

Earthquake Response of Two Adjacent Buildings Founded at Different Depths

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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 elements, whereas the soil behavior is simulated 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.

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.^(1,2,3) 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 will its presence effect the seismic response of the existing building in the three scenarios depicted in figure 2.

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In the first case, both buildings are supported on a shallow foundation, In the second case, both buildings have deep foundations. In the last case, one building 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.

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 a 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(Finite Element Method for Static and Dynamic Analysis of Structures)⁽⁵⁾, both the building and the supporting soil structure are modeled with frame elements. The soil is assumed to consist of granular material. In program GEMAS(Mixed Element Method for the Analysis of Shell Structures)⁽⁶⁾, both the building and the soil are represented by plane stress or plain 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 3 a) 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. This study was performed to support the planning of a specific hospital structure in Germany.

2. 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:

$$[M] \cdot \{ \ddot{U}(t) \} + [C] \cdot \{ \dot{U}(t) \} + [K] \cdot \{ U(t) \} = \{ F(t) \} \quad (1)$$

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 analysis.^(4,7) In the direct integration method, the equations of motion are integrated directly, without any prior transformation. For a modal 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 equations 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 1.

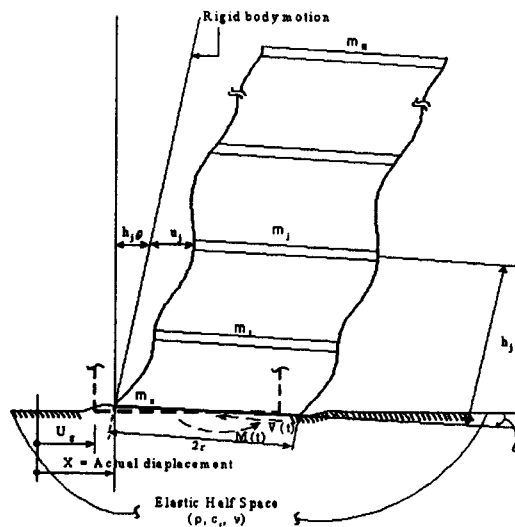


Figure 1. Idealized building-foundation system

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 displacements

K_x , 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⁾

3. INTRODUCTORY STUDIES

The cases studied herein are shown schematically in figure 2, indicating the three different foundation configurations. The case of two buildings on shallow foundations (Fig. 2a)) was analyzed using the three different models as shown in figure 3.

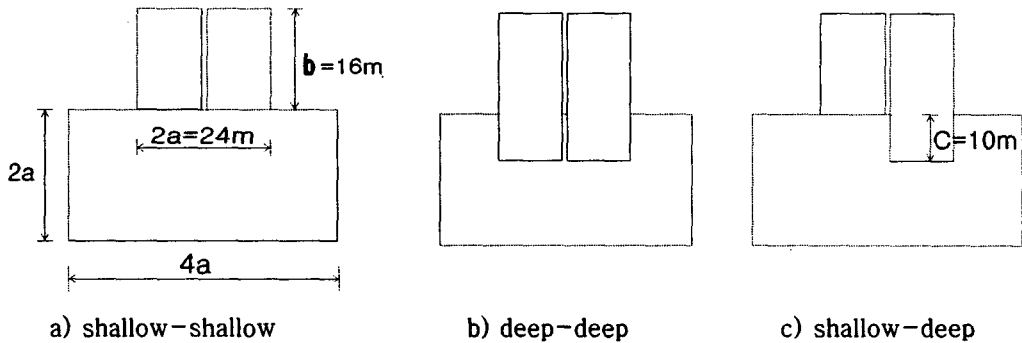


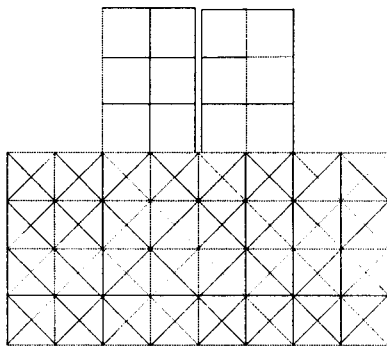
Figure 2. The different foundation arrangements

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 3 a). 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 2. 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 $4 \times 8 = 32$ plane strain elements. Model 1c is identical to model 1b, except that the soil is represented by a fine mesh of $18 \times 38 = 684$ plane strain elements.

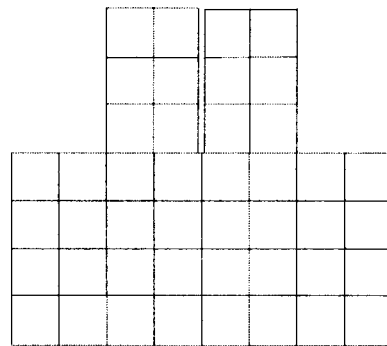
In model 2, the buildings are represented by $12 \times 16 = 192$ plane strain elements and the soil by $18 \times 38 = 684$ plain strain elements. The floor masses were lumped as usual at the floor levels. To obtain the thickness of the plane stress elements, the combined stiffness of the building is lateral load resisting elements was simulated by an equivalent structural wall.⁽⁹⁾ Models 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.

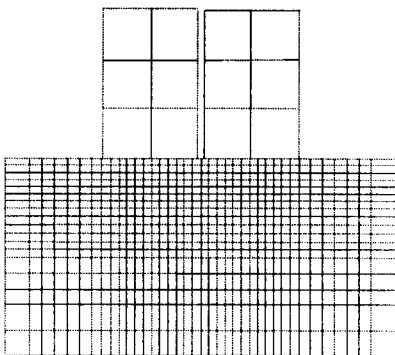
Next, an eigenvalue analysis provided the mode shapes and frequencies, again without the influence of the soil. Then, a time history analysis of the building subjected to the acceleration record of the El Centro earthquake was carried out using the normal mode method. After a careful examination of the 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.



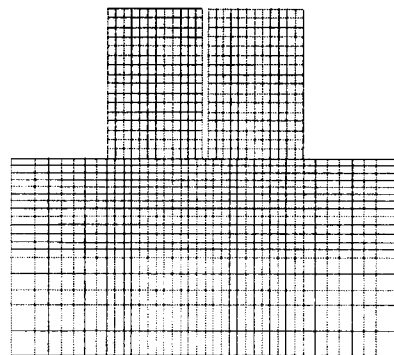
a) MODEL 1a
(FEMAS and GEMAS)



b) Model 1b
(GEMAS)



c) Model 1c
(GEMAS)



d) MODEL 2
(GEMAS)

Figure 3. Analysis models

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

Table 1. The first 5 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	97.0	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.

4. FRAME ANALYSIS RESULTS

Program FEMAS was used to analyze model 1 a), 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 4. 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.

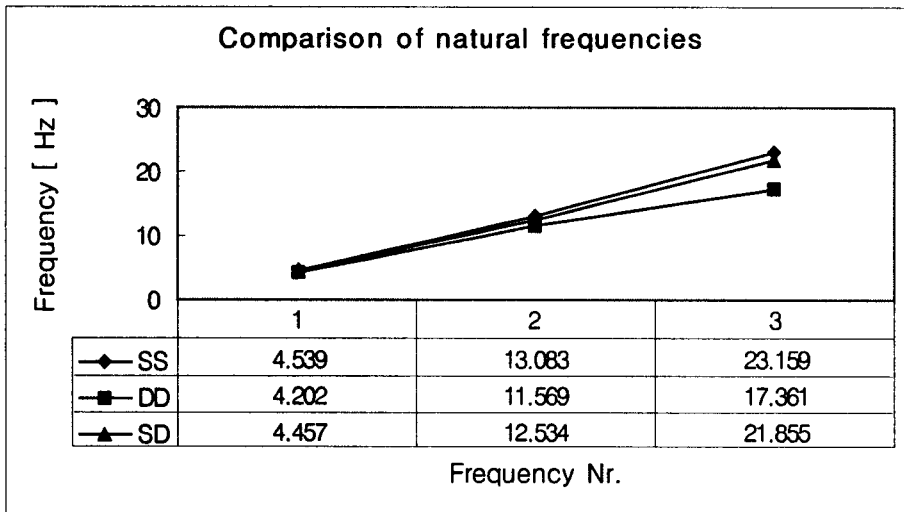
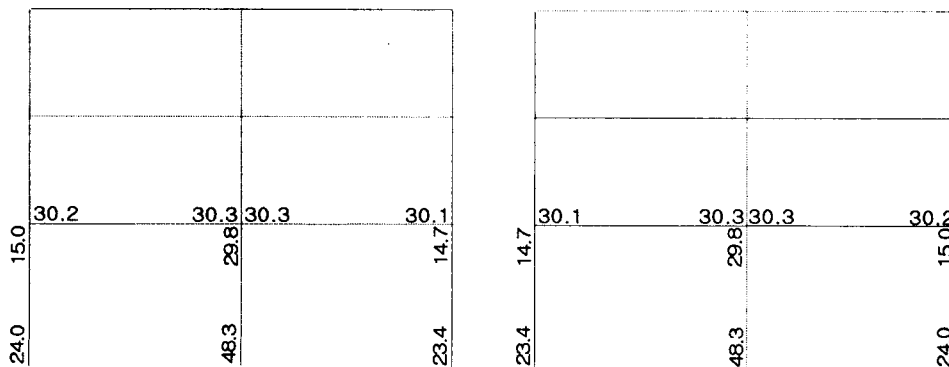
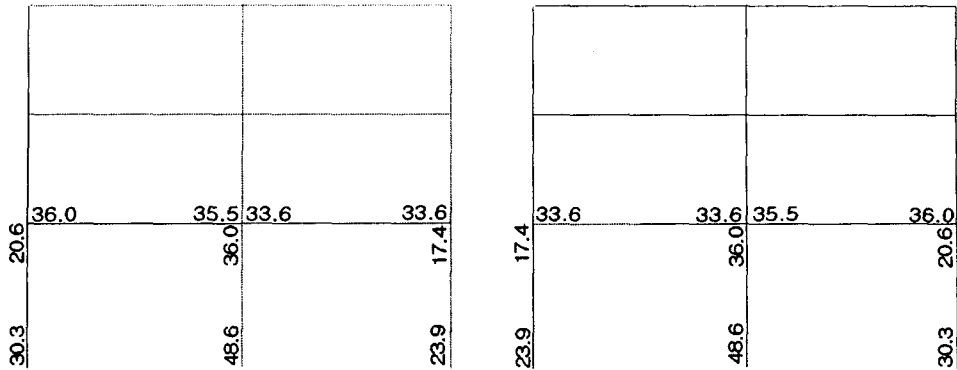


Figure 4. Comparison of natural frequencies of frame models

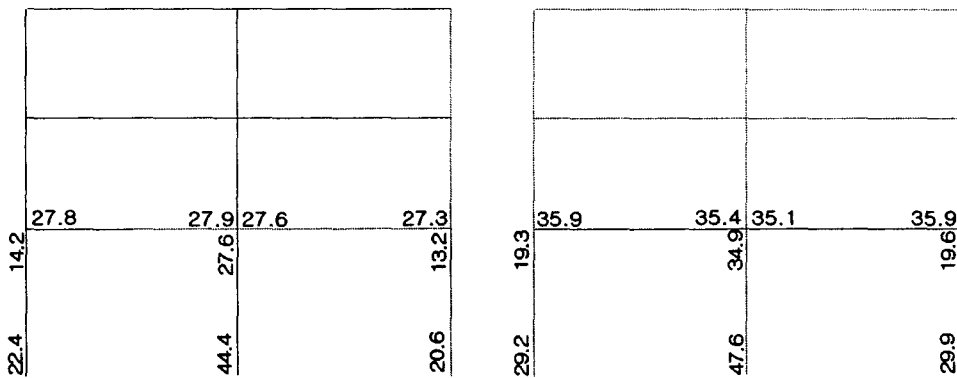
The bending moments in the beams and columns of the first story are summarized in figure 5 for all three foundation configurations. As can be seen, symmetry is maintained in that moments in the two neighboring buildings are identical in cases 1 and 2.



a) Case 1: Shallow-Shallow System (SS)



b) Case 2: Deep-Deep System (DD)



c) Case 3: Shallow-Deep System (SD)

Figure 5: Bending moments of first-story frame element, model 1

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 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 (figure 2d), in which two building was 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 6.

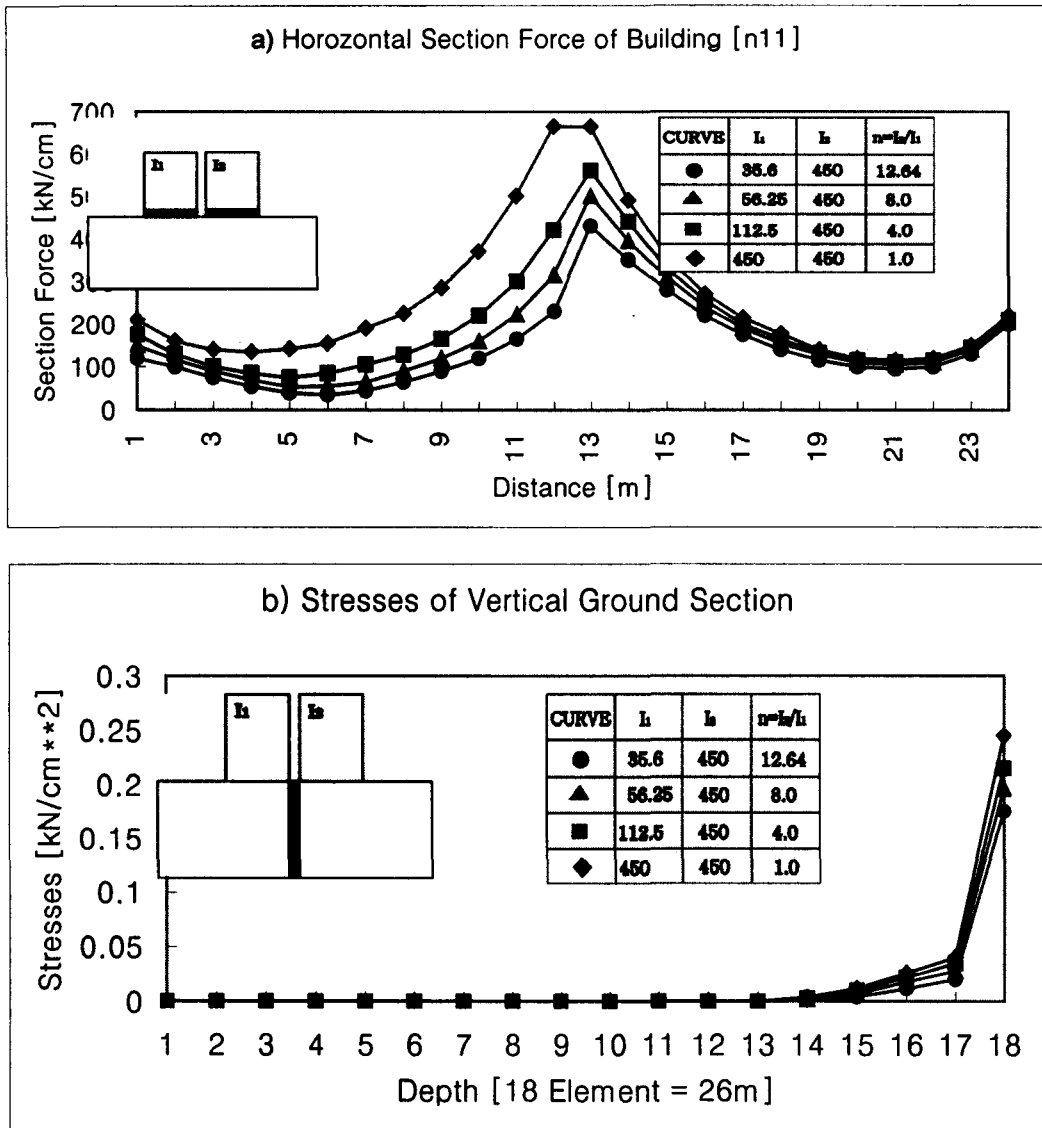
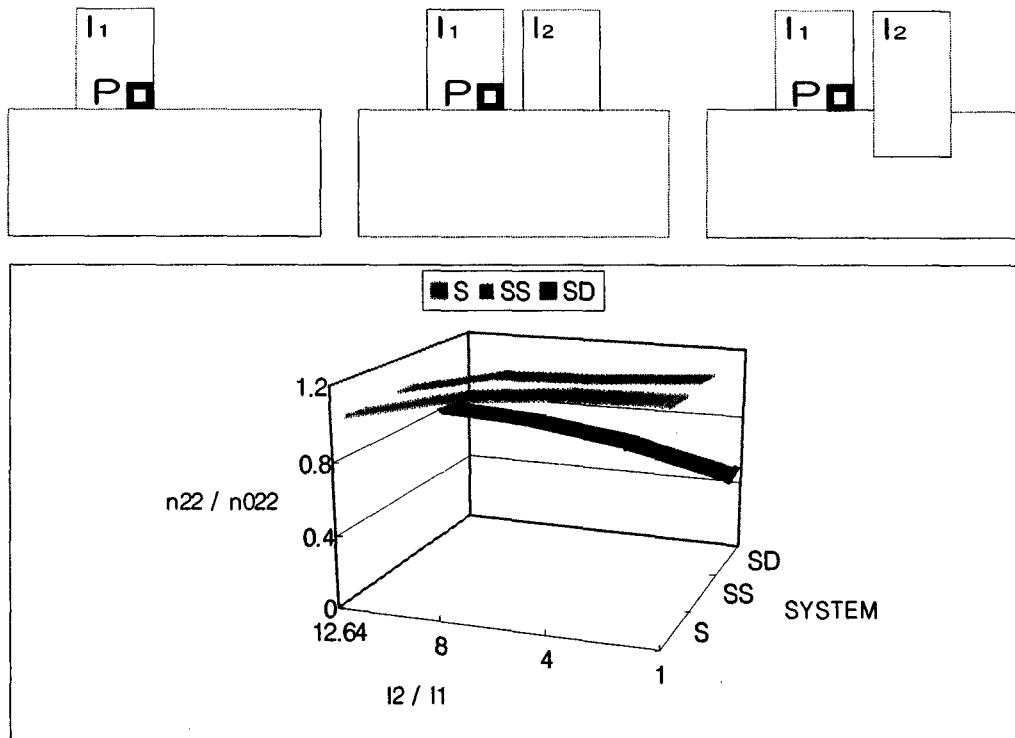


Figure 6: The section forces of buildings and the stresses of the ground

This figure 6a) 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 6b) shows the vertical stresses of ground in shallow-shallow system. That shows a sudden increase of stresses in the highest element.

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 elasticity of the soil. The following table 3 show the computed section forces n22 at the outermost right base

point P of the buildings normalized against the corresponding value n_{022} computed with $I_1 = 35.6 \text{ m}^4$. The tendencies are displayed in the following figure 7.



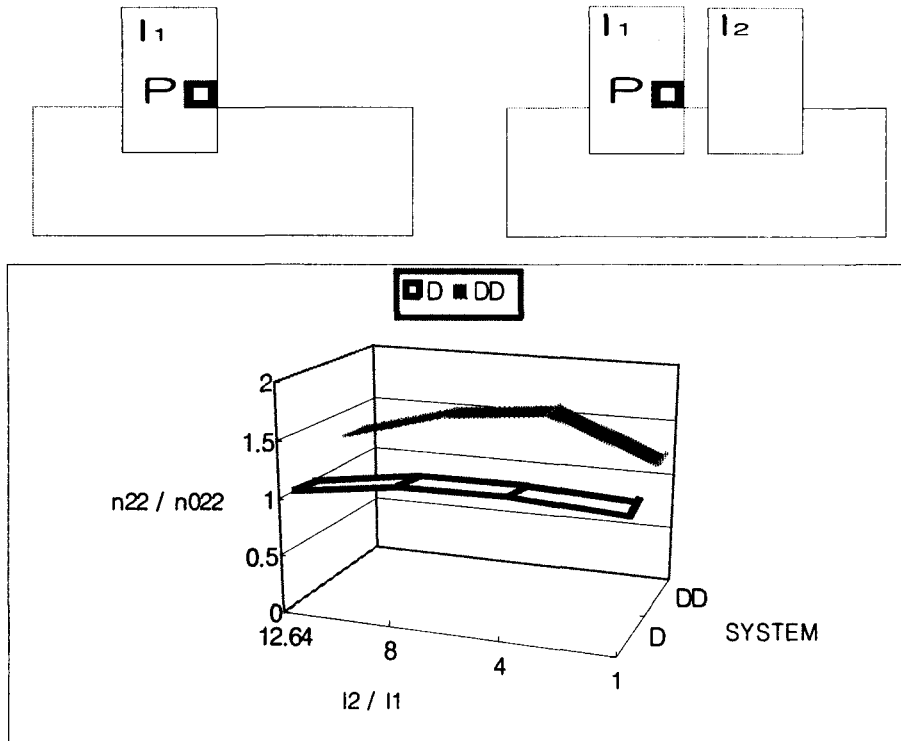
Nr.	I1	n = I2/I1	n22 / n022		
			S	SS	SD
1	35.60	12.64	1.000	1.017	0.781
2	56.25	8.0	1.133	1.141	0.746
3	112.50	6.0	1.187	1.159	0.662
4	450.00	1.0	1.201	1.199	0.513

Figure 7. Table 3.: Normalized section forces at the exterior base point depending on the I_2/I_1 ratio (shallow system, shallow-shallow system and shallow-deep system)

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 8 and table 4 shows 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.



Nr.	I1	n = I2/I1	n22 / n022	
			D	DD
1	35.60	12.64	1.000	1.267
2	56.25	8.0	1.127	1.528
3	112.50	6.0	1.134	1.620
4	450.00	1.0	1.076	1.244

Figure 8. Table 4.: Normalized section forces at the exterior base point depending on the I2/I1 ratio (deep system and deep-deep system)

As the result, figure 7, 8 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. CONCLUSION

This paper deal 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 stress 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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