기초가 서로다른 빌딩과 지반의 상호작용에 의한 지진응답 해석

Earthquake Response of Two Adjacent Buildings Founded at Different Depths

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요 지

본 논문에서는 이웃한 빌딩의 기초가 서로 상이한 경우, 구조물과 지반의 상호작용에 대한 지진응답해석을 하였다. 세 가지 시스템에 대한 두 가지 모델에 대하여 연구하였다. 첫째 모델의 경우에는 빌딩은 프레임모델로 지반은 그리드모델로 설정하였고, 둘째 모델의 경우에는 구조물과 지반을 평면응력과 평면변형률로 모델화하였다. 또한 변형된 관성모멘트는 지반의 탄성모듈과 함께 구조물의 단면력에 영향을 미치므로 함께 고려되었다. 근사해석으로는 유한요소법과 응답스펙트럼이 적용되었으며 제시된 예를 통하여 안전성을 논증하였다.

핵심용어 : 상호작용, 응답스펙트럼, 그리드모델, 지진응답

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 as well as the varying relations of inertia have a strong influence on the section forces within the buildings. The Interaction between the two buildings is demonstrated and discussed via numerical examples using the proposed method.

keywords : *soil-structure interaction, dynamic analysis, grid model, earthquake response*

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.[1)~3)] One of these influence factors is the interactionbetween 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 will its presence effect the seismic response of the existing building in the three scenarios depicted in Fig. 6.

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 buildings has a shallow and the other one a deep foundation. The building is assumed to be a reinforced concrete frame and the soil a dense gravel.

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It is known that the interaction effects between adjacent buildings can cause either magnification or reduction of the earthquake energy, based on the specific reflections and refractions of the incoming seismic waves. The literature on soil-structure interaction provides reviews on the strengths and limitations of the various techniques for modeling the seismic response of major structures. For vibratory motion with simple mode shapes, spring-mass models are considered to be adequacy. For low-rise buildings, trigonometric shape functions have been recommended.[4]

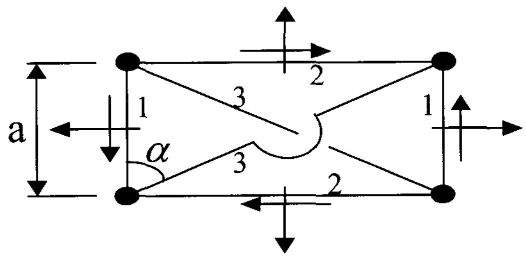
In this work, the dynamic time history analyses are performed using two different computer programs. For program FEMAS[5](Finite Element Method for Static and Dynamic Analysis of Structures), both the building and the supporting soil structure are modeled with frame elements. The soil is assumed to consist of granular material, and the modulus of elasticity of the soil is $E_g = 2\times10^5 kN/m^2$. In program GEMAS[6] (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 stresses obtained at element centers.

Numerical results will be presented for the three different scenarios outlined in figure 7a) and d), each modeled for the 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 parameter study.

2. DESCRIPTION OF DIFFERENT VARIATIONS

Structural systems can be built up of various structural elements such as, one-dimensional-, two-dimensional- and three-dimensional elements. 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.

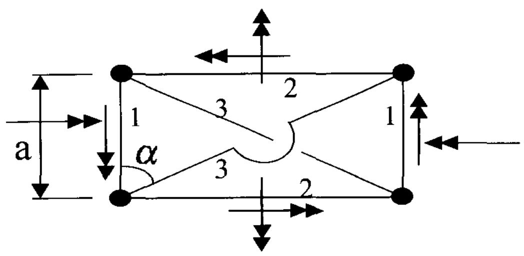


a) Plane element, $\mu = 1/3$

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

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

t=Thickness of the plane (1)



b) Plate element, $\mu = 1/3$

$$I_1 = I_0 \cdot (3\tan\alpha - \cot\alpha) \qquad I_2 = I_0 \cdot (3 - \tan^2\alpha)$$

$$I_3 = I_0 \cdot \frac{1}{\sin\alpha \cdot \cos^2\alpha} \qquad I_0 = \frac{1}{64} a \cdot t^3 \qquad (2)$$

t=Thickness of the plane

Figure 1 Simple grid model

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 stresses and plates with the grid method in simple and combined form are assembled in figure 1.

With this procedure i.e. shear walls and deck plates can be simply integrated into frame calculations. This is especially interesting if the goal is to check the global stability for which a relatively vague subdivision of plane stresses and plates in a grid is sufficient.

2.1 Comparison among the three models

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 figure 2 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= 3.10**kN/m**2. The thickness amount 50cm.

The calculation with the program GEMAS was carried out with 3×(5X10) 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.

Evaluation of the results:

The results of the calculations with diverse variations of modeling are summarized in figure 2. The results of the three different methods have only minor deviations.

2.2 Comparison between the static and dynamic models

Description of variations of modeling:

In the following, the models are discreted with elements of beam, plane and volume. On the basis of static displacement comparison, of section forces and of natural frequencies the influence of modeling variations on these condition's value is determined.

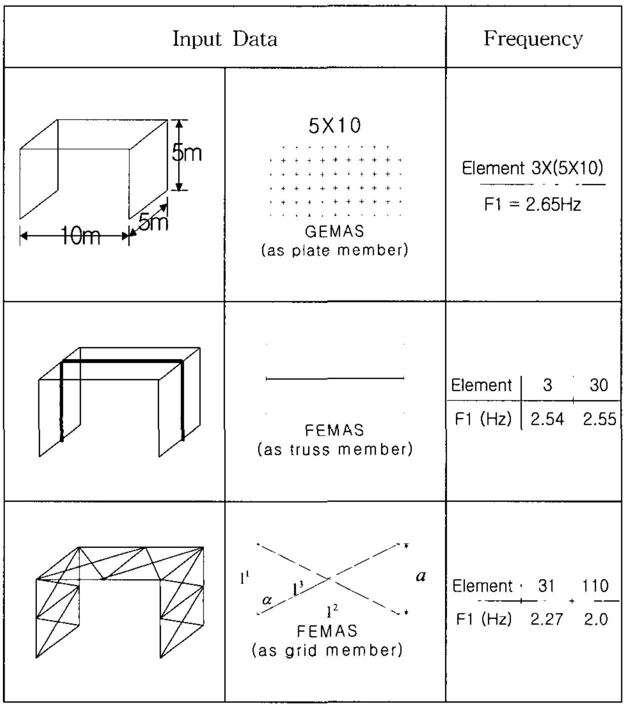


Figure 2 The dynamic frequency of the diverse elements

The models of bar structures were discreted with 3×10=30 elements. Stems and plane model have 2×10=20 perelement for the model of section. The element's volume model consists of 2X(4×10)=80 elements in both stems and 4×10=40 elements.

The results for the first four eigen-frequencies and the figure 3 and 4.

Evaluation of the results:

Identical stress values are the results for all three variations of modeling.

Ascertained displacements in the middle of the beam match likewise.

Deviations in the value of eigen-frequencies can also be ignored.

Conclusion:

All variations of modeling are qualified to depict static and dynamic behavior of elastic structure of frames.

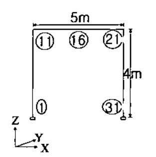
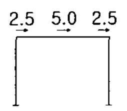
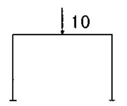
FEMAS	Static Displacement[m] (Node 16)	Dynamic Frequency	
		Hz	%
	x / z: Case 1: 0.081, 0.00; Case 2: 0.00, 0.024	f_1=2.89 f_2=3.62 f_3=6.62 f_4=9.25	x=78.31 y=73.07 --- z=27.33
GEMAS1D	**Static Displacement[m] (Node 16)**	**Dynamic Frequency**	
		Hz	%
 Case 1  Case2	x / z: Case 1: 0.080, 0.00; Case 2: 0.00, 0.024	f_1=2.90 f_2=3.63 f_3=6.68 f_4=9.33	x=78.81 y=73.57 --- z=27.51

Figure 3 Static displacements and dynamic frequencies

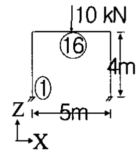
3. DYNAMIC ANALYSIS METHODS FOR BUILDINGS

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:

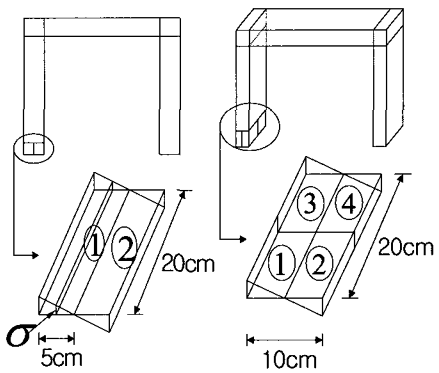
$$[M]\cdot\{\ddot{U}(t)\}+[C]\cdot\{\dot{U}(t)\}+[K]\cdot\{U(t)\}=\{F(t)\} \qquad (3)$$

where, [M]=mass matrix, [C]=damping matrix, [K]=stiffness matrix, {U}=nodal displacements vector and {F(t)}=earthquake load vector.

In the time domain, Eq. (1) is traditionally solved either by direct integration or modal analyses.[4),7)] In the direct integrations method, the equations of motion are integrated directly, without any prior transformation. For a modal analysis, an eigenvalue problem

FEMAS GEMAS1D		N[kN], K-①	Q[kN], K-①	M[kNm], node①
	Theory	5.0	1.674	2.232
	FEMAS	5.0	1.674	2.231
	GEMAS1D	5.0	1.675	2.233

GEMAS 2D and GEMAS 3D



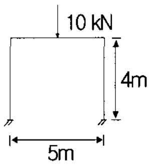
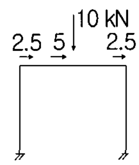
	Theory	$0.31=\frac{-5}{10\times20}+\frac{223.2}{1666.6}\times2.5$
	GEMAS2D	0.310
	GEMAS3D	0.312
	Theory	$2.0=\frac{-5}{10\times20}+\frac{1395.6}{1666.6}\times2.5$
	GEMAS2D	1.999
	GEMAS3D	1.999

Figure 4 Static section forces

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 effort. 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 figure 5.

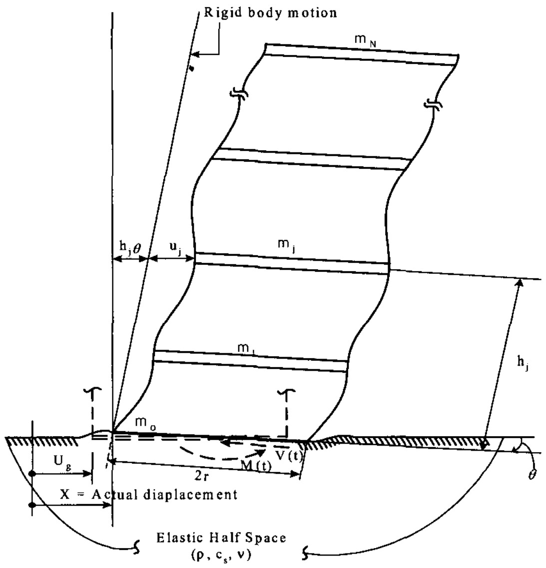


Figure 5 Idealized building-foundation system

The force-displacement relation is also represented in coupling Eq. (4):

$$\begin{bmatrix} V(t) \\ M(t) \end{bmatrix} = \begin{bmatrix} K_{rr} & K_{r\theta} \\ K_{\theta r} & K_{\theta\theta} \end{bmatrix} \begin{bmatrix} X(t) \\ \theta(t) \end{bmatrix} \tag{4}$$

where,

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

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

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

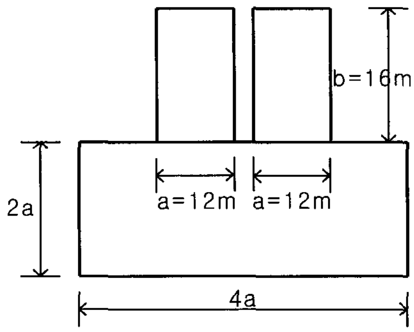
ν = Poisson's ratio for half space material

Programs FEMAS and GEMAS employ modal analysis to solve the equations of motion.

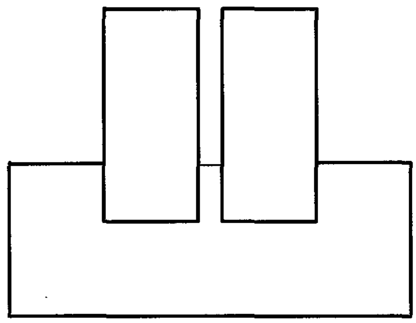
The finite element method is a numerical procedure by means of which the actual continuum is represented by an assemblage of elements interconnected at a finite number of nodal points. Details of formulation of the general method are available in the literature.[4]

4. INTRODUCTORY STUDIES

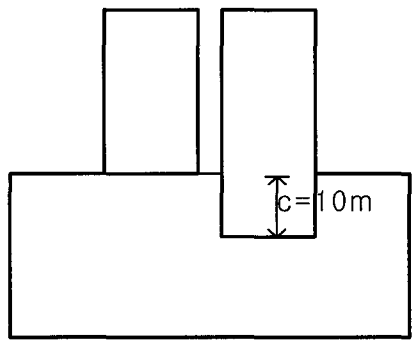
The cases studied herein are shown schematically in figure 6, indicating the three different foundation configurations. The case of two buildings on shallow foundations(Fig. 6a) was analyzed using the three different models as shown in Figure 7.



a) Shallow-shallow (SS)



b) Deep-deep (DD)



c) Shallow-deep (SD)

Figure 6 The different foundation arrangements

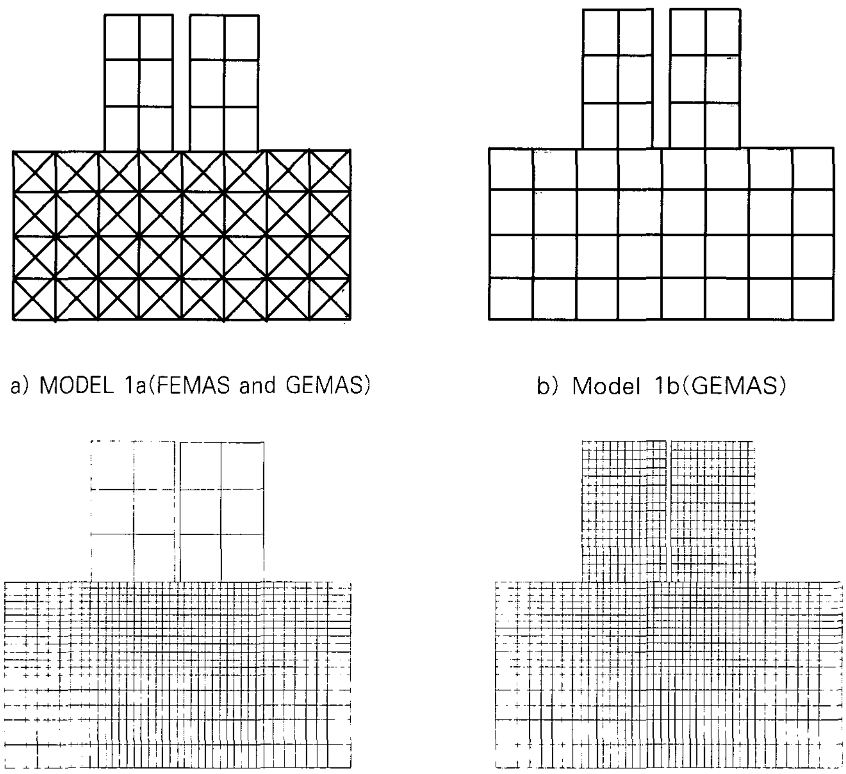
Model 1a employs one-dimensional frame elements to represent both the building frames and the soil structure below, by arranging bars in a grid-like foundation, figure 7a). The dimensions of the soil foundation included in the model were selected as 4a, 2a, b, and c, where a is the width one building, b is the height of the building and c is the depth of the building, figure 6. This model was analyzed by the frame analysis program FEMAS[5] as well as by the finite element program GEMAS.[6] Model 1b employs the same one-dimensional frame elements as model 1a to represent the building. The soil foundation, however, is modeled 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 is lateral load resisting elements was simulated by an equivalent structural wall.[10] Model 1b, 1c, and 2 were analyzed by program GEMAS.

The following preliminary analyses 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 variation of model 1, this time includes the effect of the soil.

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



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

Figure 7 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 indicates the contributions of the lowest modes 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.

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

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.

5. FRAME ANALYSIS RESULTS

Program FEMAS was used to analyze model 1a), for the three different foundation configurations shallow-shallow(SS), deep-deep(DD), and shallow-deep system(SD). The frequencies of the first three lateral modes of deformation are plotted in figure 8. 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.

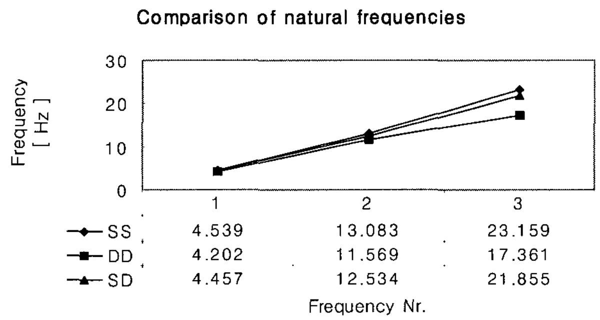


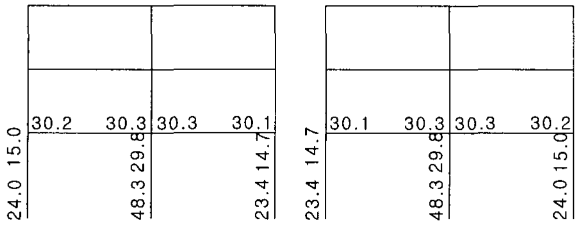
Figure 8 Comparison of natural frequencies of frame models

The bending moments in the beams and columns of the first story are summarized in figure 9. for all three foundation configurations. As can be seen, symmetry is maintained in that moments in the two neighboring buildings are identical in cases 1 and 2.

Comparing cases SS and DD, 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 37%) than in the beams (up to 19%).

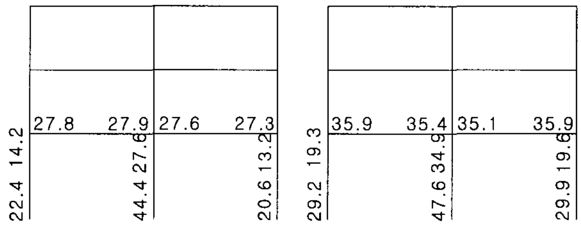
By comparing the moments in the building with one or two shallow foundations(cases SS and SD), it is observed that lowering the foundation of the neighboring building reduces building moments consistently, from 5.3% to 12%.

Finally, a comparison of the moments in the buildings with at least one deep foundation(cases DD and SD), shows that the lower



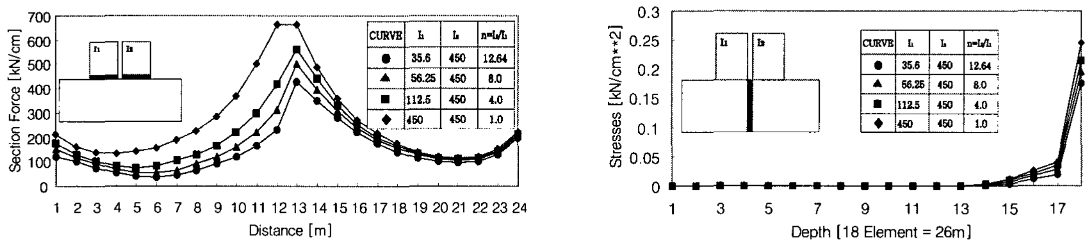
a) Case 1: Shallow-shallow system (SS)

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



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

Figure 9 Bending moments of first-story frame element, model 1



a) Horizontal section force of building (n_{11}) b) Stresses of vertical ground section

Figure 10 The section forces of buildings and the stresses of the ground

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.

6. PLANE STRESS ANALYSIS RESULTS

Program GEMAS was used to analyze model 2(Fig. 7d), 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(n11) and the stresses of vertical section of the ground(s11) are presented in figure 10.

This figure 10a) 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 figure 10b) 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 inertia of building 1 to that of building 2, has an influence on the section forces, as well as the modulus of elas-

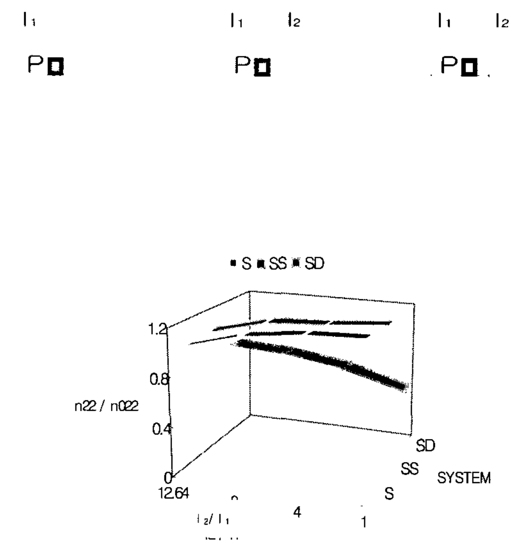


Figure 11 Normalized section forces at the exterior base point depending on the I_2/I_1 ratio (shallow-shallow system and shallow-deep system)

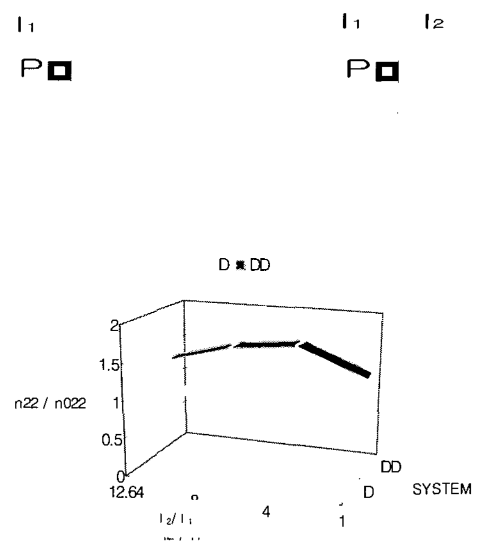


Figure 12 Normalized section forces at the exterior base point depending on the I_2/I_1 ratio (deep system and deep-deep system)

ticity 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 $I_1 = 35.6m^4$. The tendencies are displayed in the following figure 11.

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		
			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

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 figure 12 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.

Table 4 Normalized section forces at the exterior base point depending on the I_2/I_1 ratio (deep system and deep-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

As the result, Figs. 11, 12 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.

7. CONCLUSION

This paper deals with the earthquake response of buildings founded at different depths. The computations done with the frame model show that the bending moments of beam and columns differ. As the result, the greatest differences between building 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.

The analysis of the interaction of neighbouring buildings with three different plane models yielded the following conclusions.

If both buildings have shallow foundations, the interaction is small and negligible. 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. If one building is shallow and the other one deep, then the interaction renders the forces in one building 20% smaller than those in a single shallow building. Implying that in the second case, the weaker building has to be reinforced.

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