Observations of Scholte Wave Dispersion from Measurements at Two Diverse Test Sites

Hassan B. Ali, L. Dale Bibee, Jeffrey L. Becklehimer
Naval Research Laboratory Detachment, Stennis Space Center, MS 39529-5004

Abstract – The characteristics of Scholte seismic interface waves are strongly dependent upon seabed geoacoustics, particularly shear wave properties. Consequently, they may be used as an indirect means to probe the seabed. Here, observations of Scholte wave characteristics measured at two diverse test sites are presented. The responses to bottom shots, recorded on a tri-axial set of geophones and a near-bottom hydrophone, are compared for test sites off southern California and the Oregon Margin. For the California data, the Scholte waves display strong, normal dispersion, whereas the corresponding data for the Oregon test site show highly irregular, less clearly defined Scholte wave dispersion. The differences in the observed Scholte wave characteristics are attributed to the known variability between the bottom geoacoustics at the two test sites. Shear wave velocity profiles, obtained from inversion of the Scholte wave data, are consistent with this interpretation.

1. INTRODUCTION

Interest in sedimentary acoustics has increased significantly in the last two or three decades, particularly in the area of seismic interface (Scholte) waves along the seafloor. As a result, numerous studies of interface waves have been performed, particularly, though not exclusively, in shallow-water coastal regions. References 1 through 11 are representative of recent work in this area. In large part, the interest in seismic interface waves derives from the high correlation between the characteristics of these waves and the geoacoustic properties of the bottom, particularly the shear speeds and types of layering. As well as a convenient and reliable indicator of bottom geoacoustics, seismic interface waves can be a significant component of acoustic propagation, including ambient noise [2, 11, 13].

The *direct* excitation of Scholte waves requires a sound source in proximity (within a wavelength) to the seafloor, since these waves decay exponentially away from the boundary. In shallow water, particularly at very low frequencies, the condition of proximity of sound sources is often met, even for near-surface sources (wind/wave action). Contributing to the relative importance of Scholte waves in shallow water, is the fact that below cutoff frequencies the relatively thin water column ceases to be an effective waveguide for waterborne propagation. Although investigations of Scholte waves have focused largely on shallow water, there is increasing evidence that these waves also constitute a large component of seafloor seismic signal and noise in deep water [2, 11, 13]. The presence of these waves on the deep-water seafloor, even in the apparent absence of near-bottom sound sources, has led to the speculation that the roughness of the seabed in the vicinity of the receiver provides an *indirect* mechanism of Scholte wave excitation. In particular, these indirect, or secondary, Scholte waves are tentatively attributed to the scattering of the energy of incident compressional body waves into Scholte waves. The physics of this potential mechanism is the focus of a research effort currently under way at the Naval Research Laboratory–Stennis Space Center (NRL–SSC).

In this paper we present observations of Scholte waves obtained from recent NRL–SSC measurements at two diverse deep-water test sites. The objective of the paper is two-fold: first, to present new data that illustrate the behavior of Scholte waves, both on ocean bottom geophones and near-bottom hydrophones; second, to tentatively ascribe the considerable differences in the observed characteristics to differences in the bottom/subbottom structures at the test sites. Pertinent numerical modelling is currently underway, but will not be included in this paper. Prior to presenting the experimental results, a brief sketch of Scholte waves characteristics is provided to facilitate the subsequent interpretation of the data.

2. PERTINENT CHARACTERISTICS OF SEISMIC INTERFACE WAVES

Seismic interface waves, also called surface waves, propagate along the boundary between a solid and another medium. Since they are a combination of compressional and shear body waves, at least one of the propagation media must be a solid for interface waves to exist. The other medium can be a vacuum, a liquid, or a solid, in which case the corresponding interface waves is denoted a Rayleigh wave, Scholte wave, or a Stoneley wave, respectively. At low frequencies the distinction between lowest-order Rayleigh and Scholte waves becomes somewhat arbitrary. In particular, for relatively large wavelengths (λ), or small water depths (H), ($H/\lambda << 1$), the water layer acts as an insignificantly thin film, as far as the propagation is concerned. For the other extreme ($H/\lambda >> 1$), the liquid layer is effectively very thick, and the interface wave dispersion relations are determined by the geoacoustic properties of the seafloor. This is the case for the data considered here.

The Scholte wave speed is always less than the smaller of the body wave speeds (compressional or shear). In the case of homogeneous sediments, the Scholte wave speed is approximately nine tenths of the body shear wave speed for the sediments. In realistic, dispersive media the dispersion properties of Scholte waves allow one to obtain information on the properties of the seabed sediments, at least to a depth of one or two Scholte wavelengths [1]. In particular, measured dispersion curves coupled with appropriate numerical results (e.g., synthetic seismograms and dispersion curves) make it possible to determine the shear speed and shear attenuation profiles and possibly sediment thickness. Shear velocity and shear velocity gradients are the primary controls on the Scholte wave dispersion relation. As wavelength increases, the Scholte wave propagation is more sensitive to properties at greater depths below the seafloor. Since shear velocity generally increases rapidly with depth within the seafloor, these longer wavelengths propagate faster.

3. THE EXPERIMENTS

The results to be discussed derive from Scholte wave measurements in two diverse geographical areas: the Oregon Margin off the coast of Washington, and the flat marginal basin off the coast of San Diego. For both experiments the primary goal was to record Scholte waves directly generated by bottom sound sources. At each test site a number of sensors was deployed, including several ocean bottom seismometers (OBS). Each OBS consisted of a set of tri-axis geophones and an externally-mounted hydrophone clamped to the side of the OBS. Among the different sound sources used in the experiments, only the bottom explosive shots are of interest here. The bottom shots, which generally consisted of 40 lb or 50 lb demolition changes, were dropped over the side of the ship and subsequently detonated by an electric blasting cap. Detonation times were set to allow ample time for the dropped explosives to reach the seafloor, detonation being initiated by a crystal-controlled timer in an expendable pressure case. The bottom shots were deployed in a 2-dimensional horizontal pattern, with the distance from the shots to the receivers ranging from approximately 400 m to 2 km.

The seafloor geoacoustic environments at the Oregon margin site and the southern California site are generally similar. The Oregon site is located just seaward of the continental slope in water 2600 m deep. The seafloor relief is very low (<10 m), and the bottom consists of 3 km of flat-lying sedimentary layers which overly basaltic basement. The southern California site is located just seaward of the Patton Escarpment, which marks the outer limits of the southern California borderland terrain. The 3800-m water depth is somewhat greater than for the Oregon site, but in both cases the depth greatly exceeds the wavelengths of the signals considered here. The seafloor at the southern California site also consists of very flat-lying sediments with low bathymetric relief (<10 m). Deep Sea Drilling Project Site 469 is located within a few kilometers of the site, and shows that the upper sediments are hemipelagic clays and that basaltic basement occurs at a depth of 390 m below the seafloor [14]. In both cases, basement is sufficiently deep that it plays no part in the propagation of interface waves discussed here. Superficially then, the environments appear to be very similar for the propagation of interface waves on the seafloor.

Despite these general similarities, the geoacoustic properties of the upper few meters of sediment are considerably different. The upper 42 meters of the sediment at the southern California site are clays with a compressional wave speed of approximately 1510 m/s. Although shallow (<3 m) cores at the Oregon site show hemipelagic muds with sound speeds near 1500 m/s [15], the average sound speed in the upper sediments calculated from the compressional wave arrivals of the OBS data is near 1800 m/s. Since the site is located on the distal edge of the Astoria Fan, the deeper sediments (>3 m) are probably predominantly sand rather than clay, which have higher sound speeds. Examination of the 3.5 kHz seismic records from the site indicate a thin, almost acoustically transparent, sediment layer approximately 3 m thick overlying a strong reflector below which we see no penetration. Our interpretation of these data is that the sedimentary section is composed of a thin layer of hemipelagic muds overlying sand on the Oregon margin.

In what follows, the experiments at the two test sites will be referred to by their acronyms. In particular, the SOBS (Signals on Ocean Bottom Seismometers) experiment will refer to the measurement in the Oregon Margin, while SSNAP (Seismic Signals and Noise on Arrays and Penetrators) will denote the experiment off the coast of San Diego.

4. DISCUSSION OF RESULTS

A typical response to a bottom shot is given by Fig. 1, which shows the time series (seismograms) recorded by all four OBS components for a 778-m distant explosion during the SSNAP experiment. In these and subsequent seismograms it is the distribution of energy within each seismogram, not the relative amplitudes of the seismograms, which is of primary interest. As indicated on the figure, the direct waterborne signal is followed by the first and second water-column multiples and then by the arrival of the Scholte wave signal. Of all four OBS components, the vertical component of the geophone, top trace, shows the clearest presence of Scholte waves. In particular, the Scholte wave shown on this component is larger in magnitude than those of the other components, relative to the waterborne arrivals, and shows strong "normal dispersion" (lowest frequencies arriving first) expected of Scholte waves. The presence of the Scholte wave on the other components, while evident, is not nearly as prominent. While some decay of the

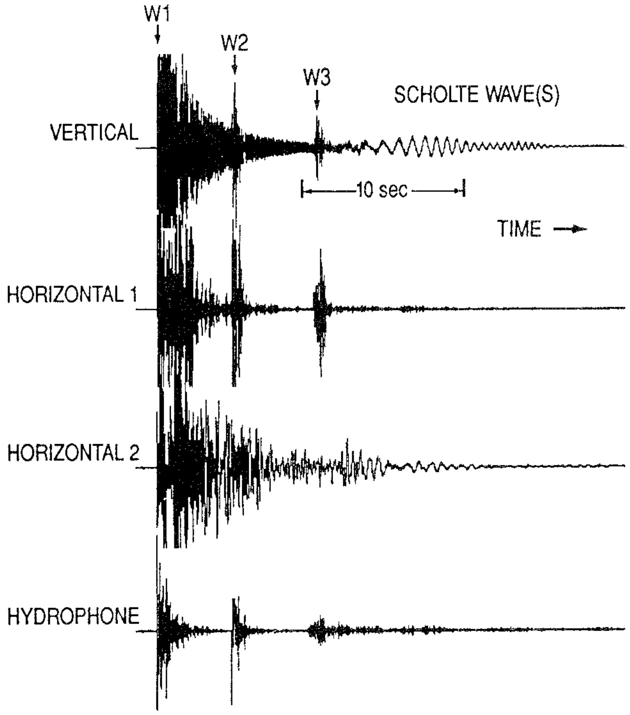

Fig. 1. OBS recordings of a 778-m distant bottom shot (SSNAP experiment) showing the direct waterborne arrival (w1), water column multiples (w2, w3), and the Scholte wave energy.

hydrophone response should be expected because the energy of the Scholte wave decays exponentially away from the interface, the hydrophone is located less than 1 m from the interface and this effect should be minimal. The differences in responses represent a more fundamental difference in the ratio of pressure to particle velocity of body waves and Scholte waves. In particular, the physics governing the coupling between the acoustic and elastic fields is more complicated than that applicable to plane waves in acoustic media. Such differences have previously been noted [10]. The responses of the horizontal components are critically dependent on their orientations relative to the source-receiver (radial) direction. In a range-independent environment, the transverse horizontal component (perpendicular to radial direction) should, theoretically, be zero, since it is uncoupled to the energy from a compressional sound source in the water. The horizontal components displayed in Fig. 1 are oriented arbitrarily with respect to the radial direction. It is clear however, that the fundamental mode Scholte wave visible on the vertical seismometer has little expression on the horizontal seismometers; but higher velocity signal, probably representing higher mode propagation, is seen.

Based on the arrival times and known source-to-receiver distances in Fig. 1, the Scholte waves group velocities were estimated to range from approximately 30 to 60 m/s. These very low Scholte wave velocities are consistent with the fact that the seafloor at the test site is covered with soft sediments with low shear speeds. It is noted that the Scholte velocities obtained here are in agreement with earlier measurements, by independent researchers, at a nearby test site [16]. Since, as noted, the Scholte wave is normally dispersed, it is reasonable to assume that the early-arriving, low-frequency wave traveling at 60 m/s has penetrated somewhat deeper into the (higher velocity) subbottom than the slower, higher frequency wave. The strong dispersion of the Scholte wave most likely indicates a steep depth gradient in the shear wave velocities.

To ascertain the frequency content of the Scholte wave, the energy spectrum of the appropriate portion of the time series was obtained. Fig. 2 shows the spectrum for the vertical geophone component. The spectrum was computed using a boxcar window of length approximately 14 seconds. OBS instrument response has not been removed, but is only slowly varying in this band. The Scholte wave energy is clearly concentrated in the 1–5 Hz band. Based on this information, we return to the time series and examine the filtered responses, using a Chebyshev 1–5 Hz bandpass filter. The result is shown in Fig. 3. The dominance of the Scholte wave in this frequency band is quite evident, at least on the vertical component. The hydrophone, too, reveals the presence of the Scholte wave, albeit at a much reduced level relative to the body waves.

We now briefly consider typical results from the SOBS experiment in the Oregon Margin. Fig. 4 shows a response to a 2-km distant bottom shot. Comparison with Fig. 1 reveals significant differences between the responses shown in the two figures. In Fig. 4, the vertical response again shows the conspicuous presence of the Scholte wave. However, in comparison to the result in Fig. 1, the Scholte wave behavior is highly irregular and displays a less clearly defined dispersion pattern. This behavior is consistent with a non-smooth or discontinuous change in the bottom sound speed gradient. Based on the known bottom geoacoustics in this area, cited earlier, this result is quite plausible. Spectral

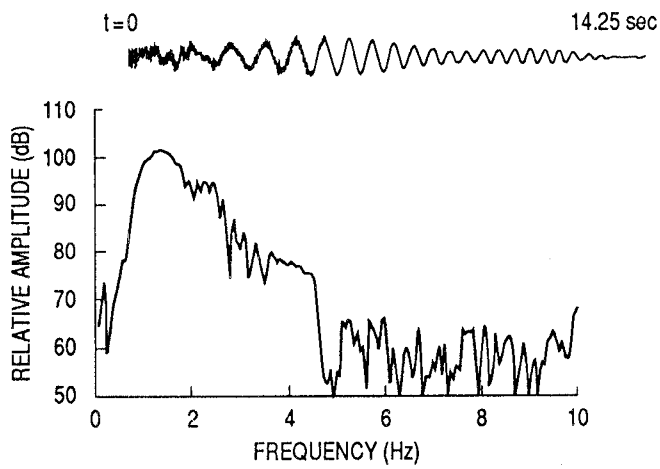

Fig. 2. Energy spectrum (bottom) of the Scholte wave portion of the time series (top) of Fig. 1 (vertical OBS component) indicating the concentration of Scholtewave energy in the 1–5 Hz band.

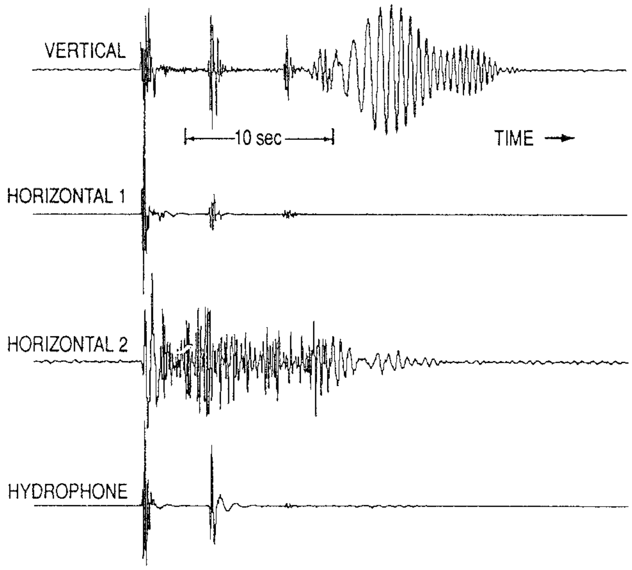

Fig. 3. Bandpass (1–5 Hz) filtered response of Fig. 1 time series, indicating prominent role of Scholte wave in this frequency band.

analysis, similar to that performed for the Fig. 1 results, shows that for this case most of the Scholte wave energy is contained in the 1–2 Hz band. The apparent difference in spectral content between the sites is probably related to the differences in fine-scale sediment statigraphy noted above. In particular, higher frequency propagation will be controlled by the thin layer of hemipelagic muds, which presumably have low shear velocity and high shear attenuation. The lower frequency signals have longer wavelengths and will be controlled by the properties of the deeper sand. A type of structural frequency filter is therefore possible.

Using the dispersion properties of the Scholte waves, the shear velocity profiles in the bottom were derived for the SOBS experiment and for the earlier experiment [16] conducted in the vicinity of the SSNAP measurements. Fig. 5 shows the results of the calculations. The higher shear wave velocities at depth for the SOBS site are consistent with a greater percentage of sand in the sedimentary structure. As noted above, the geoacoustics data suggest a step function in shear velocity at three meters for the SOBS site; however, this is beyond the resolution of the dispersion analysis technique and does not appear in Fig. 5. However, the relative complexity of the waveforms at the SOBS site, in contrast to the southern California site, is probably a manifestation of this structural detail. Full waveform elastic modeling of the time series may be capable of refining the dispersion analysis, just as waveform modeling of body waves has been used to refine models generated from travel time inversions.

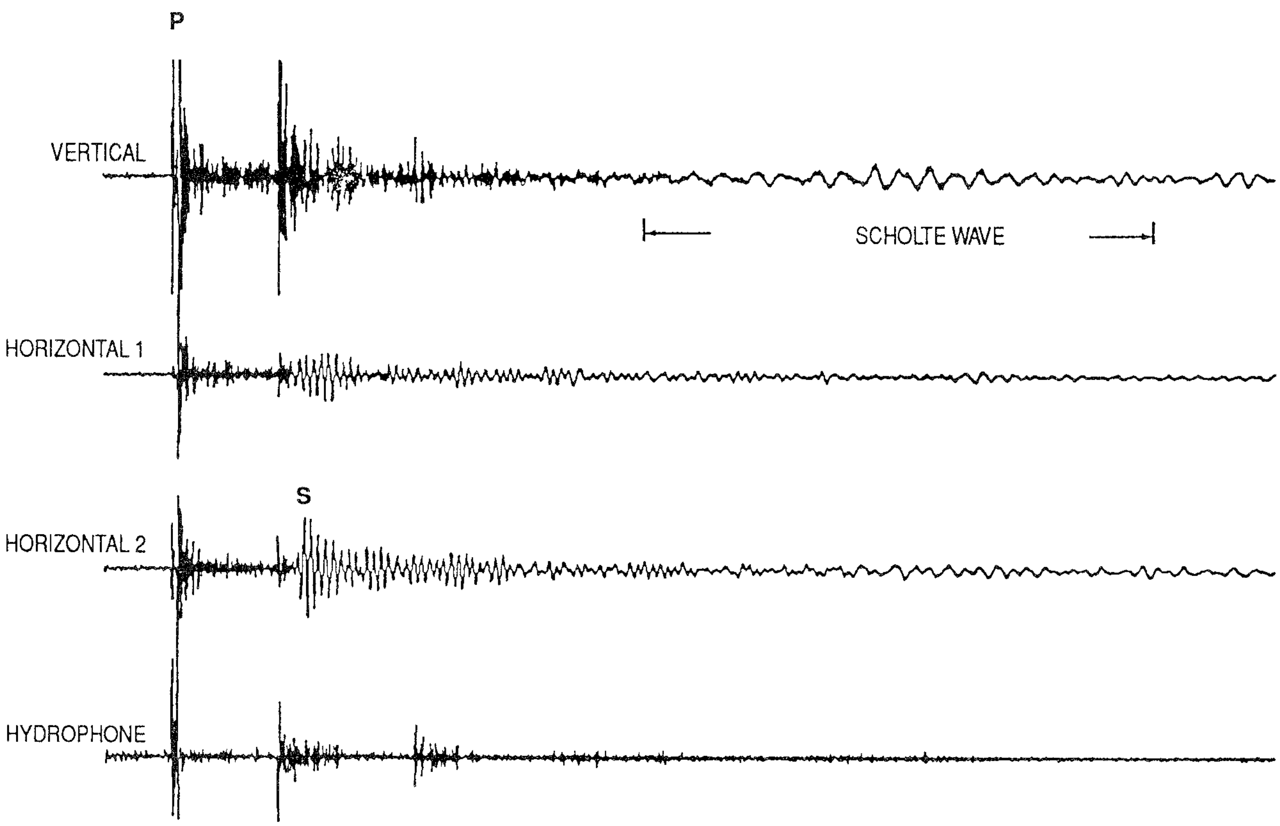

Fig. 4. OBS recording of a 2-km distant bottom shot (SOBS experiment) showing the compressional (waterborne) arrivals (P), body shear waves (S), and the Scholte wave.

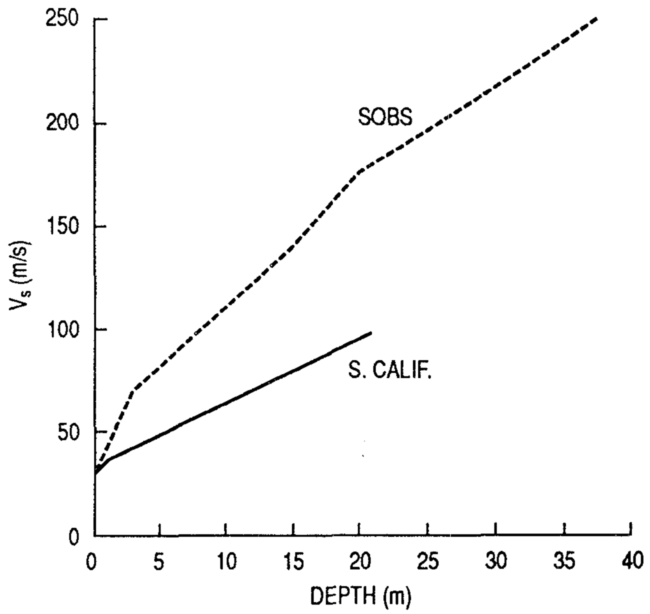

Fig. 5. Shear velocity profiles derived from the Scholte wave dispersion characteristics.

5. CONCLUSIONS

Observations of Scholte waves obtained from two diverse deep-water sites show considerable differences in the dispersive properties of these waves, and, hence, in the derived shear velocity profiles. In particular, for the SSNAP experiment off the coast of southern California, the Scholte waves show strong, normal dispersion, whereas the corresponding dispersion results for the SOBS experiment on the Oregon Margin are highly irregular and less clearly defined. The observed differences in Scholte wave characteristics are attributed to the known contrasts in the bottom/subbottom geoacoustics at the two test sites. Numerical modelling, currently underway, will address this issue.

6. ACKNOWLEDGMENTS

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