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EFFECTS OF SOIL-STRUCTURE INTERACTION ON DESIGN OF REINFORCED CONCRETE STRUCTURES FOR VARIOUS EARTHQUAKE ZONE

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ABSTRACT: In the design of reinforced concrete structures, soil-structure interaction is usually neglected considering the subsoil as a rigid base. Therefore the design process is based on the assumption that the columns at the bottom of the structure are connected to the base rigidly. However, the subsoil is a medium that deforms under load of the structure, exposed to stress and generates a reaction against the effects encountered. In this study, the effect of soil-structure interaction on design of reinforced concrete structures is investigated. The effect of subsoil under the structure to the behavior of the structure is investigated using Winkler and Modified Vlasov Model in addition to rigid base assumption. An interface is developed by the authors to use SAP2000 software and MATLAB simultaneously for the analysis so that SAP2000 software gains the ability of the analysis of mat foundation by using Modified Vlasov model. It is observed that soil-structure interaction has a significant effect on the design of reinforced concrete structures.

1. INTRODUCTION

Soil mechanic is one of the most complicated subjects of civil engineering discipline. Soil-structure interaction is important for almost every construction project such as nuclear reactor, industrial structures and multi-storey building. The analytical model of the structure becomes more realistic if soil effect in the design of an engineering structure is considered. The reliability of structural design depends on how the soil structure interaction is modeled accurately and realistically. The columns at the base are usually considered as fixed in the design neglecting the soil effect which exposes to the stresses transferred from the superstructure and which creates the reaction against these stresses. Soil effects are only taken into account in the design of foundation. The design of any superstructure ignoring the effect of subsoil underneath can be considered as an incomplete design. The soil-structure interaction can be incorporated using Winkler modelin which soil structure is represented by infinitely close springs. However, in the Winkler model being the simplest of the foundation models, the interaction between the springs are ignored and therefore the shear deformation of the subsoil is neglected. More accurate and more realistic representation of the soil-structure interaction models are crucial for a reliable design of an engineering structure. Modulus of subgrade reaction has to be given as an input data in the commercial packages since the Winkler model is used because of its simplicity. It is necessary to know the stresses and displacements at sub-base course in order to calculate this coefficient. Therefore, it is difficult to determine the modulus of subgrade reaction since it depends on various features of the soil and superstructure, foundation system and soil properties. More realistic and more reliable soil models have been investigated in recent years.

Vlasov and Leontiev (1966), adopted the simplified–continuum approach based on the variationally principle and derived a two-parameter foundation model. Kahraman vd. (2007) have investigated that 4 storey moment frame structural models with a mat foundation are analyzed which have various definitions of subgrade reactions under lateral and gravity loading. Karabörk (2009) has researched that the structure models with 3, 6, 10 stories which have the same plan and rigidity are formed. Behaviors of these models are examined for two different soils, namely soft and hard soils under the effect of three different earthquakes. Korkmaz and Demir (2012) have studied that how the soil types and properties effect the structural behavior was investigated. To investigate the effects of soil properties, nonlinear spring models were used and the model were compared to each other. Hamarat vd. (2012) studied a structural system composed of a 3-D frame superstructure and a mat foundation resting on a two-parameter elastic subsoil. The seismic behavior of the system is evaluated in the study using finite elements. Thangaraj and Ilamparuthi (2012) have considered a framed structure supported on a mat foundation system to evaluate in the influence of thickness of mat and nonlinear behavior of the soil on forces and deformation of the frame. Derdiman (2013) has investigated the effects of soils with different young's modulus on high rise building according. Frydrysek vd. (2013) have analyzed beams, frames and 3D structures resting on Winkler type elastic foundation using FEM. Ionescu vd. (2013) have studied on implementation of Boussinesq method in seism analysis of a 3D building in order to simulate the elastic foundation using ANSYS. Ahmed vd. (2014) have carried out 3D interaction analysis of building having piled-raft foundation in two layered non-cohesive soil medium using PLAXIS 3D foundation code. Avcıoğlu and Orakdöğen (2015) have showed that using the computer code which is developed for time history analysis of structures on Vlasov foundation in their study, necessary soil parameters may be updated between the time intervals and more realistic results may be obtained.

In this study, the behavior of reinforced concrete structures on elastic foundation is investigated by using the modified Vlasov model. In this way, an interface developed in Matlab was used simultaneously with Sap2000 v.15 package program. The Sap2000 program has been given the ability to solve with the Modified Vlasov method which does not exist in itself. An 8-storey building was analyzed and results are compared for three different cases of support conditions. The soil parameters, natural vibration periods, column axial forces, column bending moments and longitudinal reinforcement ratios of the columns for various earthquake zones are presented cooperatively in figures and tables.

2. MODIFIED VLASOV MODEL

Subsoil reaction of a structure resting on elastic foundation is given by

$$q_z = kw - 2t\nabla^2 w \tag{1}$$

where w is the displacement of subsoil surface, k is modulus of subgrade reaction and $2t$ is the soil shear parameter as defined below

$$k = \int_0^{H_s} \frac{E_s(1-\nu_s)}{(1+\nu_s)(1-2\nu_s)} \left(\frac{\partial \phi(z)}{\partial z}\right)^2 dz \tag{2}$$

$$2t = \int_0^{H_s} G_s \phi(z)^2 \, dz \tag{3}$$

in which E_s, υ_s and G_s are modulus of elasticity, Poisson's ratio and shear modulus of subsoil respectively. $\phi(z)$ is mode shape function describing the variation of vertical displacement within the subsoil, and it can be expressed as

$$\phi(z) = \frac{\sinh \gamma \left(1 - \frac{z}{H_s}\right)}{\sinh \gamma} \tag{4}$$

where H_s is subsoil depth to rigid base, and γ is the third soil parameter and it can be evaluated as

$$\left(\frac{\gamma}{H_s}\right)^2 = \frac{(1-2\nu_s)}{2(1-\nu_s)} \frac{\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} (\nabla w)^2 \, dxdy}{\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} w^2 dxdy} \tag{5}$$

The values of mode shape function ϕ(z) in Eq.(4) are stipulated such that $\phi(0) = 1$ and $\phi(H_s) = 0$.

The important point here is that the modulus of subgrade reaction, *k*, and the soil shear parameter, *2t*, are both dependent on a mode shape function ϕ(z) and the depth of the subsoil, H_s, as can be seen in Eq.(2) and (3). Furthermore the third parameter of the soil, γ, describing the vertical deformation profile within the subsoil, varies with the subsoil surface displacement and the subsoil depth. Therefore, the solution of this complex soil-structure interaction problem can be performed using an iterative technique, (Vallabhan and Das, 1991). The third soil parameter, γ, is set to be equal to 1 to start iterations. Then the two soil parameters are determined to analyze the frames on elastic foundation. New value of γ is obtained by using soil surface displacements obtained after the analysis of the structure. The iteration is repeated until the latest and previous values of γ within a prescribed tolerance.

3. THE SOLUTION TECHNIQUE

SAP2000 V16 and other versions have OAPI (Open Application Programming Interface) feature to enable two way data exchange. By taking advantage of that a MATLAB interface is developed for calculating soil parameters iteratively. The model created in SAP2000 program is called using MATLAB interface and the soil parameters calculated by the program coded in MATLAB. New soil parameters are calculated using MATLAB code with the soil surface displacements obtained from SAP2000. This iterative process is repeated until the difference between soil surface parameters computed in two successive iterations converges to a predetermined value. Reliability and compatibility of this solution technique with the other studies in the literature is verified in the previous study, Kılıçer vd. (2014). The flowchart for the analysis of reinforced concrete structures resting on elastic foundation using modified Vlasov model is given in Fig. 1.

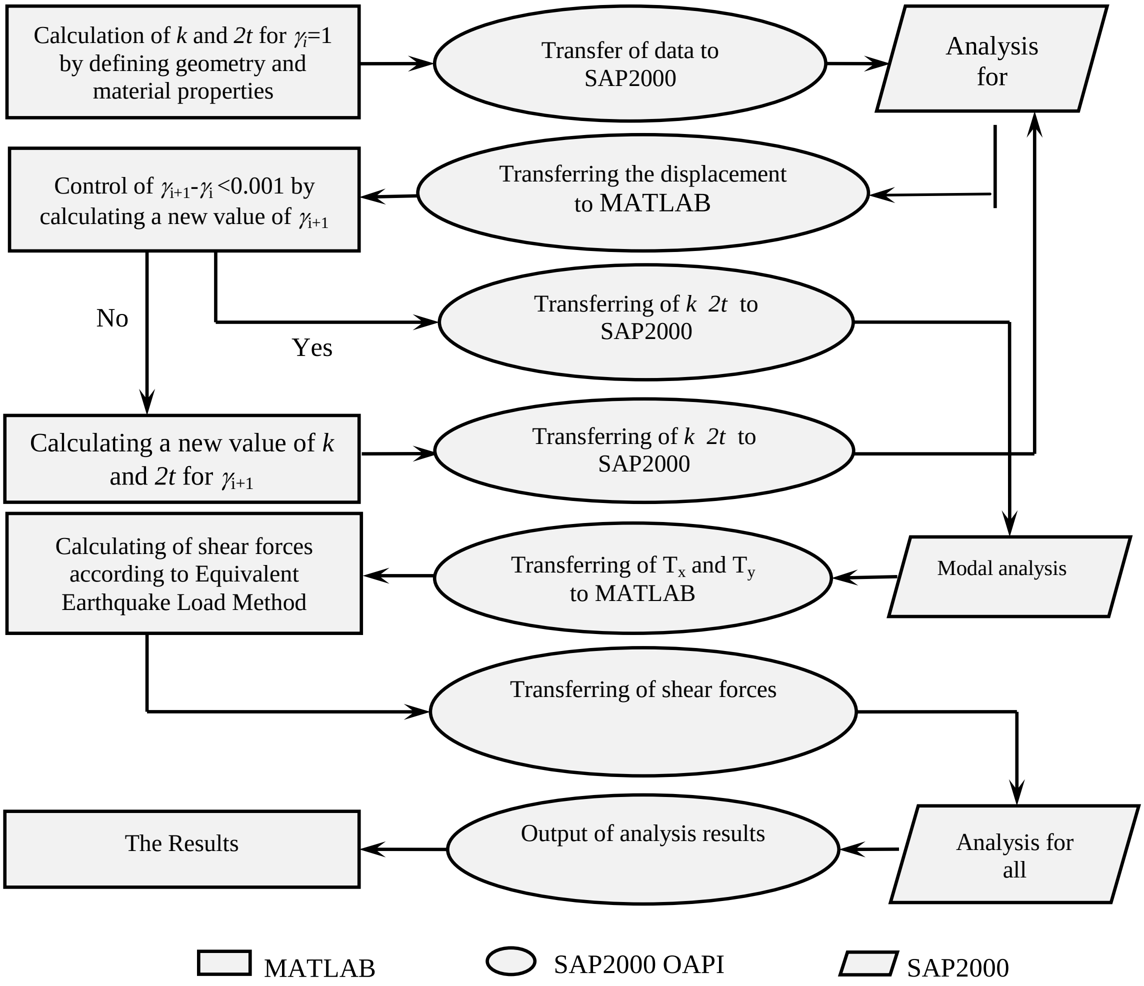

Figure 1. Flowchart for the analysis of reinforced concrete structures on elastic foundation using modified Vlasov model.

4. NUMERICAL EXAMPLE

An 8-storey rectangular building is selected for soil-structure interaction analysis. 4 different earthquake zones are considered in the study. Dimension of raft foundation is 19 m × 20 m. Raft thickness is 75cm. Height of each storey is 3.0 m. Elasticity modulus, Poisson's ratio and density of concrete are assumed as 28 GPa, 0.2 and 25 kN/m^3 respectively. Poisson's ratio and depth of soil are 0.25 and 10 m. Cross-sectional dimensions of structural elements are 50 × 50 cm^2 for columns, 30 × 60 cm^2 for beams and 30 × 225 cm^2 for shear walls. In this study, the soil type is selected as dense sand. An average is calculated and used from the values given by Bowles (1982) for elasticity modulus and subgrade reactions, E_s=65500 kN/m^2 and k=96000 kN/m^3 There are gas concrete walls with a thickness of 20 cm above all the beams. Density of gas concrete wall is 5 kN/m^3. All slabs subjected to uniform load of 2 kN/m^2 have 15 cm thickness. Equivalent Earthquake Load Method is used for earthquake analysis according to Turkish Earthquake Regulation. ±0.05 eccentricity and 1.4G+1.6Q, G+Q±Ex ve G+Q±Ey load combinations are taken into account for the analysis. The typical floor plan is shown in Fig. 2.

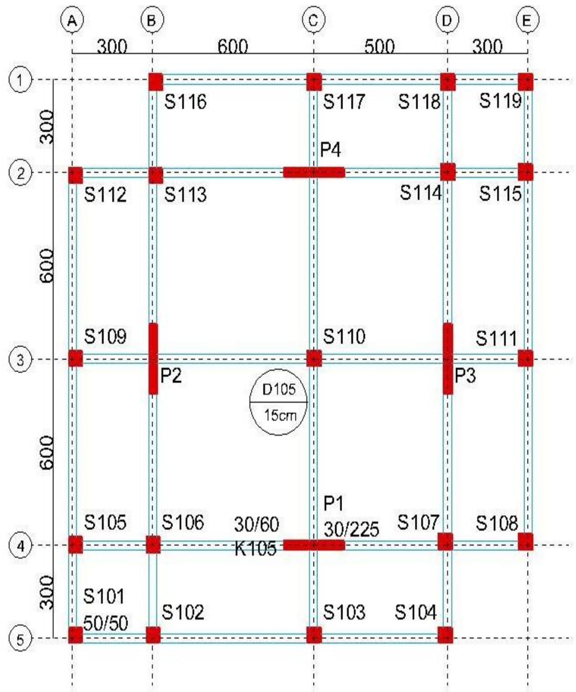

Figure 2. Typical floor plan of the structure

Natural vibration periods and base shear forces for various foundation models are given in Table 1. As seen from the table, first natural vibration period increases when the soil effect is included in the behavior, and the highest value is obtained in the case of modified Vlasov model. The effects of soil-structure interaction cause natural vibration periods to increase. Base shear force calculated according to equivalent earthquake force method decreases in modified Vlasov model because the first natural vibration period increases.

Table 1. Natural vibration period and base shear force of structure

Soil-Structure Models	T_{1x} **(sn)**	T_{1y} **(sn)**	V_{tx} **(kN)**	V_{ty} **(kN)**
Rigid base	0.7805	0.7615	6804.7880	6804.7880
Winkler Model	0.8556	0.8379	6804.7880	6804.7880
Modified Vlasov Model	0.9111	0.8952	6679.5630	6773.4370

Axial forces and bending moments in the columns at the bottom of 8-storey reinforced concrete structure are given for various subsoil models in Table 2. Usually, bending moments obtained by considering soil-structure interaction are greater than that of rigid base model. Longitudinal reinforcement ratio of columns is calculated reducing two dimensional combined bending to one dimensional combined bending in internal forces of Table 2. As shown in Fig. 3, changes in the internal forces also effects longitudinal reinforcement ratio of the columns. Greater longitudinal reinforcement ratio is required when the soil-structure interaction is taken into consideration.

Table 2. N-M values corresponding maximum column longitudinal reinforcement ratios

Number of columns	Rigid base			Winkler Model			Modified Vlasov Model		
	N **(kN)**	***M*x** **(kNm)**	***M*y** **(kNm)**	***N*** **(kN)**	***M*x** **(kNm)**	***M*y** **(kNm)**	***N*** **(kN)**	***M*x** **(kNm)**	***M*y** **(kNm)**
S101	686.17	29.96	283.36	517.18	40.97	320.83	377.97	46.61	273.29
S102	185.73	322.56	15.53	524.32	420.80	17.40	604.12	411.15	24.58
S103	912.25	309.13	0.68	920.59	494.25	3.40	964.05	502.55	37.42
S104	743.59	26.51	275.72	666.95	47.52	368.47	518.41	71.32	319.53
S105	164.14	16.12	324.94	504.37	20.14	424.15	597.29	21.08	409.61
S106	2092.58	316.42	24.61	1950.01	486.62	15.81	1806.89	456.35	27.57
S107	934.87	19.17	322.22	1061.60	35.49	481.28	933.85	4.68	506.57
S108	1320.23	16.94	271.48	1458.00	8.66	449.45	1671.82	63.05	495.36
S109	1187.29	1.69	305.31	1183.46	2.87	508.71	1206.14	33.88	537.68
S110	2342.10	3.64	283.78	2426.91	7.06	493.68	2403.18	18.45	517.37
S111	1165.81	1.54	303.89	1178.04	8.75	503.57	1225.10	48.57	531.94
S112	1349.00	17.29	272.69	1461.73	19.11	453.91	1646.65	40.97	502.08
S113	1071.78	321.79	17.28	1220.22	483.73	48.48	1087.40	521.26	19.48
S114	2013.88	23.29	316.94	1849.88	24.42	479.19	1667.53	39.62	440.39
S115	147.17	15.85	323.50	510.16	10.88	419.34	630.27	40.40	402.83
S116	1345.38	270.73	16.54	1470.96	448.39	15.20	1646.90	502.68	45.08
S117	861.49	309.06	2.03	920.69	490.49	12.92	1038.99	474.49	50.00
S118	325.38	325.67	15.10	603.59	428.13	16.59	654.29	406.93	25.25
S119	711.58	281.79	29.22	531.59	318.47	42.35	346.42	261.25	47.48

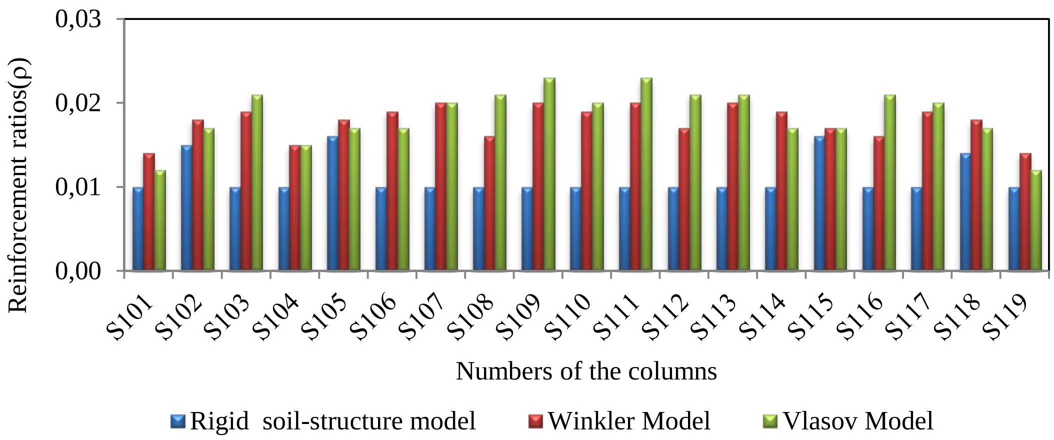

Figure 3. Longitudinal reinforcement ratios of columns

Earthquake zone is assumed to be 1st degree in the above example first. Later the earthquake zones of 2, 3 and 4th degree is considered by keeping the soil properties constant. Soil parameters for various earthquake zones are very close to each other because only horizontal loads are effected depending on earthquake zone.

Axial forces, bending moments and longitudinal reinforcement ratios of columns for various earthquake zones are presented in Fig. 4-6. Bending moments of columns are more affected compare to axial forces. Changing in column bending moments for various earthquake zones cause longitudinal reinforcement ratios to increase. As expected, the greater values of axial forces, bending moments and longitudinal reinforcement ratios are obtained in first degree earthquake zone. Minimum longitudinal reinforcement ratio of column according to regulations for the structures to be built in Turkey is 0.010. Longitudinal reinforcement ratios for 3rd and 4th degree earthquake zone are the same as seen in Fig.5 because they are actually less than the lower limit.

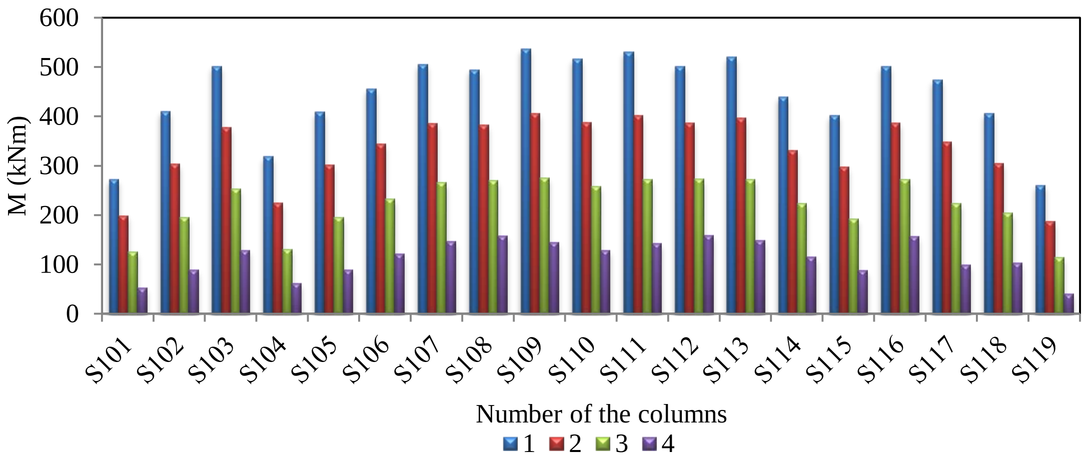

Figure 4. The column bending moment for various earthquake zone

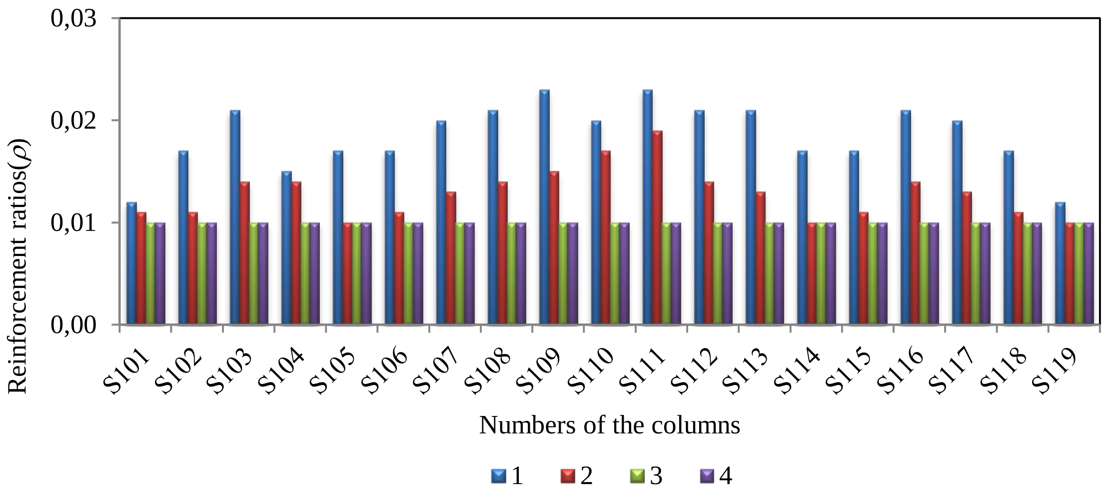

Figure 5. Longitudinal reinforcement ratios of columns

5. CONCLUSIONS

In this study, the influence of soil-structure interaction on the design and behavior of reinforced concrete structures are investigated. For this purpose, an 8-storey building on elastic subsoil is analyzed using Winkler and modified Vlasov models besides considering the structure is supported on rigid base. The numerical analysis of the building-soil system is carried out with SAP2000 program. A computing tool developed in MATLAB is presented in the study for the analysis of building using modified Vlasov foundation model. Two way data exchange between SAP2000 and MATLAB is possible via the computing tool developed for the study. The results show that significant changes occur in internal forces and longitudinal reinforcement ratios of columns when subsoil effects are taken into consideration on analysis of building. Soil-structure interaction is not only a parameter to be considered in the design of the foundation but also has significant effects on the frame. Therefore, studies to improve subsoil models for more accurate soil-structure interaction representations are always valuable.

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