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Application of shallow seismic methods to engineering, environmental and groundwater investigations

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Abstract - During the last two decades, various seismic methods have been developed and widely used to study the shallow subsurface for different purposes. This paper presents a number of examples illustrating the application of shallow seismic methods to engineering, environmental and groundwater-related investigations. The purpose of the presentation is to demonstrate what kind of information can be obtained and what kind of problems can be solved using shallow seismics. The applications considered include the following cases:
- high-resolution reflection surveys for mapping recent faulting at construction sites and for studying aquifer structure in a region suffering from insufficient water supply;
- refraction surveys for detecting a shallow salt layer in sinkhole areas and for estimating the thickness of a Roman assault ramp at an archeological site;
- shear wave survey for site effect evaluation for seismic risk assessment at a bridge construction site in a seismically active area.

The considered examples show that the results of shallow seismic surveys can provide important information for the solution of various problems related to studying the upper part of the geological section.

1. Introduction

Seismic methods have long been recognized as an effective tool for studying the shallow subsurface for a variety of applications, such as engineering problems, geotechnical evaluations, environmental studies, hydrogeological investigations, seismic risk assessment, archeology, etc. This paper demonstrates various applications of shallow seismics, including reflection, refraction and shear wave methods. The methods are based on the use of different types of

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seismic waves characterized by different modes of propagation. The common feature of all these methods is their sensitivity to spatial changes of seismic velocities in the subsurface. Analyzing the seismic data acquired at the surface, one can estimate the subsurface velocity distribution and map the corresponding structural features. For this purpose, each method implements its specific acquisition and processing techniques. A short general overview of shallow seismic methods was made by Steeples (2000).

The "high resolution reflection method" is undoubtedly the most effective geophysical technique for detailed and reliable imaging of the shallow subsurface structure. The commonly used Common Midpoint (CMP) technique involves roll-along acquisition of the reflection data, resulting in a large amount of seismic records and providing a multifold illumination of every subsurface point along reflection lines. Processing of the CMP data is aimed at focusing of the reflection energy to its proper position in time and space, enhancing considerably the signal-to-noise ratio and producing high-resolution images of various subsurface features. The processing is a multi-step (and sometimes iteractive) procedure requiring application of special software packages. The standard packages include a large number of sophisticated algorithms and usually run on workstations. Recently, several PC versions of the processing software have been developed, making the reflection surveys more cost-effective. Special care should be taken when processing the shallow reflection data; some of the processing pitfalls are discussed in Steeples and Miller (1998). The resulting time sections represent reliable images of the subsurface structure, including layer geometry, fracture and fault zones, landslide areas, etc. An overview of the shallow reflection method can be found in Steeples and Miller (1990); Brouwer and Helbig (1998) presented a detailed description of the method, including basic theory, acquisition and processing.

The "refraction method" utilizes the first arrival times of refracted waves propagating along the shallow subsurface layers. The main limitation of the method is that it requires the refractor velocity be higher than that in the overlying layers. The field acquisition, processing and interpretation of the refraction data are usually fast and simple, keeping the overall cost of the refraction surveys relatively low. The data is acquired by applying a source of seismic energy at a few points within and outside the spread of receivers. The processing and interpretation are performed using a PC-based simple interactive software. The final product of refraction surveys is a layered depth section including information on layer geometry and seismic velocities within the layers. A detailed description of the refraction method, including various interpretation techniques, is given by Palmer (1986).

The "shear waves method" can provide important information on various characteristics of the subsurface material, such as mechanical properties of soils and rocks, their lithological characteristics, porosity, etc. In this respect, the method may produce positive results where the conventional (P-wave) seismic methods fail, for example, in the case of a weak P-wave velocity contrast between two layers having significantly different S-wave velocities, or when the P-wave velocity interface is due to hydrological, rather than lithological, changes. The method usually makes use of the horizontally polarized (SH) shear waves, which requires the application of special acquisition techniques including horizontally oriented sources and receivers. For this reason, the implementation of the method may sometimes prove to be problematic, especially for relatively deep targets. Various theoretical aspects of the methods are considered in Dohr (1985a).

In the following, various applications of the shallow seismic methods are demonstrated by a number of examples.

2. Shallow reflection surveys

The shallow reflection method is by far the most effective geophysical technique for detailed and reliable imaging of the subsurface structure. Due to the high vertical and lateral resolution (provided by short dominant wavelengths and small Fresnel radius of the shallow reflections), one can perform very detailed mapping of various subsurface features, including layer geometry, fracture and fault zones, landslide areas, etc. The method is commonly implemented as the CMP technique, with its specific acquisition and processing procedures; its detailed description can be found in Brouwer and Helbig (1998) and Yilmaz (2001). The CMP sections usually represent a clear structural image of the shallow subsurface, making them a good basis for geological interpretation. The reflection method has been widely used in various geological environments for geotechnical and environmental studies (Myers et al., 1987; Branham and Steeples, 1988; Jongerius and Helbig, 1988; Treadway et al., 1988; Miller et al., 1990; Jeng, 1995; Kourkafas and Goulty, 1996; Shtivelman et al., 1998a; 1998b) and for groundwater-related investigations (Birkelo et al., 1987; Geissler, 1989; Miller et al., 1989; Miller and Steeples, 1990; Bruno and Godio, 1997; Shtivelman and Goldman, 2000).

I have selected two examples demonstrating application of the reflection method to the problems related to construction site investigation in the Mt. Carmel area of Israel and to groundwater studies in Cyprus.

2.1. Mapping shallow faults at construction site

The study area is located in the suburb of the city of Haifa (the Mt. Carmel area), at the fringe of the Kishon Graben, in the immediate vicinity of the Carmel – Yagur fault. The fault has a throw of over 1,000 m, placing rocks of Lower Cretaceous - Lower Cenomanian against Eocene to Neogene strata in the Graben. Recent studies showed that the Carmel – Yagur fault is in effect a wide fault zone with a young strike – slip component of 500 – 1500 m on some of the fault traces within the zone. The fault zone is characterized by extensive microseismic activity. The main objective of the seismic survey was detecting recent faulting at the investigated site. The reflection data were acquired along a 600 m line using 48-channel recording system. The energy source was Digipulse (truck mounted accelerated weight drop). The receivers were single 10 Hz geophones; the source and receiver spacing was 2.5 m. Fig. 1 shows an example of two field records from different parts of the line. On both records, a number of quasi-hyperbolic shallow reflection events can be identified. One can see that the records have quite a different data character, indicating lateral changes of subsurface geology along the line.

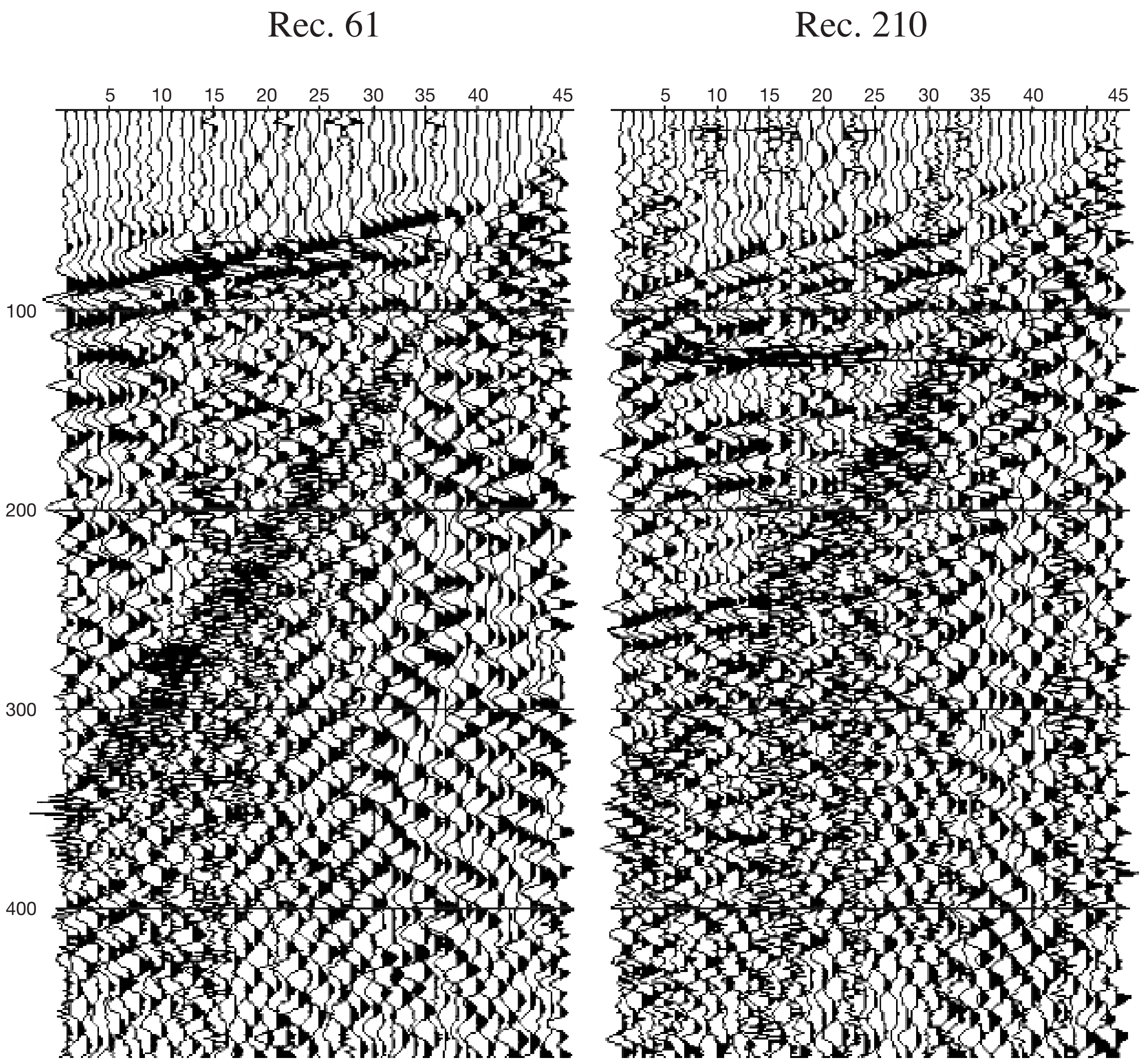

Fig. 1 - Two field records from reflection line located in Mt. Carmel area.

The results of the survey are presented in a time section in Fig. 2. The horizontal axis shows station numbers (i.e. the sequential receiver number along the line) while the vertical axis is the two-way traveltime in milliseconds. The datum of the section is the MSL.

The section may be laterally subdivided into three regions having different data character. The left (southwestern) part of the section is characterized by a sequence of NE-dipping reflections which may possibly be related to the upper part of the hard carbonate rocks forming Mt. Carmel. The reflections can be traced up to station 40, where they appear to be interrupted, probably by a fault, as marked on the section. Northeast of station 30, the reflections are overlaid by a shallow reflection sequence with much smaller dips. The reflections of the upper sequence are apparently related to young soft sediments laying unconformably on the hard rocks. The segment between stations 60 – 108 is characterized by disturbances of the reflections, apparently due to deformation and faulting. This can be clearly seen in the upper part of the section, where

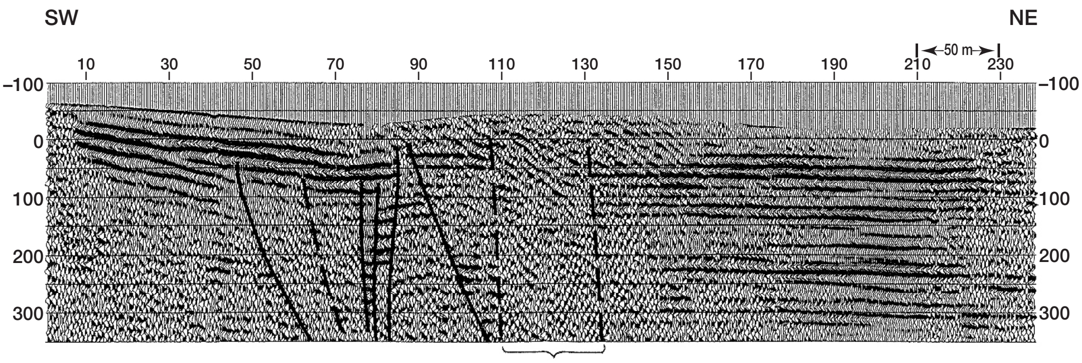

Fig. 2 - Seismic time section along the reflection line located in Mt. Carmel area.

the reflections change their dip from NE to SW between stations 60 – 85, whereas in the vicinity of station 85 their continuity is interrupted, apparently by a system of faults.

The central part of the section between stations 108 – 130 appears as a "no data" area. The possible reason for this may be that in this region the line crosses a fault zone where the layer structure is totally broken and where no reflections can be obtained.

The right (northeastern) part of the section is characterized by a sequence of undisturbed reflections which can be traced continuously between stations 130 – 220 in the upper part of the section and between stations 150 – 220 in its deeper part. The sequence has a very gentle inclination to the NE. The character of the reflections and the low velocities obtained from the reflection data suggest that the reflections are related to soft sediments and that there is no hard rock down to a depth of 200 – 250 m.

2.2. Studying aquifer structure

The investigated site is located in the western Mesaoria area of Cyprus, in the vicinity of the village of Meniko. The upper part of the geological section in the area is composed mainly of Pliocene to Middle Miocene marls of the Nicosia formation. The formation is subdivided into two units. The upper unit is composed of marls with the inclusion of thin beds of gravels and fine sandstones. The lower unit consists of gray clays and marls and includes a thin chalk layer. Between the two units, a phreatic aquifer is developed in a clastic horizon consisting of gravels and sands. The depth to the aquifer layer is about 200 m and its thickness varies from 0 to 80 m. The Nicosia formation lies uncomformably on the Pillow Lavas of the Troodos Ophiolite Complex.

The area suffers from an insufficient supply of fresh groundwater, and it is therefore important to study the inner structure of the aquifer in the area. For this purpose, a high resolution seismic reflection survey was carried out at the Meniko site. The survey was performed in the framework of the INCO-DC program, with the aim of detecting and mapping the water-bearing layers and delineating the contact between the sediments of the Nicosia formation and the igneous rocks. Two reflection lines were shot at the site with a 48 channel recorder using explosives. The receivers were single 10 Hz geophones; the source and receiver spacing was 10.0 m. Fig. 3 represents two field records from the survey. The records clearly show a sequence of reflected events down to times of about 500 ms.

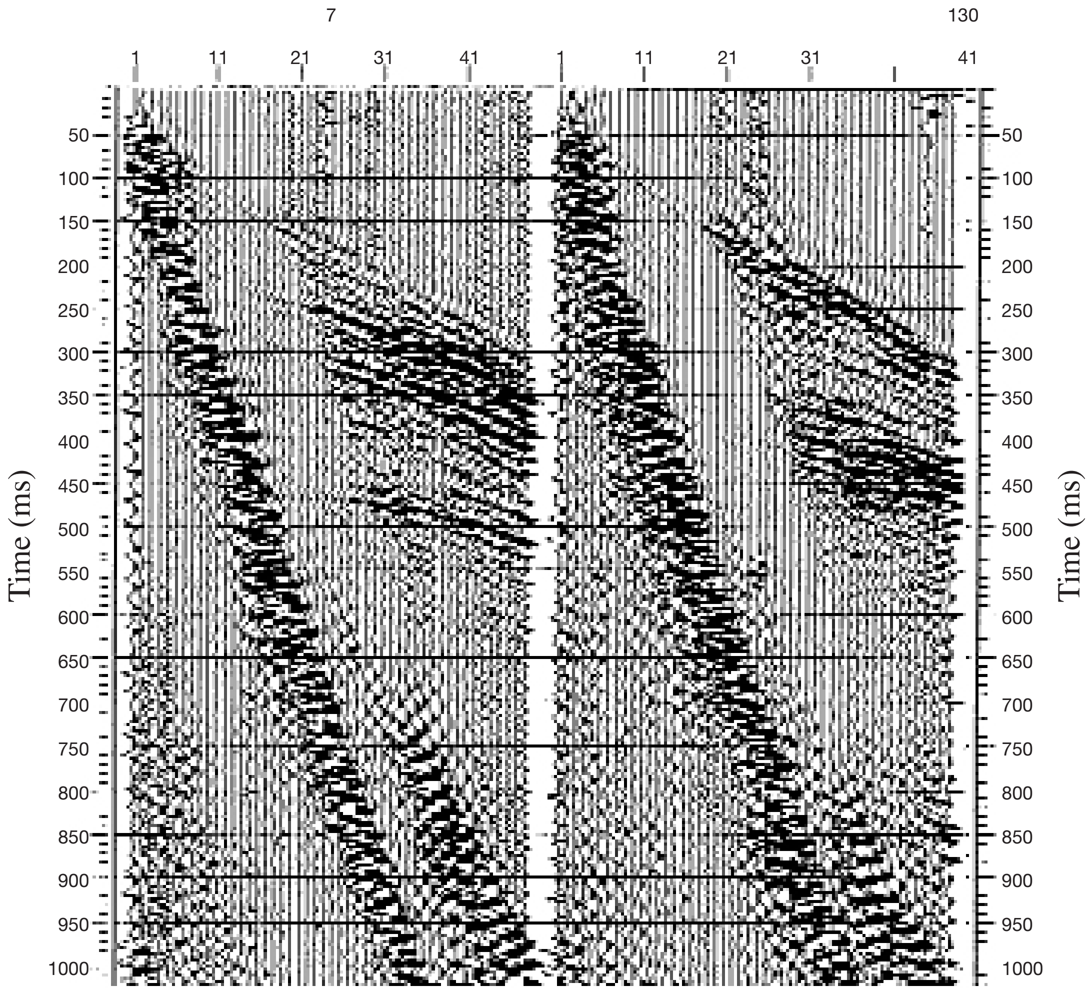

Fig. 3 - Two field records from reflection line located in Meniko area (Cyprus).

Fig. 4 shows a seismic time section along one of the reflection lines. The section presents a rather complicated structural picture of the subsurface. The continuity of the sequence of reflections appearing on the section is clearly interrupted at many locations, apparently by a system of faults, as marked on the section. Due to the fragmented character of the reflections, it is very difficult to trace them along the line. Since no velocity information from boreholes was available in the investigated area, no attempt at depth conversion of the section was made; however, rough estimates of the depth of the reflected events were made on the basis of stacking velocities obtained from the seismic data.

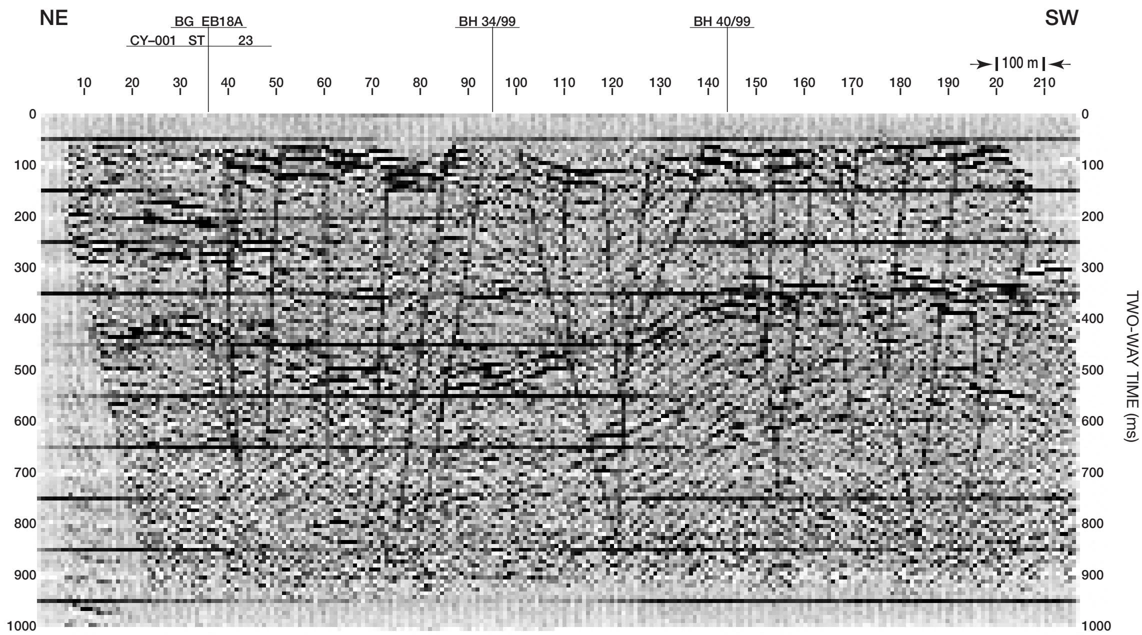

Fig. 4 - Seismic time section along the reflection line located in Meniko area (Cyprus).

The seismic line passes in a close vicinity of three water wells (EB18A, 34/99 and 40/99, as marked above the section in Fig. 4) and the borehole information was used for correlation of reflections. In borehole EB18A, drilled to a depth of 460 m, a sand and gravel aquifer layer with good water quality was penetrated between the depths of 225 – 300 m. Borehole 40/99 reached the depth of 386 m. The clastic horizon of the Nicosia formation consisting of fine sandstone, was encountered between the depths of 190 m and 220 m; the water in this aquifer was of poor quality. Borehole 34/99 was drilled down to the depth of 393 m; brackish water was found in a thin sand layer penetrated at a depth of 236 m.

The reflectors appearing on the section in the vicinity of station 35 can be correlated to the geological layers penetrated in borehole EB18A. The two shallow reflectors appearing at times of about 180 ms and 210 ms, are apparently related to two thin gravel layers encountered at depths of 134 and 165 m, respectively. The reflector appearing at a time of about 280 ms, may be related to the top of the main aquifer layer encountered at a depth of 225 m. To the SW of the borehole, continuity of the aquifer layer is interrupted by a system of faults. The two deeper reflectors appearing at times of 400 ms and 440 ms, can possibly be identified with the chalk and clay layers encountered at depths of 363 m and 372 m, respectively.

The reflector appearing in the vicinity of station 143 at a time of about 350 ms, may be related to the contact of the sediments with the igneous rocks encountered in borehole 40/99 at a depth of 317 m. This reflector has a clear NE inclination. In the vicinity of borehole 34/99 (station 95) this reflector appears at a time of about 500 ms (at about a 600 m depth) and, therefore, was not reached by the borehole.

The water-bearing sandstone layer encountered in borehole 40/99 at a depth of 190 m, and the thin sand layer encountered in borehole 34/99 at a depth of 236 m, can not be detected on the seismic section. A possible reason for this may be that the acoustic properties (seismic velocities) of these layers are similar to those of the surrounding marls and, therefore, their contact does not produce any significant reflection.

3. Refraction surveys

For many years the seismic refraction method has been used in a variety of applications, such as geotechnical, environmental, groundwater and archeological studies, as well as for the computation of static corrections in reflection data processing. The method is based on the interpretation of first-arrival times of refracted waves propagating through and along the near-surface layers. Various interpretation techniques based on simple geometrical considerations have been developed and applied for deriving information on refractor depth and velocity for relatively simple models. The main drawback of these techniques, however, is that they fail to produce reliable results in the case of complex velocity distribution above the refractor, such as abrupt velocity changes, hidden layers and velocity inversions (Lankston, 1989, 1990; Zanzi, 1990). These problems can be partly overcome by the generalized reciprocal method developed by Palmer (1980, 1981).

The following two examples demonstrate the application of the refraction method to environmental and archeological problems in the Dead Sea area of Israel.

3.1. Detecting a salt layer in sinkhole areas

The Dead Sea area is characterized by extensive development of sinkholes of different dimensions. Along the western coast, more than 700 sinkholes are exposed, with diameters varying from several meters to tens of meters and with depths reaching 15 m. Over the last years, the sinkhole development has increased dramatically, posing a severe problem for a normal functioning and development of the entire region.

In order to understand the mechanism of the sinkhole development, an integrated geophysical study was carried out in the area. The starting point of the study was the assumption that a direct relationship exists between the rapid lowering of the Dead Sea (approximately 20 m during last 20 years) and the rate of sinkhole development both in time and space. The lowering of the Dead Sea level is accompanied by a corresponding decrease of the groundwater level in the vicinity of the shore and by penetration of unsaturated groundwater into the coastal area. If this water encounters a shallow salt layer, it may cause its dissolution and formation of cavities within the salt. As a result, the overlaying material (usually poorly consolidated alluvium) collapses into the cavities, forming sinkholes at the surface. Thus, the working hypothesis of the study suggests the existence of a shallow salt layer as a necessary factor for sinkhole development. Since seismic velocity in the salt layer is supposed to be higher than that of the overlaying alluvium, it makes it a good target for the seismic refraction method. Therefore, in order to verify the existence of such a layer, seismic refraction surveys were carried out in several sinkhole areas. The following example shows the results of such a survey. A refraction line was shot in the vicinity of a number of opened sinkholes, one of which is shown in Fig. 5. The source of energy was Dynasource (a track-mounted vacuum-accelerated heavy weightdrop); the receiver spacing was 5 m. The depth section along the line (Fig. 6) shows a presence of a relatively high-velocity (2930 m/s) layer at the depths of 20 – 25 m which can be identified with salt. The layer is overlain by two low-velocity layers which can be related to the dry (the velocity of 630 m/s) and water saturated (the velocity of 1650 m/s) parts of an alluvium unit. This subsurface model was further confirmed by a borehole drilled at the site. The borehole penetrated the salt layer between the depths of 24 – 36 m.

The refraction surveys carried out in other sinkhole areas produced similar results, thus confirming the existence of a shallow high-velocity salt-related layer in these areas.

Fig. 5 - A sinkhole in the Dead Sea area.

3.2. Determining the thickness of a Roman assault ramp at an archeological site

The Masada fortress is an important historical and archeological site located in the southeastern part of the Jewish desert, in the vicinity of the Dead Sea. The fortress was built by King Herod (37 – 4 BC) atop a lofty mesa isolated from its surrounding terrain by steep cliffs 100 to 300 m high (Fig. 7). At the outbreak of the Jewish war against the Romans in 66 AD Masada was taken over by a group of zealots who continued to keep it also after the fall

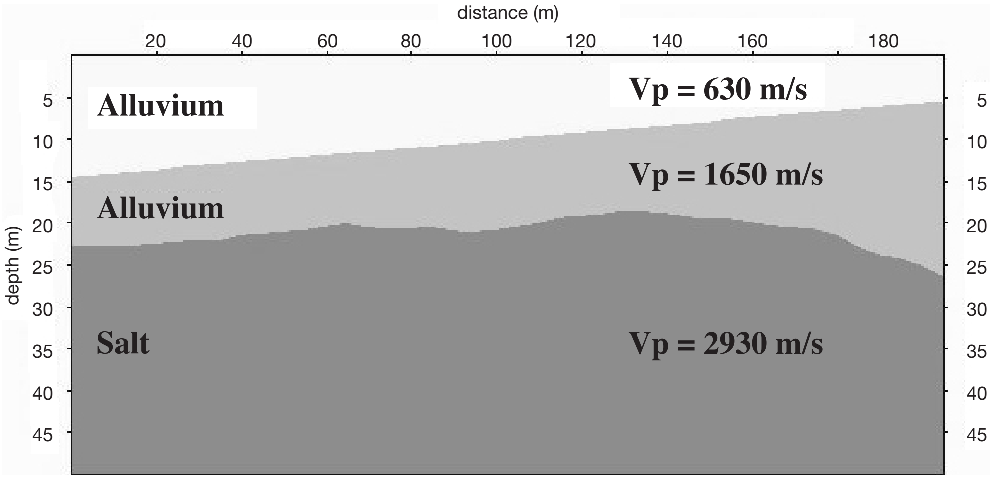

Fig. 6 - Depth section along the refraction line located in the vicinity of the sinkhole of Fig. 5.

of Jerusalem in 70 AD. The 10th Legion of the Roman army laid a siege to the fortress and eventually conquered it in 73 AD. According to the contemporary historian Josephus Flavius, the Romans succeeded in reaching the top of the mesa and breaching the defenses of Masada by building a gigantic ramp (reaching a height of 92 m) on the western side of the fortress (Fig. 7). Constructing such a huge ramp would have required thousands of workers and many months of work. Some scholars, however, argue that the numbers are contradictory and do not seem realistic.

Fig. 7 - A view of Masada from the west. The western escarpment of the mesa is interrupted by a topographic spur descending from 13 m down to about 90 m below the top of the mesa.

Recently, several researchers suggested that the Masada spur is in fact a natural topographic feature, and that the Romans just added a rather thin layer of earth material at the top of the natural spur. In order to verify this hypothesis, a seismic refraction survey was carried out along the crest of the spur. The 117.5 m long refraction line was shot with 2.5 m receiver spacing using a sledgehammer as a source. The results of the survey (Fig. 8) clearly show that the section along the spur consists of two layers with distinctly different seismic velocities. A very low velocity of 470 m/s in the upper layer is indicative of unconsolidated fill material. The layer is about 6 – 8 m thick and is apparently the remnant of the Roman assault ramp. The velocity in the second layer (about 1600 m/s) is characteristic of the consolidated chalk bedrock of the Senonian Menuha Formation, as known from the previous refraction surveys conducted in the Dead Sea area.

Thus, the results of the refraction survey confirm that the Roman assault ramp at the Masada site is a relatively thin layer of soft material piled up on top of a natural spur.

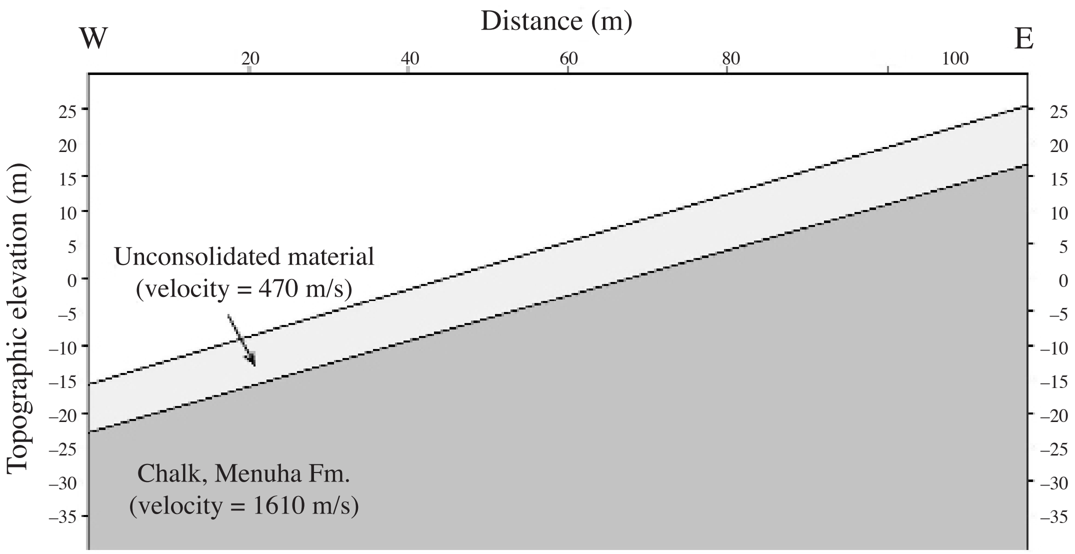

Fig. 8 - Depth section along the refraction line located on top of the Masada spur (Fig. 7).

4. Shear wave surveys

Shear waves are an important source of information regarding the structure and properties of the shallow subsurface. The velocity of shear waves (V_s) is one of the most important parameters characterizing the subsurface material, since it is directly related to mechanical properties of soils and rocks. The V_s data is widely used in construction site investigations where it serves as a basis for geotechnical evaluations and for site response computation for seismic risk assessment. Furthermore, the P- to S-wave velocity ratio (V_P/V_s) can serve as indicator of lithological and hydrological changes and porosity. Information on the V_s subsurface distribution can be obtained using shear wave seismic methods. The common practice is to use the transverse (SH) component of shear waves. For this purpose the methods usually implement specific acquisition techniques involving special horizontally oriented sources and receivers. Various aspects of shear wave applications are discussed in Dohr (1985b).

In the following, we will consider one important aspect of using shear waves in construction site investigations, namely, computation of site effect for seismic risk assessment.

Assume that at a construction site a hard rock with shear wave velocity V_{s2} and density ρ_2 is overlain by a soft layer with shear wave velocity $V_{s1} < V_{s2}$, density $\rho_1 < \rho_2$ and thickness H. In the case of an earthquake, the presence of the soft layer will cause an amplification of the ground motions at the site. The amplification is defined by a frequency-dependent site response function with the maximal value of $a_{max} = \rho_2 V_{s2} / \rho_1 V_{s1}$ occurring at the resonance frequency of $f_{res} = V_{s1} / 4H$ (Shearer and Orcutt, 1987). The above formulae show that the resonance frequency is defined solely by the parameters (shear wave velocity and thickness) of the soft layer, whereas the amplification maximum depends on the velocity (or, more precisely, impedance) contrast between the hard rock and the soft layer. If the velocity contrast is large (i.e. very soft soil over a very hard rock) and if the resonance frequency is close to that of the construction (bridge, industrial facility, etc.) planned to be built at the site, the situation may be dangerous and should be taken into account when planning the construction. The following example demonstrates such a case. A site investigation project was carried out at the site planned for constructing a new bridge across the Jordan river, several kilometers to the north of the Sea of Galilee. The site is located in the seismically active Jordan valley which is a part of the Dead Sea Transform system. In the framework of the project, a P- and S-wave refraction line was shot along the projected bridge route across the river. A number of shallow geotechnical wells were drilled along the route, and the borehole data were used for correlation with the refraction data. The resulting depth section (Fig. 9) is represented by three layers. The two upper layers are characterized by very low values of V_s (120 m/s in the upper fill and 160 m/s in the clay layer), whereas the velocity in the lower (basalt) layer is much higher (V_s = 1360 m/s). For such velocity contrast, the maximal amplification will be at least 8.5 (not considering the density

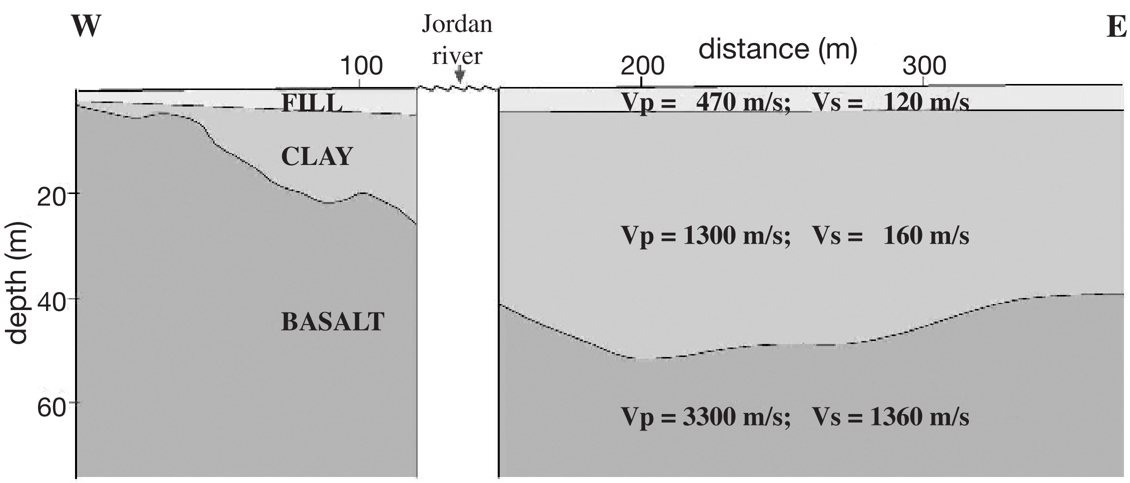

Fig. 9 - Depth section along the P- and S-wave refraction line shot along the route of a projected bridge across the Jordan river.

contrast). Since the depth to the high-velocity layer on the two banks of the river is different, varying from 2 – 25 m on the western bank to 40 – 50 m on its eastern bank, the resonance frequencies will also differ. Assuming the depth of 20 m on the western bank and 50 m on the eastern bank, the corresponding resonance frequencies will be about 2 Hz and 0.8 Hz. These estimates of the amplification and resonance frequencies are in good correspondence with the results of the seismometric (microtremors) measurements carried out at the site.

5. Summary

The considered examples show that shallow seismic methods can be an effective tool for studying the shallow subsurface for various applications. The seismic sections obtained using the high-resolution reflection method represent a clear and detailed image of the subsurface structure, making them a good basis for interpretation of the upper part of the geological section for engineering and hydrogeological problems. Seismic refraction surveys are a fast and inexpensive way to estimate the geometry and velocities of the shallow layers for a variety of applications, including environmental and archeological problems. Information on shear wave velocity distribution in the shallow subsurface, obtained from shear wave surveys, can make a considerable contribution to the important aspect of site investigation problems related to site effect evaluation for seismic risk assessment.

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