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Medium to Shallow Depth Stratigraphic Assessment Based on the Application of Geophysical Techniques

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1. Introduction

In strict terms, the word "stratigraphy" refers to the study and description of a natural succession of more-or-less parallel layers, or strata, of sedimentary rocks. However, in the fields of environmental engineering and engineering geology, the term "stratigraphy" assumes also a general and broader meaning, since it very often refers to a generic underground sequence of not always sedimentary and not only natural materials.

That said, the importance of an adequate knowledge of the site stratigraphy in engineering and environmental problems is well known. Geotechnical studies for building foundation design, waste landfill design or pre-reclamation assessment, aquifers monitoring and evaluation, and sea water intrusion control, are among the most common activities in which at least some aspects, namely thickness, composition and hydrogeology of the unconsolidated cover, depth to bedrock and conditions of the latter, must be clarified at the best. As far as the investigation depth is concerned, it could range from few meters – few tens of meters in geotechnical and waste landfill studies, to few hundreds of meters in regional hydrogeological studies and in the assessment of the fresh-water/sea-water relationships along the coastal belts.

In all the above situations, classical geological and hydrogeological surveys, integrated with direct investigations such as shallow excavations, and adequately deep and properly distributed pits and bore holes, can provide the required information.

However, this strategy can imply both technical and economical concerns, mainly regarding the distribution and quantity of direct surveys.

Actually in several, simple cases (e.g.: very small extension of the study area; limited lateral variations, that is 1D conditions, where only qualitative information is required), surface geological data along with a very small amount of direct investigations can be more than enough.

Conversely, when the stratigraphic assessment is the premise of a more complex and relevant work covering relatively large areas characterized by complex geological conditions, the following questions arise: first, what degree of accuracy is needed in the assessment of the underground stratigraphy? Second, as a consequence of the answer to the

first question and also based on the depth to the target, what type of direct investigation is more appropriate and, for instance in the case of bore holes, how are they to be distributed? Third, are the technical requirements consistent with a reasonable budget? In this context, a valuable aid may be provided by the geophysical survey techniques.

As known, these techniques provide indirect information about geological, hydrogeological, geotechnical and environmental conditions, through the study of some physical characteristics of the subsurface. For instance, if you measure a high speed of propagation of elastic waves, it is most likely associated with consolidated rocks, while low speed values should correspond to loose materials; similarly, a relatively low electrical resistivity can be associated with the presence of aquifers, while very high values should correspond to hard, dry rocks. So, the gravity method is based on the density, the magnetic method on the magnetic susceptibility, the seismic methods on the acoustic properties, namely the density and the velocity of elastic waves, the electrical methods mainly on the electrical resistivity and so on. Both the theory and the practice of geophysical methods are widely treated in many text books of applied geophysics (e.g. Dobrin, 1976; Reynolds, 1997; Sharma, 1997; Telford et al., 1990).

In this chapter, on the basis of several case studies, we shall try and illustrate in what way geophysical techniques can contribute to the stratigraphic assessment of a site providing high-level information and contributing at least to rationally planning, if not completing avoiding, the drilling campaign. In all cases, the primary method of investigation has been that of reflection seismology employed at different scales. However, this method was prevalently preceded by a gravity survey, which is essential for the proper design of the acquisition parameters, and accompanied by other geophysical data and direct surveys, such as drillings and exploratory excavations. As known, the reflection seismic method owes its great development to the fact that it has been linked, historically, to the search for oil and gas. However, in the past three decades the data acquisition and processing techniques of this method have been progressively adapted to shallow targets. In the early eighties of the past century, the term "shallow reflection" was associated to targets at depths in the order of some hundreds of meters, and applications for depths of few tens of meters, or less, were conducted only at the experimental level.

Nowadays, the use of this method with targets at depths of few tens of meters and even of few meters, has become a technical reality. In the examples illustrated in the following sections, the maximum depth to the targets ranges from a few hundred meters to a few meters and therefore it can be said to be from a medium to a very shallow depth . For an adequate knowledge of principles, data acquisition and data processing for the reflection seismic method, refer to Dobrin (1976) and Yilmaz (1987).

2. Stratigraphic assessment of a coastal plain affected by groundwater salination

The coastal plain covered in this section is a fluvial valley that also includes a river delta (Balia et al., 2003). The surface geology of the plain and its surroundings is characterized, from bottom to top, by a Paleozoic metamorphic complex outcropping on the edges of the plain, and Pleistocene and Holocene sediments and alluvium, up to a few hundred meters thick, overlying the Paleozoic bedrock. Granites (Upper Carboniferous- Permian) outcrop a

few kilometers from the edges of the valley. Before the geophysical surveys, the thicknesses of recent alluvium, ancient alluvium, and metamorphic complex in the plain were only estimated on the basis of morphology and surface geology. As regards hydrogeology, the surface water bodies are the river, its channels at the mouth, which are no longer connected with the river itself but contain incoming seawater, and several seasonal streams flowing down from the surrounding hills. Apart from the water occurring in the fractured Paleozoic rocks, from which a few small ephemeral springs issue during the cooler months, groundwater is primarily in the alluvial deposits, and the dominant, qualitative theory was that two aquifers could be distinguished: a shallow phreatic aquifer extending down to a few tens of meters, and an undefined, deeper, confined aquifer, separated from the former by a clay layer from a few meters to several tens of meters thick. The lower boundary and deeper stratigraphy of the confined aquifer were poorly understood so far.

Due to the importance of understanding at the best the hydrogeological model of the plain, a relatively intensive application of geophysical techniques was used as a tool for elucidating a number of aspects of primary importance for the realistic modeling of salination and its evolutionary trend. Among these, the following were the most important: 1) conditions of shallow and deep salination; 2) structural model of the plain, including depth to Paleozoic basement; 3) stratigraphy of the Pleistocene-Holocene sedimentary cover; 4) relationships between the phreatic aquifer and the confined aquifer.

Therefore, the primary targets of the stratigraphic assessment by means of geophysical methods were the depth to the Paleozoic bedrock and the stratigraphy of the overlying Pleistocene-Holocene cover. For these purposes, the primary geophysical method was that of reflection seismology, although gravity and electrical methods were also employed. Thus, one seismic profile was positioned and designed, based on gravity data previously acquired and processed in the frame of the same project, and on preliminary tests. In detail, the acquisition geometry was designed for a target depth of 100-200 m. A 48-channel off-end spread of single 40 Hz geophones at 5 m spacing was used, with a minimum offset of 30 m and, consequently, a maximum offset of 265 m. The acquisition system was a 48-channel seismograph with a 60 Hz low-cut filter and a 600 Hz antialias (high-cut) filter. Record length was 500 ms (millisecond) and sampling interval 0.25 ms. Small dynamite charges (30-100 g) placed in 1.5-2 m boreholes at 5 m intervals were used as an energy source, giving a maximum nominal CMP (common midpoint) fold of 2,400%. In all, 172 shots were performed, obtaining a total seismic section length of 975 m.

The data quality was satisfactory and the dominant reflection frequency was in the order of 70-80 Hz. Processing included amplitude equalization, 40-120 Hz band-pass filtering, statics, CMP sorting, velocity analysis, NMO (normal moveout) correction, CMP stacking, and time-to-depth conversion. Further more or less sophisticated processing proved not strictly necessary and was not applied. Interval velocities were computed from stack velocities by means of the Dix equation and were used for time-to-depth conversion.

The depth section reported in figure 1 shows two main reflectors, both attributable to the Paleozoic basement. The upper one lies at a maximum depth of about 280 m (CMP trace #40) and emerges more or less regularly up to a depth of less than 100 m (CMP trace #250). The morphology of the lower one, which is still present in the northern side of the section, exhibits a high at CMP trace #275, at a depth of about 100 m.

Tectonic structures like faults and fracture zones are also present. The upper reflector is associated with the boundary between the Pleistocene-Holocene cover and the Paleozoic metamorphic rocks, while the lower reflector is associated with the transition from metamorphic rocks to granite. The velocity of Pleistocene-Holocene sediments and alluvium is in the order of 1,700-2,000 m/s and the average interval velocity between the two reflectors is 2,700 m/s. These values suggest that Pleistocene–Holocene sediments are fairly consolidated. Also, due to their relatively low velocity, Paleozoic metamorphic rocks should be relatively fractured and altered, at least in the upper part. The lack of a coherent signal in the lower part of the section, from CMP trace #270 to the northwest, may be attributed to relatively homogeneous granite.
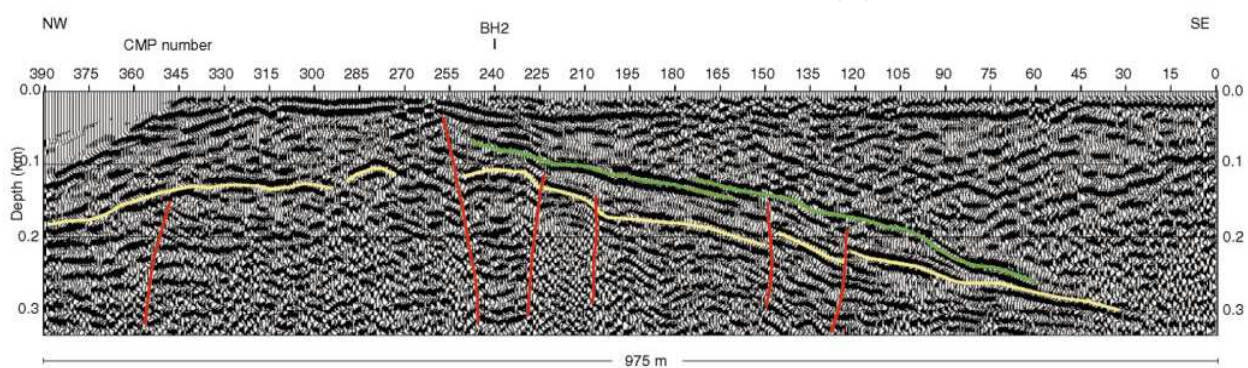

Fig. 1. Interpreted depth section of the P-wave reflection seismic profile SP2. CMP trace interval is 2.5 m . See text for description of reflectors. (After Balia et al., 2003)

Given the aim of the work, a detailed knowledge of the Pleistocene-Holocene cover was of primary interest. Thus, the data pertaining to the southernmost part of the seismic profile were processed separately, especially refining velocity analysis for shallower events. The corresponding time section is shown in figure 2. Sediments and alluvium overlying the bedrock are clearly stratified and show a low around CMP trace #100, with a maximum estimated depth of roughly 150 m. The latter structure may be associated with a paleovalley, probably related to the ancient course of the river. According to geological knowledge, reflector 1 in figure 2 (green color) corresponds to one boundary that separates Holocene materials with different characteristics (e.g. different density and velocity due to different compaction), and reflector 2 (yellow color) corresponds to the boundary between permeable Holocene alluvium and impermeable Pleistocene terraced alluvium. This suggests that mathematical modeling of the aquifers contained in the Holocene cover could be limited to a depth of 150-200 m below ground level. The total cost (planning, data acquisition, data processing and interpretation) of the seismic profile shown above is equivalent to that of two-three adequately deep boreholes. However these, even if distributed at the best, could not in any way guarantee the same complete information provided by the seismic profile.

Having solved the problem of the relationships between the cover and the Paleozoic basement, the relationships between the phreatic and the underlying confined was next. For this purpose, another reflection profile was carried out, but electrical resistivity and borehole data were also used for its hydrogeological interpretation.
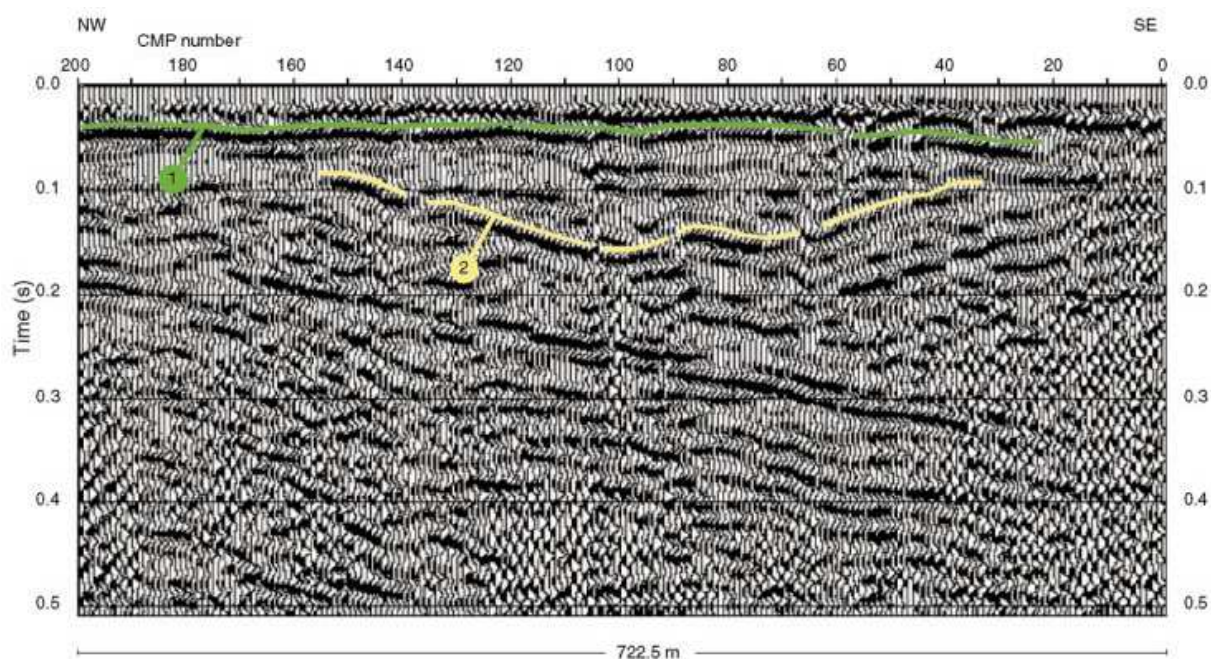
Fig. 2. Interpreted time section for the southernmost part of seismic profile SP2. See text for description of reflectors. (After Balia et al., 2003)

Concerning the seismic profile, it was designed for relatively shallow targets: data were acquired using a 24-channel off-end spread with a channel interval of 3 m and a 30 m in-line minimum offset. Single 50 Hz natural frequency geophones were used. The recording instrument was set with the following acquisition parameters: record length 200 ms, sample interval 0.25 ms, low-cut filter 70 Hz, high-cut filter 700 Hz. A shot-gun was used as energy source, with a shot interval of 3 m which, given the spread, gave a maximum CMP fold of 1,200%. The processing sequence included amplitude equalization, frequency filtering, statics, muting, CMP sorting, velocity analysis, NMO correction, CMP stacking, f-k migration, and time-to-depth conversion. The optimum stack velocity was about 1,700 m/s. The seismic section, shown in figure 3, exhibits two reflectors, not very easy to interpret. In order to perform an interpretation consistent with the real geological and hydrogeological conditions, it was decided to drill a calibration borehole (BH1 in figure 3), which was located in correspondence of the CMP position #182, that is less than a hundred meters away from the center of a vertical electrical sounding (VES9 in figure 3). The drilling capabilities allowed a depth of not more than 35.5 m, since drilling had to be stopped at the depth of 32.7 m from ground surface (about 28 m under sea level) because a hard layer of pebbles in a silty-sandy matrix containing high pressure saltwater was met. In spite of this, the obtained stratigraphy proved rather meaningful. It is shown in figure 4 compared with the corresponding resistivity and seismic columns. As can be seen, there is a close correlation among the following discontinuities:

-   transition from clay layer to layer made up of pebbles in a silty-sandy matrix and containing high pressure saltwater;
-   transition from 22 ohm-m to 3 ohm-m;
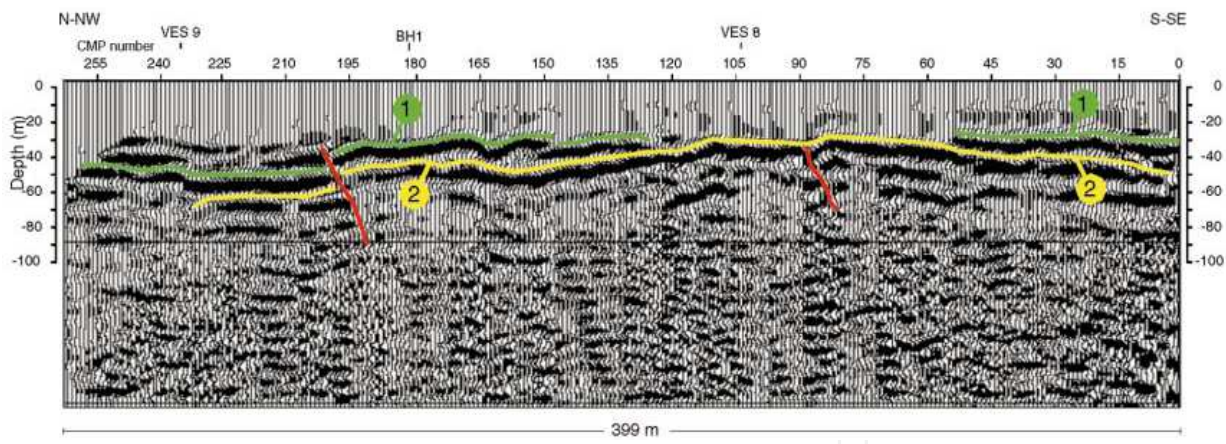-   upper reflector (reflector 1 in Figure 3).

Fig. 3. Geophysical interpretation of the seismic section acquired for clarifying the relationships between the phreatic aquifer and the underlying confined aquifer. (After Balia et al., 2003)
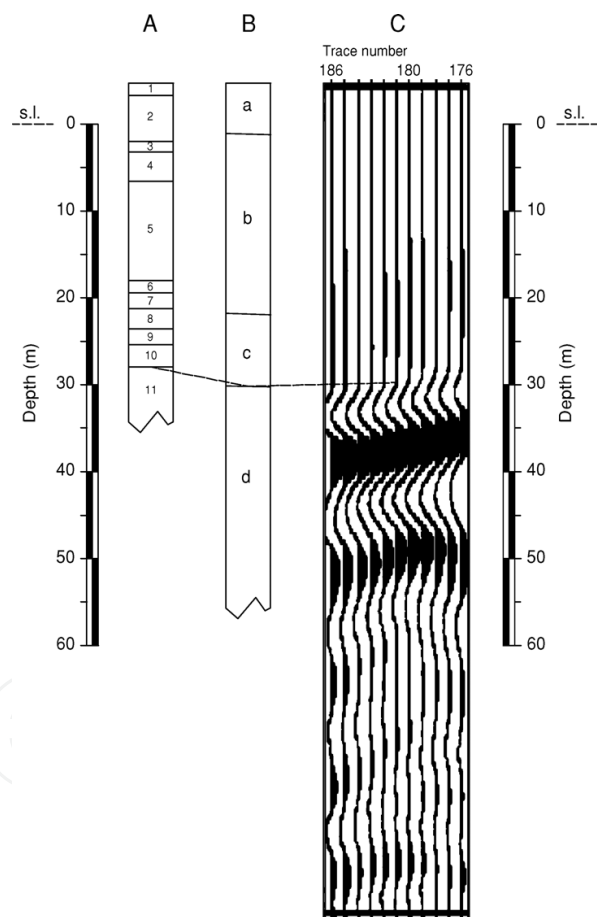

Fig. 4. Borehole stratigraphy (A) compared with the resistivity (B) and seismic (C) columns. Legend for the stratigraphic column (A): 1. clayey soil; 2. fine-coarse sand; 3. pebbles in a sandy matrix; 4. sand with microconglomerates and rare pebbles; 5. pebbles in a silty-sandy matrix; 6. coarse sand; 7. pebbles in a silty-sandy matrix; 8. silt and clay with medium-coarse sand; 9. pebbles; 10. thick clay with minor sand; 11. pebbles in a silty-sandy matrix. Legend for the resistivity column (B): a. 10-21 ohm-m; b. 5 ohm-m; c. 22 ohm-m; d. 3 ohm-m. (After Balia et al., 2003)

As regards the lower reflector (reflector 2 in Figure 3), it can only be said that it should represent the lower boundary of the layer of pebbles in silty-sandy matrix, that is of the shallowest unit of the confined aquifer.

In terms of the hydrogeological model and salination status, these results could be interpreted as follows. It is confirmed that there is a separation between the phreatic aquifer and the underlying confined aquifer and, also for this reason, they very probably have rather different histories. The former is actually affected by saltwater intrusion characterized by the present evolution depending on several factors, such as overexploitation, upstream dams, recent artificial channels that have been opened for fish-farming, and recurrent drought; while salination affecting the latter seems to be quite different and more likely to be related to vicissitudes that occurred in an ancient past when the seashore was situated several kilometers inland from its present position.

3. Stratigraphic assessment to evaluate water resources

In this second example, the problem is to ascertain the possibility of finding fresh groundwater under the Quaternary cover (Balia et al., 2008). The surface geology of the site (a coastal plain situated in a graben area) is characterized by the Paleozoic basement that outcrops on one edge of the plain and deepens very quickly towards the middle of the graben, and Pleistocene-Holocene sediments and alluvium. Apart from the surface and near-surface Pleistocene-Holocene sediments and alluvium, before the geophysical campaign the stratigraphy to volcano-metamorphic basement was substantially unknown.

The commonly accepted aquifer system model is as follows:

- a shallow, phreatic aquifer, hosted in recent alluvium, characterized by small depth to water and thickness varying in the range 10-30 m
- a deeper, multilayer aquifer, separated from the former by clay layers interbedded with gravels, with an overall maximum thickness of 20-25 m; this aquifer about 130 m thick, is partially and/or locally confined and hosted in alluvium characterized by a strongly variable permeability, so that it is rather irregular and discontinuous.

The whole hydrogeological conditions of the plain have been extensively studied, in the more or less recent past, even with the contribution of geophysical surveys (Balia et al., 2008, and references therein). In the following, the stratigraphic assessment below the Quaternary cover, that is below the already known aquifer system, is recalled. The need for this assessment was that the already known, near-surface aquifers were mostly exhausted or polluted by seawater, mainly due to overexploitation. Thus, two P-wave seismic reflection profiles were acquired and interpreted (Balia et al., 2008, and references therein). The depth-converted sections are shown in figure 5. Both sections exhibit five reflectors, numbered 1 to 5. Reflector 1 is associated to transition from near-surface Pliocene-Quaternary sediments and alluvium to Miocene sediments; this transition is situated at a depth of the order of 130-150 m, in good agreement with electrical and electromagnetic data, as well as with drillings.

Reflectors 2-4 are interpreted as transitions between different Miocene lithologies. Reflector 5 is not interpreted; however, given the depth, it is very likely to be associated to the transition between the Miocene sediments and the volcano-metamorphic basement. On the basis of the most widely accepted geological and structural scheme of the region, the latter should be

made up of Oligocene andesites in its upper part, and then by the Paleozoic, metamorphic rocks and granite. As can be noted in both seismic sections, while reflectors 1 and 2 are almost flat and continuous, reflectors 3 to 5 are increasingly undulated and discontinuous, with evidence of faulting in the deepest layers, and this could mean first that the volcano-metamorphic basement is significantly fractured, thus being suitable for hosting aquifers and, second, that some tectonic event occurred during the Miocene, most probably just before or at the same time as the deposition of the second layer, that is the one bounded by reflectors 1 and 2.
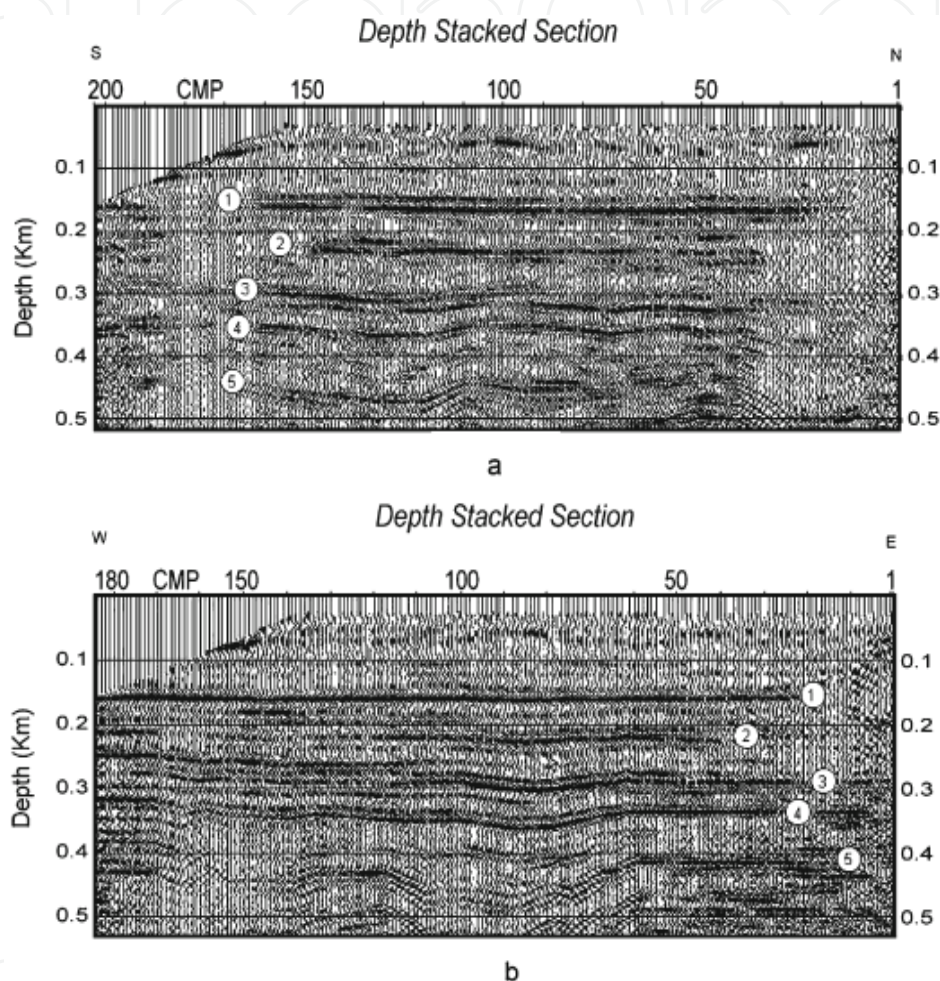
Fig. 5. S–N (a) and W–E (b) seismic depth-sections in the sample area of the plain. CMP trace interval is 2.5 m. The meaning of reflectors 1-5 is explained in the text. (After Balia et al., 2008)

In hydrogeological terms, the stratigraphic conditions described above indicate that, due to conspicuous thickness of impermeable Miocene sedimentary products, at least in the studied portion of the plain, the probability of finding freshwater at a depth of less than 350-400 m is very low, since it could be hosted only in the fractured, volcano-metamorphic basement. Actually this is not a propitious response, but will at least prevent wasting money on inadequate drillings.

Again it was necessary to check the condition of the two aquifers hosted in the Quaternary alluvium, and with regard to geophysical techniques, this was done by means of the electrical resistivity method, namely using the vertical electrical sounding (VES) technique.
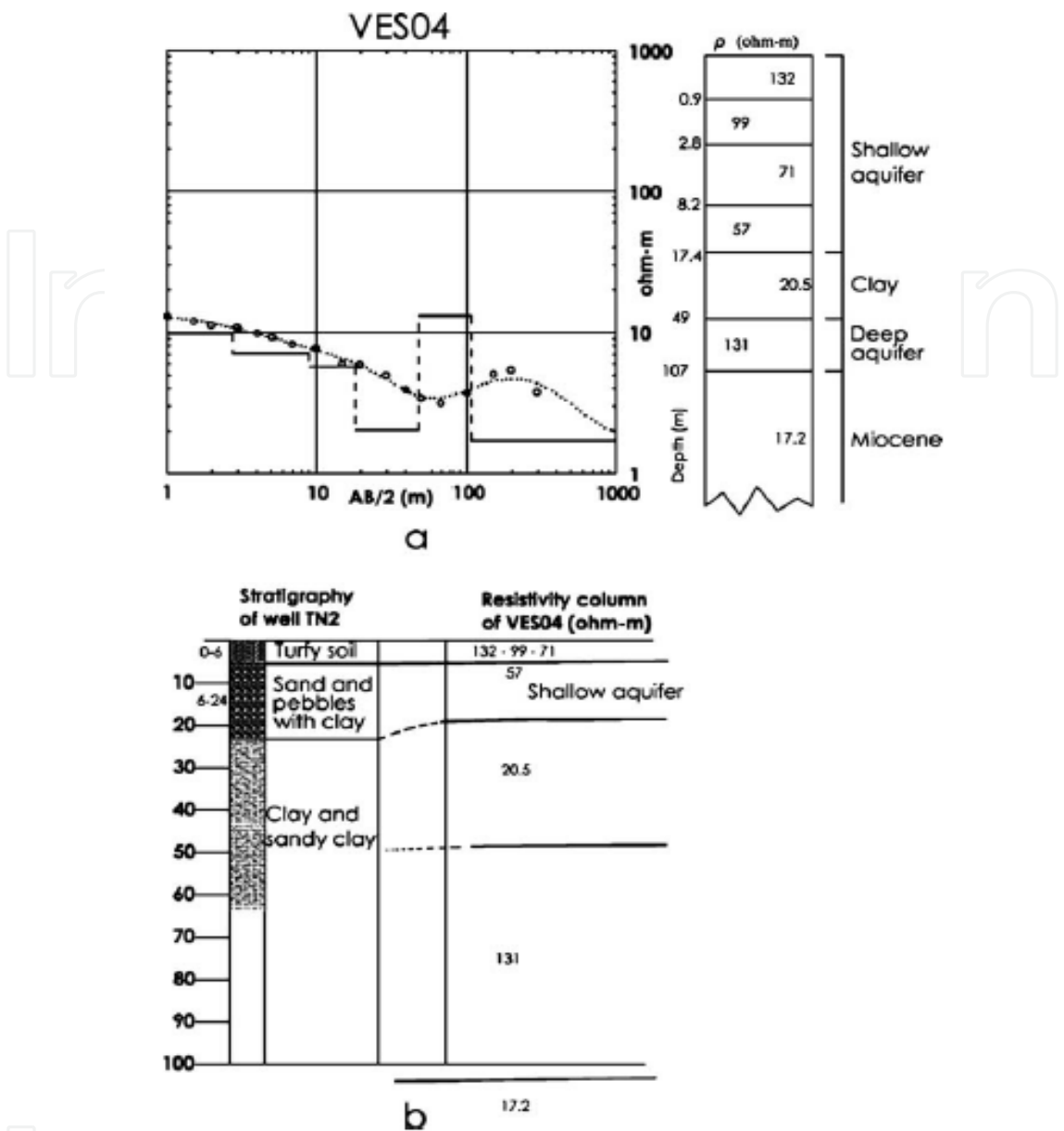
Fig. 6. Electrical resistivity curve (a–left) and interpreted resistivity column (a-right) compared with the stratigraphy from a borehole (b) (After Balia et al., 2008)

Figure 6 shows the apparent resistivity curve of the vertical electrical sounding VES04, acquired in the survey area, its interpretation in terms of true resistivity and thicknesses, and the comparison between the hydrogeological interpretation of geophysical results (top-right in figure 6), and the stratigraphic column of a well drilled in the vicinity of the VES centre). The correlation is good and, while the stratigraphy of the drilling, executed without core recovery, seems rather qualitative, the resistivity column shows several differentiations, that include the bottom of the clay layer (that is the top of the confined aquifer) and the transition to conductive Miocene materials. Drilling was stopped at a depth of 68 m, with a water flow rate of 20 liters/s, and the hydrostatic level rose close to the ground surface (Balia et al., 2008); these conditions confirmed that the deep aquifer is a confined one.

4. Assessment of a mine tailings basin by means of shallow reflection seismology and gravity

Old waste landfills represent a serious environmental problem not only for their polluting potential but also because very often they interfere with the expansion of urban areas. For these reasons, the need for site reclamation interventions is more and more felt. A site reclamation intervention should be designed and estimated carefully both in technical and economic terms, since the simple assumption of incorrect parameters is one of the major causes of inefficacious work and cost escalation. Therefore, prior to reclamation works, an accurate knowledge of the landfill is necessary, while in many cases the general information about old landfills is very poor, and even their horizontal extent and depth are inadequately known. Surface geophysical methods are non-invasive and can play an important role in delineating the waste geometry since they can provide highly detailed, widely extended and low-cost information.

In this section the case of a mine tailings pond is shown. The pond received the post-flotation wastes produced by several mines in the last decades of the past century. It extends for about 0.4 km^2, with a mean elevation at the top of 145 m above the sea level. The mine tailings, mainly made up of a calcareous matrix, have the consistence of a dense, soft, fine-grained, apparently homogeneous soil. Several dangerous substances are present in the tailings. The main threat to the environment is the possible interaction between the surface and ground waters, and the polluting liquids originating from the tailings, characterized by high concentrations of heavy metals. Moreover, the oxidation of sulfides to sulfuric acid leads to an acidic condition and speeds up metal dissolution processes. Apart from a thin cover of Quaternary alluvium, the geological environment of the small valley hosting the landfill is made up of Palaeozoic rocks, namely more or less fractured limestone and dolomite. Originally, the small valley was crossed by a stream flowing from the surrounding hills. Some boreholes were drilled in the basin, but their interval was relatively large, so that they did not allow an accurate assessment of the waste body geometry. The aim of the experiments at the tailings basin was to verify the effectiveness of some geophysical techniques in order to acquire information on the thickness of the landfill and the location of possible faults and fracture zones affecting the hosting Palaeozoic rocks, since they could represent a possible way for diffusion of the polluting substances. On the whole one gravity profile, one P-wave seismic reflection profile and one resistivity/IP profile were acquired. Shallow reflection data were acquired with the following apparatuses, parameters and geometry: acquisition system: 48-channel seismograph; geophones: single, vertical, undamped, 40 Hz natural frequency; energy source: 8 kg sledge-hammer with vertical stacking (1–3 shots/record); spread type: off-end, minimum offset 10 m, shot interval 1 m, channel interval 1 m; maximum CMP fold: 2400%; record length: 0.250 s, sampling interval: 0.00025 s; analogue filters: low-cut filter off, antialias filter 1,000 Hz. Data processing was performed with the following steps: field files editing and early mute application; sorting into CMP gathers; 60–300 Hz band-pass filtering; velocity analysis; NMO correction; CMP stack; noise attenuation (two-trace horizontal mixing). The overall quality of the seismic data was good and the velocity analysis, carried out by picking the hyperbolic patterns on the CMP gathers, revealed a rather low P-wave velocity field (240–260 m/s); the seismic section obtained through the processing sequence listed above is shown in figures 7 and 8.

Apart from the very shallow reverberations, that most probably depend on the water table, the seismic section is dominated by a very clear reflector whose depth is in the order of 10 m with respect to the ground level on the SE of the section, and then deepens to depths exceeding 15 m.
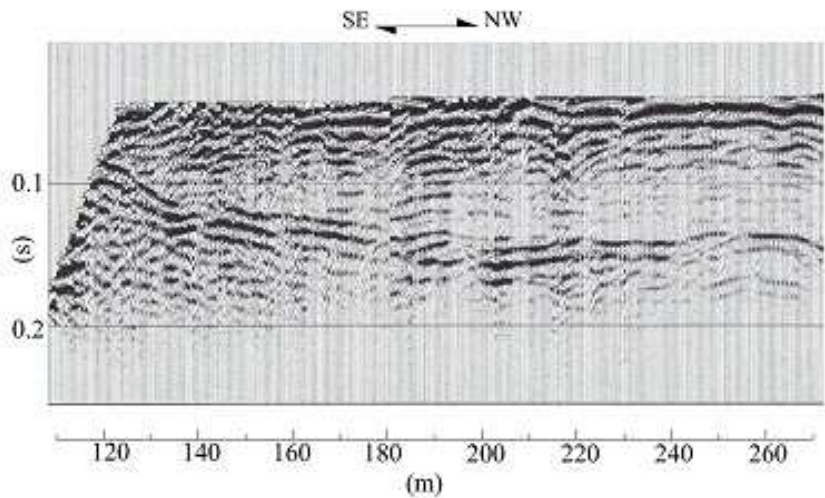

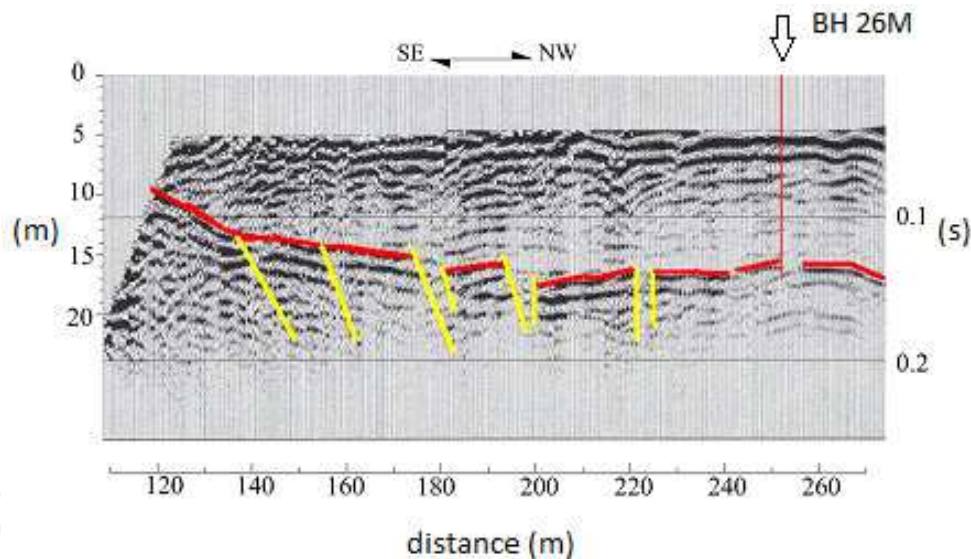Fig. 7. Seismic time section at the mine tailings basin.

Fig. 8. The same section as in Figure 7 after interpretation. The main reflector (red) and several fractures (yellow) are enhanced. The position of borehole BH 26M is indicated by the arrow. (After Balia & Littarru, 2010)

This reflector is associated with the bottom of the basin, that is with the ancient ground surface of the valley, made up of Paleozoic shales, locally named Cabitza shales. The reliability of the seismic section in terms of depth to the bottom of the basin is testified by comparison with one borehole (BH 26M) at the progressive distance of 252 m along the line. The stratigraphy of this borehole is in figure 9 and shows the top of the Paleozoic shales at a depth of 17 m with respect to the present ground surface, in perfect agreement with the depth deduced from the seismic section.
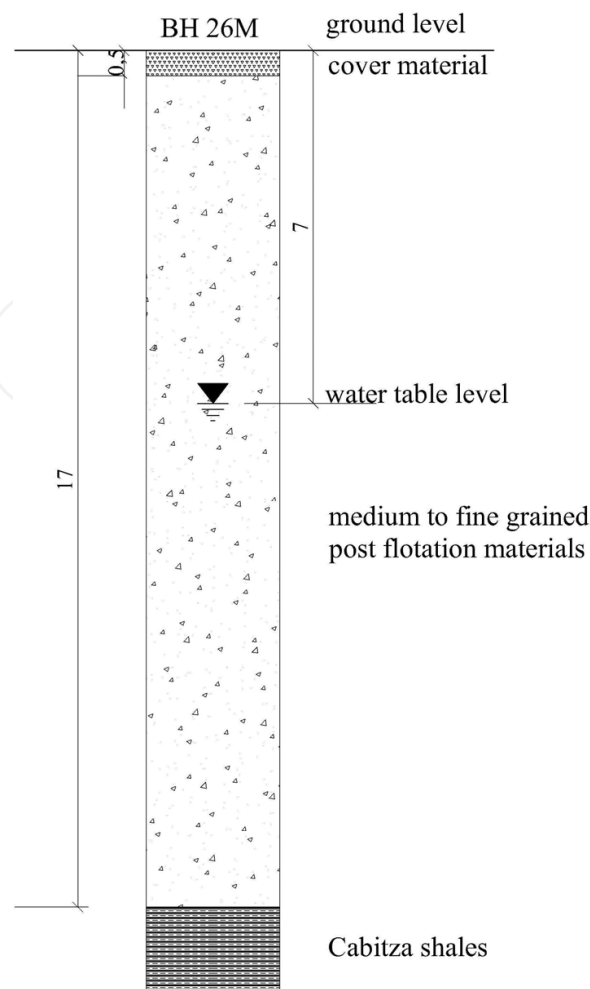
Fig. 9. Stratigraphic column of borehole BH 26M. (After Balia & Littarru, 2010)

Actually, it would not be possible to deduce the true morphology at the bottom of the basin only based on the few available boreholes. In addition, the seismic section also shows both the position and the distribution of the fractures affecting the basement, which is very useful information for the reasons mentioned above.

With regard to other geophysical methods used in this case, while the induced polarization and resistivity measurements have provided poor results, probably because of the strong electrical heterogeneity of the materials dumped in the basin, the gravity survey proved useful both designing the data acquisition parameters and to verify the results of the seismic survey. Figure 10 shows the result of the gravity anomaly modelling carried out assuming as a constraint the depth to the landfill bottom obtained by the seismic reflection survey, and allowing the density contrast between the filling material and the host rocks to vary. For the landfill, a 2.5D mass distribution model was assumed and the best fitting between the experimental and the computed gravity anomaly was obtained for a density contrast of -360 kg/m^3, meaning that since the host rocks have a density of about 2,500 kg/m^3, the filling material should have a density of about 2,140 kg/m^3. This is very reasonable and suggests that the good reflection coefficient corresponding to the reflector, and thus the good acoustic impedance contrast, is mainly attributable to the strongly different elastic characteristics between the two media and not to density contrast.
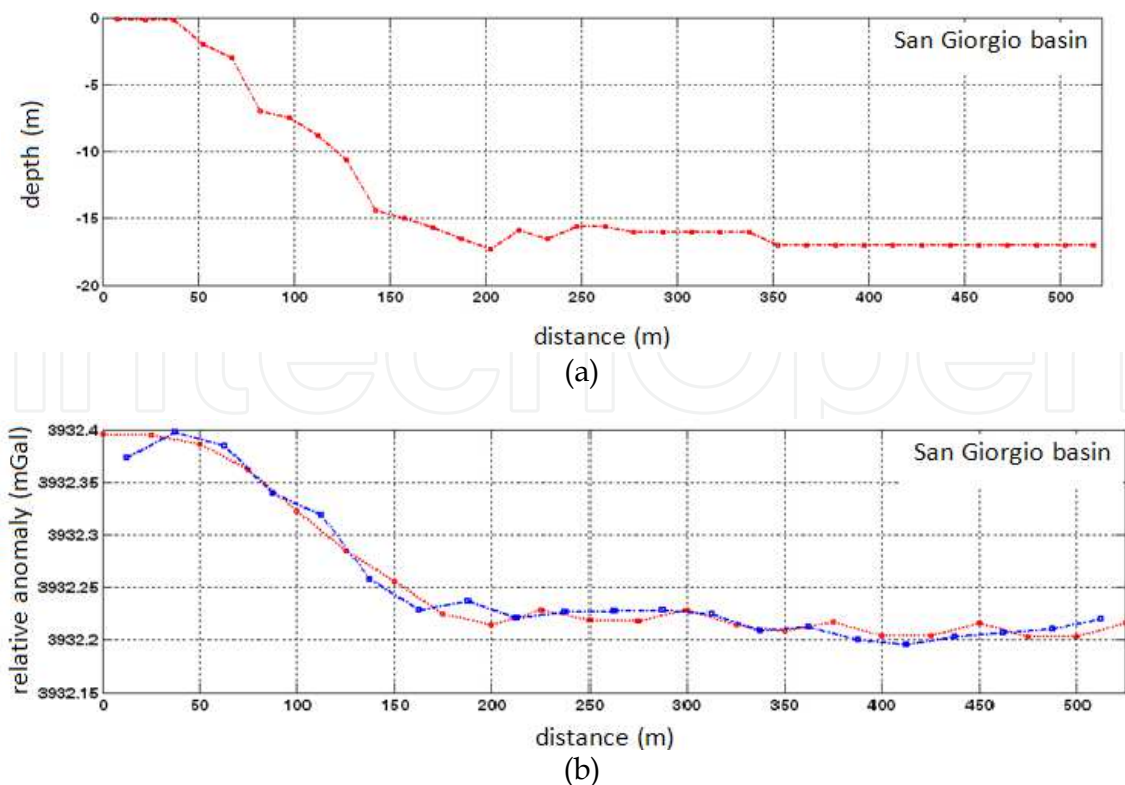
Fig. 10. Gravity model of the tailings pond: (a) depth to the bottom of the landifill as deduced from the seismic section and the outcrops of the basement; (b) measured (blue line) and computed (red line) gravity anomaly. The best fitting was obtained adopting a density contrast of -360 kg/m³ for the filling material with respect to the hosting rocks. (After Balia & Littarru, 2010)

5. A much more complicated situation

Undoubtedly, the assessment of the mine tailings pond discussed in the previous paragraph was a relatively easy problem, mainly due to flat topography, target at depths just slightly exceeding 10 m from the ground surface, and good contrast of physical characteristics between the filling and the basement. The present case concerns an old municipal solid waste landfill where mixed wastes were dumped for about 20 years, from the end of the 1960s to the end of the 1980s (Balia & Littarru, 2010). The geological environment of the site is made up of Quaternary sediments with a local thickness in the order of 5 m, overlying Oligocene-Miocene volcano-sedimentary rocks. In the area, shallow aquifers are generally scarce and of poor quality: the Quaternary sediments host a phreatic aquifer, while some brackish water lenses can be found in the Oligocene-Miocene rocks. Very likely, the waste disposal excavation had a depth that was equal to the Quaternary sediment thickness, which means that wastes were partially placed in the phreatic aquifer.

One gravity profile, several vertical electrical soundings (VES), two seismic refraction and one reflection profiles were acquired on the landfill. However, since the results of both electrical and seismic refraction measurements were of poor quality, only the gravity and P-wave seismic reflection surveys, located as in figure 11, will be presented. Data were acquired along a roughly west–east oriented profile. Gravity and topographic measurements were taken at 24 station points placed at 10 m intervals, for a total profile length of 230 m.
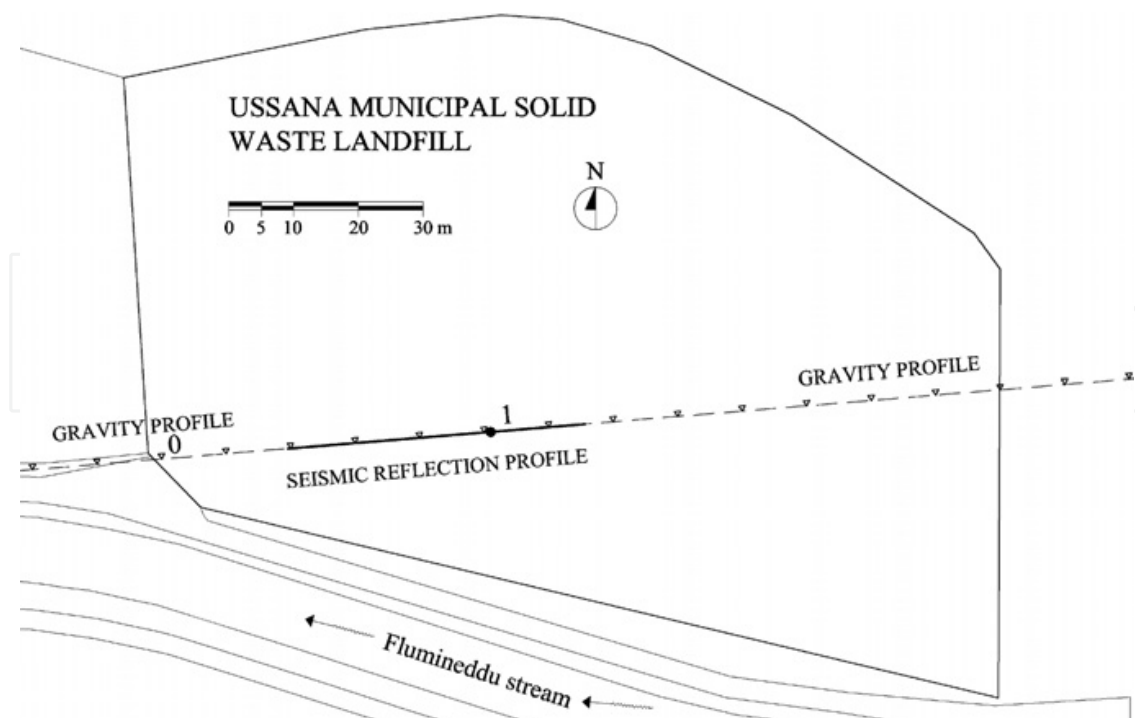
Fig. 11. Position map of the geophysical surveys at the solid waste municipal landfill. Gravity station points are indicated by small triangles; the seismic profile position is enhanced with a bold line; the location of the reference point and of the test pit are indicated with 0 and 1 respectively. (After Balia & Littarru, 2010)

The westernmost gravity station was placed 50 m west of a reference point close to the presumed western border of the landfill, and the easternmost station was 180 m east of the reference point. Figure 12 shows the relative gravity anomaly obtained after reductions, calculated assuming a mean density of 2,200 kg m³, considered representative of the rocks of the study area. A negative gravitational effect with a maximum amplitude of −0.32 mGal is rather clear, as well as its correlation with the presumed boundaries of the landfill.

Seismic reflection data were acquired with the following apparatuses, parameters and geometry: acquisition system: 48-channel seismograph; geophones: single, vertical, undamped, 50 Hz natural frequency; energy source: 5 kg sledge-hammer with vertical stacking (5–10 shots/record); spread type: off-end, minimum offset 0.8 m, shot interval 0.4 m, channel interval 0.4 m; maximum CMP fold: 2,400%; record length 0.128 s, sampling interval 0.000 25 s; analogue filters: low-cut filter off; antialias filter 1,000 Hz. On the whole 94 field records were acquired, corresponding to 234 CMP positions at 0.2 m intervals.

Data were characterized by a poor signal-to-noise ratio. Noise was mainly coherent, but abrupt quality changes from one record to the next also indicated the presence of a major, apparently random noise component; since external sources of noise were totally absent (no wind, no road traffic, no factories), this was attributed to strong variations in both subsoil and surface conditions from one shot point to the next. Velocity analysis turned out to be the most demanding operation and eventually the velocity function was derived by means of a CVS (constant velocity stack) analysis, with velocity increasing in the range 400–490 m/s at a 10 m/s step. The full processing sequence included the following steps: field files editing; low-cut 120 Hz filtering; sorting into CMP gathers; velocity analysis; dynamic corrections; CMP stack; two-trace horizontal stack (trace mixing). Eventually, the stack section obtained
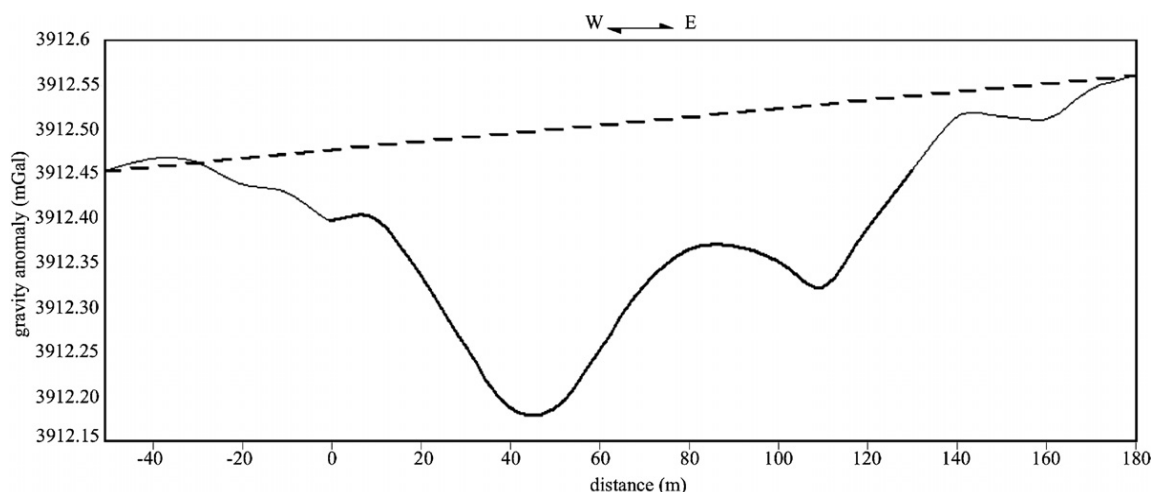
Fig. 12. The gravity anomaly generated by the waste landfill. The dashed line represents the long-wavelength field; the central part of the anomaly, enhanced with a bold line, corresponds to the presumed position of the landfill. (After Balia & Littarru, 2010)

by applying a dynamic (NMO) correction based on a velocity of 460 m/s was assumed as reliable. This section, shown in figure 13, exhibits a reflector made up of a normal-polarity, minimum-phase response generated by a positive reflection coefficient. The reflector is relatively undulated and exhibits some discontinuities; time resolution is not always good, so that time picking can be easily affected by errors of some milliseconds. The two-way reflection time along the entire section ranges between 0.014 s and 0.025 s, with a weighted mean value of 0.0178 s. An abrupt deepening of the reflector is clearly evident between the progressive distances of 37 and 40 m. Since no intermediate reflections were resolved, the mean depth of the reflector was estimated using the mean reflection time and the stack velocity (460 m/s), obtaining a value of 4.1 m. In order to verify the nature of the reflector, one test pit was excavated on the seismic profile, at the progressive distance of 52 m. This direct investigation showed a clayey capping layer with a mean thickness of 0.7 m overlying a layer of loose, dry waste about 1.45 m thick. Below the latter, wet to saturated waste, more compacted than the overlying one, mixed with sand and gravel, with a mean thickness of 0.6 m and lying on the natural bottom was found. Consequently, the local thickness of the landfill, from the ground surface to the bottom, was found to be in the order of 2.75 m, as against the 4.1 m estimated by means of the seismic data alone, adopting the average reflection time and the stack velocity for time-to-depth conversion.

However, the real reflection time corresponding to the pit position was 0.014 s. Using this time, and once more the stack velocity of 460 m/s, a depth of about 3.2 m was found. This depth is very close, though not equal, to the depth of 2.75 m estimated from the pit. Apart from the experimental errors that obviously occur when taking measurements on a real and complex model, this small—though significant—discrepancy could also be explained by the fact that the stack velocity is generally inadequate for time-to-depth conversion except for the one-layer case, which was not the case at hand, as shown by the excavation.

To refine the model of the landfill taking into account the results of the pit, first the P-wave velocity of the first layer in the vicinity of the pit itself was measured and proved to be of 430 m/s. Then, the following equation system was solved
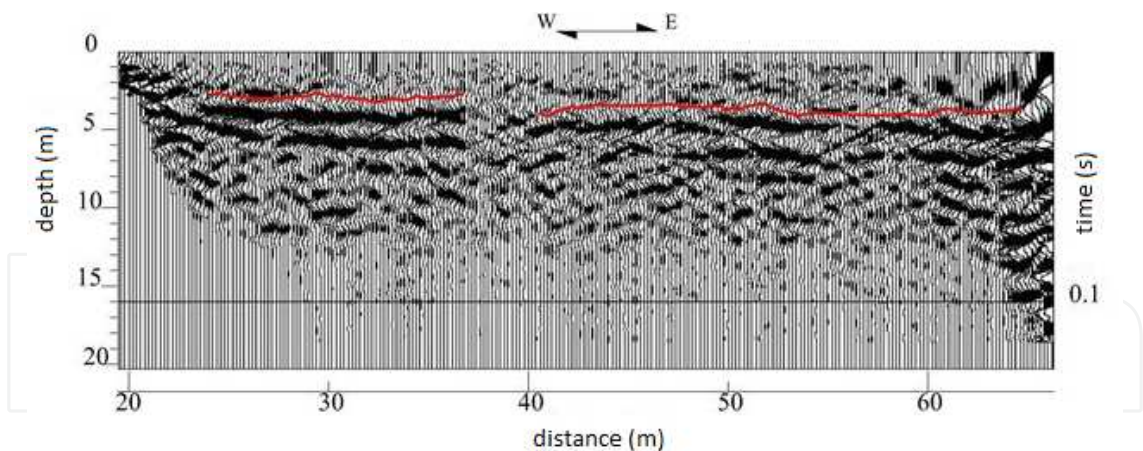
Fig. 13. Stack section (P-wave) at the municipal solid waste landfill. CMP trace interval is 0.2 m, and the reflector is enhanced by a red line. The section refers to the interval between the progressive distances of 20 m and 66 m of figure 12. (After Balia & Littarru, 2010)

$$Vrms = ((VI1^2 * t1 + VI2^2 * t2 + VI3^2 * t3)/(t1 + t2 + t3))^{1/2} \qquad (1)$$

$$tr = t1 + t2 + t3 \qquad (2)$$

$$t1 = h1/VI1 \qquad (3)$$

$$t2 = h2/VI2 \qquad (4)$$

$$t3 = h3/VI3 \qquad (5)$$

Equation (1), written for the three-layer case, gives the root mean square velocity (Vrms) as a function of the interval velocities (VIn) and the respective one-way transit times along vertical paths (tn) for each of the three layers (e.g. Sheriff, 1984). Equation (2) simply says that the total one-way reflection time (tr) is the sum of the one-way transit times pertaining to the three layers. Equations (3)–(5) give the one-way transit times as functions of the layer thicknesses (hn) and the respective interval velocities. In this case, the following quantities were known and assumed as constraints:

- the root mean square velocity, approximated with the stack velocity: Vrms = 460 m/s;
- the velocity of the first layer, measured at the surface in the vicinity of the pit: VI1 = 430 m/s;
- the layer thicknesses, measured inside the pit: h1 = 0.7 m; h2 = 1.45 m; h3 = 0.6 m;
- the total two-way reflection time, picked in the seismic section across the pit: tr = 0.014 s
- the two-way transit time for the first layer was computed: t1 = h1/VI1 = 0.00326 s.

Therefore, the only unknowns were the interval velocities of the second and third layers, for which the computation provided the following estimates: VI2 = 288 m/s and VI3 = 1,809 m/s. These velocity estimates are absolutely coherent with the respective layers: loose, dry waste the first, and wet to saturated waste, compacted and mixed with sand and gravel the second. The P-wave velocity in the bedrock (Vb) was deduced from seismic refraction data with estimated values in the range 2,500–3,600 m/s. Therefore, the seismic model for the waste landfill is that shown in figure 14: of course, it is not valid for the entire landfill, but only for the surroundings of the pit.

In this case, the gravity survey provided a good result essentially for picking out the boundaries of the landfill, while the shape of the anomaly could not be assumed as

0.70 m	------------------------------------ Clayey cap	VI1 = 430 m/s
	------------------------------------	
1.45 m	Dry waste	VI2 = 288 m/s

0.60	m Wet-saturated waste VI3 = 1809 m/s	

	Natural bedrock Vb = 2500 – 3600 m/s	

Fig. 14. The model of the landfill corresponding to the underground condition in the surroundings of the test pit, with layer thickness (left) and P waves velocity (right). (After Balia & Littarru, 2010)

representative of the morphology of the bottom. As a matter of fact, a comparison between figures 12 and 13 shows that between the progressive distances of 45 m and 66 m the absolute value of the gravity anomaly decreases eastwards, while in the same interval and direction the reflection time, and thus the depth to the bottom, increases. This means that on the eastern side of the above interval wastes become thicker but also much heavier than on the western side, thus suggesting that an accurate gravity modelling for the entire landfill is not allowed, or at least is very complicated. Concerning the seismic reflection experiment, it has been verified that the attainable resolution was not sufficient for picking out the layering inside the landfill, but only the bottom could be found. In this condition, time-to-depth conversion based only on seismic data provided results affected by an overestimate error in the order of 15–20%, as shown by the test pit. The test pit also explained why both VES techniques and refraction seismology failed. The VES technique because of the very high variability, both laterally and vertically, of the physical characteristics of the shallow layers, which caused very noisy and incoherent data. Refraction seismology clearly failed because of the velocity inversion between the first and the second layer. However, the seismic refraction data provided the P-wave velocity in the bedrock. This is a typical example of a situation in which a reliable site assessment cannot be carried out by means of geophysical techniques alone.

6. Conclusions

With most of the case histories referred to in the previous paragraphs of this chapter it has been demonstrated that it is possible to synthesize a piece of relevant stratigraphic information in a wide range of situations with the fundamental support of geophysical surveys.

In the first case this information concerned depth to Paleozoic basement, thickness and layering of Pleistocene-Holocene sedimentary cover, and relationships between the two shallow aquifers. Information at medium depth (100-300 m) was obtained by means of seismic reflection surveying, while shallow information was deduced from a combination of electrical and seismic reflection methods, completed by one borehole.

In the second case, where the aim was to predict the actual possibility of finding fresh water below the already known aquifer system, the stratigraphy of the study area was assessed down to depths in the order of 400-500 m by means of reflection seismology, and the shallow conditions were studied mainly by means of electrical resistivity measurements.

The third case, the one concerning the mine tailings basin, is a typical example of how, in favorable conditions, a single method can provide the desired information.

Conversely the last example, the municipal solid waste landfill, shows very clearly that when the underground condition is very poor, chaotic, with random variations of physical characteristics, geophysical techniques should be used with caution and the data they provide must be analyzed carefully before drawing any conclusions.

In this chapter, the most relevant geophysical method has undoubtedly been that of reflection seismology. However, beyond the results, the general significance of all the above examples lies essentially in the success of the combination of different geophysical techniques, which proved effective and useful in reducing unknowns and ambiguity. Gravity surveying, used as a starting point in all the geophysical works referred to in this chapter, provides information, at least qualitative, on bedrock morphology and structures, and allows an accurate design of reflection surveys, especially as regards spread geometry, acquisition parameters, profile position and orientation. Electrical and electromagnetic methods proved highly useful for the stratigraphic assessment at depths of less than 100-150 m.

Finally, a very important aspect concerns the planning of exploratory drillings. Clearly, when good geophysical results are available, one can perform rational borehole positioning, make preliminary estimates of the depths to be reached, and ultimately save time and costs.

7. Acknowledgements

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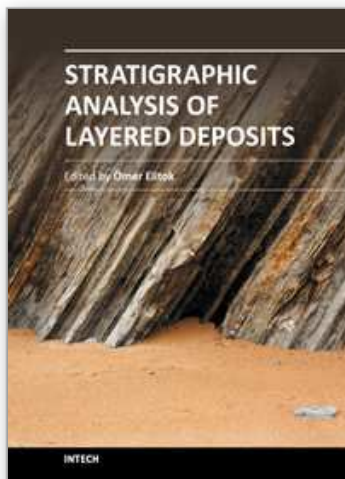
Stratigraphic Analysis of Layered Deposits

Edited by Dr. Ömer Elitok

Stratigraphy, a branch of geology, is the science of describing the vertical and lateral relationships of different rock formations formed through time to understand the earth history. These relationships may be based on lithologic properties (named lithostratigraphy), fossil content (labeled biostratigraphy), magnetic properties (called magnetostratigraphy), chemical features (named chemostratigraphy), reflection seismology (named seismic stratigraphy), age relations (called chronostratigraphy). Also, it refers to archaeological deposits called archaeological stratigraphy. Stratigraphy is built on the concept "the present is the key to the past" which was first outlined by James Hutton in the late 1700s and developed by Charles Lyell in the early 1800s. This book focuses particularly on application of geophysical methods in stratigraphic investigations and stratigraphic analysis of layered basin deposits from different geologic settings and present continental areas extending from Mexico region (north America) through Alpine belt including Italy, Greece, Iraq to Russia (northern Asia).

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