Soil Dynamics and Earthquake Engineering 64 (2014) 102–112

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

Effects of deep excavation on seismic vulnerability of existing reinforced concrete framed structures

P. Castaldo [a,*], M. De Iuliis [b]

[a] Dept. of Civil Engineering, University of Salerno, Via Giovanni Paolo II, 84084 Fisciano, SA, Italy
[b] Superior Istitute "Marini-Gioia", Via Grade Lunghe, 84011 Amalfi, SA, Italy

ARTICLE INFO

Article history:
Received 18 December 2013
Received in revised form
17 May 2014
Accepted 20 May 2014
Available online 13 June 2014

Keywords:
Seismic vulnerability
Deep excavation
Ground displacements
Seismic damage indices
Soil–structure interaction

ABSTRACT

In this paper the effects of deep excavation on seismic vulnerability of existing buildings are investigated. It is well known that deep excavations induce significant changes both in stress and strain fields of the soil around them, causing a displacement field which can modify both the static and dynamic responses of existing buildings. A FEM model of a real case study, which takes into account geometry, non-linear soil behavior, live and dead loads, boundary conditions and soil–structure interaction, has been developed in order to estimate the soil displacements and their effects on seismic behavior of a reinforced concrete framed system close to deep excavation. Considering a significant accelerometric seismic input, the non-linear dynamic responses of the reinforced concrete framed structure, both in the pre and post-excavation configurations, have been evaluated and, then, compared to estimate the modification in seismic vulnerability, by means of different seismic damage indices and inter-story drifts.

1. Introduction

The growing number of urban activities is leading, more and more often, to the use of underground space for installing urban services, transportation infrastructure, parking areas or other engineering works which require the design of deep excavations near existing buildings. Excavations inevitably induce significant changes both in stress and strain fields of the soil around them and, therefore generating permanent displacements to adjacent structures and infrastructures [1,2], and potentially causing a severe damage scenario. The approaches to estimate excavation-induced vertical and horizontal displacements can be classified in two groups: (i) empirical (or semi-empirical) methods [3–6], and numerical approaches to the boundary value problem [7–11]. Only using numerical methods and modeling soil as a deformable continuum (e.g. Finite Element models), the project-specific characteristics of the excavation system can be taken into account by considering complex soil–structure interaction. It is to underline that estimation of the effects due to deep excavation is greatly characterized by statistical uncertainty. Reliability-based design methodologies have been thus proposed to estimate the static response of structures via probabilistic or semi-probabilistic analyses [12–15].

It's straightforward deep excavation-induced effects increase the structural and seismic vulnerability of existing buildings [16–18]. This is due to both the stress–strain changes in soil domain, which can modify the seismic waves propagation, and induced foundations' displacements.

Within this issue, the present paper provides a contribution by considering a real case study: the realization of a subway station in the centre of Naples (Italy). In particular, the main aim of the work consists of evaluating the impact of a deep excavation on the seismic response of an adjacent reinforced concrete building. Site condition has been modeled by using geotechnical commercial code PLAXIS (developed by Plaxis bv) and taking into account geometry, non-linear soil behaviour, live and dead loads, boundary conditions and the soil–structure interaction. A relevant accelerometric recording has been considered to evaluate the non-linear dynamic responses of the reinforced concrete building, both in the pre and post-excavation configurations, by using code SAP2000 [19]. Modification in seismic vulnerability has been estimated through different seismic damage indices and inter-story drifts.

2. Seismic damage indices for reinforced concrete structures

With reference to seismic vulnerability of existing r.c. buildings, several damage indices have been proposed [20,21] and generally classified as local or global, cumulative or not cumulative.

---

[*] Corresponding author.
E-mail addresses: pcastaldo@unisa.it (P. Castaldo), ingdeiuliis@gmail.com (M. De Iuliis).

http://dx.doi.org/10.1016/j.soildyn.2014.05.005
0267-7261/

Table 1
Park&Ang damage index values and damage states correlation [29].

Damage level	Damage description	$D_{\text{P.A.}}$
Collapse	Partial or total collapse	≥ 1.0
Severe	Plastic hinges in nodal zones	$0.6 \div 1.0$
Moderate	Concrete cover expulsion, steel bars instability	$0.3 \div 0.6$
Light	Wide cracking pattern	$0.0 \div 0.3$

As for the local indices, the simplest non-cumulative damage index refers to the ductility demand in terms of curvature, rotations or displacements [22]. Other proposals use energetic approach to describe the cumulative behaviour of non-linear response [22–24]. Considering kinematic ductility $\mu_S = x_{\max}/x_y$ as a damage variable, and its corresponding limit value $\mu_{u.mon} = x_{u,mon}/x_y$ (ultimate monotonic ductility), the ductility damage index can be defined as:

$$D_\mu = (\mu - 1)/(\mu_{u,mon} - 1) \tag{1}$$

Similarly, considering as a damage variable the hysteretic ductility $\mu_e = E_H/(F_y x_y) + 1$, where E_H is the hysteretic energy, F_y and x_y are respectively the elastic resistance and displacement, the following energy damage index was defined by Mahin and Bertero [25]

$$D_E = (\mu_e - 1)/(\mu_{e,u,mon} - 1) \tag{2}$$

A unitary value for both the ductility (Eq. (1)) and energy (Eq. (2)) indices are conventionally related to the collapse limit state.

Using more damage variables, the Park and Ang index [26] was defined as:

$$D_{\text{P.A.}} = \frac{x_{\max}}{x_{u,mon}} + \beta \frac{E_h}{F_y \times x_{u,mon}} = \frac{\mu_S + \beta(\mu_e - 1)}{\mu_{u,mon}} \tag{3}$$

The two addends in Eq. (3) respectively represent the damage related to the displacement/rotation demand (ductility index) and the hysteretic dissipated energy (energy index), properly combined by means of the coefficient β, which can be defined as the model degrading parameter [27]. The value of β can vary between -0.3 and 1.2 with an average value $\beta = 0.15$ according to experimental tests [28]. In Table 1, Park and Ang index values and related damage states are reported [29].

With reference to global damage indices, they are, generally, evaluated as a weighted average of local damage indices D_i of each structural element [20]:

$$D = \sum \lambda_i D_i \tag{4}$$

with $\sum \lambda_i = 1$ where the parameter λ_i is the weight of the damage index corresponding to element "*i*".

In this work, the ductility demand in terms of rotations and Park and Ang index, considering $\beta = 0.15$, and their corresponding global indices will be evaluated to estimate, respectively, the local damage in each plastic hinge and global damage.

3. Problem outline and proposed procedure

Evaluation of the deep excavation-induced effects on seismic vulnerability of existing buildings requires the deployment of the following three models: (i) the geotechnical model, to be defined by taking into account the soil layers, their constitutive behaviour and geotechnical parameters; (ii) the excavation system model, which depends on the geometrical characteristics of the excavation and on the construction procedures (i.e. construction phases and technologies); (iii) the structural model of the reinforced concrete system affected by the excavation-induced displacements field, which depends on the geometrical characteristics of the excavation as well as on the structural parameters affecting static and dynamic behaviour of the framed system.

Following the definition of a reliable model, different computation phases have been developed in order to compare the seismic vulnerability of existing structures between the pre and post-excavation configurations and evaluate the effects due to deep excavation. The computation phases, employed to develop a comparative analysis, can be summarised as follows:

1. estimation of displacements at the buildings' foundations both in the pre-excavation and post-excavation configurations through non-linear static analyses which explicitly take into account the soil–structure interaction;
2. dynamic characterization of both soil and structural system in order to define their fundamental vibration modes and Rayleigh damping coefficients [30];
3. non-linear dynamic analyses of the soil–structure interaction in pre and post-excavation configurations, carried out by considering a significant input accelerogram. The aim is to evaluate the deep excavation-induced effects on the stress–strain behavior of the soil and modifications in the input signal at the structural system foundations' level;
4. evaluation of the non-linear seismic responses of structural system by imposing deep excavation-induced vertical and horizontal displacements to the foundations and considering the input accelerograms related to the pre and post-excavation configurations;
5. with reference to both pre and post-excavation configurations, evaluation of seismic damage indices and inter-story drifts, in order to quantify the effects on seismic vulnerability of the structural system due to deep excavation.

4. A case study: FEM model and non-linear static analyses

The comparative analysis is developed on a case-study: the design of an underground station, part of a new subway line in the city of Naples (Italy). The Project foresees a large open-pit excavation in a densely populated area, close to existing reinforced concrete framed buildings. The main features of the excavation are: 23.6 × 85.5 m^2 rectangular-shaped pit; 28 m maximum depth, *H*; multi-propped 50 m deep T-shaped reinforced concrete slurry walls; excavation edge is 16.5 m away from reinforced concrete buildings (Fig. 1(a) and (b)).

The excavation is planned to be carried out employing a top-down method with reinforced concrete slurry walls permanently supported by two thick reinforced concrete slabs, respectively, at the top and bottom of the open pit, and four levels of temporary struts later substituted by permanent reinforced-concrete walls (Table 2). Sixteen construction stages are necessary to perform the excavation works. The plane-strain numerical analysis of the case study is carried out by using the finite element method (FEM) implemented in the geotechnical commercial code PLAXIS (developed by Plaxis bv), adopting a mesh with 15-node triangular elements. Details on the construction stages and on the structural properties, used to reproduce the system within the numerical analysis may be found in Castaldo et al. [14].

As illustrated in Fig. 2, the 3-layer simplified soil stratigraphy has been modeled as in the follow: a loose sand upper soil layer overlying a pyroclastic sandy soil layer (locally named pozzolana) and a bottom tuff bedrock. The depth of the boundary between the pyroclastic and the tuff layers is equal to 46 m. The mechanical