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Influence of presence of adjacent surface structure on seismic response of underground structure

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ABSTRACT

A numerical study is made on the dynamic through-soil interaction between underground station and nearby pile supported surface structure on viscous-elastic soil layer, under vertically incident S wave. This paper, as a companion of another paper written by the authors [1], focuses on the influence of presence of adjacent surface structure on seismic response of underground structure, while the reference [1] centers on the influence of presence of adjacent underground structure on seismic response of surface structure. To this end, a commercial software product for finite element analysis, ANSYS, has been further developed and enhanced for calculation in frequency domain, in which hysteretic damping can be considered for both the soil and the structures, so that structure-soil-structure interaction (SSSI) can be investigated by via a direct methodology. A discussion is made on the influence of arrangement of structures, distances between structures, shaking direction of seismic wave, shear wave velocity and damping of soil, scale and burial depth of underground structure, storey number, stiffness, style and pile length of surface structure on SSSI, in terms of horizontal relative displacement of underground structure. Maximum relative displacement responses are also presented for 12 seismic inputs. Arrangement and shaking direction are two of the most important factors. The system response can be either amplified or attenuated according to the distance between adjacent structures, related to dynamic properties of the overall system. Those underground structures, surrounded by buildings with the fundamental frequency approximate to that of free field, are heavily affected.

1. Introduction

Subway station is an essential component of a country's infrastructure as it is used for transportation of vehicles and people. For this reason, it is very important for protecting human life and its service efficiency to design subway station properly. The seismic behavior of subway station is an important aspect of its overall mechanical behavior needed for establishing rational design guidelines.

With the increasing narrowing of urban ground development space, plentiful underground space structures have been constructed under the building groups and arterial roads in urban bustling business districts. Underground structures, such as subway station and underground plaza, have become increasingly common in urban construction, and they are often close to the surrounding high-rise buildings. In the metropolitans, like Kobe in Japan, structures, such as buildings, stations and tunnels, are built closely to each other on the soft soil deposit. Under such circumstances, the dynamic interaction among structures is bound to occur through the radiation energy emitted from a vibrating structure to other structures. Hence, the dynamical characteristics and earthquake response characteristics of a structure are closely related to those of the adjacent structures.

Structure-soil interaction (SSI) is an important research topic in earthquake engineering, which has attracted extensive attention for several decades. As a branch of SSI, structure-soil-structure interaction (SSSI) is a key research topic during recent years. It is an interdisciplinary field of endeavor, which lies at the intersection of soil and structural mechanics, soil and structural dynamics, earthquake engineering, geophysics and geomechanics, material science, computational and numerical methods, and diverse other technical disciplines.

Researches on SSI originate from the vibration problem between machines and foundations, which belongs to the category of linear harmonic vibration. The influence of impedance matrix of foundations and SSI on the machine operation is studied. In the 1960s, studies on anti-seismic safety of nuclear power station hastened researches on the issue of SSI under earthquake action. Owing to the development of numerical calculation theory and computer technology, especially the

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application of finite element method and boundary element method, effective measures have been provided for seismic analysis on complicated engineering structures considering the influence of SSI. Finite element method is used to handle the problems with irregular field, while boundary element method can process the problems with infinite field conveniently. Due to the finite element-boundary element coupling method, the solution scope of SSI is further expanded. Problems, with complicated shape, flexibility, burial depth of foundation, sheet separation between foundation and base, soil layers, local topography, nonlinear characteristic can be handled via numerical discretization method. In recent years, the issue of SSI under nonlinear analysis conditions has already become the mainstream direction of research work. When various theoretical analysis methods are further studied, model test and prototype test have also attracted increasing attention from scholars, to become the new hotspot of SSI study. With the successful outcome about SSI, various kinds of theoretical methods and experimental installations are used to promote the study of SSSI.

The history and current status were elucidated by the author in another paper [2]. A simple introduction will be given here. To the writer's knowledge, it is Luco and Contesse [3] in 1973 to come up with the structure-soil-structure interaction designation for this area of study first. The steady-state response of two parallel infinite shear walls placed on rigid foundations for a vertically incident SH wave is obtained and compared with corresponding values resulting from consideration of only one structure. During this period, analytical method and semi-analytical numerical method were mainly used to study the issue of SSSI, and most of them were based on elastic half-space theory. Shallow foundation or surface foundation was adopted. Besides, system with single-particle or columnar block was used to simulate the surface structures, and some work gone so far as to simulate the foundation only, without considering the upper structures. Undoubtedly, these researches have laid a solid theoretical foundation for follow-up studies, but still cannot solve practical SSSI problems.

With the rapid development of computer technology, calculation theory, and calculation software, numerical simulation and analysis became the most extensive method to study SSSI. In the 1980s, many researchers began to conduct a study through numerical methods. In 1982, Fu and Yu [4] analyzed the dynamic response of two-dimensional SSSI system placed on elastic half-space by applying substructure method. By simplifying the surface structure into a multi-particle string system, Tian and Yu [5] studied the interaction of two multi-particle systems on the elastic half-space by solving the dynamic impedance function of soil via boundary element method for the first time. In addition, Jiang et al. [6] analyzed the interaction of two multi-particle string systems on homogeneous soil layer via finite element method. According to the results, when the distance between structures is greater than the scope of 2.5 times the structure width, the influence of SSSI can be ignored.

Later, the simulation for surface structures became elaborate. Dou and Yang [7] studied the adjacent 6-storey and 21-storey three-span two-dimensional frame structures by applying finite element method. Padron et al. [8] and Alamo et al. [9] utilized finite element-boundary element coupling method to study the influence of SSSI on transversal, vertical and torsional deformation and shearing force of several 1-storey frames under S wave and Rayleigh wave in frequency domain and time domain. In addition, Fariborz and Ali [10] analyzed the seismic response of contiguous 15-storey and 30-storey steel-frame structures. In order to obtain the dynamic response of two adjacent 12-storey frame-shear wall structures under earthquake action, Li et al. [11] conducted three-dimensional finite element model to analyze adjacent high-rise structures-pile-soil interaction system. Alam and Kim [12] explored the seismic response of two adjacent 3-storey frames considering the spatial effect of seismic oscillation. Moreover, Ghandil et al. [13] studied the applicability of equivalent linearization in SSSI system by simulating soil nonlinearity via equivalent linearization.

The lumped parameter method is a common method used to analyze SSI and SSSI, in which soil is simulated by spring, mass, and damper, or an equivalent impedance function [14]. In 1998, Mulliken et al. [15] firstly made use of this method to present efficient discrete models with frequency-independent masses, springs, and dampers. Each model has modes of vibration considered independent degree of freedom for predicting the dynamic interaction between adjacent rigid surface foundations, which are supported by a homogeneous, isotropic, and linear elastic half-space. This finding is achieved through a proposed modification of the Wilson-θ method; thus, the time-lagging effects due to wave propagation are also considered. Besides, the basic foundation interaction model is extended to the evaluation of coupled building-foundation systems. Moreover, Alexander et al. [16] applied this method to study SSSI effect. After that, Naserkhaki and Pourmohammad [17] probed into the work of Mulliken et al. [15].

Test are important means for scientists and engineers to improve humans' knowledge about the nature law. In 1980, Mizuno [18] firstly clarified actual phenomena of SSSI by a series of tests such as forced vibration tests, micro tremor or measurements and earthquake observations for a full-scale building and a model structure. In recent years, more tests have been conducted on civil structures. Yin [19] and Kang [20] analyzed the dynamic interaction of underground structure and surface structure through shaking table test and numerical analysis. Besides, Pan et al. [21] conducted a forced vibration tests on two steel frames on the shear soil box. According to the results, in SSSI system, modes of vibration with approximate two frequencies and opposite phase exist, and the frequency of mode corresponding to SSI system is between the two frequencies. In addition, Trombetta et al. [22] conducted a centrifuge test on the 1-storey steel frame and 2-storey shear wall model, which shows that the SSSI effect is relatively obvious when the seismic excitation is low. By simplifying the surface structure into a single-particle system, Xiong et al. [23] conducted a shaking table test on five adjacent single-particle systems on the shear soil box, but the test results are different from the results of Pan et al. [21] and Trombetta et al. [22] in the aspects of dynamic characteristics and seismic response respectively, showing the complexity of SSSI. By simulating the soil with foam and rubber respectively, Aldaikh et al. [24] and Cacciola et al. [25] conducted shaking table tests on several adjacent single-particle systems. Owing to the limitation of test equipment, especially shaking table test, multi-storey structures are often investigated, and soil layer with the depth of one hundred meters and even several hundred meters cannot be simulated.

Obviously, less attention is paid to the problem of the interaction of adjacent surface structure and underground structure through the underlying and surrounding soil. Many researchers have done a lot of work about dynamic response of underground structure, diffraction and scatter of wave, and effect of seismic field by underground structure, but they have ignored adjacent structure and interaction between them, such as Lee [26,27], Lin [28], Hatzigeorgiou [29], Abate and Massimino [30]. Guo and Chen [31] studied the influence of subway station on the dynamic response of a nearby 6-storey frame structure by adopting the two-dimensional model. Meanwhile, Yang et al. [32], Li and Zhou [33], and Farghaly [34] explored the influence of subway tunnel on the dynamic response of a nearby frame structure with more than ten storeys. Abate and Massimino [35–37] investigated the effects of the tunnel on the response of the soil and/or of the building and vice versa. Via full-coupled FEM modeling, a cross-section of the underground network in Catania including an aboveground building was modeled to study its behavior during the expected scenario earthquake (MS = 7.0–7.4).

Indeed, more work needs to be done in order to assess the effects of interaction between surface structure and underground structure on general three-dimensional problems with different structural and subsoil configurations, and its associated risks.

A numerical study has been made by the authors [1] on the dynamic interaction between underground station and nearby pile supported surface building on viscous-elastic soil layer, under vertically incident S