

Site Response Analysis in eastern Sicily based on direct and indirect Vs measurements

Caruso S.¹, Ferraro A.², Grasso S.³, Massimino M.R.⁴

¹ Georeti S.r.l. "Geotecnica e Ricerca sulle Reti", Via Regina Margherita 367, 98028 S. Teresa di Riva, Italy; e-mail: caruso@georeti.com

² University of Catania, Department of Civil Engineering and Architecture, Viale A. Doria 6, 95125 Catania, Italy; e-mail: aferraro@dica.unict.it

³ University of Catania, Department of Civil Engineering and Architecture, Viale A. Doria 6, 95125 Catania, Italy; e-mail: sgrasso@dica.unict.it

⁴ University of Catania, Department of Civil Engineering and Architecture, Viale A. Doria 6, 95125 Catania, Italy; e-mail: mmassimi@dica.unict.it

Abstract – The paper focus on the realization of a reliable geotechnical model for a study on Seismic Response Analysis, for which one of the most important steps is represented by the accurate knowledge of shear wave velocity profiles of soil. The implementation of these tests, however, must also take into account economical aspects since, especially in some cases of minor works, it may be convenient to combine traditional tests for direct measurement of shear wave velocity (Down-Hole, Cross-Hole, SDMT) with indirect and less expensive tests (MASW).

The MASW test (Multichannel Analysis of Surface Waves), is being performed by use of vertical geophones and allows the reconstruction of the vertical profile of the velocity of the wave S based on the inversion of the dispersion curve of the Rayleigh waves. The use of this methodology is widespread for economic reasons, but requires however direct testing for an accurate validation.

I. INTRODUCTION

The city centre of Catania (Italy), which is recognized as a typical Mediterranean city at high seismic risk, was investigated by in situ tests, including also Seismic Dilatometer Marchetti Test (SDMT) and Multichannel Analysis of Surface Waves Test MASW. Seismic amplification of the ground motion phenomena were reported by historical sources following the 1693 ($M_s = 7.0-7.3$, $I_0 = X-XI$ MCS) and 1818 ($M_s = 6.2$, $I_0 = IX$ MCS) Sicilian strong earthquakes [1-4]. Seismic Dilatometer Marchetti Tests (SDMT) and Multichannel Analysis of Surface Waves Test (MASW) have been also carried out in the zone of the historical city centre, Piazza Roma, where is located the case study building of National Institute of Geophysics and Volcanology (INGV), with the aim of an accurate geotechnical characterisation, evaluating also the soil profile of shear

wave velocity (V_s). The aim of this paper is to validate the most widespread test of seismic surface for the determination of the shear wave velocity profile, by means of the measurements of the Rayleigh waves velocity. The audit was performed by comparing the results of MASW (Multichannel Analysis of Surface Waves) with direct measurements of S-wave velocity performed by SDMT (Seismic Dilatometer Marchetti Test) close to the MASW test. The test site is inside the INGV building, located in the city center (Figure 1). In order to contain the environmental noise and maximize the s/n ratio, the MASW test was performed in the courtyard behind the building and during the first daytime hours.

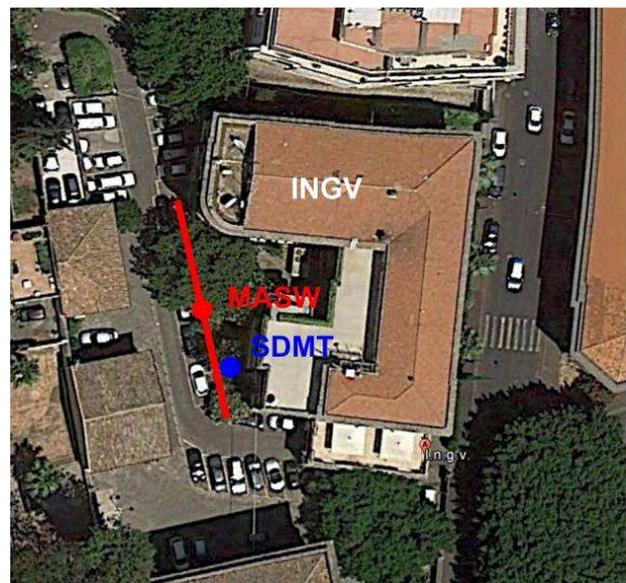


Figure 1. Location of SDMT and MASW tests in the test site of INGV building.

II. SEISMICITY AND GEOLOGICAL CHARACTERISTICS OF THE AREA

The city of Catania (Italy) was partially destroyed by the Val di Noto earthquake of January 11, 1693; the build-up areas suffered also heavy damage in occasion of the February 20, 1818 earthquake. The December 13, 1990 earthquake damaged also several public and private buildings in Catania. The Val di Noto earthquake of January, 11 1693 is the best remembered by Sicilians. The shock of January 11 which developed from the epicentre (situated at sea but not far from the coast) measured XI on MCS. The Etna earthquake that took place on February 20, 1818 was one of the feeblest ever occurred but its effects were noticed over a vast area. This event as a whole show that the quake reached the peak of IX on MCS.

Sicily consists basically of a plateau - the Hyblean Mountains - dissected by canyons and bounded towards north and west by lower, smoothly undulated to flat lands. In the Hyblean Mts., limestone, marlstone, calcarenite and intermediate rock types, mostly well lithified, are predominant.

The test site is inside the INGV of Catania (lat. 37° 30' 49" N; Long. 15° 4' 55" E), where there are lava flows, scoria cones, spatter ramparts and pyroclastic fall deposit (Pietracannone formation - lower member - Mongibello Volcano), covering the sedimentary basement consisting of blue-grey marly clays (lower-middle Pliocene). The latter emerge in the tested site. In detail, the test site consists only of sedimentary soil, as described below: 00.00 mt. - 01.50 mt.: top-soil; 01.50 mt. - 06.70 mt.: silty sand, weakly clayey, colored ranging from brown to yellowish brown; ($\gamma = 20.4 \text{ KN/m}^3$; $c' = 11 \text{ KPa}$; $\phi' = 29^\circ$), with chalky rocky elements and sandy decimetres levels with sandstone pebbles included; 06.70 mt. - 09.50 mt.: grey-yellowish clay weakly silty ($\gamma = 20.1 \text{ KN/m}^3$; $c' = 38 \text{ KPa}$; $\phi' = 16^\circ$); 09.50 mt. - 60.00 mt.: weakly silty clay blue-gray with blackish brown decimetres sandy levels ($\gamma = 20 \text{ KN/m}^3$; $c' = 51 \text{ KPa}$; $\phi' = 20^\circ$).

III. MULTICHANNEL ANALYSIS OF SURFACE WAVES (MASW) TEST

The Multichannel Analysis of Surface waves (MASW) method is one of the seismic survey methods evaluating the condition of the ground for geotechnical engineering purposes. MASW allows measurement of seismic surface waves generated from various types of seismic sources, such as sledge hammer, analyzing the propagation velocities of those surface waves, and then finally deducting shear-wave velocity (V_s) variations below the surveyed layers that is most responsible for the analyzed propagation velocity pattern of surface waves.

More convenient and better estimation of dispersion

curve can be obtained based on a multi-station test configuration (Figure 2), in which receivers are located at several locations along a straight line. The wavefield is discretized and truncated in both the time and space domain during the data acquisition.

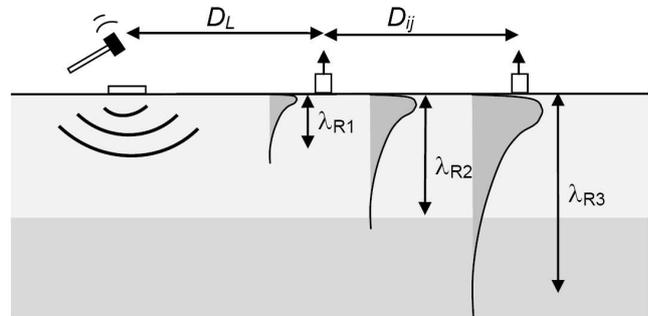


Figure 2. A scheme of multi-station surface wave testing with Rayleigh waves of different wavelengths propagating through soil.

Under most circumstances, V_s is a direct indicator of the ground strength and therefore commonly used to derive load-bearing capacity. After a relatively simple procedure, final V_s information is provided in 1-D [9].

The Rayleigh-type surface waves are generated and used to infer the shear wave velocity profile of the test site as a function of depth.

The shear wave velocity of individual soil layers is directly proportional to their shear modulus, which is their stiffness. Compared to other available methods, surface wave methods are low-cost, as well as being non-invasive and environmental-friendly since they neither require heavy equipment and nor leave lasting marks on the surface of the test site. The dispersive nature of Rayleigh-type surface waves in layered medium provides key information regarding the properties of near-surface materials.

The basis of most surface wave analysis methods is an accurate determination of the frequency-dependent phase velocity of the fundamental mode of Rayleigh waves [10]. Apart from being a function of frequency, the Rayleigh wave phase velocity is related to several groups of soil properties, most importantly the shear wave velocity of individual soil layers. Thus, by inverting the dispersive phase velocity of recorded Rayleigh waves, the shear wave velocity profile for the test site can be obtained [11].

The shear wave velocity profile can then be used to evaluate the stiffness of the top-most soil layers. Furthermore, in earthquake geotechnical design the shear wave velocity is a crucial parameter in both liquefaction potential and soil amplification assessments and when defining site-specific earthquake design loading according to Eurocode 8 [12-13].

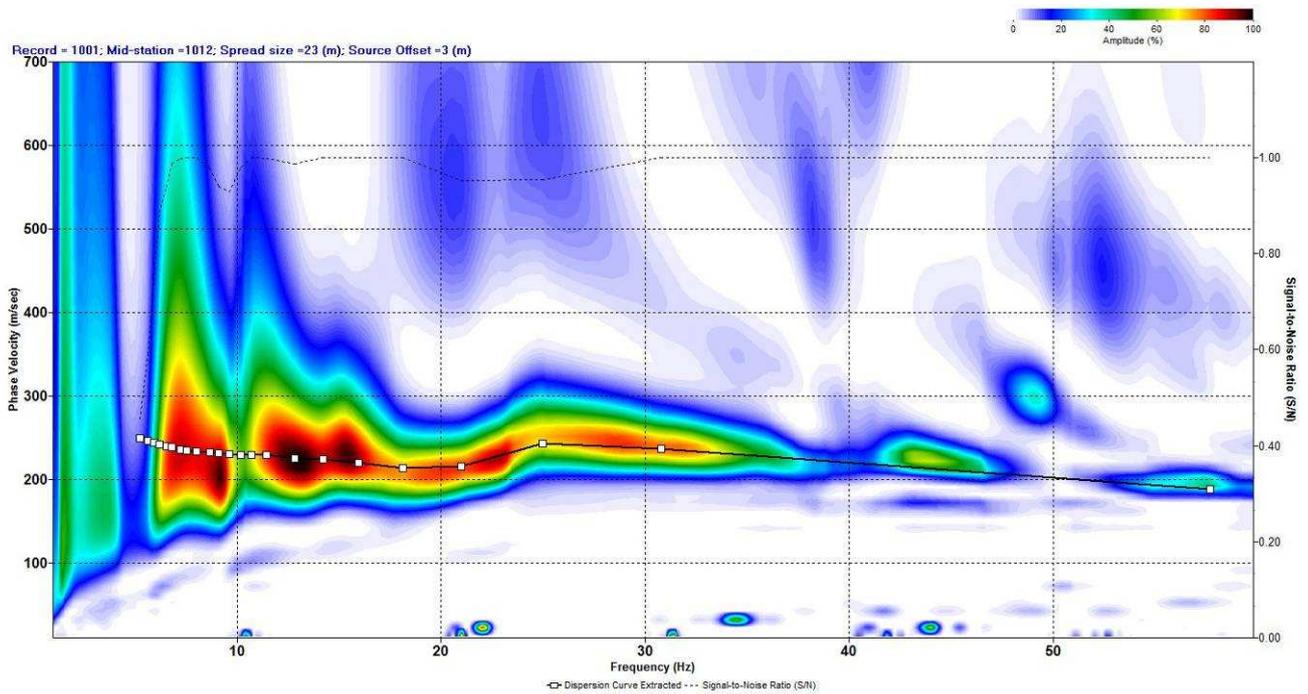


Figure 3. Spectral image (analysis Overtone) in INGV with creation of phase velocity/frequency/breadth maps.

For MASW, it has been used the DAQlink III serial number 1333. This is the third generation of portable seismograph systems. The system can be configured as a stand-alone monitoring system, a refraction system or a distributed seismic reflection system. The DAQlink III Specification are: A/D 24 bit sigma delta converter, Filters 0-10000 Hz, dynamic range 144 db, Anti-Alias Filters 85% of Nyquist frequency, Low Cut Filter User Selectable – DC, 0.1 Hz, 2 Hz, Filter Type Linear Phase, Sample Rates 1/48, 1/16, 1/8, 1/4, 1/2, 1, 2, 4, 8, 16 ms, PreAmp Gain x2 (6 dB) & x32 (30 dB) standard x1 (0 dB) & x16 (24 dB) optional, Max Input at x2 (Standard) 3.58 Volts P-P x2 (Standard) 7.16 Volts P-P x1 (Optional), Bandwidth DC to 15 kHz, Power Less than 0.4 watts per channel, Input Impedance 100k Ohms, Clock Sync GPS, Channels 24, Trigger 3-pin weatherproof. For general inversion algorithms, it's been used the SurfSeis 4.2. Using this software, the MASW method can be divided into three main steps [9]: 1. Data acquisition; 2. Dispersion analysis (Determination of a Rayleigh wave dispersion curve); 3. Inversion analysis (Determination of a shear wave velocity profile). 24 low frequency (4,5 h) geophones have been placed at a distance of 1 m between them with an impact mass of 6 kg. The seismic source was placed at a distance of 3.0, 5.0 and 7.0 m from the first geophone. Using a 1 millisecond sample rate and 1 second recording time, it has acquired the registration of 24 geophones. Subsequently, it was obtained for INGV site the spectral image (analysis Overtone) e with creation of phase velocity/frequency maps,

reported in Figure 3.

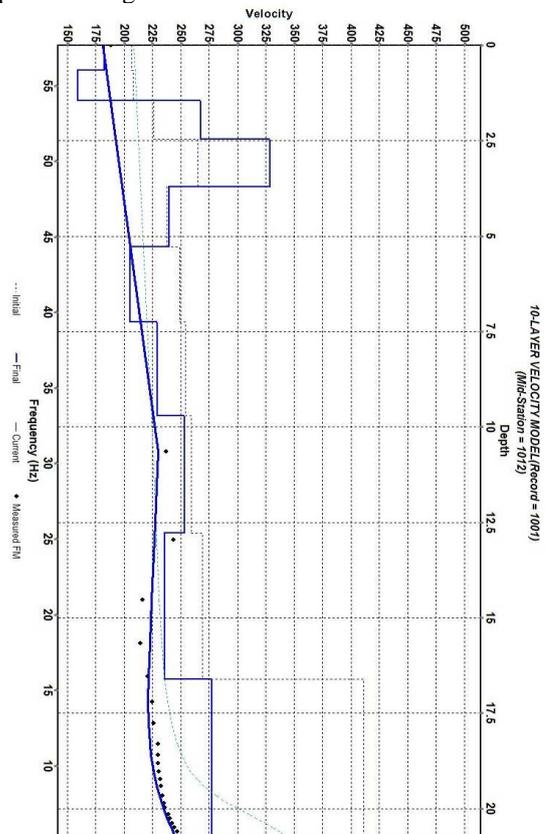


Figure 4. Experimental dispersion curve for INGV site with inversion process to ten layers velocity model.

Subsequently, it was extracted the experimental dispersion curve through interpretation of the phase velocity/frequency spectrum (overtone image), with inversion process to ten layers velocity model, reported in Figure 4.

Numerical values obtained in the interpretation are reported in Table 1.

Table 1. Numerical values of MASW test at INGV

layer	bottom depth (m)	Thickness (m)	V_s (m/s)	H / V_s (s)	RMSE
1	0.64	0.64	182.1	0.003537	5.56
2	1.45	0.81	158.7	0.005072	4.87
3	2.46	1.01	267.0	0.003768	5.42
4	3.71	1.26	328.0	0.003832	5.50
5	5.28	1.57	239.1	0.006576	5.28
6	7.25	1.96	204.4	0.009608	5.25
7	9.70	2.46	228.7	0.010739	5.20
8	12.77	3.07	253.1	0.012126	5.12
9	16.61	3.84	235.3	0.016309	5.05
10	20.76	4.15	276.9	0.014997	4.67

IV. SEISMIC DILATOMETER MARCHETTI TEST

SDMT is the combination of the standard Flat Dilatometer (DMT) introduced by [14] with a seismic module. Such module is a probe outfitted with two sensors, spaced 0.5 m, for measuring the shear wave velocity V_s . From V_s one can determine the small strain shear modulus G_0 may be determined using the theory of elasticity. The Seismic Dilatometer Test (SDMT) performed at INGV site has an effective depth of about 35 m. The SDMT [14-16] provides a simple means for determining the initial elastic stiffness at very small strains and in situ shear strength parameters at high strains in natural soil deposits. Source waves are generated by striking a horizontal plank at the surface that is oriented parallel to the axis of a geophone connects by a co-axial cable with an oscilloscope [17; 18]. The measured arrival times at successive depths provide pseudo interval V_s profiles for horizontally polarized vertically propagating shear waves. The small strain shear modulus G_0 is determined by the theory of elasticity by the well known relationships: $G_0 = \rho V_s^2$ where: ρ = mass density. SDMT obtained parameters are: Id: Material Index; gives information on soil type (sand, silt, clay), figure 5a; M: Vertical Drained Constrained Modulus, figure 5b; Cu: Undrained Cohesion, Figure 5c; Phi: Angle of Shear Resistance, figure 5d; K_D : Horizontal Stress Index, figure 5e (the profile of K_D is similar in shape to the profile of the overconsolidation ratio OCR. $K_D = 2$ indicates in clays OCR = 1, $K_D > 2$ indicates overconsolidation. A first glance at the K_D profile is helpful to "understand" the deposit).

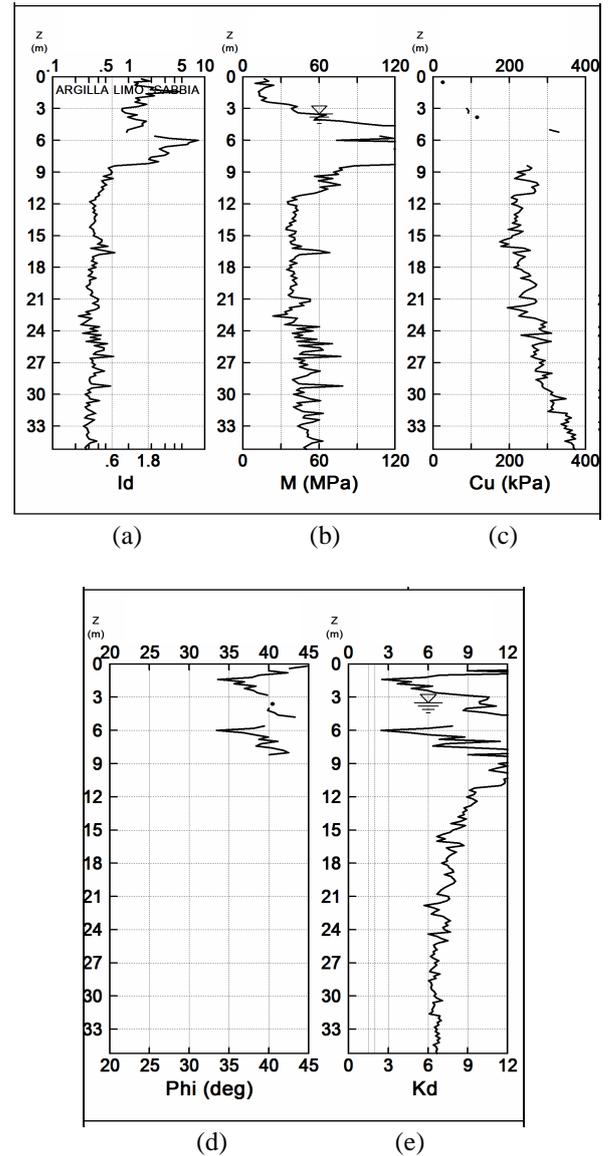


Figure 5. SDMT test at INGV site. a) Id: Material Index; b) M: Vertical Drained Constrained Modulus; c) Cu: Undrained Cohesion; d) Phi: Angle of Shear Resistance; e) K_D : Horizontal Stress Index.

Shear Waves Velocity profile obtained by SDMT is reported in Figure 6.

V. COMPARISON OF THE RESULTS

The comparison between the results of MASW and SDMT tests performed at INGV site in terms of V_s profiles, is reported in Figure 7. The two tests show comparable values of shear wave velocity V_s , except in the range 4,0 m - 8,5 m for which the results of SDMT test show higher values of V_s . Probably this is due to a disturbing factor in the upper soil strata.

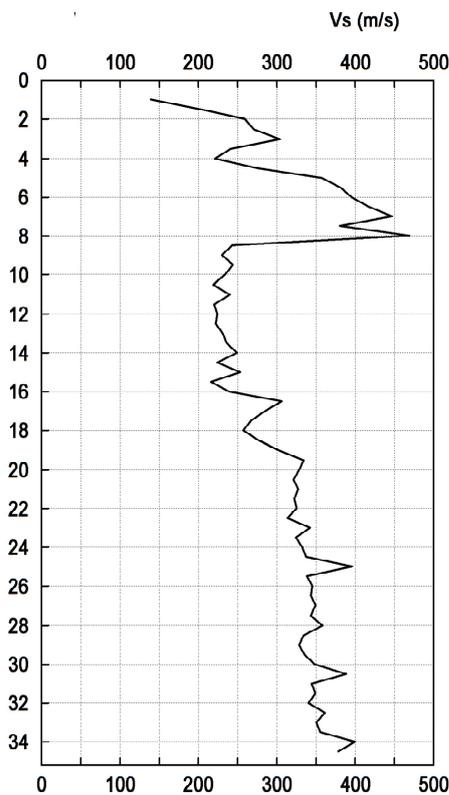


Figure 6. Shear Waves Velocity profile obtained by SDMT.

VI. CONCLUSIONS

In this paper some information concerning the geotechnical characterisation of a test site in the city of Catania (Italy) have been presented. It focused about the direct and indirect methods on Vs measurements performed through in-situ tests. The comparison between the results of MASW and SDMT tests performed at INGV site in terms of Vs profiles, show very comparable values of shear wave velocity Vs. Also the V_{s30} values are comparable between the two tests: V_{s30} MASW = 250 m/s, V_{s30} SDMT = 280 m/s. Thus it can be easily obtained a reliable geotechnical model for the study on Seismic Response Analysis, for which one of the most important steps is represented by the accurate knowledge of shear wave velocity profiles of soil. Similar studies have been performed for the zonation on seismic geotechnical hazards and also for soil-structure interaction [19-21] and retrofitting [22-26] in other sites of the city of Catania (Italy) and for the Abruzzo Region (Italy) during L'Aquila earthquake [27-30].

VII. REFERENCES

[1] Grasso S., Maugeri M. The Road Map for Seismic

Risk Analysis in a Mediterranean City. Soil MASW - SDMT

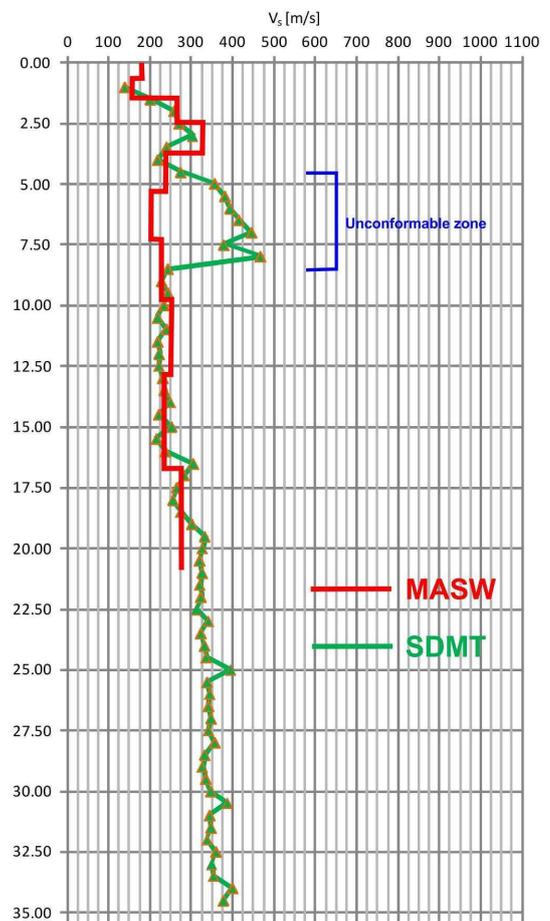


Figure 7. Comparison in terms of Vs values between MASW test and SDMT test performed at INGV.

Dynamics and Earthquake Engineering. ISSN: 0267-7261. Vol. 29 No. 6 (2009): 1034-1045. doi: 10.1016/j.soildyn.2008.12.001.

- [2] Grasso S., Maugeri M. The Seismic Microzonation of the City of Catania (Italy) for the Maximum Expected Scenario Earthquake of January 11, 1693. Soil Dynamics and Earthquake Engineering. ISSN: 0267-7261. Vol. 29 No. 6 (2009): 953-962. doi: 10.1016/j.soildyn.2008.11.006.
- [3] Maugeri M., Grasso S. The Seismic Microzonation of the city of Catania (Italy) for the Etna Scenario Earthquake (M=6.2) Of February 20, 1818. Earthquake Spectra. February 2012. ISSN: 8755-2930. DOI: 10.1193/1.4000013.
- [4] Cavallaro A., Ferraro A., Grasso S., Maugeri M. Topographic effects of the Monte Po hill in Catania (Italy). Soil Dynamics and Earthquake Engineering. ISSN: 0267-7261. Vol. 43 (2012), pp. 97-113. doi: 10.1016/j.soildyn.2012.07.022.
- [5] Bonaccorso, R., Grasso, S., Lo Giudice, E., Maugeri, M. Cavities and hypogeal structures of the historical part of the City of Catania. Advances in Earthquake

- Engineering. Vol. 14, 2005, pp. 197-223.
- [6] Grasso, S., Maugeri, M. Vulnerability of physical environment of the City of Catania using GIS technique. *Advances in Earthquake Engineering*. Vol. 14, 2005, pp. 155-175.
- [7] Grasso S., Laurenzano G., Maugeri M. And Priolo E. Seismic response in Catania by different methodologies. *Advances in Earthquake Engineering*. Vol. 14, 2005, pp. 63-79.
- [8] Grasso S., Maugeri M. Seismic Microzonation Studies for the City of Ragusa (Italy). *Soil Dynamics and Earthquake Engineering*. ISSN: 0267-7261. Vol. 56 (2014), pp. 86–97. doi: 10.1016/j.soildyn.2013.10.004.
- [9] Dorman, J., Ewing, M. Numerical inversion of seismic surface wave dispersion data and crust-mantle structure in the New York-Pennsylvania area. *Journal of Geophysical Research*. Volume 67, Issue 13, December 1962, Pages 5227–5241.
- [10] Park, C.B., Miller, R.D., Xia J. Imaging dispersion curves of surface waves on Multichannel records. *Kansas Geological Survey*. 1998. ISSN (print): 1052-3812. ISSN (online): 1949-4645. Society of Exploration Geophysicists.
- [11] Miller, R.D., Xia, Park, C.B., Ivanov J. Using MASW to map bedrock in Olathe, Kansas. *Kansas Geological Survey*. 1999. ISSN (print): 1052-3812. ISSN (online).
- [12] Bessason B., Erlingsson S. Shear wave velocity in surface sediments. *JÖKULL* No. 61, 2011, pp. 51-64.
- [13] Chih-Ping Lin, Cheng-Chou Chang, Tzong-Sheng Chan. The use of MASW method in the assessment of soil liquefaction potential. *Soil Dynamics and Earthquake Engineering*. 24 (2004) 689–698.
- [14] Marchetti, S. In Situ Tests by Flat Dilatometer. *Journ. of the Geotech Eng Div., ASCE*, Vol. 106, N°. GT3, March, 1980, pp. 299-321.
- [15] Marchetti S., Monaco P., Totani G., Marchetti D. In Situ Tests by Seismic Dilatometer (SDMT). In: "From Research to Practice in Geotechnical Engineering", ASCE Geotech. Spec. Publ. No. 180 Honouring John H. Schmertmann, 292 - 311.
- [16] Monaco P., Marchetti S., Totani G., Marchetti D. Interrelationship Between Small Strain Modulus G_0 and Operative Modulus. In: Kokusho, Tsukamoto and Yoshimine (eds), *Proc. Int. Conference on Performance-Based Design in Earthquake Geotechnical Engineering (IS-Tokyo 2009)*, Tsukuba, Japan, June 15-17, 1315-1323. Taylor & Francis Group, London.
- [17] Martin, G.K. and Mayne, P.W. Seismic Flat Dilatometer Tests in Connecticut Valley Varved Clay. *ASTM Geotech. Testing J.*, 20(3), pp. 357-361.
- [18] Martin, G.K. and Mayne, P.W. Seismic Flat Dilatometer in Piedmont Residual Soils. In P.K. Robertson and P.W. Mayne (eds), *Proc. 1st Int. Conf. on Site Charact.*, Atlanta, 2, pp. 837-843.
- [19] Massimino M.R., Biondi G. Some experimental evidences on dynamic soil-structure interaction. *COMPADYN 2015 - 5th ECCOMAS Thematic Conference on Comp. Methods in Structural Dynamics and Earthquake Engineering*; Crete; Greece; 25- 27 May 2015; Pages 2761-2774.
- [20] Abate, G., Massimino, M.R., Maugeri, M. Numerical modelling of centrifuge tests on tunnel–soil systems. *Bulletin of Earthquake Engineering*. Volume 13, Issue 7, 28 November 2015, Pages 1927-1951.
- [21] Abate, G., Massimino, M.R., Maugeri, M. Finite element modeling of a shaking table test to evaluate the dynamic behaviour of a soil–foundation system. *AIP Conference Proceedings*. 2008 Seismic Engineering Int. Conf. Commemorating the 1908 Messina and Reggio Calabria Earthquake, Reggio Calabria; Italy; 8 - 11 July 2008. Vol. 1020, 2008, Pages 569-576.
- [22] Castelli F., Maugeri M. Post-earthquake analysis of a piled foundation. *Journal of Geotechnical and Geonvironmental Engineering*, ASCE, 2013, Vol.139, no.10, pp.1822-1827.
- [23] Castelli F., Maugeri M. Dynamic characterization of municipal solid waste by SDMT. *Proceedings of Coupled Phenomena in Environmental Geotechnics, CPEG2013*, July 1-3, 2013 - Torino (Italy), pp. 307-312.
- [24] Castelli F., Lentini V., Maugeri M. Dynamic clay properties by in situ and laboratory tests for an industrial building in Catania (Italy). *Proceedings of the Second International Conference on Performance-Based Design in Earthquake Geotechnical Engineering*, II PBD, May 28-30, 2012 - Taormina (Italy), paper no.02.15, 13 pp.
- [25] Castelli F., Lentini V., Pavese A., Casarotti C., Peloso S. Valutazione della vulnerabilità sismica di edifici strategici: il caso del palazzo della Prefettura di Enna. *Atti XXV Convegno Nazionale di Geotecnica*, Baveno, 04-06 Giugno 2014, Vol. II, pp. 85-92.
- [26] Maugeri M., Castelli F. Post-earthquake analysis for a seismic retrofitting: the case history of a piled foundation in Augusta (Italy). *Geotechnical, Geological and Earthquake Engineering- Perspectives on Earthquake Geo-technical Engineering*, In Honor of Prof. Kenji Ishihara, Volume no.37, pp.415-441.
- [27] Maugeri, M., Simonelli, A.L., Ferraro, A., Grasso, S., Penna, A. Recorded ground motion and site effects evaluation for the April 6, 2009 L'Aquila earthquake. *Bull Earthquake Eng* (2011) 9, pp.157–179. DOI 10.1007/s10518-010-9239-x. ISSN: 1570-761X (print version), ISSN: 1573-1456 (electronic version).
- [28] Monaco P., Santucci De Magistris F., Grasso S., Marchetti S., Maugeri M., Totani G. Analysis of the liquefaction phenomena in the village of Vittorito (L'Aquila). *Bull Earthquake Eng* (2011) 9, pp. 231–261. DOI 10.1007/s10518-010-9228-0. ISSN: 1570-761X (print version), ISSN: 1573-1456 (electronic version).
- [29] Monaco P., Totani G., Totani F., Grasso S., Maugeri M. Site Effects And Site Amplification due to the 2009 Abruzzo Earthquake. *WIT Transactions on the Built Environment*. Vol 120: 29-40. In: *Proc. of the Eight International Conference on Earthquake Resistant Engineering Structures*. Chianciano Terme, September 7-9, 2011, p. 29-40, ISBN: 978-1-84564-548-9.
- [30] Maugeri M., Totani G., Monaco P., Grasso S. (2011b). Seismic Action to Withstand The Structures: The Case History of 2009 Abruzzo Earthquake.. *WIT Transactions on the Built Environment*. Vol 120: 3-14. In: *Proc. of the Eight International Conference on Earthquake Resistant Engineering Structures*. Chianciano Terme, Sept. 7-9, 2011, p. 3-14, ISBN: 978-1-84564-548-9.