ON THE FEMA440 REGULATIONS FOR SOIL-STRUCTURE INTERACTION

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ABSTRACT:
The accuracy of dynamic parameters of soil-structure systems with surface and embedded foundations, proposed by FEMA440 regulations, is investigated in the elastic range. This is done through comparison of implicit transfer functions behind the regulations with those computed directly from a benchmark soil-structure model. The model consists of a single degree of freedom super-structure model resting on frequency dependent soil springs and dashpots. The concept of Cone Models is used for soil impedances. Both kinematic interaction and inertial interaction effects are considered. The results are compared within a wide range of non-dimensional parameters which control the whole problem. It is concluded that for surface foundations FEMA440 overestimates the system’s response in almost all practical cases. For the case of embedded foundations, however, the result strongly depends on the soil type and the aspect ratio of the building.

KEYWORDS: Soil-Structure Interaction, Transfer Function, FEMA440

1. INTRODUCTION

Dynamic Soil-Structure Interaction (SSI) affects the behavior of structure and soil in different ways. The effect is usually investigated in two separate parts, i.e., the Kinematic Interaction (KI) effect and the Inertial Interaction (II) effect. The first effect modifies the input ground motion by filtering high frequency components of the Free Field Motion (FFM). In the other words, the motion experienced by the essentially rigid foundation, i.e., the Foundation Input Motion (FIM), is somehow the result of geometric averaging of the seismic input motion in the free-field. This phenomenon may result to multi-component FIM even if the FFM consists of one horizontal component only. The later effect, i.e., the II effect, introduces the effect of soil flexibility on the response of the structure subjected to FIM. This effect is usually considered by introducing a replacement oscillator with modified natural period and damping ratio. Many researches have been conducted to estimate the changes in the input motion due to KI as well as to evaluate the dynamic characteristics of the replacement oscillator. The latter subject has specially attracted much more attention. For surface foundation resting on half space, Jennings and Bielak [1], Veletsos and Meek [2] and Veletsos and Nair [3] computed rigorous numerical results and derived approximately analytical solutions for the period and damping of the system. The influence of the foundation embedment has been investigated by Bielak [4] for rectangular prismatic foundation in full welded contact with the surrounding soil using effective dynamic parameters. Aviles and Perez-Rocha [5,6] estimated dynamic parameters for structure on cylindrical foundation with variable side wall height embedded in a stratum on either elastic or rigid bedrock. They considered both KI and II effects in estimation of effective dynamic parameters. Stewart, Fenves and Seed [7], estimated dynamic parameters considering only II effects. In seismic codes such as NEHRP regulation [8], interaction effects are accounted for by modifying relevant dynamic properties of the structure to consider II while KI effect is traditionally ignored. In documents on seismic performance assessment and rehabilitation of buildings, such as FEMA356 [9] and FEMA440 [10], however, more detailed procedures are introduced. Here the accuracy of FEMA440 regulations on SSI effect is assessed for either surface or embedded foundations. This is done through comparison of implicit transfer functions behind the regulations with those computed directly from a benchmark soil-structure model.
2. STATE OF THE PROBLEM

The response of any linear dynamic system to specific input motions can be evaluated through the Transfer Function (TF) of the system which is a function of its dynamic characteristics. The key dynamic parameters which affect TF’s can be considered as period and damping of different vibration modes of the system which, in turn, can be calculated by eigenvalue analysis. TF for a linear system has unique shape which is defined according to dynamic characteristics of the system. However, if it is intended to replace a multi degree of freedom system with a single degree oscillator in a definite frequency range, in addition to characteristics of the system, the vector shape of the input motion and its frequency content also play important roles. In this state, the response spectrum of the system may hold its maximum at a period not matching any natural periods of the system calculated from eigenvalue analysis. Soil structure systems are in fact samples of the above mentioned general multi degree of freedom systems with multi-component input motions due to KI. So, if it is intended to replace the soil-structure system with a single degree of freedom oscillator, the dynamic properties of the replaced oscillator could not be independent of input motions. In the other word, KI effect affects the procedure of II effect estimation. That’s while FEMA440 treats II and KI independently. Ignoring the effect of rocking component of input motion, thus, may result in over- or under- estimation of the results. This problem has been studied in this research.

3. SOIL-STRUCTURE MODEL

Figure 1 shows the model used in this research. The super-structure is considered as a single mass, \( m_{str} \), with moment of inertia, \( I_{str} \), mounted on a spring with stiffness \( K_{str} \), at an elevation of \( \bar{h} \). These parameters can be representatives for the first modal mass, mass moment of inertia, the effective stiffness and the effective height of a MDOF structure respectively. The foundation is represented by a rigid cylindrical mass, \( m_f \), with mass moment of inertia \( I_f \), radius \( r \) and depth of embedment \( e \) which is in full contact with the surrounding soil. The flexibility of the surrounding soil is modeled by coupled sway-rocking impedances, \( S_{sh} \), \( S_{sr} \), \( S_{rh} \), \( S_{sr} \) based on the concept of Cone Models[11].

The equilibrium equations can then be written as follows:

\[
MX + KX = F
\]

(1)

where \( M \) and \( K \) are the mass and stiffness matrices, respectively and \( F \) is the loading vector. Substituting \( M \), \( K \) and \( F \) leads to:
where $x_s$, $x_f$ and $\phi_f$ are total displacement of the structure, the sway and rocking motions of the foundation, respectively. Also, $x^e_g$ and $\phi^e_g$ are the effective foundation input motion components resulted from KI effect. It can be shown that the Eq. (2) can be reformulated by using five dimensionless parameters, $sfixfix V_{sh} = \omega_0^2 + \omega_1^2 + \omega_2^2$, in which $V_s$ is the soil shear wave velocity.

It should be added that the material damping in the soil and structure may be included in the formulations as hysteretic form of damping by using the correspondence principle, i.e. just by multiplying the stiffness of the structure and soil by $(1+2i\zeta_{str})$ and $(1+2i\zeta_{soil})$, respectively, in which, $\zeta_{str}$ and $\zeta_{soil}$ are the material damping ratios in the structure and soil. Poisson’s ratio of soil is set to $\nu = 0.4$ in this research.

4. SURFACE FOUNDATIONS

In this section a comparison is made between the implicit TFs behind FEMA440 regulations with the exact TFs for surface foundations. Here, the so-called exact TF is considered as the response of the soil-structure model of Fig.1 to a unit amplitude harmonic free-field input motion. It should be mentioned that the frequency dependency of soil impedances is also taken into account. On the other hand, the FEMA440 TF is implicitly generated based on the equivalent period and damping suggested by the document. Figure 2 compares the two above mentioned TFs in a wide range of excitation frequencies. The abscissa in the graphs is the non-dimensional excitation frequency, $q = \omega_0^2 + \omega_1^2 + \omega_2^2$, in which $\omega_0$ is the frequency of excitation. The figure depicts the results for three values of aspect ratio $\frac{h}{r}$, as representatives of squat to slender structures, and two values of non-dimensional frequency $(a_0)_{fix}$. Using the rule of thumb introduced by Ghanad and Jahankhah [12], the values 1 and 2 for the non-dimensional frequency are somehow considered as representatives of NEHRP soil types D and E, respectively. It is seen in Fig. 2 that in all cases FEMA440 overestimates the structural response. The discrepancies are intensified as a result of any decrease in the aspect ratio, $h/r$, or increase in the non-dimensional frequency, $(a_0)_{fix}$. There is also a difference between the peak related periods in the two methods, especially for squat buildings. Looking from another point of view, Fig. 3 provides information on the equivalent period and damping ratio of soil-structure systems resulting from the two above mentioned methods. This figure helps to interpret the results of Fig. 2. As seen, FEMA440 underestimates both period and damping of the soil-structure system. The underestimation of the system period is just significant for squat buildings. However, the underestimation of damping ratio, which may severely affect the response, happens for mid-rise and slender buildings. As a result, FEMA440 almost always overestimates the effect of SSI on response of slender buildings, while it may over- or under- estimates the effect for squat buildings depending on the frequency content of the excitation.
Figure 2. FEMA440 proposed TFs versus exact TFs for soil-structure systems with surface foundation.

Figure 3. Effective system-to-structure period ratio and damping ratios for surface foundation with $h/r=0.5,1,2$ and $\nu=0.4$, $\xi_{soil}=0$. 
4. EMBEDDED FOUNDATIONS

The comparison between the exact and FEMA440 TFs for embedded foundations are depicted in Fig 4. TFs have been calculated in a way to convert the harmonic free-field input motions to the response of the soil-structure system. Thus, both KI and II effects are included in the introduced TFs. FEMA440 TFs are implicitly generated based on the recommendations made by the regulations to capture both II and KI effects. The first effect is estimated by using suggested equivalent period and damping ratio based on the concept of so-called modified Veletsos method which seems to be the application of idea proposed by Veletsos and Nair [4]. The latter effect also has been introduced through KI reduction factors. The results are shown in the same fashion as for surface foundations for two values of \((a_0)_{\text{fix}}\) and three values of \(h/r\). FEMA440 provides the dynamic parameters of embedded foundations only for the embedment ratio \(e/r=0.5\). So, here the discussion is limited to this case. It should be mentioned that FEMA440 doesn’t allow using KI reduction factors for soil type E. So, KI is ignored for generating FEMA440 TFs for the case of \((a_0)_{\text{fix}}=2\). Generally, Fig. 4 shows more discrepancies than observed for the case of surface foundations. For the case of soft soils, \((a_0)_{\text{fix}}=2\), where KI has been ignored in FEMA440 approach, TFs are overestimated in all cases. However, for the case of \((a_0)_{\text{fix}}=1\), where KI is included in both TFs, the result strongly depends on the aspect ratio of the building. Although FEMA440 underestimates TFs for squat buildings with \(h/r=0.5\), the trend is changed for more slender buildings. Figure 5 shows the change in the period and damping ratio of the system for different aspect ratios and the same embedment ratio. Because of different treatment of KI and II by FEMA440 and the so-called exact method in this study the direct comparison of the results shown in Fig. 5 is not meaningful. However, it can be used as a tool to explain the results observed in Fig. 4. As seen in Fig. 5, the implicit equivalent damping ratio suggested by FEMA440 is always underestimated. This is in fact the reason for overestimation of TFs for the case of soft soils, \((a_0)_{\text{fix}}=2\), where KI is ignored by FEMA440. For the case of \((a_0)_{\text{fix}}=1\), however, KI reduction factors may compensate this effect especially for more squat buildings. For example, for the case of \(h/r=0.5\), the reduction due to KI effect is so high that KI governs the problem leading to underestimation of the total TF.

CONCLUSION

The accuracy of dynamic parameters of soil-structure systems with surface and embedded foundations, proposed by FEMA440 regulations, is investigated in the elastic range. This is done through comparison of implicit transfer functions behind the regulations with those computed directly from a benchmark soil-structure model, including both KI and II effects. It is concluded that for surface foundations and foundations embedded in soft soils, where no KI introduced by FEMA440, the system’s response is overestimated in almost all practical ranges. However, for cases with embedded foundations in relatively stiffer soils, like soil type D where inclusion of KI effect is suggested by the regulations, the result strongly depends on the aspect ratio of the building. The regulations usually underestimates the response for squat buildings with \(h/r=0.5\) while the trend is changed for more slender structures.
Figure 4. FEMA440 proposed TFs versus exact TFs for soil-structure systems with surface foundation.

Figure 5. Effective system-to-structure period ratio and damping ratios for embedded foundation with $e/r=0.5$, $h/r=0.5, 1, 2$, $\nu=0.4$, $\xi_{soil}=0$. 

\[ \frac{T^*}{T} \]

\[ \beta_0 \]
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