한국방재학회논문집
제12권 4호 2012년 8월
pp. 17 ~ 23

Study of Interaction on Earthquake Response of Adjacent Buildings Founded at Different Depths

Kim, Dong Woo* · Kim, Sung Chil** · Huh, Young*** · Kim, Yong Min****

Abstract

The aim of this paper is to study the interaction between adjacent buildings with different foundation levels under earthquake loading conditions. Buildings and soil are represented by two different models. In the first case the building itself is modeled with standard frame element, whereas the soil behavior is stimulated by a special grid model. In the second case, the building and soil are represented by plane stress or plane strain elements. The modulus of elasticity of the ground is varied. Just like the modification of the modulus of elasticity the varying relations of inertia have a strong influence on the section forces within the buildings. The analysis is carried out using numerical program which has been developed based on the axisymmetric fein element method in corporation of grob element for soil region and wave input technique transit boundary condition. Interaction of the proposed method is demonstrated in numerical examples.

Key words : Soil-structure interaction, Grid model, Wave input technique, Earthquake response

요 지

본 연구에서는 기초 지반고가 서로 상이한 근접구조물들의 상호작용에 대한 지진응답을 해석하였다. 구조물과 지반은 각기 두 가지 모델에 대하여 연구하였다. 즉 첫째 모델의 경우에는 빌딩은 프레임 모델로 지반은 그리드 모델로 설정하였고, 둘째 모델의 경우에는 구조물과 지반을 평면응력과 평면변형률로 모델화하였으며 구조물에 대한 상대적인 관성모멘트는 지반의 탄성모듈과 함께 구조물의 단면력에 영향을 미치므로 함께 고려되었다. 근사해석으로는 유한요소기법을 사용하였고 지진파입력기법과 Transit조건 등을 적용하여 제시된 예들을 통하여 상호작용 안전성을 논증하였다.

핵심용어 : 지반-구조물 상호작용, 그리드모델, 파동입력기술, 지진응답

1. Introduction

The seismic response of buildings is known to be strongly influenced by the soil systems on which they are founded. This soil-structure interaction itself depends on many different variables, as described in the literature(Bachmann, 1995; Bathe, 1996; Befan, 1997). So far one has structure and soil of nonlinear earthquake response analysis and radiation damping etc. But now one has examined the stability of existing and new structure including soil of which interaction was considered. One of these influence factors is the interaction between adjacent buildings, and the depths of foundation obviously play a major role in this case. For example, suppose it is planned to erect a new building immediately adjacent to an existing one. How its presence affects the seismic response of the existing building in three scenarios can be depicted in Fig. 4.

In the first case both buildings are supported on a shallow foundation, in the second case both buildings have deep foundations, and in the last case one building has a shallow and the other one a deep foundation. The building is assumed to be the reinforced concrete frame and the soil of a dense gravel.

It is known that the ground affecting the dynamic behavior of structure are soil amplification and kinematic and inertial interaction(Uniform Building Code, Earthquake Regulation, 1998). In this work, constitutive method can be modeled with the finite element method. If the width is two and the hight is one, there are not any problems concerning

*Member · Adjunct Professor of Hanyang Univ. Department of Transportation & Logistics Engineering and Senior Research Engineer of Korean Society of Hazard Mitigation(E-mail : kdw817@yahoo.co.kr)
**Professor of Kyonggi Univ. Department of Civil Engineering
***Professor of University of Suwon. Department of Civil Engineering
****Member · The Doctor's course in University of Suwon, C.E.O of HanKyoulIMG

the foundation, and with transfer function one can analyze the movement of underground(Roesset, 1980; Wolf J, 1985). Material damping ratio is treated with historical behavior damping which is according to frequency with dependent characteristic and transformed complex method, and one has modeled radiation damping term with the solution of frequency domain and external wave form's magnitude is determined(Y.X Cai et al, 1997). Input method is using average fourier amplitude to find and use ground acceleration, and one can use transit and viscous boundary conditions on boundary surface.

The literature on soil-structure interaction provides reviews of the strengths and limitations of the various techniques to model the seismic response of major structures. For vibratory motion with simple mode shapes, spring-mass models are suitable. For low-rise buildings, trigonometric shape functions have been recommended(Chopra, 2006).

In this work the dynamic time history analysis is performed using two different computer programs. For program FEMAS(DIN 4149. Section 1, 1981)(Finite Element Method for Static and Dynamic Analysis of Structures) both the buildings and the supporting soil structure are modeled with frame elements. The soil is assumed to consist of granular material, and the modulus of elasticity of the soil are $E_{dyn} = 180$ and $250\ \mathrm{MN/m^2}$ and Poisson's ratio $v = 0.3$. In program GEMAS(Earthpuake Spectra, 1996) (Mixed Element Method for the Analysis of Shell Structures) both the building and the soil are represented by plane stress or plane strain elements with response quantities to be interpreted from the stress obtained at element centers.

Numerical results will be presented for three different scenarios outlined in Figs. 5(a) and (d), each modeled for two different computer programs. To permit a further understanding of the interaction effects, the modulus of elasticity of the soil is varied in a separate parametric study.

2. Dynamic Analysis Method and Description of Different Discretization's Variations

To be accessible to dynamic analysis methods, a building has to be reduced to a dynamic system which is defined by its mass, stiffness and damping. For earthquake response evaluations, the following set of equations are solved:

$$\begin{bmatrix} M_{ss} & M_{sb} \\ M_{bs} & (M_{bb}+M_{bb}^g) \end{bmatrix} \begin{Bmatrix} \ddot{U}_s(t) \\ \ddot{U}_b(t) \end{Bmatrix} + \begin{bmatrix} C_{ss} & C_{sb} \\ C_{bs} & (C_{bb}+C_{bb}^g) \end{bmatrix} \begin{Bmatrix} \dot{U}_s(t) \\ \dot{U}_b(t) \end{Bmatrix} + \begin{bmatrix} K_{ss} & K_{sb} \\ K_{bs} & (K_{bb}+K_{bb}^g) \end{bmatrix} \begin{Bmatrix} U_b(t) \\ U_b(t) \end{Bmatrix} = \begin{Bmatrix} 0 \\ f_b(t) \end{Bmatrix} \quad (1)$$

where, $[M]$ = mass matrix, $[C]$ = damping matrix, $[K]$ = stiffness matrix, s and b mean the boundary of the soil-structure and g means the ground. $\{U(t)\}$, $\{f(t)\}$ are displacement vector and load vector of the soil and structure at time domain.

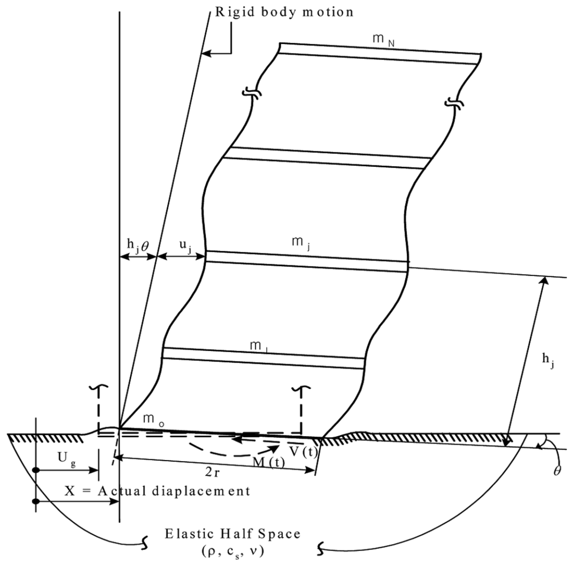


Fig. 1. Idealized building-foundation system

In the time domain Eq. (1) is traditionally solved by direct integration(Chopra, 2006; Harbord, 2005). In the direct integrations method the equations of motion are integrated directly without any prior transformation. But for a model analysis an eigenvalue problem has to be solved first to determine the frequencies and mode shapes of the combined system. These mode shapes are used to uncouple the equation of motion, which typically leads to a reduction of the overall solution efforts. The multi-degree of freedom analysis of simple linear model developed earlier can be applied to the ease of the soil-structure interaction. The idealized building foundation system is presented in Fig. 1.

The force-displacement relation is also represented in coupling Eq. (2):

$$\begin{bmatrix} V(t) \\ M(t) \end{bmatrix} = \begin{bmatrix} K_{xx} & K_{x\theta} \\ K_{\theta x} & K_{\theta\theta} \end{bmatrix} \begin{bmatrix} X(t) \\ \theta(t) \end{bmatrix} \quad (2)$$

where,

$V(t)$, $M(t)$, $X(t)$, and $\theta(t)$ = Forces and deformations

K_x, and K_θ = lateral stiffness of structure on fixed base and stiffness of foundation

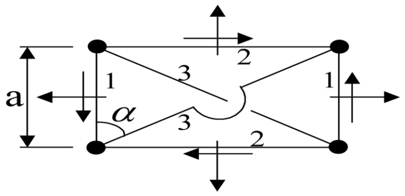
C_s = shear wave velocity = $\sqrt{G/\rho}$

v = Poission's ratio for half space material

Programs FEMAS and GEMAS employ modal analysis to solve the equation of motion. The finite element method is a numerical procedure by means of which the actual continuum is represented by an assemblage of elements interconnected at a finite number of nodal points. The following expositions deal with FEMAS and GEMAS. The program

FEMAS is based on the method of bar strengths in combination with a database which is strictly referred to node and elements. This database has constant specifications in single element. In the program GEMAS the elements of bar, area and volume are implemented in mixed and hybrid graphs. With both programs static analysis as well as dynamic calculations can be accomplished in the basis of the antwortspectrum method.

To calculate with the structural program of FEMAS the section forces have to be determined. Information about how to calculate the section forces for solving the problems of plane stress and plate with the grid method in simple and combined form are assembled in Fig. 2.



Plane element, $v = 1/3$

$$A_1 = A_0 \cdot (3\tan\alpha - \cot\alpha) \qquad A_2 = A_0 \cdot (3 - \tan^2\alpha)$$

$$A_3 = A_0 \cdot \frac{1}{\sin\alpha \cdot \cos^2\alpha} \qquad A_0 = \frac{3}{16} a \cdot t$$

t= thickness of the plane

Fig. 2. Grid model

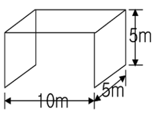
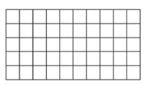
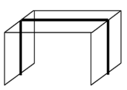
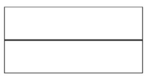
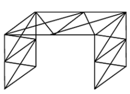
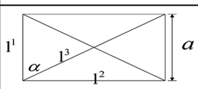
Input Data		Frequency
	5X10  GEMAS (as plate member)	Element 3X(5X10) F1 = 2.65Hz
	 FEMAS (as truss member)	Element: 3 / 30 F1 (Hz): 2.54 / 2.55
	 FEMAS (as grid member)	Element: 31 / 110 F1 (Hz): 2.27 / 2.0

Fig. 3. The dynamic frequency of the diverse elements

In the following study the influence of diverse variations of the element for the determination of natural frequency of structures of plate, truss and grid member will be verified. The given in Fig. 3 is modeled as a plate model (program GEMAS), as a truss model (program FEMAS) and as a grid (program FEMAS).

The models consist of reinforce concrete and their resiliency amounts $E_c = 3.0 \times 10^7$ kN/m^2. The thickness amount 50 cm. The calculation with the program GEMAS was carried out with 3×(5×10) elements. For the calculation for the structure of bars one element was used per columns and the beam. This is discreted with 1×3 and 3×10 elements.

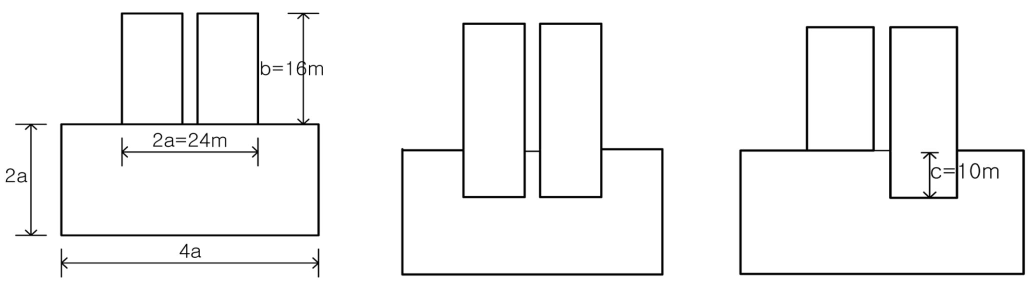
When calculating the moments of inertia one has to pay attention that it is perpendicular to the element axis. If the element axis is diagonal as in the grid model, then the diagonal has to be based as the axis for the calculation of the moment of inertia.

The results of the calculations with diverse variations of modeling are summarized in Fig. 3. The results of the three different methods have only minor deviations.

3. Introductory Studies

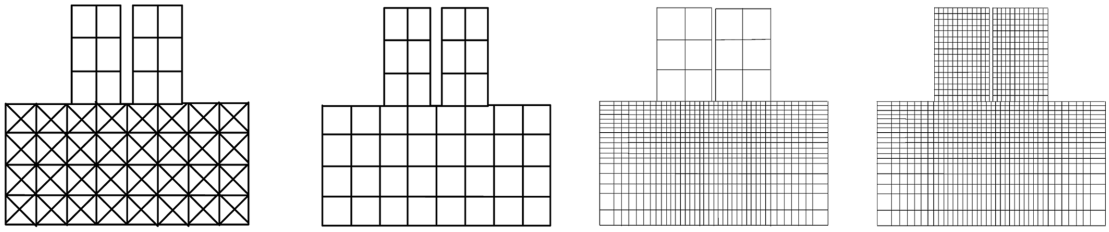
The cases studied herein are shown schematically in Fig. 4 indicating the three different foundation configurations. The case of two buildings on shallow foundations (Fig. 4(a)) was analyzed by using the three different models as shown in Fig. 5.

Model 1a employs one-dimensional frame elements to represent both the building frames and the soil structure below by arranging bars in a grid-like foundation shown in Fig. 5(a). The dimensions of the soil foundation included in the model were selected as 4a, 2a, b, and c, where a is the width of one building, b is the height of the building and c is the depth of the building as shown in Fig. 4. This model was analyzed by the frame analysis program FEMAS(DIN 4149. Section 1, 1981) as well as the finite element program GEMAS(Earthpuake Spectra, 1996). Model 1b employs the same one-dimensional frame elements as model 1a to represent the building. The soil foundation, however, is modeled



(a) Shallow-shallow (SS) System (b) Deep-deep (DD) System (c) Shallow-deep (SD) System

Fig. 4. The different foundation arrangements



(a) MODEL 1a (FEMAS and GEMAS) (b) Model 1b (GEMAS) (c) Model 1c (GEMAS) (d) MODEL 2 (GEMAS)

Fig. 5. Analysis models

Table 1. The first frequencies of model 1 with soil effect

Mode	Comp.	Frequencies[Hz]			
		Model 1a		Model 1b	Model 1c
		FEMAS	GEMAS	GEMAS	GEMAS
1	Lateral	4.56	4.45	4.58	4.46
2	Lateral	13.17	13.16	13.00	12.98
3	Vertical	21.50	20.45	17.53	17.26
4	Lateral	23.23	23.23	23.06	23.02
5	Vertical	23.72	23.75	23.73	23.72

Table 2. Modal contributions to root displacement

Mode	Comp.	Modal contributions[%]			
		Model 1a		Model 1b	Model 1c
		FEMAS	GEMAS	GEMAS	GEMAS
1	Lateral	84.5	84.6	85.2	85.3
2	Lateral	13.0	12.9	12.6	12.5
3	Vertical	97	97.6	97.9	98.9
4	Lateral	2.4	2.4	2.1	2.0

with a coarse grid of 4×8=32 plane strain elements. Model 1c is identical to model 1b except that the soil is represented by a fine mesh of 18×38=684 plane strain elements.

In model 2 the buildings are represented by 12×16=192 plane strain elements and the soil by 18×38=684 plane strain elements. The floor masses were lumped as usual at the floor levels. To obtain the thickness of the plane stress elements the combined stiffness of the building that is lateral load resisting elements was stimulated by an equivalent structural wall(Lysmer et al., 1996). Model 1b, 1c, and 2 were analyzed by program GEMAS.

The following preliminary analysis were performed with model 1a. First, a static analysis of the building for gravity loads, neglecting the soil, was performed to verify the correctness of the program and the building model.

Next, an eigenvalue analysis provided the mode shapes and frequencies, again without the influence of the soil. Then, a time history analysis of the building subjected to the acceleration record of the E1 Centro earthquake was carried out using the normal mode method. After a careful examination of the results the eigenvalue analysis and modal time history analysis were repeated for all three variations of model 1, this time including the effect of the soil.

The first 5 frequencies for each of the 4 cases including the soil effect are summarized in Table 1.

Table 2 indicates the contributions of the lowest mode to the total displacements as determined in the time history analysis. Note that compared with the building deformations soil displacements were found to be negligibly small.

The first observation of the results presented in Tables 1 and 2 is that the two computer programs give essentially the same results as they should. When comparing the results for models 1a and 1b, it is seen that except for the frequency at the first vertical mode it makes little difference whether the soil is modeled with grid-like frame elements or with plane strain elements, the generally accepted way. In the same way a comparison of the results for modes 1b and 1c shows little justification for the mesh refinement of the soil.

4. Frame Analysis Results

Program FEMAS was used to analyze model 1a), for the three different foundation configurations shallow-shallow system(SS), deep-deep system(DD), and shallow-deep sys-

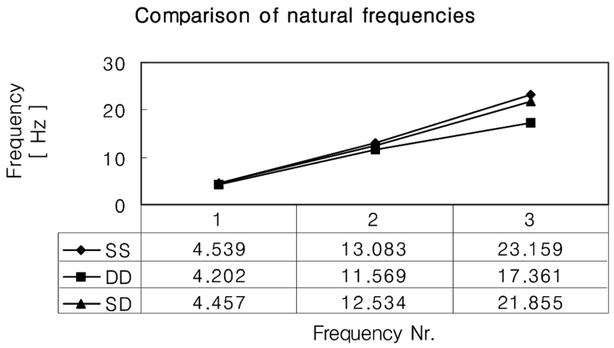


Fig. 6. Comparison of natural frequencies of frame models

tem(SD). The frequencies of the first three lateral modes of deformation are plotted in Fig. 6. As expected case 3 with two deep foundations is characterized by lower frequencies, especially in the higher modes. If only one foundation is deep, frequencies are much less affected.

The bending moments in the beams and columns of the first story are summarized in Fig. 7. for all three foundation configurations. As can be seen, symmetry is maintained in that moments when the two neighboring buildings are identical in cases 1 and 2.

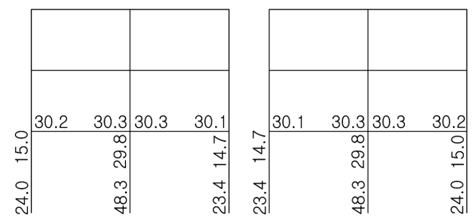
Comparing cases Shallow-shallow system and Deep-deep system it is observed that the largest moment (bottom of center column) is barely affected by the depth of foundation. All other moments are increased as the foundation is deepened, and more so in the columns (up to 35%) than in the beams (up to 20%).

By comparing the moments in the building with one or two shallow foundations (cases Shallow-shallow system and Shallow-deep system) it is observed that lowering the foundation of the neighboring building reduce building moments consistently, from 5% to 12%.

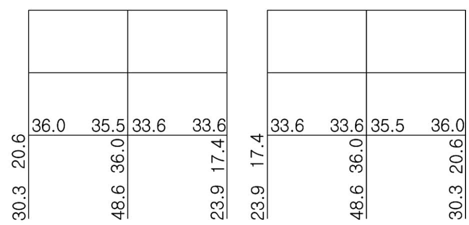
Finally, a comparison of the moments in the buildings with at least one deep foundation (cases Deep-deep system and Shallow-deep system) shows that the lower foundation of the neighboring building decreases moments in one column by up to 22%, while bending moments in the other columns and beams are changed by relatively small amounts.

5. Plane Stress Analysis Results

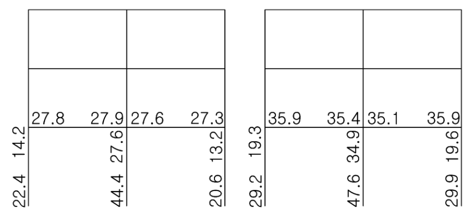
Program GEMAS was used to analyze model 2 (Fig. 5(d)) in which two buildings were represented by plane stress elements. Again, the three different foundation configurations were considered. The section forces of horizontal sections of buildings (n^{11}) and the stresses of vertical section of the ground (s^{11}) are presented in Fig. 8.



(a) Case 1: Shallow-shallow system (SS)

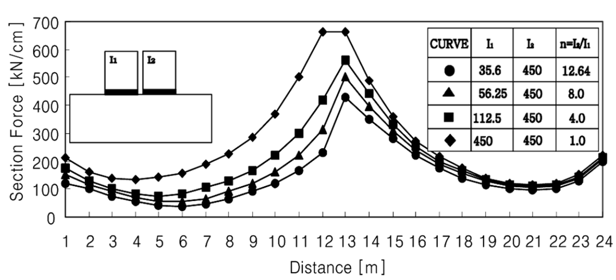


(b) Case 2: Deep-deep system (DD)

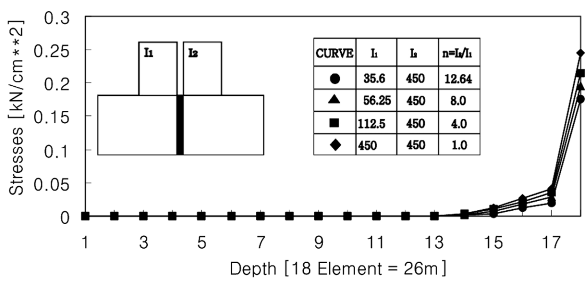


(c) Case 3: Shallow-deep system (SD)

Fig. 7. Bending moments of first-story frame element, model 1

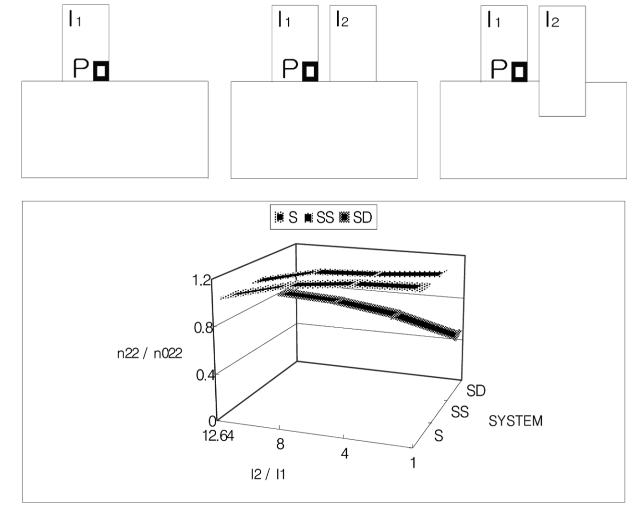


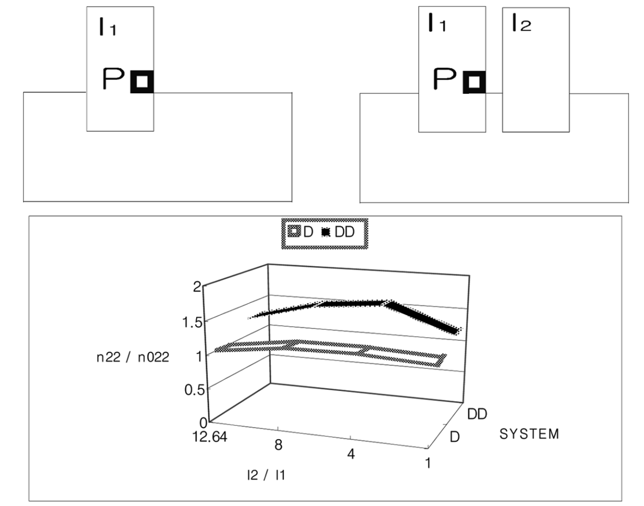
(a) Horizontal section force of building [n^{11}]



(b) Stresses of vertical ground section [s^{11}]

Fig. 8. The section forces of buildings and the stresses of the ground





Nr.	I_1	$n = I_2/I_1$	n22/n022		
			S	SS	SD
1	35.6	12.64	1.000	1.017	0.781
2	56.25	8.0	1.133	1.141	0.746
3	112.5	6.0	1.187	1.159	0.662
4	450.00	1.0	1.201	1.199	0.513

Fig. 9. & Table 3. Normalized section forces at the exterior base point depending on the I_2/I_1 ratio (shallow-shallow system and shallow-deep system)

Nr.	I_1	$n = I_2/I_1$	n22/n022	
			D	DD
1	35.6	12.64	1.000	1.267
2	56.25	8.0	1.127	1.528
3	112.5	6.0	1.134	1.620
4	450.00	1.0	1.076	1.234

Fig. 10. & Table 4. Normalized section forces at the exterior base point depending on the 2/1 ratio (deep system and deep-deep system)

This Fig. 8(a) shows the horizontal section force of the buildings in shallow-shallow system. The ratio of inertia moment changes, i.e., the section forces increase with an increasing of the moment of inertia. The Fig. 8(b) shows the vertical stresses of ground in shallow-shallow system. That shows a sudden increase of stresses in the highest elements.

The variation of moments of inertia, i.e., the ratio of moment of building 1's is inertia to that of building 2, has an influence on the section forces, as well as the modulus of elasticity of the soil. The following Table 3 shows the computed section forces n22 at the outermost right base point P of the buildings normalized against the corresponding value n022 computed with $I_1 = 35.6\,m^4$. The tendencies are displayed in the following Fig. 9.

The shallow system shows that the section forces in increasing moment of inertial increase about 20%. In the shallow-shallow system the section forces are almost as high as the section forces of a single shallow system.

But in shallow-deep system the section forces are about 20% lower than the section forces of the single shallow system. In case of decrease of the variation of moment of inertia the section forces of the shallow-deep system decrease.

The following Fig. 10 and Table 4 show a deep system and deep-deep system. In case of two deep constructed buildings the section forces are about 25% higher than the section forces of a single deep system.

As a result, Figs. 9, 10 show that the influence of the interaction on a neighbouring building seems to be little in shallow-shallow system, even weak in shallow-deep system and strong in deep-deep system.

6. Conclusions

This paper deal with the earthquake response of buildings founded at different depths. The computations accomplished with the frame model show that the bending moments of beam and columns differ. As a result the greatest differences between buildings 1 and 2 could be observed in the shallow-deep system. Concerning the plane stress model the calculation of section forces reveals that the greatest difference is also in the shallow-deep system.

A building stands on the ground. This building resists static and dynamic loads. Now a new building is erected next to the old one, the interaction of the two buildings have been examined. The analysis of the interaction of neighbouring buildings with three different plane models yielded the following conclusions.

First, if both buildings have shallow foundations, the interaction is small and negligible. Second, if the neighbouring buildings have the same deep foundation level, then due to interaction the forces in one building are 25% larger than those in a single deep building. Third, if one building is shallow and the other one deep, then due to interaction the forces in one building are 20% smaller than those in a single shallow building meaning that in the second case, the weaker building has to be reinforced.

References

Bachmann, H. (1995) *Seismic retrofitting of the structure*, Basel. Swiss.

Bathe, K.-J. (1996) *Finite Element Procedures.* Prentice-Hall, Inc.

Befan, Z. and Kim, D.-W. (1997) *Calculation research of earthquake-safety interpretation of building with different numbers of basements in hanging position,* TU Berlin.

Chopra Anil K. (2006) *Dynamics of structures: Theory and applications to earthquake engineering*, Prentice-Hall, Inc.

DIN 4149. Section 1. (1981) Construction in german earthquake areas. Load case, design, construction practice of regular structures.

Earthquake Spectra. (1996) *Special Supplement* to Volume11, November.

Harbord, R. (2005) *FEMAS: Finite element method for static and dynamic analysis of frame structures*. TU Berlin.

Kramer, S.L. (1996) *Geotechnical Earthquake Engineering*, Prentice Hall, pp. 348-422.

Kraus, S. and Kim, D.-W. (1996) *GEMAS: Mixed element method for the analysis of shell structure*. TU Berlin.

Lysmer, J., Ostadan, F., Tabatabaie, M., Vahdani, S. and Tajirian, F. (1996) *SASSI: A System for Analysis of Soil-Structure Interaction*, University of California, Berkeley, California.

Roesset, J.M. (1980) *A Review of Soil-Structure Interaction*, Lawrence Livemore Laboratory, June, pp. 125.

Seed, H.B., Ugas, C. and Lysmer, J. (1976) Site dependent spectra for earthquake resistant design. *Bulletin of the Seismological Society of America* 66.

Uncertainty and Conservatism in the Seismic Analysis and Design of Nuclear Facilities. (1986) ASCE, pp. 302.

Uniform Building Code, Earthquake Regulations.(1998), *International conference of Building Officials*, USA.

Wolf J.-P. (1985) *Dynamic Soil-Structure Interaction*, Prentice-Hall Inc., Englewood Cliffs, N.J., USA, pp. 466.

Y.X. Cai et al. (1997) Numerical Implementation of a 3-D Nonlinear Seismic S-P-S-I Methodology, Seismic Analysis and Design for Soil-Pile-Structure Interactions, *Geotechnical Special Publication* No. 70, ASCE.

◎ 논문접수일 : 2012년 05월 21일
◎ 심사의뢰일 : 2012년 05월 23일
◎ 심사완료일 : 2012년 06월 21일