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3-D Seismic Profiling

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ABSTRACT : 'Kite' is a newly developed single-channel seismic imaging system capable of producing high resolution three dimensional images of subbottom geology in one traverse of a survey region. The system consists of a horizontally towed hydrophone array and active source. The hydrophone array is towed axis perpendicular to ship direction and the airgun source at the end of the hydrophone array is excited at timed intervals during the progression. The construction of the three dimensional subbottom image was made simply by using conventional multichannel seismic reflection data processing techniques. Common source shot (CSS) gathers of the hydrophone traces are evaluated using Dix's equation for average interval velocity of each subbottom layer. From the interval velocity profile and the normal consolidation stress condition, values of shear modulus, porosity, and shear velocity are deduced from the chosen values of physical constants. The system has been successfully tested at several locations on the North Atlantic continental shelf.

INTRODUCTION

The seismic reflection method is a technique by which one maps the configuration and nature of remote and inaccessible subbottom layers. In this technique, a seismic disturbance is generated at or near the surface of the earth, and reflections, caused by changes in acoustic impedance of subbottom layer, are recorded at the surface by a spread of detectors at various distances from the source. One can construct an image of subbottom structures by the "contrast" between layers due to physical differences between subbottom layers (Silvia *et al.*, 1979; Telford *et al.*, 1990; Shon *et al.*, 1992).

To get the clear subbottom image, in conventional marine reflection seismology, a survey ship tows hydrophone arrays which are in-line with the ship's moving direction. The reason for this hydrophone spread is that the use of multiple source, multiple hydrophones per trace and the summing of common reflection point traces brings distinct improvement in the signal-to-noise ratio (Yilmaz, 1985; Dobrin *et al.*, 1988; Telford *et al.*, 1990). In other words, a typical marine multichannel data acquisition system brings multifold coverage, so that "better" two dimensional subbottom images are expectable (Mcquillin *et al.*, 1984).

In this paper, the kite system is introduced and discussed. The kite system employs an unconventional hydrophone array spread. In the kite system, a hydrophone array is towed laterally, so that the axis of hydrophone array is perpendicular to ship direction. The composite in-line record group of seismic traces for each hydrophone receiver across the array constitute a two dimensional transect of the region and the grouping of all receiver records makes up a complete three dimensional image. Images were constructed by using conventional reflection seismic data processing techniques. In addition to the three dimensional subbottom image, subbottom physical parameters such as interval velocity, porosity, shear modulus, and shear wave velocity are inferred from the common source shot (CSS) gathers. The physical parameters derived from the CSS gathers represent the "average" values of each subbottom layer rather than the values at the specific position.

KITE METHOD

Configuration and Acquisition

In conventional marine seismic reflection exploration, hydrophone arrays are in-line with the moving direction of the survey ship. The purpose of this in-line spread is to take advantage of stacking process. The use of multiple sources and multiple hydrophones per trace brings multiple coverage of the same point of the subbottom. The summing of the multiple covered subbottom common midpoints (CMP) results in distinct enhancement in the signal-to-noise (S/N) ratio. The signal-to- noise ratio is increased through an

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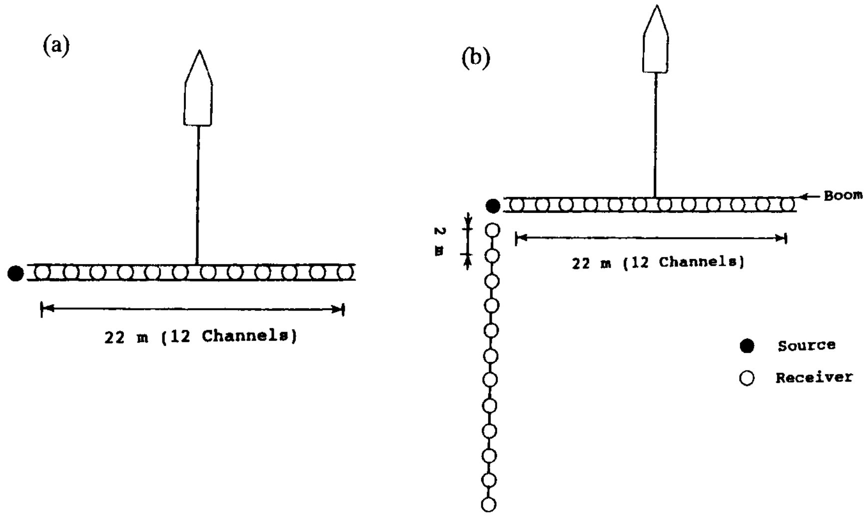


Fig. 1. (a) Schematic diagram if kite system, (b) Kite system was accompanied with the conventional methods to compare the results.

N-coverage stack by $\sqrt{N}$. In the process of stacking through normal moveout, interval velocities of subbottom layers are induced using Dix's formula (Dix, 1955; Yilmaz, 1985; Dobrin *et al.*, 1988; Telford *et al.*, 1990).

The kite system which is discussed in this paper employs a different hydrophone spread from the conventional method. Fig. 1a is the schematic diagram of the kite system (Shon *et al.*, 1992; Yamamoto *et al.*, 1992). As Fig. 1a shows, the axis of hydrophone array, boom, is perpendicular to the ship's tow direction, which is different from a typical marine seismic reflection survey in that the streamer is in-line with the ship's direction of motion. In our kite experiments, kite system and conventional in-line reflection methods are performed together to compare the results, as shown in Fig. 1b.

Subbottom features of the surveying area are, in nature, three dimensional. The main purpose of the kite system is to construct the reflectivity image of three dimensional subbottom structures. In the kite system, each channel records a two dimensional seismic section. A two dimensional seismic section normally assumes that all signals come from the plane of the profile itself, although the two dimensional section contains signals from all directions. In kite system, all channels together will construct a three dimensional subbottom image with one sweep of the receivers, while a typical marine three dimensional survey is carried out by conducting many sweeps of closely spaced parallel seismic surveys.

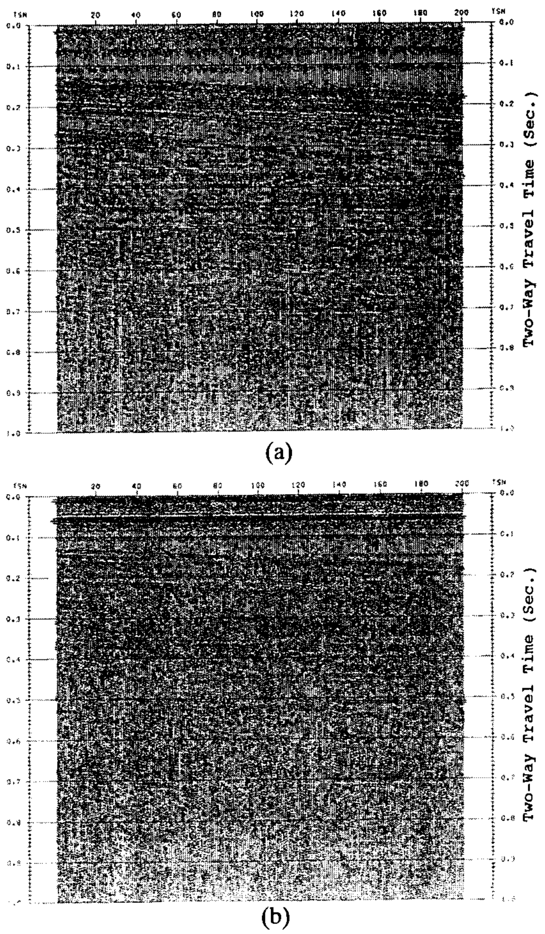
An airgun at the end of the hydrophone array is excited every two seconds while towed at ~2 knots ($\approx$ 1 m/s). Hydrophone signals are recorded at 16 khz in 12 bits using a VAX computer and an A/D converter; the recorded data is multiplexed. Demultiplexing decomposes the record to the component channel signals prior to data processing.

Data processing

Data processing is applied to the raw data, i.e., each channel data. The conventional seismic data processing is used, such as gain control, frequency filtering and deconvolution. Fig. 2a and b show examples of the processed seismic sections by conventional method and by kite system, respectively. The typical noise in the kite system is the noise due to vibration of the tow structure, boom, after source shot. However, this kind of noise is easily eliminated by bandpass and/or notch filtering, since the vibration is within the range of specific frequencies.

In conventional reflection seismology, one of the most important steps is the stacking process, because the summing of common subbottom reflection brings a distinct improvement in the seismic section. Besides the image enhancement, this process follows the normal moveout which needs the stacking velocities (often called V_{NMO}) from which interval velocities of subbottom layers are deduced.

In the kite system, the step of stacking process is not needed, but a normal moveout process is performed in shot gathers to correct all channel data to the data at zero offset. As Fig. 3 shows, in the kite



(a)

(b)

Fig. 2. Examples of the processed seismic sections by conventional method (a) and by the kite system (b).

system, stacking velocities are derived from the common source shot (CSS) gathers. For a homogeneous flat layer (Fig. 3a), the seismic event shows the hyperbola curves in the time-distance diagram (Fig. 3c). Even for a homogeneous undulated layer (Fig. 3b), the seismic events show Gaussian distribution-shown as black dots in Fig. 3c-fitted well to hyperbola curve for the case of homogeneous flat layer. In case of laterally inhomogeneous layers, the stacking velocities from CSS gathers will be the averaged values within a range of reflections between near and far-end receivers by a source-shot. Stacking velocities inferred from the CSS gathers are used for normal moveout and are used for the calculation of subbottom physical parameters.

The subbottom physical parameters derived from the kite system are the average values of n-th layer within a range of reflections; while the subbottom physical parameters deduced from conventional CMP methods are the velocities below the specific points.

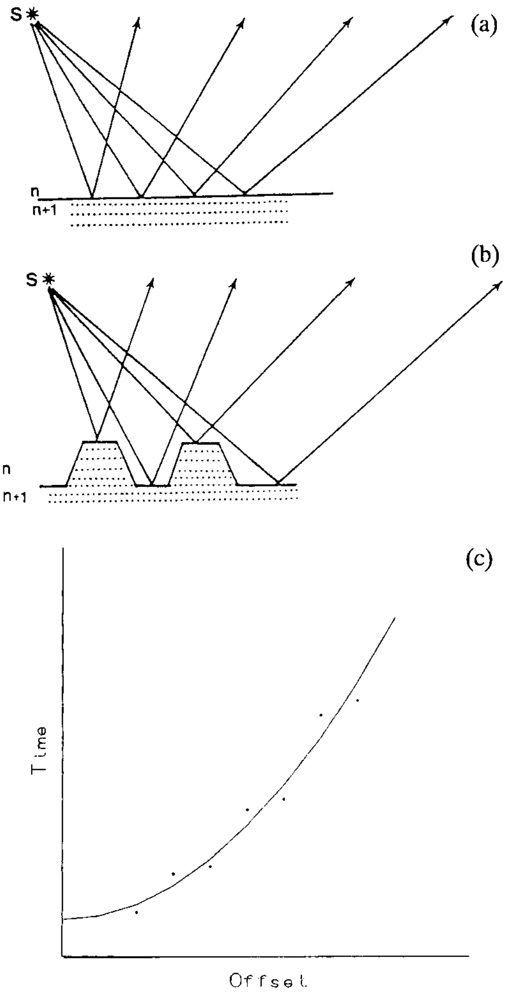


Fig. 3. The common source shot (CSS) gathers in the kite system (a) reflections for a homogeneous flat layer, (b) reflections for a homogeneous undulated layer, and (c) line: travel time-distance diagram for a homogeneous flat layer; dot: travel time-distance for a homogeneous undulated layer.

The imaging of the 3-D subbottom

Using stacking velocities, normal moveout is performed to correct each seismic section to the zero offset section. Seismic events of each normal-moveout corrected seismic section are connected to those of adjacent seismic sections to construct the three dimensional subbottom image. Fig. 4a and b show a three dimensional subbottom image constructed by geolo-

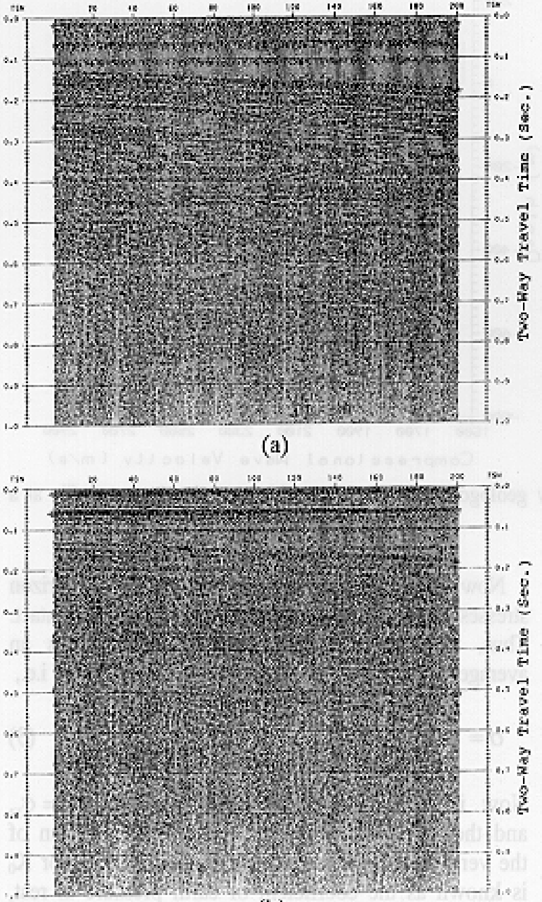


Fig. 2. Examples of the processed seismic sections by conventional method (a) and by the kite system (b).

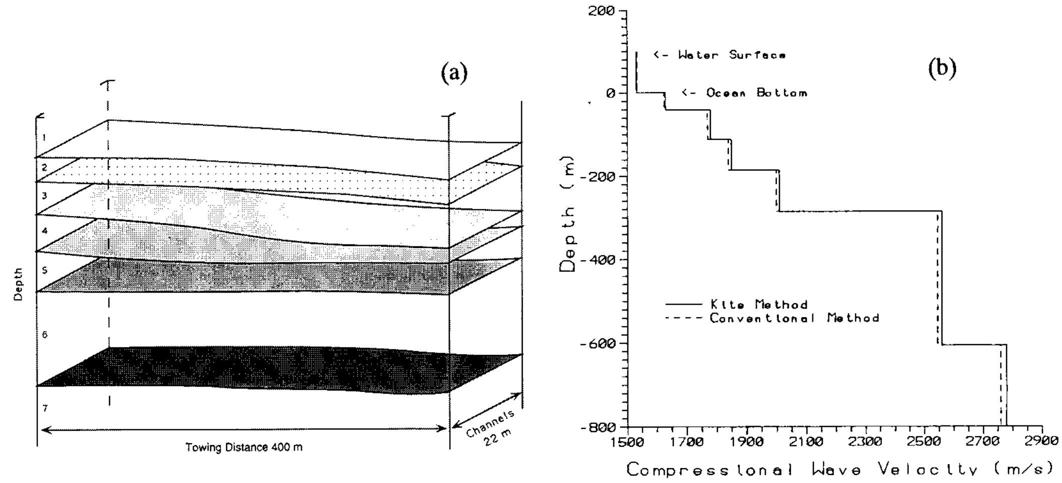


Fig. 4. (a) Three dimensional subbottom image constructed by geologoical interpretation. (b) interval velocity profile at a 100 th shot. Line

gical interpretation and interval subbottom velocity profile of the upper 7 subbottom layers including the water layer at a 100 th shot, respectively. The dashed line of Fig. 4b shows the interval velocities derived from the conventional CMP methods. Fig. 4a and b shows that the kite system is a reliable seismic method for three dimensional subbottom configuration and subbottom physical parameters.

Physical parameters of subbottom layers

Estimated stacking velocities give the approximate stepwise interval velocities using Dix's equation (Dix, 1955) as shown in Fig. 4b. The approximate interval velocities are in nature the compressional wave velocities vp. Obviously, the shear modulus, porosity, shear and compressional wave speeds can be deduced from the chosen values of physical constants (e.g. ρ_s, K_r, n_s, and K_0) (Yamamoto *et al.*, 1989; Trevorrow *et al.* 1991).

In the seabed the *in situ* shear modulus should increase with increasing confining effective stress, due to the weight of overlying sediments. The vertical effective stress σ_z is defined by the integral

$$\sigma_z(z)=\int_0^z g(\rho-\rho_w)\,dz, \tag{1}$$

which after substituting for bulk density and rearranging yields

$$\sigma_z(z)=g(\rho_s-\rho_w)\int_0^z 1-\beta(z)\,dz, \tag{2}$$

where β is porosity, and $\rho=\beta\rho_w+(1-\beta)\rho_s$ and the subscripts (w, s) refer to water and solid, respectively.

Now, vertical stresses are translated to horizon stresses through the geometry of grain-to-grain contact. Thus, the total effective confining stress σ as an average of the three components of effective stress, i.e.,

$$\sigma=\frac{1}{3}(\sigma_x+\sigma_y+\sigma_z). \tag{3}$$

Now in a horizontally stratified medium, $\sigma_x=\sigma_y$, and they are both postulated to be some fraction of the vertical stress, i.e., $\sigma_x=\sigma_y=K_0\,\sigma_z$. The factor K_0 is known as the coefficient of earth pressure at rest, and can be related to the sediment skeletal Poisson's ratio n_s by

$$K_0=\frac{n_s}{1-n_s}. \tag{4}$$

Now n_s in typical sandy and silty marine sediments can be varied in the range 0.15~0.33 (Turgut *et al.*, 1990). By taking the upper limit of 0.33 as representative, following from the fact that variations in ns over this range cause negligible changes in the derived results. This yields K_0 equal to 0.5. Thus the total effective confining stress becomes

$$\sigma=\frac{1}{3}(1+2K_0)\sigma_z=\frac{2}{3}\sigma_z. \tag{5}$$

The shear modulus μ is one of the most important descriptive parameters of a marine sediment. A wealth of experimental data has been collected relating elastic, small strain ($<10^{-5}$) shear modulus to the depositional state of sediments (Richart *et al.*, 1970; Bryan *et al.*, 1988). The data indicate that the shear modulus is proportional to the void ratio ε

and total effective confining stress σ by an empirical relation of the form (Yamamoto *et al.*, 1989)

$$\mu = A\ \varepsilon^{-m}\sqrt{\sigma} \tag{6}$$

where $A = 1.835 \times 10^5\sqrt{Pa}$ and $m = 1.12$
This empirical relation is based on both laboratory and *in situ* seismic data from unlithified sandy, silty, or mixed-clayey sediments. The void ratio ε which is the ratio of the volume of pore space to the volume of solids, is given by

$$\varepsilon = \frac{\beta}{1-\beta} \tag{7}$$

where β is the porosity, which is the volume of pore space per unit volume of sediment.
From the knowledge of both the shear modulus and sediment porosity, the speeds of acoustic wave propagation in the sediment can now be estimated by the equation:

$$v_s = \sqrt{\frac{\mu}{\rho}}, \tag{8}$$

$$v_p = \sqrt{H/\rho}. \tag{9}$$

H is one of Biot's elastic moduli, related to measurable properties of the sediments by

$$H = K_s + \frac{4}{3}\mu + \frac{(K_r - K_s)^2}{(D_r - K_s)} \tag{10}$$

where K_r is the bulk modulus of the grain material (3.0×10^{10} Pa for silicates) and K_s is the bulk modulus of the skeletal frame, which is related to shear modulus and Poisson's ratio,

$$K_s = \frac{2}{3}\left(\frac{1+n}{1-2n}\right)\mu. \tag{11}$$

The parameter Dr is given by

$$D_r = K_r\left(1 + \beta\left(\frac{K_r}{K_f} - 1\right)\right) \tag{12}$$

where K_f is the bulk modulus of the fluid component (2.31×10^9Pa). The bulk Poisson's ratio nb is determined from the equation

$$n_b = \frac{(v_p/v_s)^2 - 2}{2((v_p/v_2)^2 - 1)}. \tag{13}$$

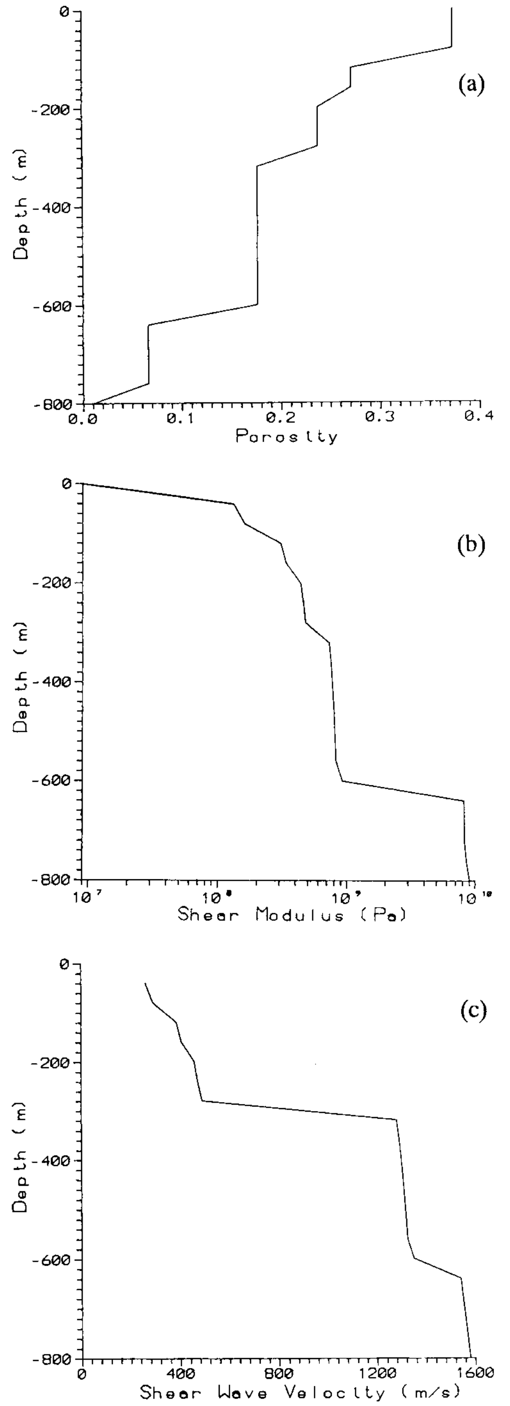


Fig. 5. (a) Porosity, (b) shear modulus, and (c) shear wave velocity profiles based on the data of Fig. 4b.

For clayey sands and silts, typically in shallow marine environment, nb ranges 0.42~0.49.

Fig. 5 shows (a) porosity β, (b) shear modulus μ and (c) shear wave velocities υ_s, deduced from the chosen values of physical constants (e.g. ρ_s, K_r, n_s, and K_0) based on the interval velocity data in Fig. 4b. These subbottom elastic physical parameters are average values, keeping in mind the point that the stacking velocities are deduced from CSS gathers.

CONCLUSION

The results show that kite has a great advantage in that it produces high resolution three dimensional subbottom images in one traverse of survey region while its data can be handled simply by conventional seismic data processing methods, although the survey was performed in shallow and narrow marine area.

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3차원 탄성파탐사

손호웅

요약 : Kite는 조사지역을 한번 횡단함으로써 3차원 지하영상을 얻기 위한, 새로이 개발된 단일채널(single-channel) 탄성파 취득시스템이다. Kite시스템은 진행방향에 수직으로 전개되는 하이드로폰(hydrophone)과 하이드로폰의 한쪽 끝에 설치하는 에너지원(source)인 에어건(air-gun)으로 구성된다. 3차원 지하영상은 기존 다중채널 반사자료 처리방법을 사용하며, 공통 소스점 모음(CSS gather)을 딕스식을 이용하여 지하층들의 평균 구간속도를 구하게 된다. 이 구간속도와 정규 고결응력으로 부터 물리상수들을 선택적으로 이용하여 전단계수, 공극율, 횡파속도 등을 구하였다. 본 시스템은 북대서양의 대륙붕에서 실시되었으며 좋은 결과를 얻을 수 있었다.