Soil Structure Interaction of Underground Structures Considering Ground Motion Coherency and Incoherency Effects: Application to Failure of Daikai Subway Station

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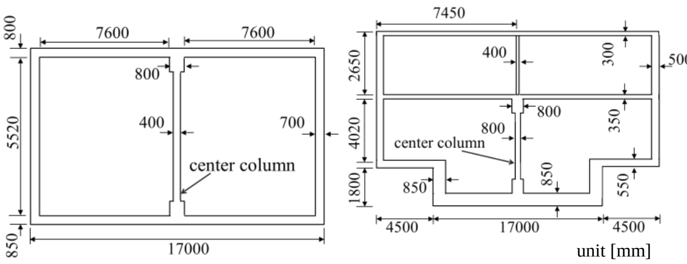
1. Introduction

Soil structure interaction (SSI) using ground motion incoherency approaches has been drawn much attention with the new regulations recently imposed on structures in nuclear facilities. In contrast to the coherent motion where all the point at the soil structure interface are in-phase, the incoherent motion represents much more realistic random wave field with out-of-phase motion at the interface [1]. In the present study, SSI in Daikai subway station which suffered heavy damage due to the Southern Hyogo earthquake in 1995 is studied using a three dimensional detailed finite element model. SSI analyses are carried out by using computational code ACS SASSI which uses deterministic and stochastic incoherency approaches [2].

In the Daikai station more than thirty reinforced concrete (RC) columns completely collapsed due to shear failure causing 2.5 m subsidence of the highway road above the station [3]. Cross sections of the platform and the two-story main station are shown in Fig. 1. The central columns in section 1 suffered complete collapse while only minor damage was reported in those of the section 2, indicating that the difference in structure geometric characteristics and local soil condition affected much on the behavior of two sections during the earthquake.



(a) Section 1: Platform (b) Section 2: Main station

Fig. 1. Cross section of Daikai station (not to scale)

2. Finite element model

ACS SASSI code uses substructure subtracting method where only the structure model and excavated soil model are necessary for complete SSI analysis. The main advantage of this analysis method is that extended surrounding soil medium is not necessary which reduces computational cost and modeling efforts. The SSI interface is identified using set of interaction nodes which are common to the both structure and excavated soil. Details of the analysis model are shown in Fig. 2. The structure is modeled using shell elements with linear elastic material properties: unit weight 23.54 kN/m^3, elastic modulus 2.89×10^7 kN/m^2, Poisson's ratio 0.2, and damping 5%. The excavated soil is modeled using solid elements with the material properties corresponding to the soil layer properties shown in Fig. 3.

The ground motion recorded by Kobe meteorological agency (JMA-Kobe) is used for coherent and incoherent analysis (Fig4a). Effect of different ground motions at the sections 1 and 2 are also studied by using multiple excitations where the amplitude of JMA-Kobe response spectrum (RS) is scaled based on the free-filed soil RS for shear wave velocities (Vs) 100 m/s and 500 m/s (Fig. 4b).

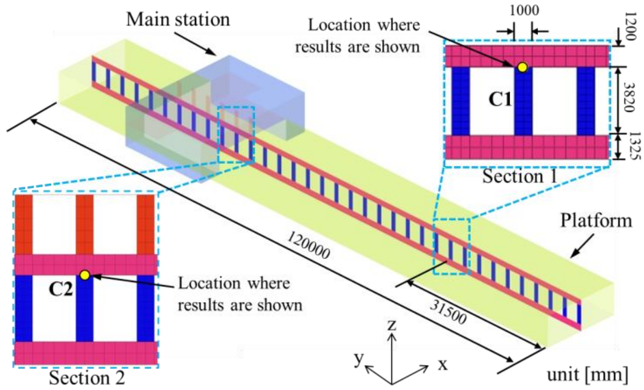


Fig. 2. Analysis model (structure model only)

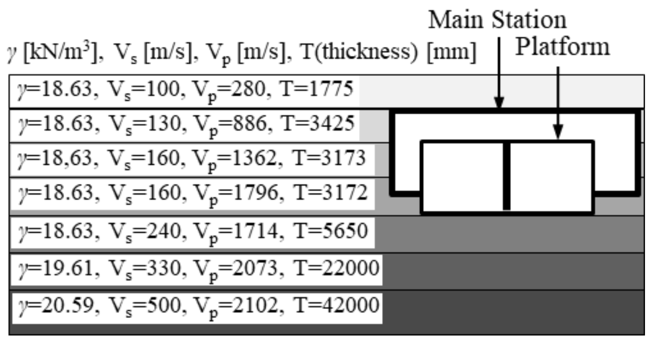
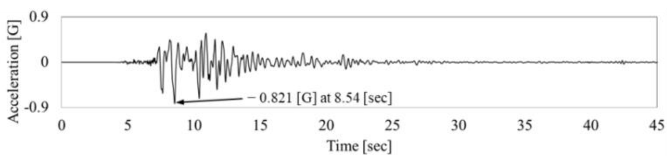
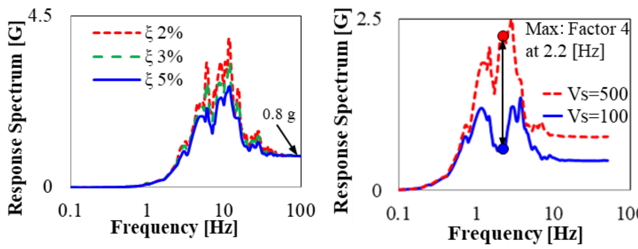


Fig. 3. Soil layer properties (damping 2%)



(a) Time history of JMA-Kobe



(b) RS for JMA-Kobe

Fig. 4. Time history and RS of JMA-Kobe

Keywords: Earthquake, ground motion incoherency, multiple excitations, soil structure interaction, underground structures
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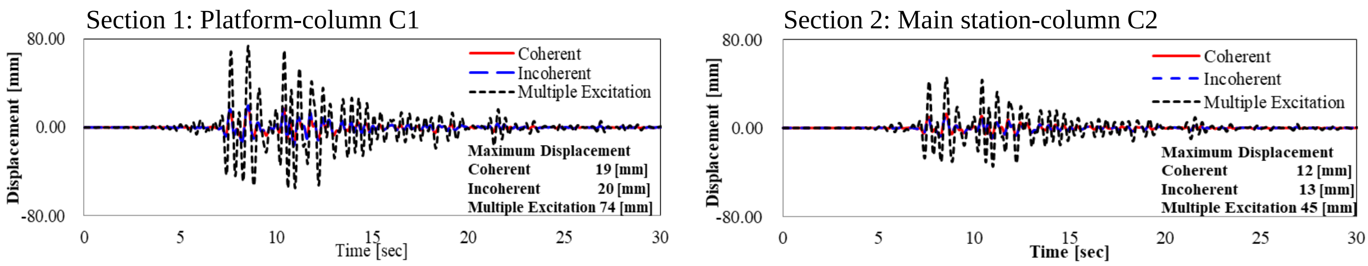


Fig. 5 Lateral displacement time histories at top of the central columns C1 and C2

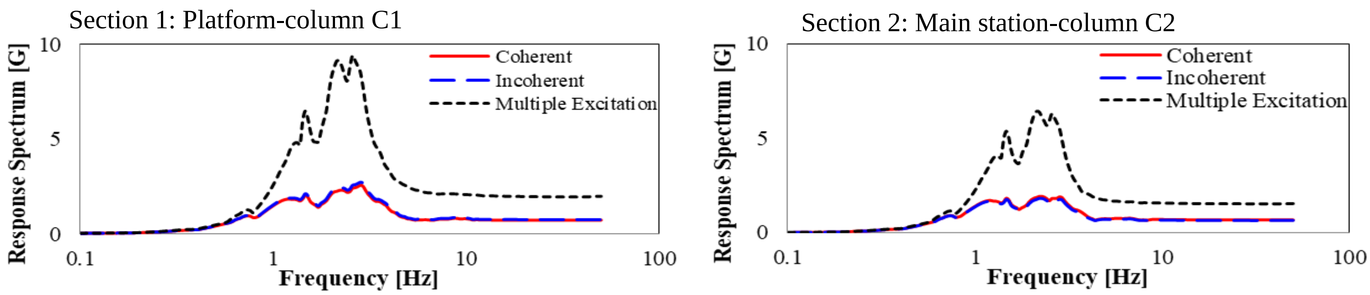
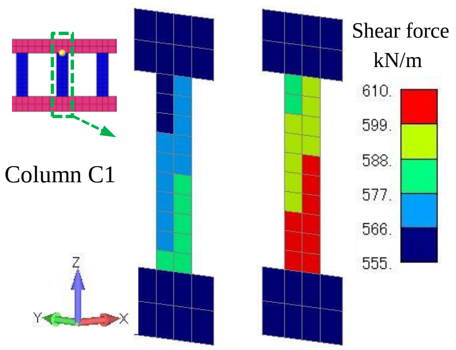
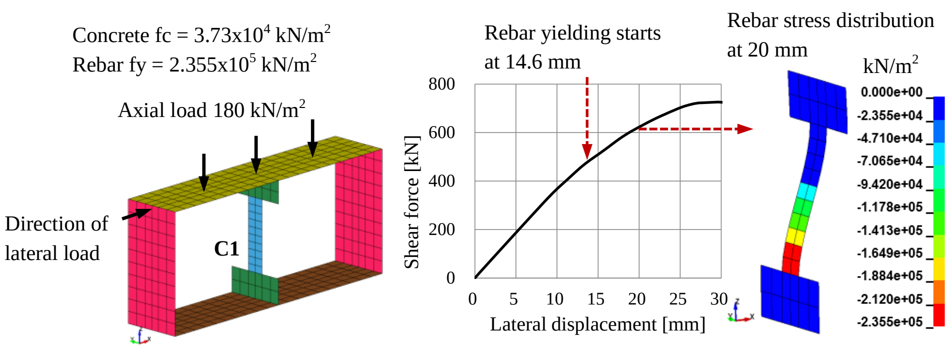


Fig. 6 Response spectra at top of the central columns C1 and C2



(a) Coherent (b) Incoherent

Fig. 7 Shear force distribution of column C1



(a) Structural system (b) Force vs. displacement, and rebar stress distribution

Fig. 8 Nonlinear pushover analysis of single column structure system

3. Numerical results

Figure 5 shows displacement relative to the base calculated at the top of the central columns for coherent, incoherent and multiple excitations. Coherent and incoherent results are nearly the same but results obtained from multiple excitations with different ground motions at platform and main station show significant increase. The ground motion at the site is not known and these two Vs values represent upper and lower bounds of RS at the site based on the soil properties in sections 1 and 2 of the station. The peak displacements of the column C1 in the platform, are 19 mm, 20 mm, and 74 mm, and those of column C2 in main station are 12 mm, 13 mm, and 45 mm for coherent, incoherent, and multiple excitations, respectively. It is seen that peak displacements of the column C1 in the platform are more than 1.5 times those of column C2 in the main station. Similar behavior is seen in the RS in Fig. 6 where the peak response amplitudes occur at frequencies 2.6 Hz and 2.2 Hz, for column C1 and C2, respectively. It is seen that higher frequencies are not affected to the column vibrations, and there is no response amplifications beyond 10 Hz. Figure 7 shows shear force distribution for column C1 for coherent, incoherent, and multiple excitations. It is seen that large shear forces at the lower end of the column with a diagonal shear force distributions indicate these columns could fail in shear. The maximum shear forces per unit length at the lower end are 586 kN/m and 611 kN/m for coherent and incoherent, respectively. Figure 8 shows results obtained from a separate nonlinear pushover analysis of a structural system with the column C1. The pushover analysis is carried out using an axial load of 180 kN/m^2 over the top slab which represents soil overburden above the station. It is seen that when the lateral displacement at top of the column C1 is 14.6 mm, rebar starts yielding, and column loses its strength when displacement reaches 25 mm.

4. Concluding remarks

The difference in structure geometric characteristics and soil condition of the platform and main station governs the behavior of two sections during the Kobe earthquake. The shear force demand and its distribution corresponding to the peak lateral displacement indicate that these columns could fail in shear due to poor detailing.

References

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