건축물의 하부구조를 고려한 지진해석과 내진설계

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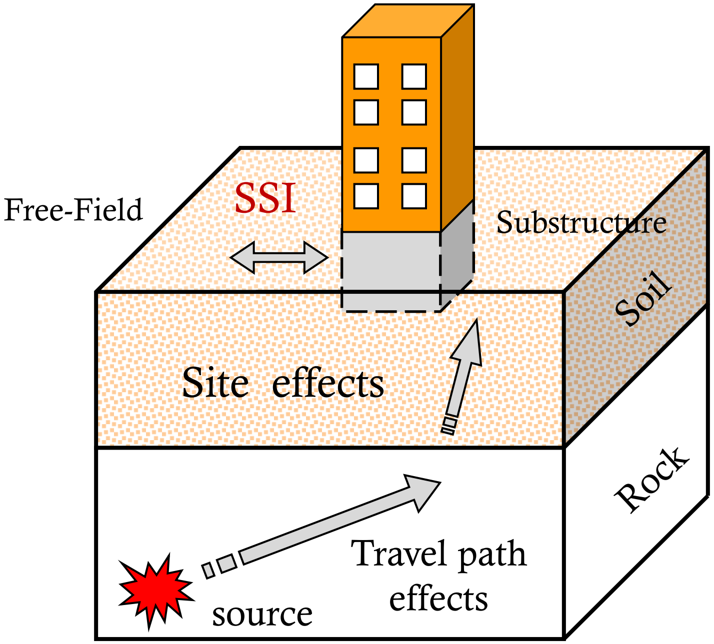
지반운동의 영향

토사지반과 하부구조의 영향

1. Site effect
2. Soil-structure interaction (SSI)



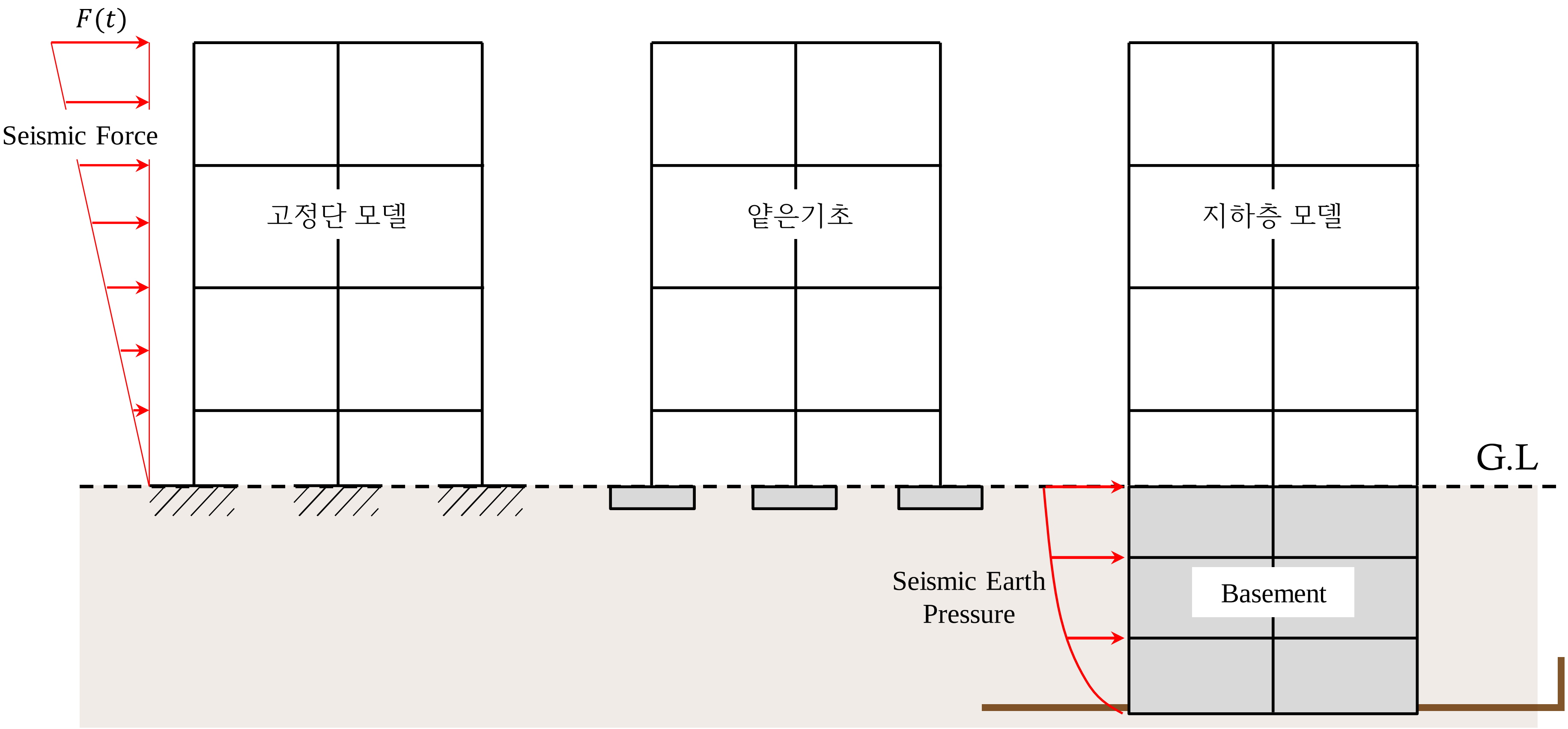
소개

지반-구조물 상호작용 (Soil-Structure Interaction)

→ 고정단 모델 : 지진하중이 증가할수록 지진응답이 비례적으로 증가

→ 얕은 기초 : 지반-얕은기초 상호작용에 따른 지진응답의 변화

→ 지하층 모델 : 지하층에 의한 지진응답의 변화



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    b. FEMA 440 (2005)
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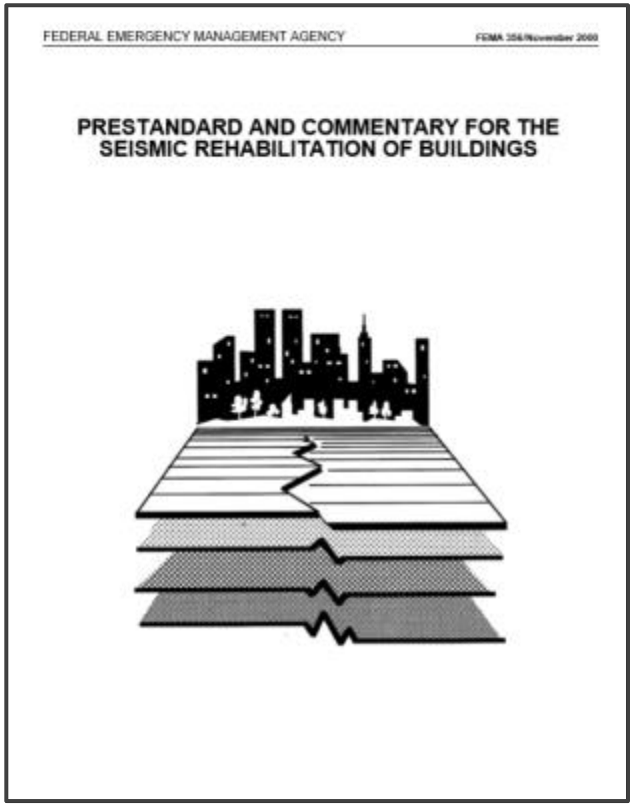
    e. 건축물 내진설계 기준 (KDS 41 17 00)
2. 얕은기초가 있는 구조물의 거동
3. 지하구조물을 고려한 건축물의 내진설계
4. 결론

1. 관련 기준 소개

FEMA 356 (2000)

SSI 효과로 고유진동주기 변화에 따른 스펙트럼 가속도가 증가할 수 있는 경우,

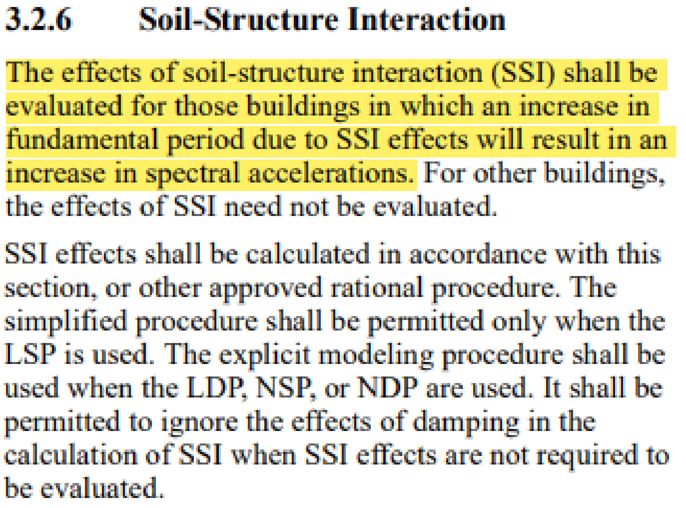
SSI 효과를 고려



FEDERAL EMERGENCY MANAGEMENT AGENCY

FEMA 356/November 2000

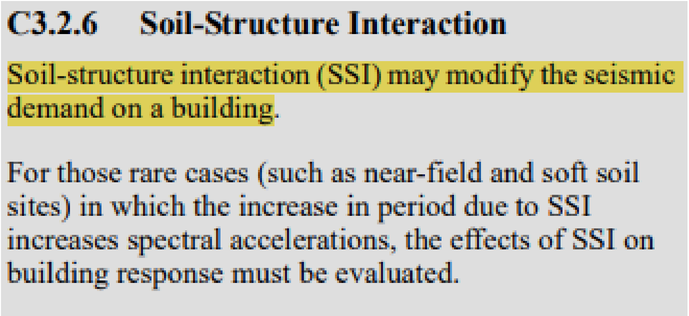
PRESTANDARD AND COMMENTARY FOR THE
SEISMIC REHABILITATION OF BUILDINGS



3.2.6 Soil-Structure Interaction

The effects of soil-structure interaction (SSI) shall be evaluated for those buildings in which an increase in fundamental period due to SSI effects will result in an increase in spectral accelerations. For other buildings, the effects of SSI need not be evaluated.

SSI effects shall be calculated in accordance with this section, or other approved rational procedure. The simplified procedure shall be permitted only when the LSP is used. The explicit modeling procedure shall be used when the LDP, NSP, or NDP are used. It shall be permitted to ignore the effects of damping in the calculation of SSI when SSI effects are not required to be evaluated.



C3.2.6 Soil-Structure Interaction

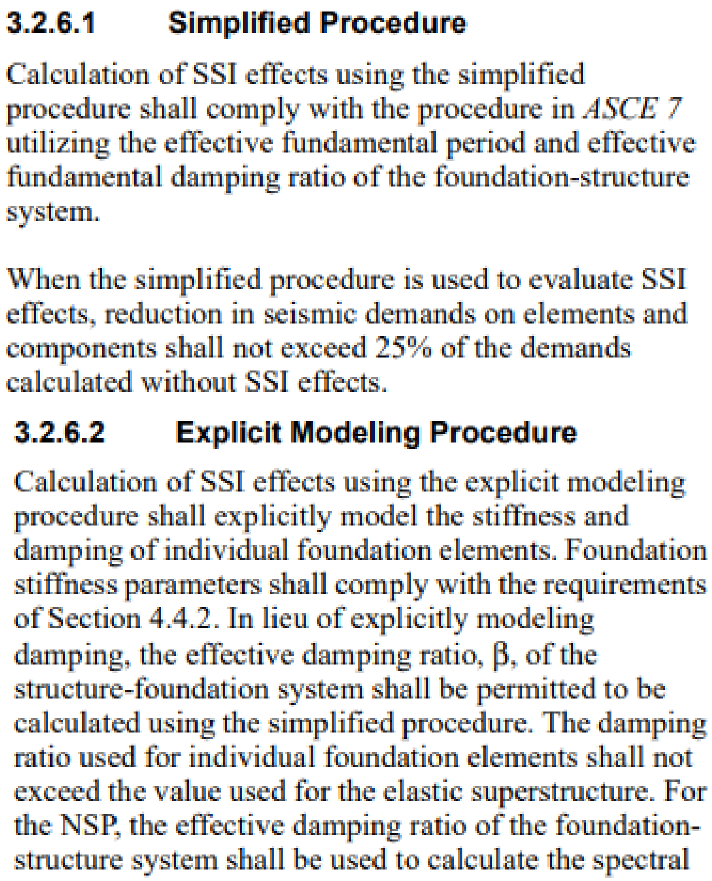
Soil-structure interaction (SSI) may modify the seismic demand on a building.

For those rare cases (such as near-field and soft soil sites) in which the increase in period due to SSI increases spectral accelerations, the effects of SSI on building response must be evaluated.

1. 관련 기준 소개

FEMA 356 (2000)

SSI 효과를 고려하는 방안으로 단순화된 절차와 모델링 절차를 제시



3.2.6.1 Simplified Procedure

Calculation of SSI effects using the simplified procedure shall comply with the procedure in *ASCE 7* utilizing the effective fundamental period and effective fundamental damping ratio of the foundation-structure system.

When the simplified procedure is used to evaluate SSI effects, reduction in seismic demands on elements and components shall not exceed 25% of the demands calculated without SSI effects.

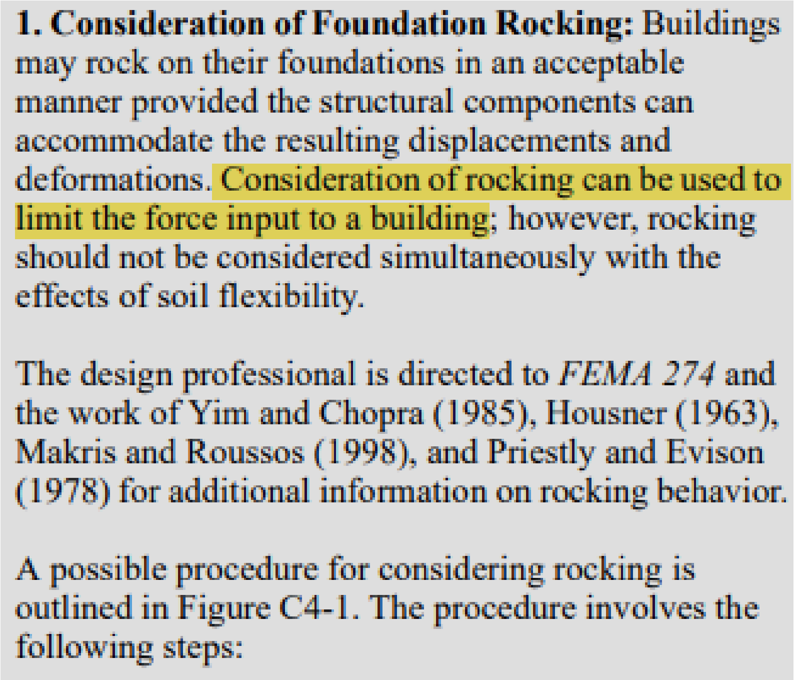
3.2.6.2 Explicit Modeling Procedure

Calculation of SSI effects using the explicit modeling procedure shall explicitly model the stiffness and damping of individual foundation elements. Foundation stiffness parameters shall comply with the requirements of Section 4.4.2. In lieu of explicitly modeling damping, the effective damping ratio, β, of the structure-foundation system shall be permitted to be calculated using the simplified procedure. The damping ratio used for individual foundation elements shall not exceed the value used for the elastic superstructure. For the NSP, the effective damping ratio of the foundation-structure system shall be used to calculate the spectral

1. 관련 기준 소개

FEMA 356 (2000)

구조 구성요소가 변위 및 변형을 수용할 수 있다면 건물은 기초 위에서 흔들릴 수 있으며 흔들림(Rocking)을 고려하여 건축물에 가해지는 힘을 제한할 수 있음



1. Consideration of Foundation Rocking: Buildings may rock on their foundations in an acceptable manner provided the structural components can accommodate the resulting displacements and deformations. Consideration of rocking can be used to limit the force input to a building; however, rocking should not be considered simultaneously with the effects of soil flexibility.

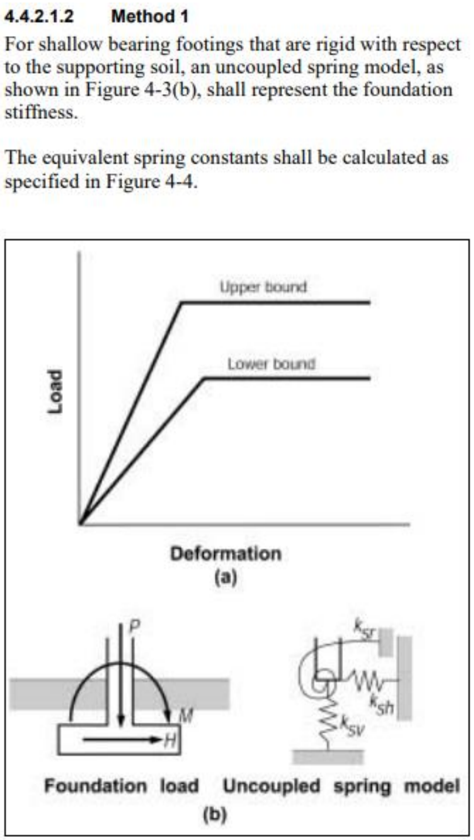
The design professional is directed to *FEMA 274* and the work of Yim and Chopra (1985), Housner (1963), Makris and Roussos (1998), and Priestly and Evison (1978) for additional information on rocking behavior.

A possible procedure for considering rocking is outlined in Figure C4-1. The procedure involves the following steps:

1. 관련 기준 소개

FEMA 356 (2000)

구조물 해석에서 흔들림(Rocking)을 반영하는 방안으로 기초 하부의 스프링 모델을 적용

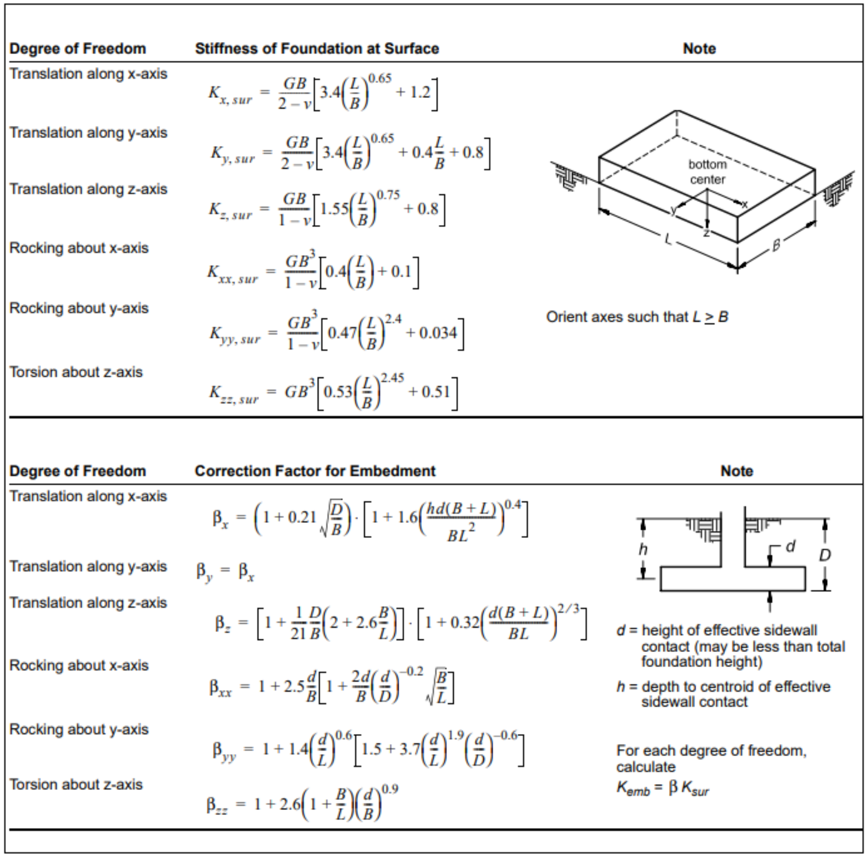


4.4.2.1.2 Method 1

For shallow bearing footings that are rigid with respect to the supporting soil, an uncoupled spring model, as shown in Figure 4-3(b), shall represent the foundation stiffness.

The equivalent spring constants shall be calculated as specified in Figure 4-4.

Foundation load Uncoupled spring model
(b)



Degree of Freedom	Stiffness of Foundation at Surface	Note
Translation along x-axis	$K_{x,\,sur} = \frac{GB}{2-v}\left[3.4\left(\frac{L}{B}\right)^{0.65} + 1.2\right]$	Orient axes such that $L \geq B$
Translation along y-axis	$K_{y,\,sur} = \frac{GB}{2-v}\left[3.4\left(\frac{L}{B}\right)^{0.65} + 0.4\frac{L}{B} + 0.8\right]$	
Translation along z-axis	$K_{z,\,sur} = \frac{GB}{1-v}\left[1.55\left(\frac{L}{B}\right)^{0.75} + 0.8\right]$	
Rocking about x-axis	$K_{xx,\,sur} = \frac{GB^3}{1-v}\left[0.4\left(\frac{L}{B}\right) + 0.1\right]$	
Rocking about y-axis	$K_{yy,\,sur} = \frac{GB^3}{1-v}\left[0.47\left(\frac{L}{B}\right)^{2.4} + 0.034\right]$	
Torsion about z-axis	$K_{zz,\,sur} = GB^3\left[0.53\left(\frac{L}{B}\right)^{2.45} + 0.51\right]$	

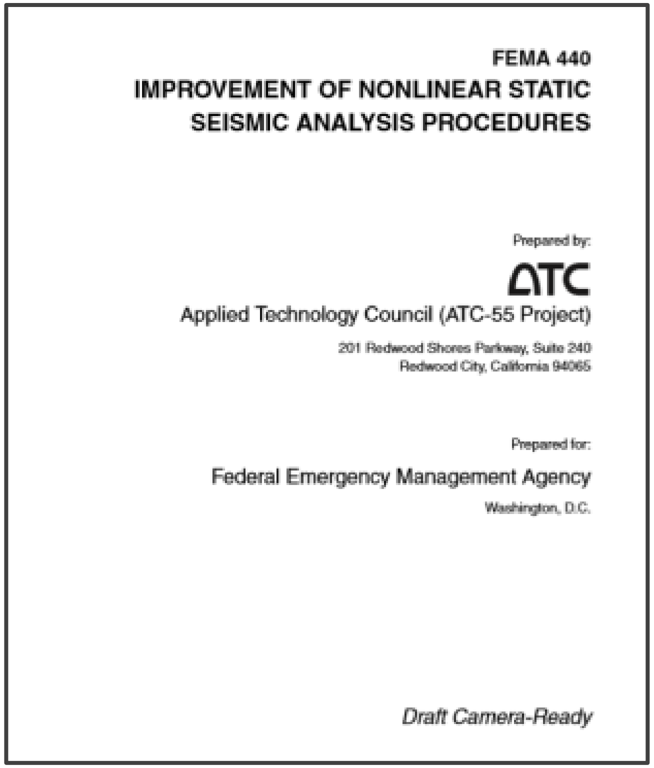
Degree of Freedom	Correction Factor for Embedment	Note
Translation along x-axis	$\beta_x = \left(1 + 0.21\sqrt{\frac{D}{B}}\right) \cdot \left[1 + 1.6\left(\frac{hd(B+L)}{BL^2}\right)^{0.4}\right]$	d = height of effective sidewall contact (may be less than total foundation height) h = depth to centroid of effective sidewall contact For each degree of freedom, calculate $K_{emb} = \beta K_{sur}$
Translation along y-axis	$\beta_y = \beta_x$	
Translation along z-axis	$\beta_z = \left[1 + \frac{1}{21}\frac{D}{B}\left(2 + 2.6\frac{B}{L}\right)\right] \cdot \left[1 + 0.32\left(\frac{d(B+L)}{BL}\right)^{2/3}\right]$	
Rocking about x-axis	$\beta_{xx} = 1 + 2.5\frac{d}{B}\left[1 + \frac{2d}{B}\left(\frac{d}{D}\right)^{-0.2}\sqrt{\frac{B}{L}}\right]$	
Rocking about y-axis	$\beta_{yy} = 1 + 1.4\left(\frac{d}{L}\right)^{0.6}\left[1.5 + 3.7\left(\frac{d}{L}\right)^{1.9}\left(\frac{d}{D}\right)^{-0.6}\right]$	
Torsion about z-axis	$\beta_{zz} = 1 + 2.6\left(1 + \frac{B}{L}\right)\left(\frac{d}{B}\right)^{0.9}$	

Contents

1. 관련 기준 소개

FEMA 440 (2005)

FEMA 440에서는 구조물 해석 시 SSI 효과를 고려하는 경우 주요 3가지 경향에 대해서 명시



FEMA 440
IMPROVEMENT OF NONLINEAR STATIC
SEISMIC ANALYSIS PROCEDURES

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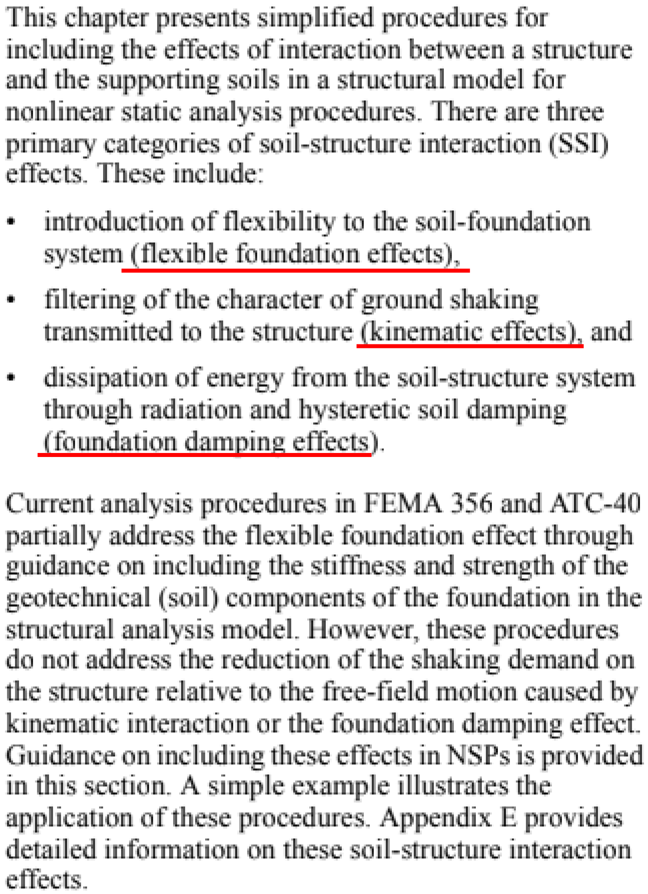
Prepared for:
Federal Emergency Management Agency
Washington, D.C.

Draft Camera-Ready



This chapter presents simplified procedures for including the effects of interaction between a structure and the supporting soils in a structural model for nonlinear static analysis procedures. There are three primary categories of soil-structure interaction (SSI) effects. These include:

- introduction of flexibility to the soil-foundation system (flexible foundation effects),
- filtering of the character of ground shaking transmitted to the structure (kinematic effects), and
- dissipation of energy from the soil-structure system through radiation and hysteretic soil damping (foundation damping effects).

Current analysis procedures in FEMA 356 and ATC-40 partially address the flexible foundation effect through guidance on including the stiffness and strength of the geotechnical (soil) components of the foundation in the structural analysis model. However, these procedures do not address the reduction of the shaking demand on the structure relative to the free-field motion caused by kinematic interaction or the foundation damping effect. Guidance on including these effects in NSPs is provided in this section. A simple example illustrates the application of these procedures. Appendix E provides detailed information on these soil-structure interaction effects.

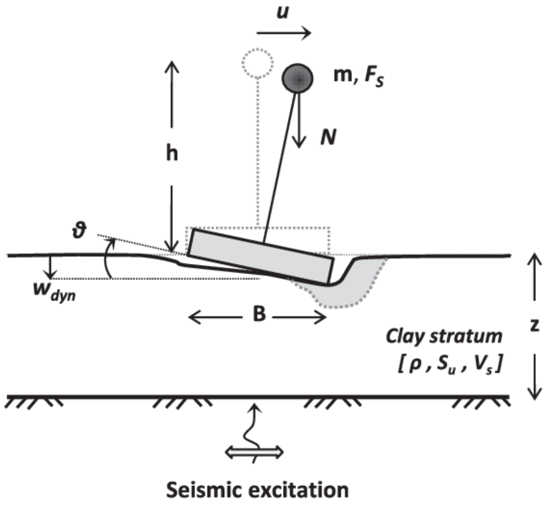
1. 관련 기준 소개

FEMA 440 (2005)

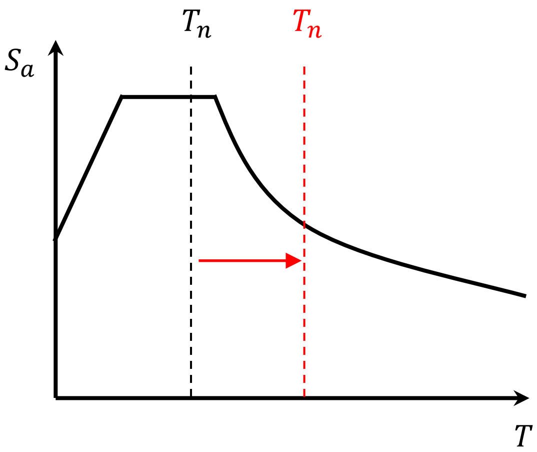
Flexible Foundation Effects

전체 구조 시스템의 응답은 기초 시스템의 구조 및 지질학적 부분에 변형을 포함

→ 이러한 SSI 효과는 고정단 모델링 접근방식과 비교하여, 구조물의 진동주기가 길어지고, 다양한 요소들간의 힘의 분포가 변화하며, 비탄성 주기 및 비탄성 거동의 모드가 변화



Foundation Rocking



Period Lengthening

1. 관련 기준 소개

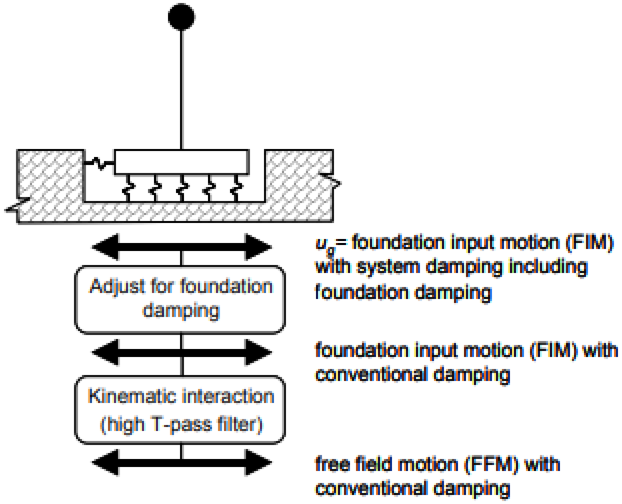
FEMA 440 (2005)

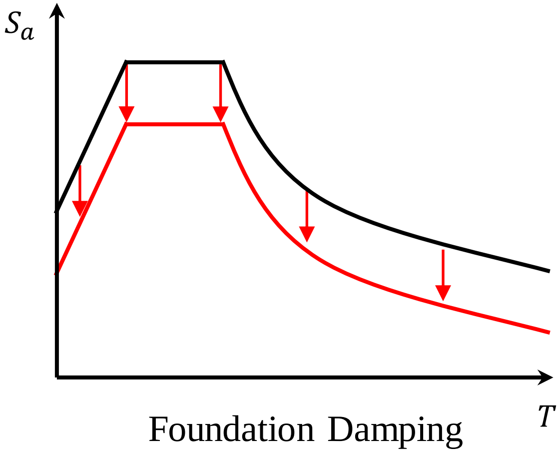
Foundation Damping Effects

기초 감쇠 효과는 기초와 지지 토양의 상대적인 움직임에서 비롯됨

→ 그 결과 구조물에 전해지는 지반 운동 스펙트럼의 효과적인 감소가 예측됨

→ 구조-기초-지반을 포함한 전체 시스템에 대한 시스템 감쇠비를 통해 시스템 모델에 적용되는 입력 운동을 수정할 수 있음





Foundation Damping

1. 관련 기준 소개

FEMA 440 (2005)

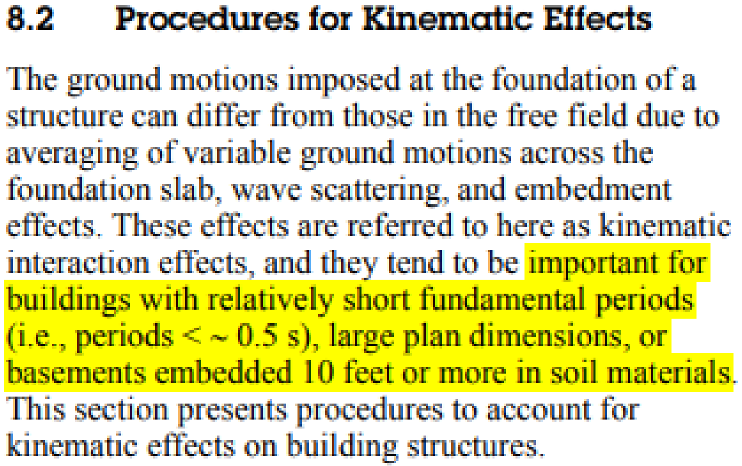
Kinematic Interaction Effects

구조물 기초에 전달되는 지반운동은 자유장 운동과 다를 수 있으며, 다음과 같은 구조물에 중요한 경향이 있음

→ 단주기 건축물 ($T_n < 0.5s$)

→ 대규모 평면치수

→ 지반에 3m 이상 내장된 지하층을 포함하는 경우 (Embedded Effect)



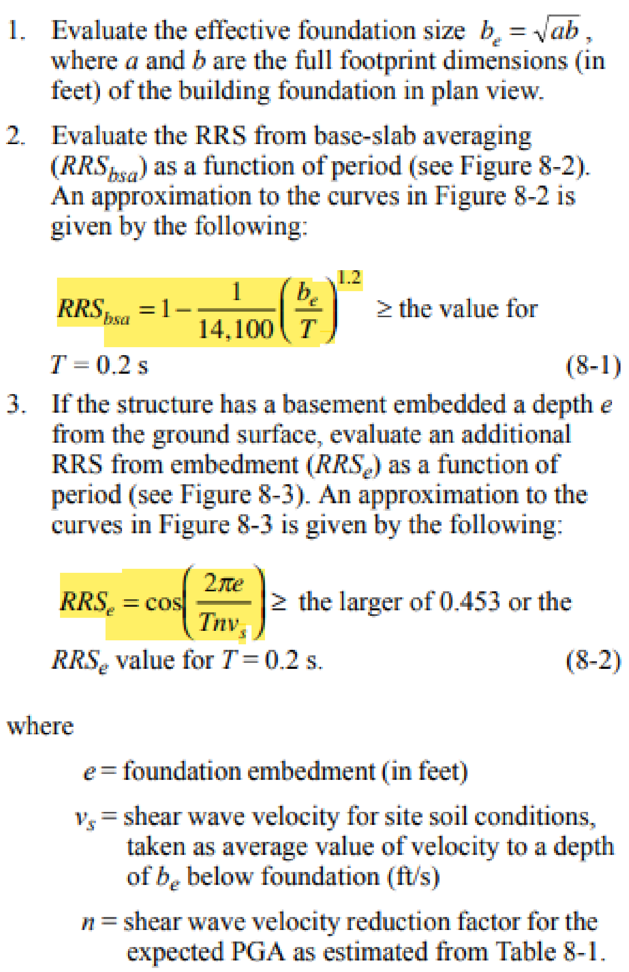
8.2 Procedures for Kinematic Effects

The ground motions imposed at the foundation of a structure can differ from those in the free field due to averaging of variable ground motions across the foundation slab, wave scattering, and embedment effects. These effects are referred to here as kinematic interaction effects, and they tend to be important for buildings with relatively short fundamental periods (i.e., periods < ~ 0.5 s), large plan dimensions, or basements embedded 10 feet or more in soil materials. This section presents procedures to account for kinematic effects on building structures.

1. 관련 기준 소개

FEMA 440 (2005)

Kinematic Interaction Effects



1. Evaluate the effective foundation size $b_e = \sqrt{ab}$, where a and b are the full footprint dimensions (in feet) of the building foundation in plan view.
2. Evaluate the RRS from base-slab averaging (RRS_{bsa}) as a function of period (see Figure 8-2). An approximation to the curves in Figure 8-2 is given by the following:

$$RRS_{bsa} = 1 - \frac{1}{14,100}\left(\frac{b_e}{T}\right)^{1.2} \geq \text{the value for } T = 0.2\text{ s} \qquad (8\text{-}1)$$

3. If the structure has a basement embedded a depth e from the ground surface, evaluate an additional RRS from embedment (RRS_e) as a function of period (see Figure 8-3). An approximation to the curves in Figure 8-3 is given by the following:

$$RRS_e = \cos\left(\frac{2\pi e}{Tnv_s}\right) \geq \text{the larger of 0.453 or the } RRS_e \text{ value for } T = 0.2\text{ s.} \qquad (8\text{-}2)$$

where

e = foundation embedment (in feet)

v_s = shear wave velocity for site soil conditions, taken as average value of velocity to a depth of b_e below foundation (ft/s)

n = shear wave velocity reduction factor for the expected PGA as estimated from Table 8-1.

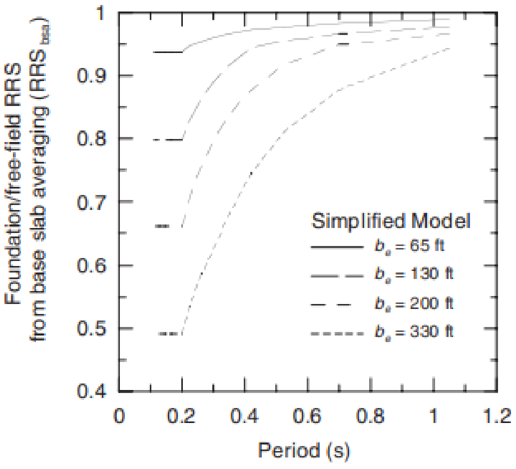


Figure 8-2 Ratio of response spectra for base slab averaging, RRS_{bsa}, as a function of perio T, and effective foundation size, b_e.

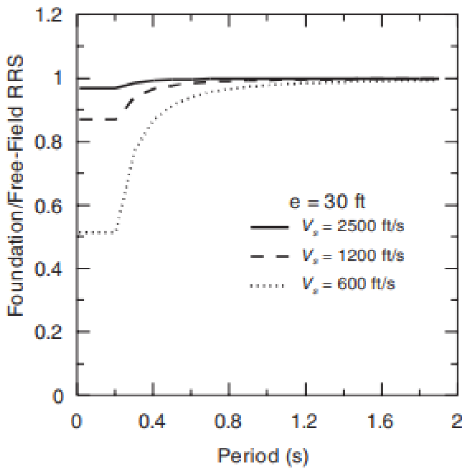
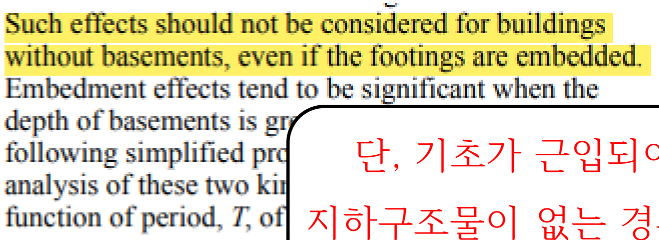


Figure 8-3 Ratio of response spectra for embedment RRS_e, for an embedment, e, of 30 feet as a function of period, T, and shear wave velocity, v_s.



Such effects should not be considered for buildings without basements, even if the footings are embedded. Embedment effects tend to be significant when the depth of basements is gr
following simplified pro
analysis of these two ki
function of period, T, of

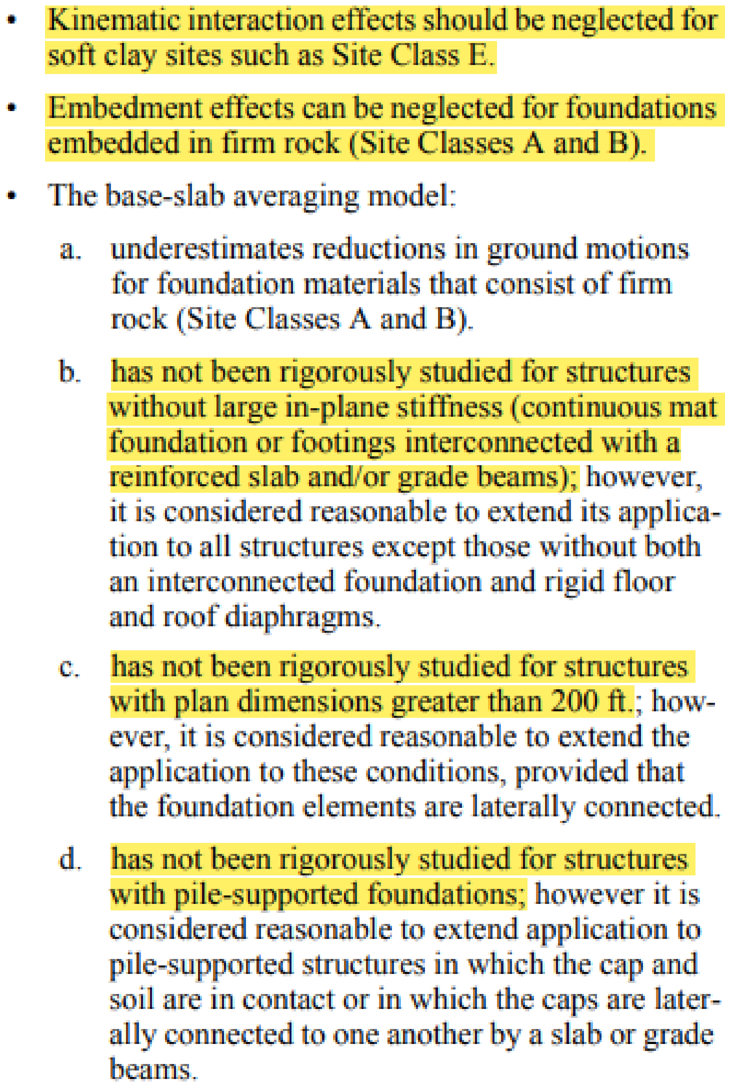
단, 기초가 근입되어 있더라도
지하구조물이 없는 경우에 대해서는
Embedded Effect를 고려할 수 없음

1. 관련 기준 소개

FEMA 440 (2005)

Embedded Effect 적용 시 제한사항

1) 연질 점토 지반조건(S_E)에 대해서는 Kinematic Interaction Effects를 무시
2) 단단한 지반(S_A and S_B)에 지지되어 있는 기초에 대해서는 Embedded Effect를 무시
3) 큰 평면 내 강성이 없는 구조물에 대해서는 연구되지 않음
4) 평면치수가 60m 이상인 구조물에 대해서는 연구되지 않음
5) 말뚝 지지 기초가 있는 구조물에 대해서는 연구되지 않음



- Kinematic interaction effects should be neglected for soft clay sites such as Site Class E.
- Embedment effects can be neglected for foundations embedded in firm rock (Site Classes A and B).
- The base-slab averaging model:
  a. underestimates reductions in ground motions for foundation materials that consist of firm rock (Site Classes A and B).
  b. has not been rigorously studied for structures without large in-plane stiffness (continuous mat foundation or footings interconnected with a reinforced slab and/or grade beams); however, it is considered reasonable to extend its application to all structures except those without both an interconnected foundation and rigid floor and roof diaphragms.
  c. has not been rigorously studied for structures with plan dimensions greater than 200 ft.; however, it is considered reasonable to extend the application to these conditions, provided that the foundation elements are laterally connected.
  d. has not been rigorously studied for structures with pile-supported foundations; however it is considered reasonable to extend application to pile-supported structures in which the cap and soil are in contact or in which the caps are laterally connected to one another by a slab or grade beams.

1. 관련 기준 소개

FEMA 440 (2005)

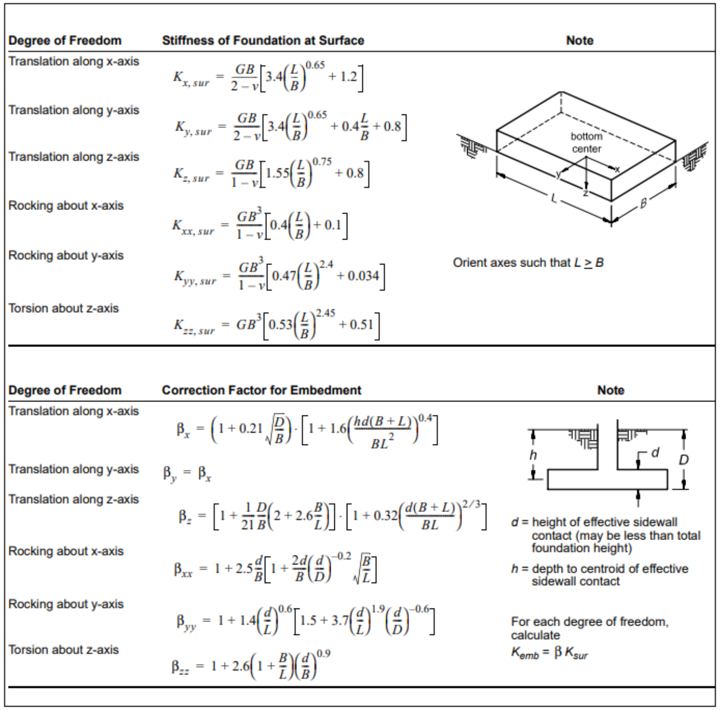
기초 강성 행렬

기초에 스프링을 적용하기 위한 강성 행렬은 FEMA 356 기준을 적용

4. Calculate the translational stiffness of the foundation, K_x. This can be evaluated using the procedures in FEMA 356 (Chapter 4) or ATC-40 (Chapter 10). For many applications, the translational stiffness can be estimated as

$$K_x = \frac{8}{2-\upsilon} G r_x \tag{8-5}$$

where G = effective, strain-degraded soil shear modulus and υ = soil Poisson's ratio (~0.3 for sand, ~0.45 for clay).



Degree of Freedom	Stiffness of Foundation at Surface	Note
Translation along x-axis	$K_{x,\,sur} = \frac{GB}{2-v}\left[3.4\left(\frac{L}{B}\right)^{0.65} + 1.2\right]$	Orient axes such that $L \geq B$
Translation along y-axis	$K_{y,\,sur} = \frac{GB}{2-v}\left[3.4\left(\frac{L}{B}\right)^{0.65} + 0.4\frac{L}{B} + 0.8\right]$	
Translation along z-axis	$K_{z,\,sur} = \frac{GB}{1-v}\left[1.55\left(\frac{L}{B}\right)^{0.75} + 0.8\right]$	
Rocking about x-axis	$K_{xx,\,sur} = \frac{GB^3}{1-v}\left[0.4\left(\frac{L}{B}\right) + 0.1\right]$	
Rocking about y-axis	$K_{yy,\,sur} = \frac{GB^3}{1-v}\left[0.47\left(\frac{L}{B}\right)^{2.4} + 0.034\right]$	
Torsion about z-axis	$K_{zz,\,sur} = GB^3\left[0.53\left(\frac{L}{B}\right)^{2.45} + 0.51\right]$	

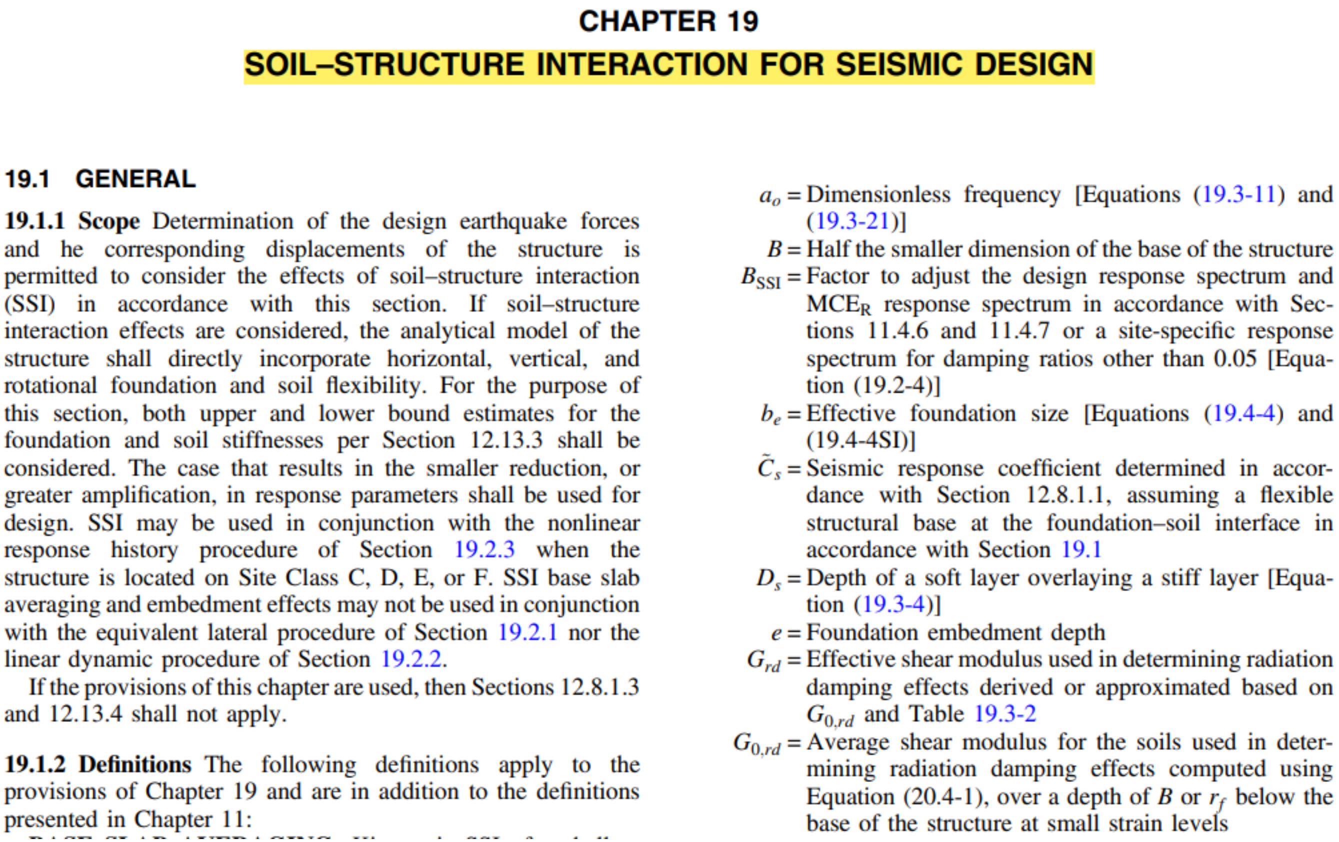
Degree of Freedom	Correction Factor for Embedment	Note
Translation along x-axis	$\beta_x = \left(1 + 0.21\sqrt{\frac{D}{B}}\right) \cdot \left[1 + 1.6\left(\frac{hd(B+L)}{BL^2}\right)^{0.4}\right]$	
Translation along y-axis	$\beta_y = \beta_x$	
Translation along z-axis	$\beta_z = \left[1 + \frac{1}{21}\frac{D}{B}\left(2 + 2.6\frac{B}{L}\right)\right] \cdot \left[1 + 0.32\left(\frac{d(B+L)}{BL}\right)^{2/3}\right]$	d = height of effective sidewall contact (may be less than total foundation height)
Rocking about x-axis	$\beta_{xx} = 1 + 2.5\frac{d}{B}\left[1 + \frac{2d}{B}\left(\frac{d}{D}\right)^{-0.2}\sqrt{\frac{B}{L}}\right]$	h = depth to centroid of effective sidewall contact
Rocking about y-axis	$\beta_{yy} = 1 + 1.4\left(\frac{d}{L}\right)^{0.6}\left[1.5 + 3.7\left(\frac{d}{L}\right)^{1.9}\left(\frac{d}{D}\right)^{-0.6}\right]$	For each degree of freedom, calculate
Torsion about z-axis	$\beta_{zz} = 1 + 2.6\left(1 + \frac{B}{L}\right)\left(\frac{d}{B}\right)^{0.9}$	$K_{emb} = \beta K_{sur}$

Contents

1. 관련 기준 소개

ASCE 7-22 (2022)

ASCE 7-22 에서는 Chapter 19. Soil-Structure Interaction for Seismic Design 을 통해 내진설계 시 SSI 효과를 고려하는 방법에 대하여 구체적으로 기술하고 있음



CHAPTER 19

SOIL–STRUCTURE INTERACTION FOR SEISMIC DESIGN

19.1 GENERAL

19.1.1 Scope Determination of the design earthquake forces and he corresponding displacements of the structure is permitted to consider the effects of soil–structure interaction (SSI) in accordance with this section. If soil–structure interaction effects are considered, the analytical model of the structure shall directly incorporate horizontal, vertical, and rotational foundation and soil flexibility. For the purpose of this section, both upper and lower bound estimates for the foundation and soil stiffnesses per Section 12.13.3 shall be considered. The case that results in the smaller reduction, or greater amplification, in response parameters shall be used for design. SSI may be used in conjunction with the nonlinear response history procedure of Section 19.2.3 when the structure is located on Site Class C, D, E, or F. SSI base slab averaging and embedment effects may not be used in conjunction with the equivalent lateral procedure of Section 19.2.1 nor the linear dynamic procedure of Section 19.2.2.

If the provisions of this chapter are used, then Sections 12.8.1.3 and 12.13.4 shall not apply.

19.1.2 Definitions The following definitions apply to the provisions of Chapter 19 and are in addition to the definitions presented in Chapter 11:

a_o = Dimensionless frequency [Equations (19.3-11) and (19.3-21)]

B = Half the smaller dimension of the base of the structure

B_{SSI} = Factor to adjust the design response spectrum and MCE$_R$ response spectrum in accordance with Sections 11.4.6 and 11.4.7 or a site-specific response spectrum for damping ratios other than 0.05 [Equation (19.2-4)]

b_e = Effective foundation size [Equations (19.4-4) and (19.4-4SI)]

$\tilde{C}_s$ = Seismic response coefficient determined in accordance with Section 12.8.1.1, assuming a flexible structural base at the foundation–soil interface in accordance with Section 19.1

D_s = Depth of a soft layer overlaying a stiff layer [Equation (19.3-4)]

e = Foundation embedment depth

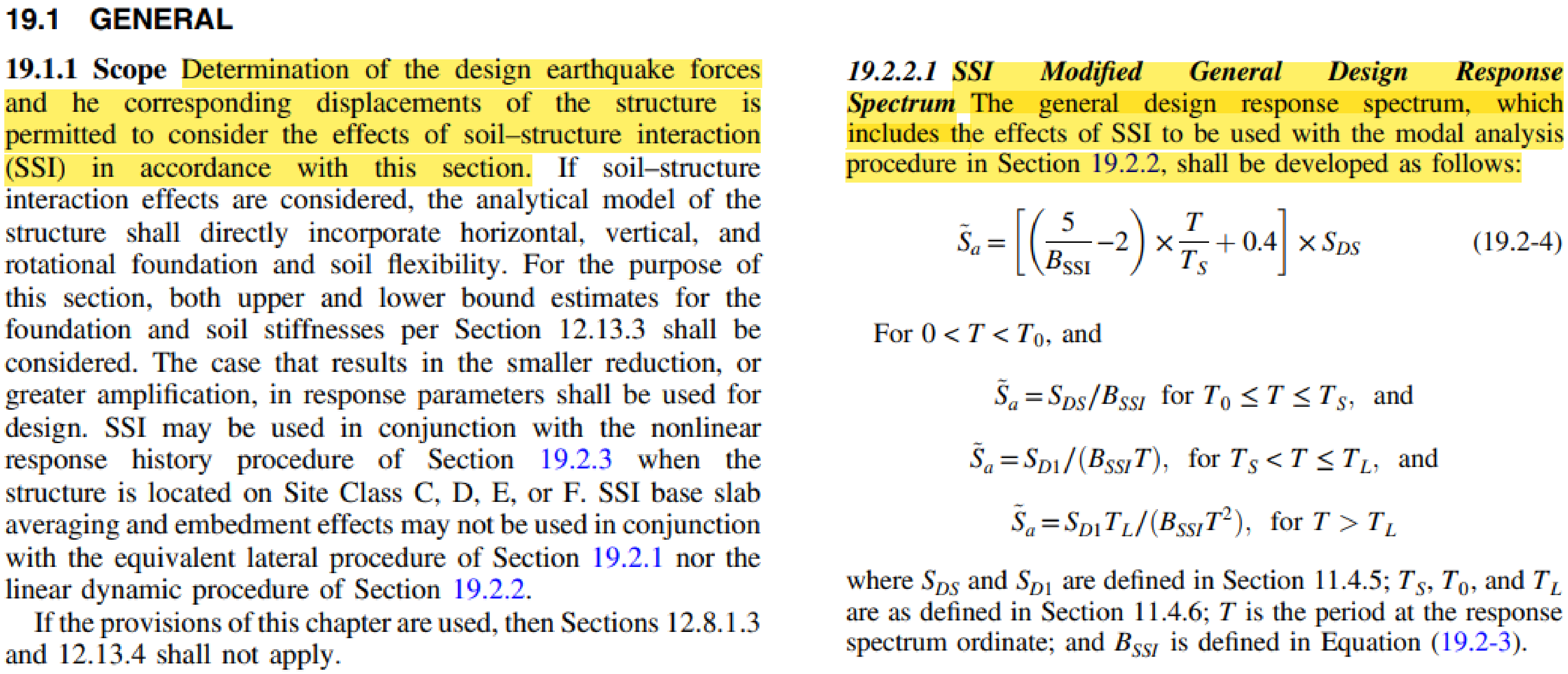
G_{rd} = Effective shear modulus used in determining radiation damping effects derived or approximated based on $G_{0,rd}$ and Table 19.3-2

$G_{0,rd}$ = Average shear modulus for the soils used in determining radiation damping effects computed using Equation (20.4-1), over a depth of B or r_f below the base of the structure at small strain levels

1. 관련 기준 소개

ASCE 7-22 (2022)

ASCE 7-22 에서는 설계 지진력과 구조물의 상대변위 결정에 SSI 영향을 고려



19.1 GENERAL

19.1.1 Scope Determination of the design earthquake forces and he corresponding displacements of the structure is permitted to consider the effects of soil–structure interaction (SSI) in accordance with this section. If soil–structure interaction effects are considered, the analytical model of the structure shall directly incorporate horizontal, vertical, and rotational foundation and soil flexibility. For the purpose of this section, both upper and lower bound estimates for the foundation and soil stiffnesses per Section 12.13.3 shall be considered. The case that results in the smaller reduction, or greater amplification, in response parameters shall be used for design. SSI may be used in conjunction with the nonlinear response history procedure of Section 19.2.3 when the structure is located on Site Class C, D, E, or F. SSI base slab averaging and embedment effects may not be used in conjunction with the equivalent lateral procedure of Section 19.2.1 nor the linear dynamic procedure of Section 19.2.2.

If the provisions of this chapter are used, then Sections 12.8.1.3 and 12.13.4 shall not apply.

19.2.2.1 SSI Modified General Design Response Spectrum The general design response spectrum, which includes the effects of SSI to be used with the modal analysis procedure in Section 19.2.2, shall be developed as follows:

$$\tilde{S}_a = \left[\left(\frac{5}{B_{\text{SSI}}} - 2\right) \times \frac{T}{T_S} + 0.4\right] \times S_{DS} \qquad (19.2\text{-}4)$$

For $0 < T < T_0$, and

$$\tilde{S}_a = S_{DS}/B_{SSI} \quad \text{for } T_0 \le T \le T_S, \quad \text{and}$$

$$\tilde{S}_a = S_{D1}/(B_{SSI}T), \quad \text{for } T_S < T \le T_L, \quad \text{and}$$

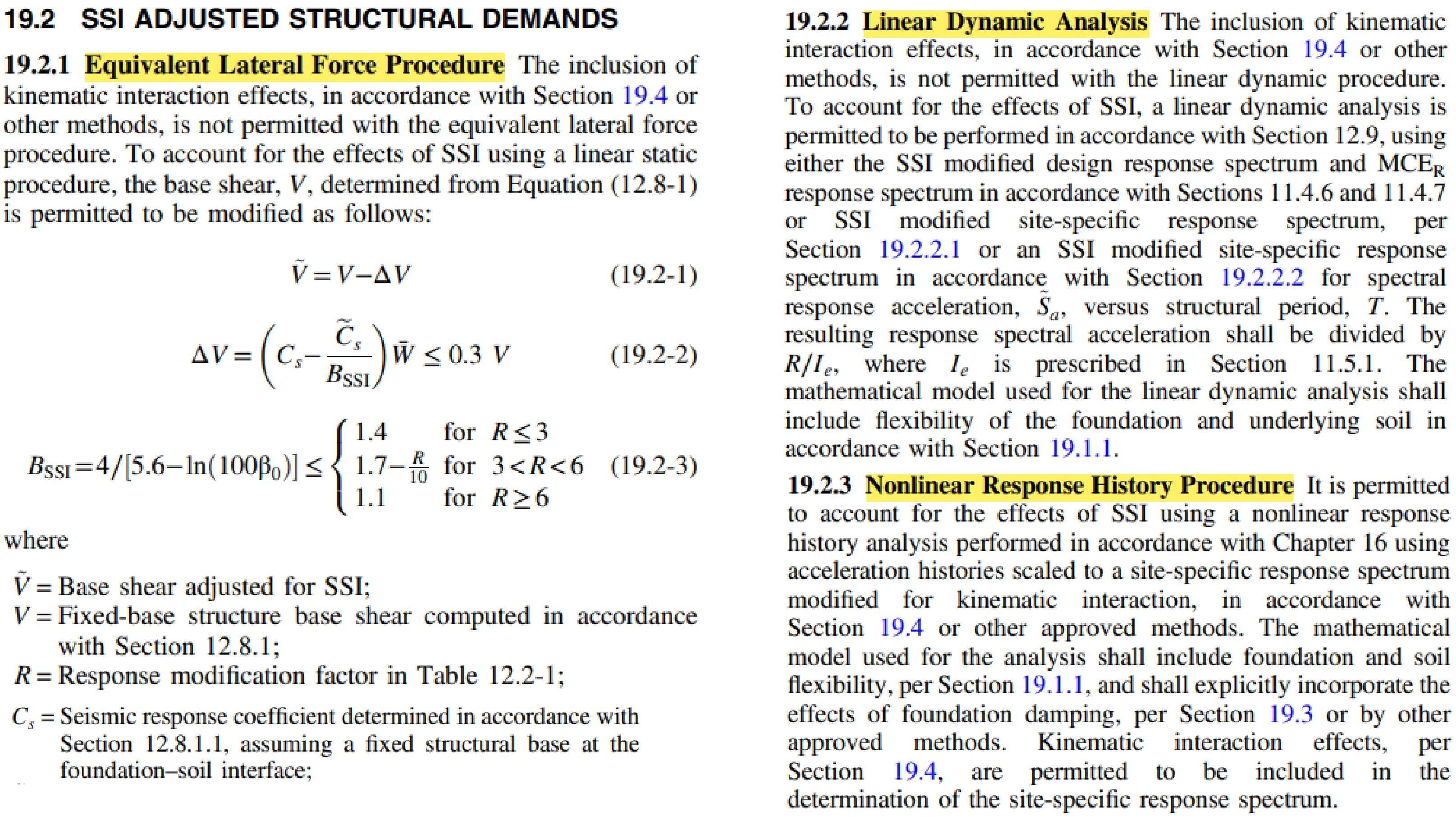
$$\tilde{S}_a = S_{D1}T_L/(B_{SSI}T^2), \quad \text{for } T > T_L$$

where S_{DS} and S_{D1} are defined in Section 11.4.5; T_S, T_0, and T_L are as defined in Section 11.4.6; T is the period at the response spectrum ordinate; and B_{SSI} is defined in Equation (19.2-3).

1. 관련 기준 소개

ASCE 7-22 (2022)

SSI 효과를 고려한 정적 및 동적 해석 방법에 대하여 구체적으로 기술



19.2 SSI ADJUSTED STRUCTURAL DEMANDS

19.2.1 Equivalent Lateral Force Procedure The inclusion of kinematic interaction effects, in accordance with Section 19.4 or other methods, is not permitted with the equivalent lateral force procedure. To account for the effects of SSI using a linear static procedure, the base shear, V, determined from Equation (12.8-1) is permitted to be modified as follows:

$$\tilde{V} = V - \Delta V \qquad (19.2\text{-}1)$$

$$\Delta V = \left(C_s - \frac{\tilde{C}_s}{B_{\mathrm{SSI}}} \right) \bar{W} \leq 0.3\ V \qquad (19.2\text{-}2)$$

$$B_{\mathrm{SSI}} = 4/[5.6 - \ln(100\beta_0)] \leq \begin{cases} 1.4 & \text{for } R \leq 3 \\ 1.7 - \frac{R}{10} & \text{for } 3 < R < 6 \\ 1.1 & \text{for } R \geq 6 \end{cases} \qquad (19.2\text{-}3)$$

where

$\tilde{V}$ = Base shear adjusted for SSI;
V = Fixed-base structure base shear computed in accordance with Section 12.8.1;
R = Response modification factor in Table 12.2-1;
C_s = Seismic response coefficient determined in accordance with Section 12.8.1.1, assuming a fixed structural base at the foundation–soil interface;

19.2.2 Linear Dynamic Analysis The inclusion of kinematic interaction effects, in accordance with Section 19.4 or other methods, is not permitted with the linear dynamic procedure. To account for the effects of SSI, a linear dynamic analysis is permitted to be performed in accordance with Section 12.9, using either the SSI modified design response spectrum and $\mathrm{MCE_R}$ response spectrum in accordance with Sections 11.4.6 and 11.4.7 or SSI modified site-specific response spectrum, per Section 19.2.2.1 or an SSI modified site-specific response spectrum in accordance with Section 19.2.2.2 for spectral response acceleration, $\tilde{S}_a$, versus structural period, T. The resulting response spectral acceleration shall be divided by R/I_e, where I_e is prescribed in Section 11.5.1. The mathematical model used for the linear dynamic analysis shall include flexibility of the foundation and underlying soil in accordance with Section 19.1.1.

19.2.3 Nonlinear Response History Procedure It is permitted to account for the effects of SSI using a nonlinear response history analysis performed in accordance with Chapter 16 using acceleration histories scaled to a site-specific response spectrum modified for kinematic interaction, in accordance with Section 19.4 or other approved methods. The mathematical model used for the analysis shall include foundation and soil flexibility, per Section 19.1.1, and shall explicitly incorporate the effects of foundation damping, per Section 19.3 or by other approved methods. Kinematic interaction effects, per Section 19.4, are permitted to be included in the determination of the site-specific response spectrum.

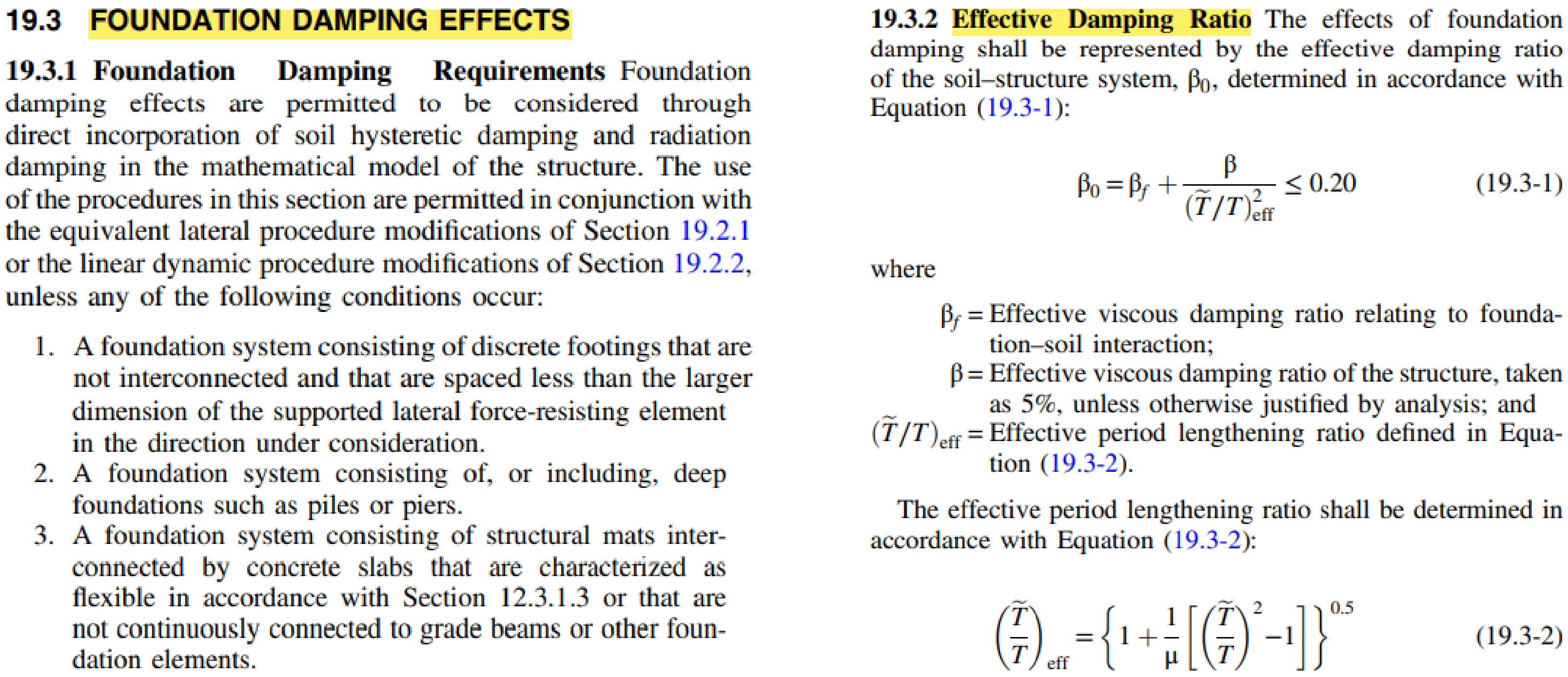
1. 관련 기준 소개

ASCE 7-22 (2022)

Soil-Structure System의 유효 감쇠비 산정

→ Soil-Structure System의 유효 감쇠비는 요구 스펙트럼의 효과적인 감소를 예측

→ 유효 감쇠비는 유연한 기초 위에 있는 시스템의 기본 주기와 고정단 모델의 기본 주기의 비율과 연관이 있음



19.3 FOUNDATION DAMPING EFFECTS

19.3.1 Foundation Damping Requirements Foundation damping effects are permitted to be considered through direct incorporation of soil hysteretic damping and radiation damping in the mathematical model of the structure. The use of the procedures in this section are permitted in conjunction with the equivalent lateral procedure modifications of Section 19.2.1 or the linear dynamic procedure modifications of Section 19.2.2, unless any of the following conditions occur:

1. A foundation system consisting of discrete footings that are not interconnected and that are spaced less than the larger dimension of the supported lateral force-resisting element in the direction under consideration.
2. A foundation system consisting of, or including, deep foundations such as piles or piers.
3. A foundation system consisting of structural mats interconnected by concrete slabs that are characterized as flexible in accordance with Section 12.3.1.3 or that are not continuously connected to grade beams or other foundation elements.

19.3.2 Effective Damping Ratio The effects of foundation damping shall be represented by the effective damping ratio of the soil–structure system, β_0, determined in accordance with Equation (19.3-1):

$$\beta_0 = \beta_f + \frac{\beta}{(\tilde{T}/T)^2_{\text{eff}}} \leq 0.20 \qquad (19.3\text{-}1)$$

where

β_f = Effective viscous damping ratio relating to foundation–soil interaction;
β = Effective viscous damping ratio of the structure, taken as 5%, unless otherwise justified by analysis; and
$(\tilde{T}/T)_{\text{eff}}$ = Effective period lengthening ratio defined in Equation (19.3-2).

The effective period lengthening ratio shall be determined in accordance with Equation (19.3-2):

$$\left(\frac{\tilde{T}}{T}\right)_{\text{eff}} = \left\{1 + \frac{1}{\mu}\left[\left(\frac{\tilde{T}}{T}\right)^2 - 1\right]\right\}^{0.5} \qquad (19.3\text{-}2)$$

1. 관련 기준 소개

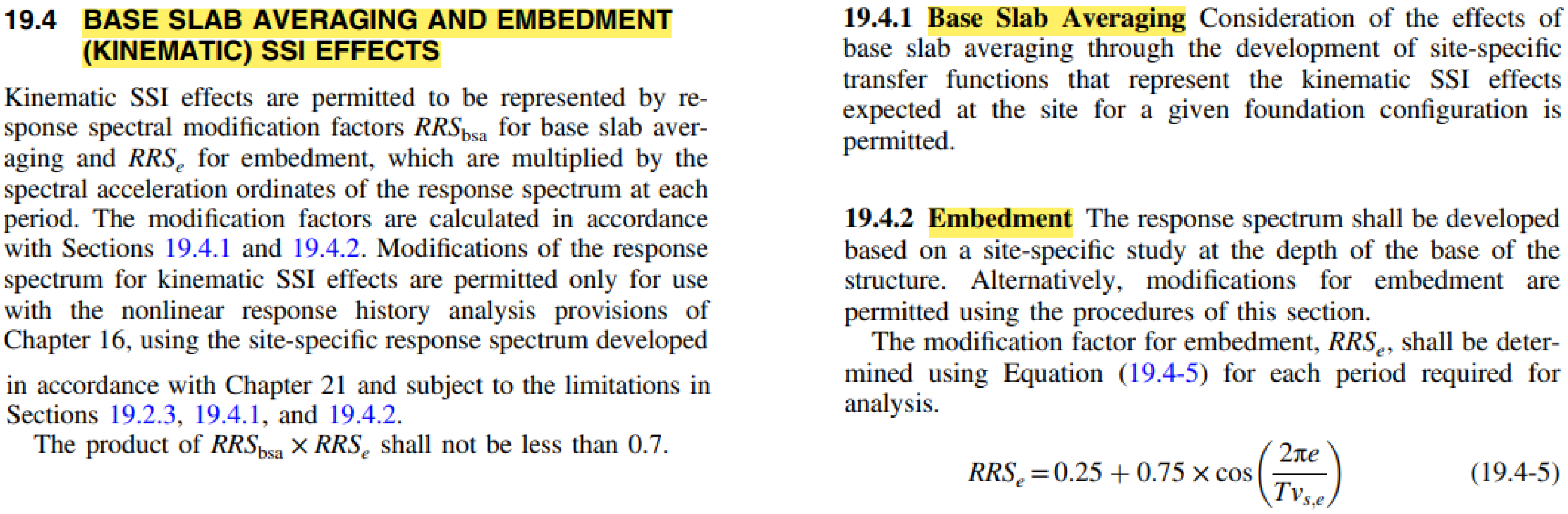
ASCE 7-22 (2022)

Kinematic SSI Effects

→ 기초 평면 형상에 따른 Effects of base slab averaging 을 고려

→ 지하층 근입에 따른 응답 스펙트럼의 감소효과를 고려

→ FEMA 440과 유사하나, 설계에 적용시 제한적인 내용들이 있음



19.4 BASE SLAB AVERAGING AND EMBEDMENT (KINEMATIC) SSI EFFECTS

Kinematic SSI effects are permitted to be represented by response spectral modification factors RRS_{bsa} for base slab averaging and RRS_e for embedment, which are multiplied by the spectral acceleration ordinates of the response spectrum at each period. The modification factors are calculated in accordance with Sections 19.4.1 and 19.4.2. Modifications of the response spectrum for kinematic SSI effects are permitted only for use with the nonlinear response history analysis provisions of Chapter 16, using the site-specific response spectrum developed in accordance with Chapter 21 and subject to the limitations in Sections 19.2.3, 19.4.1, and 19.4.2.

The product of $RRS_{\mathrm{bsa}} \times RRS_e$ shall not be less than 0.7.

19.4.1 Base Slab Averaging Consideration of the effects of base slab averaging through the development of site-specific transfer functions that represent the kinematic SSI effects expected at the site for a given foundation configuration is permitted.

19.4.2 Embedment The response spectrum shall be developed based on a site-specific study at the depth of the base of the structure. Alternatively, modifications for embedment are permitted using the procedures of this section.

The modification factor for embedment, RRS_e, shall be determined using Equation (19.4-5) for each period required for analysis.

$$RRS_e = 0.25 + 0.75 \times \cos\left(\frac{2\pi e}{T v_{s,e}}\right) \tag{19.4-5}$$

1. 관련 기준 소개

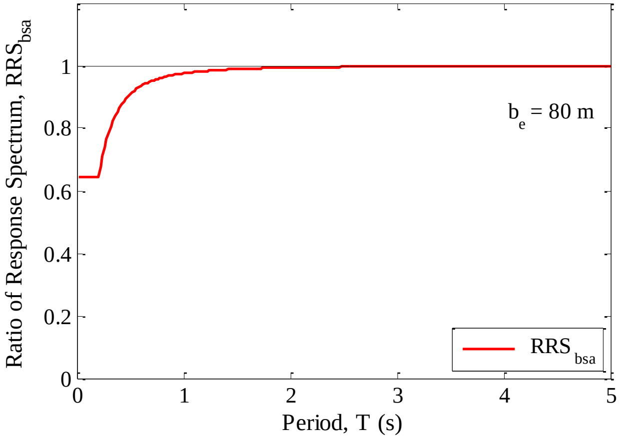
ASCE 7-22 (2022)

Kinematic SSI Effects

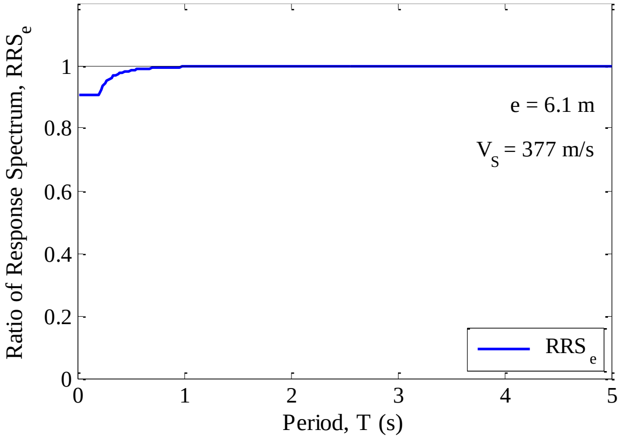
→ 기초 평면 형상에 따른 Effects of base slab averaging 을 고려

→ 지하층 근입에 따른 응답 스펙트럼의 감소효과를 고려

→ FEMA 440과 유사하나, 설계에 적용시 제한적인 내용들이 있음



<Base slab averaging>



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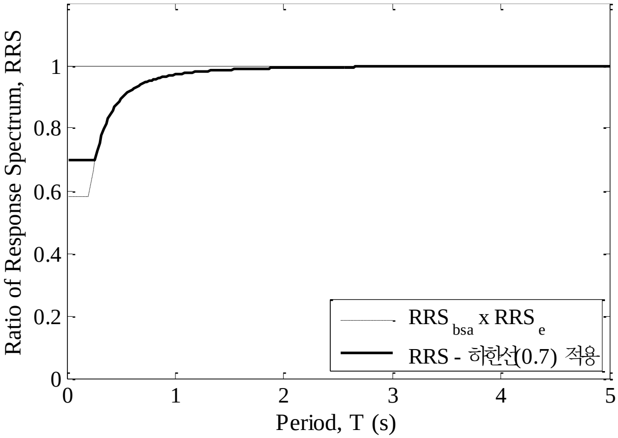

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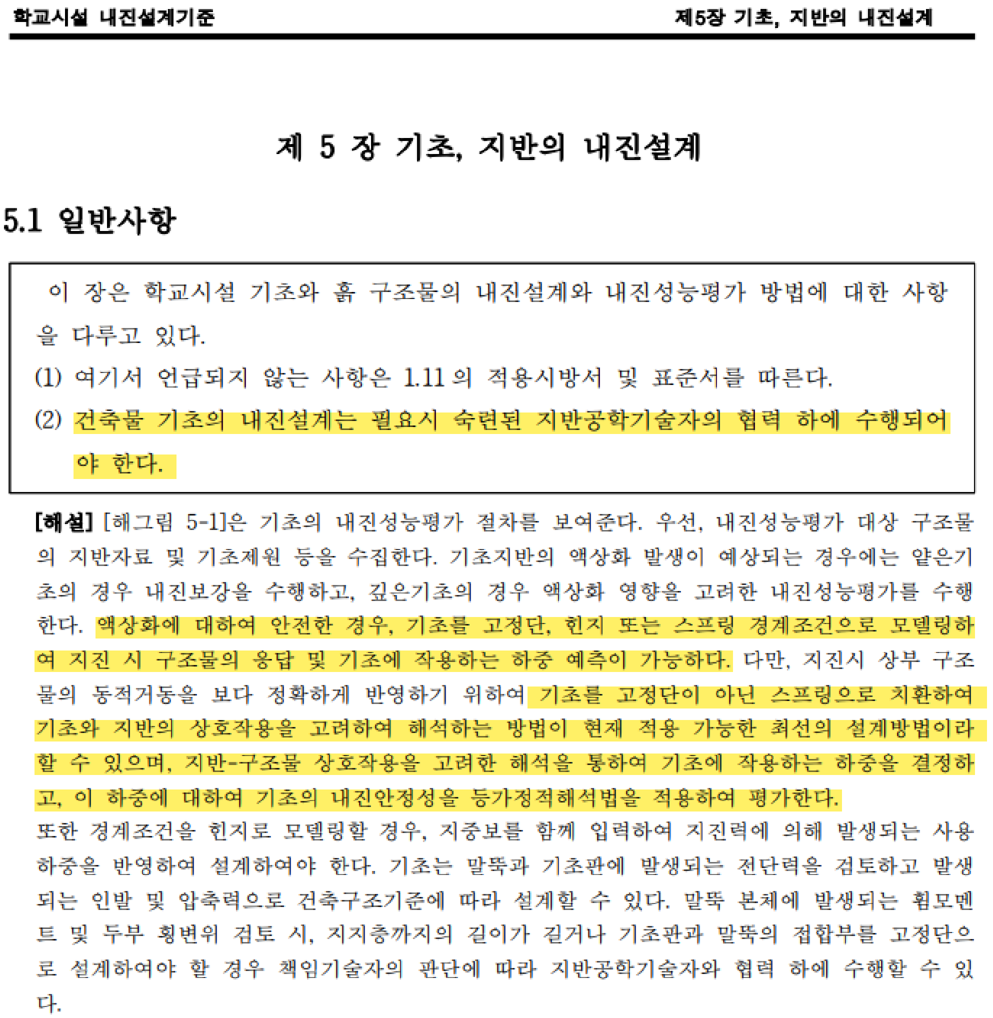
1. 관련 기준 소개

학교시설 내진설계기준 (2020)



제 5 장 기초, 지반의 내진설계

5.1 일반사항

이 장은 학교시설 기초와 흙 구조물의 내진설계와 내진성능평가 방법에 대한 사항을 다루고 있다.

(1) 여기서 언급되지 않는 사항은 1.11 의 적용시방서 및 표준서를 따른다.

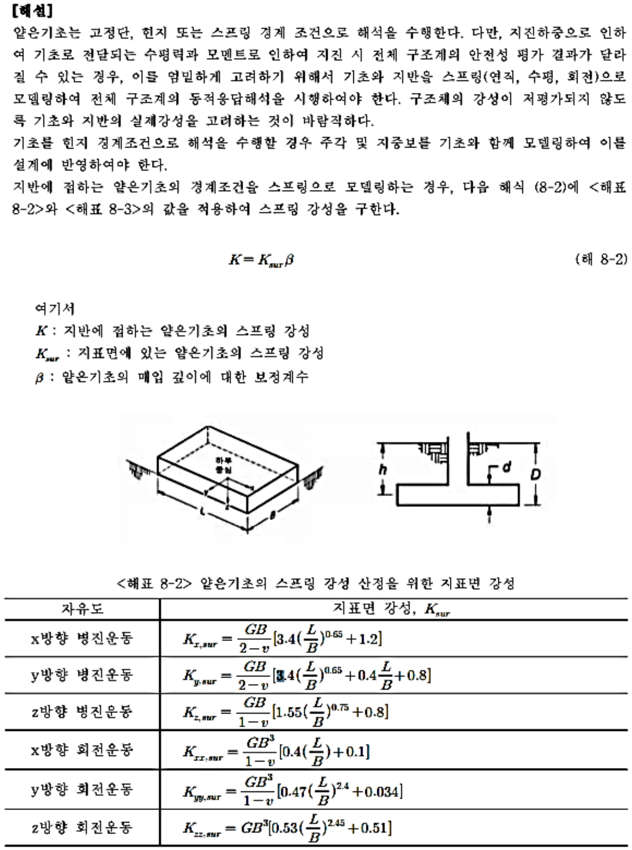
(2) 건축물 기초의 내진설계는 필요시 숙련된 지반공학기술자의 협력 하에 수행되어야 한다.

[해설] [해그림 5-1]은 기초의 내진성능평가 절차를 보여준다. 우선, 내진성능평가 대상 구조물의 지반자료 및 기초제원 등을 수집한다. 기초지반의 액상화 발생이 예상되는 경우에는 얕은기초의 경우 내진보강을 수행하고, 깊은기초의 경우 액상화 영향을 고려한 내진성능평가를 수행한다. 액상화에 대하여 안전한 경우, 기초를 고정단, 힌지 또는 스프링 경계조건으로 모델링하여 지진 시 구조물의 응답 및 기초에 작용하는 하중 예측이 가능하다. 다만, 지진시 상부 구조물의 동적거동을 보다 정확하게 반영하기 위하여 기초를 고정단이 아닌 스프링으로 치환하여 기초와 지반의 상호작용을 고려하여 해석하는 방법이 현재 적용 가능한 최선의 설계방법이라 할 수 있으며, 지반-구조물 상호작용을 고려한 해석을 통하여 기초에 작용하는 하중을 결정하고, 이 하중에 대하여 기초의 내진안정성을 등가정적해석법을 적용하여 평가한다.
또한 경계조건을 힌지로 모델링할 경우, 지중보를 함께 입력하여 지진력에 의해 발생되는 사용하중을 반영하여 설계하여야 한다. 기초는 말뚝과 기초판에 발생되는 전단력을 검토하고 발생되는 인발 및 압축력으로 건축구조기준에 따라 설계할 수 있다. 말뚝 본체에 발생되는 휨모멘트 및 두부 횡변위 검토 시, 지지층까지의 길이가 길거나 기초판과 말뚝의 접합부를 고정단으로 설계하여야 할 경우 책임기술자의 판단에 따라 지반공학기술자와 협력 하에 수행할 수 있다.

1. 관련 기준 소개

학교시설 내진설계기준 (2020)

지반-구조물 상호작용을 고려하기 위한 기초의 강성 행렬은 FEMA 356 기준을 참고하고 있음



[해설]

얕은기초는 고정단, 힌지 또는 스프링 경계 조건으로 해석을 수행한다. 다만, 지진하중으로 인하여 기초로 전달되는 수평력과 모멘트로 인하여 지진 시 전체 구조계의 안전성 평가 결과가 달라질 수 있는 경우, 이를 엄밀하게 고려하기 위해서 기초와 지반을 스프링(연직, 수평, 회전)으로 모델링하여 전체 구조계의 동적응답해석을 시행하여야 한다. 구조체의 강성이 저평가되지 않도록 기초와 지반의 실제강성을 고려하는 것이 바람직하다.

기초를 힌지 경계조건으로 해석을 수행할 경우 주각 및 지중보를 기초와 함께 모델링하여 이를 설계에 반영하여야 한다.

지반에 접하는 얕은기초의 경계조건을 스프링으로 모델링하는 경우, 다음 해식 (8-2)에 <해표 8-2>와 <해표 8-3>의 값을 적용하여 스프링 강성을 구한다.

$$K = K_{sur}\beta \qquad \text{(해 8-2)}$$

여기서

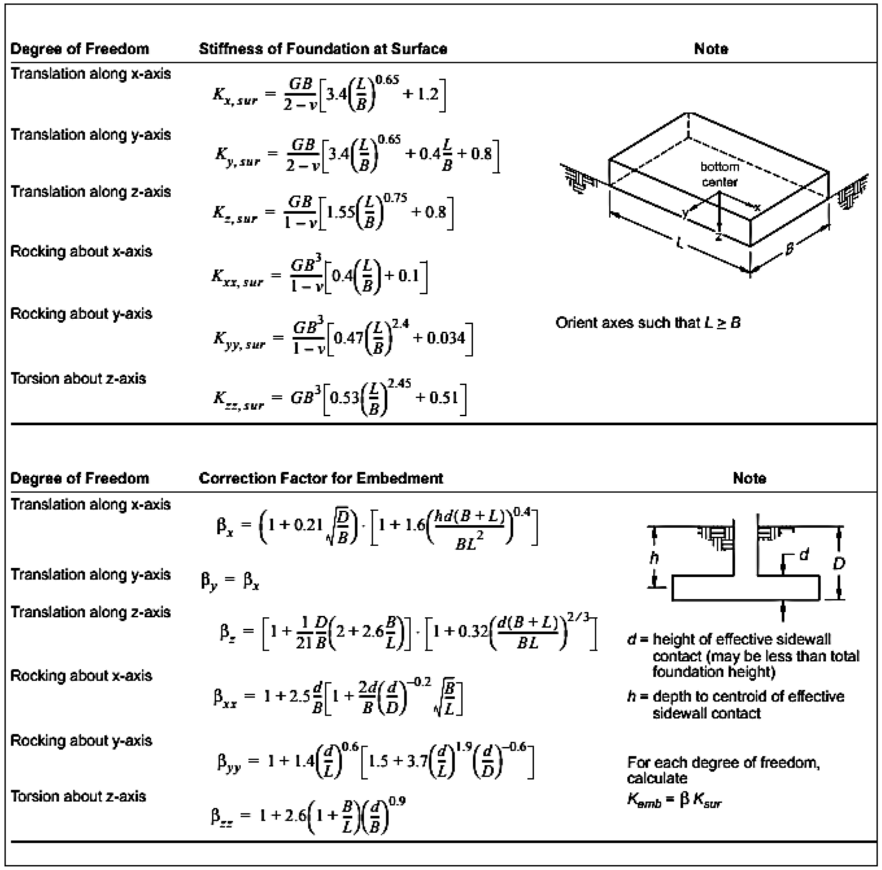
K : 지반에 접하는 얕은기초의 스프링 강성

K_{sur} : 지표면에 있는 얕은기초의 스프링 강성

β : 얕은기초의 매입 깊이에 대한 보정계수

<해표 8-2> 얕은기초의 스프링 강성 산정을 위한 지표면 강성

자유도	지표면 강성, K_{sur}
x방향 병진운동	$K_{x,sur} = \frac{GB}{2-v}[3.4(\frac{L}{B})^{0.65}+1.2]$
y방향 병진운동	$K_{y,sur} = \frac{GB}{2-v}[3.4(\frac{L}{B})^{0.65}+0.4\frac{L}{B}+0.8]$
z방향 병진운동	$K_{z,sur} = \frac{GB}{1-v}[1.55(\frac{L}{B})^{0.75}+0.8]$
x방향 회전운동	$K_{xx,sur} = \frac{GB^3}{1-v}[0.4(\frac{L}{B})+0.1]$
y방향 회전운동	$K_{yy,sur} = \frac{GB^3}{1-v}[0.47(\frac{L}{B})^{2.4}+0.034]$
z방향 회전운동	$K_{zz,sur} = GB^3[0.53(\frac{L}{B})^{2.45}+0.51]$



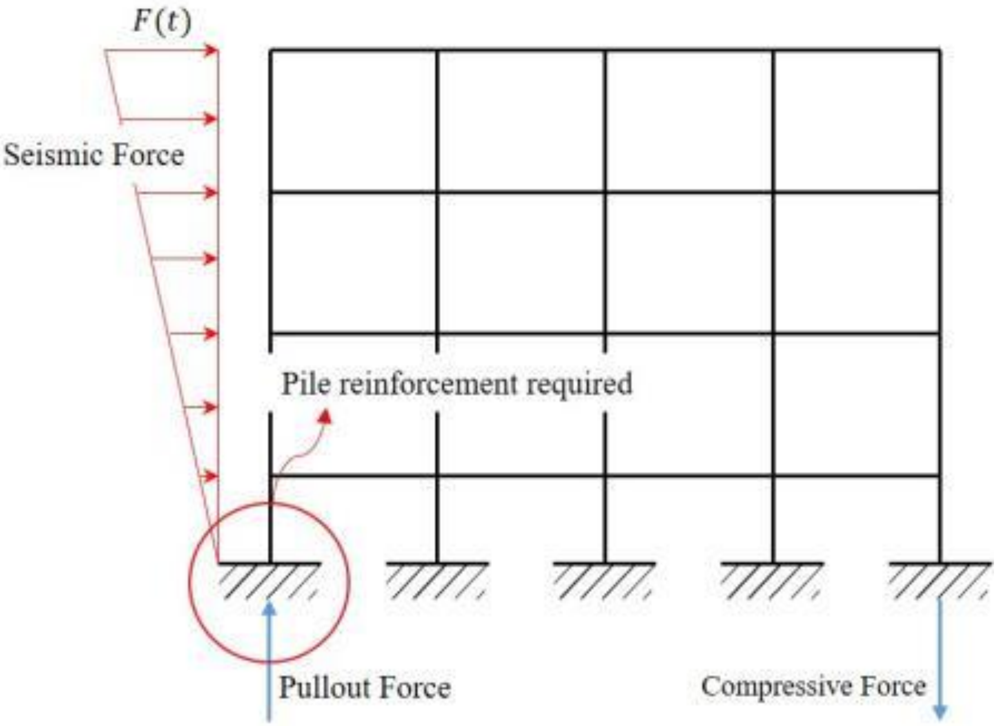
Degree of Freedom	Stiffness of Foundation at Surface	Note
Translation along x-axis	$K_{x,sur} = \frac{GB}{2-v}\left[3.4\left(\frac{L}{B}\right)^{0.65}+1.2\right]$	
Translation along y-axis	$K_{y,sur} = \frac{GB}{2-v}\left[3.4\left(\frac{L}{B}\right)^{0.65}+0.4\frac{L}{B}+0.8\right]$	
Translation along z-axis	$K_{z,sur} = \frac{GB}{1-v}\left[1.55\left(\frac{L}{B}\right)^{0.75}+0.8\right]$	
Rocking about x-axis	$K_{xx,sur} = \frac{GB^3}{1-v}\left[0.4\left(\frac{L}{B}\right)+0.1\right]$	
Rocking about y-axis	$K_{yy,sur} = \frac{GB^3}{1-v}\left[0.47\left(\frac{L}{B}\right)^{2.4}+0.034\right]$	Orient axes such that $L \geq B$
Torsion about z-axis	$K_{zz,sur} = GB^3\left[0.53\left(\frac{L}{B}\right)^{2.45}+0.51\right]$	

Degree of Freedom	Correction Factor for Embedment	Note
Translation along x-axis	$\beta_x = \left(1+0.21\sqrt{\frac{D}{B}}\right)\cdot\left[1+1.6\left(\frac{hd(B+L)}{BL^2}\right)^{0.4}\right]$	
Translation along y-axis	$\beta_y = \beta_x$	
Translation along z-axis	$\beta_z = \left[1+\frac{1}{21}\frac{D}{B}\left(2+2.6\frac{B}{L}\right)\right]\cdot\left[1+0.32\left(\frac{d(B+L)}{BL}\right)^{2/3}\right]$	d = height of effective sidewall contact (may be less than total foundation height)
Rocking about x-axis	$\beta_{xx} = 1+2.5\frac{d}{B}\left[1+\frac{2d}{B}\left(\frac{d}{D}\right)^{-0.2}\sqrt{\frac{B}{L}}\right]$	h = depth to centroid of effective sidewall contact
Rocking about y-axis	$\beta_{yy} = 1+1.4\left(\frac{d}{L}\right)^{0.6}\left[1.5+3.7\left(\frac{d}{L}\right)^{1.9}\left(\frac{d}{D}\right)^{-0.6}\right]$	For each degree of freedom, calculate
Torsion about z-axis	$\beta_{zz} = 1+2.6\left(1+\frac{B}{L}\right)\left(\frac{d}{B}\right)^{0.9}$	$K_{emb} = \beta K_{sur}$

1. 관련 기준 소개

학교시설 내진설계기준 (2020)

기초를 고정단으로 가정한 구조해석 방안은 과도한 설계지진력이 작용하는 경우 기초에 인발력이 발생

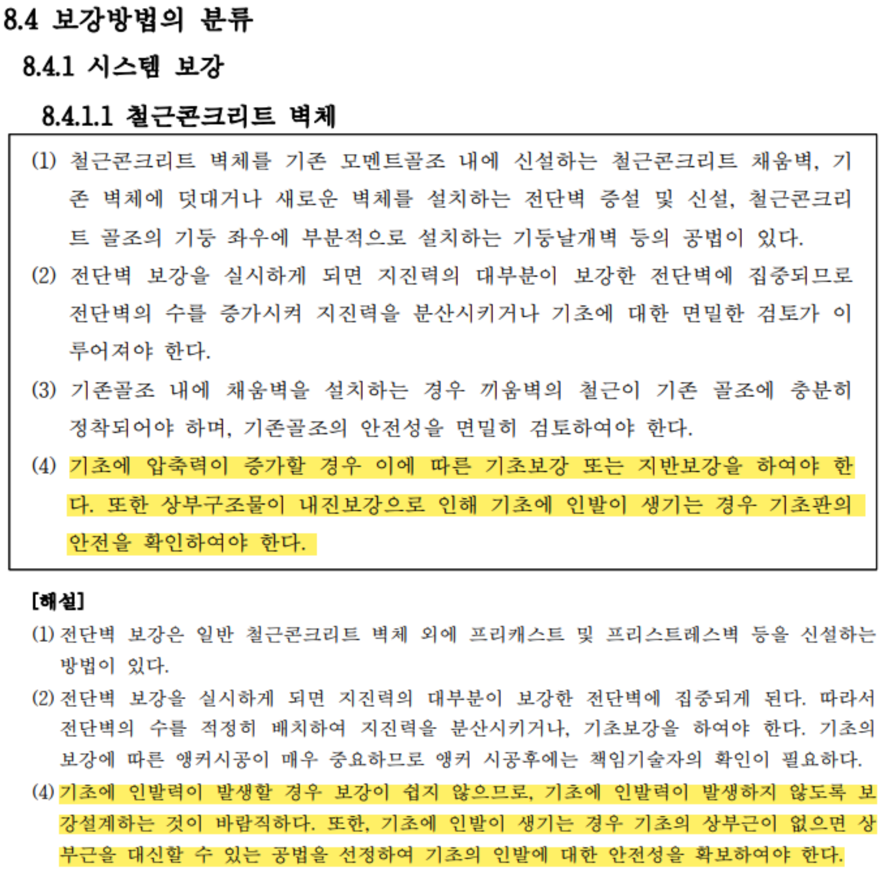


1. 관련 기준 소개

학교시설 내진설계기준 (2020)

현행 기준에서는 인발력이 발생하지 않게 설계가 수행되도록 권고

→ 과도한 내진보강 문제 발생



8.4 보강방법의 분류

8.4.1 시스템 보강

8.4.1.1 철근콘크리트 벽체

(1) 철근콘크리트 벽체를 기존 모멘트골조 내에 신설하는 철근콘크리트 채움벽, 기존 벽체에 덧대거나 새로운 벽체를 설치하는 전단벽 증설 및 신설, 철근콘크리트 골조의 기둥 좌우에 부분적으로 설치하는 기둥날개벽 등의 공법이 있다.

(2) 전단벽 보강을 실시하게 되면 지진력의 대부분이 보강한 전단벽에 집중되므로 전단벽의 수를 증가시켜 지진력을 분산시키거나 기초에 대한 면밀한 검토가 이루어져야 한다.

(3) 기존골조 내에 채움벽을 설치하는 경우 끼움벽의 철근이 기존 골조에 충분히 정착되어야 하며, 기존골조의 안전성을 면밀히 검토하여야 한다.

(4) 기초에 압축력이 증가할 경우 이에 따른 기초보강 또는 지반보강을 하여야 한다. 또한 상부구조물이 내진보강으로 인해 기초에 인발이 생기는 경우 기초판의 안전을 확인하여야 한다.

[해설]

(1) 전단벽 보강은 일반 철근콘크리트 벽체 외에 프리캐스트 및 프리스트레스벽 등을 신설하는 방법이 있다.

(2) 전단벽 보강을 실시하게 되면 지진력의 대부분이 보강한 전단벽에 집중되게 된다. 따라서 전단벽의 수를 적정히 배치하여 지진력을 분산시키거나, 기초보강을 하여야 한다. 기초의 보강에 따른 앵커시공이 매우 중요하므로 앵커 시공후에는 책임기술자의 확인이 필요하다.

(4) 기초에 인발력이 발생할 경우 보강이 쉽지 않으므로, 기초에 인발력이 발생하지 않도록 보강설계하는 것이 바람직하다. 또한, 기초에 인발이 생기는 경우 기초의 상부근이 없으면 상부근을 대신할 수 있는 공법을 선정하여 기초의 인발에 대한 안전성을 확보하여야 한다.

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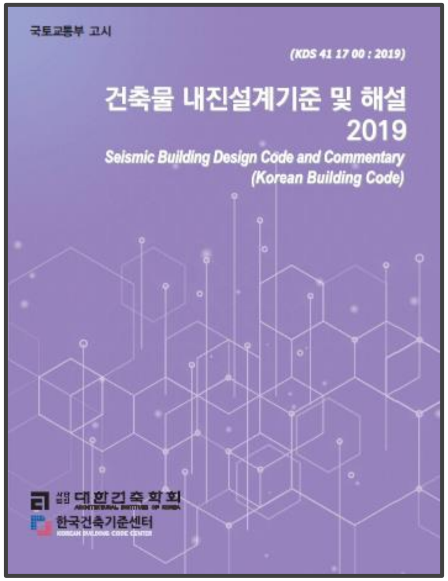
    b. FEMA 440 (2005)
    c. ASCE 7-22 (2022)
    d. 학교시설 내진설계기준 (2020)
    e. 건축물 내진설계 기준 (KDS 41 17 00)
2. 얕은기초가 있는 구조물의 거동
3. 대규모 지하구조물을 고려한 건축물의 내진설계
4. 결론

1. 관련 기준 소개

건축물 내진설계 기준 (KDS 41 17 00)



국토교통부 고시

(KDS 41 17 00 : 2019)

건축물 내진설계기준 및 해설
2019
Seismic Building Design Code and Commentary
(Korean Building Code)

대한건축학회

한국건축기준센터

- ➢ 지하구조물의 지진력저항시스템, 연성상세 등급 등을 제시하고 있음
- ➢ 지진하중 계산 방법 및 하중조합을 제시하고 있음
- ➢ 지하구조를 고려한 지진해석 및 내진설계 방법을 제시함
    - 지진하중과 설계지진토압에 대하여 안전하도록 설계해야함
    - 원칙적으로 구조물의 해석모델은 지상구조와 지하구조를 포함하고 기초면 하부가 고정된 해석모델을 사용함
    - 지하구조의 강성이 지상구조의 강성보다 매우 큰 경우, 둘을 분리하여 해석할 수 있음
    - 지하구조물과 지반을 함께 모델링할 경우 지하구조물 측면의 토사와 기반암 상부에서 기초하부까지의 토사를 포함해야함
    - 근사적인 설계방법으로 설계지진토압을 포함하는 모든 횡하중을 횡하중에 평행한 외벽이 지지하도록 설계할 수 있음

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   b. Ultimate Moment Capacity
   c. System Identification
   d. Frame 실험
   e. Frame 실험 & 제안
   f. SSI 효과를 고려한 얕은 기초의 내진설계 & 내진성능평가

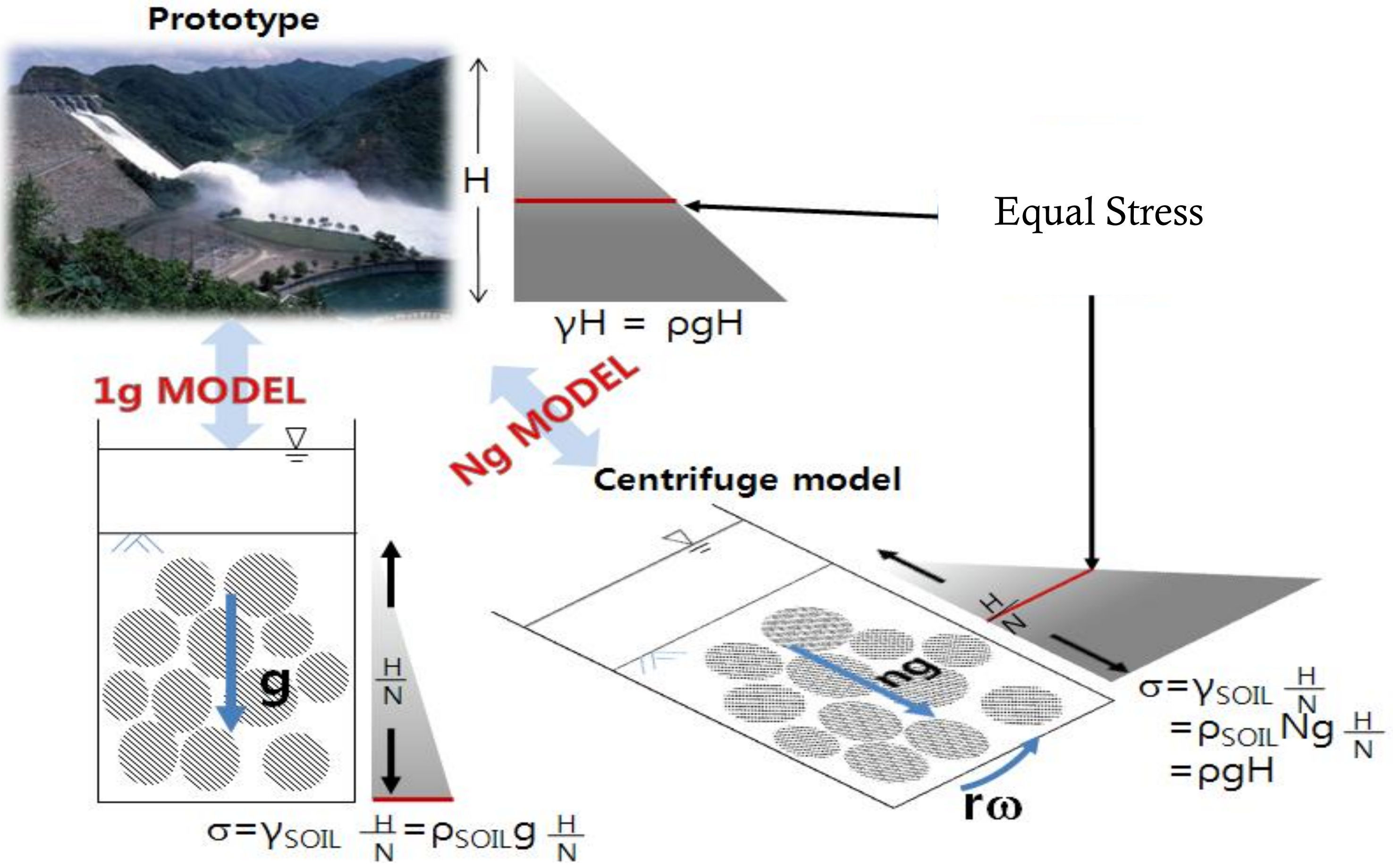
3. 지하구조물을 고려한 건축물의 내진설계

4. 결론

Centrifuge Test

Purpose

The stresses and strains of the prototype soil need to be generated in a small-scale model.

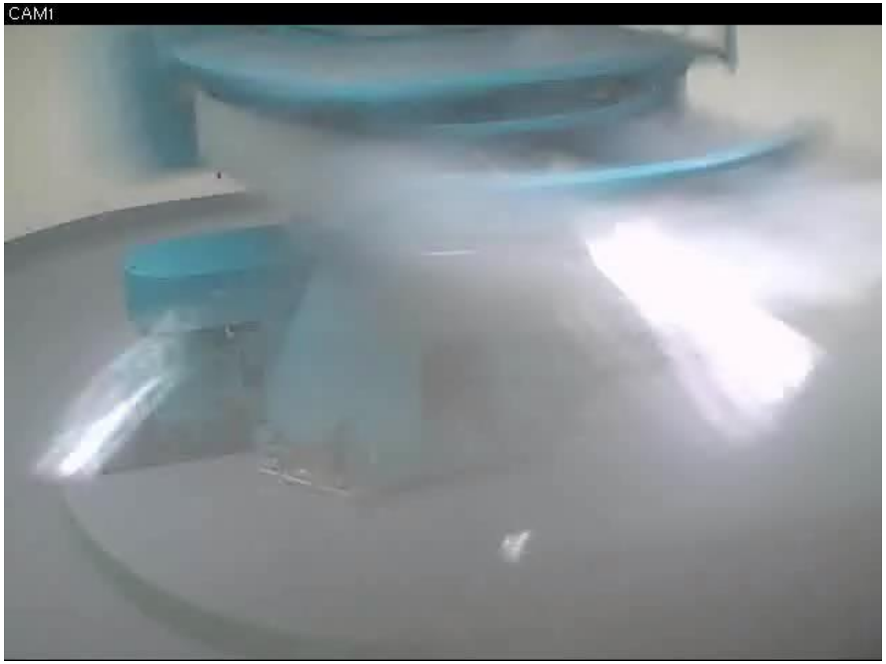


Equal Stress

Centrifuge Test

Equipment : Geo–Centrifuge with 2D–Shaker at KAIST

Platform Radius : 5.0m
Maximum Weight Capacity : 240g–tons
Maximum Centrifugal Acceleration : 130g



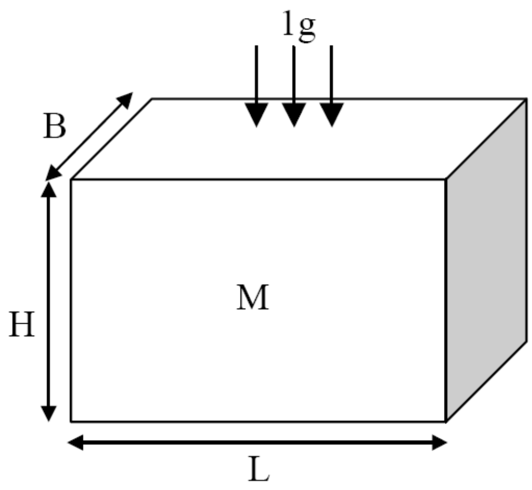
124 rpm / Centrifugal Acceleration : 80g

2. 얕은 기초가 있는 구조물의 거동

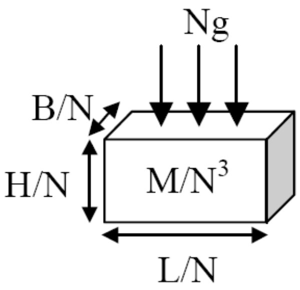
독립기초 실험

Parameter	Prototype	Small – scale model	Scale parameter	Scale
Gravity load	M (g)	m (Ng)	gravitational acceleration	N
EQ force	M (a)	m (Na)	ground acceleration	N
Period	T_p	$T_m = T_p / N$	EQ time step	1 / N

Soil $T_p = 4H / V_S$

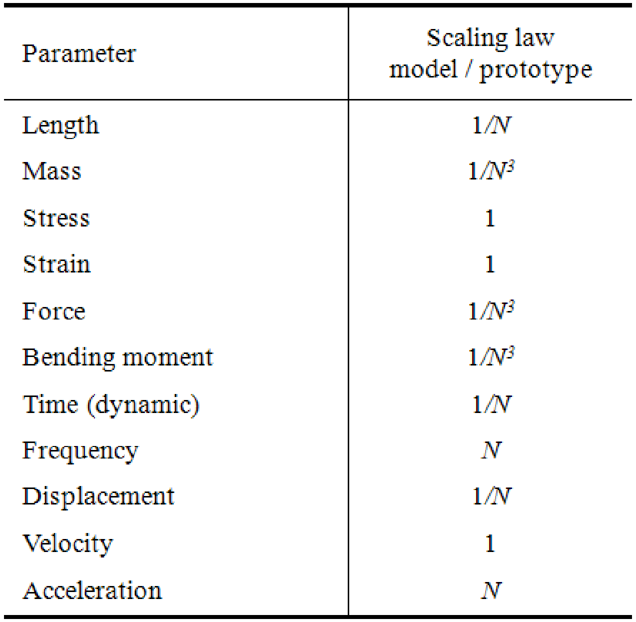


< prototype @ 1g >



< small model @ *N*g >

< Scaling Laws (Schofield 1980) >

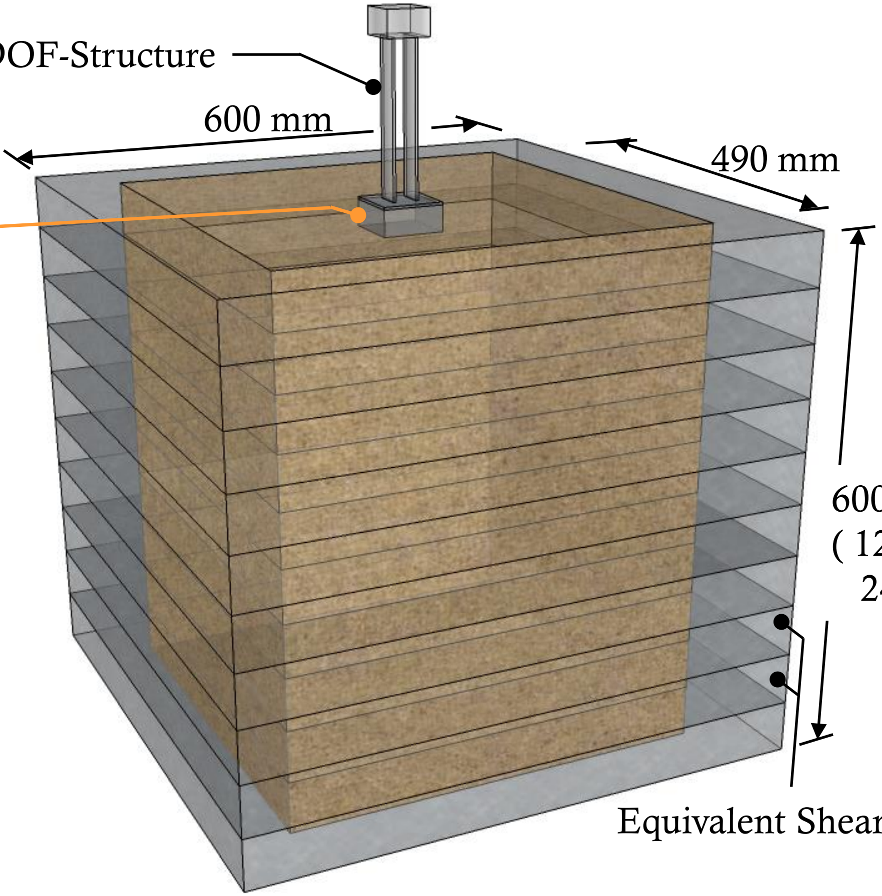


Parameter	Scaling law model / prototype
Length	1/*N*
Mass	$1/N^3$
Stress	1
Strain	1
Force	$1/N^2$
Bending moment	$1/N^3$
Time (dynamic)	1/*N*
Frequency	*N*
Displacement	1/*N*
Velocity	1
Acceleration	*N*

2. 얕은 기초가 있는 구조물의 거동

독립기초 실험

Test Specimen



SDOF-Structure

600 mm

490 mm

Shallow Foundation
(70 x 70 x 30mm)
(1.4 x 1.4 x 0.6m in 20gc
2.8 x 2.8 x 1.2m in 40gc)

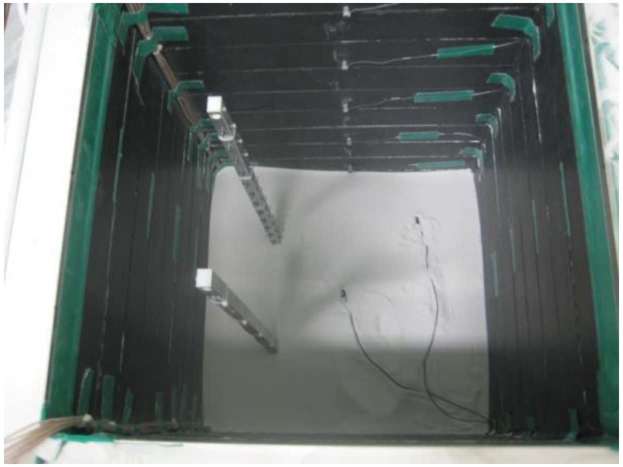
600 mm
(12m in 20gc
24m in 40gc)

Equivalent Shear Beam Box

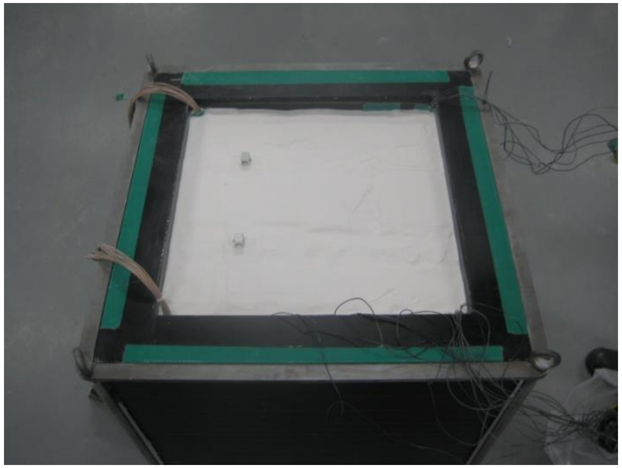
2. 얕은 기초가 있는 구조물의 거동

독립기초 실험

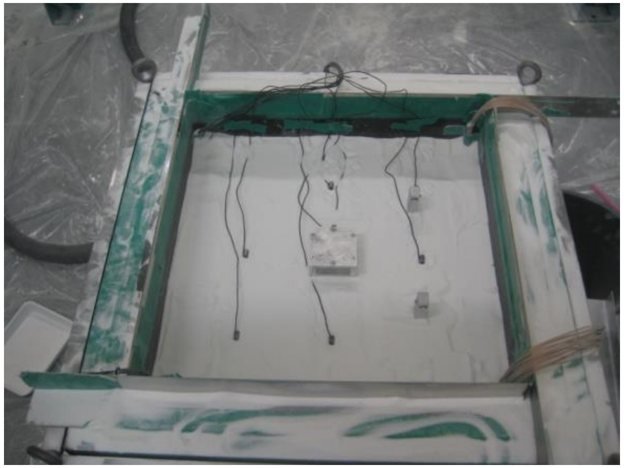
(a) Soil raining



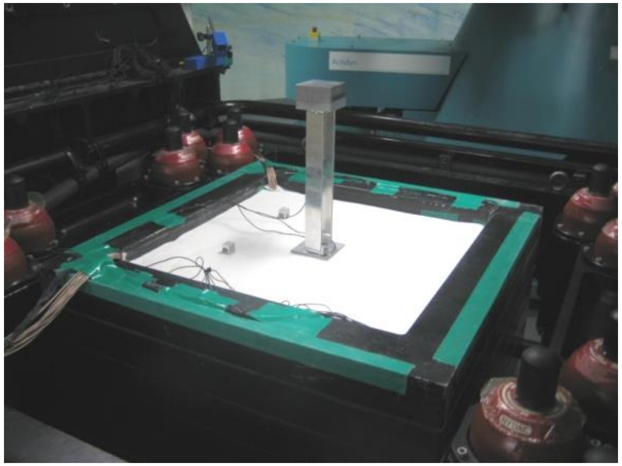
(b) Soil deposit



(c) Shallow foundation



(d) SDOF structure

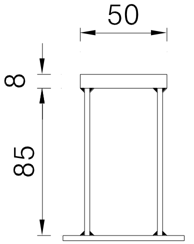


2. 얕은 기초가 있는 구조물의 거동

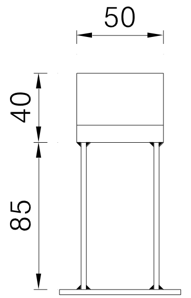
독립기초 실험

SDOF Structures

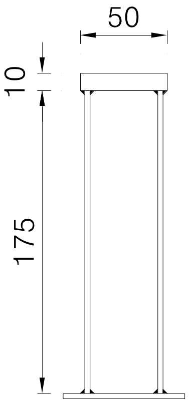
The SDOF structure was composed of a lumped mass on the top and two thin plates representing the lateral stiffness of the structure. By using the two separated plates, the structure model was designed to show the shear–deformation mode.



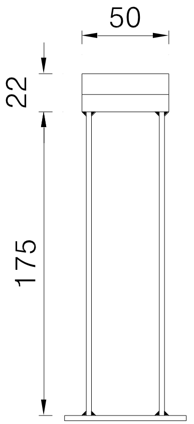
SDOF – 1
T: 0.09s @20gc
T: 0.18s @40gc



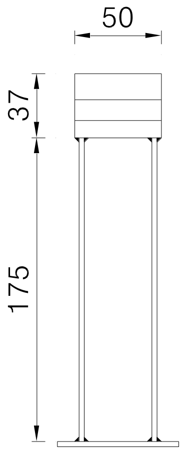
SDOF – 2
T: 0.17s @20gc
T: 0.34s @40gc



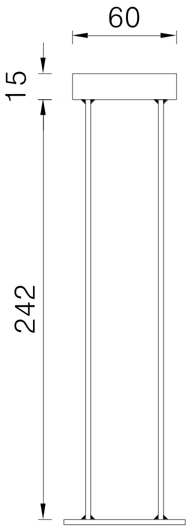
SDOF – 3
T: 0.26s @20gc
T: 0.52s @40gc



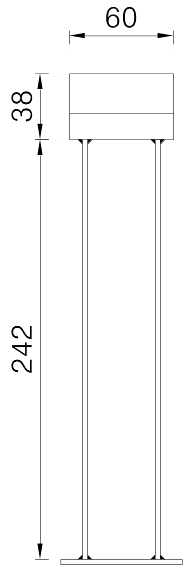
SDOF – 4
T: 0.36s @20gc
T: 0.72s @40gc



SDOF – 5
T: 0.45s @20gc
T: 0.90s @40gc



SDOF – 6
T: 0.66s @20gc
T: 1.32s @40gc



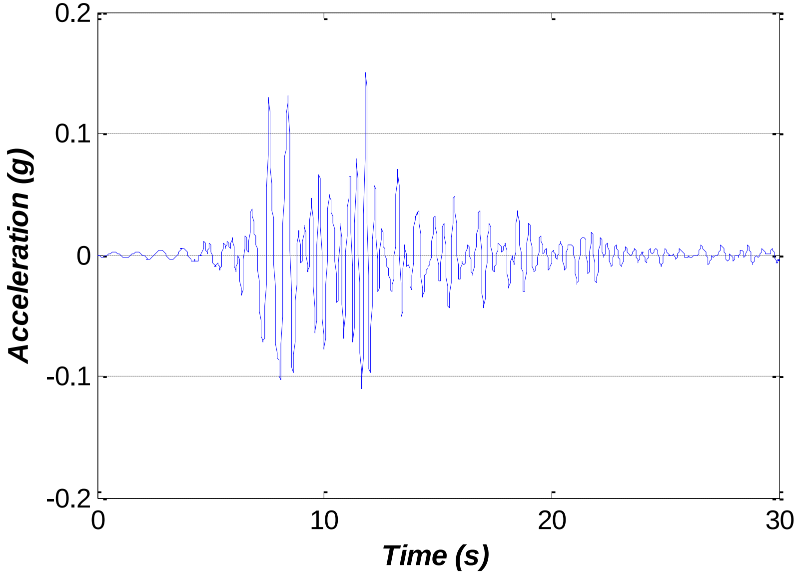
SDOF – 7
T: 1.00s @20gc
T: 2.00s @40gc

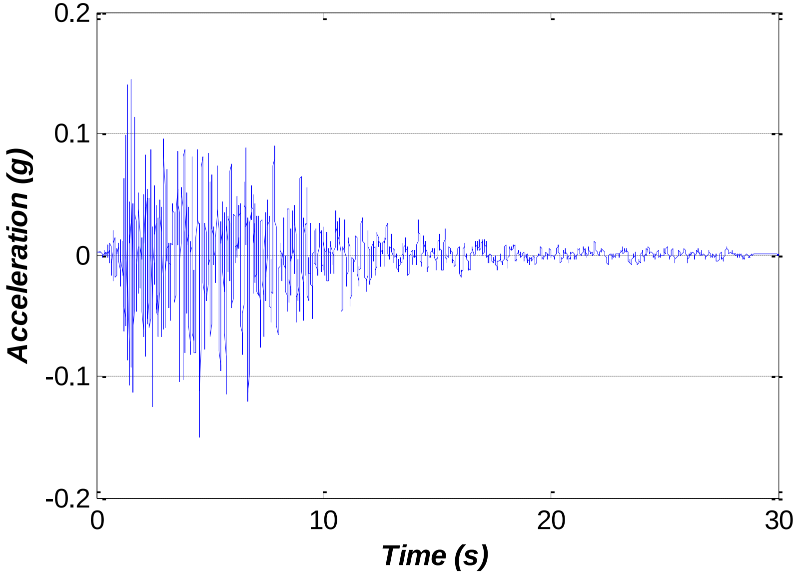
2. 얕은 기초가 있는 구조물의 거동

독립기초 실험

Input Earthquakes

Northridge(1994) and Morgan Hill(1984) earthquake accelerations were used as input earthquakes at the bottom of the ESB box. The peak accelerations of the input acceleration were gradually increased from 0.05g to 0.3g.


Northridge(1994) / Dominant Frequency : 2.4 Hz


Morgan Hill(1984) / Dominant Frequency : 4.8 Hz

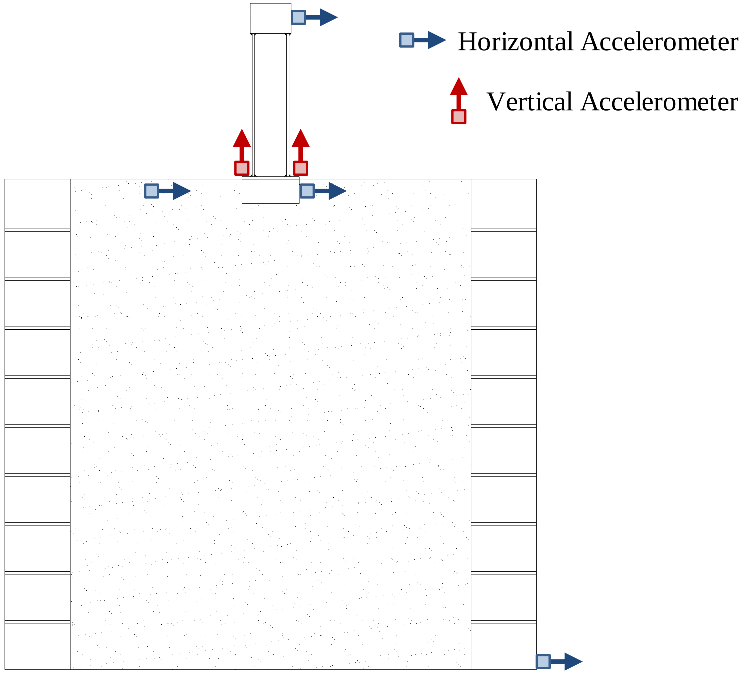
Earthquake Responses of Structures

Measurements of motions

Horizontal Acceleration at the top of Structure $\ddot{u}_t$

Horizontal Acceleration of Foundation $\ddot{u}_f$

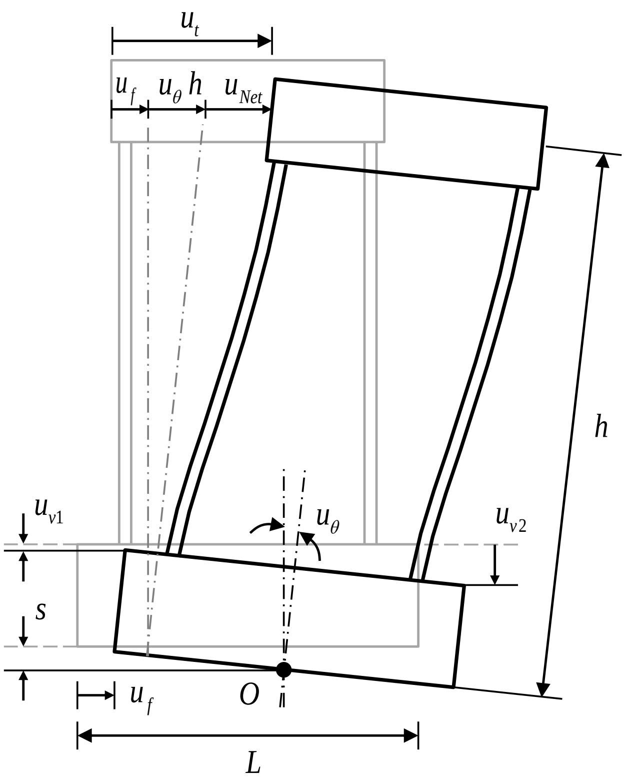
Two vertical Acceleration of Foundation $\ddot{u}_{v1}$, $\ddot{u}_{v2}$ were measured.



Earthquake Responses of Structures

Relationship of displacements

The measured acceleration of structure showed the total behavior including the displacements of the foundation as well as the structure and rocking effect of the structure.



u_t : total displacement of the structure

u_f : horizontal displacement of the foundation

u_{v1} / u_{v2} : two vertical displacements of the foundation

u_θ : rocking angle of the foundation

$$u_\theta = (u_{v1} - u_{v2}) / L_f$$

Relative displacement including the rocking effect

$$u_{Rel.} = u_t - u_f$$

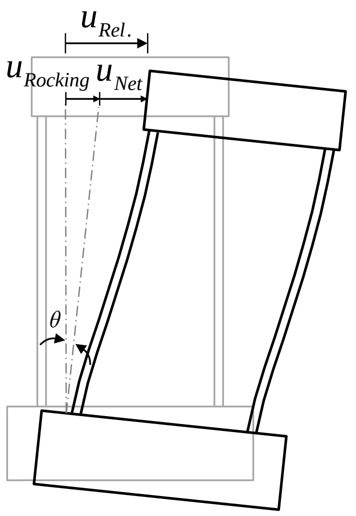
Net displacement excluding the rocking effect

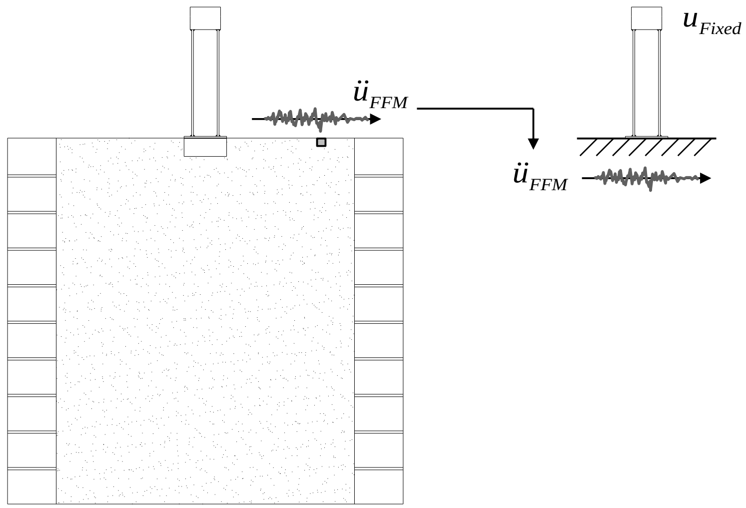
$$u_{Net} = u_{R1} - u_\theta h$$

Earthquake Responses of Structures

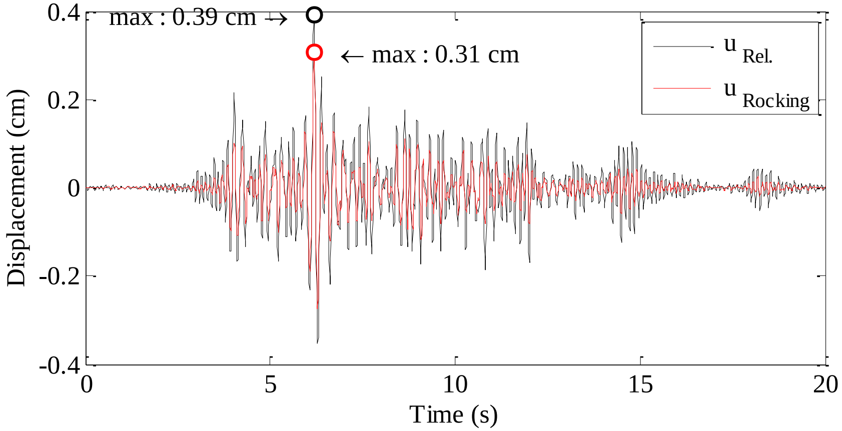
Displacement time history

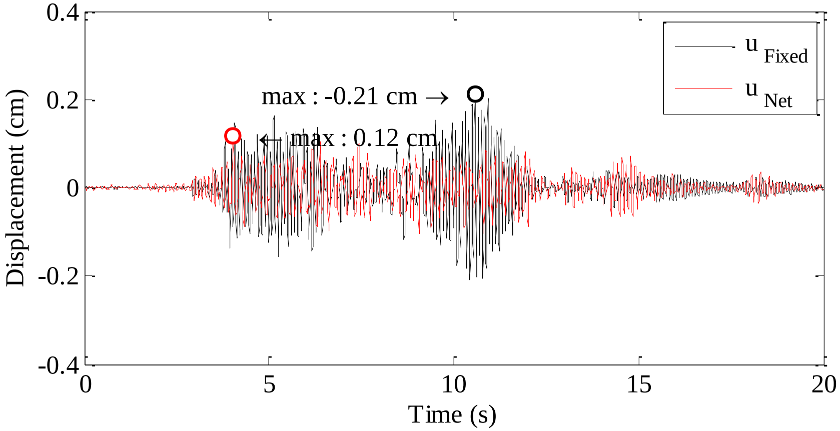
$U_{Rel.}$ VS $U_{Rocking}$ / U_{Net} VS U_{Fixed}





SDOF–1 / T_n : 0.09s in 20gc



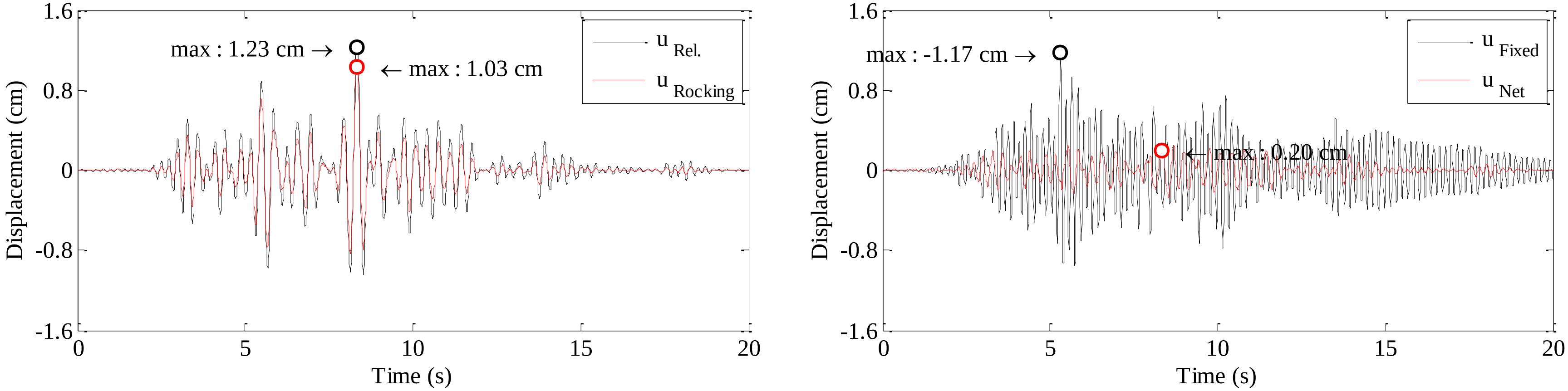


Earthquake Responses of Structures

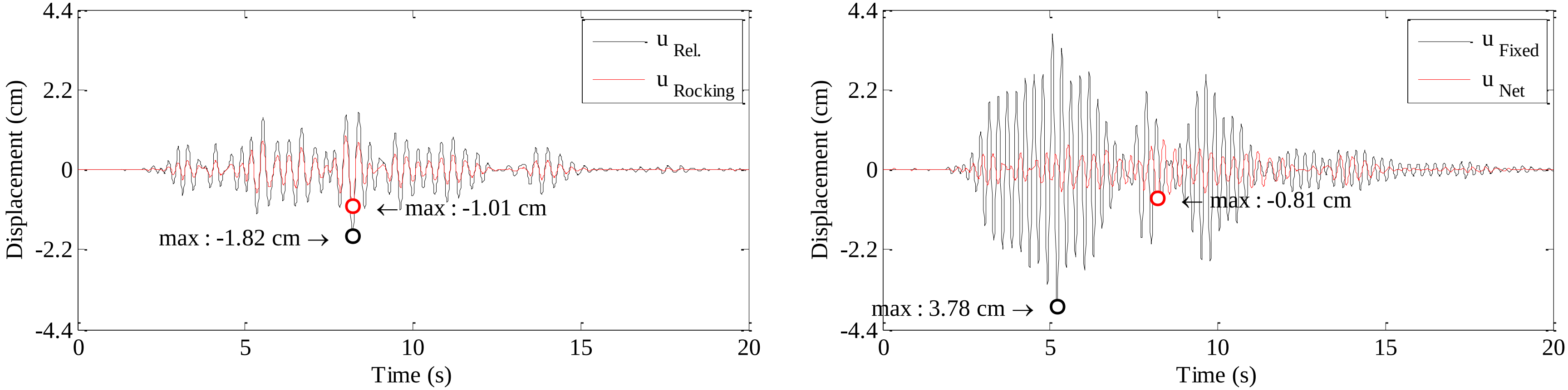
Displacement time history

Displacement time history responses of the structures showed that translation and rocking of the structure were unite periodically.

SDOF–2 / T_n : 0.18s in 20gc



SDOF–3 / T_n : 0.26s in 20gc

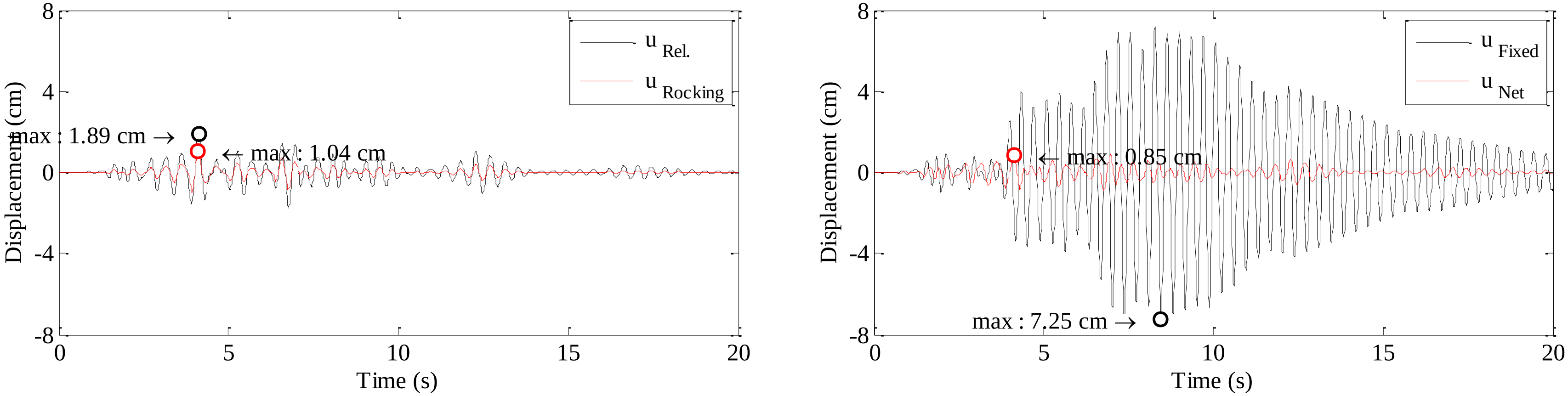


Earthquake Responses of Structures

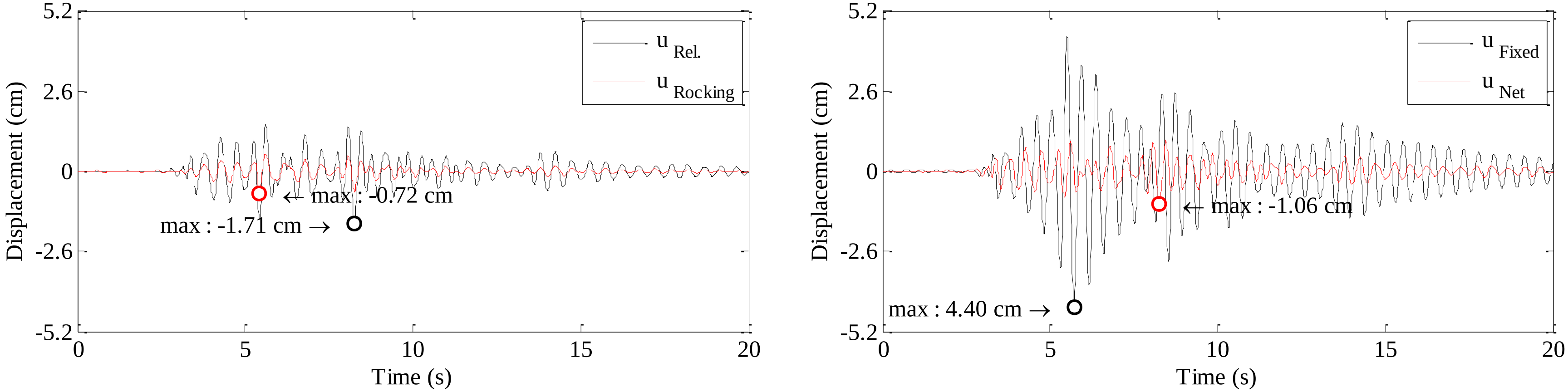
Displacement time history

Even though the responses of the structures with the fixed base model were amplified by the site effect, the rocking effects significantly increased and reduced the seismic loads of super-structure.

SDOF–4 / T_n : 0.36s in 20gc



SDOF–5 / T_n : 0.45s in 20gc

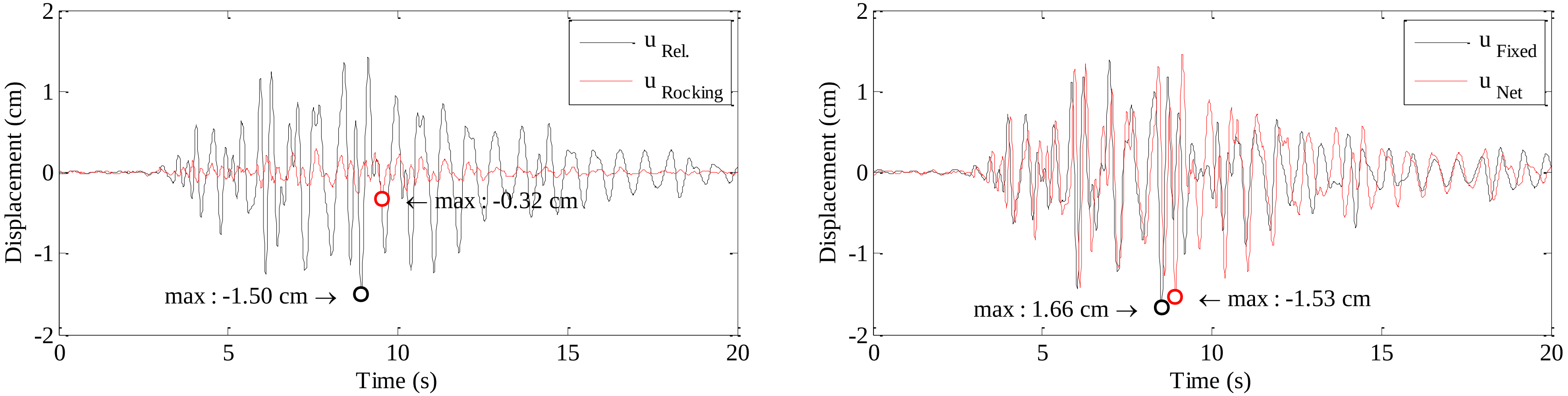


Earthquake Responses of Structures

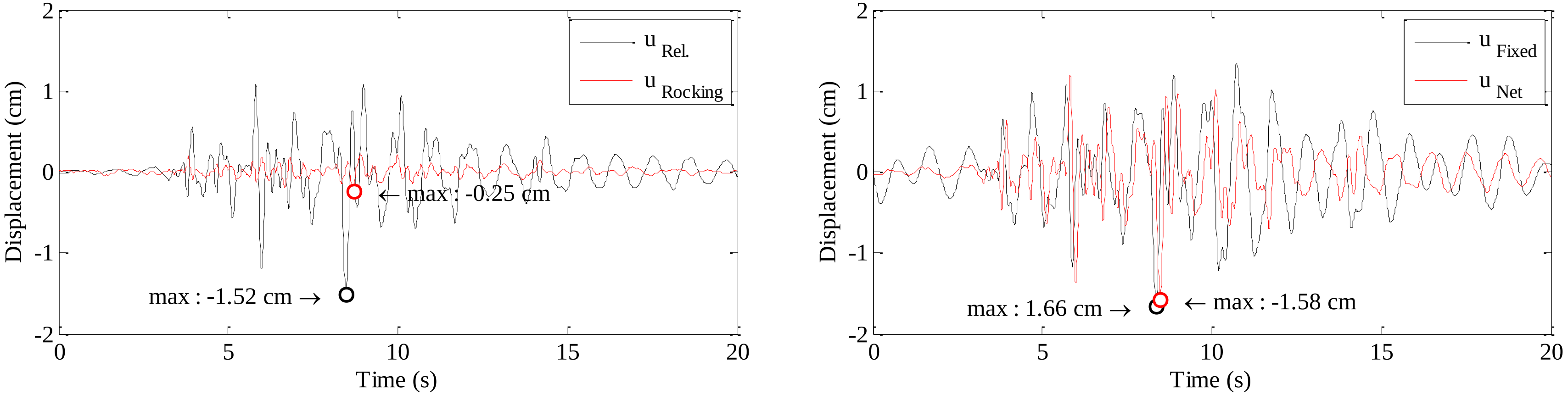
Displacement time history

For the long-period structures, the rocking effects were slight, because the seismic loads of the structures were small and unamplified by the site effects.

SDOF–6 / T_n : 0.66s in 20gc



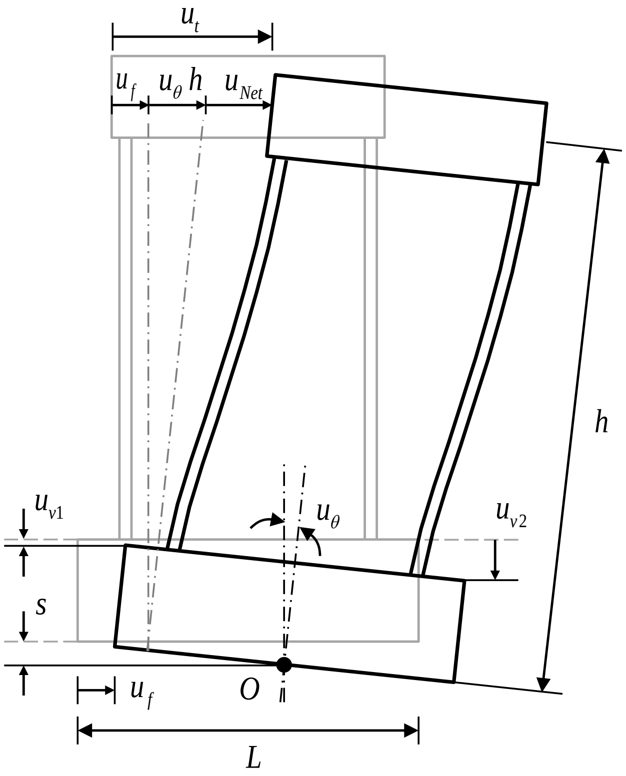
SDOF–7 / T_n : 1.00s in 20gc



Earthquake Responses of Structures

Pseudo-acceleration

The pseudo-acceleration of the structures can be estimated from the net lateral displacement U_{Net}.



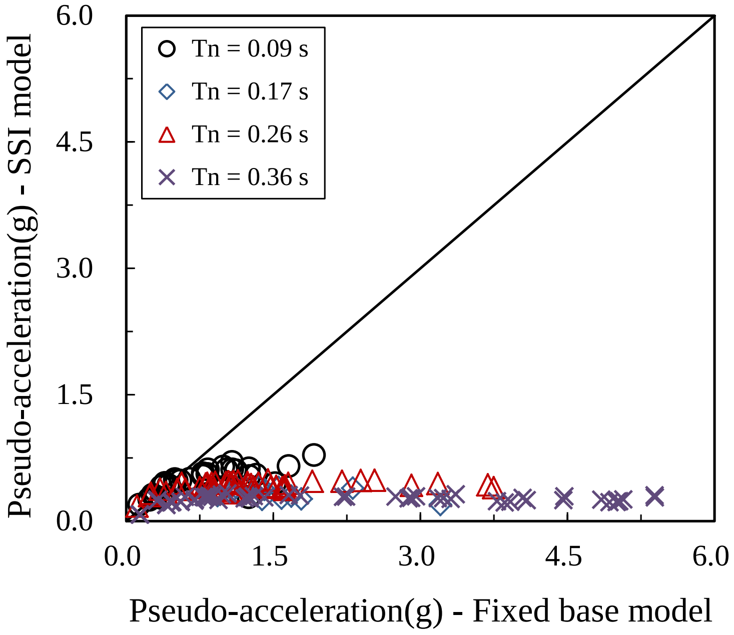
$$S_a = \frac{k_s u_{Net}}{m_s}$$

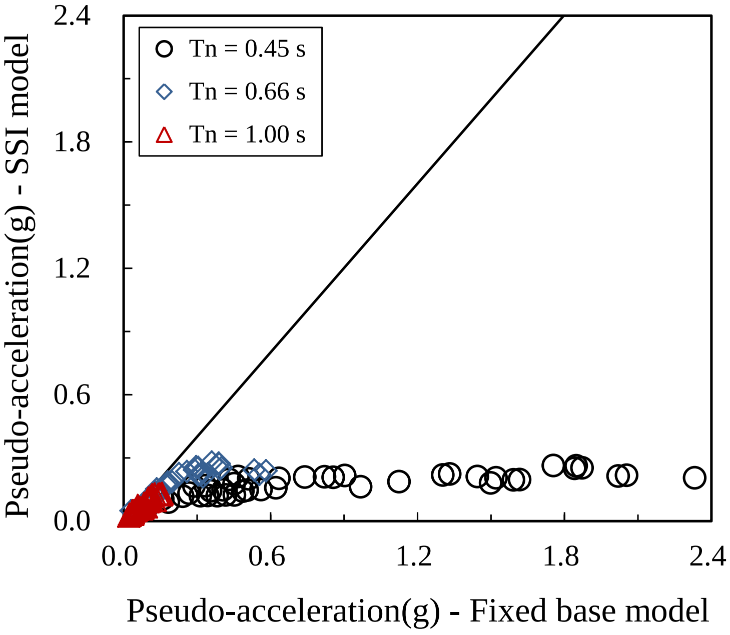
Earthquake Responses of Structures

Pseudo-acceleration

The pseudo-acceleration of the structures can be estimated from the net lateral displacement U_{Net}.

20gc / Depth to bedrock : 12m / Site period : 0.25s





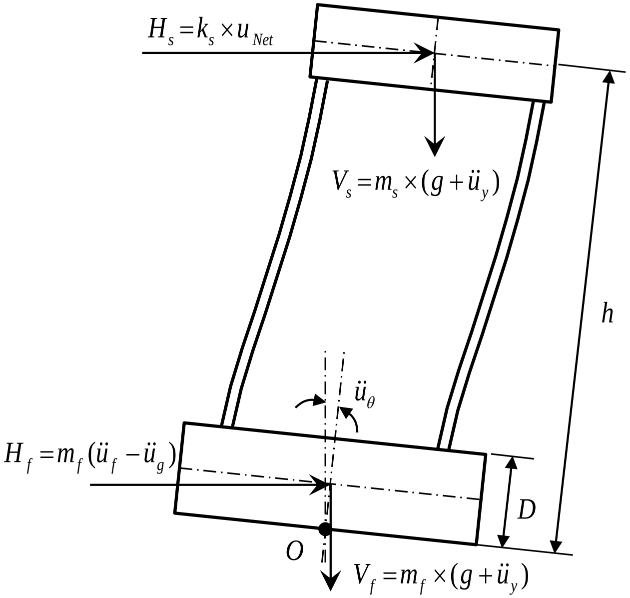
Contents

2. 얕은 기초가 있는 구조물의 거동

Ultimate Moment Capacity

Overturning moment

Overturning moment acting on the bottom of foundation was calculated as follows.

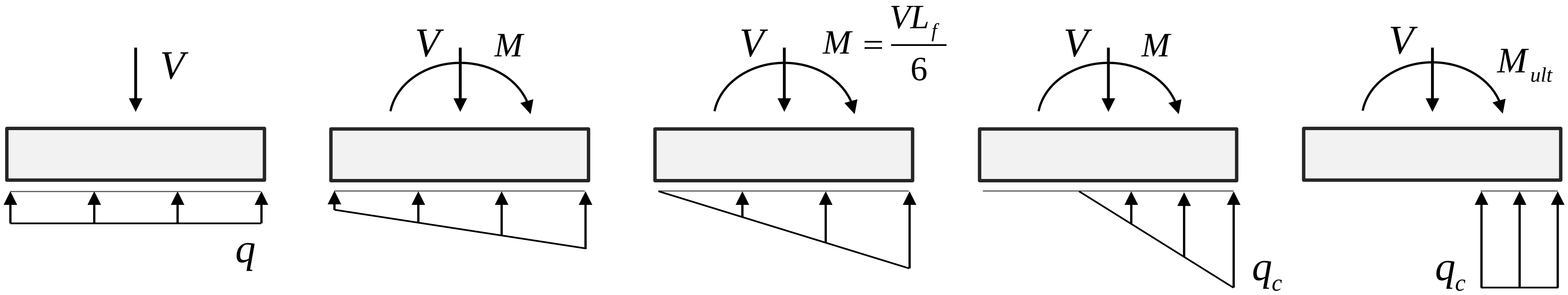


$$M_O = H_s \cdot h + V_s \cdot u_{Net} + H_f \cdot \frac{D}{2} + V_f \cdot \frac{D}{2} \cdot \sin u_\theta + I \cdot \ddot{u}_\theta$$

2. 얕은 기초가 있는 구조물의 거동

Ultimate Moment Capacity

Variation of bearing stress distribution according to the eccentricity of reaction (FEMA 274)



(a) Initial state (b) Elastic prior to uplift (c) Elastic at uplift (d) Yield after uplift (e) Inelastic limit

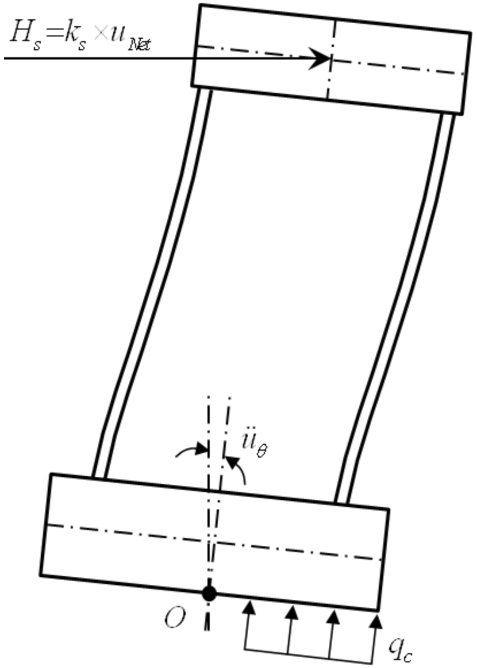
$$M_{ult} = \frac{V \cdot L_f}{2} \cdot \left(1 - \frac{q}{q_c}\right)$$

2. 얕은 기초가 있는 구조물의 거동

Ultimate Moment Capacity

한 개의 기초를 가지는 교각 형식의 구조물은 수평력에 의해 uplift가 발생할 때 응력이 기초 모서리에 집중

Ultimate moment capacity는 지반의 지지 용량 q_c에 대한 수직 하중 응력 q의 비율에 따라 달라짐



2. 얕은 기초가 있는 구조물의 거동

Ultimate Moment Capacity

Maximum spectral acceleration

Maximum spectral acceleration inducing the ultimate moment capacity of the soil-foundation system can be estimated.

$$M_O \leq M_{ult}$$

$$H_s \cdot h = S_a \cdot m_s \cdot h \leq M_{ult} = \frac{m_t \cdot g \cdot L}{2} \cdot \left(1 - \frac{q}{q_c}\right)$$

$$S_a \leq S_{a,max} = \frac{1}{2} \cdot \frac{m_t}{m_s} \cdot \frac{L_f}{h} \cdot \left(1 - \frac{q}{q_c}\right) \cdot g$$

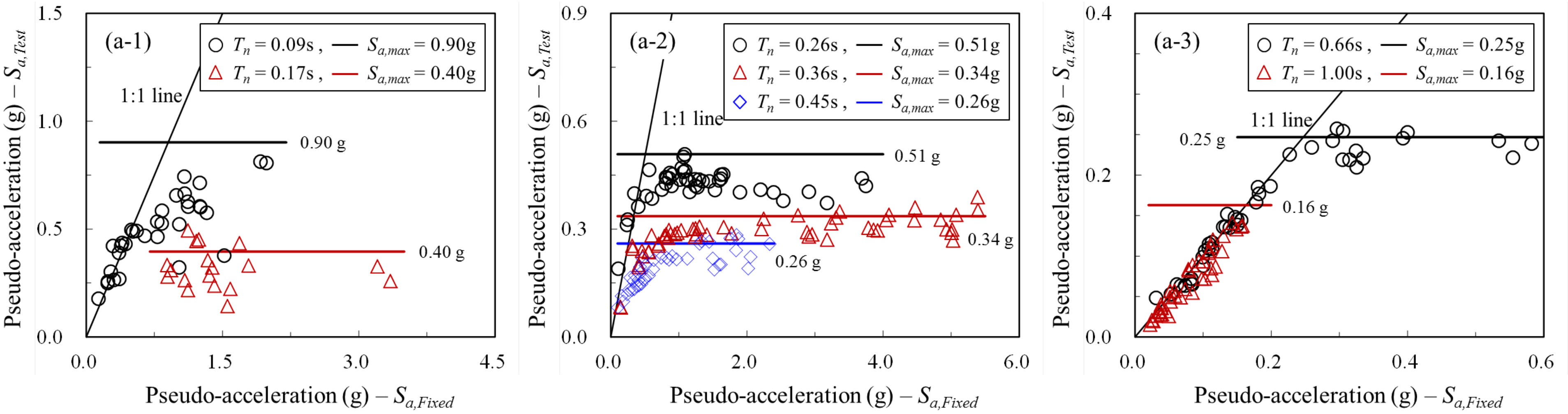
2. 얕은 기초가 있는 구조물의 거동

Ultimate Moment Capacity

Maximum spectral acceleration

The seismic loads of the structures were limited by the ultimate moment capacity of the soil-foundation system and were only 6.5~40% of those from the fixed base model.

20gc / Depth to bedrock : 12m / Site period : 0.25s



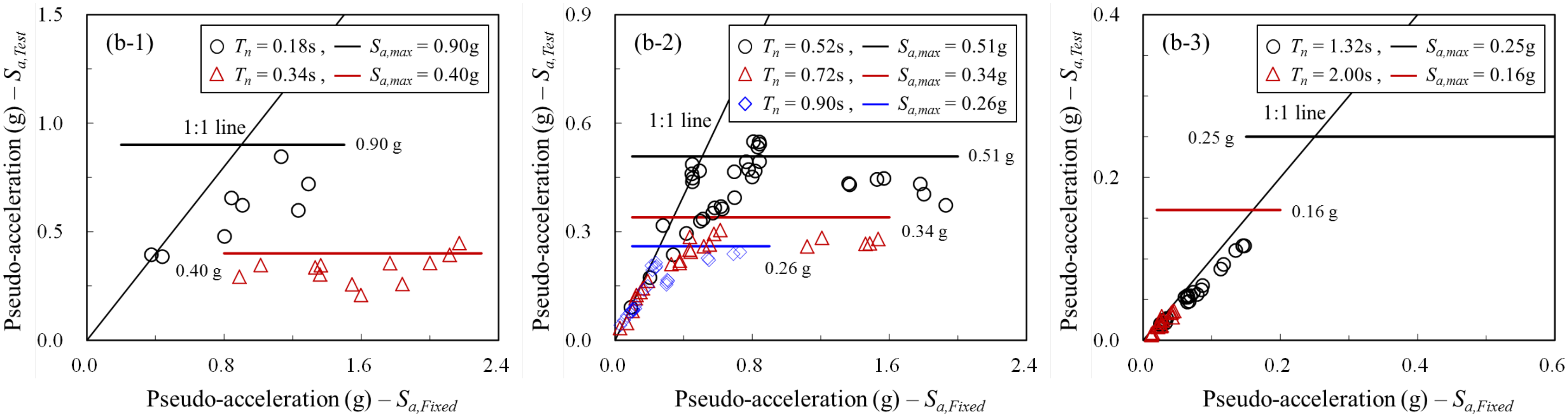
2. 얕은 기초가 있는 구조물의 거동

Ultimate Moment Capacity

Maximum spectral acceleration

The seismic loads of the structures were limited by the ultimate moment capacity of the soil-foundation system and were only 6.5~40% of those from the fixed base model.

40gc / Depth to bedrock : 24m / Site period : 0.41s



2. 얕은 기초가 있는 구조물의 거동

Ultimate Moment Capacity

Allmond, J. and Kutter, B. (2014). "Design considerations for rocking foundations on unattached piles." J. Geotech. Geoenviron. Eng., 10.1061/(ASCE)GT.1943-5606.0001162, 04014058.

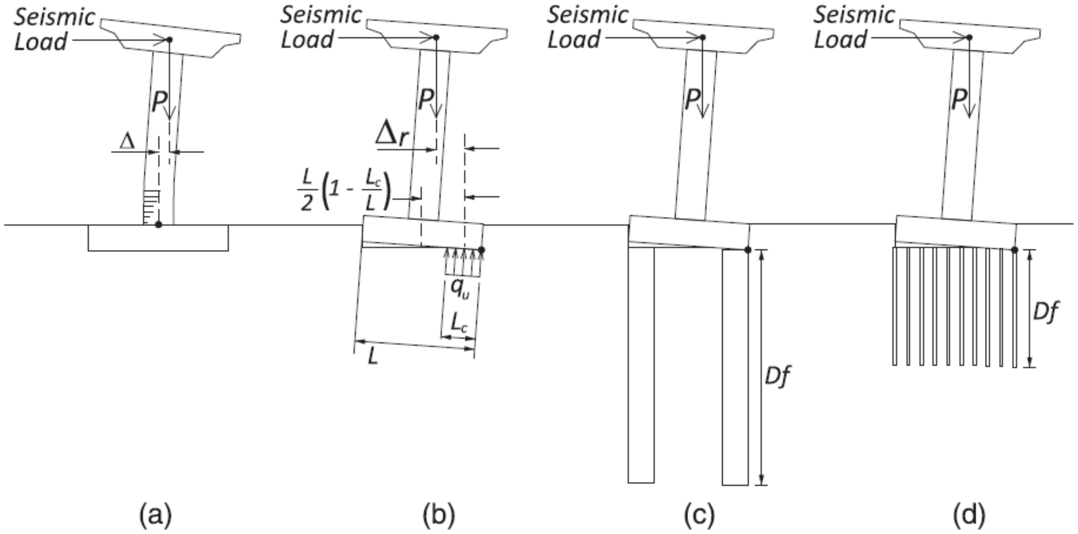
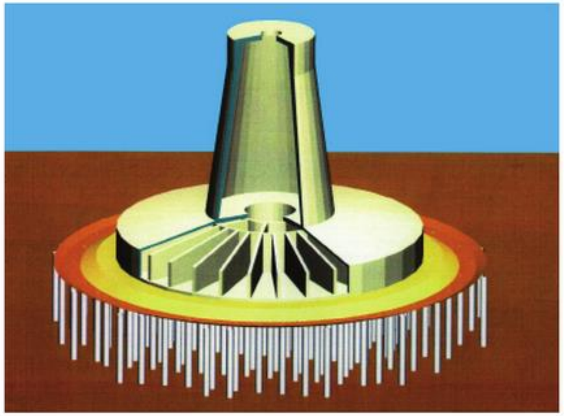
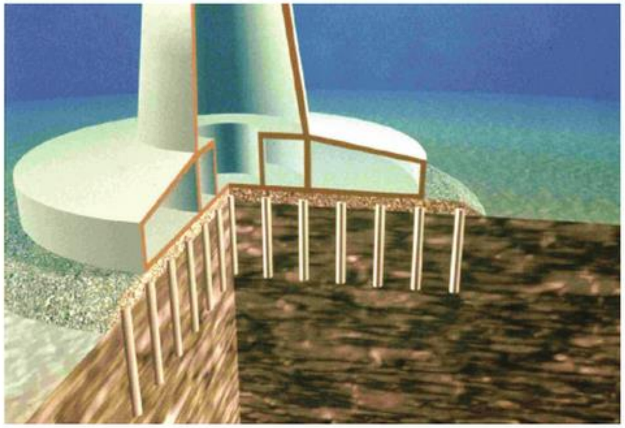


Fig. 1. Rocking foundation schematic for (a) hinging column; (b) nonpiled rocking foundation; (c) rocking foundation on piles; (d) rocking foundation on micropiles

2. 얕은 기초가 있는 구조물의 거동

Rio-Antrio Bridge





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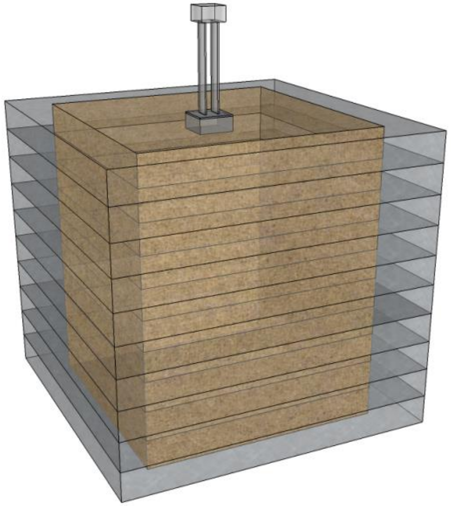
   b. Ultimate Moment Capacity
   c. System Identification
   d. Frame 실험
   e. Frame 실험 & 제안
   f. SSI 효과를 고려한 얕은 기초의 내진설계 & 내진성능평가
3. 지하구조물을 고려한 건축물의 내진설계
4. 결론

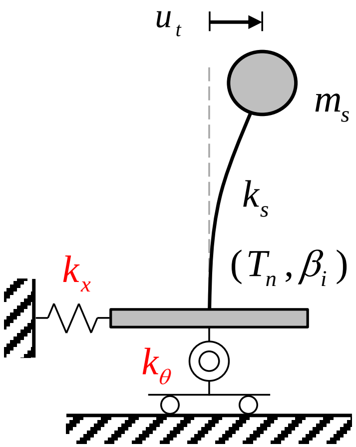
2. 얕은 기초가 있는 구조물의 거동

System Identification

Estimation of stiffness and damping ratio

known : stiffness and damping ratio of structure
unknown : translational stiffness & damping ratio of foundation
: rotational stiffness & damping ratio of foundation





Uncoupled spring model

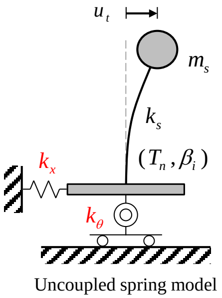
$$\begin{pmatrix} m_s & m_s & m_s h \\ m_s & m_s + m_f & m_s h \\ m_s & m_s h & I_f + m_s h^2 \end{pmatrix}\begin{pmatrix} \ddot{u}_{Net} \\ \ddot{u}_{rf} \\ \ddot{u}_\theta \end{pmatrix} + \begin{pmatrix} c_s & 0 & 0 \\ 0 & c_f & 0 \\ 0 & 0 & c_\theta \end{pmatrix}\begin{pmatrix} \dot{u}_{Net} \\ \dot{u}_{rf} \\ \dot{u}_\theta \end{pmatrix} + \begin{pmatrix} k_s & 0 & 0 \\ 0 & k_x & 0 \\ 0 & 0 & k_\theta \end{pmatrix}\begin{pmatrix} u_{Net} \\ u_{rf} \\ u_\theta \end{pmatrix} = -\begin{pmatrix} m_s \\ m_s + m_f \\ m_s h \end{pmatrix}\ddot{u}_g$$

2. 얕은 기초가 있는 구조물의 거동

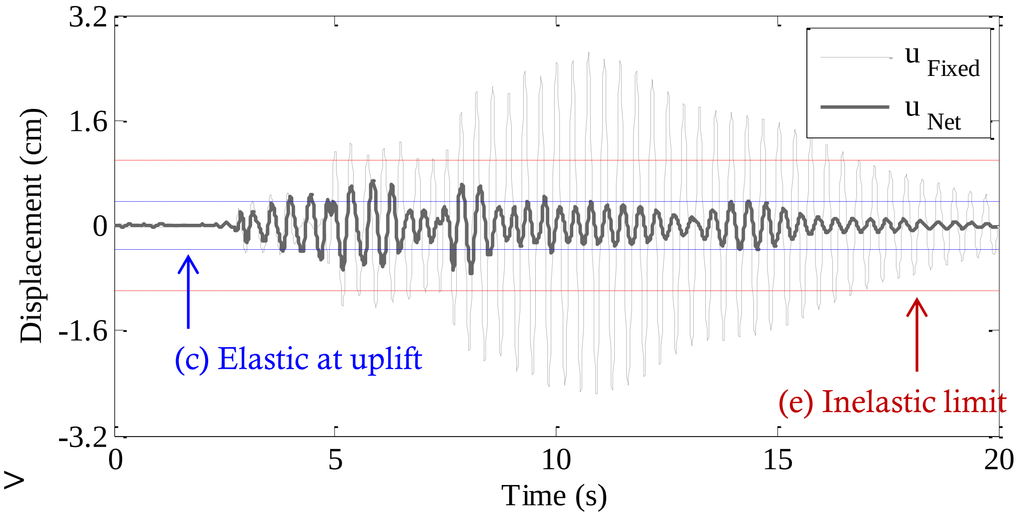
System Identification

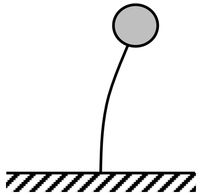
Goal of system identification

As the overturning moment increased, uplift and nonlinear behaviors occurred between the foundation and the sub-soil. Using system identification, the nonlinear properties can be estimated.

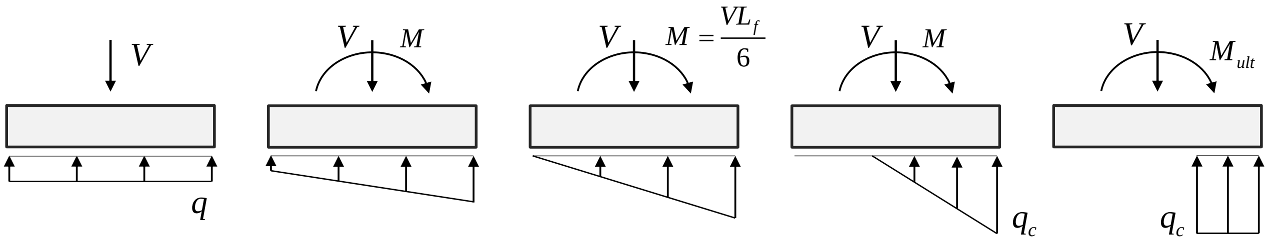


< Flexible base >





< Fixed base >



(a) Initial state (b) Elastic prior to uplift (c) Elastic at uplift (d) Yield after uplift (e) Inelastic limit

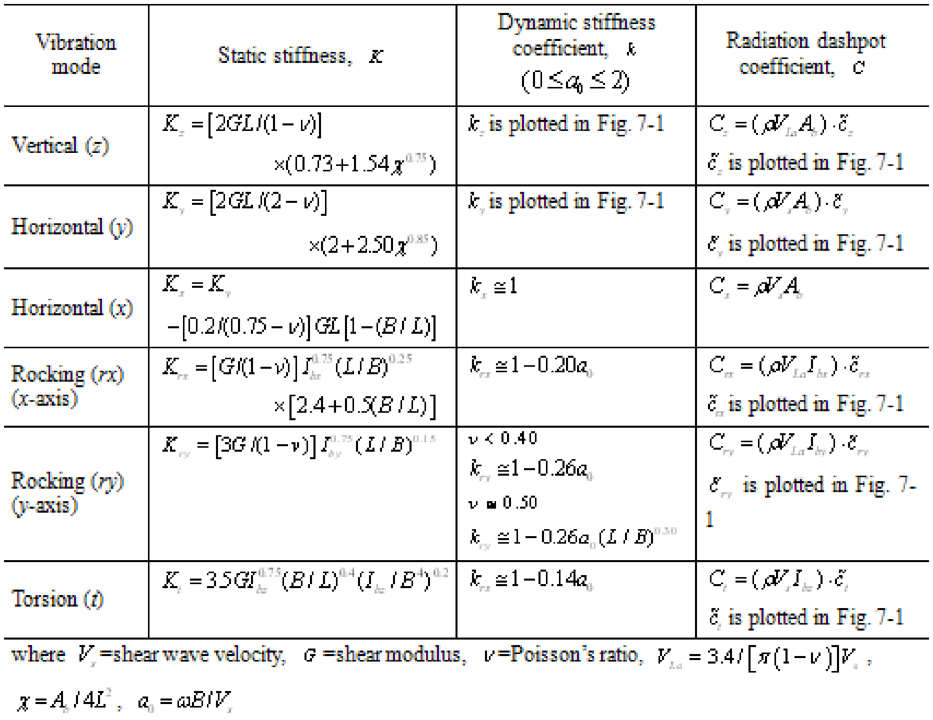
2. 얕은 기초가 있는 구조물의 거동

System Identification

Gazetas' Formulas and Charts

Gazetas proposed a set of formulas and charts for stiffness and damping ratio of soil-foundation system. It is basis of those in FEMA 356 and FEMA 440.

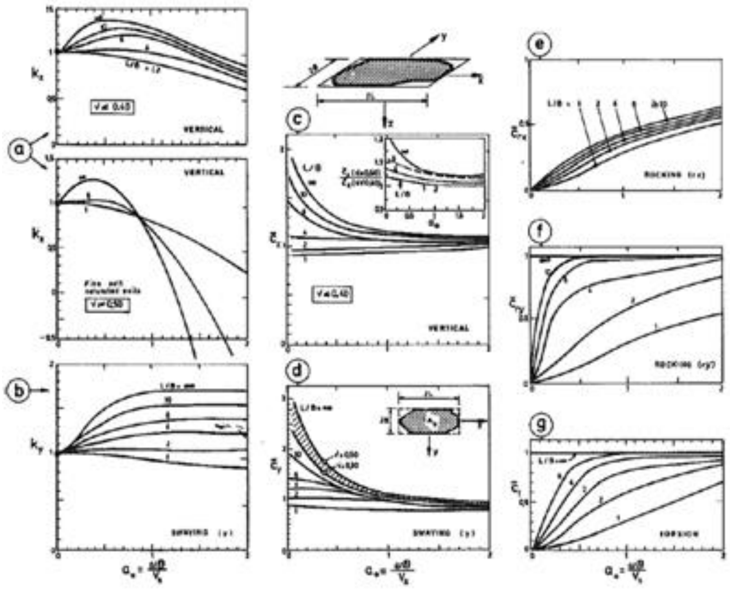
Table 7-1. Dynamic Stiffnesses and dashpot coefficient formulas (Gazetas 1991)



Vibration mode	Static stiffness, K	Dynamic stiffness coefficient, k $(0 \le a_0 \le 2)$	Radiation dashpot coefficient, C
Vertical (z)	$K_z = [2GL/(1-\nu)]$ $\times(0.73+1.54\chi^{0.75})$	k_z is plotted in Fig. 7-1	$C_z = (\rho V_{La} A_b)\cdot \tilde{c}_z$ $\tilde{c}_z$ is plotted in Fig. 7-1
Horizontal (y)	$K_y = [2GL/(2-\nu)]$ $\times(2+2.50\chi^{0.85})$	k_y is plotted in Fig. 7-1	$C_y = (\rho V_s A_b)\cdot \tilde{c}_y$ $\tilde{c}_y$ is plotted in Fig. 7-1
Horizontal (x)	$K_x = K_y$ $-[0.2/(0.75-\nu)]GL[1-(B/L)]$	$k_x \cong 1$	$C_x = \rho V_s A_b$
Rocking (rx) (x-axis)	$K_{rx} = [G/(1-\nu)]I_{bx}^{0.75}(L/B)^{0.25}$ $\times[2.4+0.5(B/L)]$	$k_{rx} \cong 1-0.20a_0$	$C_{rx} = (\rho V_{La} I_{bx})\cdot \tilde{c}_{rx}$ $\tilde{c}_{rx}$ is plotted in Fig. 7-1
Rocking (ry) (y-axis)	$K_{ry} = [3G/(1-\nu)]I_{by}^{0.75}(L/B)^{0.15}$	$\nu < 0.40$ $k_{ry} \cong 1-0.26a_0$ $\nu \approx 0.50$ $k_{ry} \cong 1-0.26a_0(L/B)^{0.30}$	$C_{ry} = (\rho V_{La} I_{by})\cdot \tilde{c}_{ry}$ $\tilde{c}_{ry}$ is plotted in Fig. 7-1
Torsion (t)	$K_t = 3.5GI_{bz}^{0.75}(B/L)^{0.4}(I_{bz}/B^4)^{0.2}$	$k_{rx} \cong 1-0.14a_0$	$C_t = (\rho V_s I_{bz})\cdot \tilde{c}_t$ $\tilde{c}_t$ is plotted in Fig. 7-1

where V_s =shear wave velocity, G =shear modulus, ν=Poisson's ratio, $V_{La} = 3.4/[\pi(1-\nu)]V_s$,

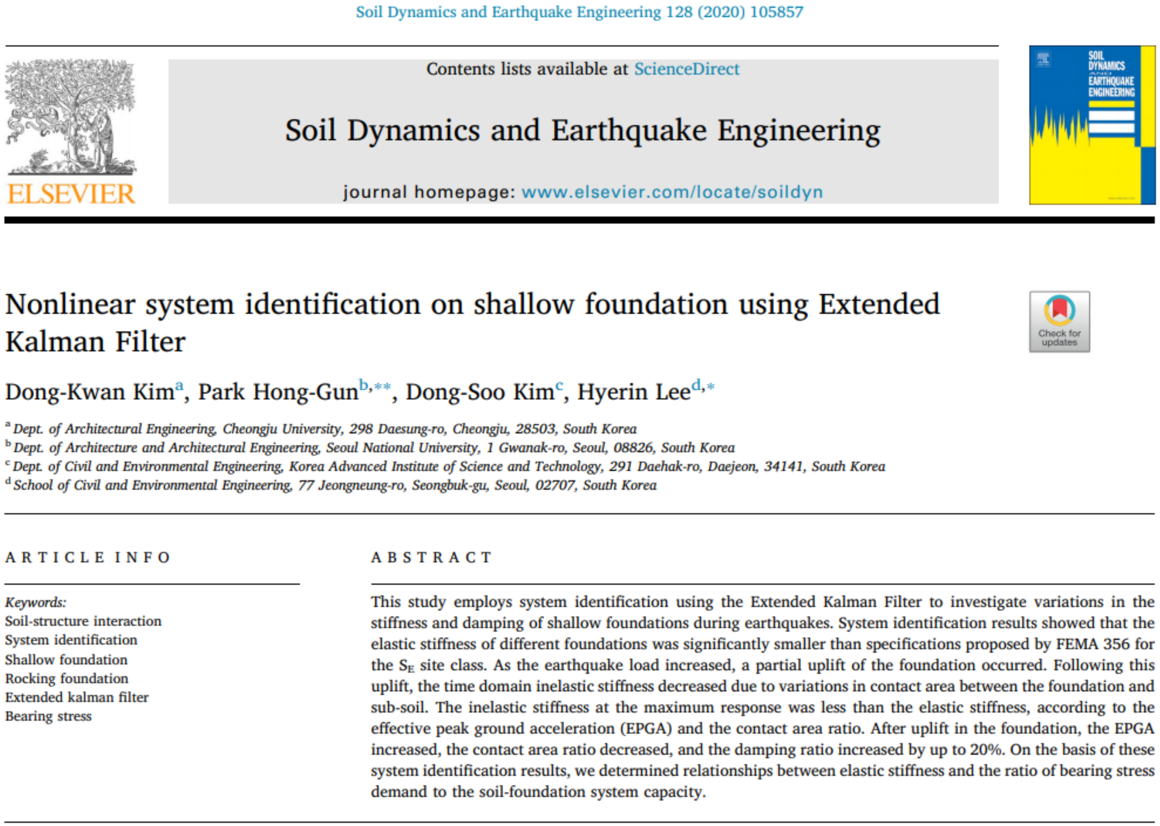
$\chi = A_b/4L^2$, $a_0 = \omega B/V_s$



2. 얕은 기초가 있는 구조물의 거동

System Identification

Kim, DK. Park, HG. Kim, DS. Lee, H (2020). “Nonlinear system identification on shallow foundation using Extended Kalman Filter." *J. Soil Dynamics and Earthquake Engineering.*, 10.1016/j.soildyn.2019, 105857.



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journal homepage: www.elsevier.com/locate/soildyn

Nonlinear system identification on shallow foundation using Extended Kalman Filter

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System identification
Shallow foundation
Rocking foundation
Extended kalman filter
Bearing stress

ABSTRACT

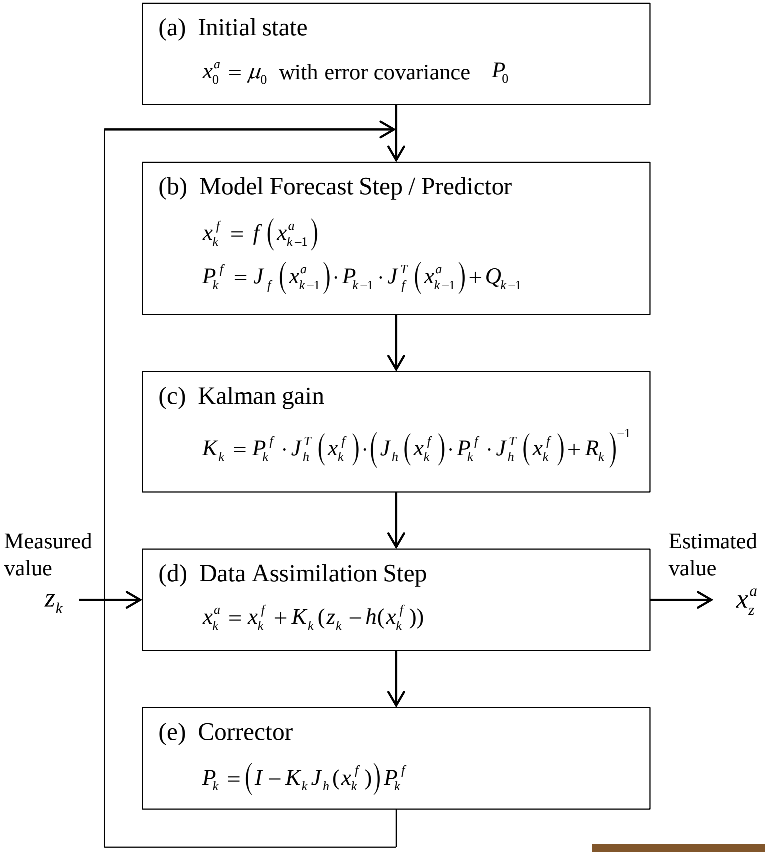
This study employs system identification using the Extended Kalman Filter to investigate variations in the stiffness and damping of shallow foundations during earthquakes. System identification results showed that the elastic stiffness of different foundations was significantly smaller than specifications proposed by FEMA 356 for the S_E site class. As the earthquake load increased, a partial uplift of the foundation occurred. Following this uplift, the time domain inelastic stiffness decreased due to variations in contact area between the foundation and sub-soil. The inelastic stiffness at the maximum response was less than the elastic stiffness, according to the effective peak ground acceleration (EPGA) and the contact area ratio. After uplift in the foundation, the EPGA increased, the contact area ratio decreased, and the damping ratio increased by up to 20%. On the basis of these system identification results, we determined relationships between elastic stiffness and the ratio of bearing stress demand to the soil-foundation system capacity.

2. 얕은 기초가 있는 구조물의 거동

System Identification

Extended Kalman Filter

Based on the measured values and the system function, the Extended Kalman Filter estimates states of targets and the unknown properties.



(a) Initial state

$x_0^a = \mu_0$ with error covariance P_0

(b) Model Forecast Step / Predictor

$$x_k^f = f\left(x_{k-1}^a\right)$$

$$P_k^f = J_f\left(x_{k-1}^a\right) \cdot P_{k-1} \cdot J_f^T\left(x_{k-1}^a\right) + Q_{k-1}$$

(c) Kalman gain

$$K_k = P_k^f \cdot J_h^T\left(x_k^f\right) \cdot \left(J_h\left(x_k^f\right) \cdot P_k^f \cdot J_h^T\left(x_k^f\right) + R_k\right)^{-1}$$

Measured value

z_k

(d) Data Assimilation Step

$$x_k^a = x_k^f + K_k(z_k - h(x_k^f))$$

Estimated value

x_z^a

(e) Corrector

$$P_k = \left(I - K_k J_h(x_k^f)\right) P_k^f$$

2. 얕은 기초가 있는 구조물의 거동

System Identification

State Space Expressions of the SSI model

To use Extended Kalman Filter, the system function should be forwarding process.

$$\{Z(k)\} = \begin{bmatrix} \ddot{u}_{Net} \\ \ddot{u}_{rf} \\ \ddot{u}_{\theta} \\ \dot{u}_{Net} \\ \dot{u}_{rf} \\ \dot{u}_{\theta} \\ u_{Net} \\ u_{rf} \\ u_{\theta} \\ k_s \\ k_f \\ k_{\theta} \\ c_s \\ c_f \\ c_{\theta} \\ \ddot{u}_g \\ \dot{u}_g \\ u_g \end{bmatrix} \quad [18\text{x}1]$$

$$\{Z(k+1)\} = G\left\{\hat{Z}(k|k)\right\} + \Phi\left(k+1|k\right)\left\{Z(k) - \hat{Z}(k|k)\right\} + \{\Gamma(k)\}\, w(k)$$

$G\{Z(k)\}$ is a system function and Tayler expansion is used for linearization

$$\Phi\left(k+1|k\right) = \left[\frac{\partial G\{Z(k)\}}{\partial Z_j}\right]_{Z(k)=Z(k|k)} \qquad (j = 1,\ldots,18)$$

[18 x 18]

$\Phi\left(k+1|k\right)$ is a transition matrix and a Jacobian matrix of $G\{Z(k)\}$

2. 얕은 기초가 있는 구조물의 거동

System Identification

Time history responses

Compared with Gazetas' formulas and charts, system identification well estimated overall nonlinear behaviors of the foundations.

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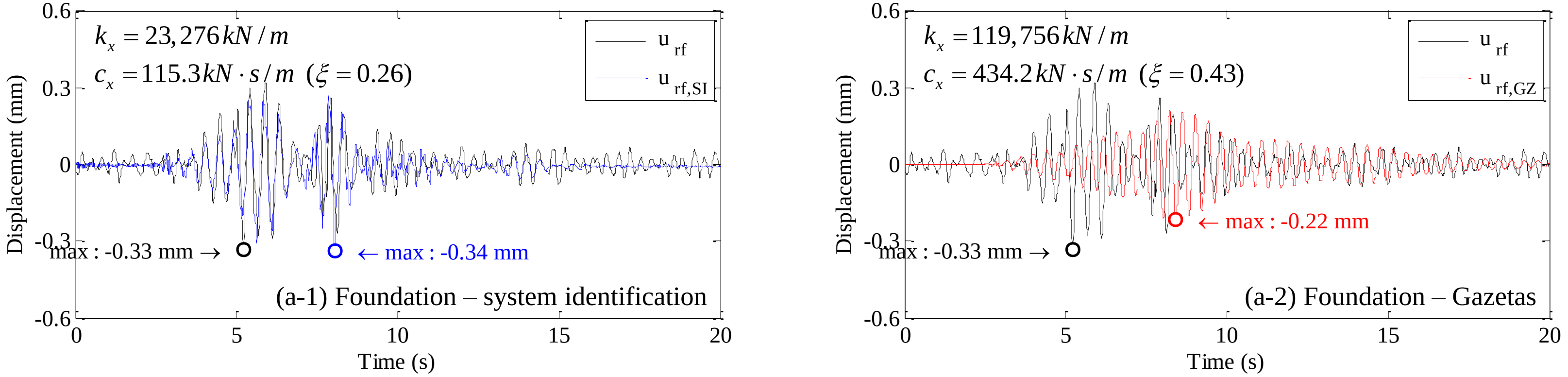

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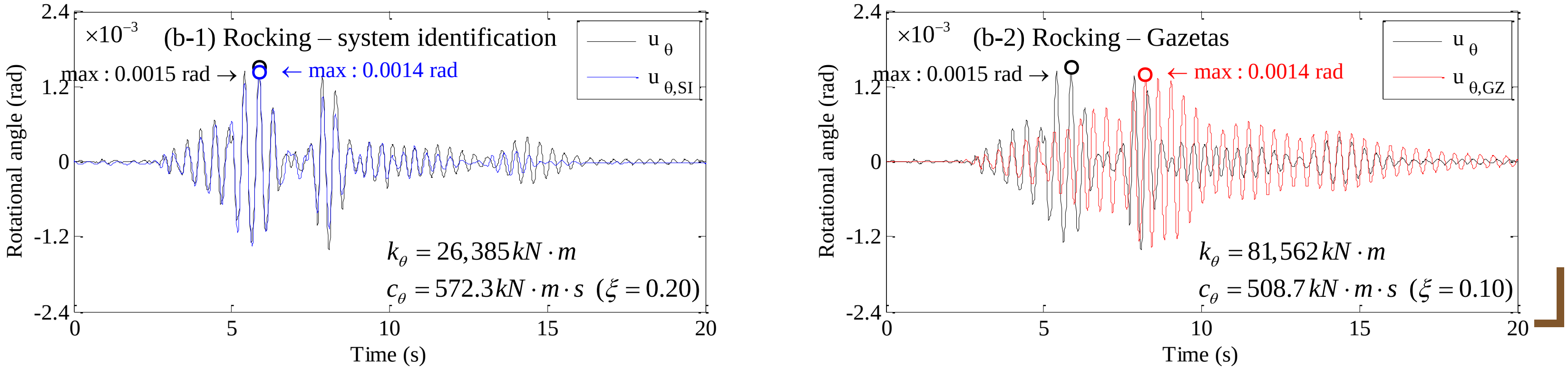


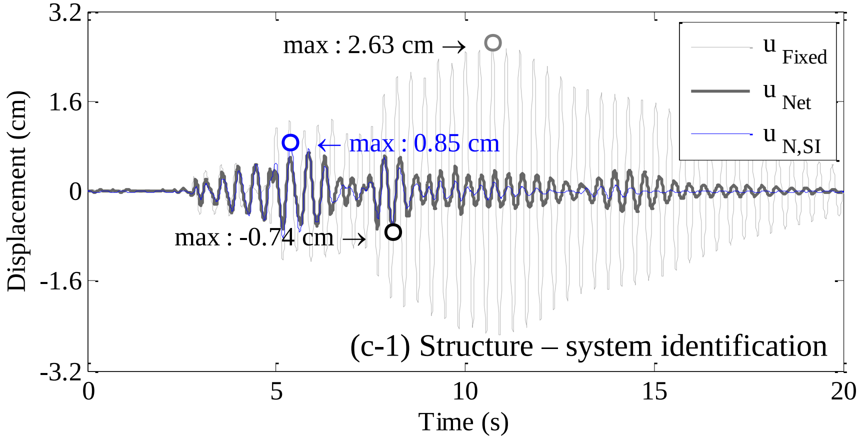
2. 얕은 기초가 있는 구조물의 거동

System Identification

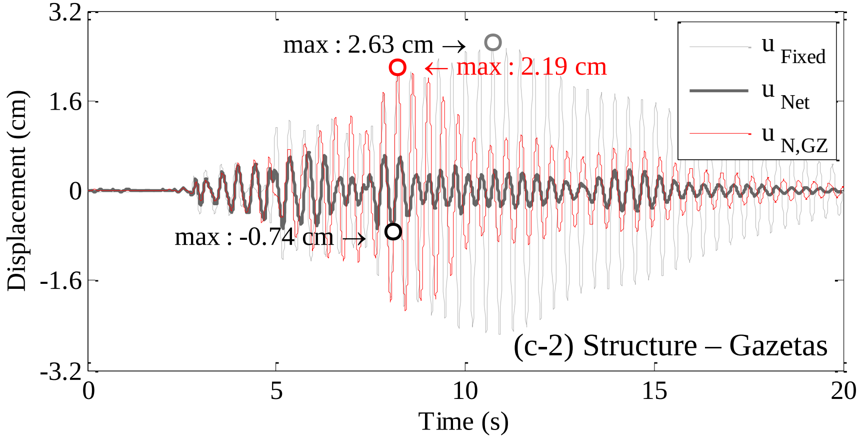
Time history responses

Net displacement from the SI was similar to the test result.

Net displacement from Gazetas' was similar to those from the fixed base model



(c-1) Structure – system identification



(c-2) Structure – Gazetas

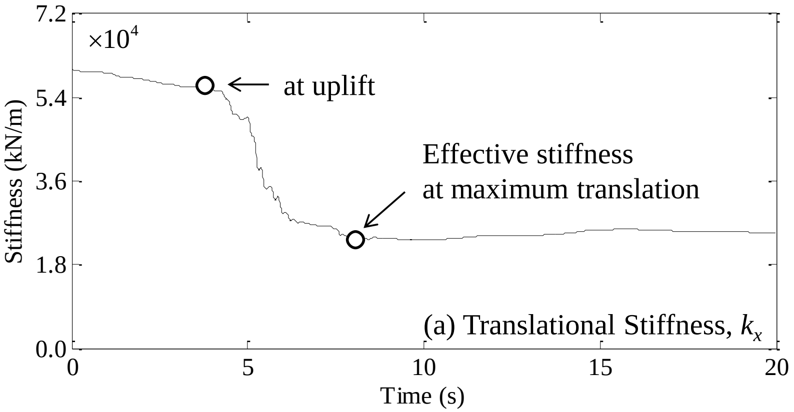
2. 얕은 기초가 있는 구조물의 거동

System Identification

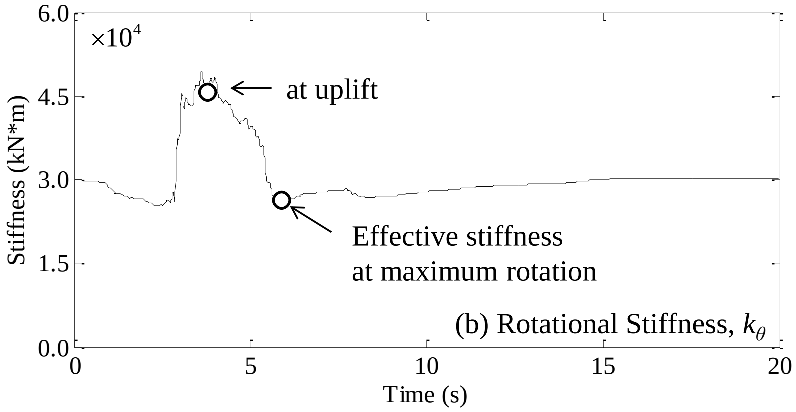
Estimated properties

Dynamic properties estimated from the SI presented nonlinear characteristics between the foundation and the sub-soil.

< Stiffness >

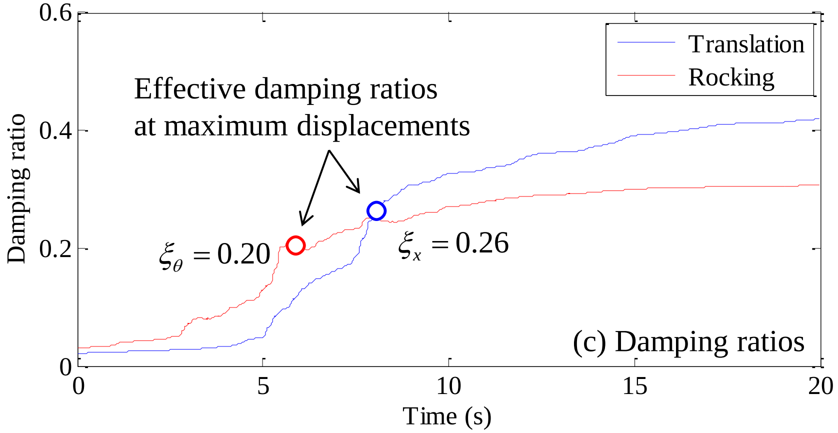


(a) Translational Stiffness, k_x



(b) Rotational Stiffness, k_θ

< Damping ratio >



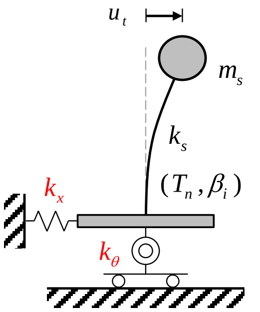
(c) Damping ratios

2. 얕은 기초가 있는 구조물의 거동

System Identification

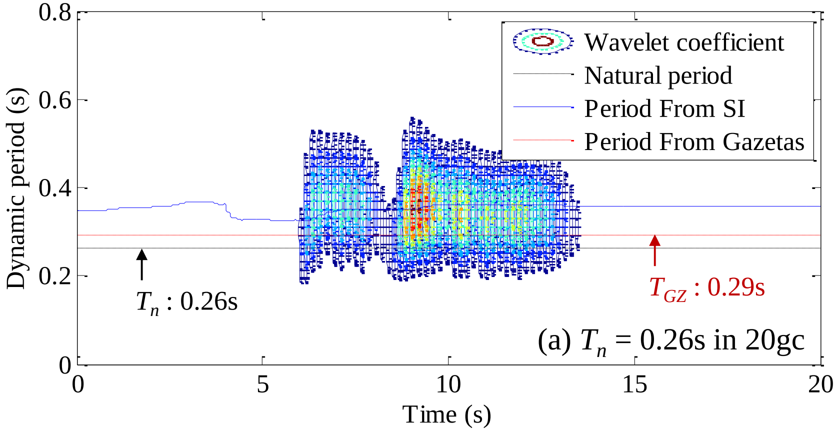
Period lengthening

Period lengthening resulting from the stiffness of SI agreed with those from Wavelet analysis, which could show variations of the periods of the structure in time domain.

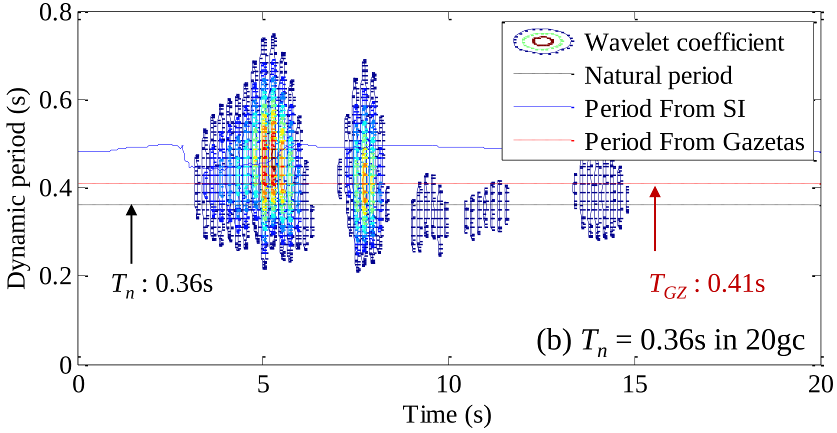


Uncoupled spring model

$$\tilde{T} = T_n \cdot \sqrt{1+\frac{k_s}{k_x}+\frac{k_s h^2}{k_\theta}}$$



(a) T_n = 0.26s in 20gc



(b) T_n = 0.36s in 20gc

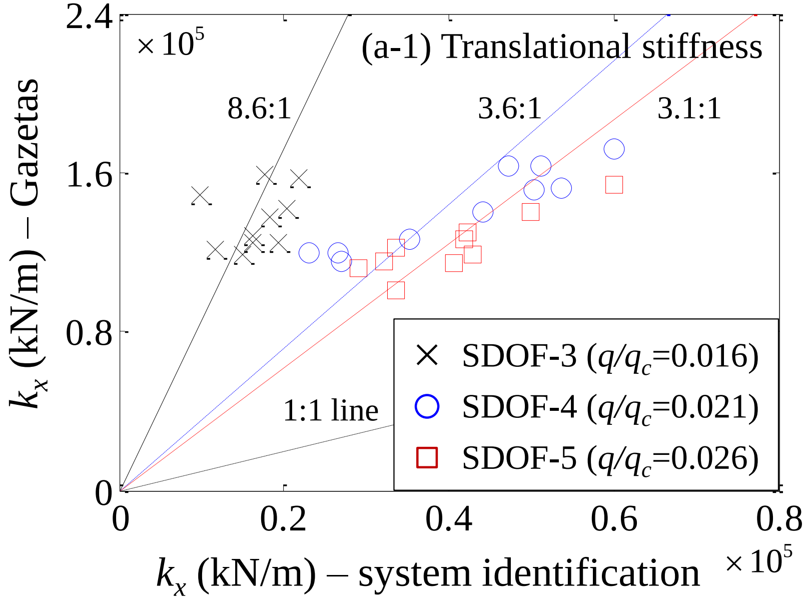
2. 얕은 기초가 있는 구조물의 거동

System Identification

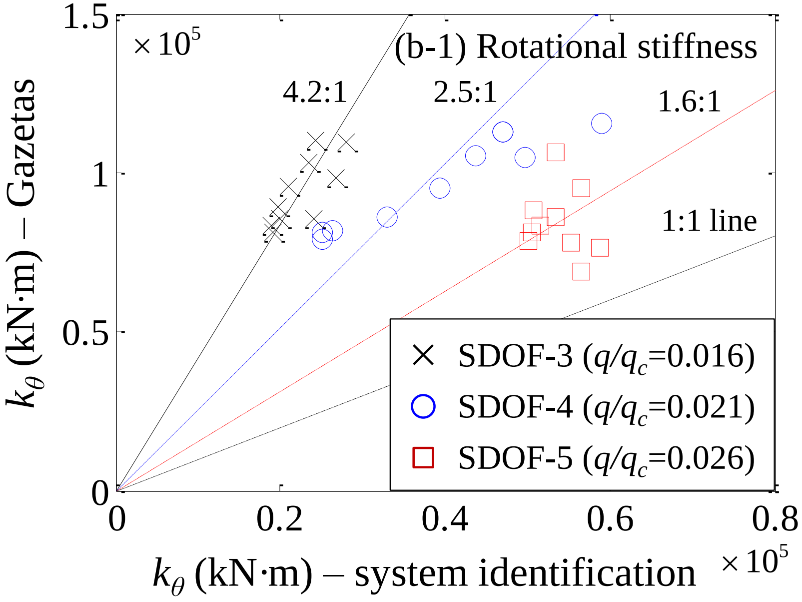
Estimated properties

As the q/qc increased, the increased contact area between the foundation and the sub-soil after the uplift affected the stiffnesses of the foundation.

< Translational Stiffness >



< Rotational Stiffness >

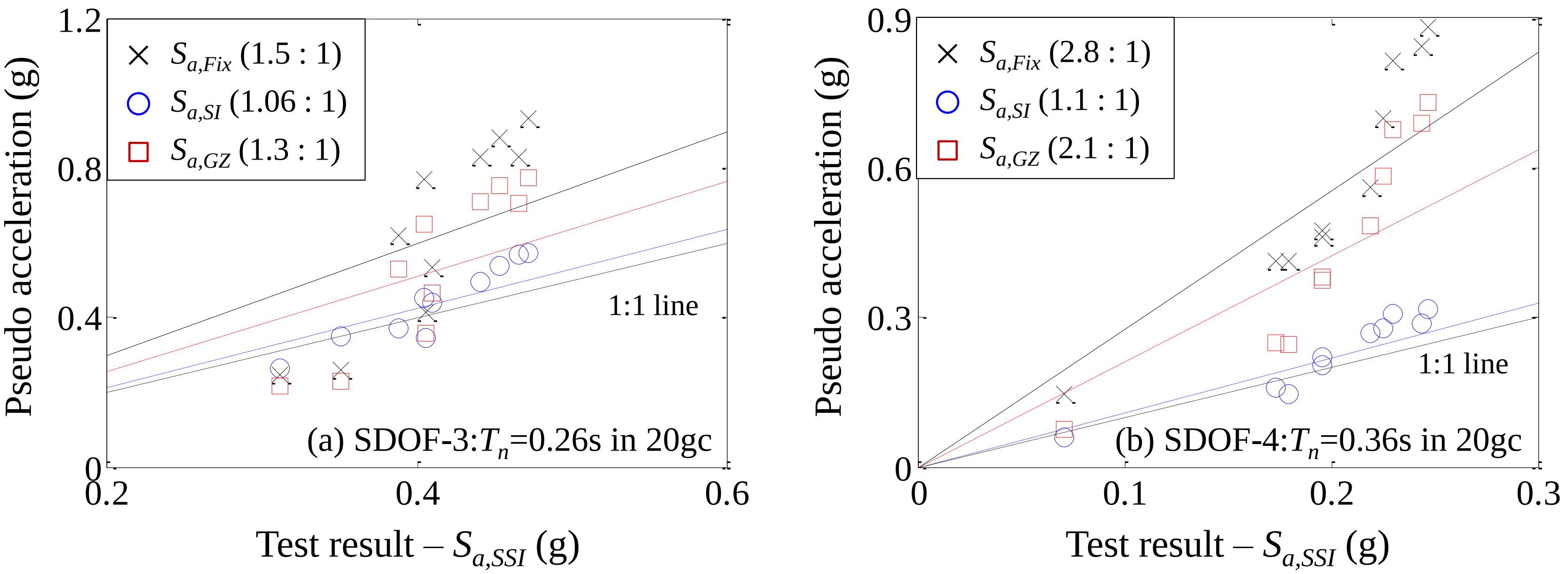


2. 얕은 기초가 있는 구조물의 거동

System Identification

Pseudo-acceleration

From the combinations of the stiffnessess and dampings, which were estimated by the system identifications, the net displacements and the seismic loads of the structures were very similar to those of the tests with reasonable accuracies.



(a) SDOF-3:T_n=0.26s in 20gc

(b) SDOF-4:T_n=0.36s in 20gc

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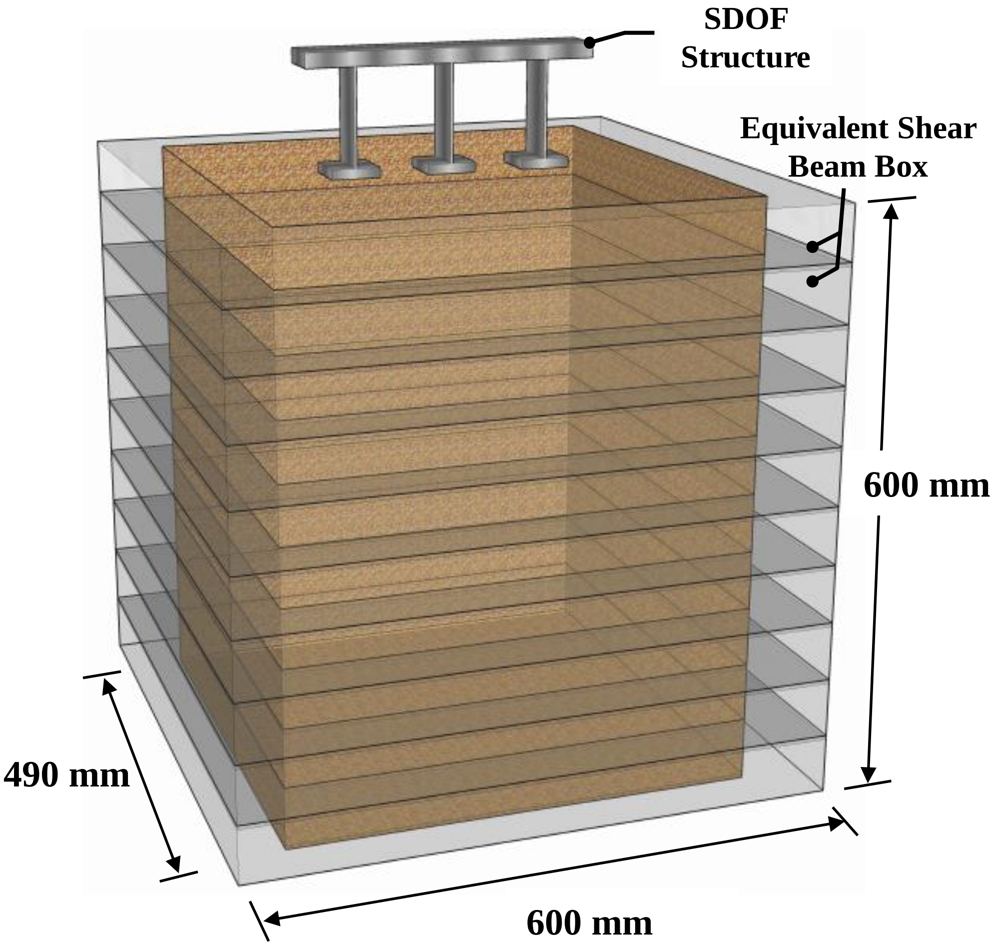
    a. 독립기초 실험
    b. Ultimate Moment Capacity
    c. System Identification
    d. Frame 실험
    e. Frame 실험 & 제안
    f. SSI 효과를 고려한 얕은 기초의 내진설계 & 내진성능평가
3. 지하구조물을 고려한 건축물의 내진설계
4. 결론

2. 얕은 기초가 있는 구조물의 거동

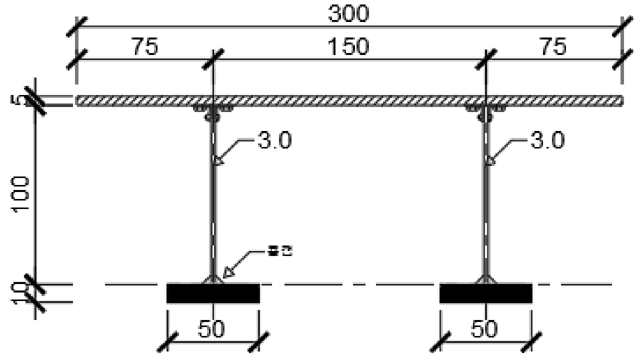
Frame 실험

Test Specimen



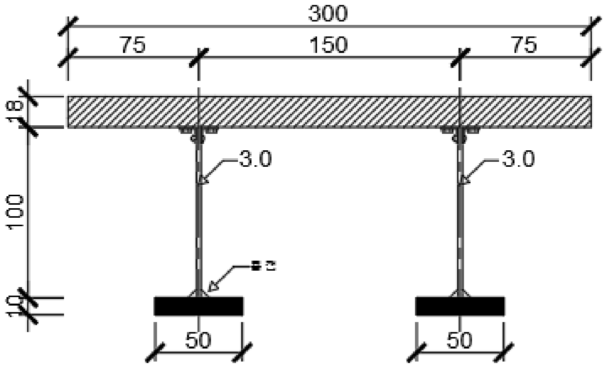
2. 얕은 기초가 있는 구조물의 거동

Frame 실험



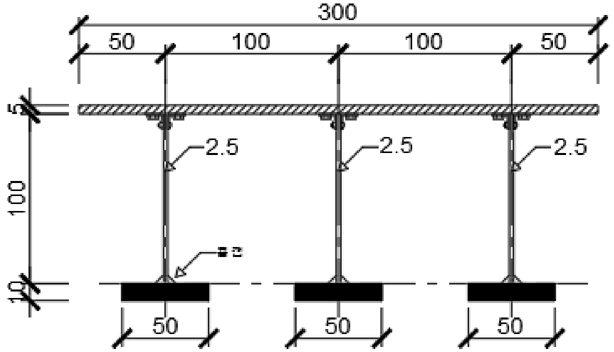
SDOF – 1

$T = 0.304\ s, weight = 12.2\ N$



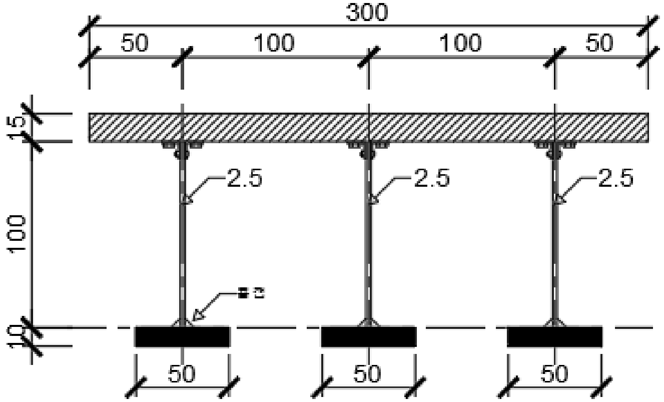
SDOF – 2

$T = 0.500\ s, weight = 28.0\ N$



SDOF – 3

$T = 0.316\ s, weight = 15.5\ N$



SDOF – 4

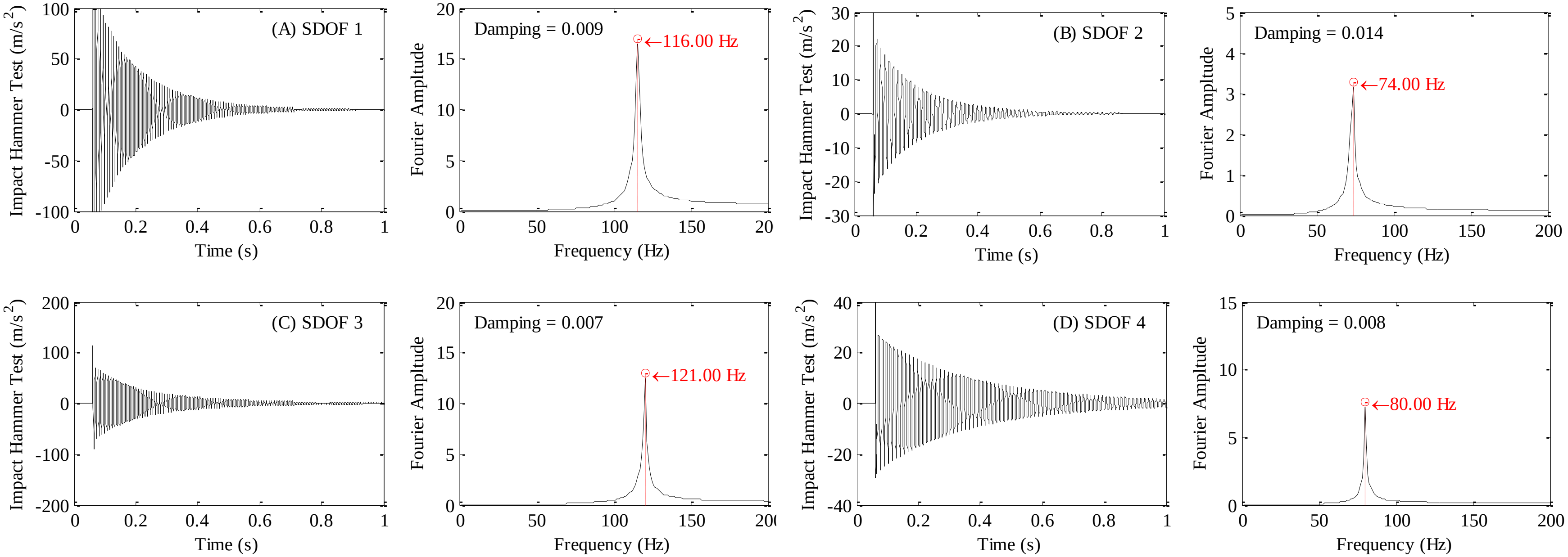
$T = 0.496\ s, weight = 27.0\ N$

2. 얕은 기초가 있는 구조물의 거동

Frame 실험

Impact Hammer Test

The natural frequencies of the structure test models were measured by performing impact hammer testing on the fixed-base structure test models and by fast Fourier transform (FFT) analysis for the test results.

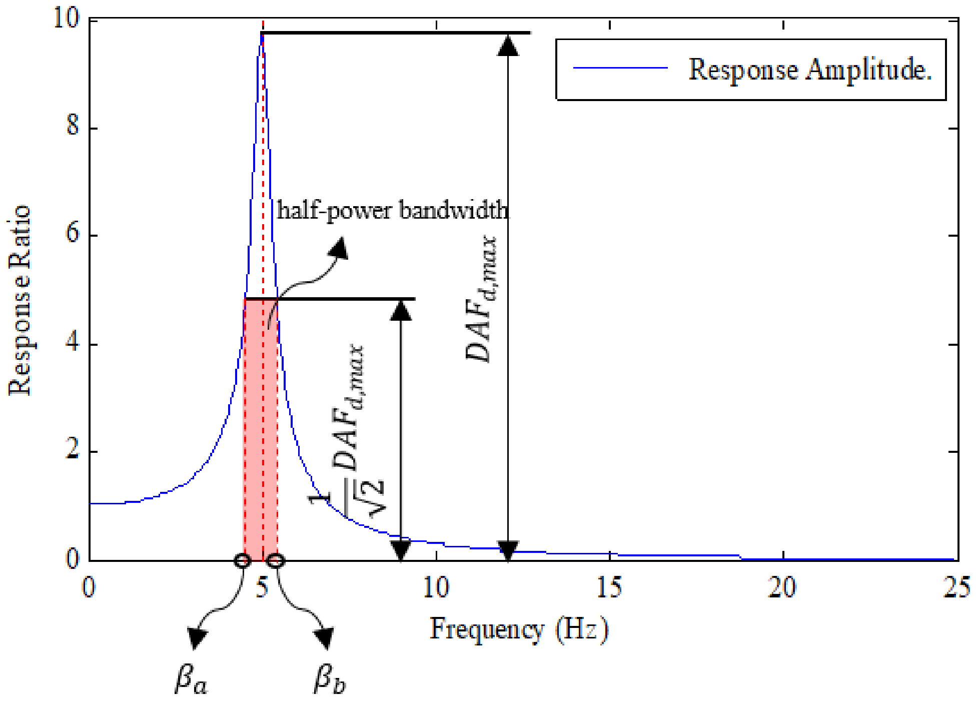


2. 얕은 기초가 있는 구조물의 거동

Frame 실험

Half Power Bandwidth

The damping ratio of the structural model was estimated using the half-power bandwidth method



$$\zeta = \frac{\beta_b - \beta_a}{2 \cdot f_n}$$

2. 얕은 기초가 있는 구조물의 거동

Frame 실험

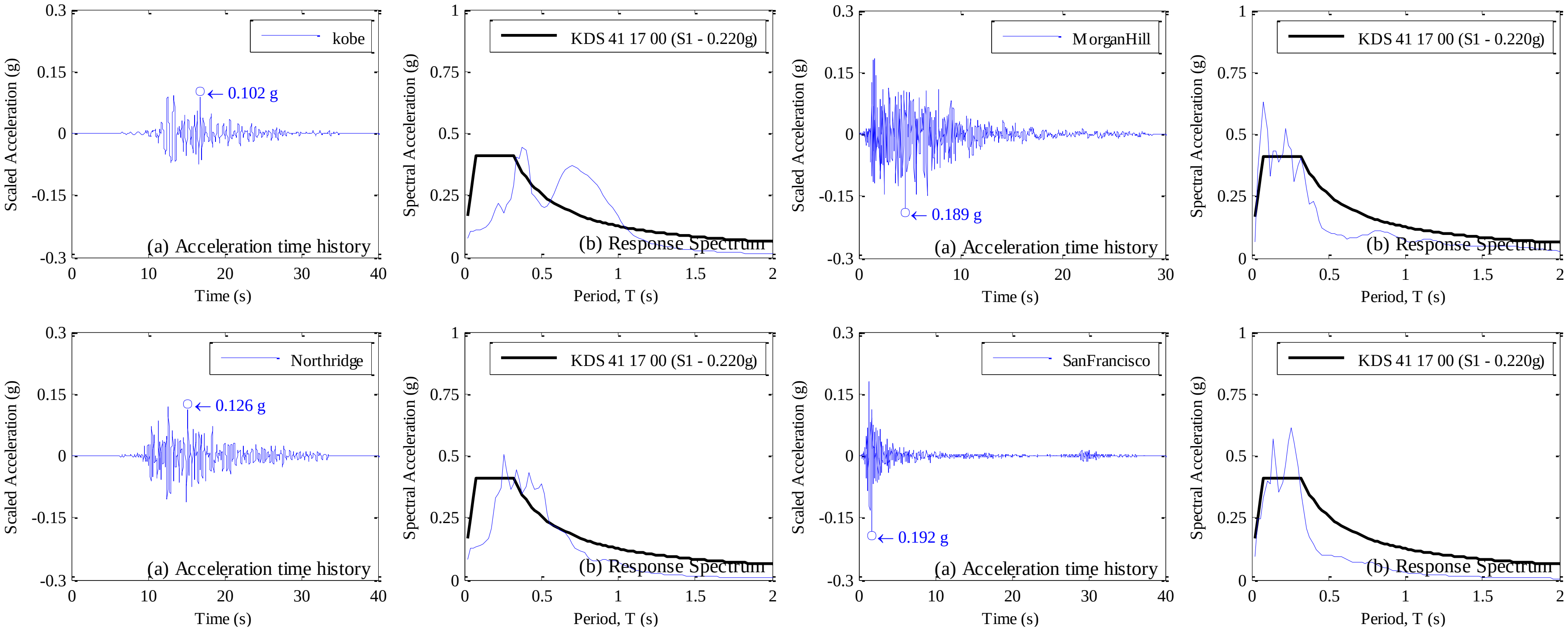
Fundamental Period & Damping Ratio

Test Model	**Weight**	**Period (s)**		**f_n (Hz)**	**β_a (Hz)**	**β_b (Hz)**	**Damping**	**Average**	
		1g	**40g**					**Period (in 40g)**	**Damping (%)**
SDOF 1	12.2 N	0.009	0.345	116.0	114.6	116.8	0.0093	0.345 s	0.91 %
		0.009	0.345	116.0	114.8	116.9	0.0090		
		0.009	0.345	116.0	114.9	117.0	0.0091		
SDOF 2	28.0 N	0.014	0.541	74.0	72.5	74.7	0.0145	0.541 s	1.39 %
		0.014	0.541	74.0	72.7	74.7	0.0137		
		0.014	0.541	74.0	72.7	74.7	0.0136		
SDOF 3	15.5 N	0.008	0.331	121.0	120.0	121.6	0.0066	0.331 s	0.83 %
		0.008	0.328	122.0	121.1	122.5	0.0058		
		0.008	0.333	120.0	118.4	121.4	0.0124		
SDOF 4	27.0 N	0.0125	0.500	80.0	79.5	80.7	0.0077	0.500 s	0.75 %
		0.0125	0.500	80.0	79.5	80.7	0.0076		
		0.0125	0.500	80.0	79.4	80.6	0.0071		

2. 얕은 기초가 있는 구조물의 거동

Frame 실험

The acceleration response spectra were derived, and the scale factor was calculated based on a rock size equivalent to the S1 rock of KDS 41 17 00. The four seismic waves with the smallest mean squared error (MSE) values were used as input



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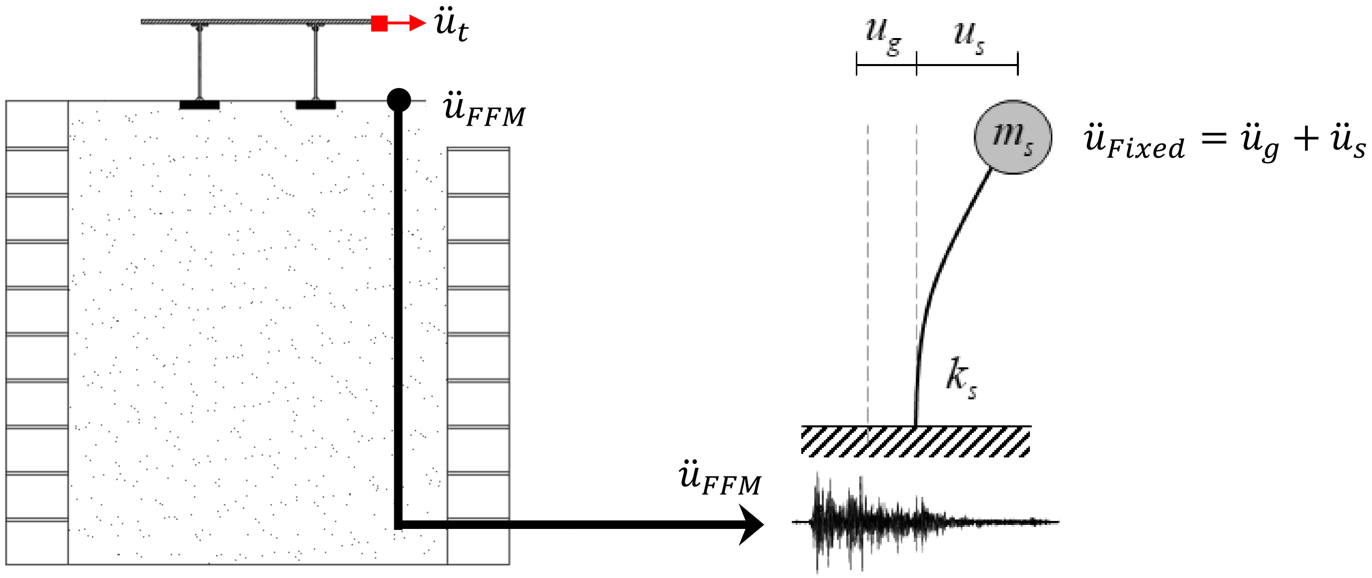
2. 얕은 기초가 있는 구조물의 거동

Frame 실험 & 제안

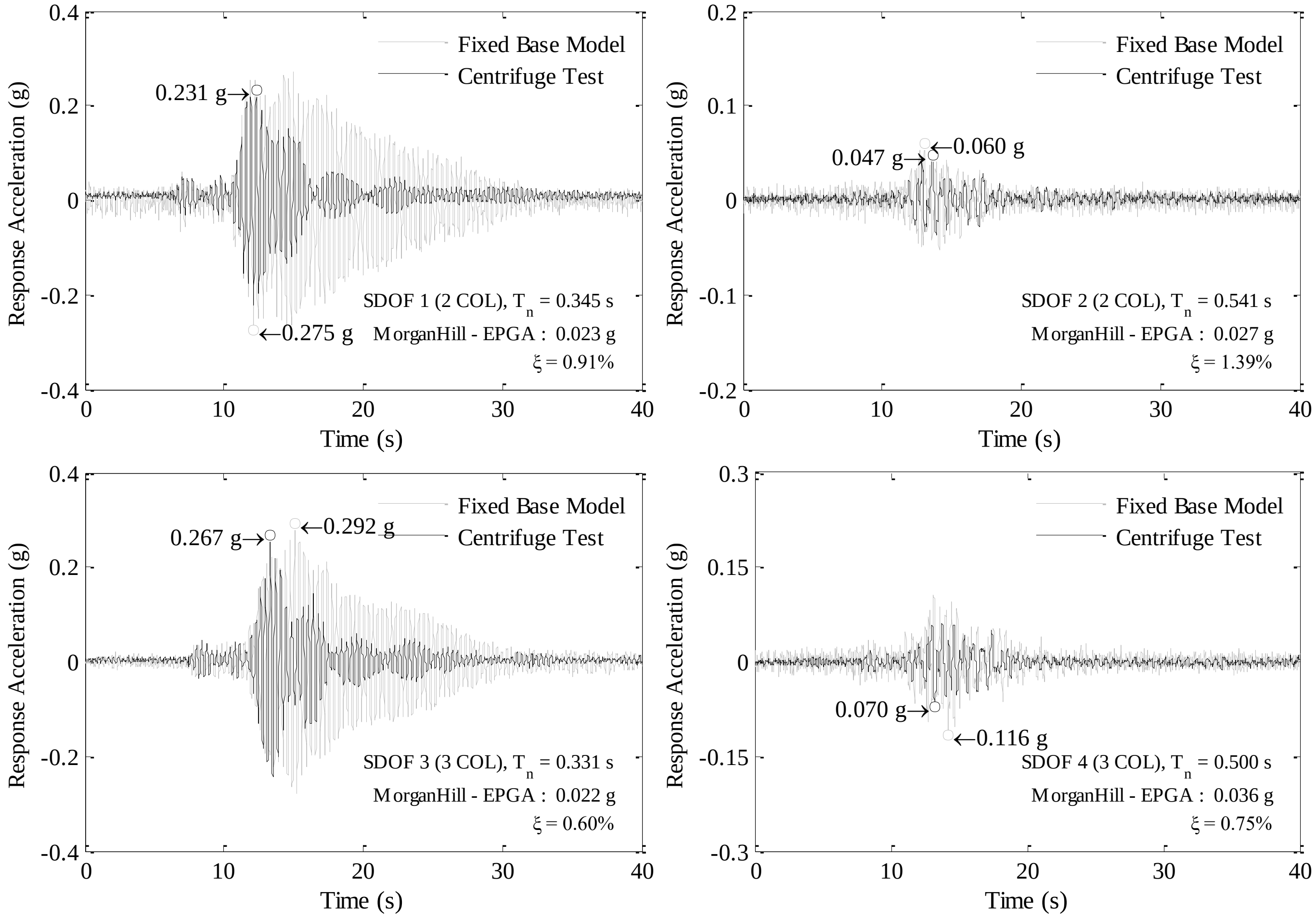
Fixed Base Model



2. 얕은 기초가 있는 구조물의 거동

Frame 실험 & 제안

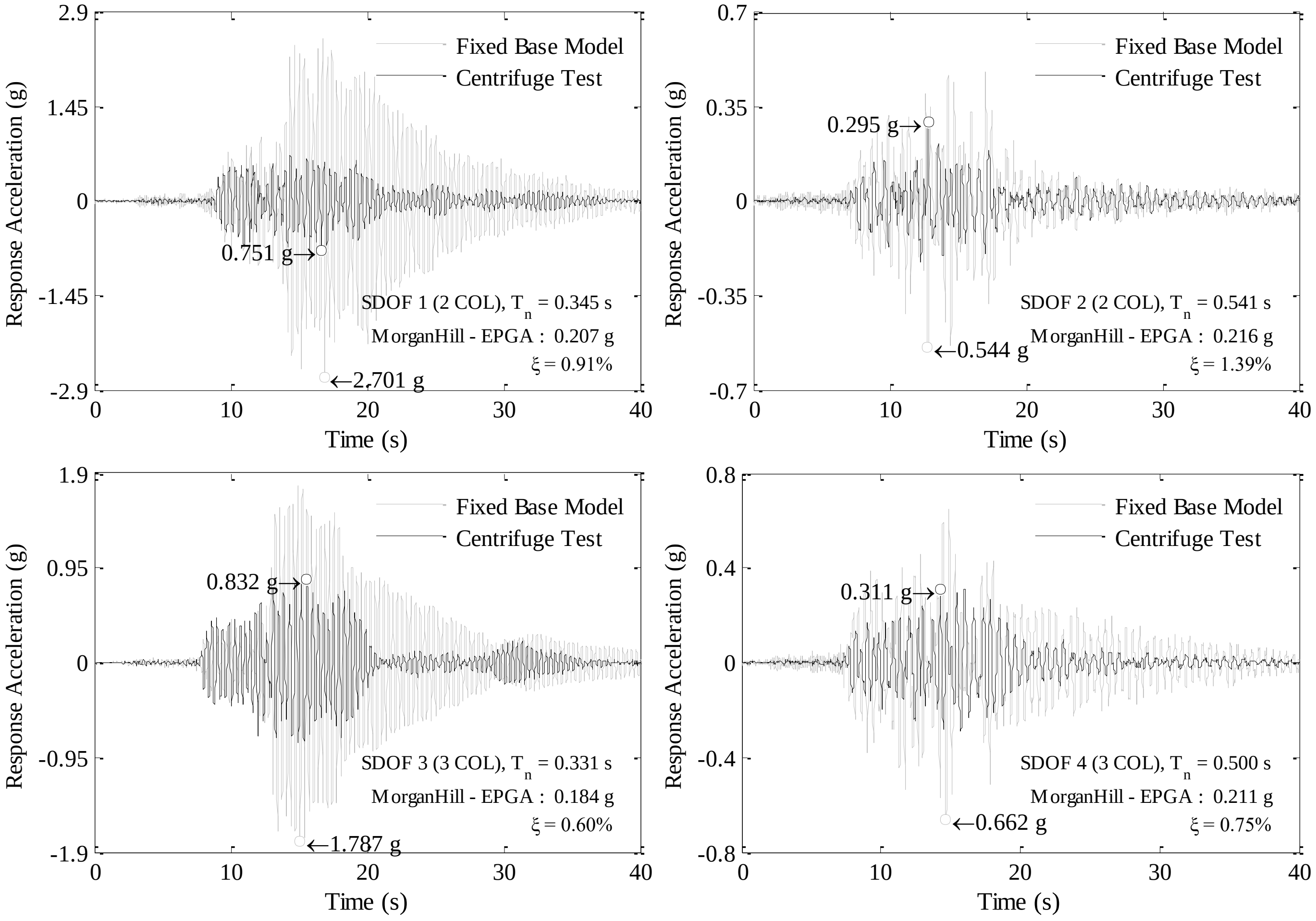
Time history responses (at low EPGA)



2. 얕은 기초가 있는 구조물의 거동

Frame 실험 & 제안

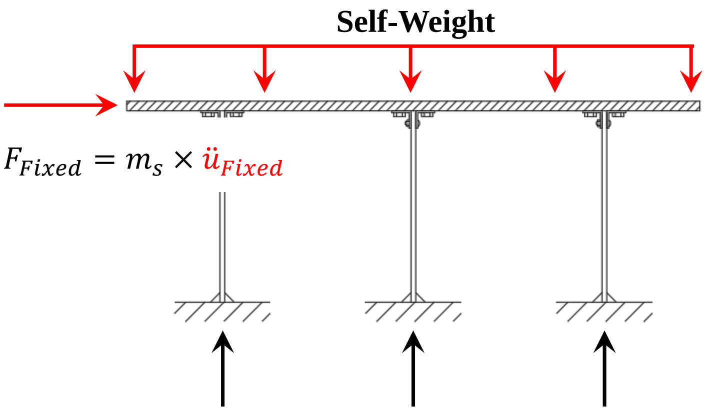
Time history responses (at high EPGA)



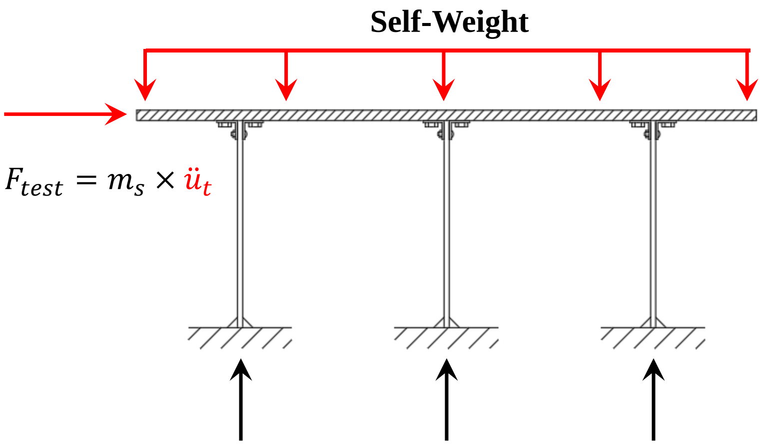
2. 얕은 기초가 있는 구조물의 거동

Frame 실험 & 제안

Vertical Reaction



(a) Fixed Base Model Reaction



(b) Test Model Reaction

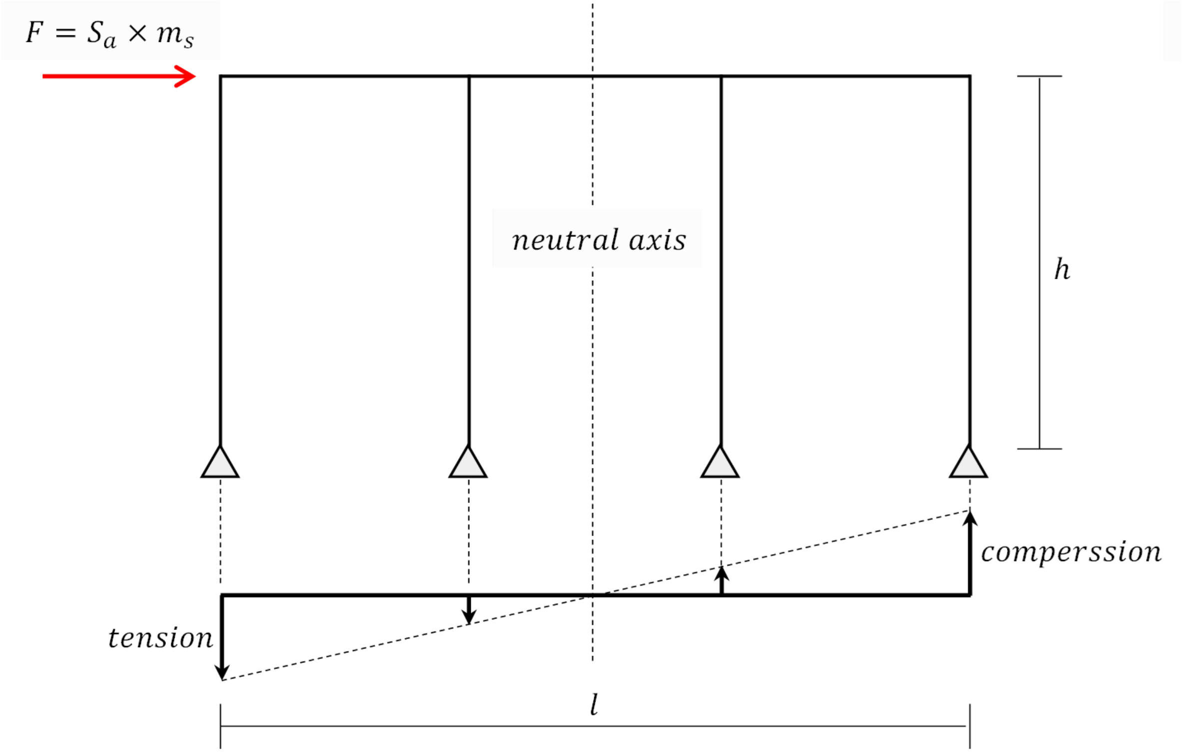
Static State Reaction of Structure (at 40g)

	SDOF 1	SDOF 2	SDOF 3	SDOF 4
Vertical Reaction, R_S	390.4 kN	896.0 kN	330.7 kN	576.0 kN

2. 얕은 기초가 있는 구조물의 거동

Frame 실험 & 제안

Vertical Reaction

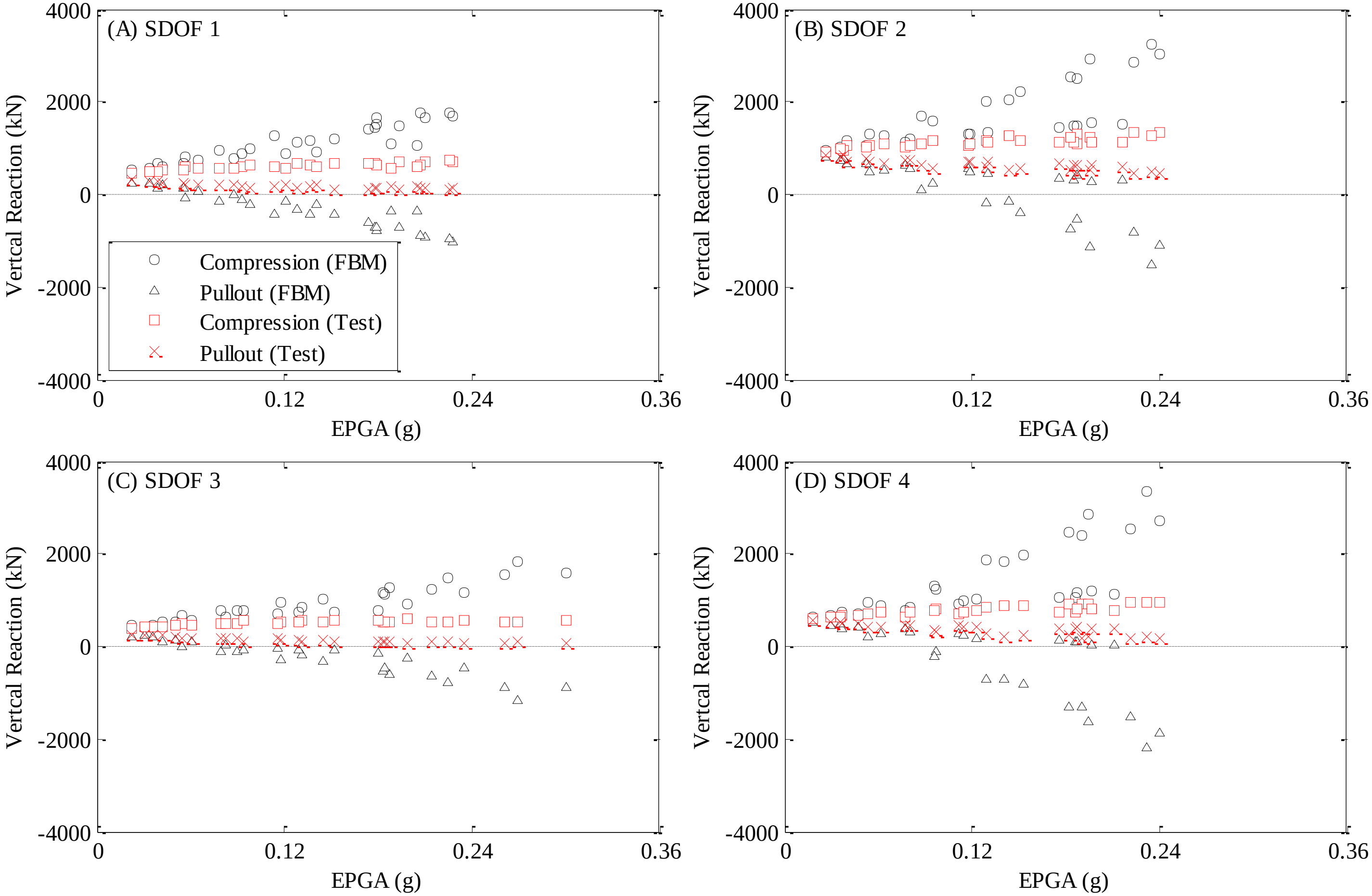


$$R_{outside} = R_s \pm \frac{F \cdot h}{l}$$

2. 얕은 기초가 있는 구조물의 거동

Frame 실험 & 제안

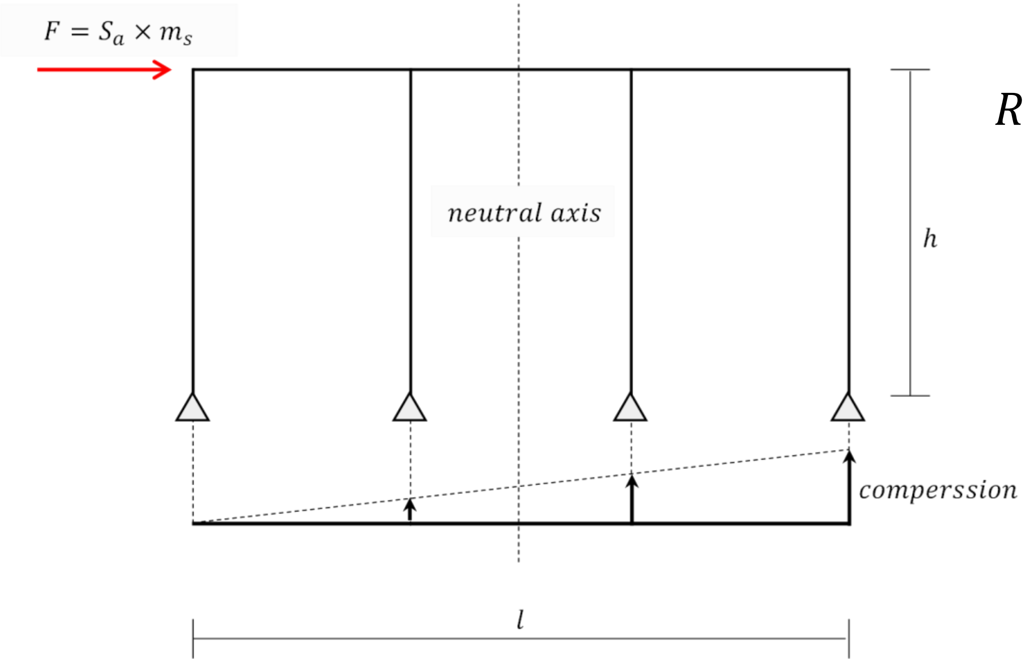
Comparison of the reaction of fixed base model and test model



2. 얕은 기초가 있는 구조물의 거동

Frame 실험 & 제안

Limit state where the reaction force is zero



$$R_{outside} = R_s \pm \frac{F \cdot h}{l} = \mathrm{R_S} - \mathrm{S_a} \cdot m_s \cdot \frac{h}{l}$$

If $R_{outside} = 0$

$$S_a = R_s \cdot \frac{1}{m_s} \cdot \frac{l}{h}$$

When $R_{left} = 0$

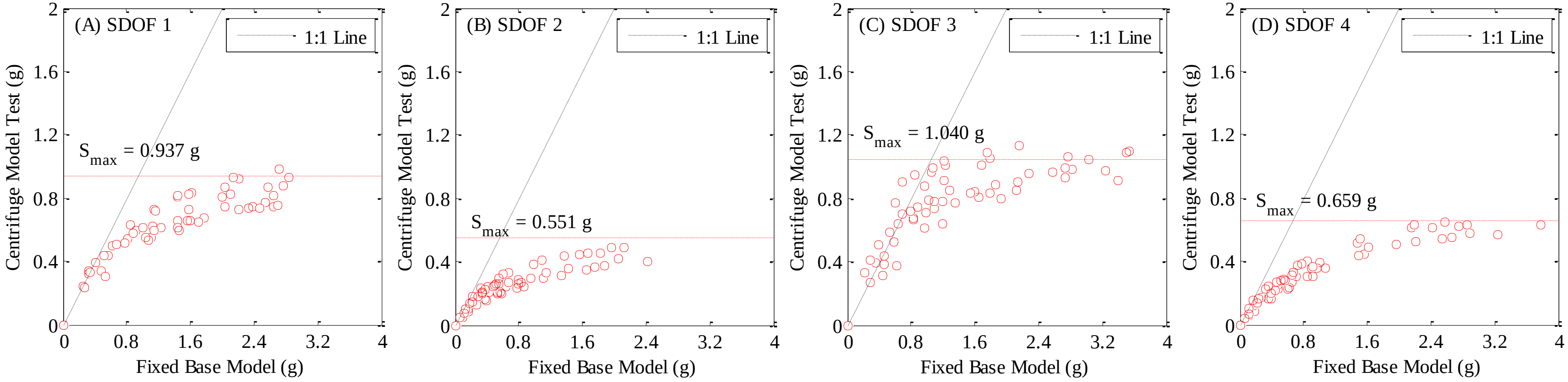
$$R_{rigth} = R_s + S_a \cdot m_s \cdot \frac{h}{l} = 2R_s$$

2. 얕은 기초가 있는 구조물의 거동

Frame 실험 & 제안

Maximum limited response acceleration of superstructure

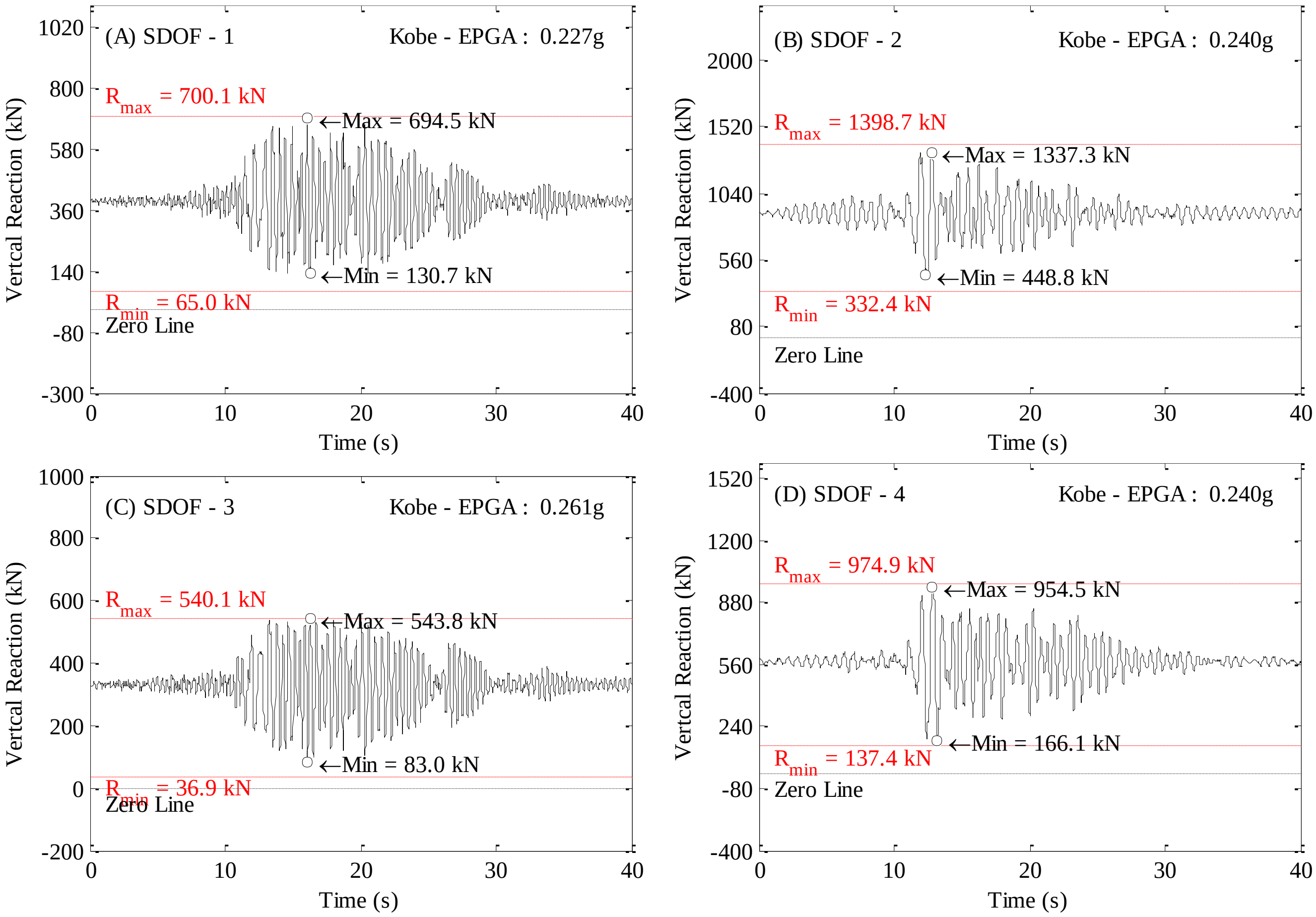
	R_s (kN)	m_s (ton)	l/h	V/V_c	$S_{a,max}$
SDOF 1	390.4	52.93	1.5	0.170	0.937 g
SDOF 2	896.0	151.17	1.5	0.384	0.551 g
SDOF 3	330.7	50.37	2.0	0.128	1.040 g
SDOF 4	576.0	132.29	2.0	0.247	0.659 g



2. 얕은 기초가 있는 구조물의 거동

Frame 실험 & 제안

Vertical Reaction Time History and Limited Vertical Reaction



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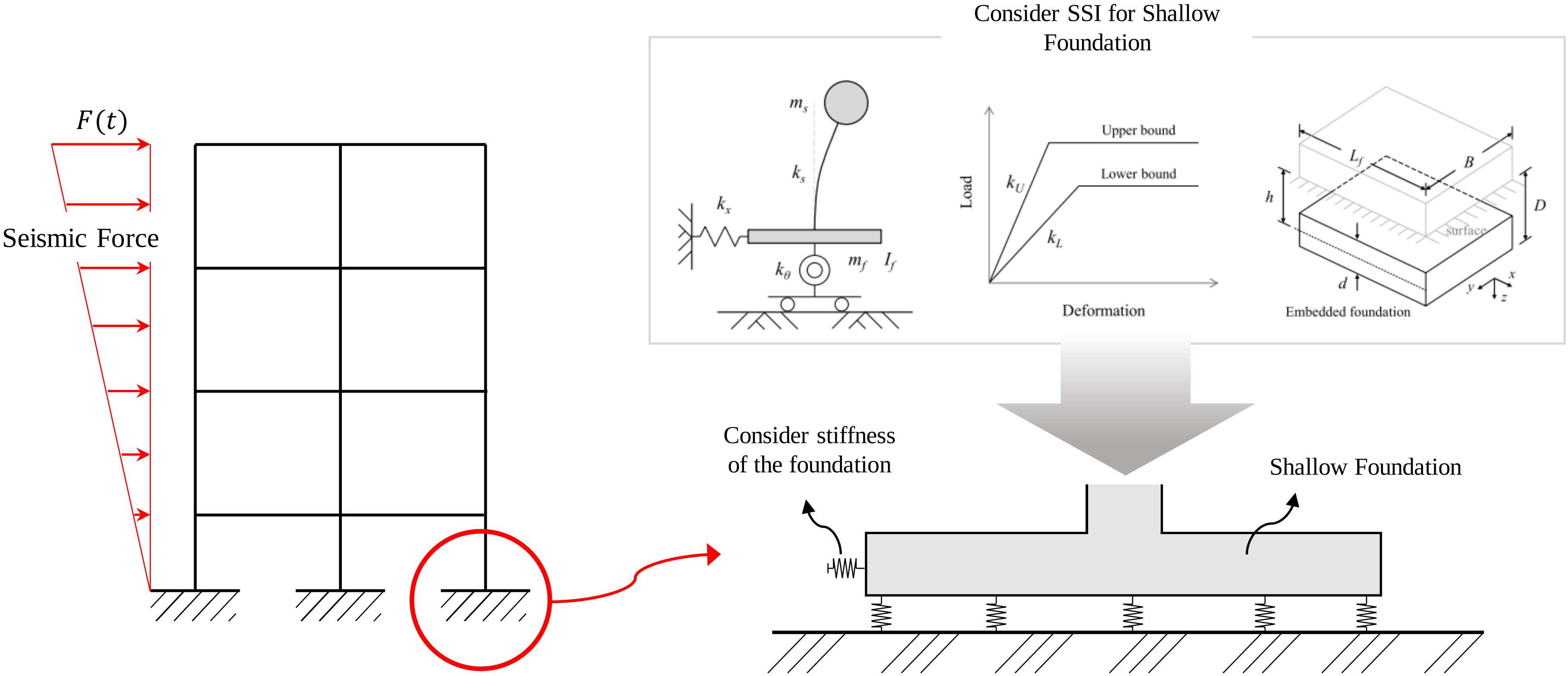
2. 얕은 기초가 있는 구조물의 거동

SSI 효과를 고려한 얕은 기초의 내진설계 & 내진성능평가

기존 고정단 조건 모델에 Spring 요소를 적용



Consider SSI for Shallow Foundation

Seismic Force

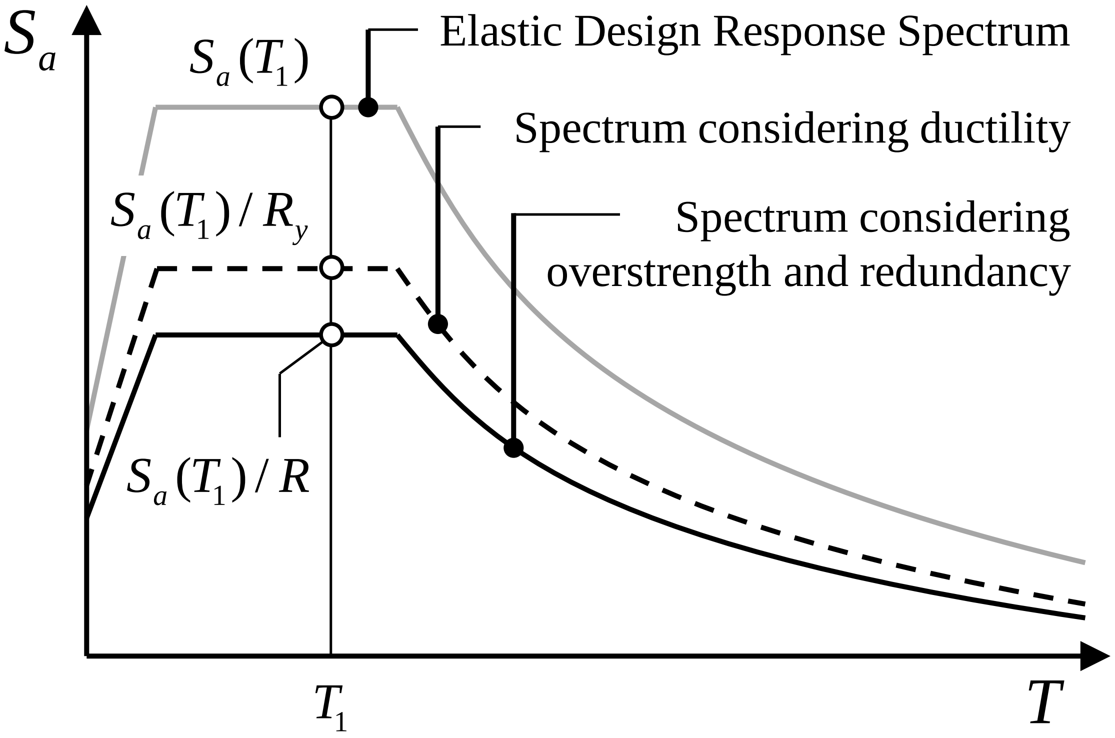
Consider stiffness of the foundation

Shallow Foundation

2. 얕은 기초가 있는 구조물의 거동

SSI 효과를 고려한 얕은 기초의 내진설계 & 내진성능평가

기존의 설계 응답 스펙트럼



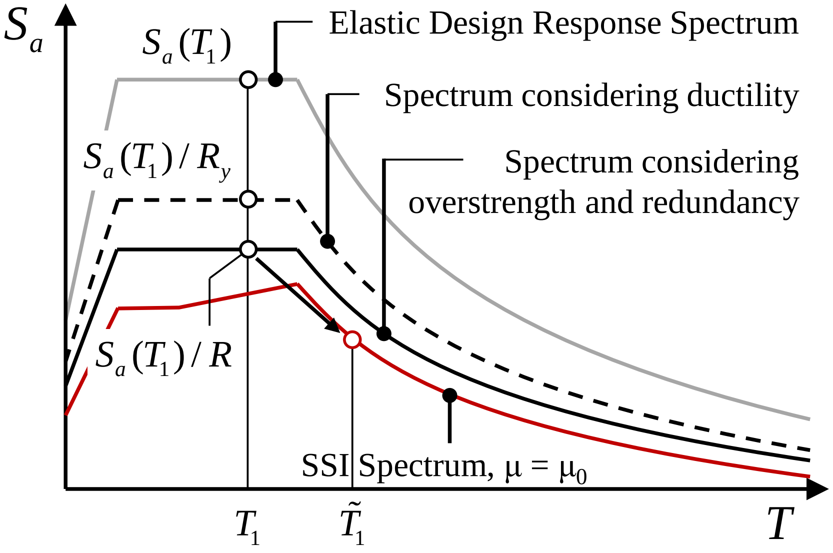
2. 얕은 기초가 있는 구조물의 거동

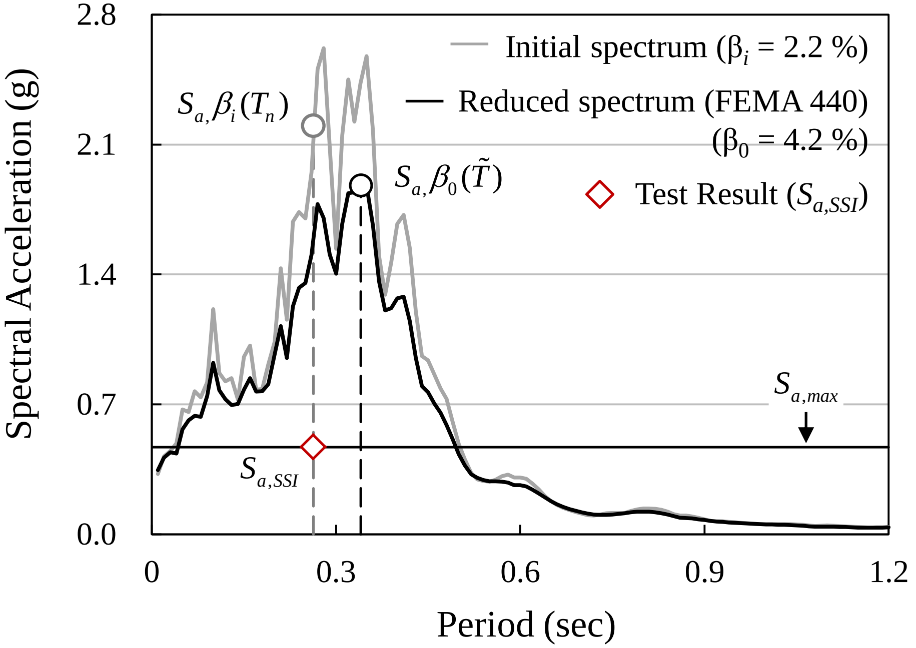
SSI 효과를 고려한 얕은 기초의 내진설계 & 내진성능평가

SSI 효과가 고려된 설계 응답 스펙트럼

→ Period Lengthening

→ Kinematic Effects





2. 얕은 기초가 있는 구조물의 거동

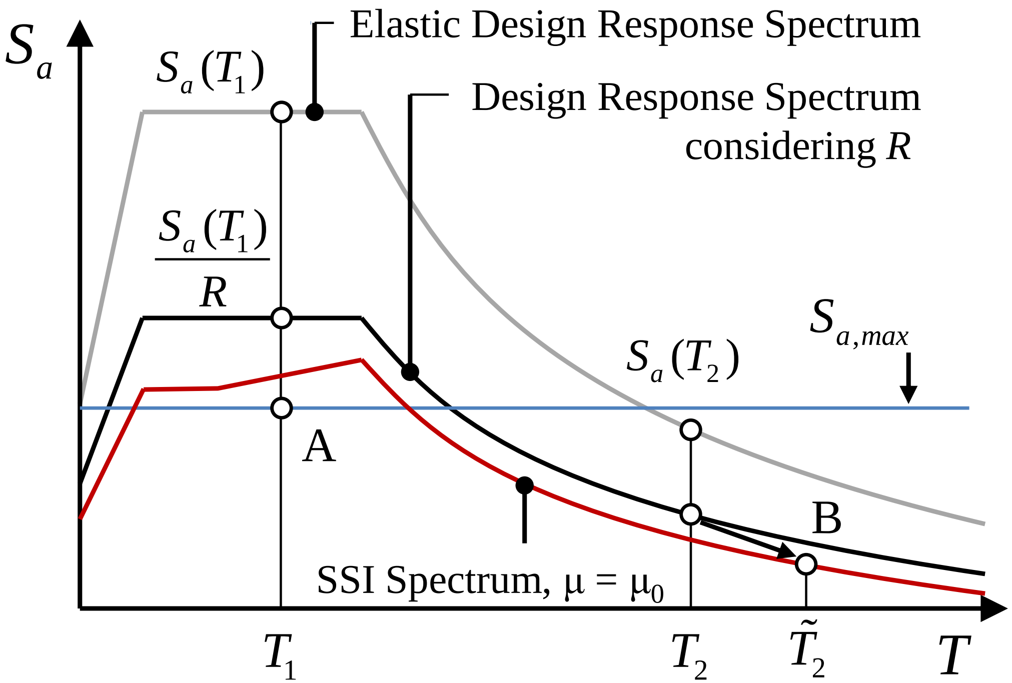
SSI 효과를 고려한 얕은 기초의 내진설계 & 내진성능평가

SSI 효과가 고려된 설계 응답 스펙트럼

→ Period Lengthening

→ Kinematic Effects

→ Ultimate Moment Capacity



2. 얕은 기초가 있는 구조물의 거동

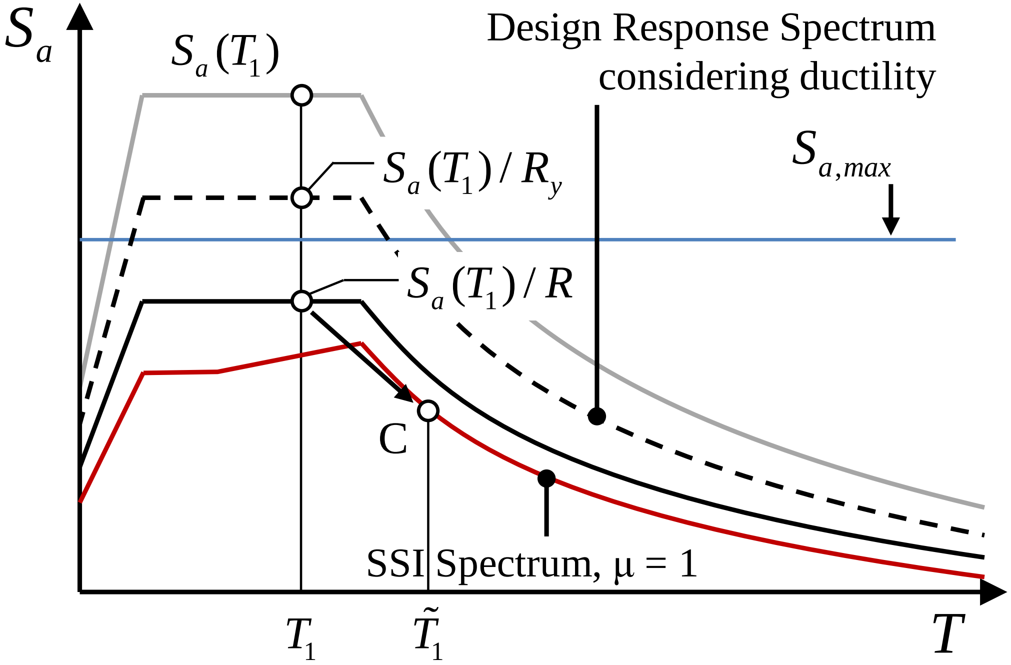
SSI 효과를 고려한 얕은 기초의 내진설계 & 내진성능평가

SSI 효과가 고려된 설계 응답 스펙트럼

→ Period Lengthening

→ Kinematic Effects

→ Ultimate Moment Capacity

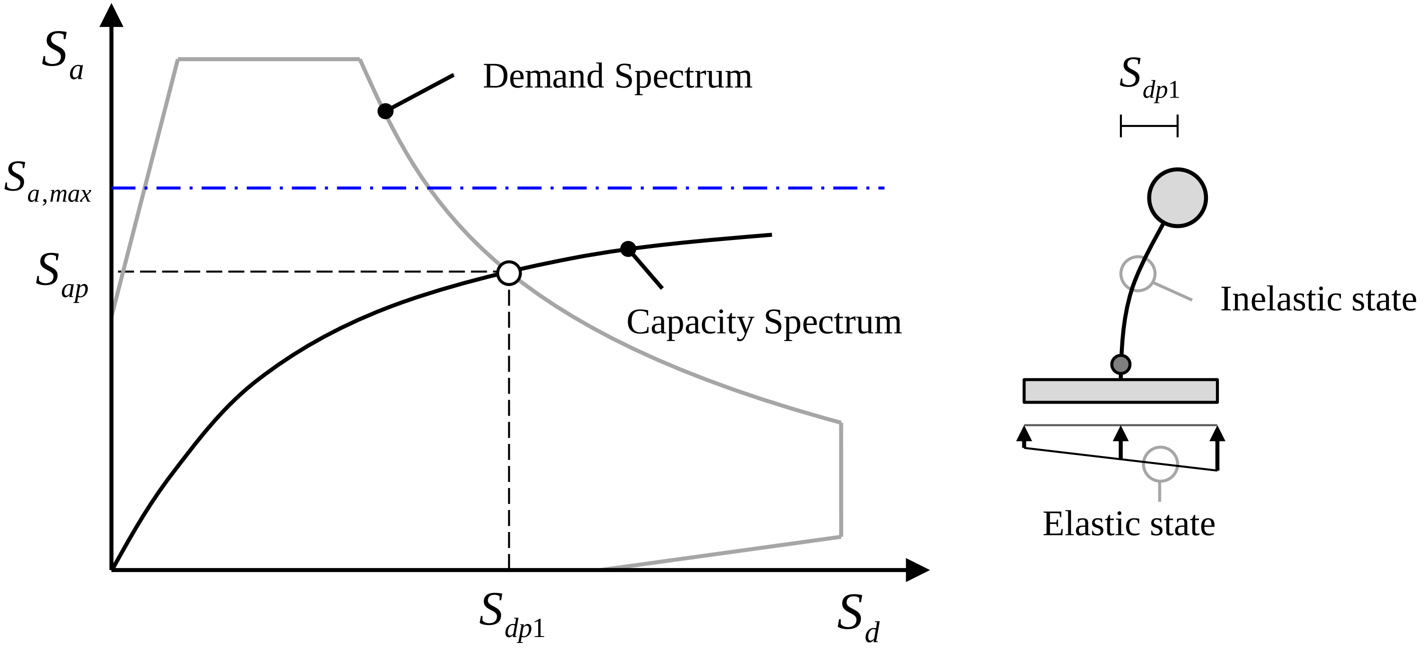


2. 얕은 기초가 있는 구조물의 거동

SSI 효과를 고려한 얕은 기초의 내진설계 & 내진성능평가

SSI 효과를 고려한 내진성능평가

1) Ultimate Moment Capacity가 성능점보다 큰 경우

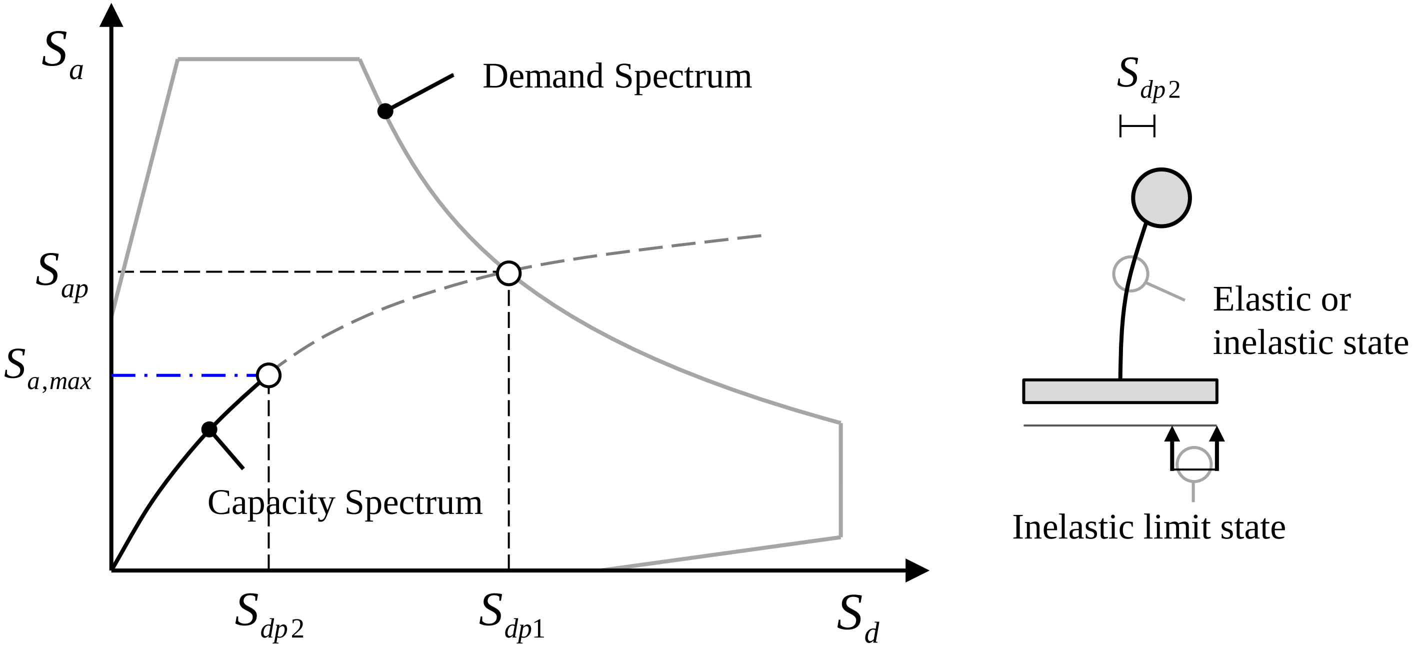


2. 얕은 기초가 있는 구조물의 거동

SSI 효과를 고려한 얕은 기초의 내진설계 & 내진성능평가

SSI 효과를 고려한 내진성능평가

2) Ultimate Moment Capacity가 성능점보다 작은 경우



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    b. 하중기반설계와 변위적합설계
4. 결론

3. 지하구조물을 고려한 건축물의 내진설계

건축 지하구조물 내진설계 재정의 배경

1) 건축물의 지하구조에 대한 내진설계를 수행하지 않거나 기준상 근거가 없는 것에 대한 감사원 등의 지적
2) 경사지에 건설되거나 지하에 큰 개구부가 있는 건축물에 대한 내진안전성 확보
3) 지상구조로부터 전달되는 지진하중에 대한 지하층구조 설계의 모호성
4) 지상구조에 대한 지하구조거동의 영향에 대한 규정 필요 (지반기준면 등)
5) 대단지 아파트와 같이 하나의 통합된 지하구조를 갖는 지상건물들에 대한 지반의 영향 규정 필요

포항지진시, 아파트 지하기둥 55개중 13개 전단파괴

대만 화롄 지진시, 지하층 파괴로 인한 기울어짐

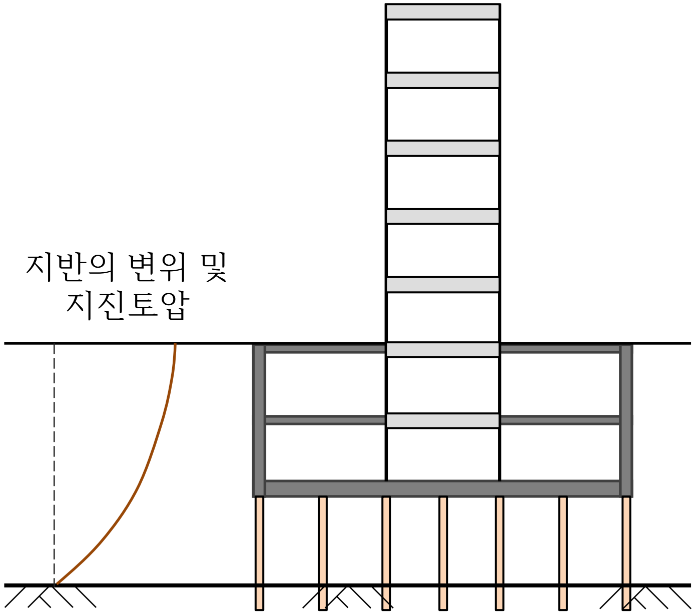
3. 지하구조물을 고려한 건축물의 내진설계

건축 지하구조물 내진설계 재정의 배경

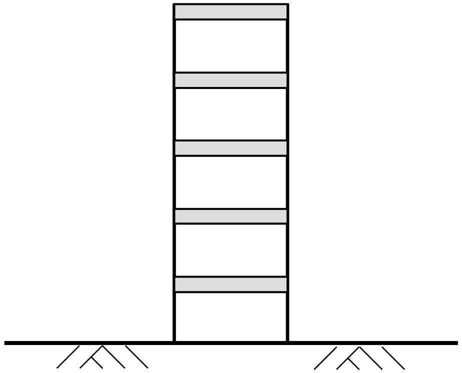
기존 설계 절차

지하구조물은 지반과 같이 움죽이는 것으로 가정 or 지반스프링 적용

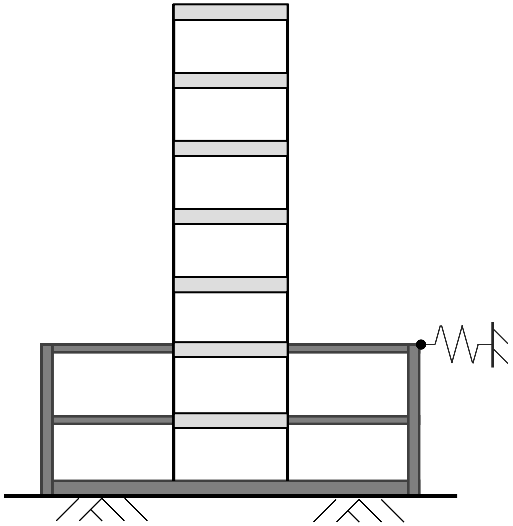
→ 지하구조물에 대한 내진설계를 수행하지 않거나, 지반으로 지진하중이 전이되어 상부구조물의 지진하중이 지하에 영향을 미치지 않는 것으로 가정



실제 조건



지하구조물 내진설계
미수행 해석모델



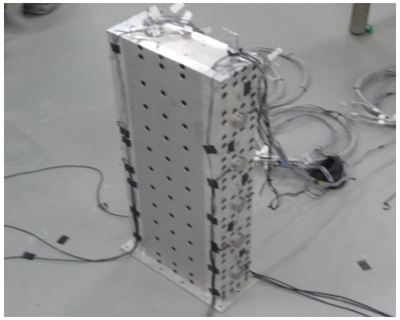
지반스프링 적용

3. 지하구조물을 고려한 건축물의 내진설계

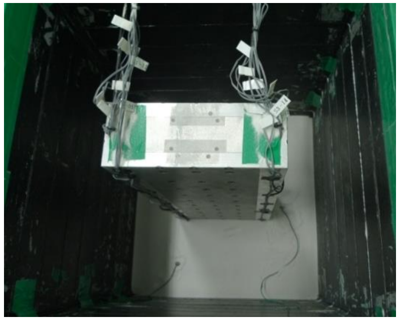
건축 지하구조물 내진설계 재정의 배경

국내 원심모형실험 : 김동관, 박홍근, 김동수, 하정곤 (2016).

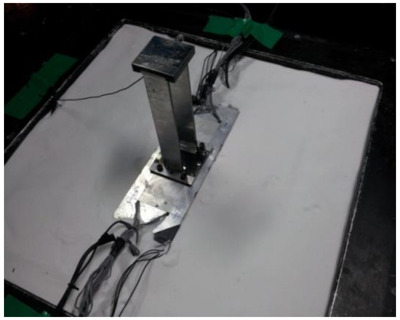
“지하층이 있는 구조물의 지진응답을 위한 원심모형실험”
지진공학회 논문집, Vol. 20 No. 4.



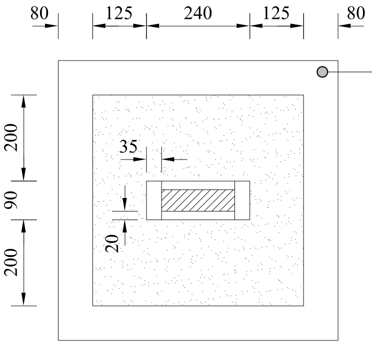
(a) Small scale basement model



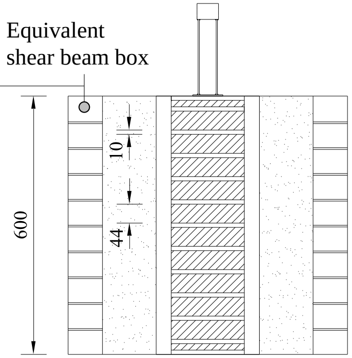
(b) Soil raining



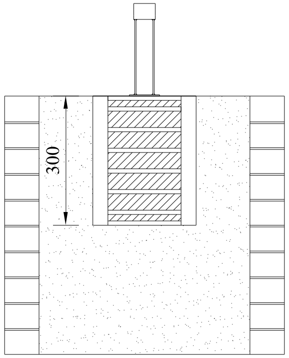
(c) SDOF structure with basement



(d) Plan



(e) Fixed basement model



(f) Half-embedded basement model

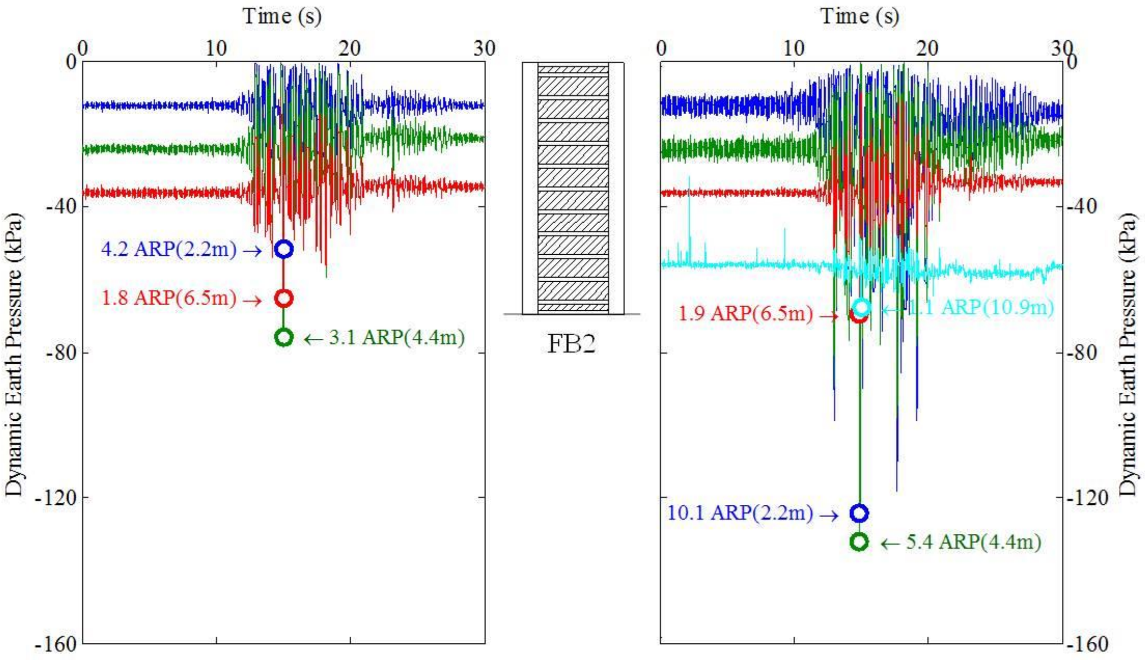
3. 지하구조물을 고려한 건축물의 내진설계

건축 지하구조물 내진설계 재정의 배경

연구결과 : 지반과 지하층 사이에 간격(Gap)이 발생하여 토압이 사라짐

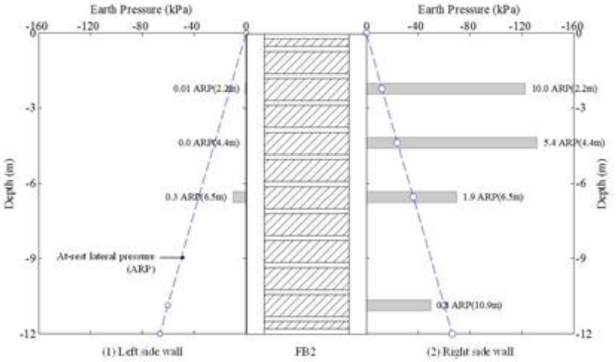
→ 편토압으로 작용되어 이에 대한 구조설계가 요구됨

→ 배면의 지반이 지하층을 지지하는 가정은 맞지 않음

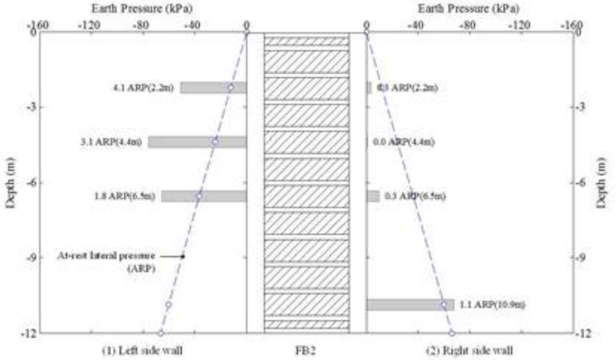


(a) Left side wall

(b) Right side wall



(a) 우측면에 최대토압이 작용할 경우, 토압분포



(b) 좌측면에 최대토압이 작용할 경우, 토압분포

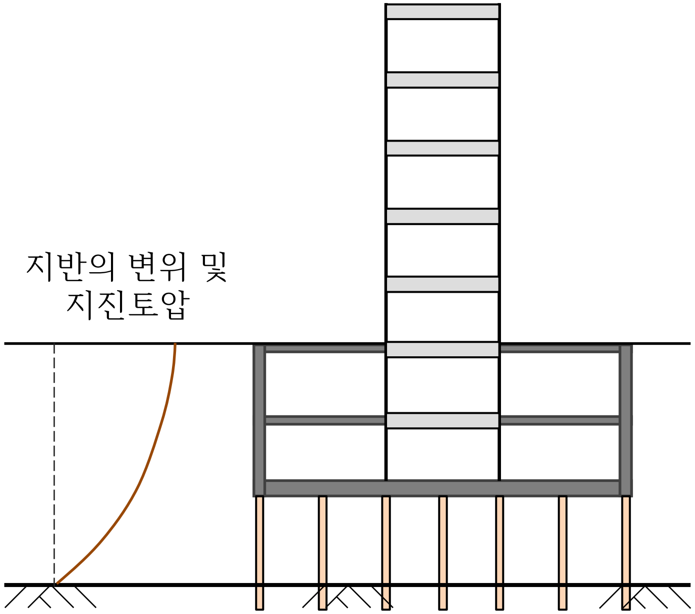
3. 지하구조물을 고려한 건축물의 내진설계

건축 지하구조물 내진설계 재정의 배경

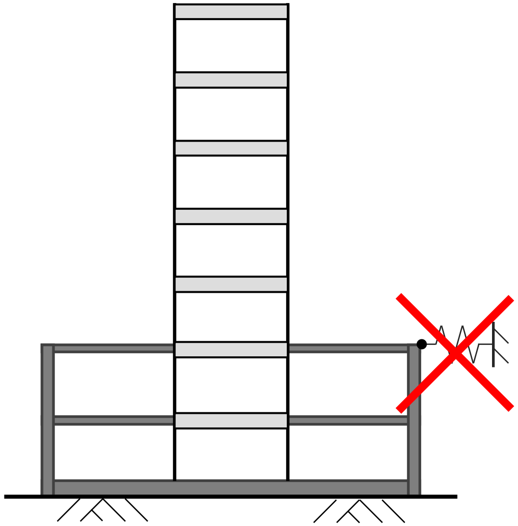
배면의 지반에 의한 지지력(지반스프링)이 없음

→ 지반으로 지진하중이 전이되어 상부구조물의 지진하중이 지하에 영향을 미치지 않는 것으로 가정이 옳지 않음

→ 다만, 지하구조물은 상부에서 내려오는 구조체+지하외벽으로 강성이 매우 큼



실제 조건



지반스프링 적용 불가

3. 지하구조물을 고려한 건축물의 내진설계

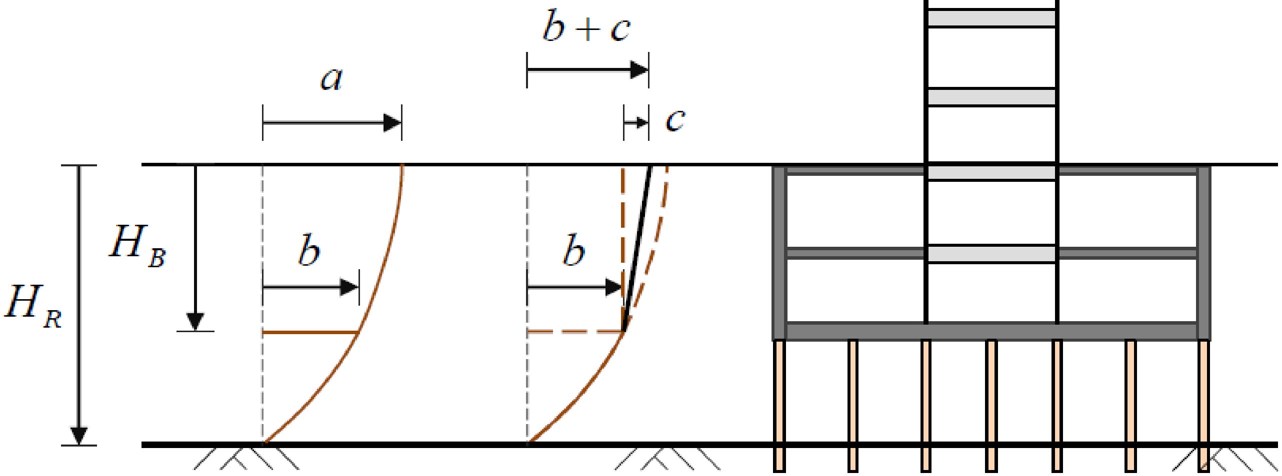
건축 지하구조물 내진설계 재정의 배경

지하구조물 강성의 영향을 고려

→ 지하구조물 내진설계 (기존 기초면 이하 지반분류시 적용)

→ 전체 구조시스템의 지진하중 산정 ⇒ 지반증폭계수의 저감

$$F_{eff} = F_{Rock} + (F - F_{Rock}) \times \frac{b+c}{a}$$

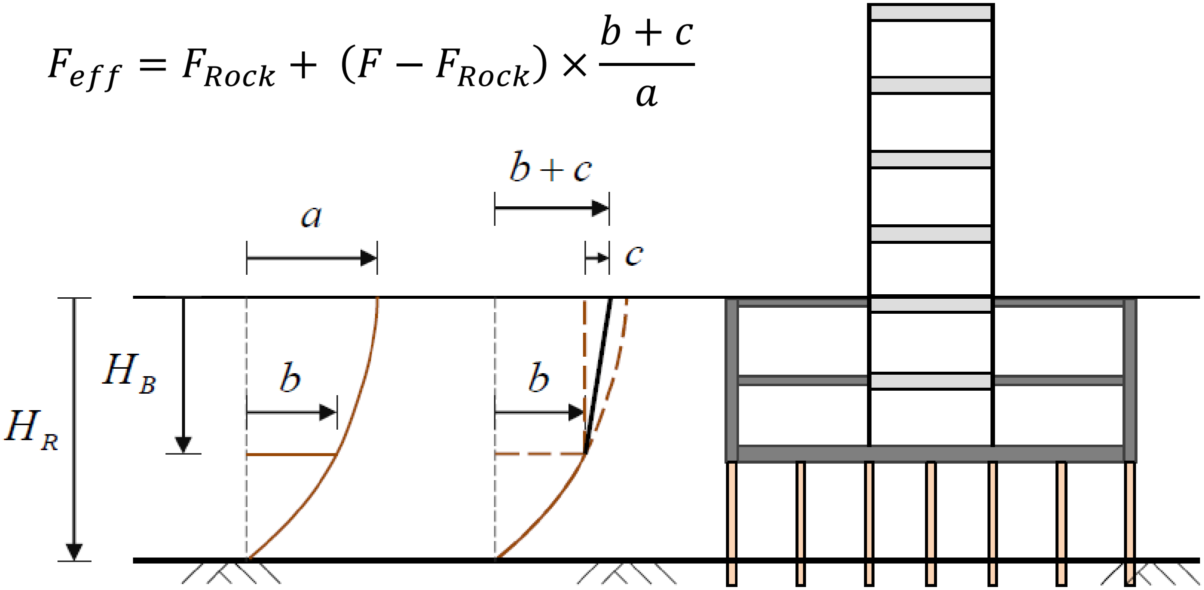


3. 지하구조물을 고려한 건축물의 내진설계

건축 지하구조물 내진설계 재정의 배경

지하구조물의 강성	지하구조물 변위	유효지반증폭계수	
매우 약하거나 고려하지 않음≒0	$b+c=a$	$F_{eff} = F_{Soil}$	지하층 고려하지 않음
지진토압에 의해 변형이 c 만큼 발생	$b+c$	$F_{eff} = F_{Rock} + (F - F_{Rock}) \times \frac{b+c}{a}$	
지하구조가 암반에 정착되어 있지 않고, 강성이 매우 큼	$b+c \cong b$ c=0	$F_{eff} = F_{Rock} + (F - F_{Rock}) \times \frac{b}{a}$	기초저면 기준
지하구조가 암반에 정착되어 있고, 강성이 매우 큼	$b+c \cong 0$	$F_{eff} = F_{Rock}$	암반 기준

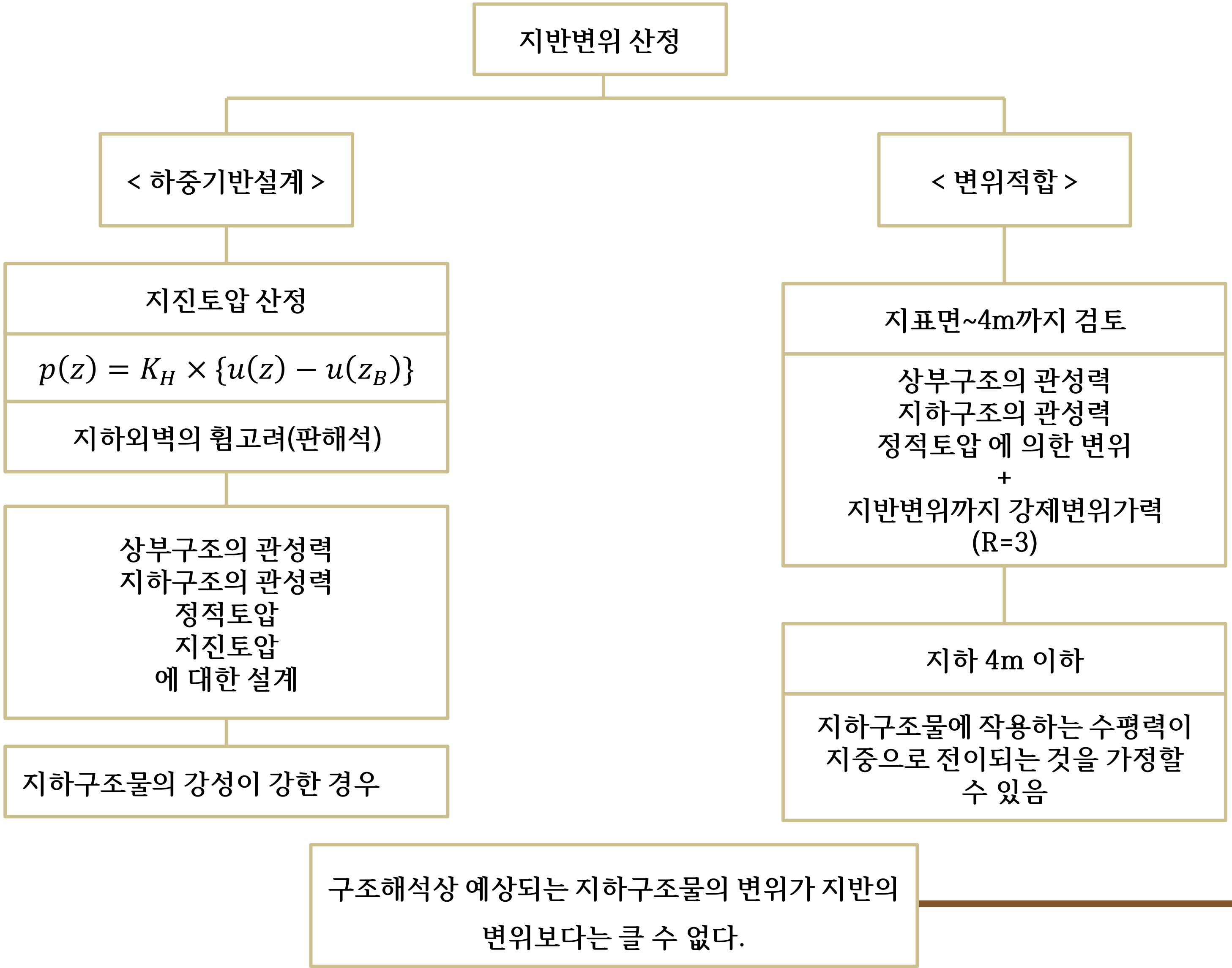
$$F_{eff} = F_{Rock} + (F - F_{Rock}) \times \frac{b+c}{a}$$



Contents

3. 지하구조물을 고려한 건축물의 내진설계

하중기반설계와 변위적합설계



지반변위 산정

< 하중기반설계 >

지진토압 산정

$p(z) = K_H \times \{u(z) - u(z_B)\}$

지하외벽의 휨고려(판해석)

상부구조의 관성력
지하구조의 관성력
정적토압
지진토압
에 대한 설계

지하구조물의 강성이 강한 경우

< 변위적합 >

지표면~4m까지 검토

상부구조의 관성력
지하구조의 관성력
정적토압 에 의한 변위
+
지반변위까지 강제변위가력
(R=3)

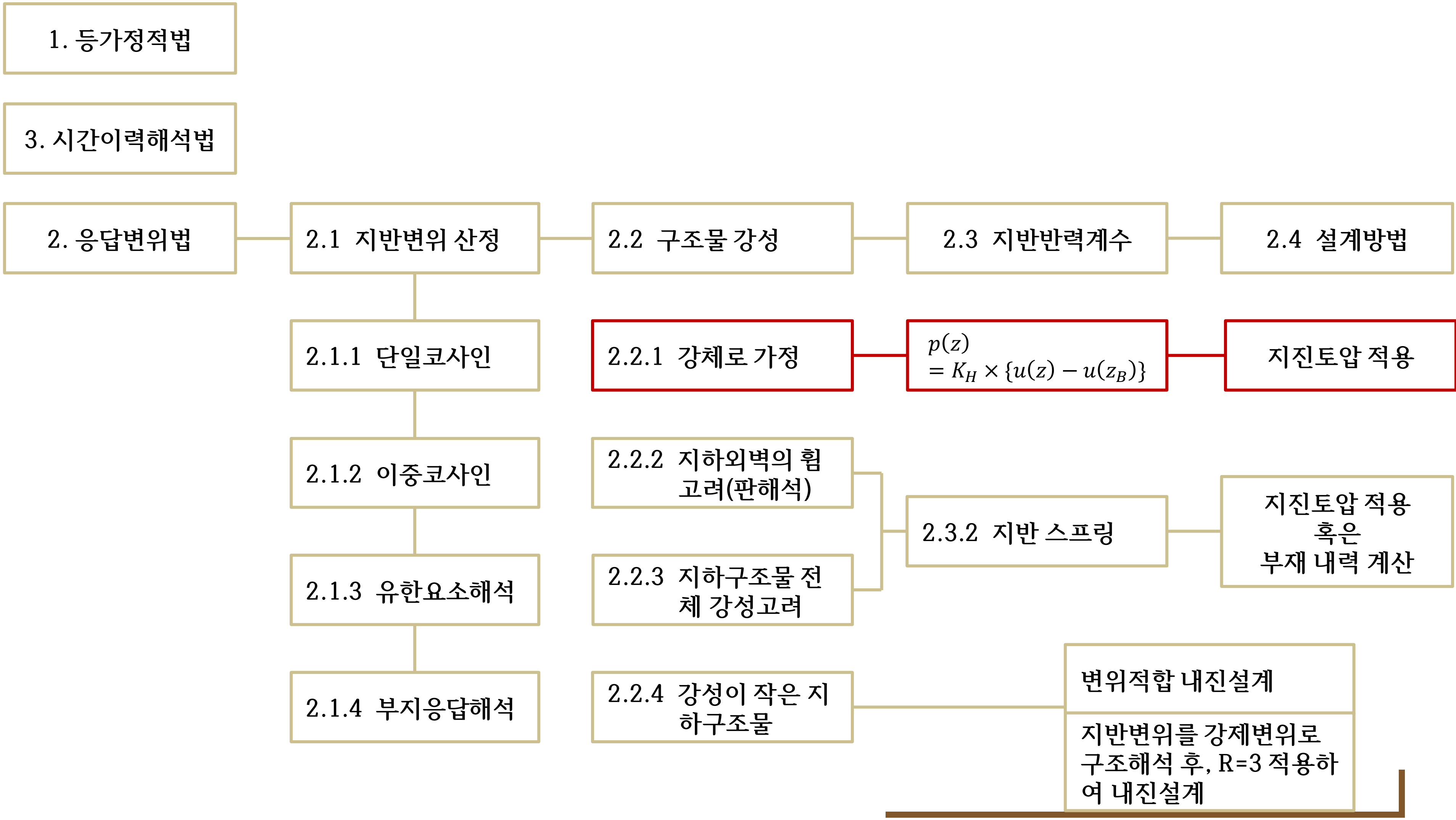
지하 4m 이하

지하구조물에 작용하는 수평력이
지중으로 전이되는 것을 가정할
수 있음

구조해석상 예상되는 지하구조물의 변위가 지반의 변위보다는 클 수 없다.

3. 지하구조물을 고려한 건축물의 내진설계

하중기반설계와 변위적합설계



1. 등가정적법

3. 시간이력해석법

2. 응답변위법

2.1 지반변위 산정

2.1.1 단일코사인

2.1.2 이중코사인

2.1.3 유한요소해석

2.1.4 부지응답해석

2.2 구조물 강성

2.2.1 강체로 가정

2.2.2 지하외벽의 휨 고려(판해석)

2.2.3 지하구조물 전체 강성고려

2.2.4 강성이 작은 지하구조물

2.3 지반반력계수

$p(z) = K_H \times \{u(z) - u(z_B)\}$

2.3.2 지반 스프링

2.4 설계방법

지진토압 적용

지진토압 적용
혹은
부재 내력 계산

변위적합 내진설계

지반변위를 강제변위로 구조해석 후, R=3 적용하여 내진설계

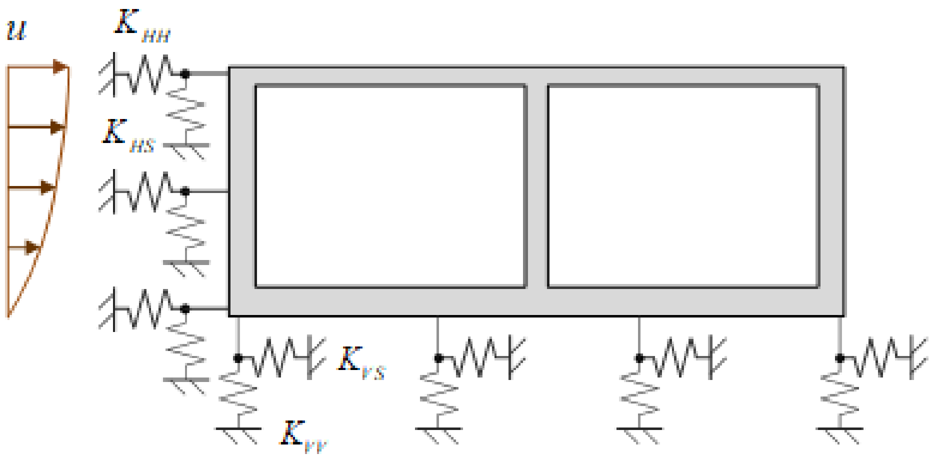
3. 지하구조물을 고려한 건축물의 내진설계

하중기반설계와 변위적합설계

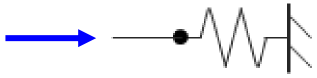
하중기반설계 – 응답변위법 (강체로 가정)

→ 지하구조물과 이를 둘러싼 지반의 영향을 고려한 지반반력계수가 적용된 해석모델에 지진시 예상되는 지반의 변위를 가하여 스프링모델의 압축력으로부터 토압을 계산

$$p(z) = K_H \times \{u(z) - u(z_B)\}$$



$\{u(z) - u(z_B)\}$



$p(z)$

K_H

고정단 지진토압

< 과대한 지진토압 산정 방법 >

3. 지하구조물을 고려한 건축물의 내진설계

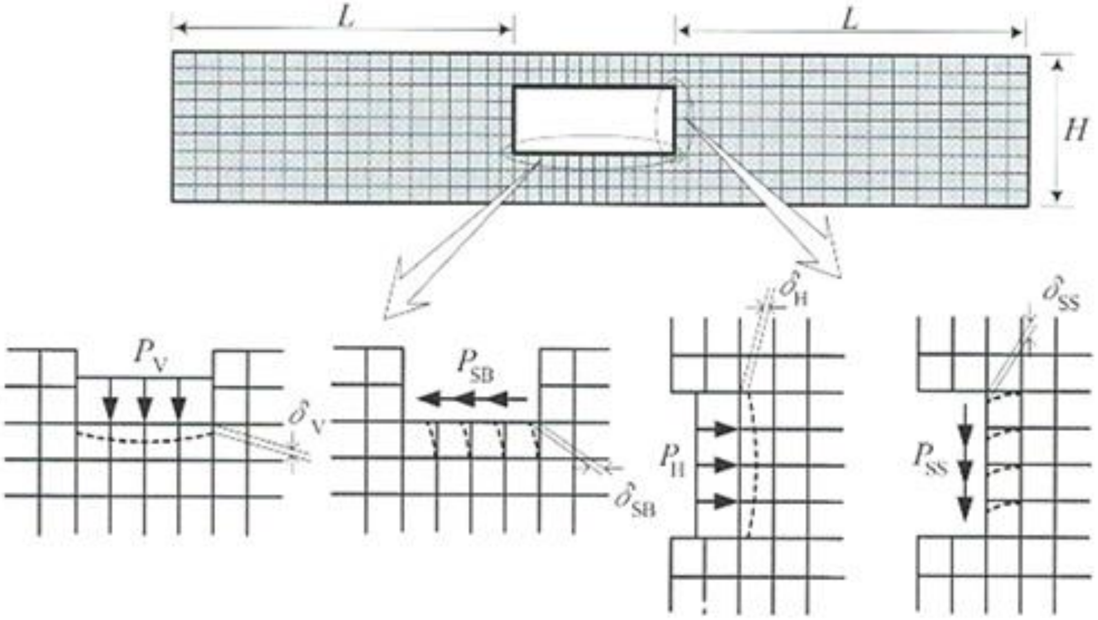
하중기반설계와 변위적합설계

하중기반설계 – 응답변위법 (강체로 가정)

→ 해석결과를 바탕으로 지반반력계수(K) 제안

$$K = \frac{\sum P}{\delta}$$

< 2차원 유한요소해석법 >



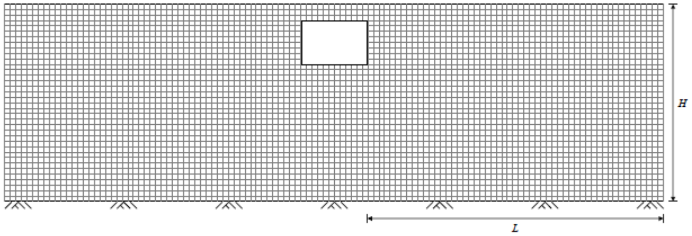
(a) K_V (b) K_{SB} (c) K_H (d) K_{SS}

3. 지하구조물을 고려한 건축물의 내진설계

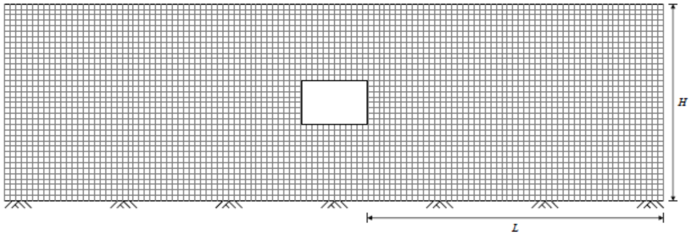
하중기반설계와 변위적합설계

하중기반설계 – 응답변위법 (강체로 가정)

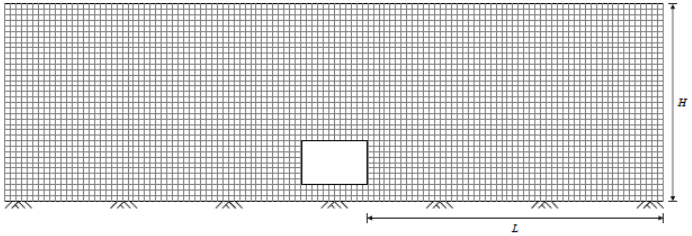
→ 해석결과를 바탕으로 지반반력계수(K) 제안



(a) 지표면으로부터 기반면까지의 깊이(H)의 1/3 이내에 위치한 토사에 대한 지반반력계수 산정



(b) $H/3$ ~ $2H/3$ 에 위치한 토사에 대한 지반반력계수 산정



(c) $2H/3$ ~ 기반면에 위치한 토사에 대한 지반반력계수 산정

Vs (m/s)	질량밀도 (ton/m^3)	프아송비	전단탄성계수(kPa)	탄성계수 (kPa)	수평지반반력계수, K_H (kN/m^3)		
					지표면 ~ $H/3$	$H/3$ ~ $2H/3$	$2H/3$ ~ 기반면
100	1.8	0.4	18000	50400	4082	5695	8770
200	1.8	0.4	72000	201600	16360	22725	34997
300	1.8	0.4	162000	453600	36809	51130	78743
400	1.9	0.4	304000	851200	69074	95948	147764
500	1.9	0.4	475000	1330000	107929	149919	230881
600	1.9	0.4	684000	1915200	155417	215883	332469
700	2.0	0.4	980000	2744000	222673	309307	476345

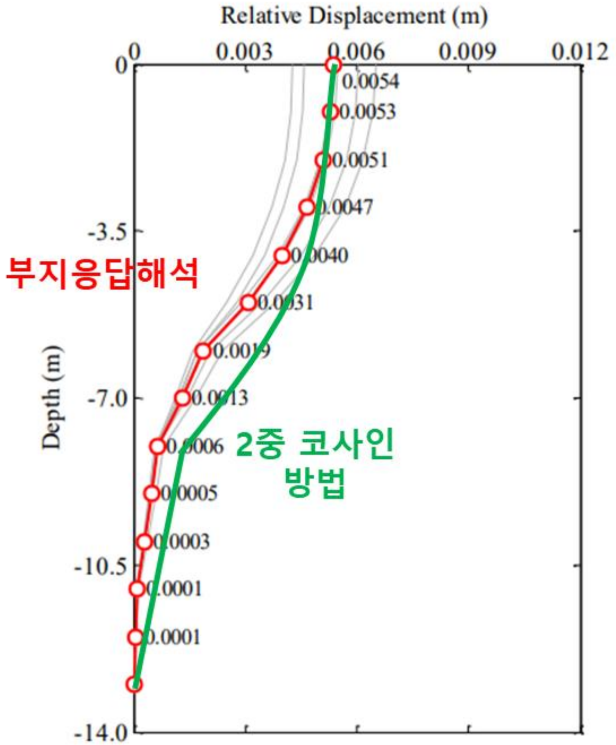
건축물의 지하구조 내진설계 지침 ((사) 대한건축학회))

3. 지하구조물을 고려한 건축물의 내진설계

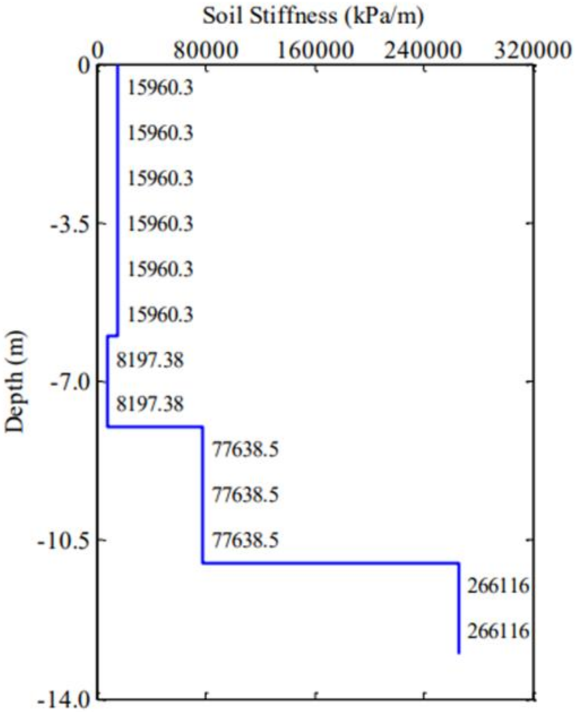
하중기반설계와 변위적합설계

하중기반설계 – 응답변위법 (강체로 가정)

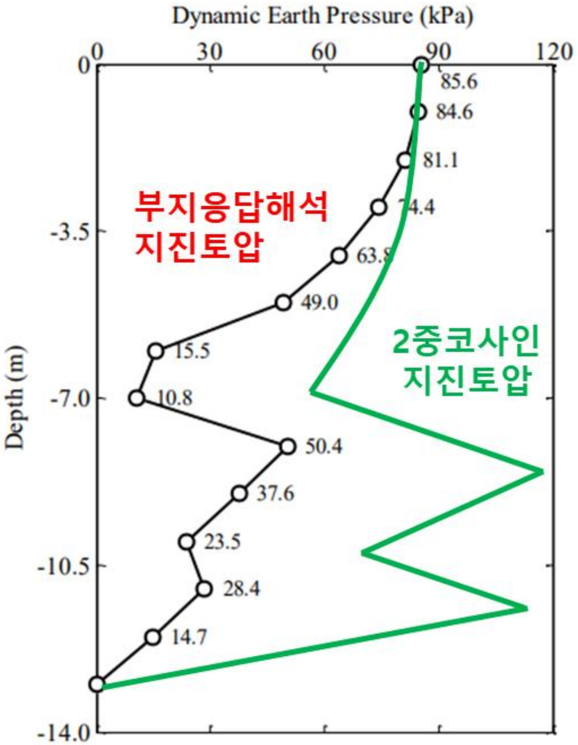
→ 단일, 이중코사인 + 지하구조물을 강체로 가정 ⇒ 과대한 지진토압을 산정



(a) 지반의 상대변위



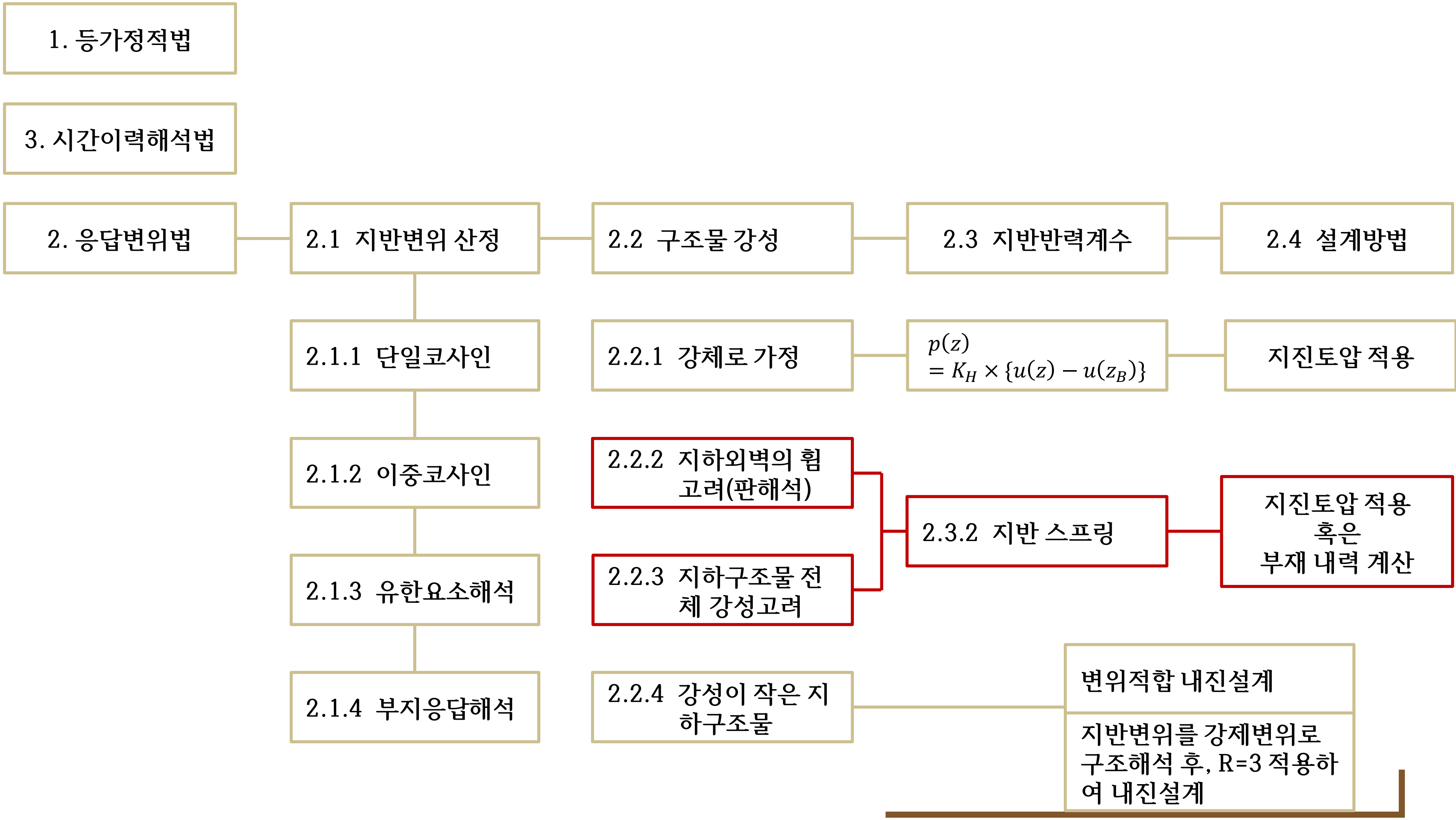
(b) 지반반력계수 주상도



(c) 지진동토압

3. 지하구조물을 고려한 건축물의 내진설계

하중기반설계와 변위적합설계



1. 등가정적법

3. 시간이력해석법

2. 응답변위법

2.1 지반변위 산정

2.2 구조물 강성

2.3 지반반력계수

2.4 설계방법

2.1.1 단일코사인

2.2.1 강체로 가정

$p(z) = K_H \times \{u(z) - u(z_B)\}$

지진토압 적용

2.1.2 이중코사인

2.2.2 지하외벽의 휨 고려(판해석)

2.3.2 지반 스프링

지진토압 적용 혹은 부재 내력 계산

2.1.3 유한요소해석

2.2.3 지하구조물 전체 강성고려

2.1.4 부지응답해석

2.2.4 강성이 작은 지하구조물

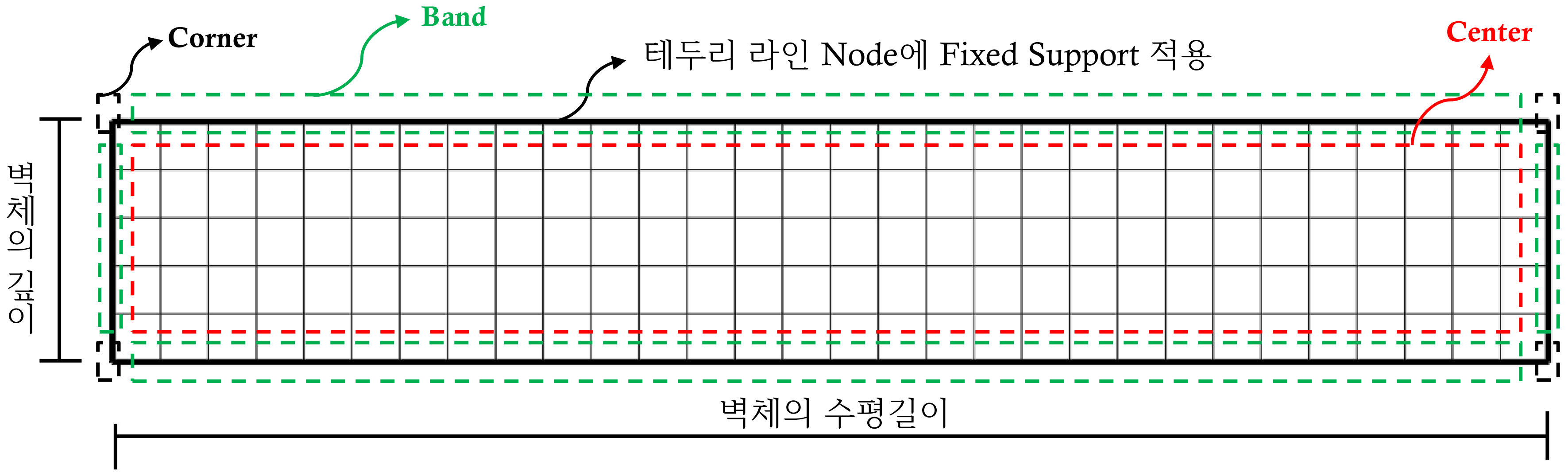
변위적합 내진설계

지반변위를 강제변위로 구조해석 후, R=3 적용하여 내진설계

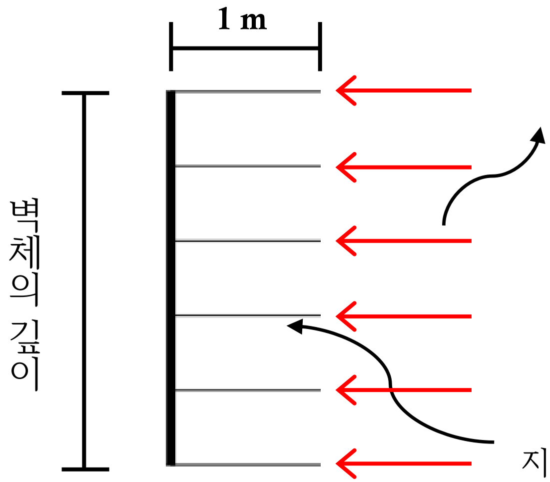
3. 지하구조물을 고려한 건축물의 내진설계

하중기반설계와 변위적합설계

하중기반설계 – 응답변위법 (지하외벽의 힘을 고려)



테두리 라인 Node에 Fixed Support 적용



지반의 변위를
강제변위로 적용

$$K_H = 16358\, kPa/m$$

$$K_{Truss} = \frac{EA}{L\,(=1m)}$$

Truss 요소 및
지반반력계수(K_H) 적용

Truss 요소의 영향 면적에 따른
Section 적용

Center : 1 m x 1 m

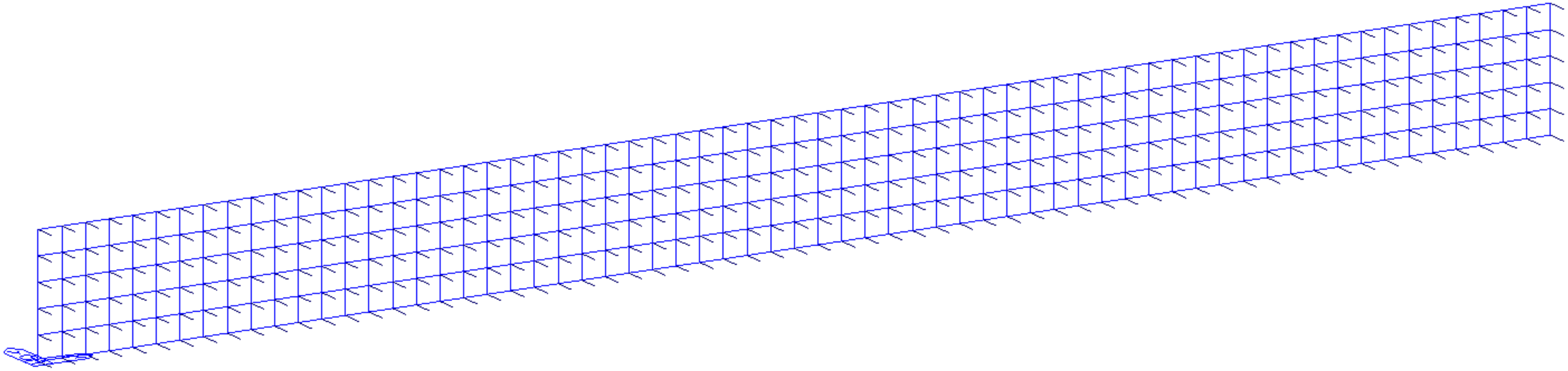
Band : 0.5 m x 1 m

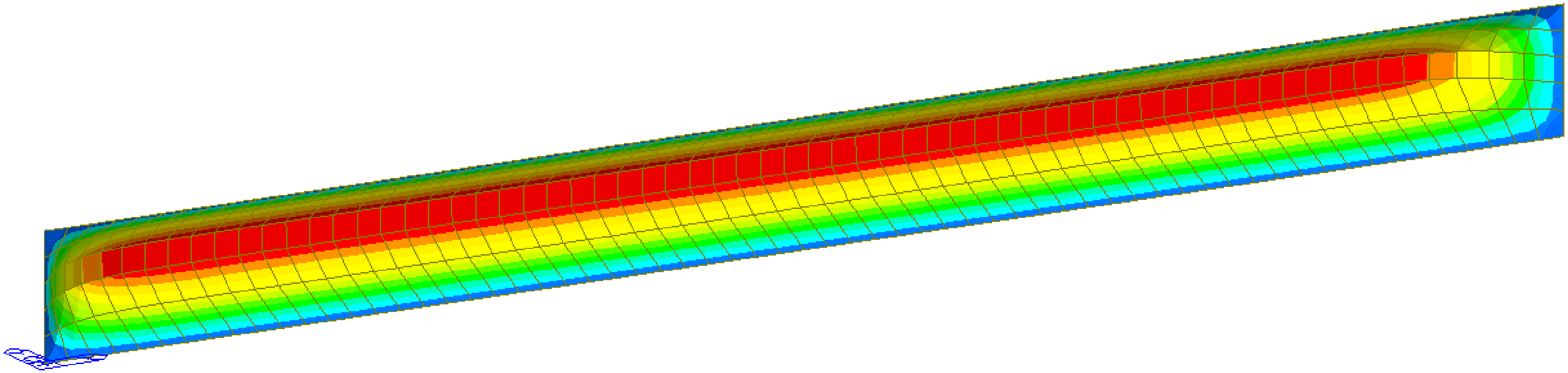
Corner : 0.5 m x 0.5 m

3. 지하구조물을 고려한 건축물의 내진설계

하중기반설계와 변위적합설계

하중기반설계 – 응답변위법 (지하외벽의 힘을 고려)





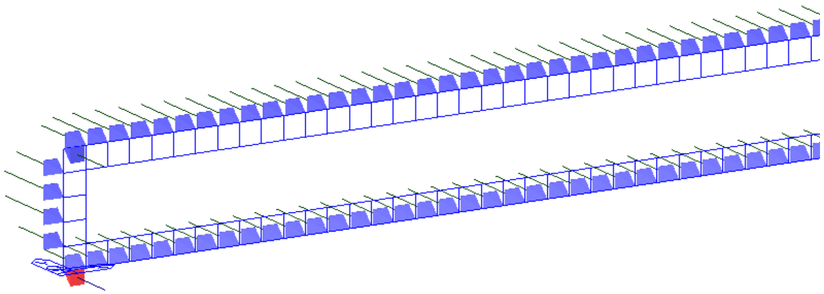
3. 지하구조물을 고려한 건축물의 내진설계

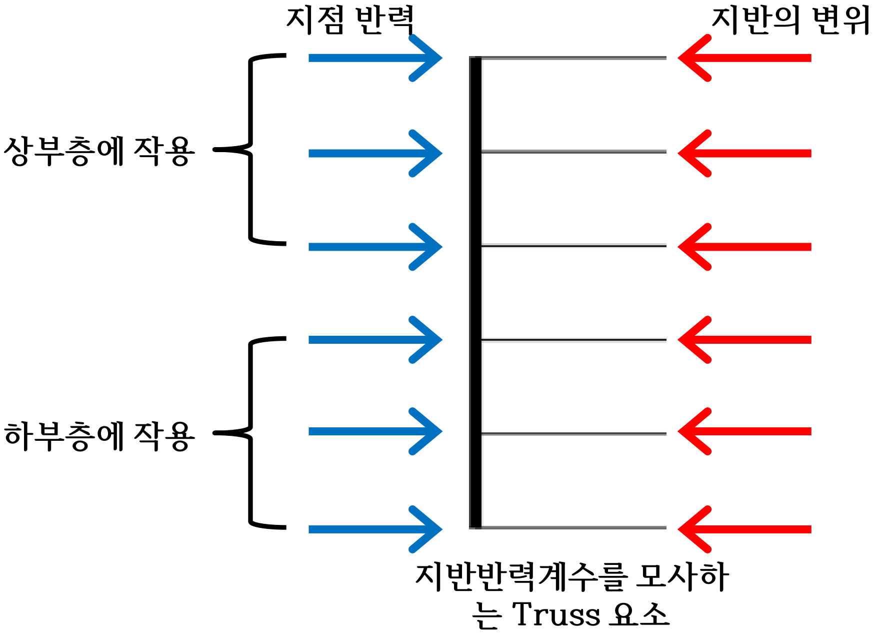
하중기반설계와 변위적합설계

하중기반설계 – 응답변위법 (지하외벽의 힘을 고려)

→ 지하외벽의 판 모델을 통한 지진토압 산정은 판 모델 테두리의 지점 반력의 합으로 산정

→ 단, 각 층에 작용하는 층별 지진토압은 각 층의 영향면적을 고려하여 산정





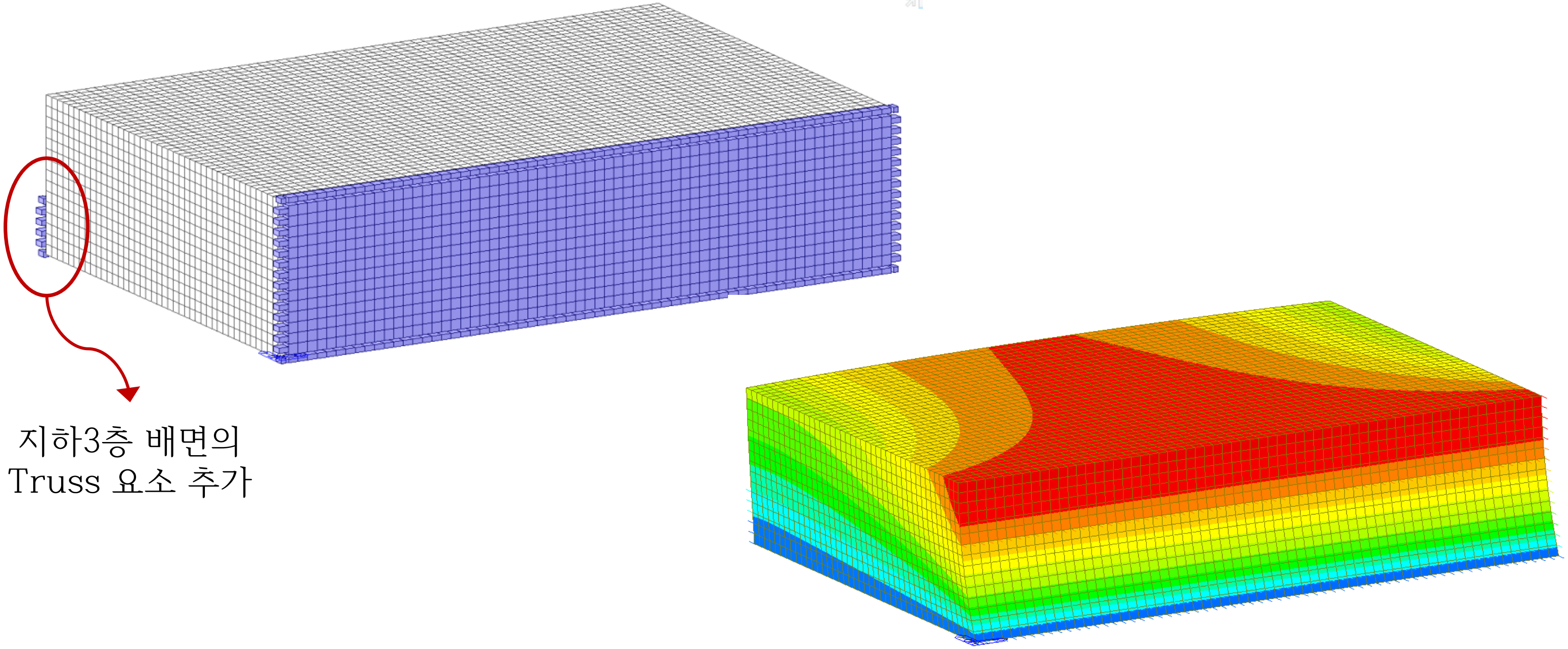
3. 지하구조물을 고려한 건축물의 내진설계

하중기반설계와 변위적합설계

하중기반설계 – 응답변위법 (지하구조물 전체강성 고려)

→ 지하외벽의 판 모델을 확장하여 지하층 전체 모델링을 통한 해석도 가능

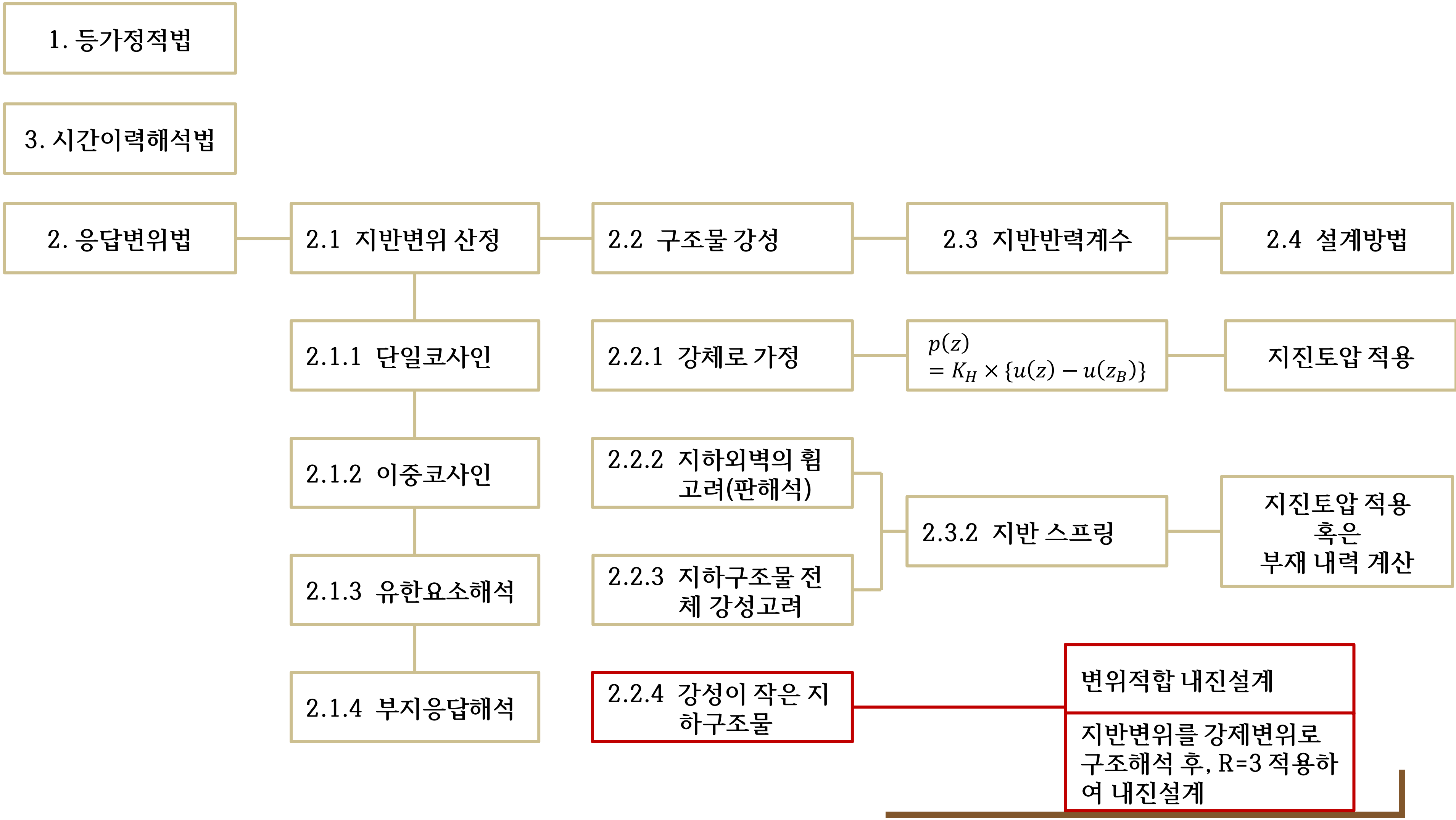
→ 단, 이러한 경우 지하 3층의 반대편 면은 지반 반력에 의한 저항이 있는 것으로 가정하고 Truss 요소를 추가하여 해석



지하3층 배면의
Truss 요소 추가

3. 지하구조물을 고려한 건축물의 내진설계

하중기반설계와 변위적합설계



1. 등가정적법

3. 시간이력해석법

2. 응답변위법

2.1 지반변위 산정

2.1.1 단일코사인

2.1.2 이중코사인

2.1.3 유한요소해석

2.1.4 부지응답해석

2.2 구조물 강성

2.2.1 강체로 가정

2.2.2 지하외벽의 휨 고려(판해석)

2.2.3 지하구조물 전체 강성고려

2.2.4 강성이 작은 지하구조물

2.3 지반반력계수

$$p(z) = K_H \times \{u(z) - u(z_B)\}$$

2.3.2 지반 스프링

2.4 설계방법

지진토압 적용

지진토압 적용
혹은
부재 내력 계산

변위적합 내진설계

지반변위를 강제변위로 구조해석 후, R=3 적용하여 내진설계

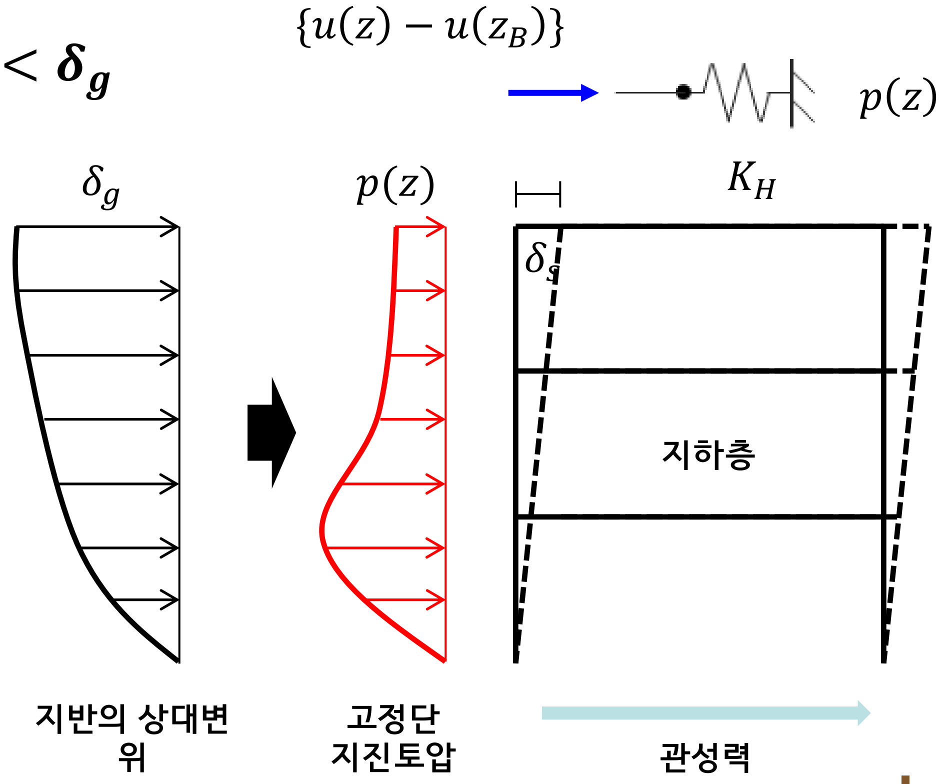
3. 지하구조물을 고려한 건축물의 내진설계

하중기반설계와 변위적합설계

지반의 상대변위에 따른 지진토압을 적용하여 내진설계 검토 시 각층에 대한 최종 지하구조물의 변위는 각층에 대응하는 지반의 상대변위보다 클 필요는 없다.

$$\boldsymbol{\delta_s < \delta_g}$$

층	지반의 상대변위 (mm)	지하층의 변위 (mm)	검토
1F (G.L)	6.09	0.9	O.K
B1	5.35	0.7	O.K
B2	3.23	0.5	O.K
B3	0	0	-



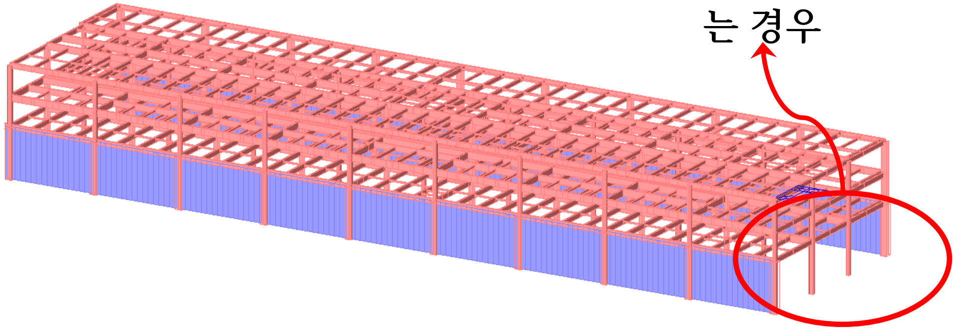
3. 지하구조물을 고려한 건축물의 내진설계

하중기반설계와 변위적합설계

지진작용 방향에 대한 저항벽체가 없거나 지하층 강성이 작은 구조물에 대해 지반의 상대변위보다 각 층에 해당하는 지하층의 변위가 큰 경우 변위적합 내진설계를 적용한다.

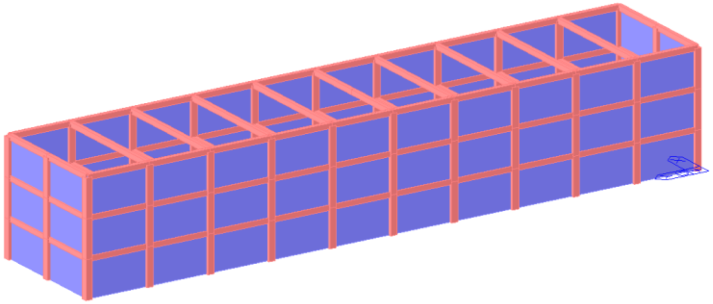
층	지반의 상대변위 (mm)	고정단 지진토압 지하층의 변위 (mm)	검토
1F (G.L)	6.09	218.4	N.G
B1	0	0	-

층	지반의 상대변위 (mm)	고정단 지진토압 지하층의 변위 (mm)	검토
1F (G.L)	6.09	8.0	N.G
B1	5.35	6.9	N.G
B2	3.23	4.6	N.G
B3	0	0	-



저항벽체가 없는 경우

터널형 구조



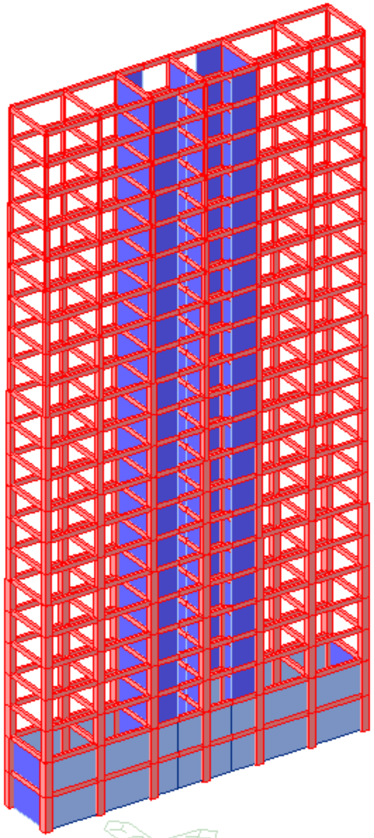
지하층 강성이 작은 구조

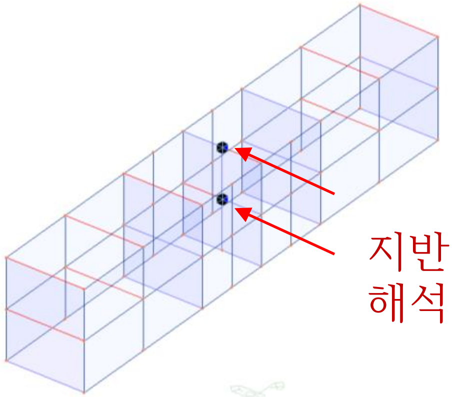
3. 지하구조물을 고려한 건축물의 내진설계

하중기반설계와 변위적합설계

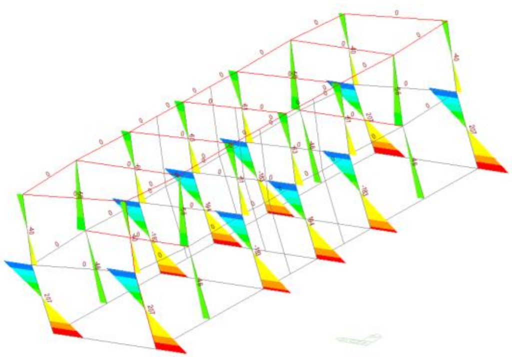
변위적합 내진설계

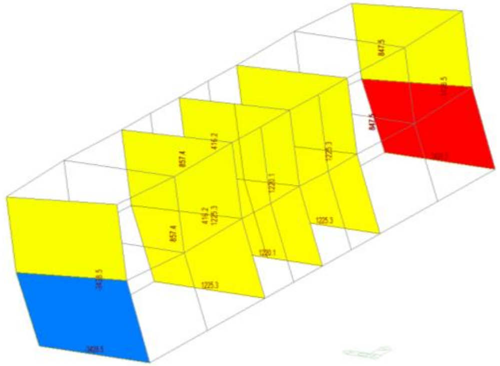
→ 지하구조의 강성이 작아서 큰 변위가 발생하고, 상대적으로 작은 내력이 발생하는 경우에 사용할 수 있는 지하구조 지진해석 및 설계방법





지반변위를 강제변위로 가력
해석결과에 R=3 반영



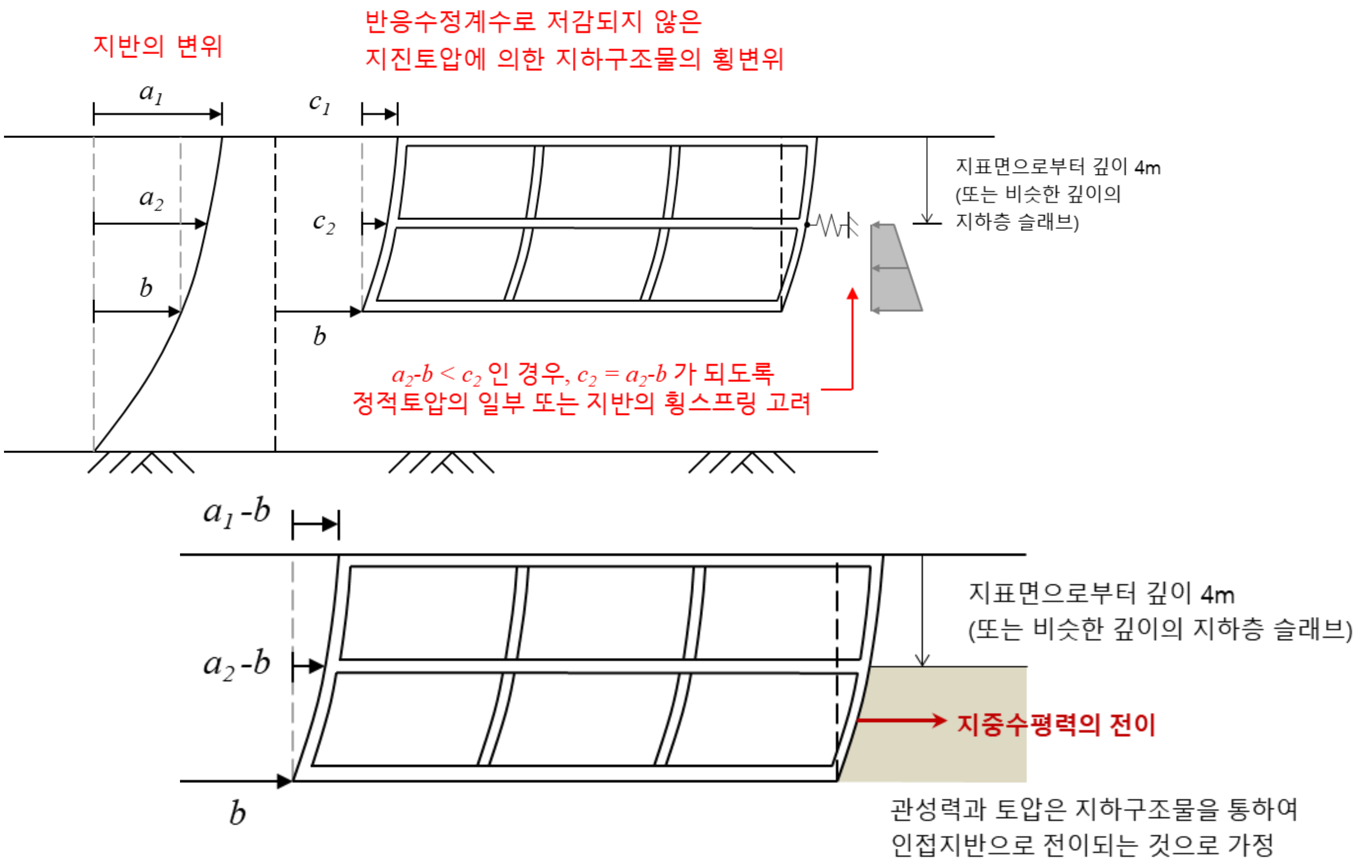


3. 지하구조물을 고려한 건축물의 내진설계

하중기반설계와 변위적합설계

변위적합 내진설계

→ 수평력이 지하구조의 4m 아래 지반에서 지하구조를 통하여 인접 지반으로 전이되는 것으로 가정 ⇒ 지반과 구조물 변형의 적합성을 고려하여 불필요한 구조설계 방지



지반의 변위

반응수정계수로 저감되지 않은 지진토압에 의한 지하구조물의 횡변위

지표면으로부터 깊이 4m (또는 비슷한 깊이의 지하층 슬래브)

a_2-b < c_2 인 경우, $c_2 = a_2$-b 가 되도록 정적토압의 일부 또는 지반의 횡스프링 고려

지표면으로부터 깊이 4m (또는 비슷한 깊이의 지하층 슬래브)

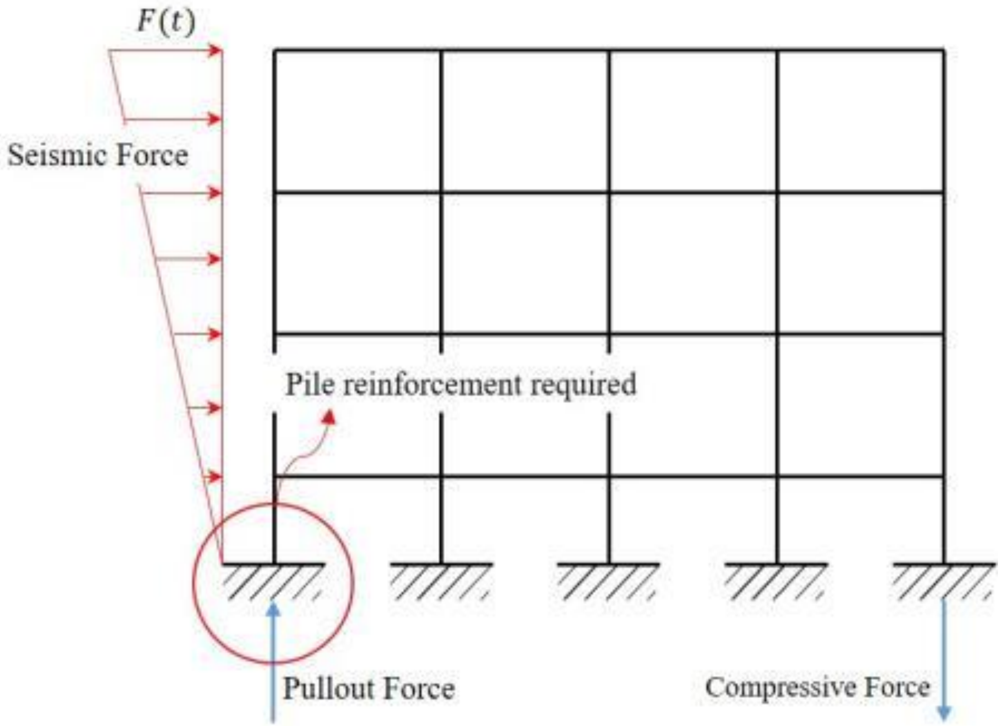
지중수평력의 전이

관성력과 토압은 지하구조물을 통하여 인접지반으로 전이되는 것으로 가정

Contents

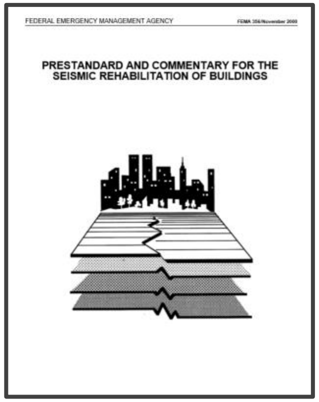
4. 결 론

1. 얕은 기초를 포함하는 건축물에 대한 내진설계에서 기존 기초 하부를 고정단으로 가정하는 해석하는 경우, 기초하부에 작용하는 인발력에 따른 과도한 내진보강 문제가 지속적으로 제기되어 왔음



4. 결 론

2. 국외 건축물 설계기준에서는 SSI 효과를 고려한 내진설계 절차에 대한 논의가 꾸준히 지속되어 왔으며 ASCE 7-22에서는 SSI 효과를 고려한 구체적인 내진설계절차에 대하여 기술하고 있음


FEDERAL EMERGENCY MANAGEMENT AGENCY
FEMA 356/November 2000

PRESTANDARD AND COMMENTARY FOR THE SEISMIC REHABILITATION OF BUILDINGS


FEMA 440
IMPROVEMENT OF NONLINEAR STATIC SEISMIC ANALYSIS PROCEDURES

Prepared by:
ATC
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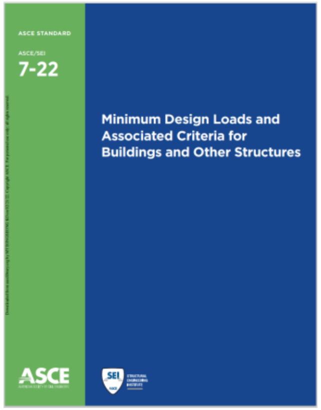
Redwood City, California 94065

Prepared for:
Federal Emergency Management Agency
Washington, D.C.

Draft Camera-Ready


ASCE STANDARD
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7-22

Minimum Design Loads and Associated Criteria for Buildings and Other Structures

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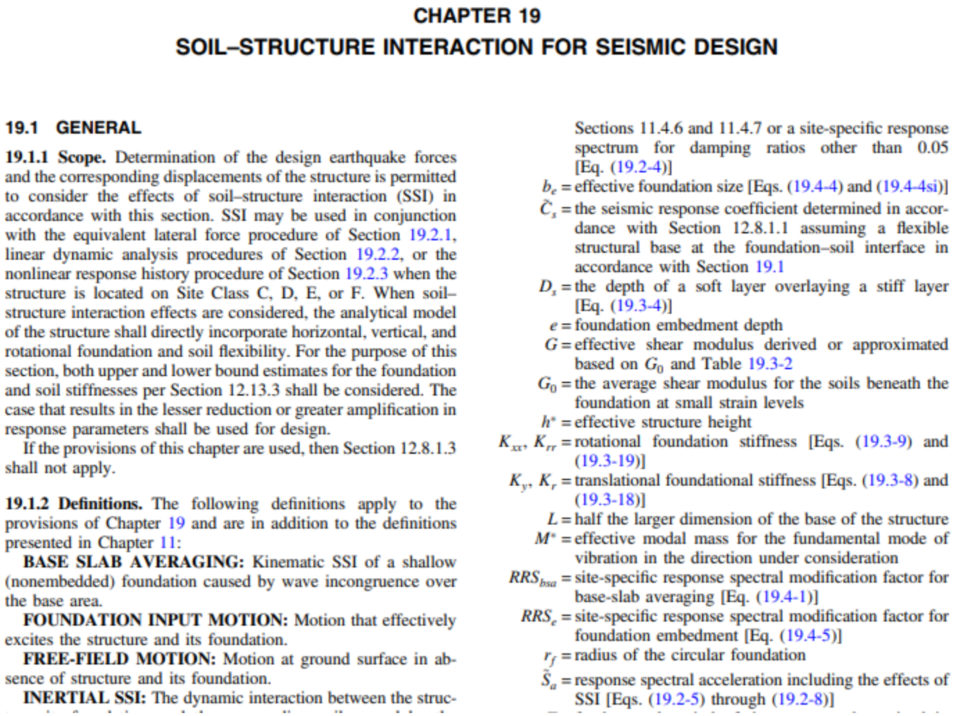

CHAPTER 19

SOIL–STRUCTURE INTERACTION FOR SEISMIC DESIGN

19.1 GENERAL

19.1.1 Scope. Determination of the design earthquake forces and the corresponding displacements of the structure is permitted to consider the effects of soil–structure interaction (SSI) in accordance with this section. SSI may be used in conjunction with the equivalent lateral force procedure of Section 19.2.1, linear dynamic analysis procedures of Section 19.2.2, or the nonlinear response history procedure of Section 19.2.3 when the structure is located on Site Class C, D, E, or F. When soil–structure interaction effects are considered, the analytical model of the structure shall directly incorporate horizontal, vertical, and rotational foundation and soil flexibility. For the purpose of this section, both upper and lower bound estimates for the foundation and soil stiffnesses per Section 12.13.3 shall be considered. The case that results in the lesser reduction or greater amplification in response parameters shall be used for design.

If the provisions of this chapter are used, then Section 12.8.1.3 shall not apply.

19.1.2 Definitions. The following definitions apply to the provisions of Chapter 19 and are in addition to the definitions presented in Chapter 11:

BASE SLAB AVERAGING: Kinematic SSI of a shallow (nonembedded) foundation caused by wave incongruence over the base area.

FOUNDATION INPUT MOTION: Motion that effectively excites the structure and its foundation.

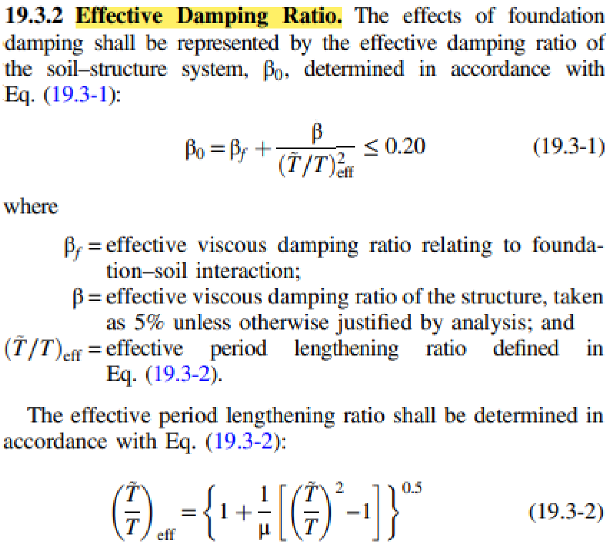
FREE-FIELD MOTION: Motion at ground surface in absence of structure and its foundation.

INERTIAL SSI: The dynamic interaction between the struc-

Sections 11.4.6 and 11.4.7 or a site-specific response spectrum for damping ratios other than 0.05 [Eq. (19.2-4)]
b_e = effective foundation size [Eqs. (19.4-4) and (19.4-4si)]
$\tilde{C}_s$ = the seismic response coefficient determined in accordance with Section 12.8.1.1 assuming a flexible structural base at the foundation–soil interface in accordance with Section 19.1
D_s = the depth of a soft layer overlaying a stiff layer [Eq. (19.3-4)]
e = foundation embedment depth
G = effective shear modulus derived or approximated based on G_0 and Table 19.3-2
G_0 = the average shear modulus for the soils beneath the foundation at small strain levels
h^* = effective structure height
K_{xx}, K_{rr} = rotational foundation stiffness [Eqs. (19.3-9) and (19.3-19)]
K_y, K_r = translational foundational stiffness [Eqs. (19.3-8) and (19.3-18)]
L = half the larger dimension of the base of the structure
M^* = effective modal mass for the fundamental mode of vibration in the direction under consideration
RRS_{bsa} = site-specific response spectral modification factor for base-slab averaging [Eq. (19.4-1)]
RRS_e = site-specific response spectral modification factor for foundation embedment [Eq. (19.4-5)]
r_f = radius of the circular foundation
$\tilde{S}_a$ = response spectral acceleration including the effects of SSI [Eqs. (19.2-5) through (19.2-8)]

4. 결 론

3. 국내에서도 경제적인 내진설계 및 내진성능평가를 위하여 SSI 효과를 고려한 내진설계방안에 대하여 지속적인 논의가 요구됨



19.3.2 Effective Damping Ratio. The effects of foundation damping shall be represented by the effective damping ratio of the soil–structure system, β_0, determined in accordance with Eq. (19.3-1):

$$\beta_0 = \beta_f + \frac{\beta}{(\tilde{T}/T)^2_{\text{eff}}} \le 0.20 \qquad (19.3\text{-}1)$$

where

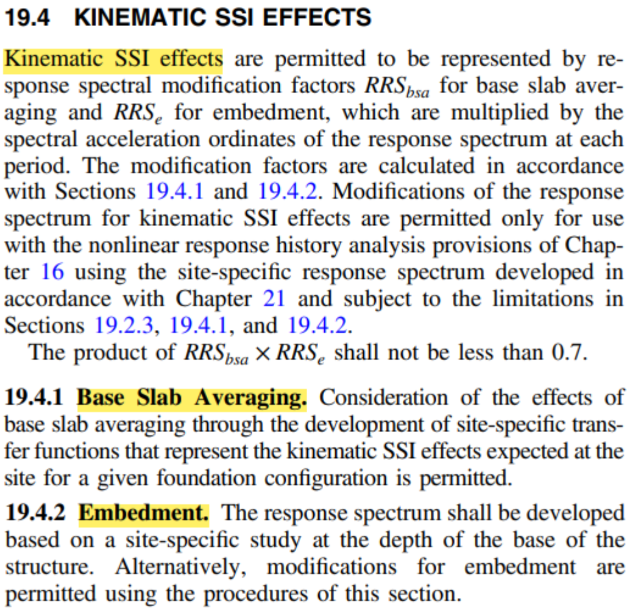
β_f = effective viscous damping ratio relating to foundation–soil interaction;

β = effective viscous damping ratio of the structure, taken as 5% unless otherwise justified by analysis; and

$(\tilde{T}/T)_{\text{eff}}$ = effective period lengthening ratio defined in Eq. (19.3-2).

The effective period lengthening ratio shall be determined in accordance with Eq. (19.3-2):

$$\left(\frac{\tilde{T}}{T}\right)_{\text{eff}} = \left\{1+\frac{1}{\mu}\left[\left(\frac{\tilde{T}}{T}\right)^2-1\right]\right\}^{0.5} \qquad (19.3\text{-}2)$$



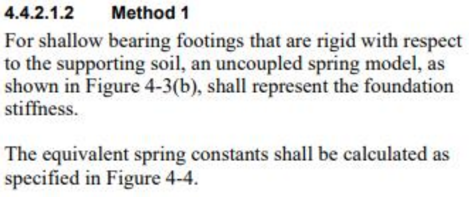
19.4 KINEMATIC SSI EFFECTS

Kinematic SSI effects are permitted to be represented by response spectral modification factors RRS_{bsa} for base slab averaging and RRS_e for embedment, which are multiplied by the spectral acceleration ordinates of the response spectrum at each period. The modification factors are calculated in accordance with Sections 19.4.1 and 19.4.2. Modifications of the response spectrum for kinematic SSI effects are permitted only for use with the nonlinear response history analysis provisions of Chapter 16 using the site-specific response spectrum developed in accordance with Chapter 21 and subject to the limitations in Sections 19.2.3, 19.4.1, and 19.4.2.

The product of $RRS_{bsa} \times RRS_e$ shall not be less than 0.7.

19.4.1 Base Slab Averaging. Consideration of the effects of base slab averaging through the development of site-specific transfer functions that represent the kinematic SSI effects expected at the site for a given foundation configuration is permitted.

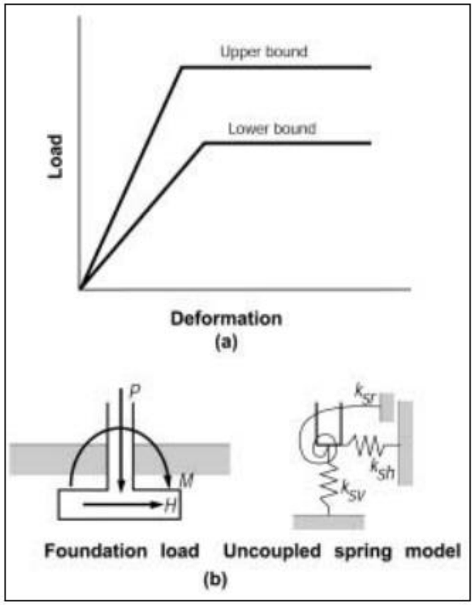
19.4.2 Embedment. The response spectrum shall be developed based on a site-specific study at the depth of the base of the structure. Alternatively, modifications for embedment are permitted using the procedures of this section.



4.4.2.1.2 Method 1

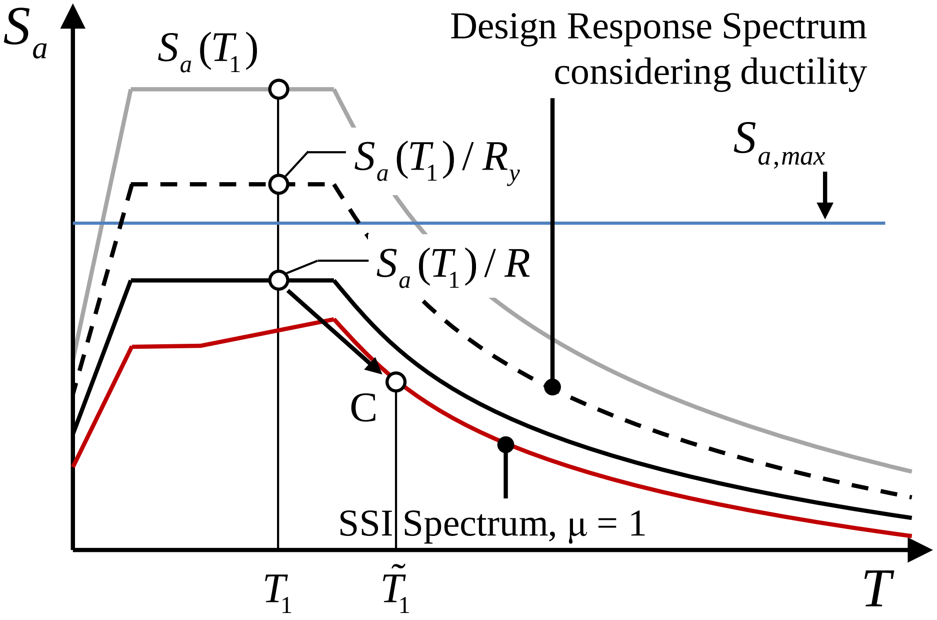
For shallow bearing footings that are rigid with respect to the supporting soil, an uncoupled spring model, as shown in Figure 4-3(b), shall represent the foundation stiffness.

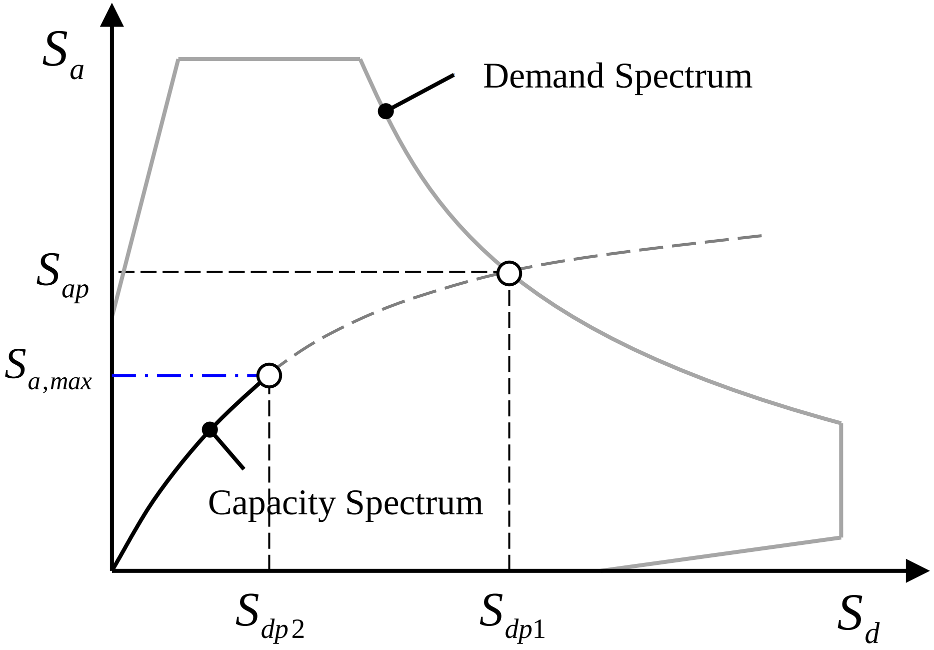
The equivalent spring constants shall be calculated as specified in Figure 4-4.



4. 결 론

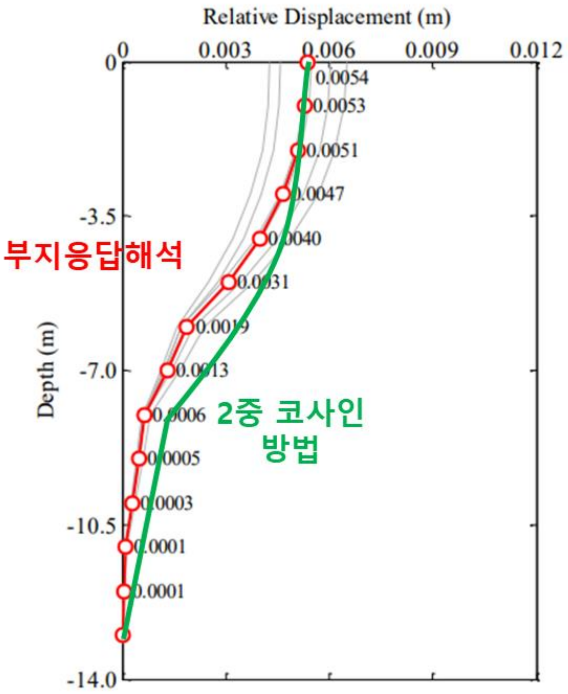
4. SSI 효과를 고려하는 경우, 상부 구조물의 응답을 제한하거나 설계 지진력을 감소시킬 수 있으므로 향후 이를 고려한 내진설계방법 접근이 필요함



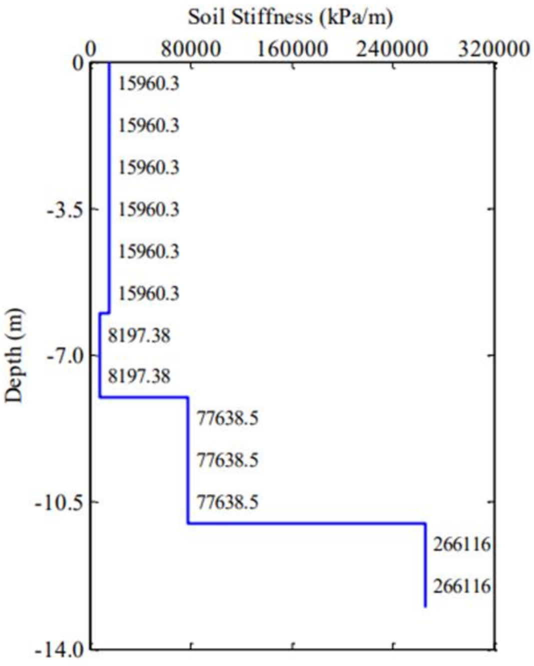


4. 결 론

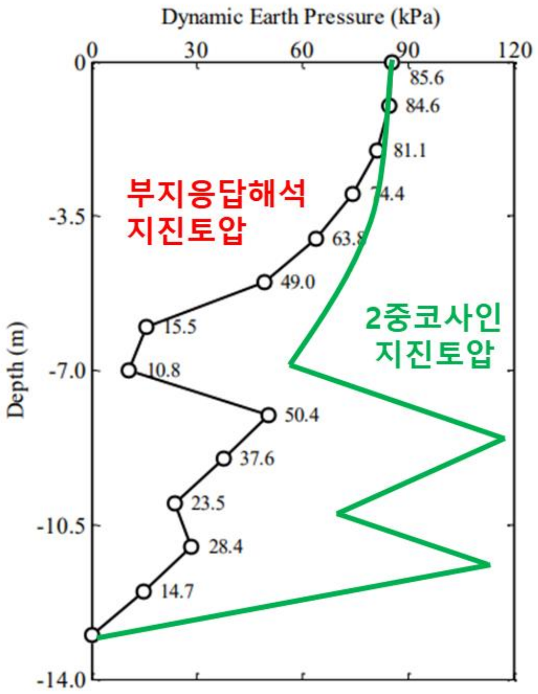
5. 지하구조물에 대한 내진설계에서 지하구조물을 강체로 가정하는 해석방안은 과한 지진하중이 산정될 수 있으며, 그로 인해 과도한 내진설계가 수행될 우려가 있음



(a) 지반의 상대변위



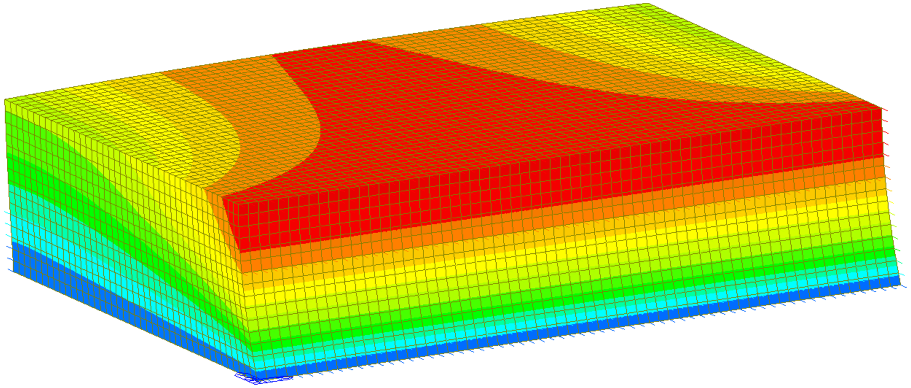
(b) 지반반력계수 주상도



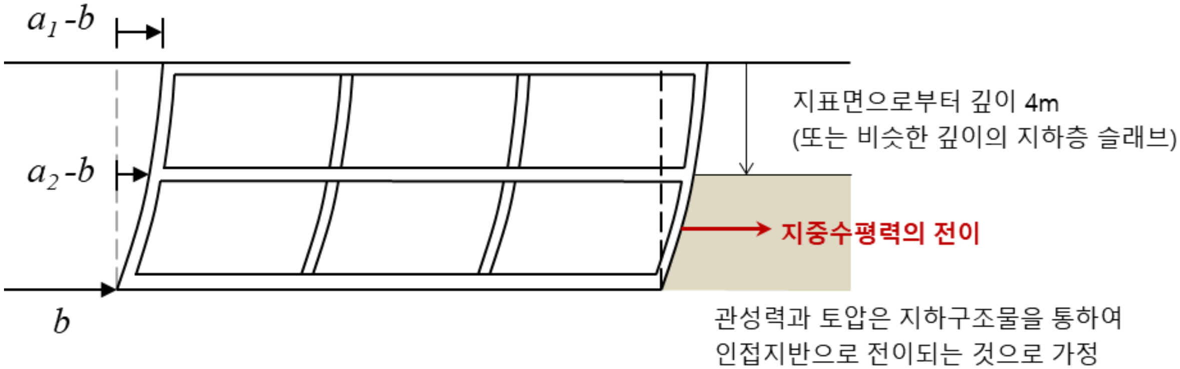
(c) 지진동토압

4. 결 론

6. 지하구조물의 변형을 고려하는 해석 방안과 지반과 구조물 변형의 적합성을 고려한 변위적합설계를 통해 불필요한 구조설계를 방지할 수 있을 것으로 판단됨



지하구조물의 변형을 고려



변위적합설계

경청해주셔서 감사합니다.