PRELIMINARY GPR SURVEY AT ROMAN SHIPS
ARCHAEOLOGICAL SITE (PISA, ITALY)

Abstract. Two surveys with ground penetrating radar (GPR) were carried out in June 2000 at the Roman Ships archaeological site (Pisa, Italy). Both surveys were undertaken at selected locations (labelled A and B), placed on the plan of excavation (-5 m from the ground surface), using a GSSI Sir System2 incorporating 35 and 200 MHz centre-frequency antennas. The main purpose of the two surveys was to test the value of radar in respect of penetration depth and, therefore, to reconstruct the geological stratigraphy, given the general not too favourable site conditions. The results showed that most of the GPR data acquired with the 35 MHz antenna were contaminated by strong reflections caused by above ground objects near the survey lines. In fact, the archaeological area is protected on every side by iron barriers, around 6 m high, in order to guarantee the stability of the walls and to contain the present shallow groundwater. Therefore, it is very important to recognise the reflections through air (surface scattering) and not to confuse them with the reflections from underground geologic features. For this motive the 200 MHz antenna has been also used. In fact the 200 MHz antenna provided adequate penetration depth and allowed better lateral continuity and resolution of the subsurface targets than both the 35 MHz and 100 MHz antennas. The comparison between the data acquired with the 35 MHz antenna and 200 MHz antenna has allowed to recognize, with greater reliability, on the radar sections acquired with the 35 MHz antenna, both the reflections from underground geologic features and the reflections through air (from side objects: i.e. metallic protection).

INDAGINI PRELIMINARI CON GPR NEL SITO ARCHEOLOGICO DELLE NAVI ROMANE (PISA, ITALIA)

Riassunto. Le indagini geofisiche hanno avuto lo scopo di mettere in evidenza le caratteristiche gisiturali dei sedimenti nel sito archeologico in cui sono state rinvenute le navi romane. È stato eseguito un rilievo elettromagnetico preliminare di tipo impulsivo (Ground Penetrating Radar - GPR) utilizzando il georadar SIR SYSTEM-2-GSSI e le antenne da 35 MHz e 200 MHz. L’indagine georadar è stata effettuata in due aree, (A e B in Fig. 1 e 3), entrambe situate sul piano di scavo (-5m dal piano di campagna); la prima (A) è situata in prossimità delle navi romane messe in luce, la seconda (B) nell’ampliamento Sud dello scavo. Un ulteriore profilo C è stato realizzato sul piano campagna a nord-ovest dello scavo ed a circa 30 m da esso. Tutta l’area scavata è protetta su ogni lato da barriere di ferro, alte circa 6 m, al fine di garantire la stabilità delle pareti e contenere le acque di falda presenti nei depositi alluvionali sovrastanti. Nell’area A sono stati eseguiti n 40 profili (per uno sviluppo complessivo di circa 800 m); di essi 38 sono stati eseguiti con antenna da 35 MHz e 2 con antenna da 200 MHz. Nell’area B sono stati eseguiti n 34 profili con antenna da 35 MHz (per uno sviluppo complessivo di circa 700 m). Il profilo C, rilevato con l’antenna da 35 MHz, è lungo 36 m. È noto che le profondità indagate con il metodo G.P.R. ed il potere risolutivo del metodo stesso dipendono dalla frequenza dell’impulso elettromagnetico inviato nel sottosuolo, oltre che dalle caratteristiche elettromagnetiche del mezzo attraversato (A.P. Annan et al., 1989). Le caratteristiche tecniche della antenna da 35 MHz ed il suo modo d’impiego (sospesa in aria a circa 60-70 cm dal suolo) rendono possibili riflessioni spurie, provenienti da oggetti posti al di sopra del piano di calpestio, e la loro ricezione da parte dell’antenna stessa. Per questo motivo sono stati eseguiti, nell’area A, i due profili con l’antenna da 200 MHz le cui caratteristiche costruttive e il metodo di impiego (a contatto del suolo) garantiscono rispettivamente una migliore schermatura laterale e una maggiore stabilità dei dati acquisiti; l’antenna da 200 MHz, ovviamente permette una minore profondità di indagine di quella consentita dall’antenna da 35 MHz. Il confronto tra i dati acquisiti con le due antenne ha consentito di individuare, con maggiore attendibilità, sulle sezioni relative all’antenna da 35 MHz i segnali provenienti dal sottosuolo e di riconoscere le riflessioni provenienti da oggetti laterali (protezione metallica dell’area scavata).
ARCHAEOLOGICAL SITE DESCRIPTION

Pisa and its system of harbours constituted an extraordinarily important focal point in the context of the Mediterranean and the traffic that took place in its waters. Historical sources suggest the existence of at least three harbours in Roman times: two, near Livorno and S. Piero a Grado, along the ancient coastline which was located much further inland than it is today (Fig. 2a), and a third landing place, whose precise location was unknown until the recent archaeological discovery near the Pisa-S. Rossore railway station. Here, in December 1998, during work to lay the foundations of a new headquarters of the Tyrrhenian line of the Italian state railways, the remains of at least sixteen Roman ships (ca. 200 B.C.-200 A.D.?) were discovered. This discovery, together with the analysis of remote-sensing data, that allowed the reconstruction of the urban course of the no longer existing “Auser” river (Fig. 2b), led archaeologists to identify the S. Rossore archaeological area with the place of the urban harbour of the Etruscan and Roman city. Apart from the evident archaeological importance, the recent discovery cast new light on the ancient environmental and geographical setting where the town of Pisa developed.

The archaeological site lies in the area known as the Pisan lowlands, a sedimentary basin of alternating continental and marine origin, whose formation
began in the Upper Miocene period (about ten million years ago), following tectonic subsidence in a region previously characterised by the formation and rise of Northern Apennines. The paleo-environment of the region was characterised by the presence of two rivers, the Arno and the now disappeared Auser, as well as minor watercourses and canals. As a result of the accumulated alluvial deposits of the Arno the coast is now at considerable distance from Pisa and the characteristics of the surrounding countryside have been significantly altered by the gradual expansion of marshland.

Data coming from archaeological excavation and geological observations (core samples) allowed to reconstruct the stratigraphy of the uppermost ten metres of sediments in the S. Rossore area. About three metres of sand rest on relatively thick clay deposits, not yet reached by the excavation. These sands in turn lie under about two metres of alternating sand and silt deposits in the northward sloping layers containing the shipwrecks and other archaeological deposits. This level tends to diminish in depth and coarseness as one moves northwards, and its stratification is tentatively attributed to exceptional flooding of the Arno, which laid down lenticular sand deposit in the dry area between the river and its right bank. The remaining layers of sediment consist of silty-clayey muds from more routine flooding and from backfill dumped in historical times (Bruni, 2000).

The excavation, moreover, revealed that in ancient times the southernmost sector of the harbour basin was subjected to a series of phenomena leading to its progressive silting up: the various lenticular sediments are, indeed, inclined northwards in the direction of the coastline, which in Roman time lay about 3-4 km west of the excavation (Fig. 2).

The nature of the sediments so far observed in the alternating sand and silt deposits lead one to infer that the area was repeatedly flooded and sometimes so violently as to move the ships and diverse portions of their cargo, though these events have not yet been dated.

**GPR SURVEY AND DATA ANALYSIS**

The GPR survey at the archaeological site of Pisa was carried out using a Sir-2 digital pulse radar system by GSSI (Geophysical Survey System Inc.) and both 35 and 200 MHz centre-frequency antennas. The survey was carried out in two areas, (A and B in Fig. 1), both placed on the plan of excavation (-5 m from the ground level); the first one (A) is located in proximity of the discovered Roman ships, the second (B) in the southern sector of the excavation. A further profile, C, was carried out on the surface plane about 30 m north-west of the excavation in S-N direction. Apart from two profiles acquired with a 200 MHz antenna, all the others were collected using a 35 MHz antenna, in order to achieve the maximum possible investigation depth.

The technical characteristics of the 35 MHz antenna and its way of employment (suspended in air at 0.6-0.7 m above ground) make possible the recording of spurious diffractions or reflections coming from objects located above the walking plan. This coherent noise can appear on radar sections either as hyperbolic events, characterised by the velocity of the electromagnetic waves in the air (0.30 m/ns) or as linear events, that often interfere among them and with possible reflections from geologic interfaces.
In fact, the energy of the electromagnetic waves travelling in the air decays as the inverse of the distance squared (geometrical spreading) while the energy of those travelling in the ground undergoes also an exponential decay due to absorption phenomena in the ground. Because of their high energy, reflections from above
ground objects can cover possible weaker reflections of geologic or archaeological origin. Moreover, in the case of metallic objects, the problem is complicated by the probable presence of multiple reflections due to the high reflection coefficient of metal. The raw data require, therefore, a careful and contemplated analysis.

If the geometrical position of the sources of possible surface scattering phenomena is known, the corresponding arrival times can be predicted and the relative correlated disturbances can be identified on the radar sections. Their removal is, however, quite more difficult. If the disposition of the scattering objects is not geometrically simple (as in area A), also their identification can be rather problematic.

In the present situation a careful analysis of the signal behaviour on parallel profiles acquired in zone B, where the geometry of the iron sheet-piling was simpler, allowed to understand the possible origin of both hyperbolic and linear (horizontal and slightly dipping) noise events (Nuzzo, 2001; Carrozzo et al., 2002). For example, for the S-N profiles, hyperbolic diffractions at the air velocity were noted at the beginning of each section caused by surface scattering from the southern side of the barrier (S_d in Fig. 3b). Two couples of linear events with opposite dips (E_1, E_2 and W_1, W_2 in Fig. 3a) were also noted. The arrival time of the northward dipping events (E_1 and E_2) regularly increased on subsequent profiles moving away from the eastern side of the barrier; on the contrary the arrival time of the southward dipping events (W_1 and W_2) regularly decreased.

Moreover an almost completely flat event was recorded at the same arrival times on every profile (as, for example, EW in Fig. 3a).

The spurious signals were better evidenced by a “partial removal” strategy purposely developed: a “mean section” (Fig. 3b) was calculated averaging all the S-N profiles in the E-W direction, and then subtracted from each original section to yield the corresponding residual section (Fig. 3c). Whereas the mean section contains all the features independent from the profile locations (diffractions from the south side, S_d; air waves bouncing back and forth between the opposite east and west side of the barrier and, thus, travelling a constant total path, EW; and underground reflections from flat surfaces), the residual sections better emphasise those features varying accordingly to the relative position of the profiles and the surrounding metallic enclosure. After this partial removal, from the analysis of their arrival times, these events (E_1, E_2 and W_1, W_2), were recognised as diffractions from the edges of the eastern and western sides of the barrier with some annexed multiples. The weak residual energy at about 35 and 130 ns (G_1 and G_2) could be due to reflections from almost flat stratigraphical boundaries. This is confirmed by similar traveltime observed on the sections acquired in area A with the 35 MHz antenna (although masked by surface scattering events) and, for the shallowest event, also on the two 200 MHz sections from the same zone (G_1 in Fig. 3d). Assuming an average velocity value v=0.07 m/ns, typical of saturated sand and silt, the two interfaces are located at depths of about 1.2 m and 4.5 m.

The radar section related to the C profile, located on the ground level out of the excavation area, and therefore away from metallic objects, results less disturbed (Fig. 3e). It is possible to individualise three reflections: the first one, approximately horizontal, is located at about 35 ns; the other two reflections are inclined northwards and are located respectively at times of 35-100 ns and 140-230 ns. Using the already assumed average velocity value (v = 0.07 m/ns), the depths of the interfaces are: about 1.2 m for the first flat reflection, about from 1.2 m to 3.5 m and from 4.9 m to 8.0 m for the dipping ones. The inclination and the depth of such interfaces are in good agreement with both the geological sequence previously described and the
results of the geoelectrical profiles carried out in the same zone (Finzi Contini and Losito, personal communication).

**Fig. 3** - June 2000 survey; (a) Original radar section from the B5 profile (Fig. 1) acquired with a 35 MHz antenna; (b) mean section obtained averaging all the S-N profiles in the E-W direction; (c) residual section after the subtraction of (b) from (a). The diffractions from the edges of the E or the W side of the barrier and some of their multiples (E₁, E₂ and W₁, W₂, respectively) are better visible on the residual section, whereas the almost horizontal events (EW), probably due to air waves bouncing back and forth between the opposite E and W sides of the iron sheet-piling, are highly attenuated. The hyperbolic diffractions from the S side (S_d) are slightly attenuated but not completely removed. G₁, G₂ denote probable geological reflections. (d) Radar section from the A6 profile (Fig. 1) acquired with a 200 MHz antenna; G₁ denotes a probable geological reflection (the zero level on the depth scale refers to the excavation plane located 5 m below the ground level). (e) Radar section from the C profile acquired on the ground level outside the excavation area with a 35 MHz antenna; R₁, R₂, R₃: subsurface reflections.
Time slice view

To facilitate interpretation of complex radar data the creation of time slices is generally useful. Time slices examine only reflection amplitude changes (or energy changes if the square value is used instead of the absolute value) within specific time intervals, and thus within consecutive soil layers of nearly constant thickness. Each time slice is, therefore, roughly comparable to a standard archaeological excavation level (Conyers and Goodman, 1997). In reality, because of possible velocity changes across the area and with depth, horizontal time slices must be considered only approximate depth slices. However, this is generally sufficient for most common applications. Areas of low reflection amplitude (or energy) indicate uniform matrix materials or quite homogeneous soils, while those of high amplitude denote areas of high subsurface contrast such as buried archaeological features, voids or important stratigraphic changes.

In the present work the time slice technique has been used to display the energy variations within the 20-60 ns two-way time windows, where the majority of anomalies were observed in all radar sections acquired in area B with the 35 MHz antenna. The selected two-way time intervals correspond to subsoil layers located, respectively, between 0.70-2.10 m in depth (assuming an average velocity value of 0.07 m/ns).

Several high amplitude anomalies (dark grey) are visible in the slice (Fig. 4b). It is, probably, related to the remains of the harbour structures of the Etruscan city.

CONCLUSIONS

The preliminary GPR survey reported in this paper showed clear evidence that there were a number of difficulties, linked essentially to the uncomfortable conditions of the archaeological site of S. Rossore (Pisa, Italy), in performing the acquisition and interpreting the data. The moderately high electrical conductivity and degree of water saturation of the investigated alluvial sediments limited the penetration depth to less than 10 m for the 35 MHz survey and to less than 2 m for the higher frequency 200 MHz survey. Moreover, the presence of a 6 m high iron barrier all around the walls of the archaeological excavation, to guarantee their stability and to contain the shallow water table, caused heavy surface scattering problems, especially on the low-frequency radar sections. The careful analysis of the 1 m spaced parallel profiles, acquired in both S-N and W-E directions in the southern sector of the archaeological excavation (at level of about 5 m below the ground surface), allowed us to distinguish the reflections from above-surface objects from those of probable geological origin. The partial removal strategy, purposely developed, allowed the identification of two reflections (at about 40 ns and 135 ns respectively) probably related to stratigraphical boundaries. Their geological meaning remains, however, doubtful, since the weak anomalies in the residual sections could be the result of an imperfect subtraction procedure. The shallowest event seems confirmed by comparable travelt ime in the 200 MHz sections. At least three flat or northward sloping reflections were identified on the radar section relative to the only profile performed outside of the excavation (at the ground level), probably related to geological or hydrogeological interfaces in the uppermost 8 m of sediments.
Fig. 4 - The south extension of the excavation were remains of the harbour structure of the Etruscan city have been found a); b) time slice; c) radar section of the BT3 radar profile.

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