Free-Field Seismic Response Analysis: The Piazza dei Miracoli in Pisa Case Study

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ABSTRACT

This paper shows the results of free-field seismic response analyses (SRA), that were performed for the subsoil conditions of Piazza dei Miracoli in Pisa. The site investigation and in particular the shear wave velocity profile is extended down to 120 m below the ground level. One-dimensional SRA were carried out by using three computer codes, EERA, STRATA and ONDA. The first two codes perform the analyses in the frequency domain considering a linear-equivalent soil model. ONDA analyses the problem in the time domain assuming a true non-linear soil behaviour. In particular, the Ramberg-Osgood constitutive model, coupled with a modified Masing criterion was assumed. The computed elastic response spectra were compared to those prescribed by the Italian Building Code, which represents the Italian implementation of Eurocodes. Some details concerning the response spectra prescribed by Italian Building Code are also given.

KEYWORDS

Non-Linear Soil Behaviour, Piazza dei Miracoli in Pisa, Leaning Tower, Seismic Response Analysis, Site Effects

INTRODUCTION

The stabilisation works of the Leaning Tower of Pisa ended in 2001 (Jamiolkowski, 2001; Burland et al., 2000, 2003). The Tower was re-opened to visitors, after a closing period long at least one decade. After re-opening, works related with the material restoration of the Tower, some recovery activities for the monuments located in Piazza dei Miracoli and the monitoring of the Tower displacements were carried out (Burland et al., 2009; Squeglia & Bentivoglio, 2015).

More recently, after the seismic events that hit the regions of Central Italy, especially the Emilia Romagna earthquake in 2012 (Lo Presti et al., 2013; Fioravante et al., 2013), the interest about the seismic response of the Leaning Tower has become relevant for the Italian geotechnical community.

It is well known that the analysis of the complex dynamic soil-foundation-superstructure interaction can be simplified studying separately (Kramer, 1996):

1. The free-field response;
2. The kinematic interaction;
3. The inertial interaction.

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The first step provides an estimate of the seismic motion variation during the propagation of the seismic waves from the bedrock to the ground surface, in terms of amplitude and frequency content, due to the presence of a weaker overlaying soil deposit. Such an analysis neglects the influence of both the foundation and the superstructure.

In this work, the analyses were carried out assuming a one-dimensional geometry, the presence of vertically propagating shear waves (SH-waves) and as constitutive models for the soil deposit: a linear-equivalent and a non-linear model (Ramberg-Osgood model).

The analyses were performed with a linear-equivalent approach using the computer codes EERA (Bardet et al., 2000) and STRATA (Kottke & Rathje, 2010) and with a true non-linear analysis method using the code ONDA (Lo Presti et al., 2006).

PIAZZA DEI MIRACOLI SUBSOIL CHARACTERIZATION

Geological and Geotechnical Site Characterization

Given the historical and cultural importance of the study-site, it was possible to consider a lot of high quality data from different site investigation campaigns (Calabresi et al., 1993; Callisto, 1996; Croce et al., 1981; Costanzo, 1994; Costanzo et al., 1994; Jamiolkowski, 1999, 2001; Jamiolkowski et al., 1993; Pepe, 1995; Rampello & Callisto, 1998) to define the geotechnical model of the Piazza dei Miracoli subsoil.

The nature of the soil deposit is characterized by an extreme variability of the physical and mechanical properties. However, 3 Horizons with quasi-horizontal sub-layering were identified (Figure 1). This fact justifies the adoption of a 1D geometry.

Horizon A, extends from the ground surface down to an elevation approximately equal to 7.40 m below the m.s.l. The first three meters of Horizon A consists of man-made soil (MG) of different origins and properties, rich in archaeological finds dating back to the eighth century B.C. and the fifth century A.D.

Beneath this man-made sub-layer some lenses of sands, silts and clays having variable thickness can be found. The bottom of Horizon A, consists of uniform-medium sands with silty and clayey lenses.

Horizon B extends between the elevation of 7.40 m and 37.0 m below the m.s.l. Horizon B is split into four sub-layers. The Upper Pancone Clay, that extends down to an elevation of 18.0 m below the sea level, is a sensitive clay slightly over-consolidated (OC) with medium to high plasticity and low consistency. The Intermediate Clays are located at elevations in between 18.0 m and 22.5 m below the m.s.l. Intermediate Clays have a variable content of silt and are characterized by medium plasticity and OCR value slightly higher compared to the Upper Pancone. The Intermediate Sands are sandwiched between Upper and Intermediate Clay layers. They are grey silty sands that were deposited in a lagoon environment. Lower Clays extend from elevations of 24.5 m and 37.0 m below m.s.l. They are normally consolidated (NC) or slightly over-consolidated silty-clays with medium consistency.

Horizon C extends from the elevation of 40 m below the m.s.l. It mainly consists of aeolian sands (i.e. coastal dunes) with interbedded layers of silt and clay having micro-fauna typical of salt water and like that observed in the upper clay.

The stratigraphic profile down to 120 m below the ground level was inferred from the geotechnical campaigns that were conducted in the 90’s. These investigations showed that the sandy layers belonging to the Horizon C are not indefinitely extended and that clayey-sandy silt lenses, having variable thickness, are present everywhere at elevations approximately equal to 65.8 and 75.2 m below the m.s.l. In Table 1 are summarized the geotechnical parameters of the soil layers that were adopted to perform the seismic response analyses (Lancellotta & Pepe, 1990a, 1990b, 1993; Lancellotta et al., 1994; Lo Presti et al., 2003). Soil classification (according to USCS System) is also reported in Table 1.
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