Response of Soil-Structure Interaction System Considering the Nonlinearity of Soil during Earthquake and Tsunami Disaster

論 文 内 容 の 要 旨

I. Introduction

I.1. Earthquake Disaster

Seismic response of structure under soil-structure interaction effect (SSI) is an impressive subject in earthquake engineering domain. Various analytical models and methods have been proposed and utilized in research and practical work. These methods can be categorized as direct and substructure (indirect) approach. Due to the simplicity requirement, substructure approach is frequently used in practical work and research field. However, the state of problem in this approach was found and needed to improve. In the existing analytical model under substructure approach, SSI problem is performed only with equivalent-linear response of soil materials in frequency domain (FD) and uses the constant value of soil properties for the whole response of structure during earthquake disaster. This restriction can cause mismatched responses and overestimated results compared to the actual response of structure under earthquake disaster.

I.2. Tsunami Disaster

After the 2011 Great East Earthquake in Japan, the effect of subsequent tsunami forces have become an impressive topic. Many RC structures were damaged and overturned. Various analytical studies and guidelines have been proposed considering the effect of tsunami forces on the overturning-moment of structure. The resisting of building to the overturning-moment is considered under four main effects: self-weight of structure, hydrostatic force, buoyant force, and tensile force of piles in case of deep foundation. However, these effects might not adequate compared to the reality responses and other effects should be considered. Besides this, the effect of near-field soil deformation after earthquake and during tsunami disaster were ignored. These can cause mismatched or overestimated results compared to the actual response of structure under tsunami disaster.

The objectives of this study are:

−Earthquake:

- To propose analytical model considering nonlinear response of soil material
- To perform and compare seismic response of RC frame structure under nonlinear and equivalent-linear SSI effect.

−Tsunami:

- To propose analytical model considering the deformation of near-field soil under earthquake and tsunami force.
- To perform and compare the overturning-moment response of RC frame structure under the effect of near-field soil deformation.

II. Free Field Ground Motion Analysis (FFGM)

II.1. FFGM Analysis in Frequency Domain (FD)

FFGM analysis in FD is widely used method for one-dimensional wave propagation motion. This method is performed with equivalent-linear analysis procedure. Furthermore, this method is used and integrated into many programs such as SHAKE, EERA, DEEPSOIL, etc. In order to perform FFGM analysis, this method was integrated into OBASAN, which is a structural analysis program but cannot perform FFGM analysis in FD yet. The FFGM analysis in OBASAN showed a good agreement for both linear and equivalent-linear analysis compared to SHAKE91, which is the latest version of SHAKE. This agreement confirmed OBASAN can perform well for FFGM analysis in FD.

II.2. FFGM Analysis in Time Domain (TD)

In order to perform FFGM analysis in TD, the output results of FFGM analysis in FD was necessary and desired. The FFGM analysis in TD was solved by using Newmark's equation with consistent mass, stiffness, and viscous damping. For the hysteretic rule of nonlinear response analysis, the modified Ramberg-Osgood model was used in this study.

−Propose New Analytical Model

- Linear Analysis

  In linear analysis, the target earthquake motion was input at the base of soil column (or surface layer) as an outcrop motion (*2E*). Then, the within output motion (*E+F*) was extracted at the base of soil column and applied this motion at the same layer of soil column (as input motion) for TD analysis. The within motion (*E+F*) of any location is an actual motion of that location.

- Nonlinear Analysis

  In nonlinear analysis, the procedure was the same as linear analysis but it was required to perform in both linear and equivalent-linear analysis in FD and the within output motion (*E+F*) of both analysis was significant to be the same or almost the same. Due to this requirement, two extra layers were added in case of this study. The first layer consisted 5m in depth and 900m/s for shear velocity while the second layer consisted 800m in depth and 8000m/s for shear velocity and supported by bedrock consisted the same shear velocity 8000m/s. Then, this within output motion (*E+F*) was applied at the same layer of soil column for TD analysis.

−Verification of Analysis Results

- Linear Analysis

  In linear analysis, the output result of FFGM in TD was verified by the results from FD analysis. These results showed a good agreement for both analysis conditions.

- Nonlinear Analysis

  In nonlinear analysis, the output result at the ground surface in TD was verified by the results from linear and equivalent-linear analysis in FD. The output result of FFGM analysis in TD showed a good agreement with linear response at the starting point and equivalent-linear response at the finishing point. These agreements confirmed that the motion started from linear and finished with nonlinear response motion. Therefore, the proposed analytical model could perform well in TD and showed a good agreement in a reasonable way.

III. Seismic Response of RC Frame Structure under SSI effect

As mentioned above, the existing analytical model of SSI problem is performed only with equivalent-linear of soil materials and the constant value of soil stiffness is applied for all periods during earthquake disaster. This restriction could cause mismatched and overestimated results compared to the actual response of structure. Thus, the analytical model considering nonlinear response of soil material was proposed in order to perform the seismic response of structure under nonlinear SSI effect.

The seismic responses of RC frame structure under both analytical model of SSI effect were performed under linear response of RC frame structure and the output response results were performed under base-shear, overturning-moment, acceleration, and relative displacements. Moreover, the hysteretic response of soil-foundation springs were also conducted.

According to the output results, it was showed that the responses of structure under equivalent-linear response of soil material were larger than the results from nonlinear response of soil material. These discrepancies showed about the overestimated results of using equivalent-linear analytical model compared to the actual response of structure under earthquake. On the other hand, the seismic responses of structure under proposed analytical model showed reasonable responses according to the nonlinear response of soil materials compared to the reality response of structure. Therefore, the proposed analytical model considering nonlinear response of soil material was a good candidate for SSI analysis problem.

IV. Overturning-Moment of Structure under Near-Field Soil Deformation Effect due to Tsunami Force

The overturning-moment of structure is a crucial factor to determine the stability of structure under tsunami forces. There are four main effects considering the resisting of building to the overturning-moment such as self-weight of structure, tensile resistance of piles, buoyant force, and hydrostatic force. However, these considerations seemed not enough compared to the actual effect under tsunami disaster. Thus, the effect of near-field soil deformation under hydrodynamic force on the overturning-moment of structure was performed and discussed in this study. In this study, the effect of near field soil deformation was divided into two main parts: after earthquake and without earthquake effect.

IV.1. Analytical Model Considering Earthquake Effect

Firstly, the FFGM analysis in TD at the ground surface was determined and the corresponding base-shear of structure considering nonlinear SSI effect was derived. Then, the boundary of near field soil was determined and the procedure was described as in the following.

- Area of surface layer was the same as the area of base structure
- Effective angle was assumed to be 45^{o}
- Area of second layer was extended corresponding to the effective angle
- The procedure was kept the same for other layers until the base of

soil column.

After that, the boundary of near-field soil column was obtained. The FFGM at the surface layer and base-shear were applied to the top of this near-field soil column. The nonlinear response of near-field soil column was performed and the corresponding response of nonlinear soil materials were achieved. These material properties were assigned as the new properties for near-field deformation effect under tsunami disaster.

Then, the response of this near-field soil column was performed under static pushover analysis under hydrodynamic force. Moreover, this near field soil column was performed in linear, equivalent-linear, and nonlinear analysis. The corresponding soil materials from these analyses were used to determine foundation stiffness and perform the linear response of structure under hydrodynamic force. Lastly, the overturning-moment of structure under near-field soil deformation after earthquake under tsunami force were achieved.

IV.2. Analytical Model without Earthquake Effect

In this case, the procedure was the same as under earthquake effect but the soil properties were used as the initial state without effect from earthquake disaster. Then, the overturning-moment of structure under near-field soil deformation due to tsunami force was achieved.

IV.3. Verification of Analysis Results

After obtaining the results from the analyses, it was showed that the overturning-moment from linear analysis was larger than that from equivalent-linear and nonlinear analysis, respectively, under the effect of earthquake and without earthquake. According to these results, the proposed analytical model considering near-field soil deformation under tsunami disaster was performed well compared to fixed base structure. Therefore, this proposed analytical model was a good candidate for considering the effect of near-field soil deformation on the overturning-moment of structure during tsunami disaster.

V. Conclusion

−Earthquake Disaster

In earthquake engineering domain, SSI problem is regarded as the significant subject. In the existing of SSI analytical model, the seismic response of structure can be performed only with equivalent-linear response of soil materials. This restriction can cause mismatched responses and overestimated results compared to the actual response of structure under earthquake disaster. Therefore, the analytical model considering nonlinear response of soil material was proposed. The FFGM analysis of proposed analytical model in TD showed a good agreement results compared to the FFGM analysis in FD. These agreements confirmed that the proposed analytical model can perform well and facilitates performing the seismic response of structure under nonlinear SSI effect.

The comparison of both SSI analytical models were performed. The results showed that the seismic responses of structure under equivalent-linear SSI effect were larger than those under nonlinear SSI effect. This discrepancy showed about the overestimated results of using the existing analytical model of SSI effect while the proposed analytical model considering nonlinear SSI effect showed the actual response results according to the nonlinear response of soil properties during earthquake disaster. Therefore, the seismic response of structure under nonlinear SSI effect under substructure approach was a potential candidate for SSI problem.

−Tsunami Disaster

After the 2011 Great East Earthquake in Japan, the effect of tsunami force on the overturning of RC structure has become an impressive issue. Thus, many analytical studies have been proposed considering the resisting of building to overturning-moment. There are four main effects that are using to determine the overturning-moment of structure. These effects include self-weight of structure, tensile resistance of piles, buoyant force, and hydrostatic force. However, these effects seemed not enough under tsunami disaster. Therefore, an analytical model considering the near-field soil deformation effect on the overturning-moment of structure under tsunami disaster was proposed.

This effect was divided into two main parts: after earthquake and without earthquake effect. The results from both effects showed a good agreement for linear, equivalent-linear, nonlinear analysis, respectively. This agreement confirmed that the proposed analytical model considering the near field soil deformation on overturning-moment of structure under tsunami force was performed well compared to the fixed base structure and can contribute to the design guideline for the resisting of building to overturning-moment under tsunami disaster.