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NANOZONATION IN DENSE CITIES: TESTING A COMBINED METHODOLOGY IN BARCELONA CITY (SPAIN)

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Abstract

Microzonation is widely used in seismic risk evaluations to define the predominant period values, which are usually associated with extended areas of a few hundred meters. However, the representative values corresponding to these areas are obtained from few measurements in each area. Thereby, results are accurate only in the case of depth-dependent soils. However, not detected narrow and sharp lateral changes in soil are potentially the cause of imprecision and could be a source of specific errors. This paper aims to present several tests conducted in order to emphasise the importance of accurate selection of points, to underscore the necessity of more precise and detailed evaluations, and to suggest a possible methodology to select the most appropriate data acquisition points. Results highlight the need to divide microzonation areas into smaller zones for a precise evaluation in locations where sudden changes in soil characteristics exist. Therefore, in such sites the requirement of nanozonation appears; defining zones with the same soil response. Distance between vibration measurements could be the main problem for nanozonation; data acquisition in areas with irregular geology can be time-consuming when a precise analysis is required. In the most complicated environments or in dense cities, it could even be unfeasible. Consequently, it is necessary to establish a functional methodology to adequately distribute the measurement points throughout the area. On this occasion, three sites in Barcelona city were studied. This city is surrounded by mountains at NW, W and S, and by the Mediterranean Sea at N and E. As a consequence, the shallow geology is characterized by many paleochannels and streams that are currently buried. These geological structures most likely affect the soil response. Several tests were carried out to determine this dependence. The tests were based on Ground Penetrating Radar (GPR) surveys to define the paleochannels position and on vibration measurements in order to define properly the soil response. The results from both methods were compared to the known geology to accurately define the effect of the shallow geological structures in the predominant period and in the GPR images. Areas with the same geological unit but different materials were identified in the GPR images, allowing the selection of the most appropriate distance between vibration measurements in each place. As final result, predominant periods that were measured over the same geological unit but over different material showed changes higher than the 40% in short distances. This procedure could improve the soil response maps, including nanozonation.

Keywords: microzonation, soil response, ground-penetrating radar, nanozonation, shallow geology, H/V.

1. Introduction

Soil response microzonation has been widely applied in seismic risk studies during the decades since Nakamura's [1989] contribution. A significant number of studies were based on the existence of large, laterally homogeneous soils (up to 100 m) (e.g., [Alfaro et al., 2001]; [Navarro et al., 2001]; [D'Amico et al., 2002]; [Gosar and Martinec, 2009]). However, these studies rarely consider the effects of small geological structures on the predominant period [Caselles et al., 2010], even in cases when these elements could severely affect the seismic risk analysis. As a result, microzonation is a potential cause, in such geology, of imprecision and could be a source of specific errors and, therefore, of possible critical damage to some structures. Furthermore, soil response effects due to geological change effects on short distances could explain several reports of damage in buildings shaken by earthquakes [Saita et al., 2004]. These reasons have lead to the definition of the concept of nanozonation [Ordaz, personal communication], describing the nanozone as the area of each geological structure presenting homogeneous characteristics for soil response application. A correct evaluation of changes induced by the abrupt lateral heterogeneities requires consideration of the H/V ratio method capabilities and limitations ([Cadet, 2007]; [Bard, 2008]). Usually the site predominant period is assumed to be the only reliable parameter that can be obtained by means of H/V ratio ([Plitz et al., 2009]). Notwithstanding, recent works ([Lunedei and Albarello, 2010]; [Sánchez-Sesma et al., 2011]) could elucidate the issue. The viability of the H/V ratio method for seismic microzonation in dense cities is discussed in D'Amico et al. [2008], Castellaro and Mulargia [2010] and Cadet et al. [2011].

Nanozonation models could be relevant in cities built on soils characterized by important, sharp and small changes. This is the case of Barcelona, a dense city built on a sedimentary basin placed between the mountains (in the Northwest) and the sea (in the Southeast). The basin is crossed by a lot of active streams and paleochannels, flowing from the mountains to the coast and producing sharp lateral changes in the subsurface materials. The positions of the most important paleochannels and streams are known approximately. However, many of them are not defined exactly. Furthermore, locations are, in many cases, determined from historical information that is not always accurate or not well documented. Borehole data seems to indicate that these geological structures present significant thickness, sometimes up to 20 m. Notwithstanding, in some places paleochannels are a few meters thick (less than 10 m). These two aspects (the non-exact position and the variability of its thickness) complicate the selection of representative sites for measuring soil response. In this sense, a good knowledge of these narrow geological structures could be crucial to define a proper soil response, knowledge that is becoming more and more relevant in earthquake engineering.

The main difficulty in nanozonation could be detecting the effect of narrow elements and sharp lateral geological changes. An accurate location and the evaluation of the geological materials dimension in widespread areas can be obtained in two different ways: by a dense grid of measurements and by detection using other geophysical surveys. The use of a dense grid of measurement points could permit the identification of all interesting geological changes. The difficulty is due to the huge number of measuring points, this methodology being time-consuming. Detection of anomalies by means of an alternative geophysical survey could precisely define the position of different geological features.

Subsequently, prospecting evaluation could help in the detection of those geological formations associated with soil response changes. This knowledge allows the definition of a non-regular grid of representative measurement points: in zones affected by narrow and lateral changes the grid should be denser, while in laterally homogeneous subsoil, the microzoation characteristic intervals should be appropriate. Consequently, an accurate geophysical survey could provide enough information to permit measuring soil response in all the geological structures of interest using the minimum number of points. Weighing different factors, such as handling, data acquisition time and reliability, one of the most feasible geophysical methods is Ground-Penetrating Radar (GPR). GPR survey is able to identify shallow geological structures (e.g., [Pérez-Gracia et al., 2000]; [Bristow and Pucillo, 2006]; [Van Den Bril et al., 2007]) and changes in ground materials (e.g., [Pérez-Gracia et al., 2009]; [Malik et al., 2010]) as well as to detect changes in water content (e.g., [Huisman et al., 2003]). In addition, GPR signal is not affected by most usual urban noises, such as soil vibrations, although electromagnetic emissions must be carefully considered.

In this paper, three sites are chosen to check the nanozonation methodology proposed and to underscore the effect of paleochannels and streams in Barcelona city. This evaluation was executed considering the previous argument. Then, GPR survey, borehole information and historical documentation were correlated and used to define the position and size of shallow geological formations. Historical data provides information about the potential position of some underground streams and paleochannels. Notwithstanding, historical documents have different and often unknown scales. Also, scale of current geological data in site 2 is 1:5000, and in sites 1 and 3 is 1:25000. GPR data is used to define the most probable area affected by streams and paleochannels, and geological data from geological maps and boreholes facilitates to recognize possible targets (layers and shallow streams). Afterwards, the vibration measurement points were selected considering these previous results. After selecting the measurement point, the fundamental period of soil response was determined by the horizontal to vertical ratio (H/V) method.

2. Methodology

The proposed soil response methodology consists of measuring H/V ratio from random vibration noise acquired in an irregular grid, changing the distance between measurements depending on the shallow geology. Four phases are required: first, to find and evaluate all the historical, geological and geotechnical previous information; second, to detect precisely shallow geological anomalies by means of appropriate geophysical surveys; third, to organize the H/V acquisition survey, designing the most appropriate irregular grid; fourth, to acquire vibration noise data at the selected points and to analyze the obtained results.

Many geophysical surveys were frequently applied to study shallow geology: seismic refraction and reflection, resistivity imaging, GPR and others, as well as integrated evaluations (e.g., [Sloan et al., 2007]). Nevertheless, surveys in a dense city are complex due to environmental noise and difficult access. For this reason, the survey should be brief to avoid disturbance in the traffic and the usual city services. Considering these assumptions, GPR appeared as the best survey option.

2.1. Geological setting and previous studies in the experimental sites

Barcelona city is located in a basin about 12 km long and 5 km wide, between the Mediterranean Sea (SE), Collserola Hills (NW), Monjuic Hills, Llobregat delta (SW) and Besos delta (NE) (Fig. 1). The city is built over Quaternary deposits, overlying Tertiary materials and Palaeozoic substrate that outcrops in the surrounding mountains ([Ventayol et al. 2000], [IGC 2009]). The study described in this paper is completely focused on the quaternary deposits structured in a particular formation called "Tricicle". The name Tricicle indicates the repetition of the same geological structure: a succession of three faces of red clay, yellow slime and a pink limestone of few centimetres thick.

The plane is formed over a horst system, as can be seen in the three geological sections in Fig. 1. Tertiary outcrops among the quaternary formations in some places, due to the fault system. The complex structures of the tertiary lead to an abrupt variation of thickness in the quaternary deposits and generate lateral contacts between diverse tertiary materials.

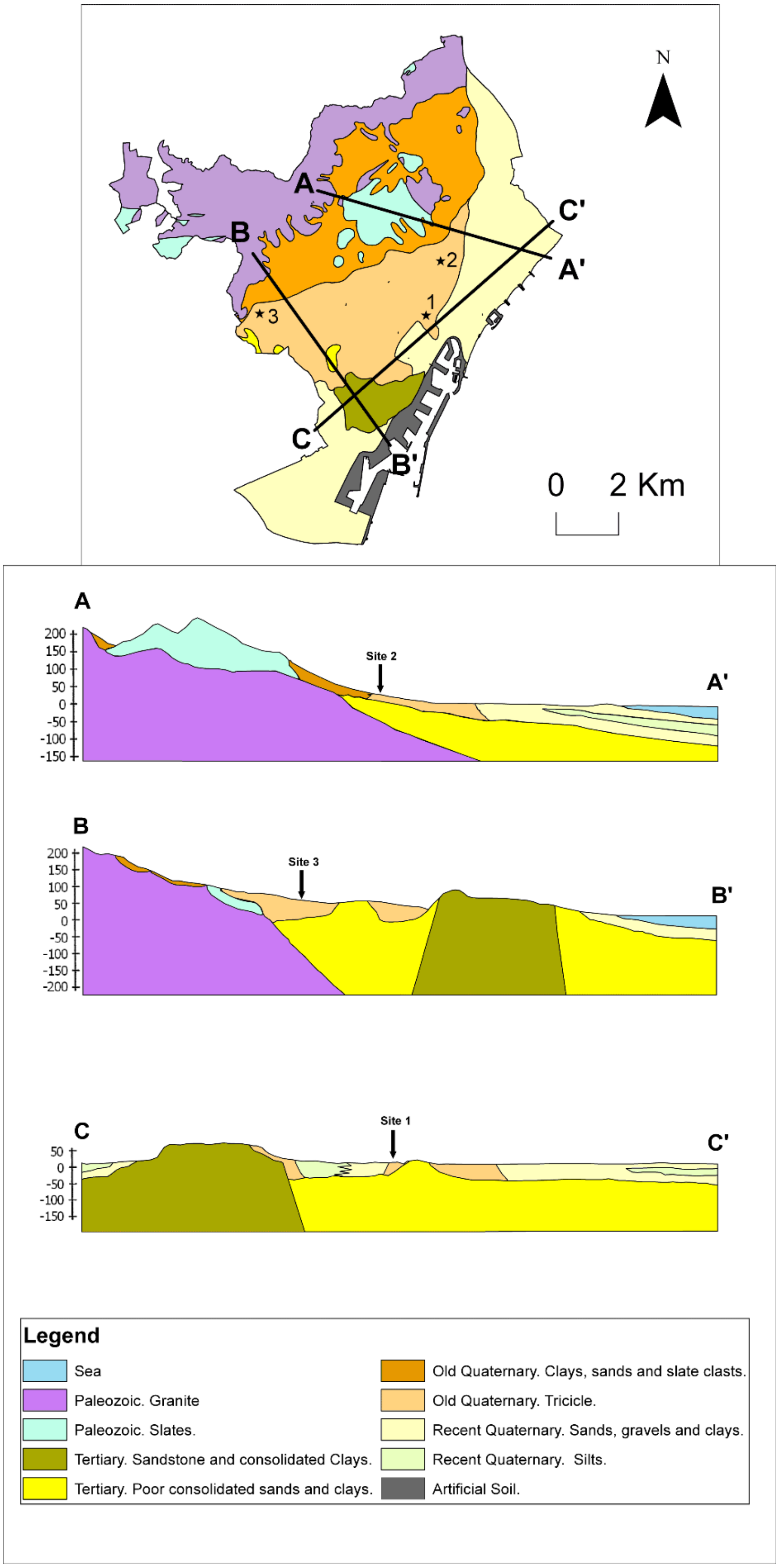

Figure 1. Figure 1. Geology map and cross-sections AA', BB' and CC' of Barcelona (obtained from [IGC, 2009] and [UPC, CLABSA & Ajuntament de Barcelona, 1997]). 1, 2 and 3 indicate the position of the selected sites.

Previous soil response studies in Barcelona roughly divide the city into five sections [Cid et al., 2001]: (1) rock, where rock is expected, in the mountains surrounding the city (Montjuic and Collserola), obtaining a soil transfer function without amplification peak; (2) soil 1, close to the sea and presenting an important thicknesses of non-consolidated sand layer (deltaic), obtaining the first amplification peak at about 2.5 Hz and amplification of 2.5 ; (3) soil 2 in the plain of Barcelona, characterized by a geological formation known as Tricycle, where the amplification peak is found at about 5 Hz and amplification of 2.5; (4) soil 3, near the mountains and characterized by small thicknesses in sediments, the amplification peak being about 5 Hz and amplification of 2.25; and (5) artificial soil, corresponding to non-studied zones (Fig. 2). The three selected sites are placed in different areas in the soil 2 zone, where similar soil responses can be expected, because this zone is considered homogeneous. Nevertheless, possible differences due to small geological heterogeneities are detected and evaluated in this study. Streams and paleochannels filled by gravel, sand, clay and slate gravel, cross the Tricicle formation. The thicknesses of these filler materials could be higher than 35 m [IGC, 2011]. Although abundant historical data describe and situate a large number of paleochannels and streams ([Cerda, 1855]; [Vazquez, 1861]; [Arandes, 1998]; [Anonymous, 1713]; [Anonymous, 1492]), considerable imprecision appears in their position due to vague, old cartography and difficulties in historical data interpretation. Geotechnical maps of Barcelona city show buried streams, but different documents show different locations ([Ventayol et al, 2000]; [IGC, 2009]; [ICG, 2011]). The soil seismic response evaluation requires their accurate location.

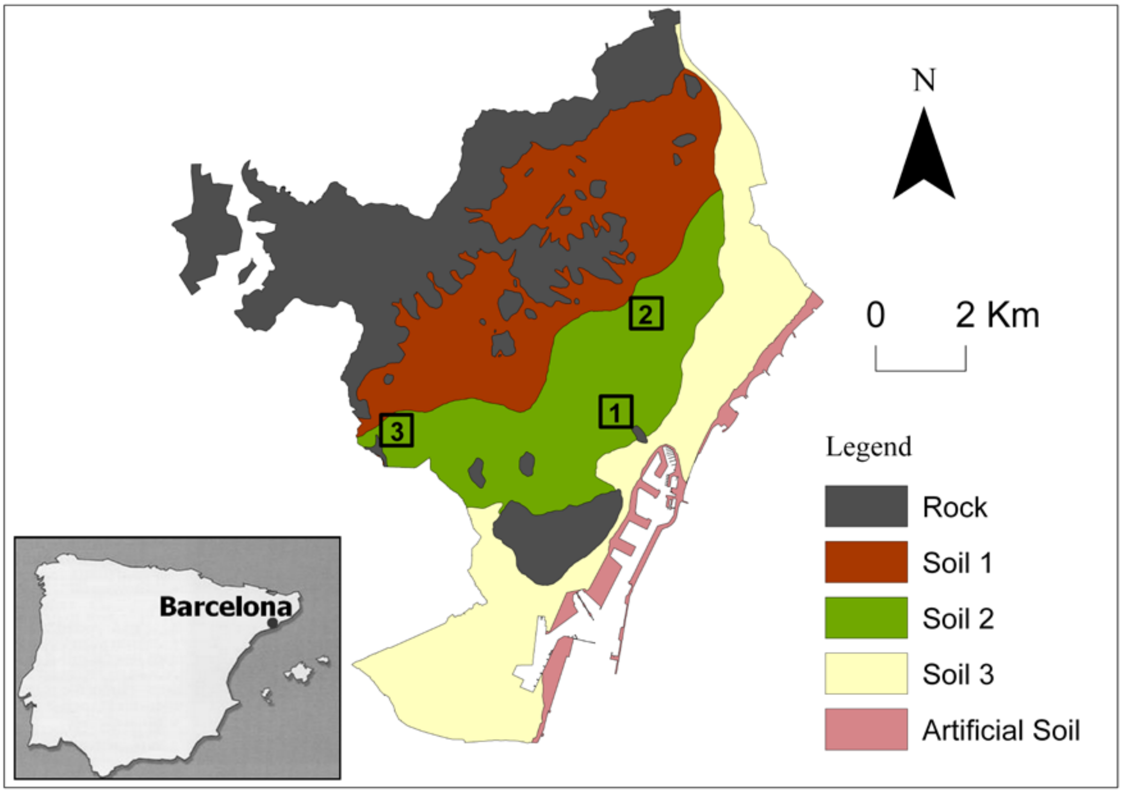

Figure 2. Seismic zonation map of Barcelona [Cid et al., 2001], showing the three studied sites: site 1, in Catalonia Square (CS); site 2, near Sagrada Familia (SF); site 3, close the University Campus Station (UCS).

The first selected site is placed in downtown Barcelona, in Catalunya Square (CS), where a wide subterranean stream exists. Two other small paleochannels are also known of in this area ([Arandes, 1998]; [Ventayol et al, 2000]). Geological and geotechnical information, derived from 12 boreholes reaching a maximum depth of 60 m, indicate thicknesses up to 25 m for these structures (Fig. 3). Notwithstanding, the rock basement is not detected in any borehole, even Ventanyol et al. [2000] report that marl outcrop near the site (about 500 m to the SE). Geotechnical results reported great lateral variability of sands, clays and gravels. Borehole S14 (Fig. 3) indicates that Pliocene formation is found at 25 m deep at this point, however, 84 m distant from S14 point (in borehole S11) the same geological formation appears at about 20.5 m deep. The shallowest 30 m in this zone presents a large percentage of gravels, and historical information reveals the existence of old stream courses, even though the location is not properly indicated. A previous H/V study [Alfaro et al. 2001] indicates a great variability of the dominant period values in short distances (less than 500 m), from 1.67 s to 1.00 s. Nevertheless, in this study, measurement points are always spaced more than 250 m.

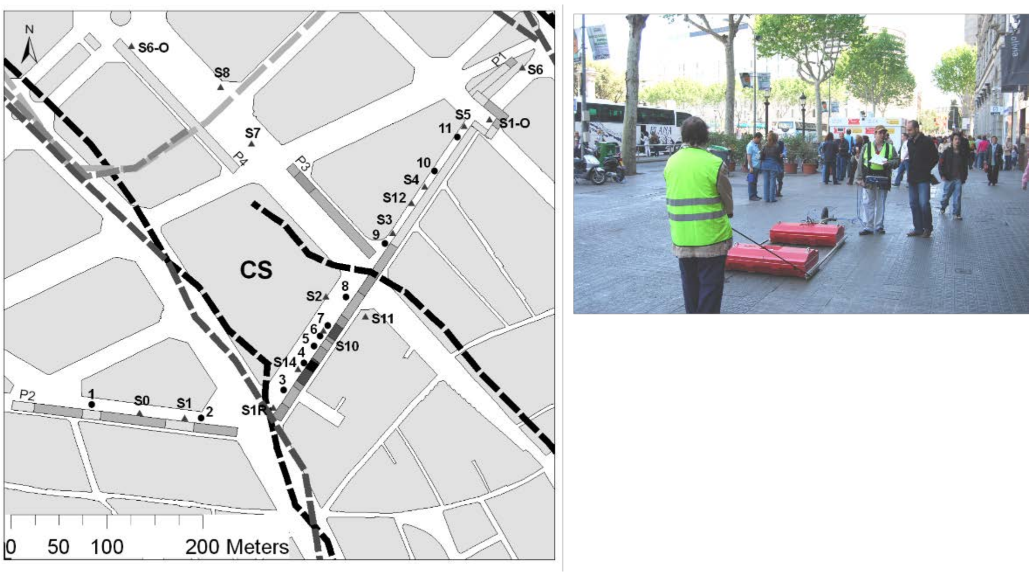

Figure 3. Site 1 in Catalonia Square (CS). Position of torrents according to different authors (in dashed lines from dark to clear: [Ventayol et al., 2000]; [Arandes, 1998]; [Vazquez, 1861]; [Cerda, 1855]). In continuous lines, position of the GPR profiles. Different colours indicate the noise amplitude due to scattering in GPR images (from dark to clear: very strong scattering, strong scattering, medium scattering, weak scattering and very weak scattering). Borehole: triangles. Old well: star. H/V amplification measurement points: numbers 1 to 11.

The second site (Fig. 4) is close to the Sagrada Familia basilica (UNESCO world heritage building), in Mallorca Street (SF). The construction of this basilica started at the end of the 19th Century, between the old city and the surrounding villages (today incorporated within the city). An important stream close to the basilica is described in documented information ([Cerda, 1855]; [Vazquez, 1861]; [Arandes, 1998]; [Anonymous, 1713]; [Ventayol et al, 2000]). Several excavations due to maintenance work also provide evidence of the existence of groundwater near the basilica. According to Ventayol et al. [2000], there is less than 20 m of clays, silts, gravels and centimetric limestone crusts over Pliocene formation. This information might indicate the existence of moderate and wide thickness of paleochannels. Also, the Sagrada Familia area was studied with 23 boreholes, which provide discrete points of information about the shallow geology. Borehole information reports a 6 to 17 m thick Pleistocene formation over Pliocene sands and clays, reaching a depth of more than 60 m. Lateral variability of these two formations are especially significant, and rock basement is not reached in any borehole. Alfaro et al. [2001] describe a single soil response measurement of 1.71 s. However, 500 m away, soil response measurements range between 1.00 to 1.99 s [Alfaro et al., 2001].

Figure 4. Site 2 near the Sagrada Família Basilica (SF). Position of a torrent according to various sources (in dashed lines from dark to clear: [Ventayol et al., 2000]; [Arandes, 1998]; [Vazquez, 1861]; [Cerda, 1855]). Radar profiles in bars (white spots, strong reflectors, and from dark to clear: strong scattering and weak scattering). Boreholes: triangles. H/V amplification measurement points: numbers 1 to 12.

The third site (Fig. 5) is also placed in the basin, but near the hills and close to the University Campus underground Station (UCS). Evidence of one subterranean stream was detected during tunnelling work 50 m downstream from the site. Possible paleochannels in this area should be narrow and shallow. According to the geological map [Ventayol et al., 2000], the depth of clays and gravels is less than 20 m, with outcropping marls appearing about 300 m away. Borehole information is obtained from 7 points less than 100 m around the studied area, showing about 22 m of sands, clays and gravels over granitoid bedrock, reaching 24 m in some places. The upper formation (Pleistocene) reaches a depth of about 15 m, extending to 19 m in some cases. Additionally, the existence of a quasi-vertical fault in this area is known. Close to this area and about 500 m downstream, several streams converge on Riera Blanca stream, one of the most important streams in Barcelona ([Cerda, 1855]; [Vazquez, 1861]; [Arandes, 1998]; [Anonymous, 1713]; [Ventayol et al., 2000]). Unfortunately, the exact positions of these streams are not accurately described. Groundwater is also seen in the existence of an old water-well, most likely over one of these streams and near site 3. According to this geotechnical and geological information, soil response measurements are expected to be moderately variable in this zone. Previous H/V measures surrounding this third area ([Alfaro et al., 2001]; [Caselles et al. 2010]) should corroborate the expected variability: 0.27 s measured at Cervantes Park (550 m upstream from the studied zone) and at Adolf Florensa Street (390 m downstream), 0.22 s measured at Technical University of Catalonia Campus (450 meters from the area, in direction of the Collserola mountains), and 0.14 s obtained in Gran Capitan street (less than 130 meters from Campus point and 450 meters away from the studied zone).

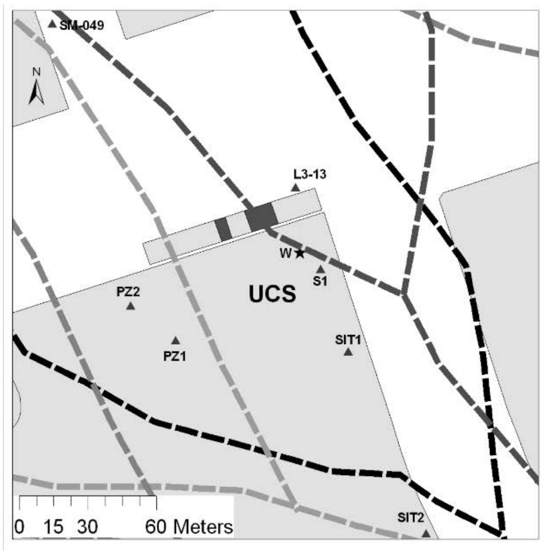

Figure 5. Site 3 close to the University Campus Station (UCS). Position of various torrents according to different sources (in dashed lines from dark to clear: [Ventayol et al., 2000]; [Arandes, 1998]; [Vazquez, 1861]; [Cerda, 1855]). Radar profiles in bars (from dark to clear: strong scattering, low scattering). Boreholes: triangles. Old well: star. HV measurements were performed at every meter along all the radar profile.

2.2. **GPR survey**

Ground penetrating radar (GPR) is a non-destructive geophysical survey based on the emission, transmission and reception of high-frequency UWB electromagnetic waves. An emitter antenna, placed on the ground surface, produces an electromagnetic wave that is propagated through the ground. Changes in the ground's electromagnetic properties modify the impedance. Partial reflections of the energy are produced in the interfaces between materials with different electromagnetic properties. Some of this reflected energy returns to the surface, where a receiver antenna detects the signal (Fig. 6). Radar data records the amplitude of the reflected wave and its two-way travel time (TWT). TWT of the reflected wave depends on the distance to the anomaly and on the wave velocity. This time can be converted into depth by means of the wave velocity. GPR emission is characterized by the spectra central frequency. GPR usually operates with central frequencies from 10 MHz to 2 GHz. Higher frequencies offer better resolution, but less penetration depth and are inadequate in geological surveys. Consequently, lower frequencies are the most appropriate in order to define the shallowest geology properly, reaching approximately 50 m under perfect ground conditions.

Radar imaging is usually characterized by continuous anomalies due to changes in the electromagnetic parameters of the medium (Fig. 6). Other typical anomalies are the hyperbolas caused by small size targets embedded in the medium. These anomalies are generated because the antenna emits a cone of energy and detects the target before reaching its vertical projection (Fig. 7). The shape of the hyperbola depends on the wave velocity.

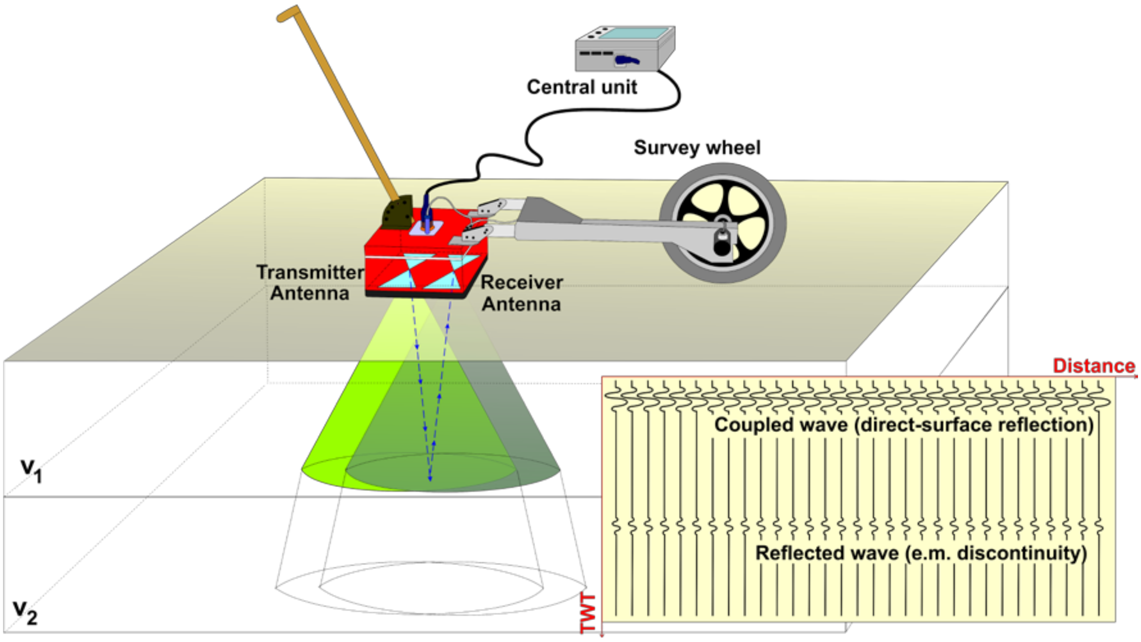

Figure 6. Schematic radar survey and radar imaging caused by a continuous reflector.

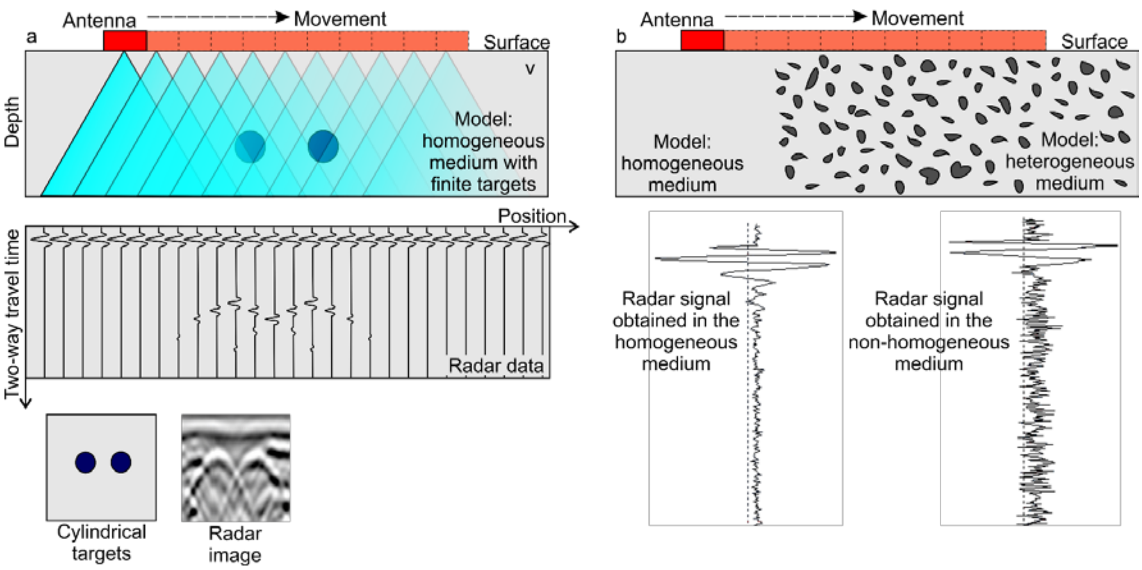

Figure 7. Radar signals obtained from different media. a) Reflections and signal occurred in cylindrical targets embedded in a homogeneous medium. b) Comparing radar signals obtained from homogeneous and non-homogeneous media.

Anomalies showed in figures 6 and 7a are clear effects due to discontinuities in the medium. However, other effects could also affect the received signal. Also, clutter is a usual noise in GPR data, mainly in the case of non-shielded antennas. This noise should be due to reflections on external targets. The anomalies associated to these reflections are superimposed to other anomalies caused by targets embedded in the studied medium. In order to distinguish the anomalies caused by external reflectors, during radar data acquisition tasks, elements that could produce noise (e.g., street lamps) are carefully annotated and positioned. In addition, these anomalies were also detected during the processing task by identifying the wave velocity. In the case of external reflections, they use to be straight lines which slope corresponds to the wave velocity in air, or hyperbolas presenting a different shape than others caused in internal targets. Internal anomalies could be associated to lower wave velocities. The ground texture could be associated with scattering phenomena. Small-sized heterogeneities disperse the incident energy. An elevated number of small targets can cause the scattering of energy, increasing the background noise in each radar trace (Fig. 7b). This phenomenon might help in the detection of paleochannels where the clay and other tiny particles were probably removed. As a result, bigger grain size materials make up a more heterogeneous medium [(Pérez-Gracia et al., 2010)].

In Catalunya Square, more than 1000 meters of GPR data (Fig. 3) were obtained from 4 profiles with a 100 MHz nominal centre frequency bistatic antenna, using a 500 ns time window. Position was determined through a survey wheel. During the radar data acquisition, a vertical band pass filtering with cut-off frequencies of 25 and 200 MHz was applied. This filter was used in order to diminish the electromagnetic noise present in the city centre. Post-acquisition data processing consists of a linear manual gain to compensate the geometrical spreading and a low-pass filter with a 200 MHz cutoff frequency. The GPR profile length assures the detection of the assumed stream and the possible paleochannel in the area.

In the Sagrada Família zone (Fig. 4), GPR data was acquired through a bistatic rough terrain antenna (RTA) with 25 MHz nominal centre frequency. Position was determined by means of a survey wheel and GPS points. Radar data was obtained in a 325 meters single profile along the Mallorca Street, starting in the junction with Marina Street, and finishing in the junction with Sicilia Street. In this area the floodplain of the stream and possible paleochannel should be located. The length of the profile also reaches the point measured by Alfaro et al. ([2001]). The lower frequency of this antenna and the low electromagnetic noise in this zone allowed a time window of 700 ns. Raw data was processed with a band-pass frequency filter with cut-off frequencies of 1 MHz and 60 MHz and plateau frequencies of 5 MHz and 30 MHz. Wow baseline was corrected by using a dewow filter, and high loss was compensated with an energy decay gain.

In the third area (Fig. 5), near the University Campus Station, an 80 m long GPR profile was carried out with a bistatic 100 MHz nominal centre frequency antenna applying the same filters used in the Catalunya Square profile. Position was determined by means of a hip chain. The profile crosses the area where two shallow streams are likely to exist.

In the three sites, maps of subterranean pipelines, wires and underground constructions were available, and they were used to distinguish these targets from the geological ones. Also, radar data was compared to borehole information (Fig. 8) and with geological maps in the three test sites. Finally, the total length of the profiles was compared to the topographic maps of the city (scale 1:100), obtaining a maximum error of about 1 m in the position of the antenna.

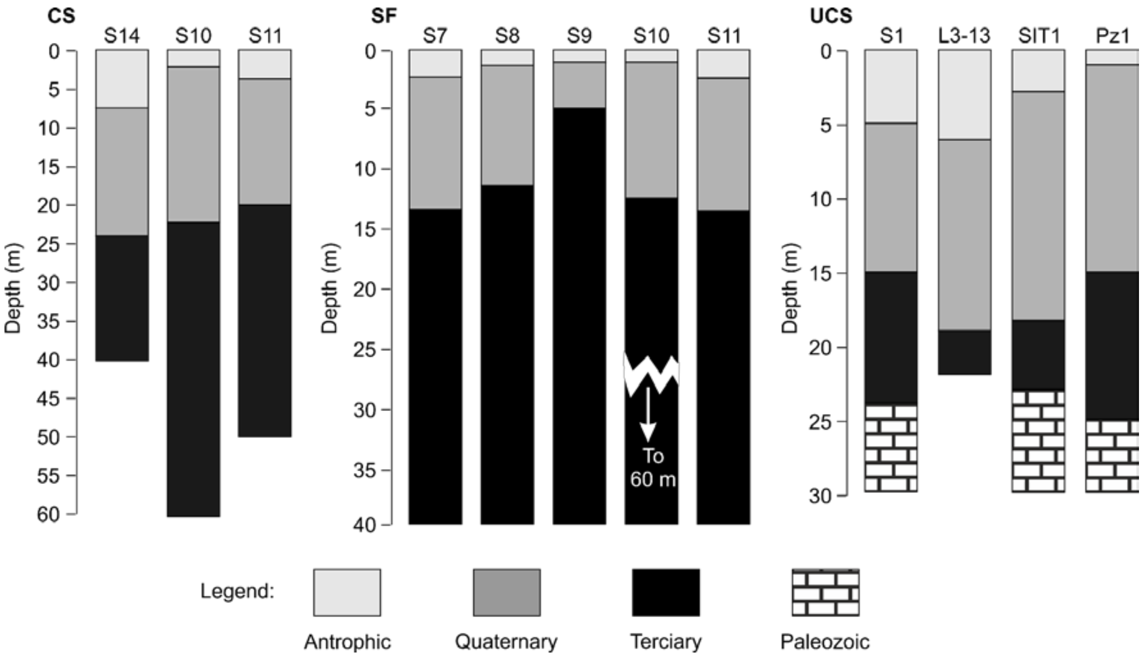

Figure 8. Borehole data obtained in the studied sites.

2.3. GPR results and correlation with historical and geotechnical data

2.3.1. Site 1

In site 1 (Catalunya Square), GPR wave velocity was determined in the shallowest materials by using the hyperbolic reflections on tubes and pipelines. The average velocity value was 8 cm/ns. Deeper velocities were estimated comparing the GPR continuous reflections to the stratigraphic information from close boreholes (Fig. 8). These velocities were used to convert the two-way travel time into depths. Radar image shows a first anomaly corresponding, most likely, to the contact between anthropogenic materials and the shallowest quaternary deposits. The depth of the contact looks irregular (it is found between 0 to 8 meters), probably denoting an irregular layer thickness. This contact is detected in the profiles, *but the image is irregular (see Fig. 9). Over the anomaly most likely associated to this contact, small hyperbolas are caused by pipelines and wires*. The shallower layer is also detected in boreholes *(Fig. 8)*, also presenting irregular thickness. Borehole data determined that silts, sands and gravels underlie this anthropogenic level with an irregular grain size distribution percentage. Radar penetration depth is no higher than 10 m in this area, and the contact between the Quaternary and Tertiary layer is not detected. Some irregular elements on the radar images denote the existence of small shallow changes in the Quaternary materials.

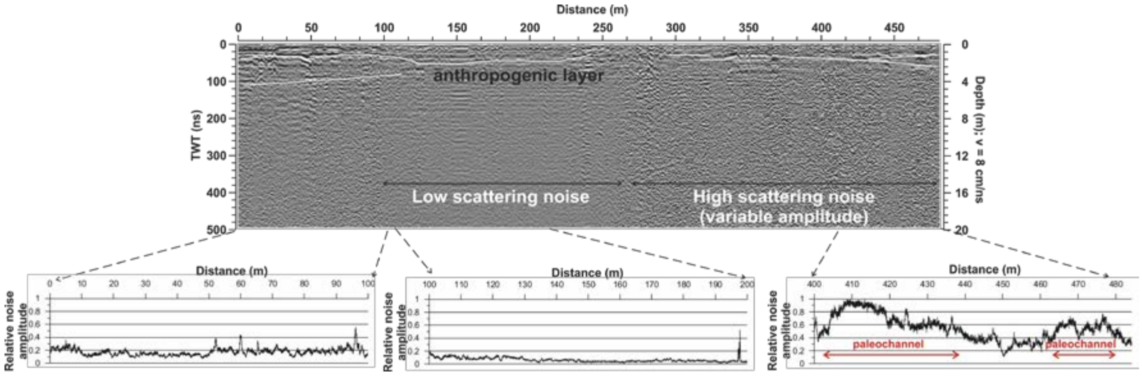

Figure 9. GPR image of the longest profile in CS and relative amplitude noise.

However, the most remarkable effect in GPR data was the large differences in the background noise, depending on the antenna position. It was assumed that this noise could be caused by scattering and it depended on the grain size materials. This effect is recorded in different places. For example, in Fig. 9 (profile 1 in site 1) radar data epitomize noise differences depending on the zone; low noise was detected between 100 m and 270 m, and an irregular high noise was recorded between 270 m and 475 m. The background noise amplitude of each signal was drawn to emphasize the differences between sectors. The maximum amplitude corresponded to two known and important paleochannels. Also, comparing the noise amplitude pattern and the known geological borehole information, it was possible to correlate low amplitude noise with sectors with low gravel content. Furthermore, high scattering amplitude noise seems to correspond with high gravel content. These results most likely point to the dependence between grain size and noise amplitude in radar signals. However, other causes could produce an increase in the background noise signal and must be carefully considered in each particular survey such as external electromagnetic emissions and changes in ground consolidation properties.

2.3.2. Site 2

In the Sagrada Famila zone (site 2), the GPR line was along Mallorca Street, where ground information was available from several boreholes (Fig. 4 and 11). Radar data (Fig. 9) seem to show an irregular medium formed by non-homogeneous alluvial clusters. In the shallowest part of the image, reflections appear to correspond to current urban structures. Reflections caused in street lamps and other external targets could be seen in the upper part of the image. The slope of the straight lines caused in these targets corresponds to a wave velocity of, approximately, 30 cm/ns. Also, other strong and superficial anomalies between 5 and 20 m are caused in a well wedge (the slope of the straight reflections indicates that wave velocity is about 30 cm/ns). Anomalies between 50 and 100 m are produced in the new foundation reinforced wall of the Sagrada Familia basilica. Probably, reflections between 120 and 140 m most likely correspond to an old subterranean war refuge. These subterranean anomalies are between 5 and 10 m deep and cause strong multiple reflections. The shallowest layer, very likely related to anthropogenic activities and reaching a depth of 8 m, could be defined (Fig. 10). Changes in Quaternary alluvial deposits probably cause the most irregular anomalies in the deepest zones of the profile. These anomalies are observed as small and irregular reflections. In this radar image, the two zones are characterized by high background noise, most likely due to scattering. One of them is 15 m in length and starts at the beginning of the GPR image but the signal is contaminated by underground constructions. The other one is detected between 155 m and 220 m approximately, and represents a clear noisy area. Small hyperbolas due to diffraction phenomena are superimposed on reflections that probably are originated in shallow geological changes. Surrounding this area, two transition zones between high and low noise can be interpreted in the radar data.

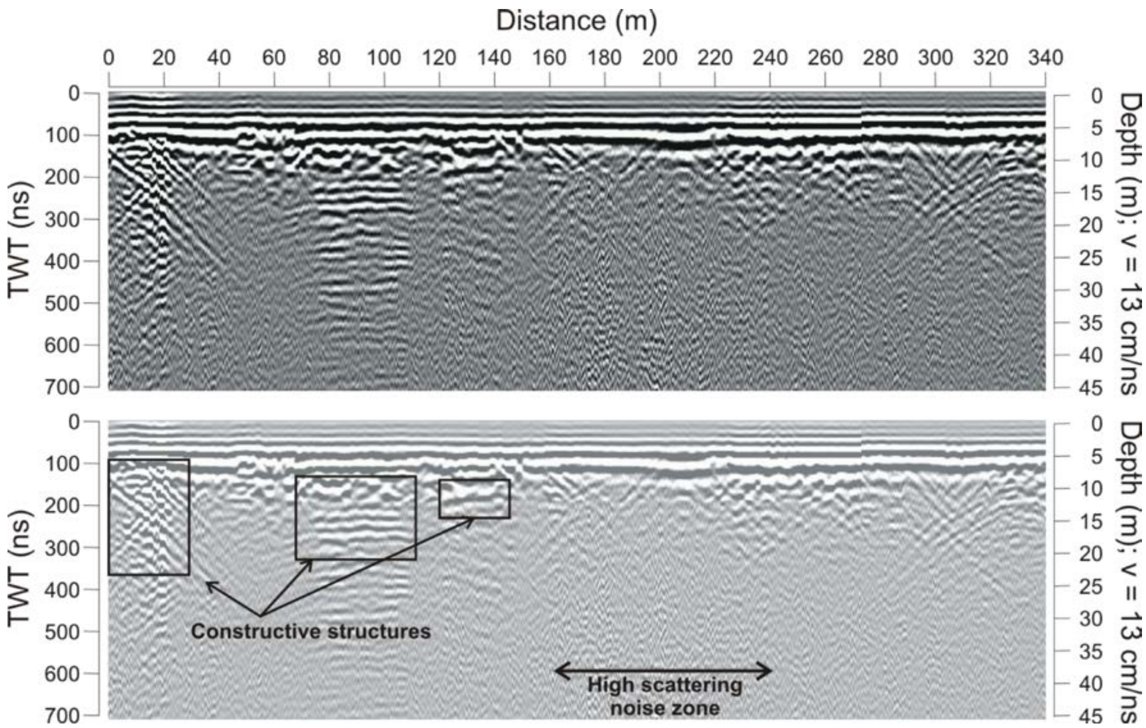

Figure 10. GPR results (up) and interpretation (down) at site 2.

2.3.3. Site 3

The University Campus Station zone (site 3) is close to the mountains, still in the quaternary basin (tricycle materials). GPR data reveal the irregular contact between an anthropogenic material layer and the sedimentary layer (tricycle) presented in borehole data at a depth ranging from 1 to 6 meters (Fig. 8). In the radar images, a continuous, shallow and irregular anomaly could be associated to the contact between the anthropogenic layer and the Quaternary materials, arriving in some places at a depth of 4 m (Fig. 8 and 11). Radar penetration depth makes unable to detect the contact between sedimentary layers and bedrock, although this contact is more superficial in this area than in other parts of the city. Other anomalies placed in the anthropogenic layer are associated to pipelines. The most significant anomalies are two strong and irregular reflections that were interpreted as shallow in-filled and seasonal streams (Fig. 11). Under the anomalies, the background trace noise seems to increase, suggesting possible scattering. In the geological maps of Barcelona there are two subterranean streams known as “Torre Melia” and “Molins” in this *area (ICG, 2011; Ventanyol et al., 2000)*. These two seasonal streams connect downstream and form a more important one called “les Roses”, close to the GPR profile (Fig. 5).

Analyzing the GPR signal, it is possible to observe that the first anomaly is wider (about 20 m) and deeper (radar images seem to indicate the existence of anomalies and changes at about 15 m) than the second one (about 10 meters wide and 8 to 12 meters deep). A remarkable fact is that the GPR images obtained in this third zone are quite different from radar data acquired in the other sites, because the streams are evidently delimited, while in the other cases boundaries are not defined well enough. Also, in this case, the targets could be found at a shallower depth, being in this case better defined. It is remarkable to notice the multiple reflections caused in these shallow and strong reflectors that are combined with other reflections caused in deeper targets in the same place. Moreover, reflections are stronger as the background noise, due to scattering, is more defined and delimited. The differences are likely to be due to the different depth and to the filling materials.

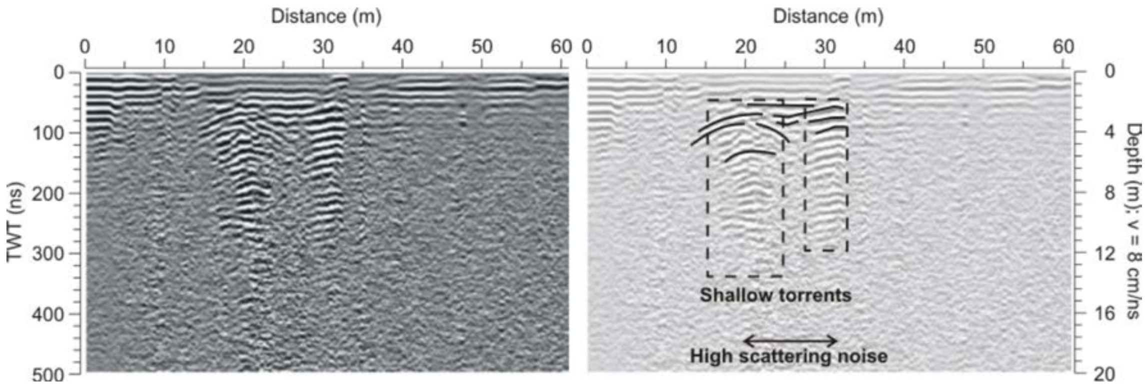

Figure 11. Radar image obtained at site 3.

2.3.4. General GPR results

Radar results corroborate some historical and geotechnical information about the number of streams but in all the cases the position is clearly different and radar has precisely delimited the extension of the floodplain. In Catalunya Square, a wide flood plain (200 meters) appears in radar images showing maximum scattering noise in two zones in the central part (Fig. 3), while historical data indicated two flows in the limits of the square. A well that exists today is located in the area where radar data presents the first scattering maximum. In Sagrada Familia, the maximum GPR scattering appears more than 20 meters distant from the place where geotechnical and historical reports suggest the existence of the “Riera del Notari” stream, and show a width of about 80 meters. In the final zone (UCS), the displacement between historical data and GPR locations seems to be about 50 m in North-West direction. This zone is in the west part of the city, where few historical reference points exist. Furthermore, this area is one of the most affected by the deformation produced by changes between map projections, it is one of the areas most affected by cartographic mistakes. Radar determines precisely the position of the two narrow streams of about 20 and 10 meters wide and of 20 and 10 meters deep respectively.

2.4. Design of the irregular H/V grid and ambient vibration measurements

Regular ambient noise measurement is usually applied in cities and other human environments, measuring in dense cities such as Barcelona can be a difficult task. In this dense urban area, a great number of transient sources continuously affect each measurement. This fact forces each window to be treated independently. In order to increase the number of stable windows, removing the unstable ones, it might be necessary to increase the total recording length. Unfortunately, sometimes it is impossible to obtain long enough series without transient signals in the same temporary window. Consequently, this phenomenon can limit the resolution in the frequency domain. Also, according to SESAME project ([SESAME 2003], [Bard, 2008]) the length of the window is related to the predominant period. In order to observe a period (with enough resolution) correctly, it is highly recommendable to analyze a continuous time series of at least 10 cycles and a minimum of 10 stable windows.

Measurements in three components were performed with a low-noise seismograph from Micromed. In all cases, the sampling frequency was 128 samples per second (sps). Different length measurements and different time windows were considered depending on the different predominant periods expected at each site and also on the expected stability of the signal.

The same processing was applied to the data obtained in the three zones, following standard steps. The signal was firstly visually inspected to identify possible strong transient noise. Secondly, each window was multiplied by a Parzen window. Thirdly, FFT was computed to change to frequency domain. Time signals were cut in windows overlapping 50%. SESAME [2003] suggests avoiding overlap; nevertheless the results with and without overlapping are very similar [Caselles et al. 2010]. Moreover, overlapping windows allow more data to be drawn upon when unusable windows are removed. Additionally, overlapping windows can be a useful procedure to ensure that all used time has equivalent weighting in the computation. Fourthly, smoothing was done in a frequency band of 0.5 Hz. Fifthly, Horizontal to Vertical Spectral Ratio (HVSR) was calculated using the ratio of the averaged horizontal component to the averaged vertical component. Energy of each window was balanced using its inverse total energy [Caselles et al. 2010]. Finally standard deviation was calculated as indicated in SESAME [2003].

2.4.1. Site 1

In Catalunya Square (Fig. 3), windows of more than 17 s were expected to be used as a previous study ([Alfaro et al., 2001]) found predominant periods ranging from 1.67 to 1 second close to this area. Therefore, in absence of disturbing transient noise, a minimum of 5 minutes are needed. However, this zone is placed in downtown Barcelona, where *significant disturbing transient noise* is almost always expected. For this reason, 30 minutes were recorded during the hours when lower transient noise was expected. Two measurements were obtained at both sides outside the stream and seven measurements on the possible areas corresponding to the stream, two of them over the zone with maximum GPR scattering. Stable windows of 32 s were used.

2.4.2. Site 2

In the Sagrada Familia zone (Fig. 4), the expected predominant period ranges from 1 to 2 s ([Alfaro et al., 2001]). This zone has high disturbing transient noise especially during the day but also at night, so it was decided to record 30 minutes in each different point along the GPR line. Four measures were planned

South-West of the radar profile outside the zone with high GPR scattering noise, three in zone where GPR scattering is maximum, four at the place where geotechnical and historical information seems to place the stream, and one North-East of the profile. Good stable noise windows of 46 s were selected in order to obtain the predominant period at each point. The selected window length was of 32 s in points where it was not possible (points 1, 2 and 12 in Fig. 4). Several measurements were repeated during the night in order to minimize the transient sources and improve the results. Notwithstanding, results were quite similar.

An example of HVSR ratio and their unitary normalized stability for point 7 in site 2 is presented in Fig, 12 (right).

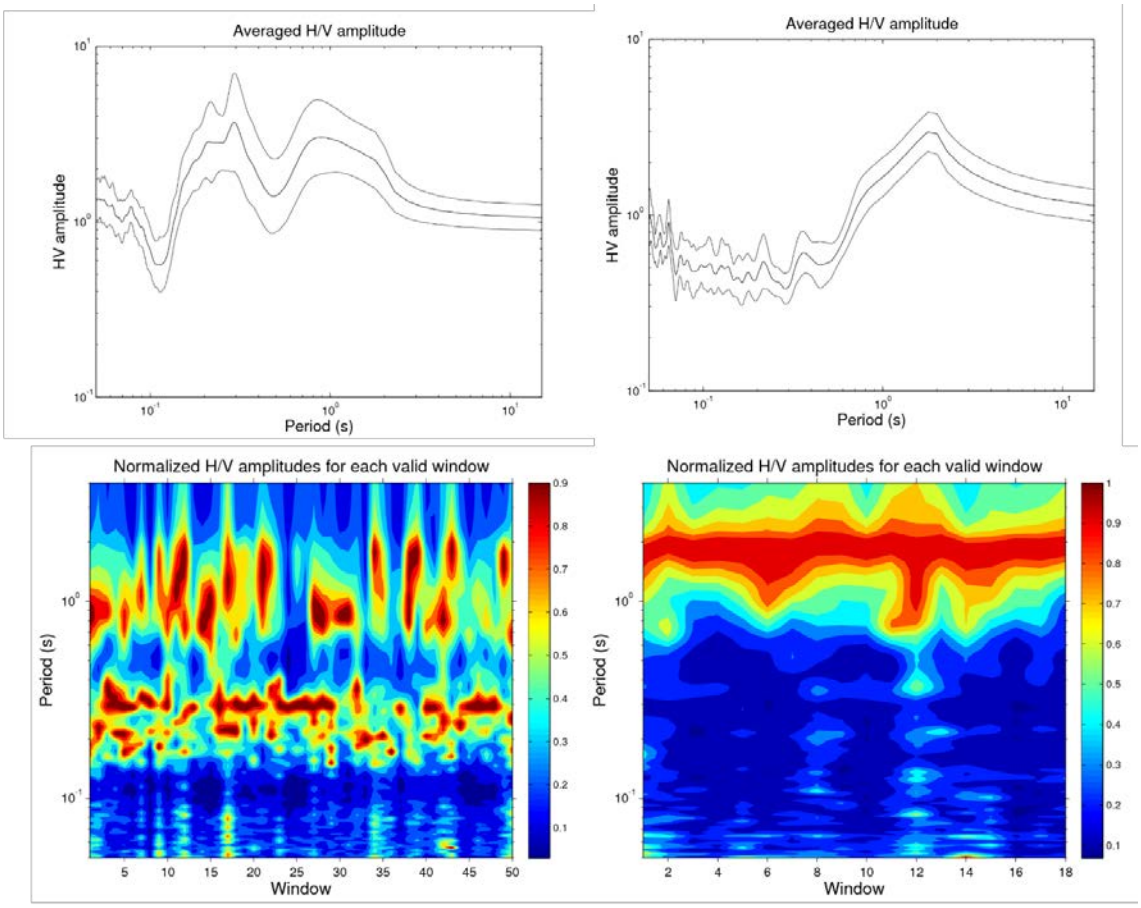

Figure 12. H/V curve with standard deviation and normalized stability for (left) 24 m at site 3 and (right) point 7 at site 2.

2.4.3. Site 3

The predominant period expected in the University Campus Station zone (UCS) is lower than in the other two areas, ranging from 0.14 to 0.27 second ([Alfaro et al., 2001]; [Caselles et al. 2010]). Also, in this area of Barcelona, there is less disturbing transient noise. Nevertheless, the narrow dimension of the streams forces a dense grid of measurement points. Therefore, noise was measured in 37 points during 16 minutes, the distance between points being 1 m in the possible streams positions and 4 m away from these areas. Stable windows of 16 s were selected and processed in a standard way.

An example of HVSR ratio and their unitary normalized stability in the point at the meter 24 at site 3 is showed in Fig. 12 (left).

3. Results

3.1. H/V results

In Catalunya Square (site 1), H/V results indicate a high predominant period variation along the GPR line, showing a range between 0.82 s and 1.52 s (see Table 1 and Fig. 13 left). This range denotes a rate change of about 46%. However, more significant for the seismic risk evaluation is the fact that the change occurs mainly in only 67 m between 1.52 s at point 8 and 0.84 s at point 9, distanced about 70 m.

The predominant period in the second site (Sagrada Familia) presents the lowest changes detected in the three sites, being only 15% in about 65 m. There, the predominant period presents high values in all the points, but results are especially high in point 7, reaching the minimum value in point 4 (Table 2, Fig. 13 centre).

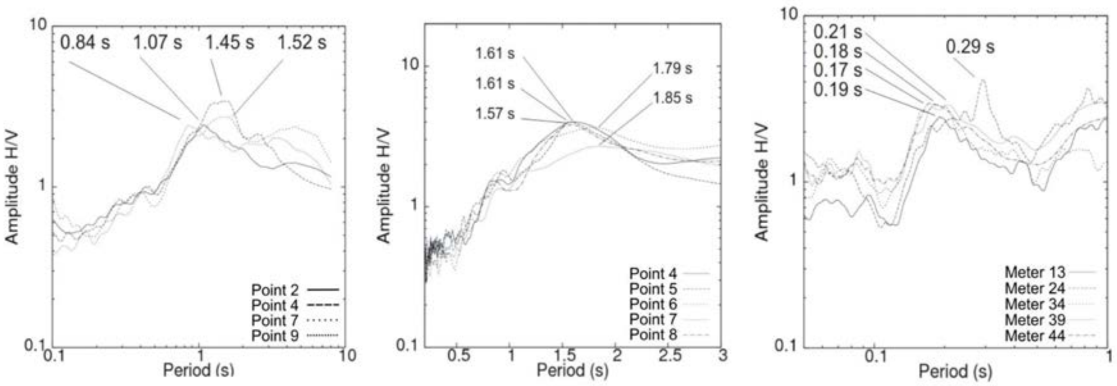

Figure 13. Representative HV curves for all sites. Left: H/V spectral ratio curves for points 2, 4, 7 and 9 in CS. Centre: H/V spectral ratio curves for points 4, 5, 6, 7 and 8 in SF. Right: H/V spectral ratio curves for meters 13, 24, 34, 39 and 44 in UCS.

The H/V results in UCS (site 3) indicate that at almost all points the predominant period values range between 0.17 s and 0.21 s. The exception is the point at 24 m which shows a predominant period of 0.29 s (Fig. 13 right). These values represent a change of about 41% in predominant period, similar to CS change, but in this case the distance is only of about 10 m. Nevertheless, the extension of the anomaly is small.

3.2. Methodology

Historical and geotechnical map information in Catalunya Square (site) has been important in designing GPR survey but not accurate enough for H/V emplacement selection. GPR survey defined the possible existence of two streams or paleochannels (Fig. 3), while Ventayol et al. ([2000]) reported two at the boundaries of the square, and Aranda ([1998]) indicated the existence of only one on the left of the Square. Radar profile has shown that these two streams seem to exist but are centred more inside the square and a wide floodplain lies under almost all the square. Radar interpretation has permitted the focus of the H/V measurements in the square, locating only two measurement points in the square, one on each side. The scattering of radar waves correlate with H/V high values and low scattering corresponds with low period soil response. Radar profile information correlates perfectly with the maximum soil response at point 4. Nevertheless, radar data H/V measures seem not to corroborate the exact position of the maximum period of soil response being displaced about 30 m. H/V seems to be more affected by deeper materials (more than 30 m deep) detected in borehole S11 (Fig. 3).

In Mallorca Street (site 2), historical and geotechnical data were especially important in designing the GPR survey. In this site, radar noise caused by the scattering was also recorded 30 m away from the documented paleochannel location. GPR results allow the definition of a large separation between vibration measurement points 1 and 2 (Fig. 4). The distance between measurement points was smaller in the areas where GPR detects high scattering noise level (points 6, 7 and 8) and also in the zones where geological maps indicate the possible existence of streams and paleochannels (points 2, 3, 4 and 5). The maximum value corresponds to the centre of the noisy area detected by means of GPR, while point 4 is placed in a low noise GPR image, suggesting once more a correspondence between GPR background noise and H/V predominant period values. Ambient vibrations were recorded in particular points selected after analysing the GPR signal and the borehole information (Fig. 4). Low predominant period values correspond to low GPR noise amplitude, while high period values correspond to elevated GPR noise amplitude and to the paleochannel area.

In the University Campus Station zone (site 3) historical and geotechnical information suggested the existence of several streams. This information was used to define the best site for a GPR profile. Microtremor acquisition points were obtained in irregular steps, spacing the points according to the proximity to the GPR anomalies. The points at 24 m and 39 m are over the anomalous zones detected with GPR, the point 24 m being over the most important anomaly. The only one different soil response period corresponds to this point. However, no evident changes are detected over the smaller GPR anomaly.

Figure 14 shows the relationship between predominant periods and the GPR background noise level, probably due to scattering in the three sites.

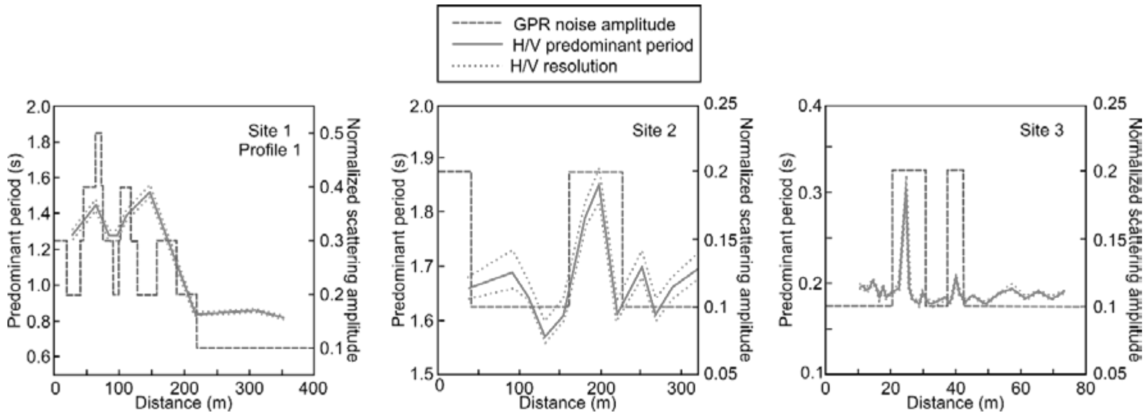

Figure 14. Relationship between GPR scattering noise, HV predominant periods and H/V resolution in the three studied sites.

4. Discussion

To evaluate the methodology, the comparison between historical, geotechnical, GPR, H/V and boreholes is indispensable.

At site 1, CS, changes in the measured predominant period values correlate reasonably well with historical and geological data, the maximum period value being obtained over a known and important subterranean stream, named "Torrent del Mala" (Rambles of Barcelona). Borehole S14 (Fig. 3) is also over this point. Moreover, GPR images contain the maximum background noise in the signal just over this point (Fig. 3 and 9). This noise is assumed to be caused by scattering due to grain size materials. Notwithstanding, historical geological maps show a different stream position, 50 m from the anomalous zone, the possible displacement being due to changes in the water course as a result of natural or anthropogenic cause. Figure 14 also demonstrates a certain correlation between minimum H/V predominant periods and low GPR noise. This site also indicates a limitation of the methodology, GPR can not detect deep anomalies in some geological structures, being limited by the wave attenuation. A possible example of this limitation could be the results in point 8, where high H/V period did not correspond to the high scattering in GPR data but with deep borehole information.

Comparing the results to other results obtained in more general previous studies [Alfaro, 2001], it is noticeable that the predominant period is similar in many points, ranging between 1 s and 1.63 s. However, in points 9, 10 and 11 (Fig. 3) the value is under 1 s. This zone corresponds to the lowest GPR noise (Fig. 9).

In site 2 (SF), the maximum predominant period of the H/V ratio, obtained in point 7 (Fig. 4), clearly correlates to the most elevated GPR background noise zone (table 2). Point 6, also placed over the same GPR zone, presents a high value for the predominant period (table 2). In this case, GPR results were limited by the anomalies detected in concrete areas, caused by reflections from lateral underground constructions. The reflections obscure the effects of the scattering noise, and, as a result, it is nearly impossible to use GPR to assure the existence of shallow geological changes. This effect is visible in two areas, between 5 m and 30 m, and between 50 m and 125 m (Fig. 4).

In site 3, predominant period values are similar to the results obtained in previous studies near the University Campus [Caselles et al., 2010]. Only at point 24 does the result differ clearly, showing a value of 0.29 s. This value shows a remarkable similarity to other periods obtained in previous studies in nearby areas, between site 3 and the neighbouring hills. Point 24 is situated in the middle of the first and widest GPR anomaly, most likely corresponding to an underground stream. The H/V ratio presents a 40% variation in the predominant period. Despite this interesting correlation, it is important to note that the predominant period measured over the second and narrower GPR anomaly does not reveal differences with the other periods (in the case of point 24). It is possible that very small geological structures slightly affect microtremor measures that could be detected with appropriate geophysical surveys. In these particular cases, borehole data could be useful in order to understand the shallow structures detected with a single measure. In this specific site, they are particularly useful because they reach the rock basement. Geological columns from boreholes S1 and L3-13 (Fig. 5) show the thickest anthropogenic layer compared to the other columns, probably due to the proximity of the stream.

4. Conclusions

The purpose of the possible methodology presented and tested in this paper was to include the effect of lateral abrupt changes in shallow geology, which may induce soil response variations, into the analysis of seismic risk. The methodology was applied in three sites in Barcelona, and the results were compared to previous and more general studies. The observed differences and contrasts between some discrete points of measurement and the previous general values assumed denote the need of improve the current microzonation map of Barcelona and, in some cases, the traditional microzonation methodology. The three investigated sites are on the same geological formation (Tricicle). In the previous studies [Cid, 2001], this geological formation is considered as a single unit, presenting only one H/V ratio predominant period values. However, the predominant results obtained in each of these three sites are quite different, changing the order of magnitude in some cases. Evidently, this fact leads to the suspicion that a proper microzonation in Barcelona is not viable looking at only the soil type or soil composition. Obviously, soil composition is an important characteristic to define seismic soil response zones, but more detailed information based on the thickness and density of the materials, shear velocity and rock basement depth is also essential to accurately determine the soil response. Additionally, Barcelona city is located in a basin crossed by a system of streams and paleochannels that produce an important lateral variability in the shallow geology and could be a cause of the change in the seismic response of the soil. Consequently, homogeneous zones defined with their soil characteristics (composition, consolidation and thickness) could present anomalous behaviour due to these structures underneath.

Therefore, the predominant period values obtained in previous studies (e.g., [Alfaro et al., 2001]), might not be representative for each whole defined zone. The cause is that measurement points were chosen without considering these possible geological lateral changes. The different values presented in diverse previous works epitomize this assumption. It can be illustrated considering the two points near to Catalunya Square (site 1). In previous works ([Alfaro, 2001]), predominant periods of 1.00 s and 1.67 s were obtained. This large difference must be associated with local features, in this case to the presence of the paleochannel. In this example, the second point provides a non-representative value, greater than expected, most likely because the measurement was over the stream. As a consequence, soil response evaluations need prior and accurate knowledge of the local geology of the zone. This information could help in the selection of measurement points, avoiding single measurements in non-representative sites. Therefore, in order to assign appropriate predominant period values to each zone, a detailed nanozonation is required, always depending on the surface and the particular geology of each site.

The proposed and tested methodology is based on the application of prior evaluations to define the shallow geology, identifying position and size of superficial geological structures. This information is the base from which to select the grid of measurement points. Prior evaluations are comprised of historical, geological, and geotechnical studies as well as geophysical surveys. Combining direct but discrete measurement point information from boreholes with indirect measurements by means of geophysical surveys probably provides enough detail to select the most appropriate measurement grid. The particular case of subterranean streams and paleochannels especially requires these combined sources because position in old documents and maps might not coincide to the actual location. Additionally, in many cases, especially for older data, these structures are represented as lines over a map. As it can be observed in the results, for soil response, the streams and streams cannot be considered a single line but a wide zone including the flood plain, especially in the lower part of the city. As a consequence of these considerations, geological and geotechnical maps could be appropriate as preliminary tools, but more information is necessary to define the points where to measure. Currently, new geotechnical maps of Barcelona include the flood plain, but unfortunately the entire city is not represented.

To select the most appropriate geophysical survey, several facts were considered: data acquisition velocity, management, accessibility and possible interferences and noise. GPR appeared as the most useful geophysical prospecting method for obtaining sufficient data, the data acquisition being faster than with other techniques. GPR survey was able to provide information about the shallow geological structures, and environmental noise caused by traffic and human activity affected the signals little.

Intensive microtremor measurements require considering some important facts during data acquisition and processing. HV period resolution is quite important to accurately determine the predominant period. Better resolution could be achieved by increasing the window length. Nevertheless, obtaining continuous signal, without transitory energy could sometimes be difficult when measuring in cities, even for a single window. Population and buildings in cities make the data acquisition difficult and intensive grids complicate changing the emplacement. Thus, a balance between a sufficient number of stable windows (reliable HV curve) and long enough windows (reliable change according to the resolution) is always necessary. Other additional difficulties are measurements close to buildings or other structures such as trees or lampposts that could affect the results, and wind increases their effect. Certainly, this effect could be minimized by selecting points far enough from these structures, and by acquiring data on calm days. However, this effect must be assumed for small distances between points when expected abrupt lateral changes require detailed measurements.

Particular results in Barcelona indicate that lateral geological changes could significantly modify the predominant period values. As a result, a regular grid of points to obtain the H/V ratio could lead to inaccurate results. Results provided different soil site responses even when all data were acquired in the same geological zone. This fact most likely indicates the necessity to improve the microzonation in Barcelona city.

Two sites with wide sedimentary layers bear a displacement of the peak to higher periods in areas where GPR image presents high background noise level. This noise in GPR data is assumed to be caused by scattering in areas with bigger soil grains (high percentage of gravels). This behaviour was detected in site 1, where changes in the predominant period are significant, reaching 45%. This notable variation could be significant and might be considered in seismic risk maps. Nevertheless, noise in GPR data could be caused by many different sources and the existence of paleochannels, streams or other geological structures must be confirmed or rejected by means of complimentary studies. In these cases, high GPR noise level might not correspond to changes in the H/V ratio.

The third site was over a thin sedimentary layer. There, changes in the predominant period depend mainly on the geological structure thickness. GPR data contains two anomalies interpreted as filled-in streams. H/V ratio pattern over the smaller anomaly (about 6 m wide) is similar to H/V ratio in other points with no anomalies. In this case, the effect due to a shallow and small geological structure is too small to be detected, and the peak corresponds only to the sedimentary layer effect. This result most likely demonstrates that those geological anomalies do not always cause perceptible changes in the predominant period. However, the predominant period over the biggest anomaly (about 10 m wide) is 40% higher than the results obtained from the surrounding points. In this case, an anomaly a few meters wide is enough to produce a visible HV change.

To summarize, results obtained in this analysis clarify the large and unexpected variability in previous microzonation studies and maps, demonstrating that differences could be caused by an insufficient number of data acquisition points, and the relevance of small geological changes existing in the same geological structures.

The high variation observed in some places in less than one hundred meters highlights the importance of nanozonation in some geological structures. The large differences in changes in the predominant period, mainly in Catalunya Square, could cause different structural responses in close buildings placed over different geological structures. In Catalunya Square, a reinforced concrete skyscraper of about 30 floors will present soil-structure interaction if the building is in the middle of the Square (point 8), whereas, only 16 floors will be required if the building is at point 11. However, not all of the detected changes are as important as those observed in Catalunya Square; the change in the soil response period in Sagrada Familia area could be considered small and unimportant. In other places, such as in the zone of University Campus Station, although the period variation is important and can affect concrete buildings from 3 to 6 floors, the period anomaly has a small width (less than 3 m). In this case, the detected anomaly is smaller than those observed in the buildings in the area. However, the geological structure that caused this anomaly could be large enough to partially affect a part of the foundations. In this case, the building seismic behavior might very likely be modified. This fact could be especially relevant in the case of large structures, such as many of the cultural heritage buildings.

To conclude, the results in the three tests suggest the importance of nanozonation in certain seismic risk studies, mostly in complex geological areas, where irregular structures might appear in the subsoil. The proposed combined methodology has been demonstrated to be useful in properly defining the predominant period in areas crossed by subterranean streams and paleochannels. Geophysical surveys even detected geological structures that cause indistinguishable changes in the H/V ratio predominant period. However, GPR provides indirect information about the ground structures, and could not clearly detect other small or deeper sedimentary structures. Nanozonation could be especially relevant in cities with large cultural heritage structures, which could be partially affected by changes in the ground. These detailed evaluations could be relevant in accurate seismic risk studies.

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