Some Considerations in Seismic Analysis of Spatial Structure Accounting for Soil-Structure Interaction

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Abstract

The seismic analysis of spatial structure in the last 40 years was developed from the static to the dynamic analysis, from the elastic analysis to the elasto-plastic analysis, from the deterministic to the stochastic analysis, and from the uniform seismic excitation in one dimension to the non-uniform seismic excitation in multi-dimensions. The practices show that the model of the spatial structure should be built not only including the roof structure, but the supporting structure and even the foundation as well. Seismic analyses for the nuclear plant, the offshore flatform and the high-rise building have shown that the seismic response of those structures considering the soil-structure interaction (SSI) effect varied a lot compared with that of rigid-connected model. However, few studies have been done for seismic analysis of spatial structures accounting for soil-structure interaction. In present paper, the 3D BNWF(Beam On Nonlinear Winkler Foundation) SSI model for the shallow foundation and the 3D dynamic p-y model for the deep foundation, the earhtquake input model, the elasto-plastic hysteritic model suitable for the superstructure and the substructure are put forward for the seismic analysis of spatial structure. The research will lay a good foundation for the 3D nonlinear analysis of spatial structure incoporating the SSI under strong earthquake shaking and further promote the performance based design of the spatial structure.

Keywords: spatial structure, soil-structure interaction model, seismic input, non-proportional damping.

1. Introduction

The seismic analysis of the spatial structure such as the space frame, the tensegrity in the past was performed without incorporating the effect of the supporting element and the soil medium, which the structures are rested on. The soil medium, in effect, is not rigid, which may decrease the stiffness of the structure and hence increase the natural period of the structure. Sekhar[23], Koushik[13][14] suggest such a increase in the natural period will increase or decrease the response of the structure depending on the locations of the natural period in the design response spectrum. The spatial structure has its characteristic such as the closed frequencise compared with other structures like the high rise building, the offshore platform, which have carried out extensive researches on SSI as in J.L.Wegner[12], Marios[15] and H.Shakib[10]. Much more modes are needed in the mode combination in the spatial structure than the high-rise building where the first several modes contribute the most part of the response. Moreover, the seismic analysis of the spatial structure should be in 3D, which is different from the 2-D analysis in the high rise building.

The soil structure interaction is a hot topic in the 14th world conference on earthquake engineering (WCEE) held in beijing 2008 where about 50 papers are concerned about it. Four US-Japan workshops on the soil-structure interaction have been held since 1998. UC Berkeley has carried out innovative research on the nuclear plant and the dam accounting for the SSI. Relavent SSI programmes such as the SASSI, FEAP,GEOFEAP etc has been developed. The SSI effect is accounted for in the relavent code to consider the performance based design of the tall buildings. FEMA356[7] and the ATC40[1] partially address the flexible foundation stiffness and the strength of the geotechnique components of the foundation in the structural analysis model. FEMA440[8] provides the procedure for the kinematic effect and the procedure for the foundation damping and the effect of them on the reduction of demand on the structure.

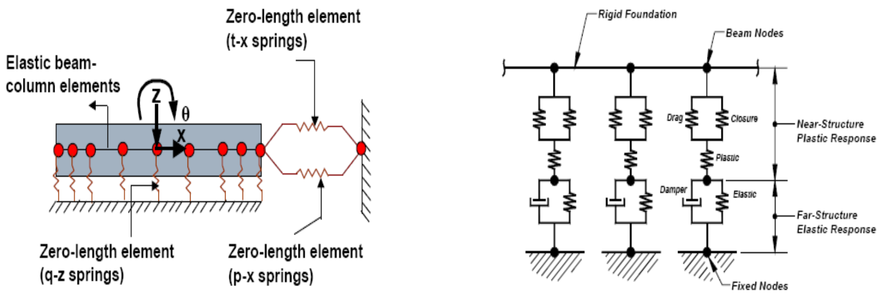
What's the behavior of the spatial structure under the seismic action especially under the strong earthquake shaking when the effect of the supporting element and the soil medium are considered in the whole structural model? When the soil medium is considered in the model, the related problems such as the soil-structure interaction model, earthquake input model, the non-proportional damping, the elasto-plastic model of the superstructure and the nonlinear constitutive relationship of the soil under the strong earthquake shaking should be solved correctly if you want to yield much more rigorous seismic behavior of the spatial structure.

2. Soil-structure interaction model for spatial structures

As we know, the spatial structure includes the roof, whic has the space frame and the tensegrity etc; the supporting structure such as the column and the infilled wall or the reinforced concrete frame; and the foundation, which have the shallow foundation and the deep foundation depending on the load in the superstructure and the soil stratum. The 3-D analysis model for the shallow foundation and the pile foundation are in the following respectively.

2.1. Shallow foundation

In most of the foundation of the space frame, the reticulated shell and dome, the foundation in the analysis is modeled as strip foundation or mat foudation. In the shallow foundation, the soil half space is ususlly represented by the impedance matrix in the frequency domain as in the Ricardo Dobry [20]. The impedance functions of the rigid massless foundation are utilized to incorporate the effect of soil-structure interaction. George Gazetas, Ricardo Dobry[9] studied the impedance function extensively. The three translational stiffnesses and three rotational stiffness about the three mutually perpendicular axes and the corresponding damping coefficient are obtained considering the effect of the shape and the embedment of the footing. However the method is not able to capature the nonlinear behavior at the soil-foundation interface, which includes the gap between the soil and the foundation, the settlement of the foundation, sliding and uplift under strong earthquake shaking. Sivapalan [24], Bruce[4] put forward the BNWF model shown in Figure1 (a). The 2D interaction model based on the winker model for the strip foundation of the spatial structure considers the nonliner behavior. Those springs in the Figure1 (a) simulate the vertical load-displacement behavior, horizontal passive load-displacement behavior and the horizontal shear-sliding behavior. The soil medium could be divided into the near field to model the soil nonlinearity and the far field to model the energy dissipation which is shown in the Figure 1 (b). The strip foundation could be divided into three zones shown in Figure 2 to account for the nonuniform stiffness distribution of the soil medium. The nonlinearity for those springs is simulated by the initial stiffness, the yield displacement and the ultimate load. The model has the capacity to account for the separation by the gap element. However, the model above is only in 2D without considering the interaction in the transverse direction. In the model of the spatial structure, the soil structure interaction in the tranverse direction should be considered by the active earthquake pressure or the passive pressure acting in the transverse direction.



(a) (b)

Figure 1: The BNWF scheme

2.2. The pile foundation

When the structure is located in the soft clay, the pile foundation is selected in the practice. The typical soil-pile structure modelssuch as the Nogami model by Nogami[19] and the Matlok model by Matlock [16] etc are 2D model. Ross W. Boulanger[21] put forward the dynamic p-y method for analyzing the soil-pile-structure interaction which is also in two dimentions. In the 3D seismic analysis of space structure, the soil-pile interaction model should be in 3D and the dynamic nonlinear p-y analysis model shown in Figure 3 is very effective. The p-y element should be in both the lateral and transverse direction. One p-y element is shown in the Figure 4. The simulation of the nonlinear behavior is by the elastic (p-y^e), plastic(p-y^p)and the gap component in series. The gap component have the closure spring and the drag spring. Also the spring should be used in the vertical direction to simulate the frictions between them and the tip bearing of the pile. The nonlinear p-y element shown in the shown in Figure 4. A full soil pile interaction model is shown in Figure 5. The interaction between the soil and the pile in the vertical direction could be modeled by the friction between the soil and the pile and the interaction between soil and the pile tip. This configration could capature the performance of the spatial structure under the seismic actions in three dimensions.

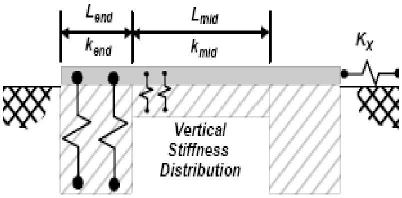


Figure 2: The three zone of BNWF

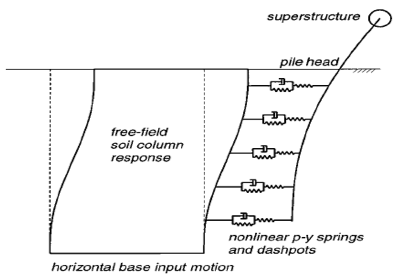


Figure 3: The dynamic p-y analysis model

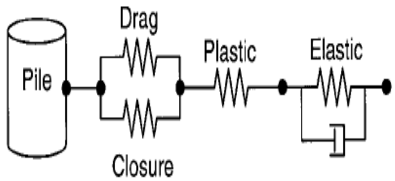


Figure 4: The component of the p-y element

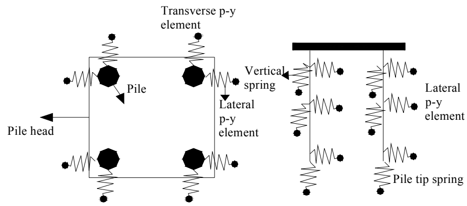


Figure 5: The full soil-pile interaction model

3. Seismic input for the whole structure

If the roof structure is only considered in the seismic analysis, the input earthquake records in the analysis are different from the one recorded at the free field because the input earthquake record is the one that transmited from the free filed to the top of the supporting structure,which in most cases is amplified. For the shallow foundation, the seismic wave could be input from the bottom of the strip foundation and for the deep foundation from the pile tip. Three different seismic waves are selected in the past: two recorded strong earthquake record such as the kobe earthquake record and one artificial synthetic seismic wave which is compatible with the design response spectrum. One problem in the selected seismic waves above is that they are recorded far away from the epicenter. M.Ali Ghannad [18] suggests that the earthquake record near the fault has notable characteristics such as the velocity time hisories containing large amplitude and long period period caused by the forward directivity effects and acceleration time histories with high frequency content. These characteristics makes the response of the structure different from the response expected in the far fault earthquake. The near-fault time histories has the greater vertical component. To the spatial structure, it is susceptible to the vertical vibration due to relative weak vertical stiffness of the roof. In the seismic analysis of spatial structure incorporating the soil-structure interaction, the near fault earthquake motion records should be input in three dimension, which has great significance.

Dimitrios and Cornell[6] put forward the IDA (incremental dynamic analysis), which make the response of the structure has the statistic character by selecting many earthquake record according to the Mgnitude, the distance to the epicenter and the source mechanism.

4. Non-proportional damping problems induced by different materials of the structure

In most cases, the spatial structure includes three material: steel roof, concrete column,and the soil medium. In the seismic analysis, the energy dissipation mechanism in the three materials is different. Moreover, there is the radiation damping when the vibration of the superstructure is transmited into the soil. So the damping in the soil should be the plus of the material damping of the soil and the radiation damping of the soil. The radiation damping is represented by the far field of the p-y element in the soil-pile interaction model. Shibata [25] put forward the weighted damping ratios of the structure. In the seismic analysis of the spatial structure, the varible damping solution put forward by H Bolton Seed [11], which is based on the utilizing the Rayleigh damping expression, is formulated. The following expression is used for each element.

R.W.Clough[22] and Anil.k.Chopra[3] put forward the damping matrix by the substructure method which considers that the damping matrix of the substructure with same materia is Rayleigh damping matrix.

$$C_s = a_{0s} m_s + a_{1s} k_s \qquad (1)$$

$$C_c = a_{0c} m_c + a_{1c} k_c \qquad (2)$$

Where the m_s, m_c are the mass matrix of the steel substructure and concrete substructure respectively, k_s, k_c are the stiffness matrix of the steel substructure and concrete substructure, C_s, C_c are the damping matrix of the steel substructure and concrete substructure respectively.

For the steel substructure, the two coeffcients are as follows:

$$\begin{Bmatrix} a_{0s} \\ a_{1s} \end{Bmatrix} = \frac{2\xi_s}{\omega_m + \omega_n} \begin{Bmatrix} \omega_m \omega_n \\ 1 \end{Bmatrix} \tag{3}$$

Where the ξ_s is the damping ratio of the steel substructure.

The two coefficients for the concrete substructure are as follows:

$$a_{0c} = \frac{\xi_c}{\xi_s} a_{0s} \tag{4}$$

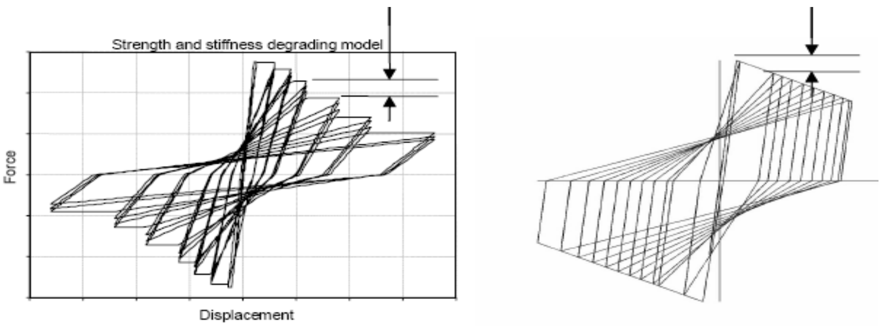
$$a_{1c} = \frac{\xi_c}{\xi_s} a_{1s} \tag{5}$$

Then the total damping matrix could be assembled. Now, the software such as the NASTRAN and the ABAQUS has the function.

5. Elasto-plastic model of the superstructure and soil under strong ground motions

5.1 The elasto-plastic model of the superstructure

The elasto-plastic model of the steel roof is usually the Ramberg-Osgood model. As far as long-span steel roof structure, the nonlinearity is also from the geometric nonlinearity that should be considered in the analysis. For the concrete supporting element, there are two different types of strength degradation model put forward in the [12] shown in Figure 6(a) and Figure 6(b). Both exibit the inelastic and the stiffness degradation. In the Figure 6(a), it maintains the its strength during the given deformation and then lost the strength in the next circle. And the stiffness is decreased next circle. The slope of the post-elastic is positive. But in the Figure 6(b), the strength degradation occurs in the same circle resulting in the negative post-elastic stiffness. The two different models are used to determine the seismic performance of the structure.



(a) (b)

Figure 6: The two different hysteretic model of column

5.2 The elasto-plastic model of the substructure

The model for the substructure considering the soil-structure interaction is shown from the Figure 1 to Figure 4. The dynamic nonlinear p-y analysis accounts for the effect of the near field and the far field. The far field is modeled by the elastic spring (p-y^e)and the dashopot to simulate the radation of the energy from the inertial interaction between the superstructure and the foundation. The near field is modeled by the nonlinear spring(p-y^p) to simulate the nonlinear soil. The gap component includes the closure(p^c-y^g)in parallel with the drag element(p^d- y^g). The gapping behavior includes the a residual resistance that may be treated as the drag force on the pile.The drag force is determined by the parameter C_d which is equal to 0.3 suggested by wilson[26]. The $y= y^e + y^p + y^g$ and the $p= p^c + p^d$. The behavior of the component in the model is shown in the Figure 7.

The nonlinear p-y curve for the soft clay and the sand were put forward by the Matlock [17]and the API[2]. The two curves has been extensively used by the researchers to analyze the SSI for the pile support structure especially the nonlinear response under strong earthquake shaking.

For the strip foundation shown in Figure 1, the three springs are characterized by the nonlinear curve. The ultimate load is defined for both the t-x element and p-x element, while the q-x element has a reduced strength in tension to account for the soil-foundation separation via gap element. The elastic material capatures the far field behavior and the plastic component capatures the near field behavior. The nonlinear parameters ofhe three spring are similar.

In the elastic region, the load f is is linear with the displacement x by the initial stiffness:

$$f = K_1 x \tag{6}$$

The elastic region of the curve by relatiing the yield load f_0 to the ultimate load f_{ult} through the parameter C_r .

$$f_0 = C_r f_{ult} \tag{7}$$

The expresion for the nonlinear curve is as follows:

$$f = f_{ult} - (f_{ult} - f_0)[\frac{cx_{50}}{cx_{50} + \left|x - x_{op}\right|}]^{\,n} \tag{8}$$

Where x_{50} is the displacement where the 50% of the ultimate load is reached. x_0 is the displacement of yield. c and the n is the parameter that control the shape of the curve.

In the analysis of the strip foundation, two parameters shown in Figure 2 are selected to account for the distribution and magnitude of the vertical stiffness along the footing length: the stiffness intensity ratio $R_k = k_{end} / k_{mid}$ and the end length ratio $R_e = L_{end} / L$.

Harden[5] developed a analytical equation for the end stiffness ratio. In the ATC-40, it suggested a constant value of 9.3 and suggest $L_{end} = B/6$ from each end of the foundation.

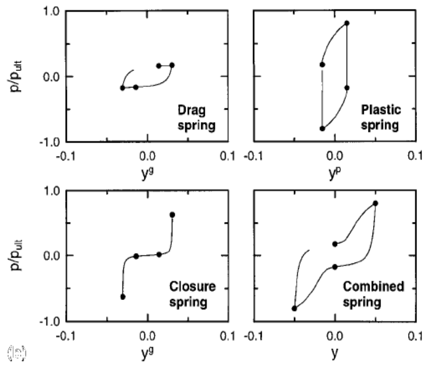


Figure 7: The typical behavior of the components in the p-y model

6. Conclusions

Considering the characteristic of the spatial structure, the dynamic analysis should be in direct integration in three dimension to capture the nonlinear response of the structure. The key to the research is the building of the 3-D SSI model in the shallow foundation and the deep foundation that could capature the ninlinear effect under strong earthquake shaking. The parameters in the model should be determinted correctly. The earthquake input should pay special attention to the effect of near fault time histories on the nonlinear structural response. With points above conserdered, the effect of SSI on the spatial structure could be determined and will further promote the performance-base design of the spatial structure.

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