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Finite element analysis of DSSI effects for a building of strategic importance in Catania (Italy)

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Abstract

Structural response to earthquakes has to be definitely considered a multidisciplinary subject, depending on many factors among which local site effects and dynamic interaction between soil, foundations and structures. The present paper deals with the multidisciplinary Dynamic Soil Structure Interaction (DSSI) analysis concerning the INGV building in Catania (Italy) by means of FEM 2D modelling. The building is a masonry structure situated in an area characterized by a high seismic hazard. The dynamic analysis was performed by adopting seven different accelerograms, scaled at the same PHA with reference to the estimated seismicity of the investigated area. Linear visco-elastic constitutive models were adopted for both the soil and the structure; nevertheless, soil non-linearity is taken into account according to EC8, adopting degraded shear modulus and increased damping ratio. The dynamic response of the system was analysed in the time and frequency domains. The main goals of the paper are: i) to investigate the amplification input effects, considering and not considering the DSSI; ii) to highlight the influence of soil layer variation in the coupled system response; iii) to compare the obtained results with the ones given by simpler 1D free-field soil analyses; iv) to compare the acceleration spectra obtained by 1D and 2D analyses with those provided by Italian technical code, NTC08. The performed analyses show the influence of DSSI in the seismic response of the system in terms of PHA and frequency contents.

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Keywords: FEM modelling; masonry structure; amplification ratios; Fourier amplitude spectra; national technical codes

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1. Introduction

Structural response to earthquakes has to be definitely considered a multidisciplinary task, depending on many factors among which local site effects [1,2,3] and dynamic interaction between soil and structures [4,5,6,7]. Dynamic Soil-Structure Interaction (DSSI) phenomena have been widely investigated since the 1970s by means of theoretical approaches [8,9], field and laboratory studies [10] as well as numerical modelling [11,12]. In particular, FEM modelling allows us full-coupled soil-foundation-superstructure analyses.

The present paper deals with the FEM 2D modelling of a full-coupled soil-structure system concerning the INGV (Istituto Nazionale di Geofisica e Vulcanologia) building in Catania (Italy), which is characterized by a high seismic hazard [13,14]. The building is a masonry structure of strategic importance. The involving soil is characterized by inclined layers, so the 2D modeling allowed us to highlight the possible influence of soil layer variation. The dynamic analysis was performed by adopting seven different accelerograms, scaled at the same PHA with reference to the estimated seismicity of the investigated area. The response of the system was analysed in the time and frequency domains. The main goals of the paper are to investigate the amplification input effects considering and not considering the DSSI; comparing the results obtained by 2D analyses with those of simpler 1D analyses [15] and with that of Italian technical code, NTC08 [16]. Soil non-linearity was taken into account according to EC8 [17].

2. The case-history

The INGV building is located in the historic center of Catania and it was built at the end of 1800. The building and its subsoil were subjected to recent investigations in the framework of the Research Project POR-FESR Sicilia 2007-2013 finalized to the reduction of the seismic risk in the Eastern Sicily. The building is a masonry structure (Fig. 1) whose bearing walls were built of lava stone; the foundations are an enlargement of these walls, and they were embedded for a depth equal to 2.5 m. The floors are in brick and concrete downloading on curbs in reinforced concrete resting on the walls. As for the soil, in 2010, the red boreholes reported in Figure 1a were executed and laboratory and in situ tests were carried out. In 2014 the blue boreholes were executed (Fig. 1a). SPT, DH, CH and SDMT were also performed. Finally, laboratory tests for soil description and classification, direct shear tests, oedometer tests, resonant column tests and torsional shear tests were carried out on undisturbed samples. Then two cross-sections were defined: the red and blue lines in Figure 1a. A third cross-section (green line) was considered in the analyses, in order to take into account a section corresponding to the Northeast façade of the building (Fig.1b). The bedrock was at about 200 m from the ground level. But in the presented analyses it was fixed at 40 m (conventional bedrock), according to previous 1D analyses, which showed no significant amplification from z = 200m to z = 40m. The adopted soil profile is shown in Fig. 1b. The main geotechnical properties are summarized in Table1, where the main mechanical parameters of the structure are also reported.

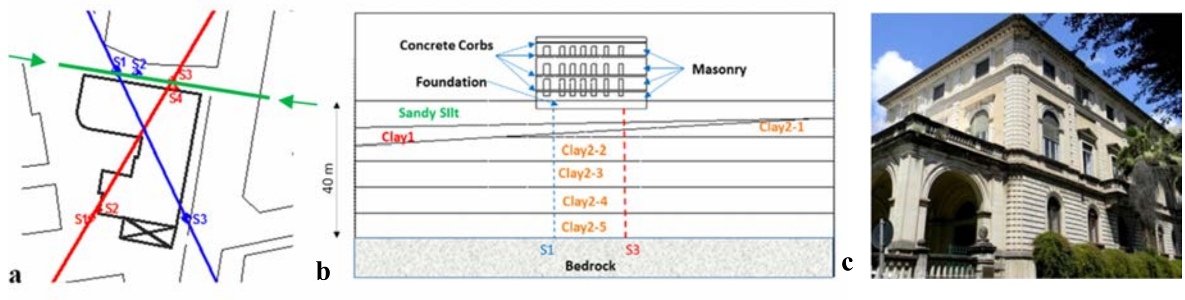

Fig. 1. INGV building: (a) plan view; (b) analysed section (see green line in Fig. 1a); (c) photo.

Table 1. Mechanical parameters for all the involved materials (α, β = Rayleigh coefficient)

Type	H (m)	V_s(m/s)	ρ (kNs^2/m^4)	G (kPa)	v	E (kPa)	D (%)
sandy silt	6.7	107.4	2.04	23531	0.3	61180	10
clay1	2.8	115.8	2.01	26953	0.4	75469	10
clay2-1	1.56	118.2	2.01	28082	0.4	78630	10
clay2-2	6.6	133.2	2.01	35662	0.4	99853	10
clay2-3	7.2	151.8	2.01	46317	0.4	129687	10
clay2-4	7.2	166.2	2.01	55521	0.4	155459	10
clay2-5	7.2	186	2.01	69538	0.4	194706	10
Masonry	-	-	-	-	0.25	861000	8
Concrete Curb	-	-	-	-	0.3	28757x10^3	5

3. Seismic inputs

Seven accelerograms were adopted as seismic inputs at the base (40 m from the ground level) of both 1D and 2D models:six synthetic accelerograms evaluated assuming the source to be along the Hyblean-Maltese fault and generating the seismic ground motion scenario (1693 earthquake) [18]; one accelerogram recorded during the 1990 earthquake at the Sortino station (Fig. 2). In order to fit the accelerograms at the reference area, they were scaled at the same maximum expected acceleration (PHA = 0.282 g), corresponding to the SLV state and considering the building as "strategic" type, according to NTC08 [16].

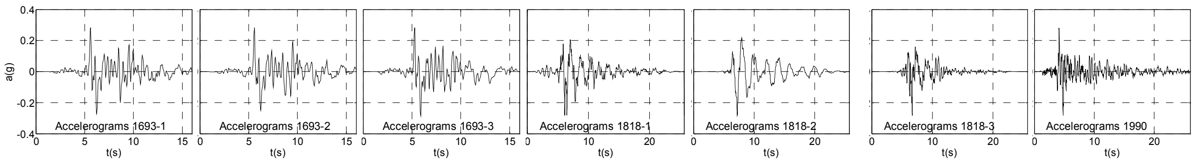

Fig. 2. Adopted inputs scaled to the same PHA = 0.282g.

4. 2D DSSI analyses

4.1. FEM modelling

In order to evaluate the seismic response of the described soil-building system, a 2D finite element modelling was developed using the ADINA code [19]. The width of the soil deposit was chosen in order to minimize as much as possible boundary effect. The height of the soil deposit derives from the previously discussed considerations about the conventional bedrock. Figure 3 shows the adopted mesh, including the geometry and the boundary conditions. The soil was divided into 6layers, some of which are inclined, according to the stratigraphy described in Figure 1. As regards the boundary conditions, the nodes of the soil vertical boundaries were linked by "constraint equations" that impose the same horizontal translation at the same depth [20]; all the nodes of the base of the mesh were restrained in the vertical direction. Special contacts were modeled between the building and the soil, in order to model possible foundation sliding and/or uplifting. Both the soil and the structure were modeled by the linear visco-elastic constitutive model. Nevertheless, soil non-linearity, extremely important in soil mechanics [21,22,23] is taken into account as suggested by EC8 [17]: thus, G_s/G_{s0} = 0.36 and D_s= 10% were fixed, with reference to the above-mentioned estimated peak acceleration at the soil surface. For the masonry the conventional properties values were adopted, according to NTC08 [16]: E_m was degraded by 50% according to [24]; D_m = 8% was chosen. Table 1 summarizes all the adopted mechanical parameters.

4.2. Results of the FEM 2D analyses

With reference to the three different alignments shown in Figure 4, the results of the 2D FEM analyses are presented in terms of amplification ratio R_a (Fig. 5a) and amplification function A (Fig. 5b): two on the left and on the right of the structure, i.e. in free-field conditions (named FF_{left} and FF_{right}, respectively) and one under the structure (named SSI). Figure 5a shows no significant amplification from 40 m up to 35 m, for all the three alignments. Then, in the FF_{left} and FF_{right} alignments, quite all the inputs de-amplify from 35m to 10m and suffer a strong amplification in the last 10m up to ground level. At the FF_{left} alignment there are values greater than those achieved for the FF_{right} alignment (about 10%); this result is due to the major thickness of the first two layers “sand” and “clay1” on the left of the structure and to the absence of the “clay2” layer, that has better mechanical characteristics than the first two ones. In the SSI alignment, the trends of R_a are similar to those obtained in free-field conditions, but the existence of the structure increases the amplification of all the signals. The computed amplification ratios are generally significantly higher than that suggested by NTC08[16], equal to 1.29. As for the comparison shown in Figure 5b, it is evident that, for the free-field conditions, the natural frequency of the soil is 0.94 Hz regardless of the soil profile, which slightly changes from right to left. Along the SSI alignment, the soil changes its frequency content: the first two fundamental frequencies of the system are f_1 = 0.88 Hz and f_2 = 3.5 Hz.

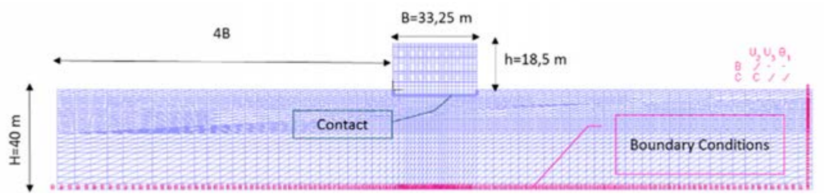

Fig. 3. Adopted mesh with geometry and boundary conditions.

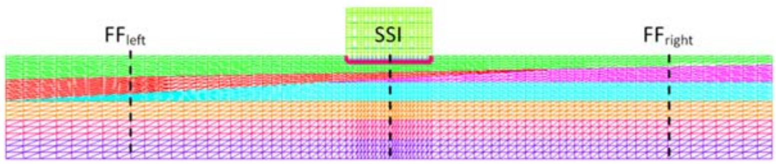

Fig. 4. Location of the three investigated alignments (different soil layer colours refer to the stratigraphy shown in Fig. 1b).

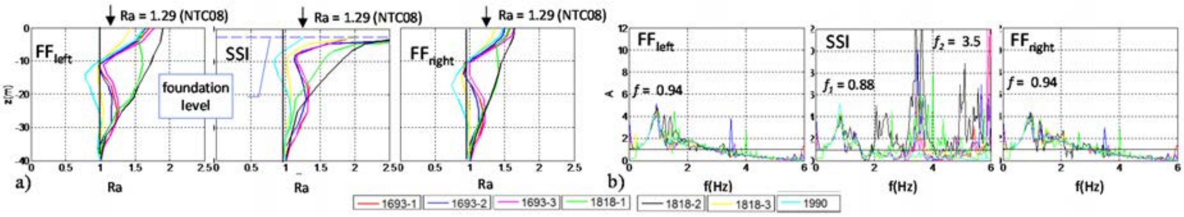

Fig. 5. Results of 2D FEM analyses: (a) amplification ratios; (b) amplification functions.

5. 1D free-field analyses

The results of the FEM 2D analyses were compared with simpler and widely used 1D analyses, here performed by means of STRATA numerical code [15]. All the three alignments FF_{left}, SSI and FF_{right} were considered, obviously ignoring the structure. Linear-equivalent-elastic analyses were performed, taking into account the soil non-linearity as before explained (Section 4.1).As in Section 4.2, the achieved results are presented in terms of amplification ratio R_a (Fig. 6a) and amplification function A (Fig. 6b).

By 1D analyses there are not evident differences among the alignments, because all represents free-field conditions and, moreover, it is not possible to model the inclination of the soil layers. The natural frequency of the soil is 1.04 Hz, which is similar to that obtained by the FEM-2D modeling in free-field conditions (f = 0.94 Hz), but different to that estimated including the structure (Section 4.2). This is one of the big limits of 1D modeling.

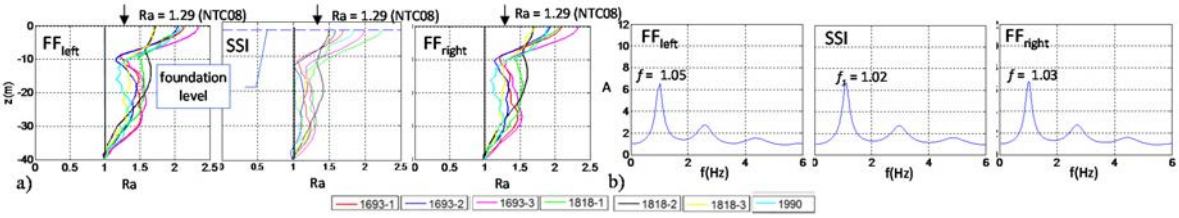

Fig. 6. Results of 1D analyses: (a) Amplification ratios; (b) amplification functions.

6. Comparison between 1D and 2D analyses

Figure 7 shows the average spectra achieved by FEM-2D modeling (red line), by 1D-modeling (green line) and according to NTC08 [16] (blue line), obtained by setting a structural damping of 8%. It is possible to notice that between the average spectra achieved for the free-field conditions (FF_{left} and FF_{right}) there are not substantial differences: a first fundamental period T = 0.42 s and a second fundamental period T = 1.27s can be observed in 1D and 2D analyses. For the central alignment, the fundamental period moves towards T = 1.27 s considering DSSI, highlighting once more the importance of multidisciplinary studies.

In general, for T ≈ 0.8-3 s, the average spectra given by the 1D and 2D analyses are more conservative then that given by NTC08 [16]. Along the central alignment (SSI alignment), by the 2D full-coupled soil-structure analysis the maximum spectral acceleration $S_{e,max}$ = 1.03 g at T = 1.28 s is obtained, while by the 1D analysis $S_{e,max}$ = 1g at T = 0.42 s is obtained. The period of the structure fixed at the base is T_{FB} = 0.4 s. The period of the structure including the subsoil is T_{DSSI} = 0.88s. Thus, according to T_{FB} 1D analysis is more severe than NTC08, while 2D analysis is less severe than NTC08. According to T_{DSSI} both 1D and 2D analysis are more severe than NTC08 and in any case 1D analysis is the most severe. Moreover, considering 2D full-coupled analysis moving from TFB to TDSSI the spectral acceleration decreases, thus neglecting DSSI is conservative. Nevertheless, for values of T slightly higher than the computed T_{DSSI} the situation changes drastically. Thus, a very careful evaluation of the design period and DSSI phenomena has to be performed through a multidisciplinary approach.

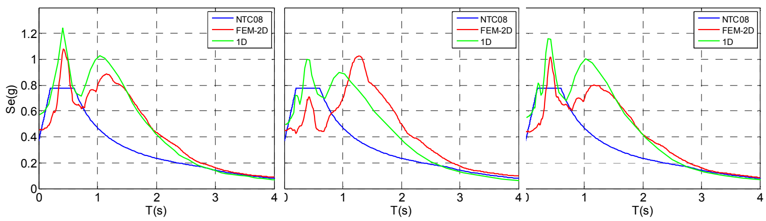

Fig. 7. Comparison among average elastic response spectra by NTC08, FEM-2D analyses and 1D analyses, along the three alignments.

7. Conclusions

The paper deals with 2D full-coupled soil-structure analyses for the strategic INGV building in Catania (Italy). Simpler 1D free-field response analyses were also performed. The comparisons of the achieved results, by the 1D analyses ignoring the structure and by the full-coupled soil-structure FEM-2D approach, shows that the computed stratigraphic amplification ratios are always greater than the value provided by NTC08. This result is more noticeable towards the southwest side of the investigated INGV site, because on the southwest side there is a soil layer with poorer mechanical properties. Moreover, the responses in frequency domain highlight the importance of performing numerical analyses that take into account DSSI phenomena, in order to observe the changes due to DSSI in terms not only of peak acceleration but also of predominant frequencies. The 1D analysis gives average response spectra more severe than that of NTC08 for all the significant periods and more severe than that given by the FEM-2D analysis for periods less than 1.2 s. The DSSI analyses provide lower values of spectral acceleration for period less than 0.7 sec, but it presents larger values for high periods, typical of structures without unrealistic fixed-base.

Acknowledgements

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References

[1] M. Maugeri, G. Totani, P. Monaco, S. Grasso, Seismic action to withstand the structures: The case history of 2009 Abruzzo earthquake. Proc. 8th World Conf. on Earthqu. Resist.Eng. Structures, ERES 2011. WIT Transactions on the Built Environment. 120 (2011) 3-14.
[2] P. Monaco, G. Totani, F. Totani, S. Grasso, M. Maugeri, Site Effects And Site Amplification due to the 2009 Abruzzo Earthquake. WIT Transactions on the Built Environment. 120 (2011) 29-40.
[3] F. Castelli, V. Lentini, M. Maugeri, One-dimensional seismic analysis of a solid-waste landfill. AIP Conference Proceedings. Volume 1020, Issue PART 1, 2008, pp.509-516.
[4] M. Loli, I. Anastasopoulos, G. Gazetas, Nonlinear analysis of earthquake fault rupture interaction with historic masonry buildings. Bullettin of Earthquake Engineering, 13 (2015) 83–95.
[5] M.R. Massimino, G. Biondi, Some experimental evidences on dynamic soil-structure interaction. COMPDYN 2015. 5th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, 2015, pp. 2761-2774.
[6] G. Biondi, E. Cascone, M. Maugeri, Displacement versus pseudo-static evaluation of the seismic performance of sliding retaining walls. Bulletin of Earthquake Engineering, 12(3) (2014) 1239-1267.
[7] E. Cascone, O. Casablanca, Static and seismic bearing capacity of shallow strip footings. Soil Dynamics and Earthquake Engineering, 84(May 01) (2016) 204-223.
[8] G. Gazetas, Analysis of machine foundation vibrations: State of the art. SOIL DYN EARTHQ ENG; 2(1) (1983) 2–42.
[9] E. Voyagaki, I.N. Psycharis, G. Mylonakis, Rocking response and overturning criteria for free standing rigid blocks to single-lobe pulses. SOIL DYN EARTHQ ENG; 46 (2013) 85-95.
[10] G. Biondi, M.R. Massimino, M. Maugeri, Experimental study in the shaking table of the input motion characteristics in the dynamic SSI of a SDOF model. Bulletin of Earthquake Engineering. 13(6) (2015) 1835-1869.
[11] D. Pitilakis, M. Dietz, D. Muir Wood, D. Clouteau, A. Modaressi-Farahmand-Razavi, Numerical simulation of dynamic soil-structure interaction in shaking table testing. SOIL DYN EARTHQ ENG; 28(6) (2008) 453–467.
[12] G. Abate, M.R. Massimino, M. Maugeri, Finite element modeling of a shaking table test to evaluate the dynamic behaviour of a soil-foundation system. AIP Conference Proceedings. Volume 1020, Issue PART 1, 2008, pp. 569-576.
[13] S. Grasso, M. Maugeri, The Road Map for Seismic Risk Analysis in a Mediterranean City. Soil Dynamics and Earthquake Engineering. 29(6) (2009) 1034-1045.
[14] A. Cavallaro, A. Ferraro, S. Grasso, M. Maugeri, Topographic effects of the Monte Po hill in Catania (Italy). Soil Dynamics and Earthquake Engineering. ISSN: 0267-7261. 43 (2012) 97-113.
[15] Kottke, Albert R., and Rathje, Ellen M., Technical Manual for Strata. PEER Report 2008/10. Univ. of California, Berkeley, California.
[16] NTC_2008. D.M. 14/01/08 - Norme tecniche per le costruzioni, Gazzetta Ufficiale Repubblica Italiana, 14-01-08 (In Italian), 2008.
[17] EC8, Design of structures for earthquake resistance. European Pre-standard. ENV 1998. Europ. Com. for Standard.Bruxelles, 2008.
[18] S. Grasso, G. Laurenzano, M. Maugeri, E. Priolo, Seismic response in Catania by different methodologies. Advances in Earthquake Engineering.Volume 14, 2005, pp. 63-79.
[19] ADINA, Automatic Dynamic Incremental Nonlinear Analysis. Theory and Modelling Guide, ADINA R&D, Inc. Watertown, USA, 2008.
[20] G. Abate, M.R. Massimino, Finite element modeling of a shaking table test to evaluate the dynamic behavior of a soil-foundation system. 2008 Seism. Eng. Int. Conf. Commemorating the 1908 Messina and Reggio Calabria Earthquake, MERCEA 2008.AIP Conf. Procs. 1020, Issue PART 1, 2008, pp. 569-576.
[21] A.Pecker, R.Paolucci, C.T.Chatzigogos, A.A.Correia, R. Figini, The role of non-linear dynamic soil-foundation interaction on the seismic response of structures. B EARTHQ ENG. 2013.
[22] G. Abate, C. Caruso, M.R. Massimino, M. Maugeri, Validation of a new soil constitutive model for cyclic loading by fem analysis. Solid Mechanics and its Applications. Volume 146, 2007, pp. 759-768.
[23] A. Pecker, C.T. Chatzigogos, Non linear soil structure interaction: impact on the seismic response of structures. Proc. XIV European Conf. on Earthquake Engineering. August 2010, Ohrid, FYROM, Keynote lecture.
[24] Circolare 02/02/09 n. 617, Istruzioni per l'applicazione delle «Nuove norme tecniche per le costruzioni» di cui al decreto ministeriale 14 gennaio 2008. Gazzetta Ufficiale Repubblica Italiana, 26-02-09 (In Italian), 2009.