기초지반고가 상이한 지반-구조물-구조물의 상호작용에 의한 지진응답 해석연구

Study of Soil-Structure-Structure Interaction on Earthquake Response with Different Foundation Arrangement

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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 three different models. In the first and second cases the building itself is modeled with standard frame and equivalent bar element, whereas the soil behavior is stimulated by a special grid model. In the third 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 developed based on the axisymmetric fine element method in corporation of rough 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-structure interaction, grid model, wave input technique, earthquake response

요 지

본 연구에서는 이웃한 빌딩의 기초가 서로 상이한 경우 상호작용에 대한 지진응답을 해석하였다. 구조물과 지반은 각기 세 가지 모델에 대하여 연구하였다. 즉 첫째와 둘째 모델의 경우에는 빌딩은 프레임모델과 bar모델로 지반은 그리드모델로 설정하였고, 셋째 모델의 경우에는 구조물과 지반을 평면응력과 평면변형율로 모델화하였으며 구조물에 대한 상대적인 관성모멘트는 지반의 탄성모듈과 함께 구조물의 단면력에 영향을 미치므로 함께 고려되었다. 근사해석으로는 유한요소기법을 사용하였고 지진파입력기법과 Transit조건 등을 적용하여 제시된 예들을 통하여 지반과 구조물-구조물의 상호작용 안전성을 논증하였다.

핵심용어 : 지반-구조물-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-structure interaction itself depends on many different variables, as described in the literature(Bachmann, 1995; Kramer, 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 consid-

ered. 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 will effect the seismic response of the existing building in the three scenarios can be depicted in Fig. 4 and 8.

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

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Numerical results will be presented for the three different scenarios outlined (DIN 4149, 1981) in Fig. 4 and 8, 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.

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 = $\sqrt{G/\rho}$

ν = poisson'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 antwort spectrum 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 with the grid method in simple and combined form are assembled in Fig. 2.

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 reinforced concrete and their resiliency is $E_c=3.0 \times 10^7$ kN/m². The thickness amounts 50cm. The calculation with the program GEMAS was carried out with $3 \times (5 \times 10)$ elements. For the calculation for the structure of bars

Plane element, $\nu = 1/3$

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

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

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.

one element was used per column and one per 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. 4a) was analyzed 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. 5a). 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 as well as by the finite element program GEMAS. 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 stress elements and the soil by $18 \times 38 = 684$ plane strain

Fig. 4. The Different Foundation Arrangements.

Fig. 5. Analysis Models 1 and 2.

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; Seed *et al.*, 1976). 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 the 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.

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

Table 1. The First Frequencies of Model 1 With Soil Effect

Mode	Component	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	Component	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

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 sys-

Fig. 6. Comparison of Natural Frequencies of Frame Models.

tem(SS), deep-deep system(DD), and shallow-deep system(SD). The frequencies of the first three lateral modes of deformation are plotted in Fig. 6. As expected, case 2 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 the 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 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 reduced building moments consis-

tently, 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%(the second building's left down part of the column), while bending moments in the other columns and beams are changed by relatively small amounts.

5. Equivalent Bar Analysis Results

Two Buildings with different foundation levels and the same foundation levels are represented by the equivalent bar model. The buildings are modelled with beam elements. the ground is simulated according to the model of the grating method. Program FEMAS was used to analyze bar model 3, for the three different foundation configurations shallow-shallow system (SS), deep-deep system(DD), and shallow-deep system(SD).

a) Shallow-shallow system (SS) b) Deep-deep system (DD)
C) Shallow-deep system (SD)

The first 5 frequencies for each of the 3 cases including the soil effect are summarized in Table 3. 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 columns of building 1 and 2 are summarized in Table 4. Related to the Shallow-shallow system and Deep-deep system, the bending moment of building 1 and 2 are equal in all stories respectively. In the Shallow-deep system, the bending moments in the columns of building 2 are about 11% greater than those of building 1.

Fig. 7. Bending Moments of First-story Frame Element, Model 1.

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

Fig. 8. Analysis of Equivalent Bar Models 3.

Table 3. The First Frequencies of Model 3 with Soil Effect

Frequency Nr.	Analysis Bar Model		
	Shallow-shallow system (SS)	Deep-deep system (DD)	Shallow-deep system (SD)
1	2.587	2.312	2.331
2	2.595	2.333	2.588
3	13.966	12.131	12.956
4	14.249	13.176	14.005
5	31.085	16.951	20.567

6. Plane Stress Analysis Results

Program GEMAS was used to analyze model 2 (Fig. 5d), 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. 9.

This Fig. 9a) shows the horizontal section force of the buildings in shallow-shallow system. The ratio of inertia moment

Table 4. Bending Moments of Each Story Equivalent Bar Model

System	Shallow-shallow system (SS)			Deep-deep system (DD)			Shallow-deep system (SD)		
Building	Element Number	Node	Moment [kNm]	Element Number	Node	Moment [kNm]	Element Number	Node	Moment [kNm]
B 1	1	1	98.772	3	3	105.289	1	1	98.837
		2	55.285		4	59.169		2	55.346
	2	2	55.285	4	4	59.169	2	2	55.346
		3	19.352		5	26.299		3	20.364
	3	3	19.352	5	5	26.299	3	3	20.364
		4	0.000		6	0.000		4	0.000
B 2	4	5	98.772	8	9	105.291	6	7	103.759
		6	55.285		10	59.184		8	57.866
	5	6	55.285	9	10	59.184	7	8	57.866
		7	19.352		11	26.338		9	22.544
	6	7	19.352	10	11	26.338	8	9	22.544
		8	0.000		12	0.000		10	0.000

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

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

Fig. 9. The Section Forces of Buildings and the Stresses of the Ground

Nr.	1	n= 2/ 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	4.0	1.187	1.159	0.662
4	450.00	1.0	1.201	1.199	0.513

Fig. 10. & Table 5. Normalized Section Forces at the Exterior Base Point Depending on the $|2/|1$ Ratio (shallow-shallow system and shallow-deep system).

changes, i.e., the section forces increase with an increasing of the moment of inertia. The Fig. 9b) 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 elasticity of the soil. The following Table 5 shows the computed section forces n_{22} 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 Fig. 10.

The shallow system shows that the section forces in increasing moment of inertia 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. 11 and Table 6 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 the result, Figs. 10, 11 show that the influence of the interaction on a neighbouring building seems to be little in

Nr.	1	n= 2/ 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	4.0	1.134	1.620
4	450.00	1.0	1.076	1.234

Fig. 11. & Table 6. Normalized Section Forces at the Exterior Base Point Depending on the $|2/|1$ Ratio (deep system and deep-deep system).

shallow-shallow system, even weak in shallow-deep system and strong in deep-deep system.

7. Conclusion

This paper deal with the earthquake response of buildings founded at different depths. The computations done with the frame model and the equivalent bar 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, and it also reveals that the section forces with no modification of material are greater than those ones having modification of material.

A building sits 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 section forces in one building are 25% larger than those in a single deep building. Third, if the foundation of

one building is shallow and the other one deep, then due to interaction the section 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.
- 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.
- Cai, Y.X. *et al.* (1997) Numerical Implementation of a 3-D Non-linear Seismic S-P-S-IMethodology, Seismic Analysis and Design for Soil-Pile-Structure Interactions, *Geotechnical Special Publication* No.70, ASCE.
- Chopra Anil K. (2010) *Dynamics of structures: Theory and applications earthquake engineering*, Prentice-Hall, Inc..
- DIN 4149. Section 1. (1981) Construction in german earthquake areas. Load case, design, construction practice of regular structures.
- 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.
- Makris, N. and Chang, S.P. (2000) Effect of viscous, viscoplastic and friction damping on the response of seismic isolated structures, *Earthquake Engineering and Structural Dynamics*, Vol. 29, No. 1, pp. 85-107.
- Roeset, J.M. (1980) *A Review of Soil-Structure Interaction*, Lawrence Livermore Laboratory, June, p. 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, p. 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, p. 466.

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