SOIL AMPLIFICATION IN SANTIAGO DE CUBA

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Introduction. The Cuban territory is placed on the border between the Gonave Microplate and the North American Plate. The city of Santiago de Cuba is located in the south-eastern part of Cuba island, very close to the Oriente Fault Zone, which is the main tectonic feature of the plate boundary in the eastern part of Cuba. South-eastern Cuba is the most tectonically active region throughout the country and the largest earthquakes occurred there. In fact, 22 of the 28 major catastrophic events in the history of the island were located in this part of Cuba (Chuy, 1999). The earthquakes causing of the most damaging effects in the area of Santiago de Cuba occurred in 1766 and 1852, with Imax = IX MSK, and 1932, with Imax = VIII MSK [where MSK is the Sponheuer-Medvedev-Karnik macroseismic intensity scale (Medvedev *et al.*, 1964)].

The municipality of Santiago de Cuba, with a population of nearly half a million inhabitants (492,891), is the second most populated city and one of the oldest of the island. The city is located in a sedimentary basin around the Santiago de Cuba Bay, which is connected southwards to the Caribbean Sea. The reliefs around the basin are semi-mountainous with several marine terraces and the coastal plains and plateaux are found in the proximities of the coast. The basin of Santiago de Cuba is a depression caused by the subsidence of the area.

For commercial reasons and from the constructive point of view, the settlements developed around the bay, where recent sediments of Neogene-Quaternary age outcrop. These soft sediments cause that the effects of the earthquakes are more intense causing panic among residents and structural damage to buildings in some cases.

The constant population growth and the frequent seismic activity in the region have motivated the development of various research projects aimed at reducing the seismic risk. Currently, the National Seismological Research Center, in collaboration with the National Institute of Oceanography and Experimental Geophysics, is developing a project with the goal of improving the seismic hazard estimates of the Cuban national territory, considering the detailed characteristics of the soil: Santiago de Cuba has been taken as a study case.

The aim of this work is the elaboration of the soil amplification map for Santiago de Cuba, from the definition of a 3D geotechnical model of the terrain and 1D and 2D modelling of the local response of soils. The information given by the map of the amplification factors (AFs) for Santiago de Cuba is fundamental in urban planning and designing and can be used also in investigations and actions aimed at seismic risk reduction.

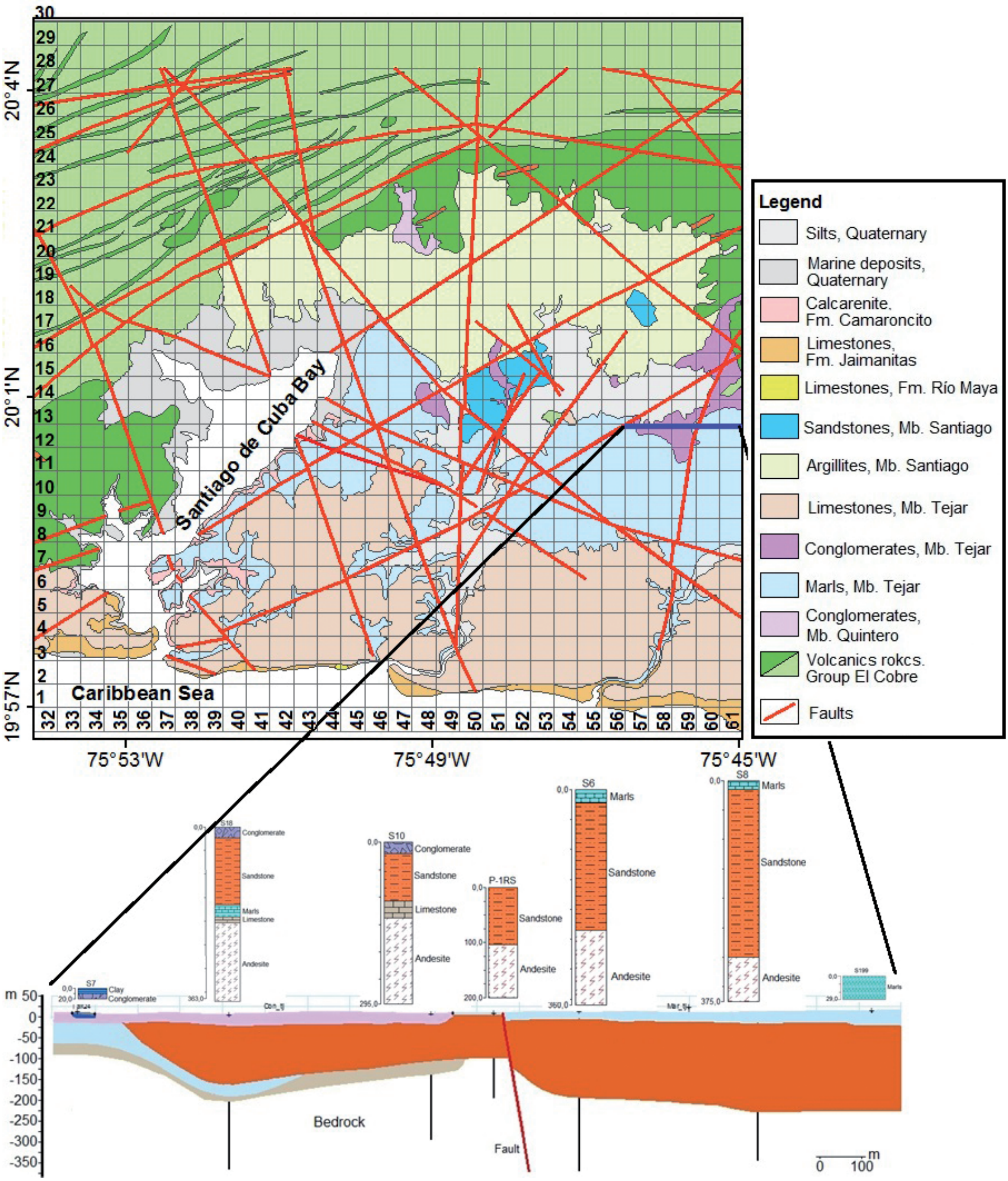

Fig. 1 – Summary of the main stratigraphic units present in the study area with distribution of the 61 profiles (grey lines) and an example of geological interpretation in depth.

Basic data. The geology of Santiago de Cuba (Fig. 1) is characterized by the presence of volcanic and volcanic-sedimentary rocks of Paleogene age, such as: tuffs, tuffites, lavas, and so on, often crossed by intrusions of igneous rocks; this group crops out in the mountainous parts and also in other parts of the city. Marls, conglomerates, argillites, and limestones of Neogene age, occupy almost the entire basin, plateaux and the coastal hills. Recent sediments of Quaternary age, such as clays, sands, and gravels [for more details, see Rivera *et al.* (2013)] are located in the proximity of the coast and floodplains. The basement of the basin is mainly constituted by Paleogene rocks, volcanic-sedimentary rocks of the Cobre Group and some bodies of andesite and basalt (Medina *et al*., 1999).

The study area is crossed by numerous geologically active normal and strike-slip faults (Medina *et al*., 1999), these faults cut the basin with different directions but without any documented seismicity. However, they play an important role in characterizing the deep geometry of the basin and, consequently, they condition the local amplification characteristics of the soils. The main seismotectonic structure of southern Cuba is the Oriente Fault, it constitutes a displacement fault that causes the horizontal translation of tectonic blocks. Its geometry and tectonic regime were better defined by Calais and Mercier de Lépinay (1990, 1991) through the interpretation of marine geophysical data. Moreno *et al*. (2002) characterized the activity of the local faults and their stress regime.

We have developed a 3D geotechnical model of the Santiago de Cuba (Rivera *et al*., 2013) on the basis of 61 geological profiles (Fig. 1) calibrated on all the available geological [geological-tectonic map of Santiago de Cuba at the scale 1:25,000 of Medina *et al*. (1999) and stratigraphic Cuban lexicon of Carrillo *et al*. (2009)], geophysical (electrical and seismic soundings), and geotechnical (geological and geotechnical boreholes) data. These profiles cross the entire city in a regular grid of 500 m × 500 m and take into account the superficial and deep soil topography, the shear wave velocity (V_S) in each layer, and the physical-mechanical properties of the layers themselves. The geological model has, then, identified the areas where a 1D or 2D modelling is more suitable.

The deep geological and geotechnical information come from several geotechnical surveys: 550 soil profiles from geotechnical boreholes, performed by a local engineering and geological research institution (ENIA-Santiago) belonging to the Cuban Ministry of Construction, and 11,120 logs of geological borings from the Geominera East Company (EGMO), collected in a data set by Mendez *et al*. (2001).

The two methods of local geophysical prospecting of refraction seismics and electrical resistivity were performed along 33 seismic profiles. Twelve 10-Hz vertical geophones, disposed equidistantly, were used in the first method, aiming at determining the velocity variations of the longitudinal waves in depth according to the different layers; the ground was energized by a 10-kg hammer on an aluminium plate. Sixteen steel electrodes, disposed equidistantly with respect to the site, were used in the second method, aiming at determining the distribution of the lithological heterogeneities in the ground. These methods have the limitation that only the surficial layers can be characterized.

All information about the stratigraphic wells, together with all tectonic and geophysical data, were stored in several databases, with their coordinates, maximum depth, phreatic level, thickness, lithological description, stratigraphic characteristics, and physical-mechanical properties of each layer.

The electrical resistivity values derived from the interpretation of the cited profiles were adjusted in accordance with those obtained by Orellana (1982), Das (2001), and Loke (2004). The velocity of the longitudinal waves, obtained by $V_S = V_P \cdot 1.74$ (Moreno *et al*., 2002), was compared with that obtained by Redpath (1973) and Das (2001), and confronted with the interpretation of the electrical resistivity (tomography) and of the geological wells nearby to geophysical profiles.

The velocity at the different depths for each material has been calculated from the geophysical characteristics of the outcropping layers of that material, neglecting the superficial layers with a depth less than 1 m and taking into account its maximum depth. For the deeper layers, where it was not possible to calculate the velocity experimentally, we have taken into account the average values of densities and seismic wave velocities (Sadovskii *et al*., 1973). In this way, we have obtained a trendline that allows us to calculate the velocity values in any point of the deep layers (Tab. 1). The density values (Tab. 1) were obtained from the data of the geotechnical boreholes and compared with the available literature (NAVFAC, 1982).

Tab. 1 - Average velocities (V_S) and depth (h) for main materials in the study region.

Soil	Density (kg/m^3)	Av. Vs (m/s)	Av. Depth (m)	Trendline
Silty clay	1.85	179	2.19	$V_s = 3.2591 \cdot h + 171.86$
		400	70.00	
Clay	1.87	290	3.18	$V_s = 1.566 \cdot h + 285.02$
		700	265.00	
Sand	1.89	348	4.20	$V_s = 2.5251 \cdot h + 337.39$
		600	104.00	
Gravel and sand	1.91	443	4.27	$V_s = 1.5107 \cdot h + 436.55$
		500	42.00	
Conglomerate	1.95	300	3.00	$V_s = 5.9524 \cdot h + 282.14$
		800	87.00	
Marl clay	1.93	438	5.60	$V_s = 3.7945 \cdot h + 416.75$
		800	101.00	
Sandstone	1.94	504	8.92	$V_s = 1.3795 \cdot h + 491.69$
		700	151.00	
Limestone marl	2.04	622	8.06	$V_s = 1.936 \cdot h + 606.4$
		800	100.00	

Soil classification. The geology of the site has been often used to justify the local shaking increase observed during earthquakes. Many researchers have proposed empirical correlations between surface geology and local seismic severity. The use of surface geology in seismic microzoning is very practical and applicable to many areas. In this work, we have used the geological map of the region (Medina *et al.*, 1999) to define a soil classification and get an approximate estimation of the local effects. The various stratigraphic units have been classified according to the NERHP (BSSC, 2001) provisions (Tab. 2 and Fig. 2).

Tab. 2 - Soil classification according to the NERHP provisions (BSSC, 2001) for the stratigraphic units in the study area.

Stratigraphic units	Geological description	NERHP
Fm Varadero	Marine beach deposits.	E
Fm Río Macío	Deposits of alluvial valleys.	E
Fm Jaimanitas	Biodetrital limestones, carz, very fossiliferous with shell and corals.	B
Fm Camaroncito	Calcarenite with gravel	C
Fm Río Maya	Biohermal limestone, dolomite, clays and intercalation of polimictict conglomerates.	B
Mb Santiago	Calcareous argillite, silty sands wih intercalation of aleurolite and calcilutites.	D
Mb Tejar	Biodetritical limestones, calcareous sands, marls, calcarenite, conglomerates and polymictict grits.	C
Mb Quintero	Polimictict conglomerates.	C
Gp El Cobre	Volcanic and volcanic-sedimentary rocks. Tuff, tuffites, limestones, lapilli, lavas.	B

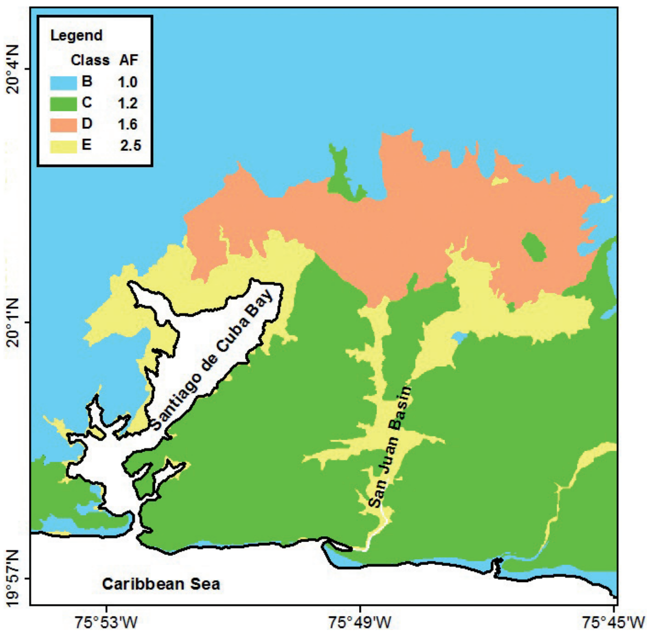

Fig. 2 – AFs for the Santiago de Cuba broader region according to the NERHP (BSSC, 2001) provisions on the basis of soil types derived from surficial geology.

1D modelling of site effects. The local seismic response is a very important task as the ground shaking caused by earthquakes can be significantly amplified by the soil geotechnical characteristics, causing localized heavy damage to buildings and population. 1D and 2D modelling techniques are applied to quantify the soil amplification with respect to the expected ground motion at bedrock.

From the geotechnical model (Rivera *et al.*, 2013), we have obtained 225 stratigraphic models for the whole study area (15 km × 15 km). We have considered a grid of points every 250 m, associating each of them to a stratigraphic model. The uniform hazard response spectra (UHRSs) at bedrock calculated by Alvarez *et al.* (2015) have been taken as ground shaking, considering a partition of the study region into 6 sub areas.

Two techniques for soil modelling have been applied: a 1D modelling of seismic wave propagation in a stratified halfspace, and a 2D modelling using the boundary element technique in a lineal analysis. The 1D modelling [software PSHAKE by Sanò and Pugliese (1991)] was applied in sectors where the geotechnical model shows a homogeneous soil behaviour in depth (almost flat parallel layers). The 2D modelling [software BESOIL by Sanò (1996)] was used in areas of complex stratification with strong lateral variations; this code applies a fast numerical calculation of the seismic wave propagation in space. Both modelling techniques request the geometry of the different soil layers and their geotechnical properties (V_S, density, Poisson coefficient, damping). The modelling of the wave motion has been calculated from the bedrock depth to the free surface.

The AF for each model has been estimated as the ratio of the output over the input spectrum in the range of periods from 0.1 to 0.5 s. Fig. 3 shows the values of the AFs obtained for Santiago de Cuba. No amplification is expected along the coast of the Caribbean Sea with the exception of a small portion to the SW, where Quaternary sediments appear. A similar behavior can be seen to the north and west of the bay, where volcanogenic sedimentary rocks outcrop. A small sector located to the east of the bay shows deamplification: it coincides with more than 100-m thick sandstones. The largest amplifications refer to low compact soils (for example clay, sand or gravel).

Comparison between local AFs and those of building codes. AFs based on the NERHP (BSSC, 2001) soil classification have been defined in addition to the local AFs calculated by modelling. The AFs computed by soil modelling (Fig. 3) differ from those obtained from the soil classification (Fig. 2) by the NEHRP provisions (BSSC, 2001) because both 1D and 2D modelling techniques take into account various soil parameters than shallow geological characteristics only, they are: the complete stratigraphic section from the free surface to the bedrock, the thicknesses of the various layers with the respective values of density and velocity, the degradation curves of each material and the specific UHRS for each site.

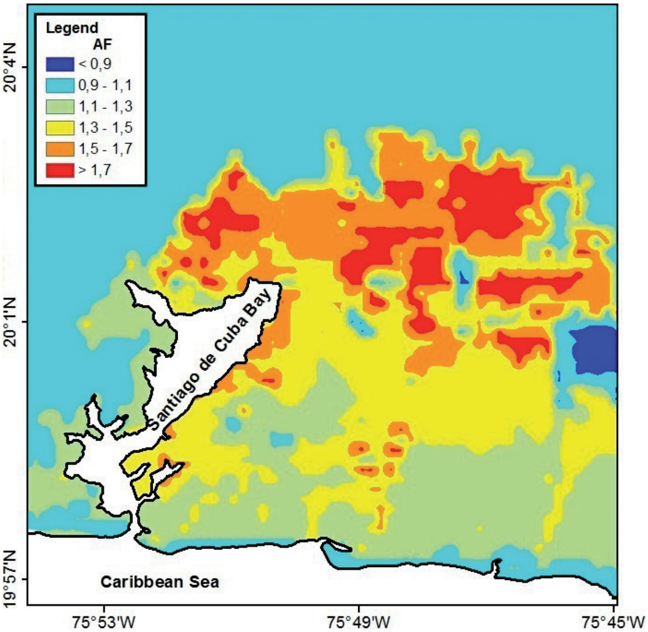

Fig. 3 – AFs for the Santiago de Cuba broader region computed from 1D and 2D modelling as the ratio of the output over the input UHRS in the range of periods from 0.1 to 0.5 s.

The AFs based on the NERHP (BSSC, 2001) soil classification (Fig. 2), show a high amplification (AF from 1.6 to 2.5) where Quaternary sediments and argillites of the Mb. Santiago outcrop. More precisely, the highest amplifications (2.5) are estimated around Santiago de Cuba Bay and along the river valleys, where the most recent Quaternary sediments outcrop. Amplifications between 1.2 and 1.6 are estimated in the Neogene sediments, whereas no amplification is expected around the southern border of the coast, where the limestone of the Fm. Jaimanitas outcrop, and to the north and NW of the bay, where volcanogenic sedimentary rocks of Gp. Cobre outcrop.

The AFs based on 1D and 2D modelling (Fig. 3) show larger variability than those in the NEHRP map especially in the poorly compacted Neogene - Quaternary sediments, classified in Fig. 2 as stiff or soft soils. The highest amplifications (AF larger than 1.7) correspond to the thickest sediments.

When comparing the map (Fig. 2) with AFs based on the NERHP provisions (BSSC, 2001) with that based on 1D and 2D modelling (Fig. 3), we see that the modelling leads to lower AFs along the western coast of the Santiago de Cuba Bay as well as along the San Juan Basin. Almost no amplification is expected in a few sectors of limited dimensions by modelling, conversely, a low amplification is suggested by the NEHRP soil classification. Moreover, there is a good agreement by modelling and NEHRP AFs where the soil is classified as stiff soil (NEHRP class D), although some spots with high AF (larger than 1.7) appear in the map based on the modelling results.

Conclusions. From the geotechnical model (Rivera *et al.*, 2013), we have obtained 225 stratigraphic models for the whole study area of Santiago de Cuba, taken into account the local geology (tectonic setting and geological description: age, lithological description, stratigraphic characteristics, sediment thickness) and geotechnical information (physical-mechanical properties: density, Poisson coefficient, damping). The static soil properties (shear wave velocity) have been defined from data of geophysical prospections and using the relationship of Moreno *et al.* (2002).

The expected AFs for Santiago de Cuba have been estimated from the NERHP (BSSC, 2001) soil classification (Fig. 2), based on the stratigraphic units present in the study area, and from the 1D and 2D modelling (Fig. 3), taking into account the local soil properties and 6 suitable UHRSs for bedrock.

The AFs from modelling have been estimated as the ratio of the output over the input spectrum in the range of periods from 0.1 to 0.5 s. The results show that no amplification is expected along the coast of the Caribbean Sea with the exception of a small portion to the SW, where Quaternary sediments appear. A similar behavior can be seen to the north and west of the bay, where volcanogenic sedimentary rocks outcrop. A small sector located to the east of the bay shows deamplification: it coincides with more than 100-m thick sandstones. The largest amplifications refer to poorly compacted soils of Neogene-Quaternary age.

The comparison between the results obtained following the two different approaches has highlighted the generalized larger amplification expected according the modelling of the soil local response, because both 1D and 2D modelling procedures take into account various soil parameters than shallow geological characteristics only.

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References

Alvarez L., Villalón M. and Lindholm C.; 2015: Seismic Hazard for Cuba. Report, CENAIS and NORSAR Archives.

BSSC (Building Seismic Safety Council); 2001: NEHRP recommended provisions for seismic regulations for new building and other structures. Part 1 – Provisions, 2000 edition. BSSC, Washington D.C., 374 pp.

Calais E. and Mercier de Lépinay B.; 1990: A natural model of active transpressional tectonics: the en echelon structures of the Oriente deep along the northern Caribbean transcurrent plate boundary (Southern Cuban margin). Rev. Inst. Fr. Pét., 45, 147–160.

Calais E. and Mercier de Lépinay B.; 1991: From transtension to transpression along the Southern Caribbean plate boundary off Cuba: implications for the recent motion of the Caribbean plate. Tectonophysics, 186, 329–350.

Carrillo D., Echavarría B., Castellanos E., Triff J. and Núñez K.; 2009: Léxico Estratigráfico de Cuba. Archivo del Instituto de Geología y Paleontología, La Habana

Chuy T.J.; 1999: Macrosísmica de Cuba y su aplicación en los estimados de peligrosidad y microzonación sísmica. Tesis en opción al Grado de Doctor en Ciencias Geofísicas. Fondos del CENAIS y del Ministerio de Educación Superior.

Das B.M.; 2001: Principios de ingeniería de cimentaciones. International Thomson Editores, S.A. de C.V. ISBN 970-686- 035-5, pp. 137-143.

Loke M.H.; 2004: Tutorial: 2-D and 3-D electrical imagining surveys. https://www.ualberta.ca/~unsworth/UA-classes/223/loke_course_notes.pdf.

Medina A., Escobar E., Ortiz G., Ramírez M., Díaz L., Móndelo F., Montejo N., Rodríguez H., Guevara T. and Acosta J.; 1999: Reconocimiento geólogo-geofísico de la cuenca de Santiago de Cuba, con fines de Riesgo Sísmico. Empresa Geominera de Oriente, Santiago de Cuba, 32 pp.

Medvedev S., Sponheuer W. and Kárník V.; 1964: Neue seismische Skala Intensity scale of earthquakes, 7. Tagung der Europäischen Seismologischen Kommission vom 24.9. bis 30.9.1962. In: Jena, Veröff. Institut für Bodendynamik und Erdbebenforschung in Jena, vol 77. Deutsche Akademie der Wissenschaften zu Berlin, pp 69-76.

Méndez I., Ortiz G., Aguller M., Rodríguez E., Llull E., Guevara T., López T., Guilart M., Mustelier M., Gentoiu M. and Lay M.; 2001: Base de datos digital de los levantamientos regionales de Cuba Oriental. Empresa Geólogo-Minera de Oriente (E.G.M.O.) y Oficina Nacional de Recursos Minerales (O.N.R.M).

Moreno B., Grandison M. and Atakan K.; 2002: Crustal velocity model along the southern Cuban margin: implications for the tectonic regime at an active plate boundary. Geophys. J. Int., 151**,** 632–645.

NAVFAC (Naval Facility Engineering Command); 1982: Maximum density of the compacted materials. Microzonazione sismica. Procedure per elaborare una carta di pericolosità sísmica. ISBN 978-88-7758-797-8.

Orellana E.; 1982: Prospección Geoeléctrica Continua. Editorial Paraninfo.

Redpath B.; 1973: Seismics refraction exploration for engineering site investigations. U.S. Army Engineer Waterways Experiment Station Explosive Excavation Research Laboratory, Technical Report E-73-4, Livermore, California, 51 pp.

Rivera Z.C., Garcia J., Slejko D. and Medina A.; 2013: Geotechnical model for Santiago de Cuba city. In: 32° Convegno Nazionale del Gruppo Nazionale di Geofisica della Terra Solida. Atti - Tema 2: Caratterizzazione sismica del territorio, pp. 330-334.

Sadovskii M.A., Nersesov I.L., Medvedev S.V. and Liamzina G.A.; 1973: Main principles of the seismic microzoning. Voprosii Inzheniernoi Seismologii, Moscow, 15, 3-34, in Russian.

Sanò T.; 1996: BESOIL. Un programma per il calcolo della propagazione delle onde sismiche. Italian National Seismic Service, Rapporto Tecnico SSN/RT/96/9.

Sanò T. and Pugliese A.; 1991: PSHAKE, Analisi Probabilistica della Propagazione delle Onde Sismiche. Ente per le Nuove Tecnologie, L'Energia e L'Ambiente (ENEA), Direzione Sicurezza e Protezione.