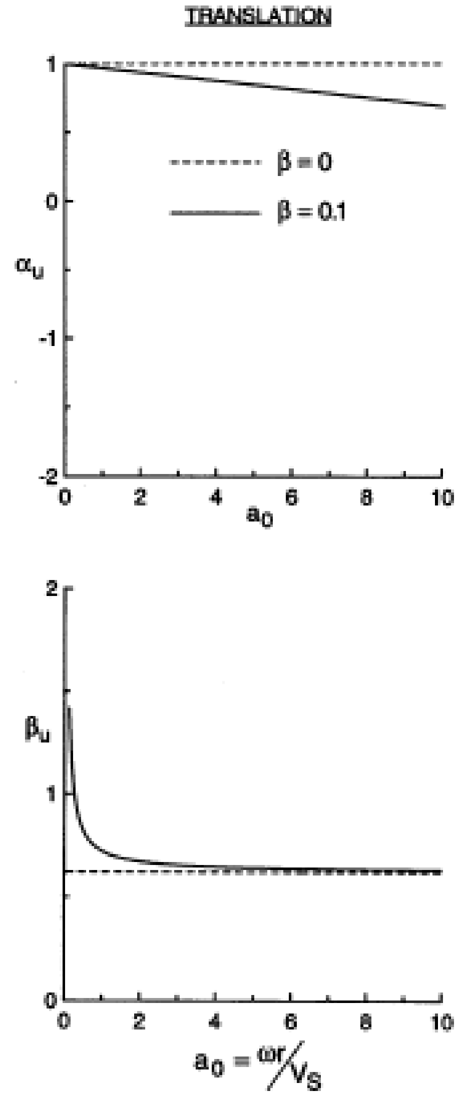
$$r_1 = \sqrt{\frac{A_f}{\pi}}, r_2 = \sqrt[4]{\frac{4 I_f}{\pi}}$$

Simulation of foundation

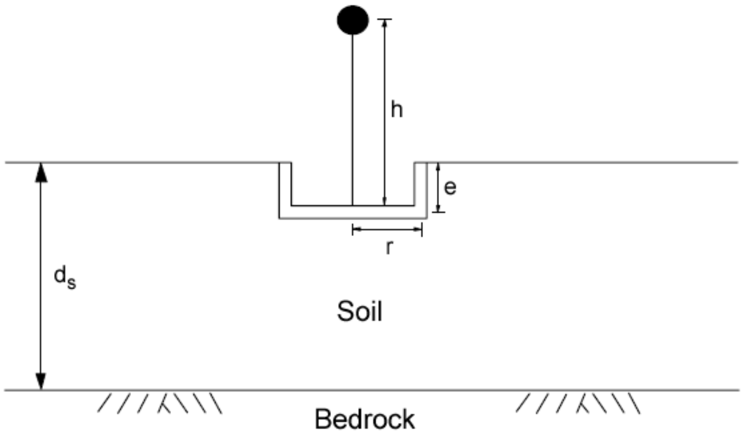
Important parameters that should be included in foundation modeling:

Stiffness: Most indirect methods assume that the foundation behaves as rigid body.

Significant difference from real behavior, i.e., in the case of a flexible foundation of a superstructure with rigid inner core.



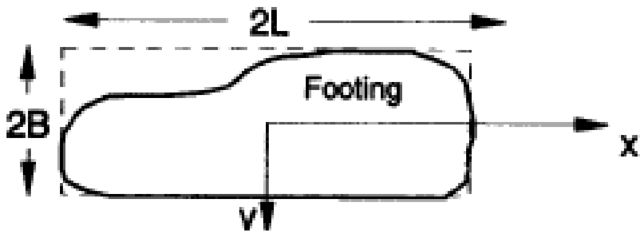
Simulation of foundation



- Embedded foundations

$$(K_u)_{FL/E} = K_u\left(1+\frac{2}{3}\frac{e}{r}\right)\left(1+\frac{5}{4}\frac{e}{d_s}\right)\left(1+\frac{1}{2}\frac{r}{d_s}\right)$$

$$(K_\theta)_{FL/E} = K_\theta\left(1+2\frac{e}{r}\right)\left(1+0.7\frac{e}{d_s}\right)\left(1+\frac{1}{6}\frac{r}{d_s}\right)$$



- Geometry

Soil-Structure Interaction in Seismic Codes and Guidelines

- Eurocode – American & Japanese codes
- Greek recommendations for Retrofit in (KANEPE)
- FEMA 440 – Inelastic Static Analysis

When SSI should be taken into consideration?

FEMA 440

Kinematic Interaction

- Important for small eigenperiods (<0.5 sec), large dimensions of foundation, and for embedded foundations at a depth greater than 3.0 m.

- It can be omitted for embedded foundations in stiff soil.

When SSI should be taken into consideration?

Greek Code for Retrofit - KANEPE

Soil-Structure Interaction should be considered when the period increase leads to an increase of spectral acceleration.

- Simplified procedure - elastic static analysis.
- Detailed procedure – elaborated modeling – dynamic analysis and nonlinear methods.

For the simplified procedure a decrease up to 25% of seismic demand at individual structural members is acceptable.

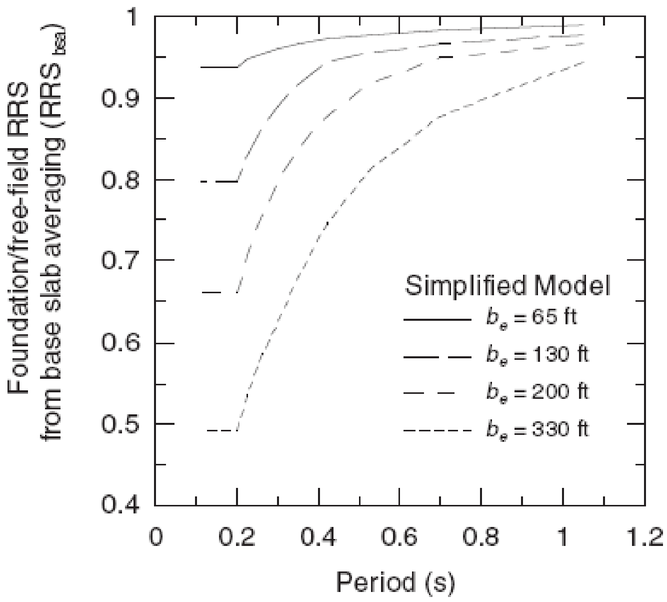
FEMA 440 Procedure

A. Kinematic Interaction

1. **Calculate the effective structural stiffness of foundation with dimensions *a* and *b*:**

$$b_e = \sqrt{a \cdot b}$$

2. **Calculate period-dependant Response Spectra Ratio from base slab averaging (RRS_{bsa}).**



FEMA 440 Procedure

A. Kinematic Interaction (cont'd)

3. Calculate an additional period-dependant Response Spectra Ratio from embedment effects (RRS_e).

$$RRS_e = cos\left(\frac{2\pi e}{Tnv_s}\right) \geq max\left\{0.453, RRS_{e(T=0.2\,s)}\right\}$$

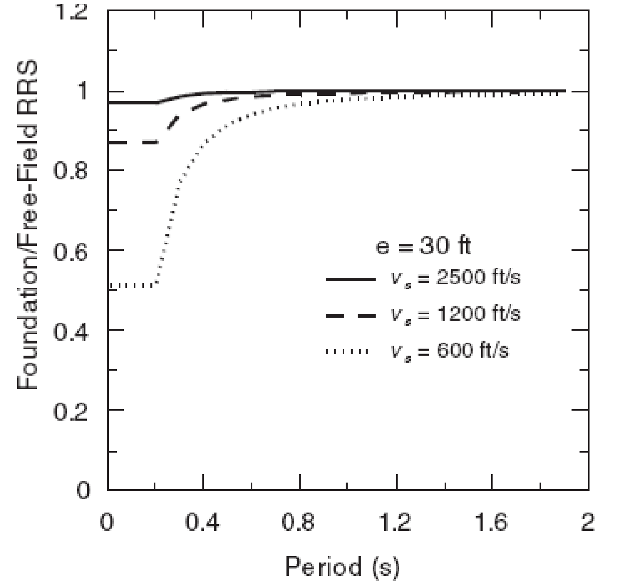
e: foundation embedment (in feet)

v_s: average shear wave velocity, to a depth of b_e below foundation (ft/s)

n: shear wave velocity reduction factor for the expected PGA

Table 8-1 Approximate Values of Shear Wave Velocity Reduction Factor, *n*

	Peak Ground Acceleration (PGA)			
	0.10g	0.15g	0.20g	0.30g
n	0.90	0.80	0.70	0.65



FEMA 440 Procedure

A. Kinematic Interaction (cont'd)

4. Evaluate the product of RRS_{bsa} times RRS_e to obtain the total *RRS* for each period of interest.

$$RRS(T) = RRS_{bsa}(T) \cdot RRS_e(T)$$

5. The spectral ordinate of the foundation input motion at each period is the product of the free-field spectrum and the total *RRS*:

$$RS_{FIM} = RRS(T) \cdot RS_{freefield}(T)$$

Greek Recommendations for Retrofit - KANEPE

Simplified procedure

Effective translational period:

$$T' = T_o \sqrt{\left[1 + \frac{k_o}{k_x}\left(1 + \frac{k_x \cdot h_{ef}^2}{k_\varphi}\right)\right]}$$

where

T_o, k_o: period and stiffness for fixed-base assumption

k_x, k_φ: translational and rotational stiffness of foundation

h_{ef}: effective hight

2/3 of the total height for multistory buildings

total height for single story buildings

Greek Recommendations for Retrofit - KANEPE

Flexible-base damping ratio, ζ΄:

$$\zeta' = \zeta_o + \frac{\zeta}{\left(T'/T\right)^3}$$

where

ζ: fixed-base damping ratio for the superstructure (usually 5%)

ζ_o: foundation damping

(h_{ef}, foundation dimensions, T'/T_o ratio, PGA)

Early history and evolution

Historical aspects and development of the soil-structure interaction field can be found on *State of the Art* reviews, i.e., WHITMAN *et al* (1967), McNEIL (1969) and GAZETAS (1983), RICHART *et al* (1970), DAS (1983), PECKER (1984), HAUPT (1986), SIEFFERT *et al* (1992), SPYRAKOS (2003), MYLONAKIS *et al* (2006).

Early history and evolution

Indicatively certain significant approaches and methods developed during the previous century are reported related to surface foundations:

- **1904: LAMB studied the vibrations of a linear elastic half-space to a harmonic load acting on a point.**

- **1936: REISSNER analyses the response to a vertical harmonic excitation of a plate placed at the surface of a homogeneous elastic half-space. The existence of energy dissipated by radiation is reported for the first time.**

<u>Early history and evolution</u>

- **1953 to 1956: SUNG, QUILAN, ARNOLD *et al.* and BYCROFT clarified and generalized the work of REISSNER on movements corresponding to the <u>six degrees-of-freedom</u> of the footing.**

- **1962 to 1967: AWOJOBI *et al.* and ELORDUY *et al.* extended the previous methods. The idea that soil - footing behavior in vertical displacement can be represented by a single-degree-of-freedom system with stiffness and damping as constants independent of frequency (<u>lumped parameters</u>) is firstly introduced by HSIEH and especially LYSMER.**

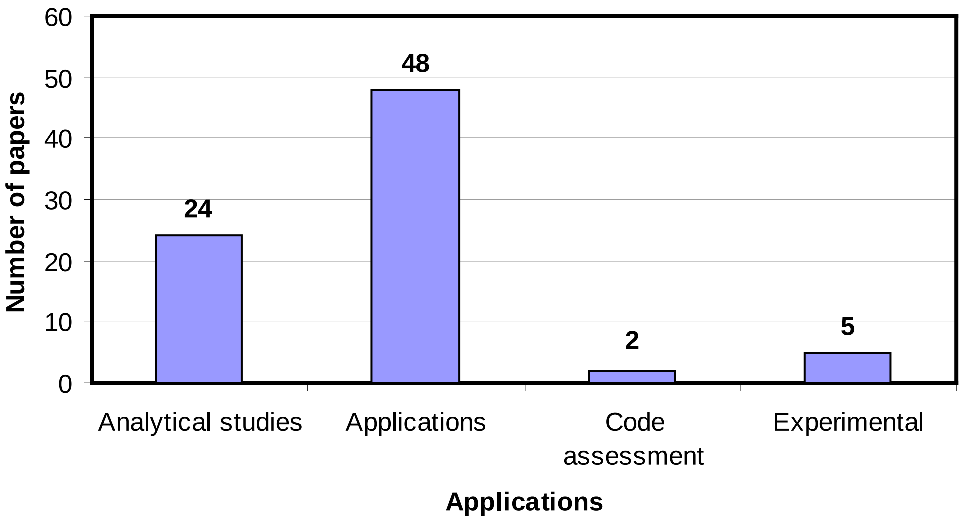
Early history and evolution

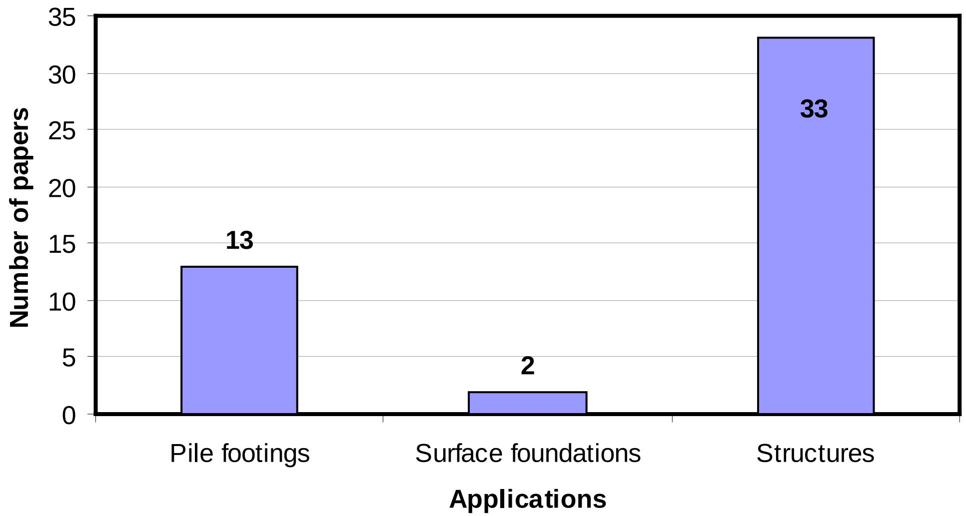
- **1962 to 1967 (cont'd): This simplified approach commonly designated as "Lysmer's analogy", has been extended to all movements by RICHART and WHITMAN. Fictitious masses are used to allow for an easier adjustment of the resonance frequencies.**

- **Late '60s early '70s: Development of "impedance functions" are presented in the form of two frequency dependent functions: the first being the real, the second the imaginary part of the complex dynamic stiffness**
- **Significant contribution of Greek researchers.**

SSI at the recent 14th World Conference on Earthquake Engineering (China, October 12~17 2008)

79 scientific papers on SSI





Distribution depending on application

SSI and study of modal characteristics based on recorded data

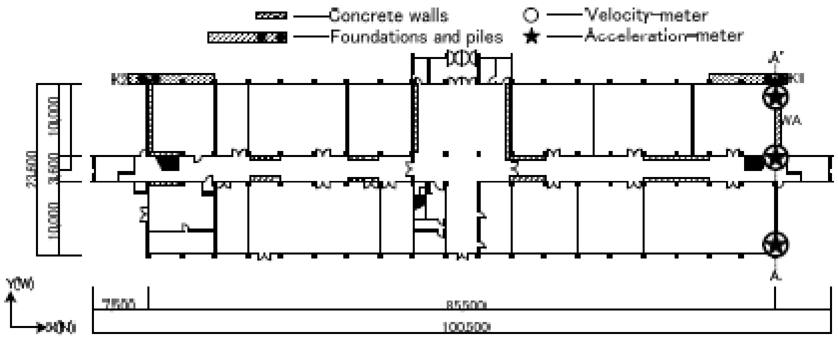


Fig. 1 Plan on the first floor of the retrofitted building

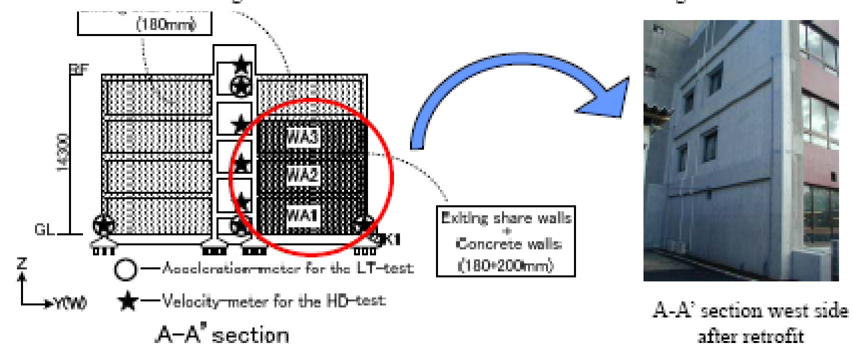
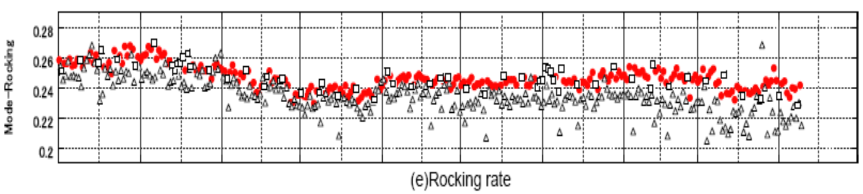


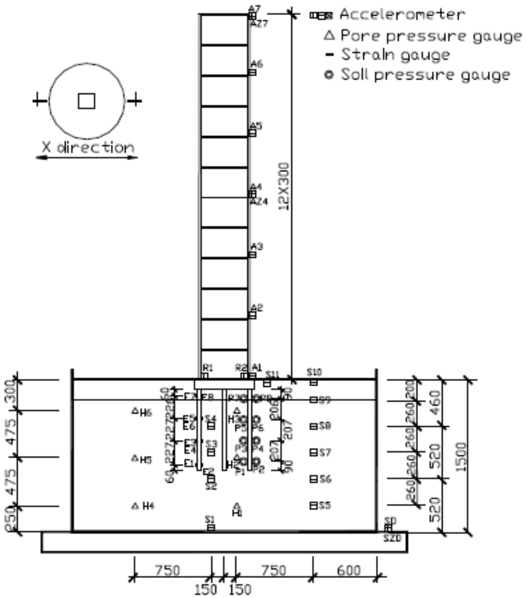
Fig. 2 A-A' section of the building after retrofit and measurement installations for ambient vibratic

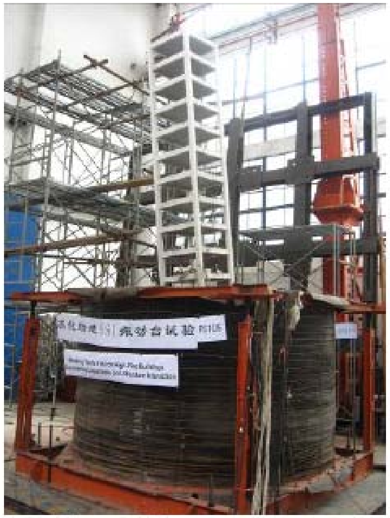


Retrofit of a multistory building in Japan

- Study of the effects of retrofit procedures

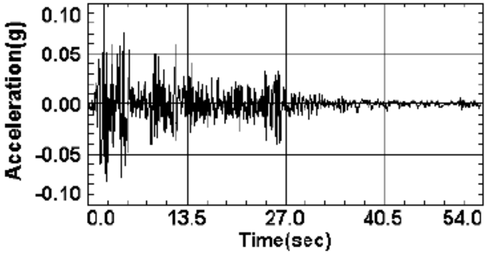
SSI and experimental testing on earthquake simulator



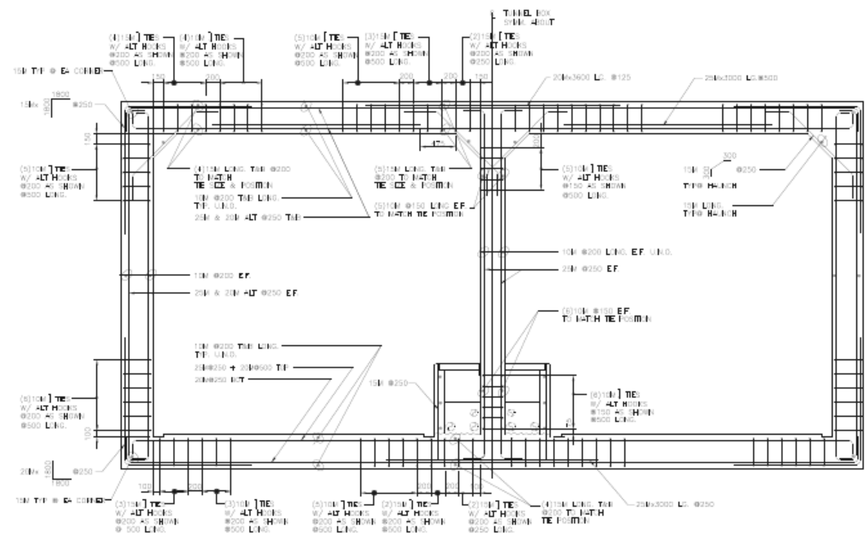


SSI Experiments

Soil Liquefaction



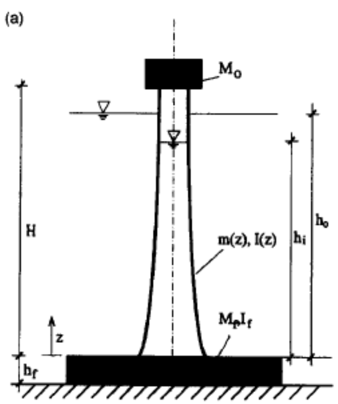
SSI and underground structures

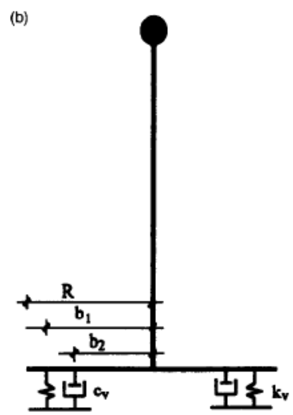


«Cut and cover» tunnel (6.6 km)

Rapid Transit System, Vancouver Canada

Soil-Structure-Liquid Interaction with foundation uplift





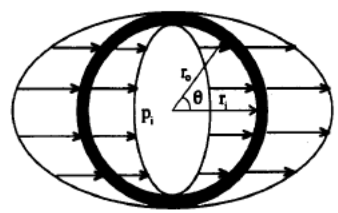
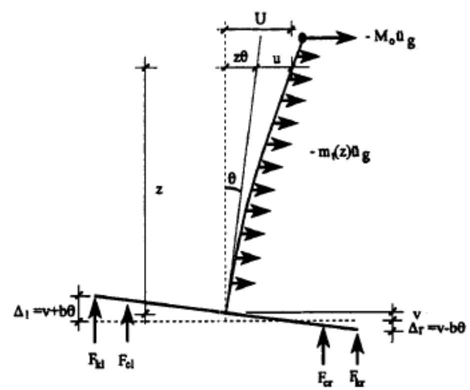
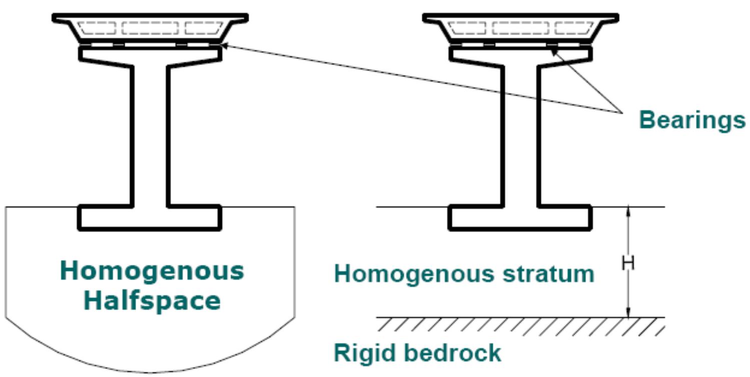
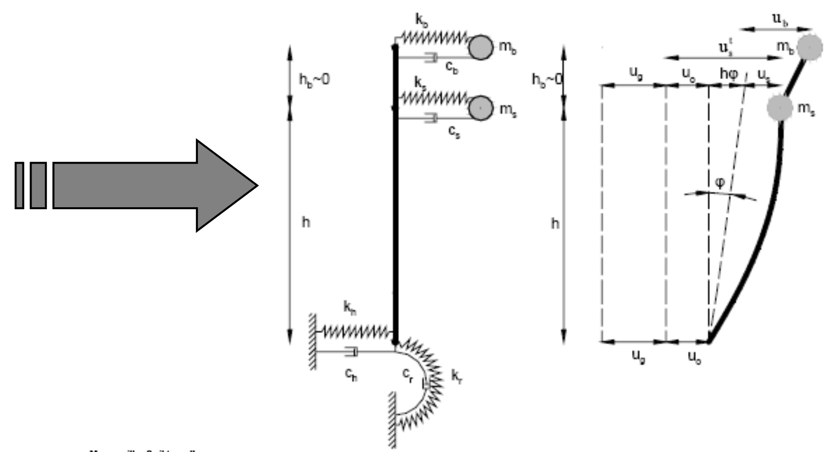


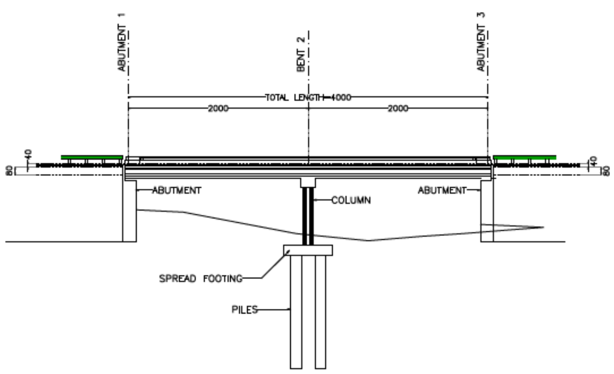
Fig. 3. Hydrodynamic pressure.

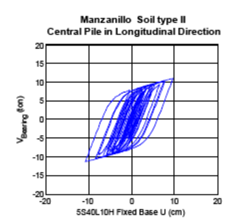


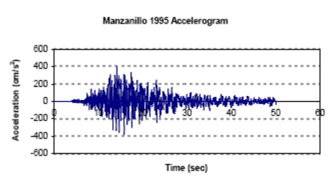
SSI and seismic isolation











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