# Using surface waves for studying the shallow subsurface

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**Abstract -** Surface waves are an important source of information about the shallow subsurface. Dispersion of surface waves is closely related to the structure and properties of the subsurface material and, in particular, to shear wave velocity $V_s$. The vertical distribution of the $V_s$ can be estimated on the basis of the dispersion analysis of different kinds of surface waves contained in conventional (P-wave) seismic records. On land data, dispersion curves of Rayleigh waves can be usually identified in a wide range of frequencies, whereas data from shallow-water marine surveys usually contain a low-velocity, low-frequency wave train identified with Scholte waves, with the dispersion curves located in a narrow frequency range. The $V_s$ estimation procedure includes identification and picking of the dispersion curves of the surface waves, followed by inversion of the curves; the inversion results in a stepwise curve defining the vertical distribution of the $V_s$. Application of the method to the data of both land and marine surveys enables us to obtain estimates of the $V_s$ down to depths of 40-50 m. The advantages and limitations of the surface wave method for $V_s$ estimation, as compared to the S-wave refraction technique, are discussed. Surface waves can also be effectively used for detecting and mapping various subsurface inhomogeneities (such as voids, fracture and fault zones, etc.). Since strong lateral variations of $V_s$ related to the inhomogeneities are expressed as clear anomalies in the corresponding dispersion patterns, tracing the dispersion anomalies along seismic profiles can be used for detecting the inhomogeneous regions. In order to facilitate continuous tracing of the dispersion patterns, special types of seismic sections, based on stacking of surface waves in frequency domain, can be utilized. A brief discussion of the stacking procedure is followed by a number of examples illustrating its application.

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## 1. Introduction

The study of the upper part of the geological section is an important aspect of a vast variety of applications, such as geotechnical site investigation, environmental and groundwater studies, seismic risk assessment, etc. The geological structure of the shallow subsurface layers is usually rather complicated and is typically characterized by fast lateral and vertical variations in physical properties and often by tectonic deformations and faulting. One of the most important parameters characterizing the shallow subsurface is the seismic velocity of shear waves ($V_s$), since this parameter is directly related to mechanical properties of soils and rocks. In particular, $V_s$ can provide important information for construction site investigations where it serves as a basis for geotechnical evaluations and for site response spectra computation for seismic risk assessment. The $V_s$ data can also be of paramount importance for various offshore geotechnical applications, such as construction and extension of seaports, planning of artificial islands and offshore pipeline design. Moreover, lateral changes in $V_s$ can be indicative of various kinds of subsurface inhomogeneities, such as cavities, tunnels, fracture and fault zones, etc.

Information on subsurface distribution of $V_s$ can be obtained using shear wave seismic methods. These methods usually implement specific acquisition techniques involving special horizontally oriented sources and receivers. In many cases, however, the *S*-wave techniques prove to be problematic and not effective enough to produce good quality shear-wave data. The problem is especially severe in the marine environment, since shear waves do not propagate in water, whereas simulation of a land survey (i.e. application of horizontal sources and receivers) at the sea bottom does not seem to be practical even in very shallow water.

An alternative approach to $V_s$ estimation uses the data of the surface waves contained in conventional (P-wave) seismic records. The main advantage of this approach is that it does not require any special acquisition technique. The method implemented is based on the analysis of the dispersion properties of surface waves, i.e. the dependence of propagation velocity of different spectral components of the waves upon their frequency. This dependence (expressed by dispersion curves) is closely related to the vertical distribution of $V_s$ in the subsurface. Analyzing the dispersion relations derived from the surface waves contained in P-wave seismic records, one can obtain estimates of shear wave velocities. During the last decade, various modifications of the method have been successfully used in a variety of applications (Gabriels et al., 1987; Barrows et al., 1988; Nazarian and Stokoe, 1988; Rix et al., 1988; Jongmans and Demanet, 1992; Al-Eqabi and Herrmann, 1993; Chávez-García et al., 1995; Gitterman et al., 1996; Abraham et al., 1998; Bitri et al., 1998; Shtivelman, 1999). A similar approach using interface waves was applied in a marine environment for estimating $V_s$ below the sea bottom in shallow water (Rauch, 1986; Chapman and Staal, 1991; Shtivelman, 1999, 2001).

In the following, two aspects of surface wave applications are discussed. The first one aims at estimating shear wave velocity distribution in the shallow subsurface, whereas the second one deals with the detection and mapping of various kinds of subsurface inhomogeneities.

## 2. Estimating $V_s$

As mentioned above, the surface waves method (SWM) for estimating $V_s$ is based on dispersion analysis of different kinds of surface waves contained in conventional (P-wave) seismic records. Usually, the method utilizes phase velocities of surface waves. In land surveys, the vertical component of Rayleigh waves is used for the analysis. In marine surveys, the analysis involves the pressure field measured in water and related to interface waves (Scholte waves). At high frequencies, Scholte waves consist mainly of Stonely waves localized in the vicinity of the liquid/solid interface, whereas at lower frequencies they consist of Rayleigh waves propagating in the layers below the sea bottom (Chapman, 1991). Since the interface waves attenuate very fast as the distance to the liquid/solid interface increases, it is necessary to position the receivers as close as possible to the sea bed. It can easily be done in shallow water, where cables and receivers (hydrophones) can be put at the sea bottom.

### *2.1. The method*

Various modifications of the SWM, including two-channel and multi-channel versions, were described elsewhere (see, for example, McMechan and Yedlin, 1981; Rix et al., 1988). Generally, the multi-channel version of the SWM can be defined as an estimation procedure which includes the following steps:

- Transformation of seismic records from the original T-X (time-distance) domain into either F-C (frequency - phase velocity) or F-K (frequency - wavenumber) domain. The F-C

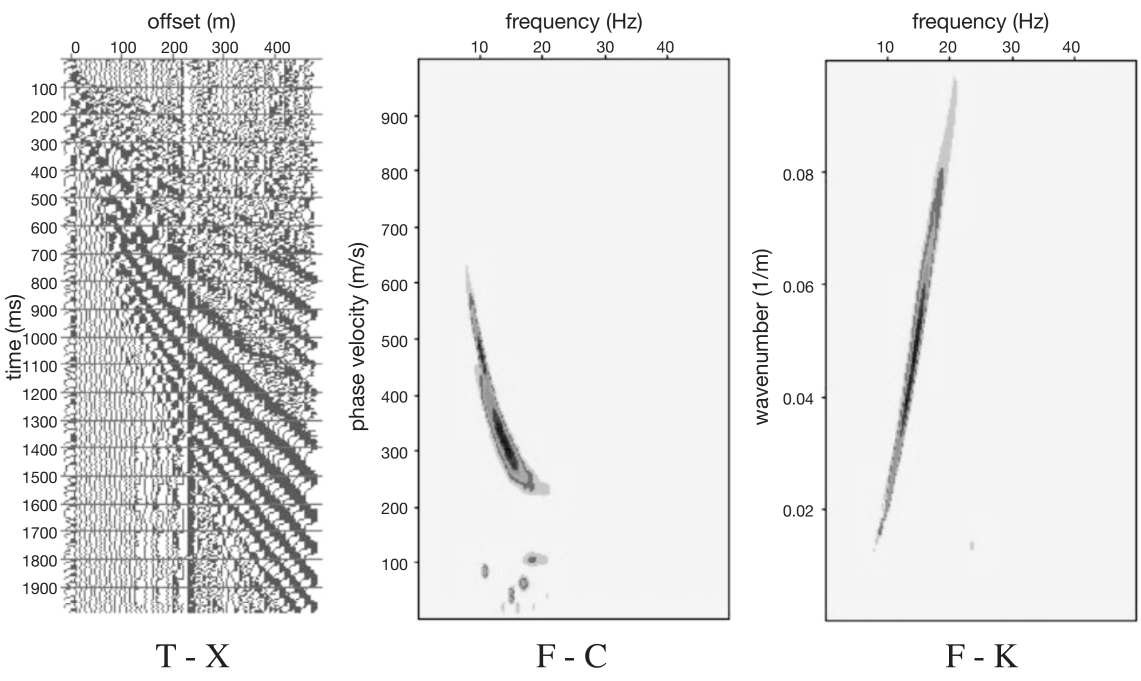


**Fig. 1** - Left - a seismic record in T-X (time - distance) domain; center - F-C (frequency - phase velocity) panel of the record; right - F-K (frequency - wave number) panel of the record.

transformation can be performed by slant stacking of seismic traces in the frequency domain and is suitable for any kind of source - receiver geometry. The F-K transformation is performed by two-dimensional Fourier transform and is limited to the case of evenly spaced traces with off-end source - receiver geometry. In certain cases the F-K approach can produce a better resolution, especially at low frequencies. The dispersive patterns associated with surface waves usually appear as dominant events on the F-C or F-K panels, as illustrated by Fig. 1.

- Identification of dispersive events on the F-C or F-K panels followed by interactive picking of the events. This step results in a set of frequency - phase velocity pairs specifying dispersion curves.
- Specification of an initial model for inversion of the dispersion curves. The initial model may be based on the available a priori information, such as well data, P-wave refraction sections, etc. The model used for inversion of marine data should include a water layer with a specified thickness. Usually, different initial models are tried, and the model giving the best fit (the smallest misfit) is chosen.
- Inversion of the dispersion curves using an iterative technique (e.g., damped linearized least-squares method). At each iteration, computation of theoretical dispersion curves for an updated model is performed using a modeling technique [e.g. the Schwab - Knopoff method (Schwab, 1970; Schwab and Knopoff, 1970)]. The stopping criteria can be a small absolute value of the RMS misfit and small relative changes of the misfit value between two sequential iterations. The inversion results in a stepwise curve $V_s$ defining a layered model which specifies the vertical distribution of shear wave velocity.

*2.2. Advantages and limitations of the SWM*

Like any other technique, the SWM method has its advantages and limitations, which should be taken into account when considering a possible application of the method to a specific problem and evaluating its results.

The main advantages of the SWM, as compared to the S-wave refraction technique, may be formulated as follows (Shtivelman, 1999):

- The SWM does not require application of a special acquisition technique, since it can use the data of the conventional (P-wave) seismic surveys.
- In many cases, for various reasons it is difficult to obtain S-wave refraction data of reasonable quality. On the other hand, surface waves are usually dominant events on seismic records. Therefore, the SWM can often be the only non-destructive technique for estimating $V_s$, especially in the marine environment.
- The conventional refraction method assumes that the subsurface model can be specified by a small number of relatively thick constant velocity layers with sharp velocity contrasts between the layers. If this assumption does not hold (e. g. if the subsurface velocity changes gradually with depth), then the standard refraction interpretation may fail. The SWM in principle can treat any vertical velocity distribution.

- Depth estimate of a chosen target refractor in the refraction interpretation depends on the velocity distribution in the layers above the refractor. The errors in the estimated velocity caused by vertical velocity changes within the layers, hidden-layer problem or velocity inversion, may result in significant errors in the depth estimate. The SWM does not suffer from such limitations.
- The layers with the velocity inversion can not be revealed by the first break refraction method, but do not pose a problem for the SWM.
- The refraction method is essentially a low-resolution technique. The SWM can produce much higher vertical resolution, especially in the very shallow part of the geological section. The resolution of the SWM is limited by the detailing in the specification of dispersion curves and depends on a number of layers specified for the initial model used for inversion of the curves.

The main limitations of the SWM can be defined as follows:

- The results of the method depend on the correct specification of the dispersion curves of surface waves used for the analysis. Sometimes it is difficult to perform a reliable identification of the curves; in such cases, the application of the SWM may be problematic.
- The method is based on a one-dimensional model, i. e. it assumes that the subsurface model does not include lateral changes in velocity and layer geometry. Experience shows that this limitation is not too strong and that meaningful results can still be obtained for the cases when the model differs significantly from the 1D case. To increase the reliability of the results, one can apply the method to the records of direct and reversed shooting from refraction surveys or to a number of sequential records from reflection surveys and then average the resulting $V_s$ distributions.
- The dispersion curves derived from seismic records are always band - limited. Usually, the high-frequency part of the curves is sufficient to obtain estimates of $V_s$ at shallow depths, whereas the deeper part of the model is related to the low-frequency part of the curves which may be lacking from the data. Therefore, the deep part of the model is usually ill-constrained and, as a result, the velocity and depth of the lower layer obtained by the method may be somewhat different from their actual values.
- For technical reasons, the depth range of the method is usually limited to several tens of meters, depending on the power of the energy source, the frequency characteristics of receivers and the range of source - receiver offsets. The maximal depth for which reliable $V_s$ estimates might be expected can be roughly estimated as half of the maximal wavelength contained in the corresponding dispersion curve. For example, assuming that the lowest detected frequency is 10 Hz and that the corresponding phase velocity is 600 m/s, then the maximal depth is about 30 m.

### *2.3. Examples of the SWM application*

The SWM was applied to a vast variety of conventional (P-wave) seismic land and shallow-water marine data acquired in refraction and reflection surveys in various areas. The equipment and parameters used for the surveys are specified in Shtivelman (1999). Figs. 2 and 3 represent two examples of such applications. The top-left part of the figures shows field records used for analysis. At the top-center, F-K panels of the records are represented; on the panels, the horizontal axis is frequency in Hz and the vertical axis, wavenumber in $m^{-1}$. The top-right part of the figures shows the resulting $V_s$ distribution graphs, where the horizontal axis is velocity in m/s and the vertical axis, depth in meters.

LAND DATA - Fig. 2 shows an example of the SWM application to land data. The P- and S-wave refraction surveys conducted at the site enabled us to obtain reliable estimates of both P- and S-wave velocities, so that the results of the SWM could be compared with the $V_s$ values obtained by the refraction survey (Fig. 2, bottom). The top-left part of Fig. 2 shows a record from the P-wave refraction survey. The record displays a well defined dispersion pattern representing the fundamental mode of Rayleigh waves. On the F-K panel (top-center), the dispersion curve can be readily identified within the frequency range between 8 and 23 Hz. The resulting $V_s$

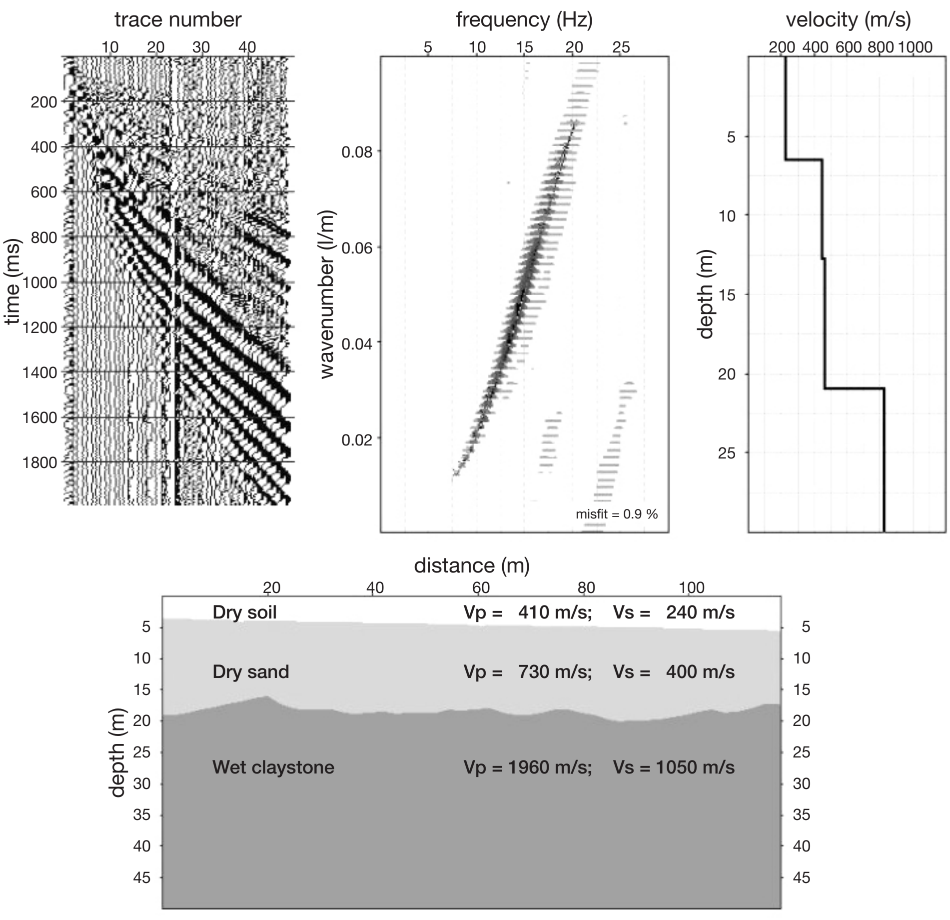


**Fig. 2** - Top - an example of estimating $V_s$ for land data: left - a seismic record in T - X (time - distance) domain; center - F - K (frequency - wave number) panel of the record; right - the estimated vertical distribution of $V_s$. Bottom - depth section along a refraction line located at the same site as the above example.

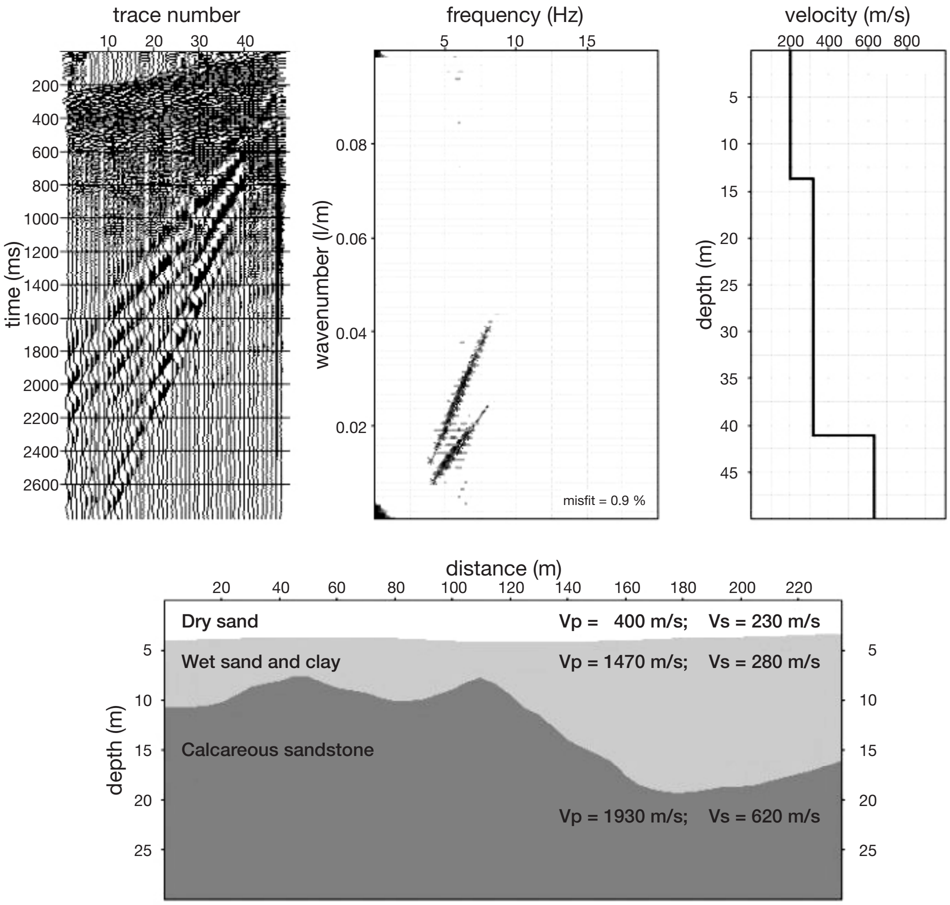


**Fig. 3** - Top - an example of estimating $V_s$ for shallow water marine data: left - a seismic record in T - X (time - distance) domain; center - F - K (frequency - wave number) panel of the record; right - the estimated vertical distribution of $V_s$. Bottom - depth section along a land refraction line located in the vicinity of the study area.

distribution (top - right) can be approximated by a three-layer model with the $V_s$ values of 220 m/s, 430 m/s and 820 m/s, correspondingly. The upper layer is about 7 m thick; the lower layer appears at depth of about 21 m.

The $V_s$ values estimated by the SWM correspond reasonably well with the velocities obtained in the S-wave refraction survey (Fig. 2, bottom). The lower value of $V_s$ in the third layer obtained by the SWM, as compared to the refraction section (820 m/s vs 1050 m/s) is apparently due to the lack of data in the low-frequency part of the corresponding dispersion curve (i.e. at frequencies less than 8 Hz in Fig. 2, top - center).

MARINE DATA - Fig. 3 shows an example of $V_s$ estimation below the sea bottom. The investigated site is located in the Mediterranean Sea, in the area planned for extension of the port of Haifa (Shtivelman, 2001). A number of reflection and refraction lines were shot at the site. The application of the SWM is demonstrated on one of the refraction lines; the water depth along the line was about 6 m. The record used for the analysis (Fig. 3, top - left) shows a well defined pattern of a low-frequency, low-velocity dispersive wave train which may be identified with Scholte waves. The dispersion curves of the first two modes can be clearly seen on the F-K panel in a very narrow frequency range of 3-12 Hz (Fig. 3, top - center). Both curves were used for inversion. Several runs of the inversion with various initial models including from 3 to 6 layers were made; the three-layer model giving the best fit was finally chosen. The resulting $V_s$ distribution below the sea bed (Fig. 3, top - right) is represented by velocities of 200 m/s, 320 m/s and 630 m/s. These values are in good correspondence with the results of the land refraction survey carried out in the vicinity of the investigated site (Fig. 3, bottom). According to these results, the model at the site contains poorly consolidated sand (the upper layer), more consolidated sand and clay (the second layer) and calcareous sandstone (the lower layer) appearing at a depth of about 41 m.

## 3. Mapping subsurface inhomogeneities

The strong dependence of the dispersion properties of surface waves upon the $V_s$ distribution suggests that strong lateral variations of the $V_s$ in the subsurface may manifest themselves as pronounced anomalies in the corresponding dispersion patterns mapped on seismic records. Since the penetration depth of various spectral components of surface waves depends on their frequency, the dispersion anomalies can be expressed by a strong decrease of spectral amplitudes at certain frequencies corresponding to the depth range of the subsurface inhomogeneities. This can be illustrated by the synthetic example represented in Fig. 4. The top of the figure shows a three-layer model including a void at the top of the second layer. For this model, three records of SH waves were computed at the locations marked by the arrows. The bottom of the figure shows dispersion patterns of Love waves obtained for the three records. The figure clearly demonstrates how the character of the dispersion patterns changes along the model: whereas the left (undisturbed) part of the model produces a well defined dispersion pattern within a relatively wide range of frequencies varying between 6 and 37 Hz, in the central part of the model (above the void) the spectral energy of the Love wave is localized within a narrow range of 18 - 27 Hz. The absence of lower frequencies at this location is due to the fact that the spectral components with the penetration depths corresponding to the void position and deeper, cannot propagate through the void and are filtered out by it.

The above example suggests that the dispersion anomalies detected along seismic lines can serve as indicators of various subsurface inhomogeneities, such as voids, fracture and fault zones, etc. Detecting the anomalies requires continuous tracing of the dispersion patterns along the lines. A continuous representation of the dispersion patterns can be achieved by linear stacking of surface waves in the frequency domain. Several recent publications discuss the possibility of imaging subsurface objects with the linear stacking using the phase velocity functions estimated from a single shot gather. Park et al. (1998) describe a procedure of stacking uncorrelated shot gathers and illustrate its application for imaging a near-surface tunnel. Leparoux et al. (1999) apply a similar procedure to receiver gathers obtained from an impulsive

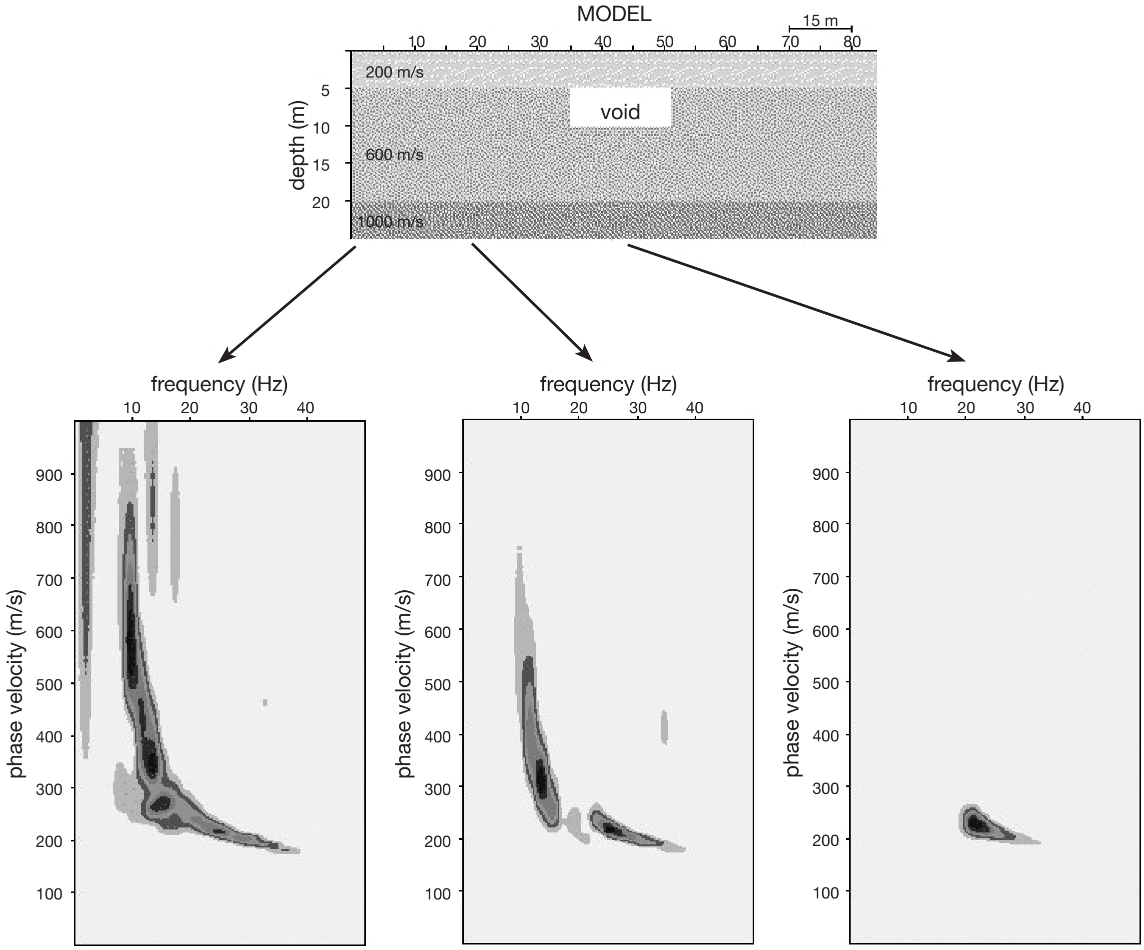


**Fig. 4** - Top - a three-layer model with a void at the top of the intermediate layer; the small figures within the layers designate shear wave velocities. Bottom - dispersion patterns of Love waves computed at three locations marked by the arrows.

source for imaging a shallow cavity. Both approaches suffer from an ambiguity in establishing surface locations of stacked traces, so that their results are dependent on shot-receiver geometry. Besides, the stacking results can be influenced by changes of spectral properties and of surface conditions of the sources and receivers along the line.

Shtivelman (2002) proposed a method for continuous representation and tracing of the dispersion patterns, based on stacking of surface waves in the common midpoint (CMP) domain. The advantages of this approach are that it defines unambiguously the surface locations of the stacked traces, and that it averages the properties of all the sources and receivers participating in the given CMP gather. Moreover, the CMP stack can provide a better spatial resolution since its spatial sampling is twice as dense as that of the common shot or common receiver stacks. At each CMP, the stacking is performed with the velocities obtained by spatial interpolation of the phase velocity functions (defined by the corresponding dispersion curves) estimated at a number of locations along the seismic line.

### *3.1. Stacking of surface waves*

In order to facilitate continuous tracing of the dispersion patterns of surface waves along a seismic line, it is convenient to represent them in the form of a section along the line, just as for reflections. Such a section should emphasize surface waves having a given dispersion characteristic, while suppressing all other kinds of waves. This can be achieved by stacking the surface waves in the frequency domain on the basis of their phase velocities defined by the corresponding dispersion curves. The stacking procedure is described in detail in Shtivelman (2002). The main points of the procedure are as follows:

- Phase velocity analysis, resulting in a set of dispersion curves, is performed at a number of selected locations along the seismic line. A spatial interpolation between the dispersion curves produces a phase velocity profile $C\,(f, y)$ (where $f$ is frequency and $y$ is the CMP coordinate).
- Linear stacking of frequency components in the CMP domain is done using the velocity functions defined by $C\,(f, y)$:

$$U_\Sigma\,(f, y) = \sum_{m}^{M} U_m\,(f, x) \exp\left(-2\pi i f x_m / C\,(f, y)\right), \tag{1}$$

  where $U_\Sigma\,(f, y)$ is the resulting stacked trace, $U_m\,(f, x)$ is a trace within the given CMP gather, $x_m$ is the source - receiver offset for this trace, and $M$ is the number of traces defining the range of summation (maximal offset).
- Mapping the power spectra of the stacked traces from the frequency ($f$) into wavelength ($\lambda$) domain results in a stacked section $|U_\Sigma\,(\lambda, y)|^2$ which may be regarded as representing a spatial spectral energy distribution of the constructively stacked surface waves in the $\lambda$ - $y$ domain, and can be used for mapping lateral anomalies of the dispersion patterns along seismic lines. In particular, an abrupt decrease of the spectral energy at a certain location on the section may be related to a strong attenuation of the corresponding wavelengths due to a subsurface inhomogeneity below the respective location. Furthermore, since the penetration depth of the surface waves is usually roughly approximated by half their wavelength, the section may give an estimate of the depth to the inhomogeneity. In the following, for the sake of brevity this section is called the PSS (power spectrum section).
- Transforming the stacked traces from the frequency domain into time domain results in a time section $u_\Sigma\,(t, y)$ which may be regarded as representing a spatial phase distribution of the constructively stacked surface waves and can provide an additional indication of lateral changes of the dispersion patterns. In particular, a phase discontinuity at a certain location on the section may indicate a lateral change of the dispersion pattern caused by a subsurface inhomogeneity below the respective location.

*3.2. Examples of surface wave sections*

The method was applied for imaging various kinds of subsurface inhomogeneities on both synthetic and real data (Shtivelman, 2002). Consider two examples illustrating such applications.

SYNTHETIC EXAMPLE - Fig. 5 shows a three-layered model including a void in the upper layer. The shear wave velocities in the layers were 200 m/s, 600 m/s and 1000 m/s, respectively, as marked in the figure. The same constant density was assumed for all layers. Along the model, a roll-along survey was simulated by computing a series of seismograms of SH waves using the method of finite differences (Shtivelman, 1984). The simulated line consisted of a single spread of 84 receivers with the receiver spacing of 1.4 m. Within the spread, a source was applied every 2.8 m, thus giving the total of 42 records with 84 traces each.

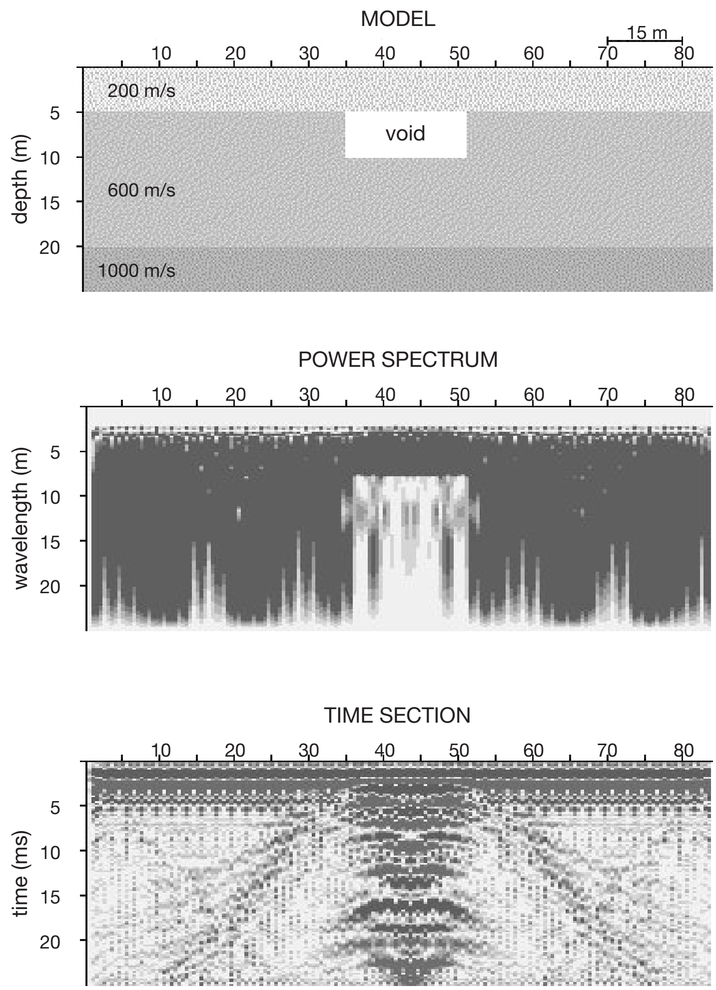


**Fig. 5** - Top - the same model as in Fig. 4. The surface wave sections obtained for the model (center and bottom) display a pronounced anomaly corresponding to the void's location.

Both surface wave sections computed for this model (Fig. 5, center and bottom) clearly show a prominent anomaly in the region corresponding to the void location. On the PSS, the top of the anomaly corresponds to the wavelength of about 15 m, so that the half-wavelength overestimates the depth to the object by about 2.5 m (7.5 m versus 5 m). The absence of wavelengths shorter than 5 m in the uppermost part of the PSS is due to the lack of high frequencies in the corresponding dispersion patterns, as can be seen from Fig. 4 (bottom, right).

REAL DATA EXAMPLE - Fig. 6 shows the implementation of the surface wave stacking for imaging a known object, a public underground shelter 40 m long and 2.5 m deep. Above the shelter, a 144 m long seismic line was shot with a 1.5 m source and receiver spacing, using a sledgehammer as a source. The total of 96 shot records with 48 traces was acquired. Both sections in Fig. 6 display a prominent anomaly in the region between stations 30 and 57 corresponding to the shelter's location, as marked below the PSS. The absence of short wavelengths at the top of the anomalous region is apparently due to a strong attenuation of the corresponding high frequencies by very soft fill material above the shelter.

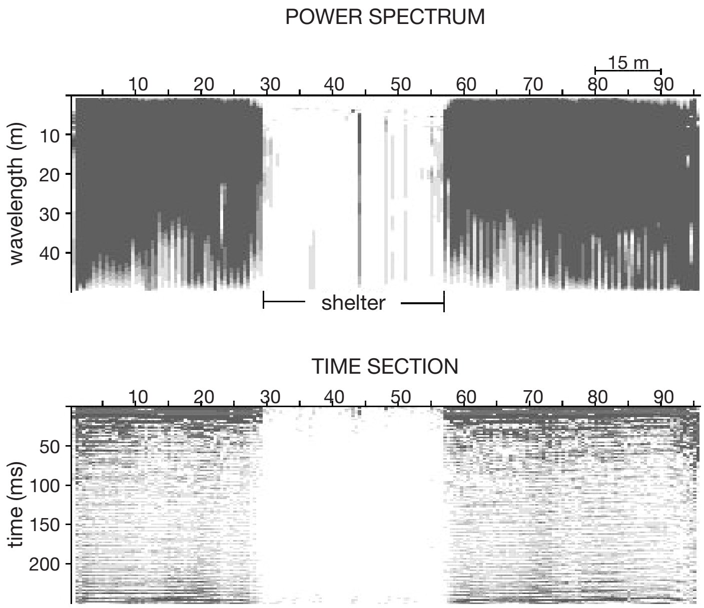


**Fig. 6** - Surface wave sections above an underground shelter. The anomaly in the center of the sections corresponds to the shelter's location marked below the PSS.

## 4. Summary

The data from conventional (P-wave) seismic refraction and shallow reflection surveys can be successfully used to retrieve information on $V_s$ in the shallow subsurface. On land data, dispersion curves of Rayleigh waves can be observed in a relatively wide range of frequencies. The estimated $V_s$ values correspond reasonably well with the available results of S-wave refraction surveys. The data from shallow-water marine surveys contain a well defined low-velocity, low-frequency dispersive wave train identified with Scholte waves. The dispersion curves of the waves are localized within a narrow frequency range; the resulting $V_s$ distribution below the seabed correlates reasonably well with land refraction data from the vicinity of the marine surveys.

Lateral variations of $V_s$ in the shallow subsurface can cause significant disturbances of the dispersion patterns of surface waves. In order to facilitate a continuous tracing of the dispersion patterns along seismic lines, a method of CMP stacking of surface waves in the frequency domain can be used. Application of the stacking procedure to synthetic and real data shows that it can be an effective technique for imaging various kinds of subsurface inhomogeneites. Strong localized anomalies appearing on the surface wave sections can be related to localized subsurface objects, such as voids, tunnels, etc. Lateral position of the objects can be determined quite well, whereas their depth can be roughly estimated by half-wavelength of the corresponding anomaly.

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