論文の内容の要旨

APPLICATION OF META-MODELING THEORY TO CONSTRUCTION OF CONSISTENT SEISMIC RESPONSE ANALYSIS MODELS CONSIDERING SOIL-STRUCTURE INTERACTION

(構造物-地盤の相互作用を考慮した整合する地震応答解析の構築のためのメタモデリング理論の適用)

ムハンマド リズワン　リアズ

After the recent strong earthquakes such as the Niigataken-Chuetsu-Oki earthquake and the Great Tohoku Earthquake, there is a need for the re-evaluation of seismic design of important structures such as nuclear power plant (NPP) for severe events of extremely rare possibility. Establishing the methodologies for an accurate and reliable seismic analysis of such structures of critical importance is essential to ensure their safety. For an accurate seismic response analysis of an important and massive structure such as an NPP, soil-structure interaction (SSI) is a fundamental issue and its careful consideration is necessary during analysis.

Conventionally, a mass spring modeling has been employed for the seismic analysis of structures with the structure modeled as a set of a few or a few tens of masses, connected by springs representing the stiffness of the structure. The SSI has been considered by considering the structure and soil separately and replacing the effect of soil as a soil-spring. These models, basically developed for simple settings of structure in an era of lesser computational resources, require experience and need of making several simplifications for the structure, foundation and the soil and hence lack objectivity. There is an absence of a unified approach for checking the quality of different simplified models constructed for the same structure. Further, these conventional models have been based on conservative estimation of response to guarantee higher factors of safety and lack the ability to quantitatively show the concrete margin of safety for a structure which is important to know, especially after the recent earthquake experiences.

On the other hand, when using the 3D solid elements based FEM analysis, there is no need to consider the SSI explicitly and the effect of SSI appears in the solution when a model of a soil-structure system is analyzed. The latest computers are able to perform seismic response analysis of a soil-structure model with DOF of the order of millions. Even with the availability of resources of high performance computing, the importance of simplified models cannot be neglected. These models are needed at the beginning of a complex analysis to perform preliminary simulations and to see the effect the different parameters. These simplified models are also useful during the probabilistic seismic risk analysis because of their simplicity and lesser requirement of computational resources.

Keeping the above facts in mind, there is a need of more advanced numerical analysis of estimating structural seismic response, particularly accounting for effects of SSI to get a concrete estimate of the safety of the structure for any future earthquake scenario which has not been considered previously. It is also necessary to make a link between the conventional analysis and such more advanced numerical analysis, in order to improve the former as well as to validate the latter.

Meta-modelling theory is being proposed in order to strengthen a link between structural mechanics (the conventional models) and continuum mechanics. Meta-modelling theory is a modelling methodology to construct a model which is consistent with continuum mechanics. The key concept is that all modelings solve the same problem of continuum mechanics but use different mathematical approximations, without using any physical assumption.

In this thesis, meta-modeling theory is used to clarify the soil structure interaction in the view point of structural and continuum mechanics and to show that the conventional soil-spring model can be objectively derived from the continuum mechanics by using purely mathematical approximations and without using any physical assumption. Use of physical assumptions means solving a different problem and hence the consistency of simplified model with that of the continuum mechanics modeling is lost. The objective of this study is to apply meta-modeling theory to construct a consistent seismic response analysis model to consider SSI. The scope of this study includes clarifying SSI according to meta-modeling theory, proposing a methodology to construct a consistent mass-spring model that can approximate the solution of solid element FEM model and showing the usefulness of the proposed methodology with the help of numerical experiments.

After a detailed literature survey, the mathematical analysis of a general soil-structure interaction problem is performed. This analysis is needed to clarify the mathematical characteristics of the problem and to rigorously formulate the problem in the framework of the meta-modeling theory. The assumption of an ideal rigid foundation is explained, which is the basis of the sub-structuring approach that is used for SSI analysis.

Next, the underlying approximations that are made in introducing the soil spring for SSI is clarified by rigorously formulating SSI. Since soil spring modeling that is made for the evaluation of SSI is a simplification of the continuum mechanics problem, its applicability is limited; in other words, the soil spring modeling could be either a good or bad modeling, depending on the continuum mechanics problem. For a simple soil-spring to be a good modeling or to be applicable, there are some requirements which need to be satisfied for a structure, soil and an input ground motion. However, we have to emphasize that this simplified modeling may not be applicable to any soil-structure problem and cannot give a good approximate solution for a particular set of structure, soil and input ground motion.

A structure which is suitable for the application of the soil spring modeling is the one which is simple and symmetric. These two conditions ensure that center of rotation of the plate remains at the center of the plate and there is no significant shift in the center of rotation of the plate during the seismic excitation. However for a complicated and unsymmetrical structure, this condition is hardly satisfied and the soil spring may give a poor evaluation of SSI. The next important requirement is the satisfaction of the condition of a rigid foundation. A foundation which is significantly stiffer than both the structure and the soil is required. Furthermore, the foundation should be rigidly connected to the structure and the soil to avoid any separation and slip which are not accounted for in constructing the soil spring.

In general, a site consisting of few geological rock layers has a more or less continuous distribution of natural frequencies of surface waves, and hence it is difficult to select a limited number of frequencies in which the soil spring is constructed. However, a uniform and stratified geological structure has a scattered distribution of surface waves, if the direction of the propagation is restricted to the vertical direction only. This condition ensures the applicability of the soil spring modeling. As for a site of soil layers which has a scattered distribution of vertical surface waves, the applicability of the soil spring modeling is ensured as well.

Next, a methodology of constructing a consistent mass-spring soil-spring model for the structural seismic response analysis that accounts for SSI is developed. Starting from the Lagrangian of continuum mechanics and selecting suitably approximated displacement functions, the variational problem of the Lagrangian is converted to an initial value problem of the mass-spring soil-spring model. A key issue is the explicit expressions of the mass and the stiffness constants, which are rigorously derived from the Lagrangian. As the simplest case, the governing equation of a single mass-spring system for a structure with rigid body foundation and a soil spring is derived, based on an assumption of one-dimensional deformation (or uni-directional displacement). Since the objective of this dissertation is the seismic response analysis of an NPP building considering SSI, the characteristics of an NPP building and underlying soil are discussed in order to clarify the applicability and limitations of the mass-spring soil-spring model that is constructed according to the developed methodology.

Next, numerical experiments are performed to show the usefulness of the mass-spring soil-spring models constructed. A simple two-storey structure and an NPP structure with sufficiently large soil-domains are considered. The frequency values and the displacement response at the top of the structure are compared for the constructed mass spring soil spring model and the FEM model to examine the performance of the constructed simplified models. The frequency values approximately coincide and this similarity of the frequency value obtained from FEM analysis and the mass spring models shows the consistency of the constructed mass spring model. Further, it is seen that the displacement response obtained from the mass-spring model is fairly consistent with that of the finite element model. The accuracy of the response can be further improved by considering more than one modes of the structure.

Next, the possibility of using modal analysis performed using a high fidelity model to get a consistent mass-spring model for a complicated structure is shown. A methodology to construct a consistent mass-spring model is already developed but it has certain limitations, such as the need to have equal number of Eigen modes and mass points of the mass-spring model. This requirement may easily be satisfied for a simple structure for which knowing the response at top of structure or each floor's response is sufficient, but for a complicated structure such as an NPP, for which the response at several locations where critical instruments are to be placed is needed other than the floor response, an improvement of the methodology is needed for the conversion of modal analysis to mass-spring model.

The target is to construct a consistent mass-spring model which, using the first few dominant modes of the structure, can approximate the solution of a high fidelity model. Using the already developed methodology for the construction of a consistent model, a methodology for conversion of modal analysis to a mass-spring model is presented. However, a perfect conversion of the modal analysis to a conventional mass spring model is not possible. The obtained mass and stiffness matrices result in the same natural frequency as that of the 3D FEM analysis. However, the presence of non- zero and negative terms in the mass matrix are due to the approximate solution and the purely mathematical treatment of the problem. One option can be to further force the off diagonal terms of mass matrix to zero by minimization and checking the effect on the frequency, however it is expected to significantly change the frequency since some of the off-diagonal terms are of the same order as those of the diagonal terms.

As future works, the developed mass spring soil spring model should be extended to reproduce more than one modes of the structure as well as the soil which is the case in this study. The applicability and limitations of the stick model should be studied and its performance for the evaluation of the dynamic response of the structure should be examined. The developed models should be extended to consider the non-linear cases to get more benefits of the simplicity and the lesser computational effort needed for a simplified model. It is straightforward to apply meta-modeling to non-linear elasto-plasticity problem in which strain and stress increments are linearly related.