Soil Dynamics and Earthquake Engineering 109 (2018) 33–45

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

Site response analysis of an urban area: A multi-dimensional and non-linear approach

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ARTICLE INFO

Keywords:
Seismic site response
Numerical simulation
Site effects
Finite Element method
Non-linear analysis
Multi-dimensional approaches

ABSTRACT

This paper critically examines the numerical predictions of the seismic site response of both ideal and real cases as obtained by means of mono- and multi-dimensional Finite Element (FE) approaches. Ideal case-studies are first considered, aiming at validating the adopted numerical approach against existing analytical or simple numerical solutions. Then a three dimensional model of the Bovino urban area, located in southern Italy, was generated taking into account the real site conditions. Numerical analyses were thus carried out adopting a non-linear elasto-plastic soil constitutive model implemented in a commercial FE code. The following issues were investigated in detail: geometrical schemes, horizontal direction of the input motion, calibration of the constitutive model and non-linear soil response. Most of the obtained numerical results, presented in terms of amplification factors, indicate that larger amplifications occur when the more realistic multi-dimensional schemes are adopted as compared to the mono-dimensional ones.

1. Introduction

It is well known that the seismic motion recorded at the ground surface can differ significantly, in terms of amplification, duration and frequency content, from that observed at the horizontal outcropping of the bedrock. This is due to the following issues: sequence and thickness of soil layers, shear wave velocity profile, velocity contrast between soil and bedrock, non-linear soil behaviour, topography, geometry of the soil layers and direction of the input motion. Fig. 1 shows an ideal site subjected to different amplification phenomena: topographic, related to the non-horizontal ground surface, and the so-called valley amplification, that is due to all the possible combined effects of the above mentioned issues but the topographic one. In some particular cases, characterised by both horizontal ground surface and horizontal soil layers, seismic site effects reduce only to those due to the stratigraphy, stemming from the shear wave velocity profile, and, if engaged, the non-linearity of the dynamic soil response.

The above local effects may lead, for the same seismic event, to rather different damage patterns on structures and infrastructures, sometimes triggering instability processes (e.g. landslides) induced by the combination of both local pre-existing geotechnical conditions and local seismic site amplification effects [e.g. 1,2].

In general, it is possible to recognise one-dimensional (hereafter called 1D) and two- or three-dimensional (2D and 3D, respectively) seismic site effects. The 1D ones are related to the sequence and thickness of the soil layers and to the dynamic behaviour of the soils. Thus, vertically heterogeneous media, characterised by a horizontal ground surface, are prone to 1D effects [3]. On the contrary, for areas characterised by irregular stratigraphic geometry and surface topography, the back-predictions carried out assuming 1D site conditions might differ substantially from field monitoring data, due to the above 2D and 3D effects [4].

The pioneering work of Aki et al. [5] focused on the combined geometrical and stratigraphic effects on the seismic site response. In particular, the Authors highlighted that the presence of a soft valley on a rigid bedrock leads to an amplification pattern, linked to 2D effects, which differs from that expected on the sole basis of 1D effects. In fact, the presence of a soft valley or of an outcropping hill can possibly lead to a greater amplification due to the focalisation of the seismic waves. Another possible 2D effect is that of extending the duration of the ground surface signal as compared to that observed under 1D conditions.

Most of the following studies have extended the Aki et al. [5] work focusing on 2D site effects with reference to soft valley [6–9] or irregular ground surface [10–13] configurations. Gatmiri and Arson [14] carried out a set of parametric analyses of various ideal cases

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https://doi.org/10.1016/j.soildyn.2018.02.026
Received 3 November 2017; Received in revised form 7 February 2018; Accepted 23 February 2018

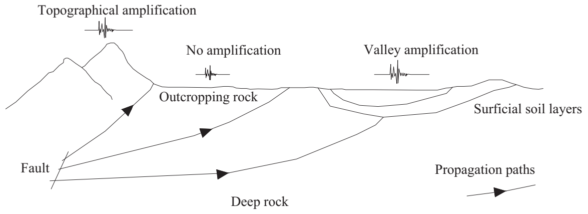

Fig. 1. Different seismic amplification phenomena for an ideal site.

characterised by 2D effects, illustrating the predictive capabilities of numerical approaches to simulate multi-dimensional seismic site response problems. Additionally, the work of Bouckovalas and Papadimitriou [15] presented numerical results for step-like ground slopes in a uniform visco-elastic soil. They concluded that even a purely horizontal excitation, as vertically propagating S-waves, results in considerable (parasitic) vertical motion at the ground surface near the slope, due to the generation of Rayleigh waves.

It is worth noting that all the above studies generally assume simplified site conditions, that are: ideal sub-interface (e.g. semi-elliptical or trapezoidal shaped contact between the soil deposit and the underneath bedrock) or hill (e.g. triangular or semi-circular) geometries, linear visco-elastic constitutive hypotheses and regular excitations (e.g. Ricker wavelet or sinusoidal signal) characterised by low frequency contents ($f_{max} < 3$ Hz).

More recently, a number of studies were focused on 3D effects with reference to both ideal case studies [16–19] and real case histories [20–26]. Once again, similarly to the 2D case studies, simplified hypotheses were generally assumed. However, 3D approaches can be extended in principle to include within a unique numerical model all the possible complexities that characterise reality, as for example nonregular ground conditions, topography and, eventually, the source of the seismic waves itself. In general, it was observed that the higher the dimensionality of the analysis, the higher the dominant frequency and the larger the maximum amplification.

In this paper, we present numerical results for the seismic site response analyses as obtained by mono- and multi-dimensional schemes, adopting a relatively advanced constitutive model to describe the soil behaviour. At first, we refer to ideal case studies in order to validate the numerical approach. Then the Bovino urban area, located in the southern part of Italy, is considered and a representative real accelerogram, with a frequency content up to 10 Hz, is selected. A detailed comparison between numerical results is presented in order to investigate the effects on the seismic site response of the following elements: geometrical schematisations, direction of application of the input motion, calibration of the constitutive model and non-linear soil behaviour.

2. Case studies

As mentioned above, this paper focuses on the class A prediction of the seismic site response of a specific urban area, named Bovino, located in the south-eastern part of Italy. Prior to carry out the detailed 3D analyses of such a case, a number of parametric analyses were carried out with reference to simplified (1D and 2D), thus idealised, schematisation of the problem, aiming at separately highlighting the different role of the many factors affecting it. In this section a description of the specific case is first illustrated, followed by the ideal analyses and, only then, by the more comprehensive 3D site response predictions.

Bovino is one of the most beautiful medieval Italian villages and is also known as the “800 portals town”. In the whole urban area complex site effects are expected, as pointed out by qualitative seismic microzonation studies [27], since the subsoil is characterised by lithological heterogeneity, significantly widespread seismic impedance contrasts and irregular topography. As such it was selected for the research activity summarised in this paper.

In the following the assumed overall geological setting is that proposed by Petti [28], Cotecchia et al. [29] and Santaloia et al. [30]; the same Authors also pointed out the presence of landslide phenomena in the same area which, however, will not be considered in the following for the sake of brevity.

The area under investigation is characterised by four geological units briefly described in the following:

- Bovino Synthem (BOV), that is a Pliocene sedimentary succession formed by silty clays with sands, lying on conglomerates and sandstones;
- Faeto Flysch Formation (FAE), which can be subdivided into an upper marly-calcareous member (FAE1) and a lower clayey-marly one (FAE2). FAE1 consists of calcarenites and calcareous marls interbedded with a few clayey levels, while FAE2 is formed by high plasticity clays, which can be locally pre-sheared, interbedded with few and thin calcareous strata;
- Unit W1, represents the either weathered or remoulded version of the above FAE2, as a consequence of either shallow landsliding or deeper and older tectonic movements;
- Unit V1, that is the result of a further fluvial remoulding of the FAE2 clays.

The geotechnical model, derived consistently with the geological one, was defined by analysing twelve boreholes and eight V_S profiles carried out in the area in order to recognise the strata characterised by the same mechanical behaviour [31]; additionally, thirty-two undisturbed soil samples were retrieved during the drilling of the continuous boreholes. The outcome of this interpretative effort led to the identification of three mechanically homogeneous geotechnical units, each characterised by average values of the unit weight, shear wave velocity, Poisson's ratio and plasticity index summarised in Table 1.

The map of the outcropping geotechnical units is sketched in Fig. 2a. In the same figure, a grid of 22 sections is presented. In particular, Fig. 2b, c illustrate the two representative Section 6 and 12. It should be noted that the first one is essentially characterised by the so called valley condition, which in this case is about 300 m large and 32 m deep. Section 12 indicates an outcropping hill, characterised by an average slope inclination of about 15%, and a valley area (large about 100 m and 30 m deep).

In general, the maximum depth of Unit 1 is about 32 m, decreasing from Section 6 to 3, while the average thickness of Unit 2 is about 10 m. Fig. 3 illustrates the thickness of Unit 1 in the investigated area, pointing out the 3D valley condition characterised by a wide irregular sub-interface.

Due to the lack of specific laboratory tests, the non-linear $G_s(\gamma)/G_0$ and $D(\gamma)$ curves for the geotechnical Units 1 and 2 were assumed from literature data [32] as a function of the plasticity index PI $= 22\%$ (Fig. 4).

The geotechnical Unit 3, considered as the seismic bedrock due to its relatively high shear wave velocity, was assumed to behave as a linear visco-elastic material: in fact, a small amount of bedrock damping, $D(\gamma) = 0.01\%$, was considered for this stratum.

Table 1
Characteristics of the geotechnical units.

Geological Unit	Geotechnical Unit	γ_{sat} (kN/m^3)	V_S (m/s)	ν	PI (%)
V1, W1[a]	1	18	200	0.25	22
W1[b]	2	18	800	0.25	22
FAE, BOV	3	18	1200	0.25	/

[a] inside the main landslide area.
[b] outside the landslide area.