Soil Dynamics and Earthquake Engineering 79 (2015) 149–170

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Seismic analysis of the soil–structure interaction for a high rise building adjacent to deep excavation

Navid Yeganeh [a,*], Jafar Bolouri Bazaz [a], Ali Akhtarpour [a]

[a] *Civil Engineering Department, Faculty of Engineering, Ferdowsi University of Mashhad, Iran*

A R T I C L E   I N F O

Article history:
Received 21 April 2015
Received in revised form
27 July 2015
Accepted 31 August 2015
Available online 1 October 2015

Keywords:
Building–excavation interaction
High rise building
Deep excavation
Accurate instruments
Seismic analysis
$FLAC^{2D}$

A B S T R A C T

Soil–structure interaction is referred to the process in which the soil response is influenced by the structure motion while the latter is influenced by the soil motion. It is of note that the excavation adjacent to the buildings can intensify the effects of soil–structure interaction. In the current research, the soil–structure interaction model and the building–excavation interaction model along with the fixed–base structure model were analyzed on the basis of finite difference method using $FLAC^{2D}$, which is capable of analyzing the soil–structure interaction issues. Furthermore, the modified Mohr–Coulomb constitutive model was employed for the soil medium, allowing the implementation of dependency of stiffness on stress as well as the materials unloading behavior by means of the powerful programming language FISH (short for FLACish). Validation of the numerical model was accomplished based on the data extracted from the Tiltmeter installed on one of the columns of the building adjacent to the excavation and the Load Cells placed on the anchors of the excavation wall. The results illustrated that due to the high stiffness and rigidity of the retaining structure system, modeling of the building adjacent to the excavation, whether as surcharge or structural frame, would only influence the settlement profile of the building foundation under static conditions. On the other hand, in the seismic analysis, the type of modeling of the building adjacent to the excavation exerted a remarkable impact on the pile deformation, the bending moment of the pile, the condition for connection of the anchors and soil, the criteria for estimating the probable damage of the structure adjacent to the excavation, and the permanent settlement profile.

1. Introduction

Soil–structure interaction is an interdisciplinary field of science which encompasses soil and structural mechanics and dynamics, earthquake engineering, geophysics, geomechanics, mathematical–numerical methods, technical fields, and so forth [1]. Generally, the structure is considered fixed–base in calculating the force implemented by earthquake on the structure, disregarding the flexibility of the soil under the structure. Nevertheless, the past experiences and observations have indicated the fact that soil deformation changes the characteristics of the free field motion at ground level, in addition to changing the structure reaction against earthquake due to interaction with the structure [2]. As a general rule, soil–structure interaction yields certain results such as a diminishment in the base shear but an escalation in the structure period (reduction of the frequency), the system damping, and contribution of the rocking mode to the total response. Yet, it is hard to clearly discuss the $P-\Delta$ effect and lateral displacements of the structures without conducting the interaction analysis for each project.

Laying a particular emphasis on soil-structure interaction as a phenomenon influencing the dynamic behavior of structures can be traced back to early 1930s. The theory proposed by Reissner in 1936 for investigating the foundation vibrations is to be regarded as the point of departure for soil–structure interaction studies [3]. Wolf has extensively elaborated on the principles and the effects of soil–structure interaction, the modeling of soil–structure–foundation, the equations of motion as well as the analysis methods and their relevant responses [4]. There is a very limited set of criteria in the seismic design codes for scrutinizing the effects of soil–structure interaction. Meanwhile, Act ATC 3–06 [5] can be considered as the first ground rule in particularizing some guidelines to consider the effects of the interaction in the design stage of buildings. The simplified criteria of soil–structure interaction have been itemized in Acts FEMA 302 and FEMA 303 [6]. Likewise, Chapter 19 of Standard ASCE–7 [7] has addressed the impacts of soil–structure interaction in the seismic design of the building structures; nonetheless, the presented criteria only deal

* Corresponding author. Tel.: 98 9153034728.
E-mail addresses: nvd_yeganeh@yahoo.com, nvd-yeganeh@stu.um.ac.ir (N. Yeganeh).

http://dx.doi.org/10.1016/j.soildyn.2015.08.013

with shallow foundations while taking no notice of deep foundations.

The analysis methods involved in soil–structure interaction can be divided into two principal categories, namely the direct and multi-step or substructure. In the former, the entire system of the structure–foundation–soil is modeled as exhibited in Fig. 1 and is analyzed in one single step. This method is majorly advantaged with the possibility of assuming nonlinear behavior for soil and structure materials along with possibility of modeling complex geometries. Nevertheless, the method is disadvantaged with the bulky volume of inputs and outputs, its complexity, and being time consuming. However, in the latter method, the linear problem of the soil–structure interaction is split into a series of simpler problems, following which the results are incorporated using the principle of superposition [8].

Although the interaction among the building, foundation, and soil environment considerably modifies the real behavior of the structure compared to that of the fixed–base structure, implementing the effect of excavation on the soil–foundation–structure set has been sidelined in the literature. In this respect, it can be referred to a study investigating the effects of a deep excavation with 28 m maximum depth, on the seismic vulnerability of an 8–story, 2–span reinforced concrete framed structure. The plane–strain numerical analysis of the case study carried out by using the geotechnical commercial code PLAXIS and SAP software, pointed out a not negligible surge in seismic vulnerability for the R.C. structure [9]. Another research explored the effect of earthquake on an excavation with a diaphragm wall plus one row of anchors having a depth of 9.5 m and a nearby assumed 5–story concrete building in PLAXIS software, which concluded that augmenting the initial anchor pre–stressing force compared to a certain balance value keeps the final anchor force unchanged after earthquake [10]. The analyses of a 10–story building close to a 28–m excavation supported by a 0.7–m thick slurry wall using the SOIL–STRUCT program showed that the roof displacements with the settlement type of smooth asymptote are greater than that of those with concave downward asymptote. In addition, the effect of changing the steel yield stress on the roof displacements is significant; although it is the other way around for concrete building frames [11]. In some papers, a framework has been further refined and extended for the probabilistic assessment of the excavation–induced building damage and the building serviceability problems [12] and [13].

In contradiction to the building-excavation interaction issue, the soil–pile–structure interaction problem has been substantially studied. In this regard, the role of seismic soil–pile–structure interaction is usually considered beneficial to the structural system under seismic loading since it lengthens the lateral fundamental period and leads to higher damping of the system in comparison with the fixed–base assumption. It is necessary to underline that the pile foundations ascend the lateral displacements of the superstructure compared to the fixed–base assumption, and lessen the lateral displacements by comparison with the shallow foundation case owing to the rocking components [14]. Ignoring the real deformability of the soil–pile system may affect the predicted

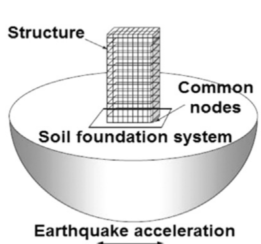

Fig. 1. The soil–structure system in the Direct Method.

damage level of structural and nonstructural elements as well as the lateral load–carrying mechanism of soil–structure systems during an earthquake [15]. The inelastic seismic behavior of soil–pile raft–structure system has been perused on the basis of the bidirectional interaction caused by ground motions which occur in two orthogonal directions and making use of a bidirectional hysteresis model which is capable of simulating biaxial interaction between deformations in two principal directions of any structural member [16].

The majority of building codes treats low and medium rise regular buildings with multi–level underground stories similar to buildings with surface foundations. Conversely, the soil–structure–interaction issue generally depends on the stiffness of the foundation and the number of underground stories so that the soil–structure–interaction effects are leading for buildings resting on flexible ground surface with no underground stories, and gradually decline with the increase of the number of underground stories [17].

Despite the fact that the accuracy of excavation analysis is affected by the corner effects [18] and a three–dimensional numerical soil–structure model treats the behaviors of the soil and the structure with equal rigor [14], the plane–strain analysis of a high rise building–deep excavation interaction is practically utilized owing to the fact that the large computer storage and computation time are normally demanding for the three–dimensional analysis of such an issue by means of the direct method. In this connection, it can be clearly emphasized that the far distant boundaries of numerical model from the excavation zone, an avalanche of structural elements and their corresponding segments, and the existing structures irregularity in plan and height, plus the inherent concept of the dynamic analysis process are the factors which might contribute to hinder the numerical analyses. Indeed, in one of papers [19] focused on differences between two–dimensional and three–dimensional analyses, the numerical modeling of a single–story, single–span building frame next to a 10–m excavation was performed with the finite element method via PLAXIS demonstrated that the bending moment at the mid–span of the structure by three–dimensional calculation is roughly 30% less than the result of two–dimensional analysis. In this issue, to avoid large numerical and time efforts, a newfangled three–dimensional finite element model is proposed utilizing linear elastic single degree of freedom structure and also a nonlinear elasto–plastic constitutive model for soil behavior proposed in order to capture the seismic soil–structure interaction [20].

While a plethora of research has been devoted to investigating the interaction between tunnels and the existing structures [21] and [22], there is a paucity of research on excavation. The current paper made use of the direct method by employing FLAC^{2D}, as finite difference software, which is capable of analyzing the soil–structure interaction.

On the whole, diverse methods have been recommended for implementing the effect of building on geotechnical modeling, which includes the surcharge method, the equivalent elastic beam method [23], and the laminate beam method [24], along with modeling the entire structural frame. The reason why the structural frame method is the most accurate modeling methodology is its consideration of the criteria needed for modeling the buildings adjacent to excavations such as the structure's weight, geometry, and stiffness. Accordingly, the current research investigated two methods for modeling the buildings adjacent to excavation, namely the structural frame method and the surcharge method.

2. The surveyed project

The application study under investigation is the International Economic and Financial Center of Mashhad (IEFCM) situated in the