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Laboratory/In situ Sound Velocities of Shelf Sediments in the South Sea of Korea

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Compressional sound velocities of shelf sediments in the South Sea of Korea, were measured in situ and in the laboratory for six cores. In situ sound velocity was measured using the Acoustic Lance (frequency of 7.5-15 kHz), while laboratory velocity was measured by the pulse transmission technique (frequency of 1 MHz). Physical properties were relatively uniform with sediment depth, suggesting little effect of sediment compaction and/or consolidation. Average in situ velocity at each core site ranged from 1,457 to 1,488 m/s, which was less than the laboratory velocity of 1,503 and 1,604 m/s. In muddy sediments the laboratory velocity was 39-47 m/s higher than in situ velocity. In sandy sediments, the difference was greater by an average of 116 m/s. Although the velocity data were corrected by the velocity ratio method based on bottom water temperature, the laboratory velocity was still higher than the in situ velocity (11-21 m/s in muddy sediments and 91 m/s in sandy sediments). This discrepancy may be caused by sediment disturbance during core collection and/or by the pressure of Acoustic Lance insertion, but it was most likely due to the frequency difference between in situ and laboratory measurement systems. Thus, when correcting laboratory velocity to in situ velocity, it is important to consider both temperature and frequency.

Key words: Laboratory/in situ velocity, Physical properties, Velocity correction, South Sea, Korea

Introduction

The compressional wave velocity (or sound velocity) in marine sediments is an important geoacoustic parameter, especially in shallow water, as it has a significant effect on sound propagation in the water column (Rajan and Frisk, 1992). In the few meters below the seafloor, the velocity is of considerable interest in geophysics, underwater acoustics, ocean engineering, and naval applications (Richardson, 1986; Stoll, 1985; Fu, 1994; Fu et al., 1996). Sound velocity is important in explaining the physical properties of the seafloor and for converting reflection seismic data to depth. The important factors that affect sound velocity are physical properties (e.g., porosity, water content, density), sediment texture, overburden pressure, and temperature of the sediment. In particular, temperature effects can be pronounced in water-saturated sediments, as the temperature changes the compressibility of the water. The velocity of marine sediments can be estimated using empirical relationships (Hamilton, 1971) and/or physical models (Biot, 1956; Stoll, 1985; Buckingham, 2004) as well as direct laboratory and in situ measurements. Methods of in situ velocity measurement have been developed (Barbagelata et al., 1991; Fu and Wilkens,

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1996) and successfully deployed in various unconsolidated marine sediments, including those of the inner shelf of southeastern Korea (Gorgas et al., 2003), Mid-Atlantic Ridge pelagic oozes (Fu and Wilkens, 1996), the Eel River shelf of California (Gorgas et al., 2002), the western Baltic Sea, and Eckernförde Bay, Germany (Wilkens and Richardson, 1998). Laboratory measurements have also been reported (Birch, 1960; Boyce, 1976; Hamilton, 1971; Richardson, 1986). Direct laboratory measurements of sound velocities from sediments around the Korean Peninsula have been conducted (Kim, 1989; Kim and Kim, 2001; Kim et al., 2001). However, laboratory measurements present problems recreating in situ sound velocity because of the different environment in the laboratory, such as temperature, pressure and measurement frequency, as well as disturbance of the samples during coring. In this study, in situ velocity was measured directly using the Acoustic Lance in the seafloor of the South Sea of Korea. Laboratory measurement was also conducted on the cores. This study presents and compares the in situ and laboratory velocity of shelf sediments and attempts to correct laboratory velocity to in situ conditions.

Materials and Methods

Study area

The study area is located on the continental shelf of the southern part (South Sea) of Korea which is relatively flat with gradual deepening toward the outer shelf (Fig. 1). The study area can be divided into an inner and outer shelf by water depth (at about 70-80 m). Holocene mud is distributed parallel to the coast, in the so called mud belt, with thickness of 20-30 m (Park, 1983; Park and Yoo, 1988). This mud extends from the west (Yellow Sea) to the southeast of Korea (East Sea). Its width depends on the geological and oceanographic condition of the local area. Relict sand is distributed outside the mud belt at the 70-80 m water depth contour line, and marks the boundary of the inner and outer shelf (Park and Yoo, 1988; Kim et al., 1992; Min, 1994). The Nakdong and Seomjin rivers (Fig. 1) are the dominant sources of fine-grained sediment in the southern and southeastern inner shelves of Korea. The Nakdong River discharges about 10×10^6 ton/yr of sediment and the Seomjin River contributes about 0.8×10^6 ton/yr (Park and Chu, 1991). This sediment is primarily responsible for the mud belt in areas south and southeast of Korea. The ocean currents in the study area are dominated by the Tsushima Warm Current and the South Korean Coastal Current (Zheng and Klemas, 1982). The Tsushima Warm Current flows northeastward with seasonal variation, being strongest in summer and weakest in winter (Korea Hydrographic Office, 1982). The coastal current also flows northeastward along the southern coastline and contributes to the dispersal of fine-grained sediments

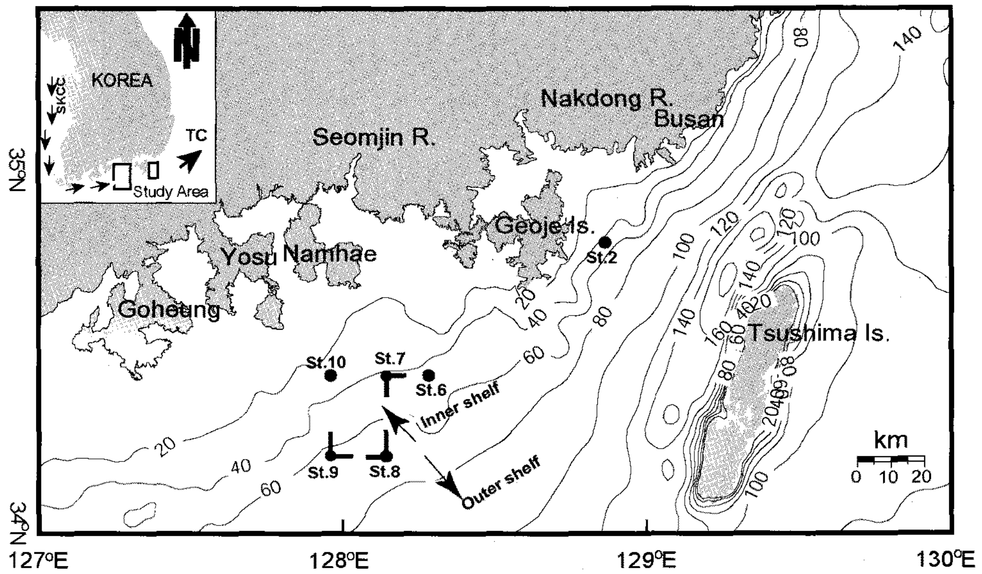

Fig. 1. Map showing bathymetry and the coring sites. The study area is divided into inner shelf and outer shelf area around water depth of 70-80 m. Current system around the study area (TC: Tsushima Current and SKCC: South Korean Coastal Current) is illustrated in a box. Heavy lines denote the selected profiles shown in Figs. 3 to 5. Contours in meters.

supplied by the rivers (Kim et al., 1986). In addition, tidal current helps transport and redistribute the sediments, particularly in the near-coastal area. Tidal current flows along the coastline (SE-NW direction) with relatively strong velocity and enhances the formation of the band-shaped mud belt (Korea Hydrographic Office, 1982).

In situ velocity measurement and core sampling

Six sediment cores were obtained using a piston corer from the R/V Tamyang of Pukyong National University. In situ interval sound velocity was measured in conjunction with core sampling using the Acoustic Lance (Fig. 2). To compare laboratory and in situ sound velocities, laboratory sound velocity was measured for the same cores. For calculation of the velocity ratio, the in situ temperature and salinity of the bottom water was also measured using a conductivity-temperature-depth profiler (SeaBird Electronics, SBE 911). Temperature was measured as 12-14°C, and salinity was measured as between 33.53 and 34.32 psu. The sampling sites were located using a Global Positioning System (GPS) device. Sub-bottom profiles at the sampling sites were obtained using a chirp sonar profiler (Datasonics, CAP 6000A). The Acoustic Lance, which measures in situ interval sound velocity, consists of: mechanical (gravity/piston corer), electronic-acoustic parts (recording telemetry, receiving circuit, firing circuit, and power supply) (Fig. 2). The top of the corer contains two pressure vessels for recording telemetry and a power supply. A broadband cylindrical hydrophone was used as a source transducer. The resonant frequencies of the Acoustic Lance are 7.5 and 15 kHz (longitudinal and radial modes of the cylindrical source) with a center frequency of about 10 kHz. Receivers are arrayed with 50 cm spacing along the corer pipe. Signals are stored in individual channel memories and are downloaded to a computer after deployment. Measurement accuracy at 50 cm spacing is about 1%. Detailed descriptions of the Acoustic Lance have been given by Fu and Wilkens (1996) and Fu et al. (1996).

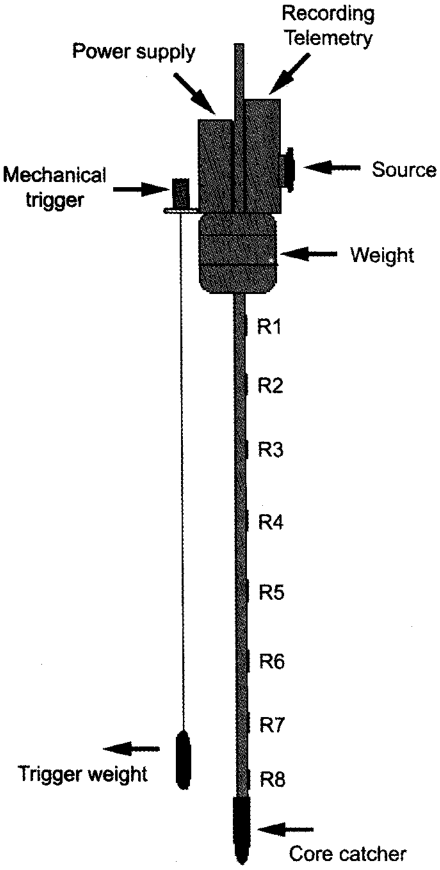

Fig. 2. Diagram of the Acoustic Lance that was developed at the University of Hawaii, Manoa. For in situ velocity measurement, eight receivers (R1-R8) were attached to the outer wall of a piston corer.

Laboratory measurement and correction of laboratory velocity

After splitting each cores into two halves, sound velocity and grain size were analyzed in one half, and physical properties were analyzed for the other half at about 20 cm intervals, depending on the sediment types. The sound velocity was measured (ca., 2.54 cm path length in the horizontal plane) using an automated velocity measurement technique with a 1 MHz PZT transducer (Kim et al., 1999) modified from the pulse transmission technique (Birch, 1960). During the measurement of sound velocity, the temperature of core sediments was equilibrated with the laboratory temperature (23°C). Velocity accuracy was approximately 1%. Physical properties (porosity, density, water content) were determined by the gravimetric method, and corrected for 35‰ salinity (Boyce, 1976). Weights of wet and dry samples were measured using an electronic balance and sample volumes were determined by a manual pycnometer (Micromeritics, Pycnometer 1305). Grain size of the fine fraction (<0.062 mm in diameter) was analyzed by a Micromeritics Sedigraph 5000ET. And the coarse fraction was sieved by a Ro-tap sieve shaker for analysis (Folk and Ward, 1957). Laboratory velocity was corrected to in situ conditions based on bottom water temperature by using the velocity ratio of laboratory velocity to water velocity computed by Clay and Medwin's equation (Clay and Medwin, 1977) under laboratory conditions (23°C, 1 atm). Pressure and salinity also affect velocity, but this effect can be ignored due to the very small range in variation of 1 or 2 m/s in the sediments of shallow water depth.

Results

Characteristics of sediments

According to chirp sonar profiles, the Holocene mud layer in the inner shelf is more or less than 10-20 m thick, delineated by a mid-depth reflector from the underlying relict sediments (Figs. 3 and 4). Its thickness decreases gradually from the inner shelf to the outer shelf, and the mid-depth reflector eventually reaches near the seafloor (Fig. 5). The mid-depth reflector is distributed sub-parallel to the seafloor and is characterized by a strong acoustic reflector with high acoustic impedance, caused by high density and velocity in the coarse sandy sediments. The inner shelf sediment of the study area consists mainly of silt and clay, forming homogeneous mud with some shell fragments (Fig. 6), except for station 8 in the outer shelf which is largely composed of sand and muddy sand. The mean grain size of inner shelf sediment, ranges from 8 to 9ϕ, increasing toward the outer shelf (about 3-4ϕ) (Table 1). The porosity ranges from 70-76% in the inner shelf sediments (Sts. 2, 6, 7, 9, and 10), with an average of 48% at the single outer shelf site (St. 8). The wet bulk density is

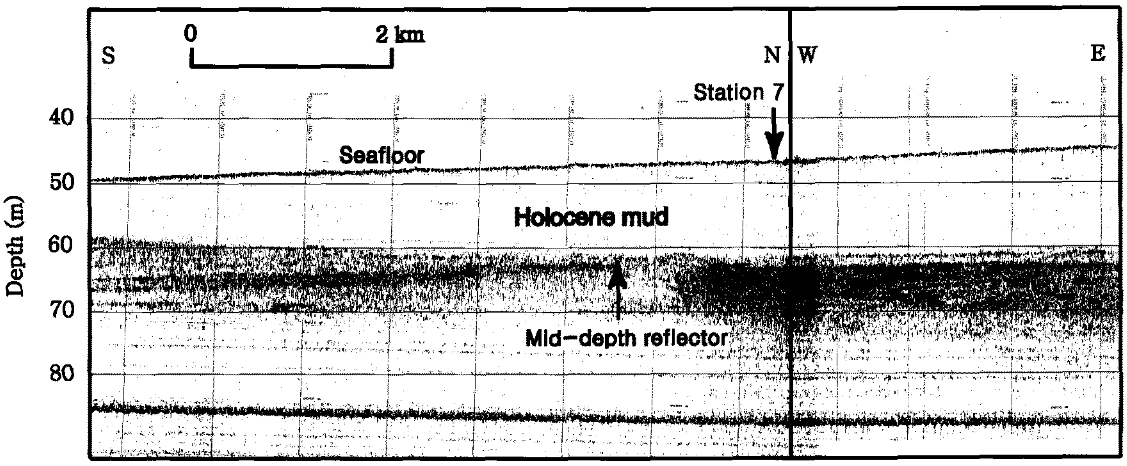

Fig. 3. Chirp sonar profile obtained from Station 7. Note the transparent acoustic image (i.e., Holocene mud) between seafloor and mid-depth reflector, caused by relict sandy sediments.

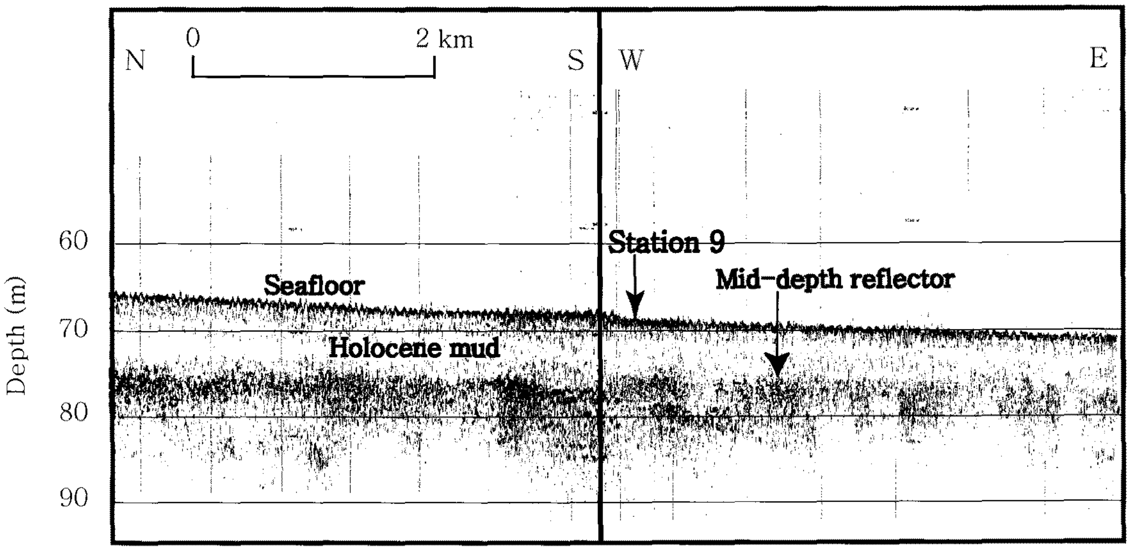

Fig. 4. Chirp sonar profile obtained from Station 9. Note the transparent acoustic image between seafloor and mid-depth reflector, caused by relict sandy sediments.

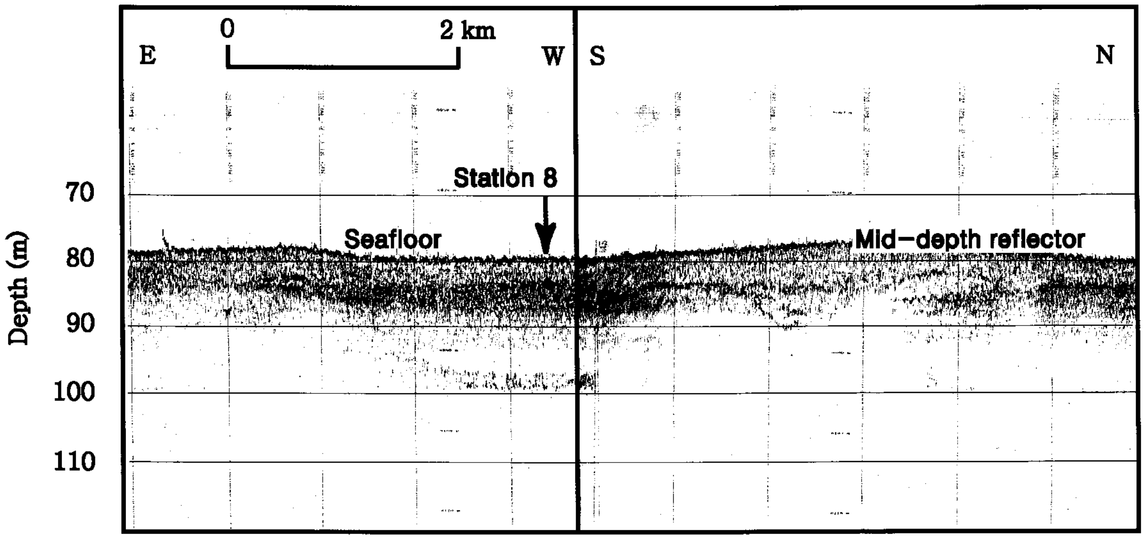

Fig. 5. Chirp sonar profile at the Station 8. Note that seafloor and mid-depth reflector appear at the same depth.

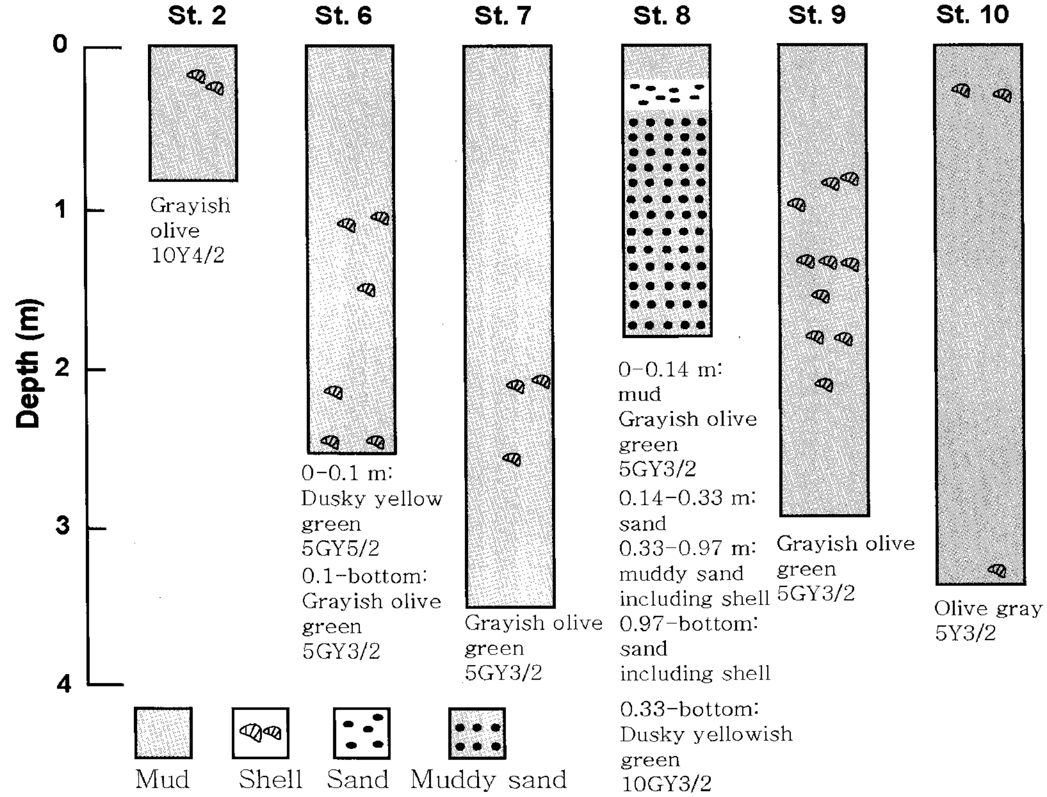

Fig. 6. Core lithology based on sediment textures, sedimentary structures and compositions. Except Station 8, most of the cores are composed of homogeneous mud.

between 1.44 and 1.51 g/cm^3 in the inner shelf sediments and 1.92 g/cm^3 in outer shelf sandy sediments. The grain density ranges from 2.51 to 2.74 g/cm^3 in the inner shelf sediments, and is 2.58 g/cm^3 in outer shelf sediments. Inner shelf and outer shelf sediments have water content of 50-55% and 28%, respectively.

Laboratory and in situ sound velocity

Average laboratory sound velocity in each sediment core of the inner shelf is between 1,503 and

Table 1. Average values of mean grain size, physical properties, velocities, and velocity difference for the cored sediments

St.	Mean grain size (ϕ)	Porosity (%)	Wet bulk density (g/cm^3)	Grain density (g/cm^3)	Water content (%)	Laboratory velocity (A) (m/s)	Corrected laboratory velocity (B) (m/s)	In situ velocity (C) (m/s)	ΔT (m/s) (A-C)	ΔT (m/s) (B-C)
2	8.95	76	1.44	2.72	55	1,503	1,473	1,457	46	16
6	9.04	74	1.46	2.69	54	1,504	1,480	1,459	45	21
7	8.29	71	1.48	2.51	51	1,505	1,477	1,458	47	19
8	3.86	48	1.92	2.74	28	1,604	1,579	1,488	116	91
9	8.54	70	1.49	2.58	50	1,509	1,485	1,464	45	21
10	8.61	72	1.51	2.74	51	1,503	1,475	1,464	39	11

1,509 m/s, but is higher than 1,604 m/s in the outer shelf (Table 1). Meanwhile, in situ velocity ranges from 1,457 to 1,464 m/s in the inner shelf, and is 1,488 m/s in outer shelf sediments.

Discussion

In the study area, sub-bottom profiles show a strong mid-depth reflector (Figs. 3, 4, and 5), which represents relict sand deposited during the last glacial sea level lowstand (Min, 1994; Park et al., 1996). The transparent acoustic character between the seafloor and mid-depth reflector probably represents recent homogeneous muddy sediments (Holocene mud) transported and deposited from the adjacent rivers (e.g., Seomjin and Nakdong rivers). This is supported well by the lack of significant downcore variation of sediment texture and physical properties in the inner shelf sediments (Figs. 6 and 7). This result agrees well with those of Sung (1994) and Kim et al. (1992, 2001). The thickness of the transparent acoustic section decreases seaward and eventually disappears near the outer shelf (Fig. 5), corresponding to the gradual increase in grain size from mud (8-9ϕ) to sand (*ca.*, 4ϕ) (Table 1; Fig. 7), and indicating the veneered recent mud on the relict sand (Kim et al., 2001). Physical properties (e.g., porosity, water content, density) of unconsolidated marine sediments are important variables contributing to sound velocity variation (Hamilton, 1971). Porosity and water content show a slightly decreasing pattern with depth (Fig. 7), due to the small effect of compaction caused by the increase of overburden load (Mosher et al., 1994). The wet bulk density, which is controlled by porosity and grain density, is almost constant with depth (Fig. 7) and correlated with mean grain size as well as porosity and water content. Similar results in the study area were reported by Kim et al. (1992, 2001). The grain density is relatively constant with depth, indicating small variability in mineral composition. In general, lithologic variability is described predominantly by changes in grain size distribution, and is, in turn, responsible for the variation of physical properties. Thus, physical properties of recent muddy sediments seem likely to well reflect the variation of sediment texture (mainly mean grain size) rather than the effect of diagenesis (e.g., compaction and/or consolidation).

The sound speed determined from the elasticity and density of the medium varies in the ocean and depends on various properties of the sediments, salinity, pressure, and temperature (Wilson, 1960; Del Grosso, 1974; Clay and Medwin, 1977; Chen and Millero, 1977). The sound speed equation for seawater developed by Clay and Medwin (1977) is accurate within 0.6 m/s, if accurate temperature, salinity, and depth data are available. Salinity and pressure in shallow soft sediments do not significantly affect sound speed, but temperature leads to a decrease in sound speed (approximately 3 m/s/°C in seawater), caused by the decrease of the bulk modulus with decreasing temperature, even though density increases. Kim et al. (2004) reported a similar result measured directly for fluid and fluid mud. In general, it is difficult to directly compare velocity data when the data have not been corrected for temperature measurement. According to Hamilton (1971), variations in room temperature can easily cause velocity variations on the order of 20 to 30 m/s (about 1 to 2%). The effect can be greater than those caused by lithological differences. Thus, temperature measurements should always be made with velocity measurements. In fully saturated sediments, if the velocity of bottom water is provided, laboratory values of sediment velocity can be corrected to a seafloor value (in situ velocity) using the velocity ratio (sediment velocity/water velocity) (Hamilton, 1971). Hamilton (1971) experimentally investigated the relationship between in situ and laboratory velocity ratios and reported that these ratios were approximately the same. Using the measured tem-

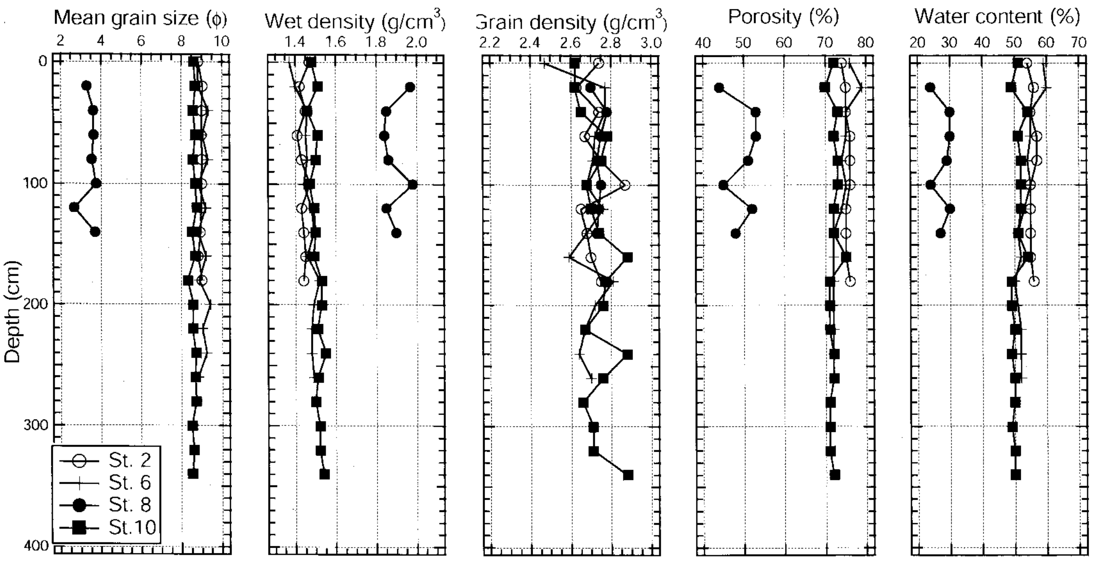

Fig. 7. Profiles of mean grain size, density, porosity and water content at Sts. 2, 6, 8, and 10. Station 8 is quite different from other stations.

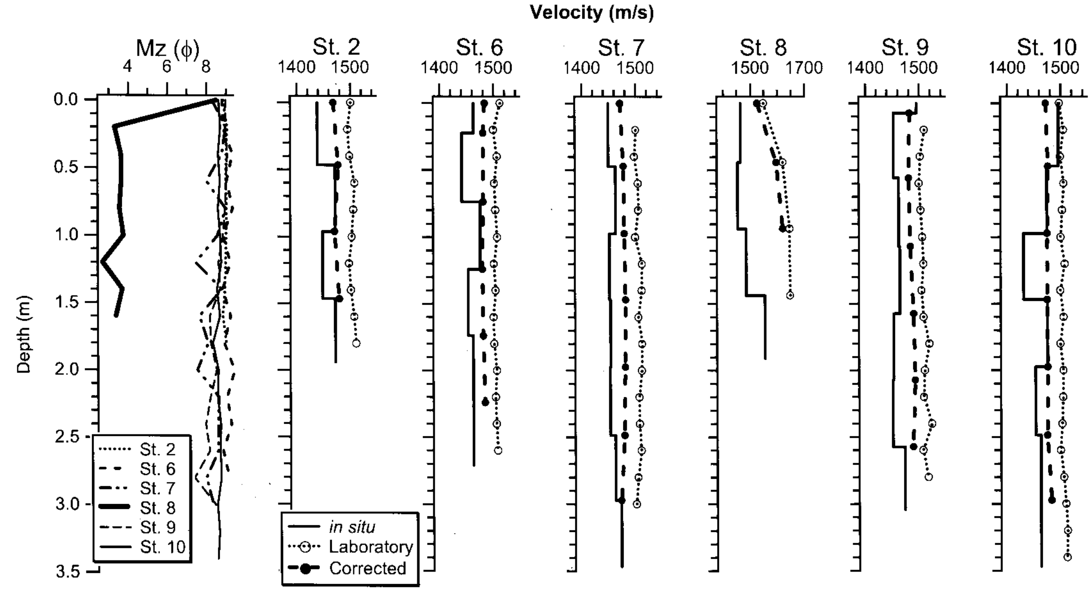

Fig. 8. Profiles of the velocities (laboratory, in situ, and corrected laboratory velocity) for each station. In situ velocity is the interval velocity between receivers and shows the lowest value. The profile of mean grain size is repeated for velocity data comparison.

perature and salinity data, the sound velocity of seawater was calculated using Clay and Medwin's equation (Clay and Medwin, 1977). As expected, the corrected laboratory velocity calculated using the velocity ratio method was closer to the in situ velocity than was the uncorrected laboratory velocity (Table 1; Fig. 8). Nevertheless, a small regular discrepancy still existed between in situ and corrected velocity data. The relationship between velocity and mean grain size shows that the velocity decreases with decreasing mean grain size (Fig. 9). However, the difference between in situ and laboratory values changes significantly according to mean grain size. A gap of 11-21 m/s remained for the muddy sediments (within the stated error bars of the measurements), and a significant gap of 91 m/s remained for the sandy sediments (Fig. 9). The correlation between laboratory and in situ velocity ratios is also poor and

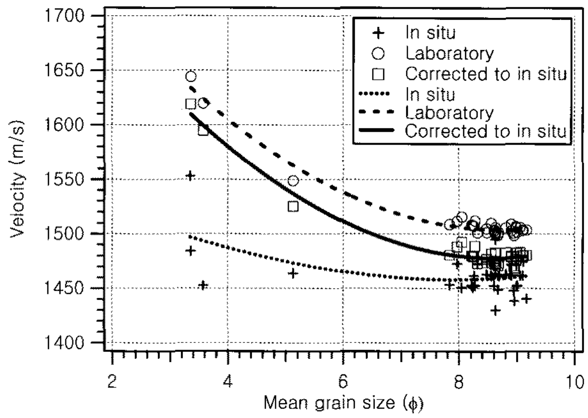

Fig. 9. Velocity (in situ, laboratory, and corrected) versus mean grain size. Laboratory velocity value is the highest. Note that the gap of regression curves increases with increasing mean grain size.

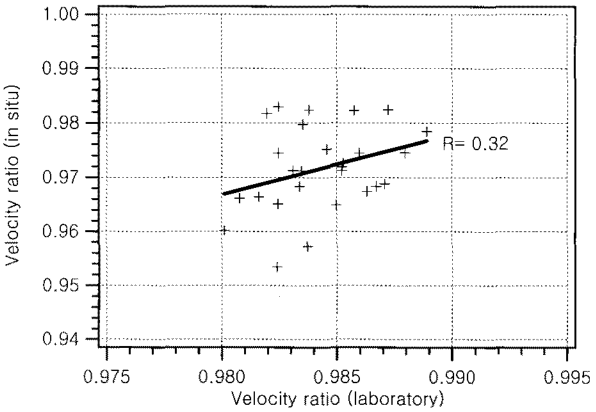

Fig. 10. The relationship between laboratory and in situ velocity ratios. Note the poor correlation.

scattered (Fig. 10). This discrepancy may well be the result of comparing an interval measurement with discrete point measurements. In addition, sediment disturbance can affect velocity due to the deformation of sediment structure during core collection (Hamilton, 1971) and/or Acoustic Lance insertion (Fu et al., 1996), the difference of penetration depth of the Acoustic Lance and the length of the recovered corer. Fu and Wilkens (1996) noted that the Acoustic Lance cannot exactly indicate its penetration depth when the core pipe does not penetrate completely into the sediment layer. Another error of penetration depth is caused by tilt of the corer. Further, in situ data are interval velocities and cannot be directly correlated with laboratory data measured at discrete points. Temperature-corrected laboratory velocity was higher than that of in situ velocity measurements (Table 1; Fig. 8). It is interesting that the difference between laboratory and in situ velocity was larger (about 91 m/s) in sandy sediments than in muddy sediments (11-21 m/s) (Table 1; Figs. 8 and 9). Buckingham (2004) suggested that attenuation and velocity dispersion increase with grain size. Thus, the velocity difference between laboratory and in situ measurements in sandy sediments should be greater than that in muddy sediments, indicating that laboratory velocity can be overestimated compared to in situ velocity measured at a lower frequency. It is reasonable to suspect that these factors and causes together are responsible for the difference of velocity. Robb et al. (2006) suggested that velocity is generally nondispersive in sands. Best et al. (2001) reported that velocity dispersion is high in poorly sorted sediments when mud and sand are present in nearly equal proportions. Furthermore, the velocity variation with frequency is nonlinear. Therefore, there is still contention over the frequency dependence of both sound velocity and attenuation in marine sediments.

Acknowledgements

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