THE JOURNAL OF THE ACOUSTICAL SOCIETY OF KOREA Vol.22, No.4E 2003. 12. pp. 167~175

Shear Wave Velocity in Unconsolidated Marine Sediments of the Western Continental Margin, the East Sea

Gil-Young Kim*, Dae-Choul Kim**
*Research Institute of Marine Science & Technology, Korea Maritime University
**Department of Environmental Exploration Engineering, Pukyong National University

(Received September 23 2003; accepted November 28 2003)

Abstract

Shear wave velocity was measured and grain size analysis was conducted on two core samples obtained in unconsolidated marine sediments of the western continental margin, the East Sea. A pulse transmission technique based on the Hamilton frame was used to measure shear wave velocity. Duomorph ceramic bender transducer-receiver elements were used to generate and detect shear waves in sediment samples. Time delay was calculated by changing the sample length from the transducer-receiver element. Time delay is 43.18 μs and shear wave velocity (22.49 m/s) is calculated from the slope of regression line. Shear wave velocities of station 1 and 2 range from 8.9 to 19.0 m/s and from 8.8 to 22 m/s, respectively. Shear wave velocities with depth in both cores are qualitatively in agreement with the compared model[1], although the absolute value is different. The sediment type of two core samples is mud (mean grain size, 8-9Φ). Shear wave velocity generally increases with sediment depth, which is suggesting normally consolidated sediments. The complicated variation of velocity anisotropy with depth at station 2 is probably responsible for sediment disturbance by possible gas effect.

Keywords: *Shear wave velocity, Velocity anisotropy, Unconsolidated marine sediments, Continental margin, the East Sea*

I. Introduction

The shear wave velocity is the most difficult quantities to measure, and consequently the most poorly known. Sediment coring techniques can cause sample disturbances that can significantly affect shear wave velocity measurements in laboratory. This is particularly true of the loosely-consolidated sediments that often make up the upper few meters of the seafloor, and the relationship between shear wave velocity and sediment type is poorly defined. In addition, Richardson et al.[1] show that sediment shear modulus (or rigidity) produce various vertical gradients resulting from overburden pressure. Thus, measuring and interpreting values of near-surface shear wave velocity are complicated.

Recently, scientists from such various fields as seafloor engineering, geophysics, civil engineering and underwater acoustics have devoted considerable attention to the measurement of sediment shear wave velocity as well as dynamic shear modulus. These sediment properties are important to predicting and interpreting the slope stability, the consolidation behavior, and the strength of marine foundations. Numerous attempts[2-6] have been made to measure shear wave velocity of natural and artificial sediments in the laboratory. Most of these measurements have been based on the ceramic bender transducer developed by Shirley[7]. Shear wave velocities have also been measured on artificial sediments[8-10]. Richardson

---

Corresponding author: Gil-Young Kim (gykim@mail1.pknu.ac.kr)
Research Institute of Marine Science & Technology, Korea Maritime University, Yeongdo-ku, Busan 606-791, Korea

[11] measured in situ shear wave velocity of siliciclastic sediment by using In-Situ Sediment geoAcoustic Measurement System (ISSAMS).

Seismic refraction techniques[12] have also been used to determine shear wave velocities in unconsolidated marine sediments. Hamilton[13-15] and Bryan and Stoll[16] estimate shear wave velocity using empirical relationships between sediment physical properties and burial depth and calculate velocities based on models by the Biot[17] and/or Stoll[18]. But measured shear wave velocities from sediments in near the surface are often lower than those predicted by the empirical relationships[14,16]. Especially the upper few meters of sediments include a zone of rapid changes in the physical, geotechnical, and chemical properties. Because laboratory measurements are frequently made on disturbed sediments, shear wave velocity might differ from the idealized physical model result[1].

The purpose of this paper is to present shear wave velocity of unconsolidated marine sediments in the western continental margin of the East Sea and to compare with velocities predicted from a model of Richardson et al.[1] for verification. The data we present will refer to measure shear wave velocity and establish geoacoustic model of study area in future.

II. Materials and Methods

Two core samples were obtained in conjunction with a geophysical survey in the western continental margin of the East Sea during November of 2001 (Table 1; Fig. 1). Mean grain size distribution was analyzed by dry sieving for the sand-sized fraction and by a Micromeritics Sedigraph 5000ET for the silt- and clay-sized fraction[19]. Sediment shear wave velocity was measured at 10 cm depth intervals using a pulse technique based on the Hamilton frame. Pulse generator (Model: Wavetek 178, 50 MHz) and oscilloscope (Model: LeCroy 9400A, Dual 175

Table 1. Locations, water depth, and length of the obtained two core samples.

Station	Latitude	Longitude	Water depth	Core length
St. 1	36°52.6248N	130°07.547E	2.205 m	270 cm
St. 2	36°06.1N	130°05.24E	1,481 m	400 cm

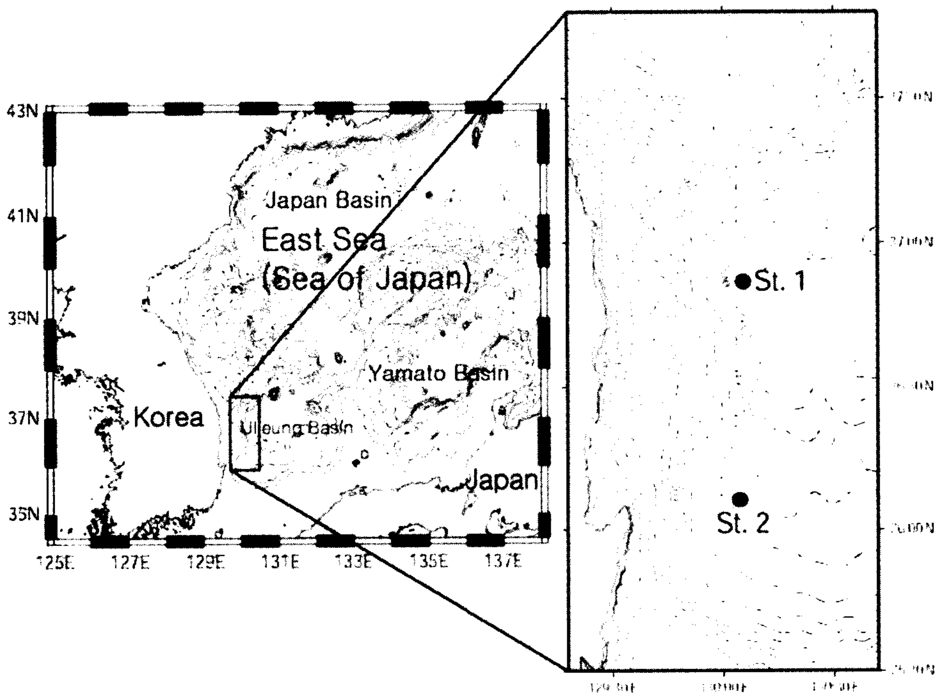

Figure 1. Map showing core sample locations and bathymetry around the study area. Depth in meters.

MHz) were used to generate the transmitting pulse and receive the signals passed through sample.

A duomorph ceramic bender transmitter and receiver (Fig. 2), designed and constructed at the Naval Research Laboratory-Stennis Space Center, was used to measure shear wave velocity. The duomorph ceramic bender elements were potted in a soft silicone rubber, and polyurethane resin holds the ceramic element. Shear waves are generated as sine wave pulses every 10 ms. The transmitter was driven by a 10V p-p pulsed sine wave. Driving frequency was selected as 500 Hz after repeatedly comparing various frequencies to a similar sediment type. Driving frequency generally depends on sediment type. Various investigators demonstrated that soft sediments such as clays should be measured at lower frequency than sands[1,2,8].

Time delay measurements (43.18 μs) were made over varying sediment thickness for same sediment at a single frequency (500 Hz). Shear wave velocity (22.49 m/s) is then calculated (Fig. 3). A time delay was subtracted from each measurement to account for the transit time of the pulse through the electrical and mechanical system. Shear wave velocity of sediment samples was calculated from the time delay and sample length, and measured at both the horizontal and the vertical direction to core-axis. The shear wave motion from the bender element is essentially polarized, so measurements can be made over the same travel path, both parallel and perpendicular to the axis of symmetry.

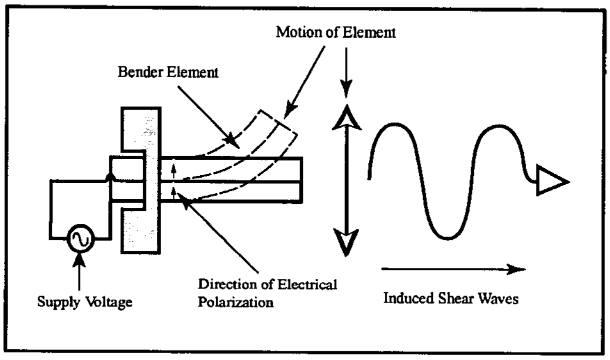

Figure 2. Typical shear wave transducer utilizing bender transducer-receiver elements. The ceramic bender elements were potted with soft silicone rubber.

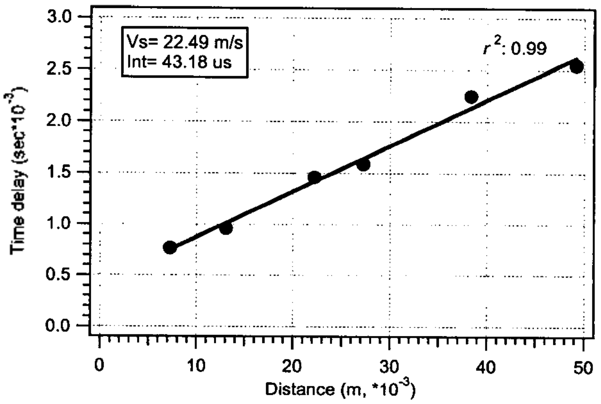

Figure 3. System delay (Int) and shear wave velocity (Vs) calculated from the same muddy sediments. Slope gives Vs= 22.49 m/s, Int= 43.18 μs, respectively.

III. Results

The measuring results of shear wave velocity are listed

Table 2. Shear wave velocity of horizontal and vertical directions for core-axis and sediment type at station 1.

Depth (cm)	S-wave velocity (m/s)			Sediment type
	Horizontal direction	Vertical direction	Mean	
5	8.1	9.6	8.9	Mud
15	9.2	9.6	9.4	Mud
25	8.4	9.7	9.1	Mud
35	8.9	8.3	8.6	Mud
45	9.1	9.4	9.2	Mud
55	8.7	9.4	9.0	Mud
65	9.0	10.3	9.6	Mud
75	11.0	10.2	10.6	Mud
85	14.7	10.8	12.8	Mud
95	22	16.0	19.0	Mud
105	15.5	12.6	14.1	Mud
115	14.8	13.4	14.1	Mud
125	15.0	13.7	14.3	Mud
135	13.5	11.6	12.5	Mud
145	16.1	12.0	14.1	Mud
155	14.7	11.2	13.0	Mud
165	14.0	10.9	12.4	Mud
175	14.2	11.1	12.6	Mud
185	12.3	11.6	12.0	Mud
195	14.3	12.3	13.3	Mud
215	13.6	12.4	13.0	Mud
225	11.7	12.5	12.1	Mud
235	16.5	13.6	15.0	Mud
Average	12.8	11.4	12.1	

Table 3. Shear wave velocity of horizontal and vertical directions for core-axis and sediment type at station 2.

Depth (cm)	S-wave velocity (m/s)			Sediment type
	Horizontal direction	Vertical direction	Mean	
5	9.6	8.0	8.8	Mud
15	11.5	9.9	10.7	Mud
25	10.2	11.0	10.6	Mud
35	12.3	12.4	12.3	Mud
45	15.8	12.0	13.9	Mud
55	13.2	12.5	12.9	Mud
65	7.9	9.9	8.9	Mud
75	11.4	10.7	11.0	Mud
85	14.2	11.9	13.0	Mud
95	14.8	11.9	13.4	Mud
105	15.0	14.2	14.6	Mud
115	12.5	13.9	13.2	Mud
125	14.7	15.5	15.1	Mud
135	17.0	12.8	14.9	Mud
145	16.4	16.8	16.6	Mud
155	20.7	16.2	18.4	Mud
165	16.1	14.3	15.2	Mud
175	19.6	15.4	17.5	Mud
185	16.8	13.9	15.4	Mud
195	15.8	14.7	15.2	Mud
205	21.8	16.2	19.0	Mud
215	18.7	16.4	17.6	Mud
225	18.9	23.5	21.2	Mud
235	16.8	15.3	16.0	Mud
245	15.0	17.5	16.3	Mud
255	17.8	13.2	15.5	Mud
265	13.5		13.5	Mud
275	16.0	15.6	15.8	Mud
285	15.7	14.3	15.0	Mud
295	16.9	14.1	15.5	Mud
305	15.8	17.2	16.5	Mud
315	19.4	15.0	17.2	Mud
325	15.7	13.6	14.7	Mud
335	19.1	24.8	21.9	Mud
345	22.3	21.8	22.0	Mud
355	18.4	25.3	21.8	Mud
365	17.3	17.5	17.4	Mud
375	21.0	17.2	19.1	Mud
385	16.3	14.2	15.2	Mud
395	16.8	14.7	15.8	Mud
Average	16.0	15.0	15.5	

in Tables 2 and 3. Shear wave velocity anisotropy is calculated by applying an equation of compressional wave velocity anisotropy[20] using velocity values to both the horizontal and vertical directions.

Shear wave velocity at station 1 ranges from 8.1 to 22.0 m/s (average 12.8 m/s) in the horizontal direction (perpendicular to core axis), and from 9.6 to 19.0 m/s (average 11.4 m/s) in the vertical direction (parallel to core axis) (Table 2). Shear wave velocities increase rapidly between 80 cm to 100 cm in depth, but were uniformly low (~10 m/s) in the shallow depths. Shear wave velocities in the deeper intervals fluctuate with higher values than in the shallow depths (Fig. 4). Sediments at station 1 consisted of primarily silt- and clay-sized particles (mean grain size, 8-9ϕ, mud) (Table 2), and mean grain size decreases slightly with depth in the sediment (Fig. 4). Thus, the increase in shear wave velocity with depth is not due to sediment grain size, but likely the result of increased overburden pressure. Shear wave velocity anisotropy generally increases with sediment depth, reflecting to some degree the velocity pattern (Fig. 4).

Shear wave velocity at station 2 ranges from 9.6 to 20.7 m/s (average 16.0 m/s) in horizontal direction (perpendicular to core axis), and between 8.0 and 25.3 m/s (average 15.0 m/s) in the vertical direction (parallel to core axis) (Table 3). Shear wave velocity increased from 9.6 m/s near the sediment-water interface (0-50 cm) to between 15 and 20 m/s at 400 cm in depth (Fig. 5). Mean grain size (8.7-8.9ϕ) is near constant with depth (Fig. 5). Thus, the increasing shear wave velocity pattern with depth is similar to station 1. Velocity anisotropy with depth is not correlated with the velocity pattern.

IV. Discussion

Shear wave velocity gradients with sediment depth can be predicted for the upper few hundred meters of sediment using the poro-viscoelastic model[21] and/or empirical relationships[14,16]. But these models mostly overestimate the measured shear wave velocities by 100 to 500%[14], and predictions from the Bryan and Stoll model are

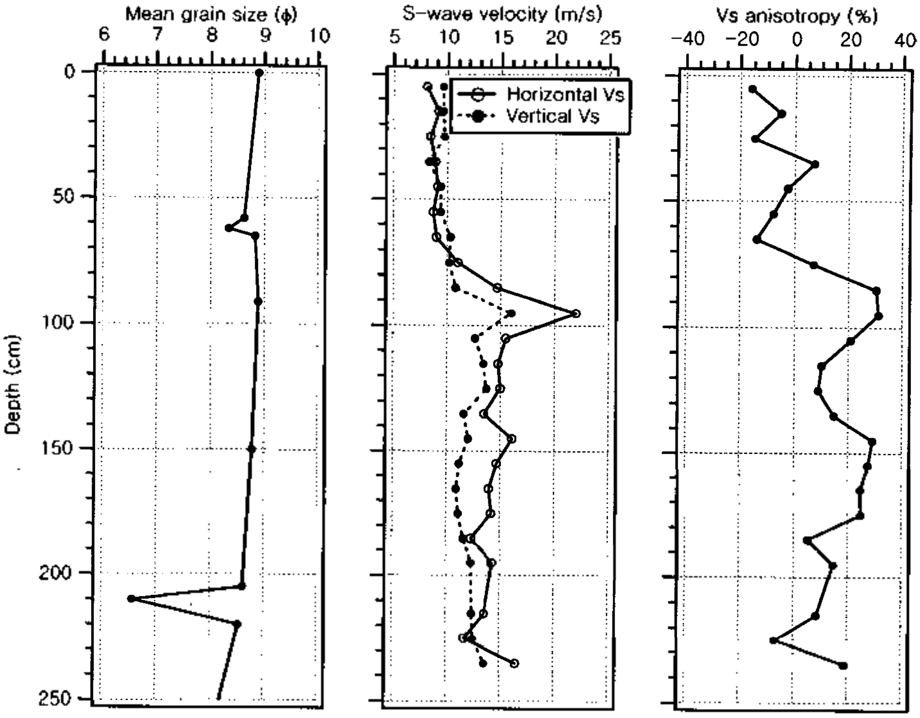

Figure 4. Profiles of mean grain size, horizontal and vertical shear wave velocities, and velocity anisotropy with sediment depth at station 1.

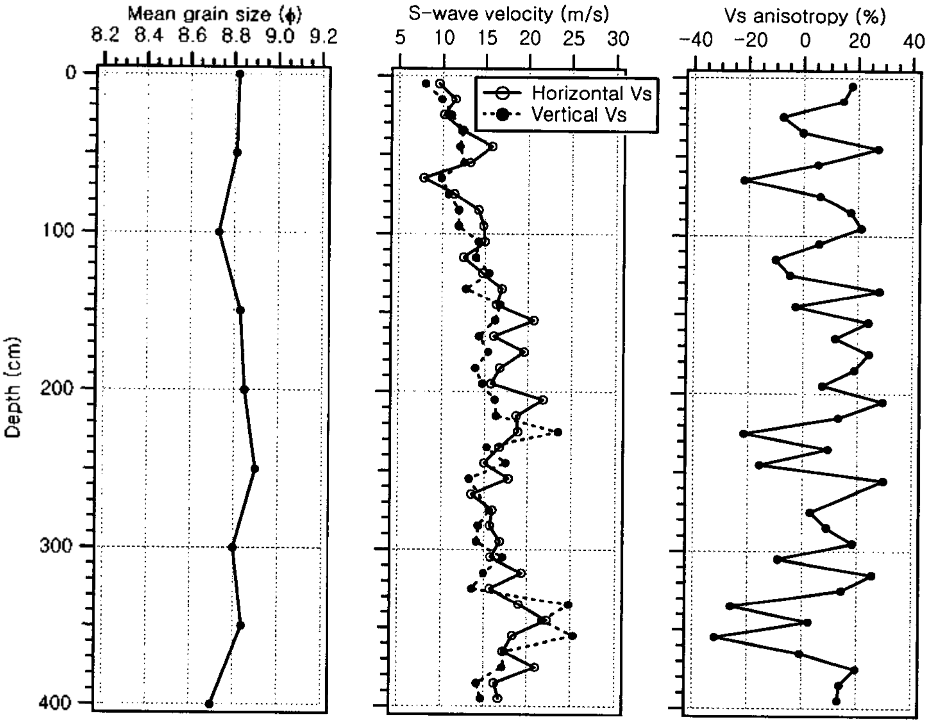

Figure 5. Profiles of mean grain size, horizontal and vertical shear wave velocities, and velocity anisotropy with sediment depth at station 2.

roughly 50% higher than the measured values[1]. Hamilton's values[14] range from 116 to 125 m/s for silty clay sediments. Therefore, these models are not reasonable to predict shear wave velocity gradient near surface sediments.

Richardson et al.[1] newly suggest that in situ shear wave velocity gradients in the upper 2 m of sediment can be predicted by the following:

$Vs = (85/e)\ D^{0.3}$

Vs = Shear wave velocity (m/s)

e = Void ratio

D: Depth in meters below the sediment-water interface

But this predictive relationship can be applied only to sediment that consist of a single sediment type and should not be applied to layered or mixed sediments[1].

Shear wave velocity gradients of this study are simultaneously plotted with depth with a model of Richardson et al.[1] (Fig. 6). The shear wave velocity is mean value of horizontal and vertical direction. Vertical gradients of station 1 and 2 generally increase with fluctuations. The trend is also similar to Richardson et al.[1]'s model (Fig. 6), but the results of this study are lower than the model of Richardson et al.[1] (Fig. 6). Hamilton[14] and Bryan and Stoll[16]'s models have higher values than those of Richardson et al.[1] for a similar sediment type. These results suggest the models should be modified according to environmental parameters such as sedimentary processes and environments, various sediment types, degree of consolidation and compaction, and burial depth.

Shear speeds in unconsolidated sediments are sensitive to overburden pressure or compaction. This observation has led to numerous studies of the effects of pressure on the elastic properties of unconsolidated sediments[22]. Thus, this has allowed a more carefully controlled set of observations, particularly with respect to the degree of saturation.

Shear wave velocities of this study increase with burial depth (Fig. 6) caused by increased overburden pressure. This suggests that the sediments were allowed, to some degree, to compact and consolidate with depth. These variations with depth did not occur with other physical properties (Personal communication). Thus, the shear wave

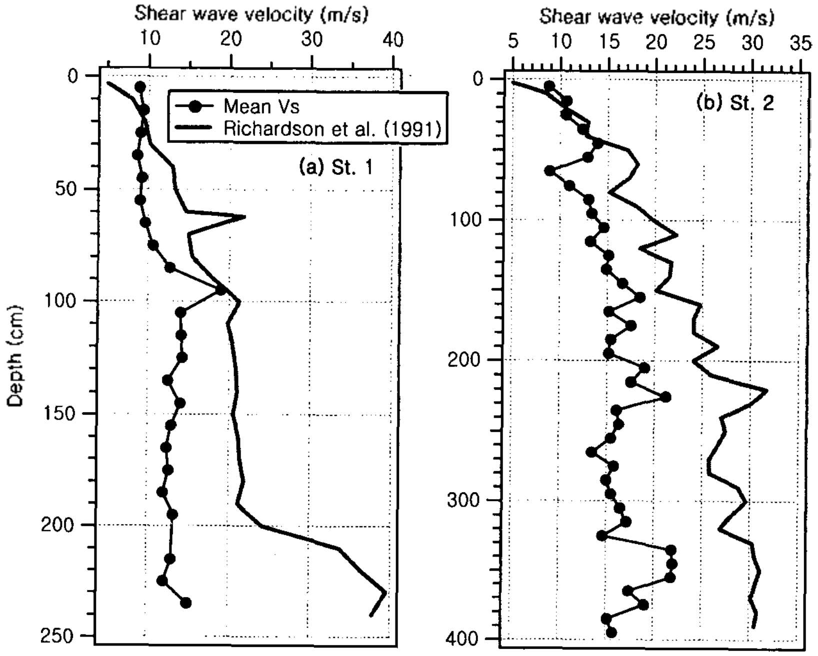

Figure 6. Profiles of shear wave velocity with sediment depth at stations 1 (a) and 2 (b). velocity is the mean value from horizontal and vertical velocities. The data is also compared with the predicted by Richardson, M. D., Muzi, E., Miaschi, B., and Turgutcan, F.[1].

velocity might be used as an index of compaction and consolidation of sediments. The shear wave velocity was found to vary with approximately the one-fourth power of pressure[23-26]. Hamilton[14] also recommended using a depth (pressure) exponent of one-fourth for prediction of shear wave velocities in sands, based on both in situ and laboratory measurements. However, these data showed considerable scatter in the pressure exponent with values varying from approximately 0.2 to 0.4.

The peaks at 60 and below 210 cm intervals of Richardson et al.[1]'s model at station 1 are probably responsible for low void ratio caused by coarse-sized sediments (Figs. 4 and 6a). Unfortunately, the shear wave velocity at these intervals was not measured due to sediment disturbance and that such coarse particles were too difficult to handle for measurement. In case of station 2, the variations show similar fluctuations with sediment depth (Fig. 6b), but the pattern did not show gradual variation relative to station 1. The differences of absolute values between this data and Richardson et al.' model[1] gradually increase from nearly 0 to 30 m/s with sediment depth (Fig. 6). The shear wave velocity also strongly depends on sediment disturbance, measurement conditions (*in situ* and laboratory, frequency), degree of rigidity by physical and chemical processes and biological activity during deposition. Thus, the two models cannot be compared directly. Furthermore, the differences between laboratory and *in situ* shear wave velocities may result from various factors such as disturbance of sediments during collecting and handling, changes in pore pressure and /or physical characteristics as sediments are removed from the seafloor, differences in frequencies used for the measurements *in situ* and at laboratory, models may not adequately describe the transmission of acoustic waves through sediments, poor measurement techniques, and the natural variability of shear wave velocity[1].

Shirley and Hampton[2] reported shear wave speeds of 6 to 29 m/s for a water saturated kaolinite clay allowed to settle under the influence of gravitational and interparticle forces for 120 hrs and as low as 20 m/s for silt and clay. Richardson et al.[4] measured shear wave velocity of 10-15 m/s for silty clay and clayey silt. These data are comparable with the present result.

The shear wave velocity anisotropy with sediment depth differs from two core samples (Figs. 4 and 5). The possible cause of velocity anisotropy in marine sediments is the contribution of pore and crack alignment, which can be determined through velocity measurements on samples. Anisotropy may be largely affected by water in flat pores and cracks aligned parallel to bedding. Thus, horizontal velocity is generally faster than vertical velocity since vertical velocity is slowed due to lower velocity in water while horizontal velocity is not appreciably affected[20]. The shear wave velocity between the horizontal and vertical directions at station 1 supports the discussed result, but this is not true for station 2 (Figs. 4 and 5). This is probably due to sediment disturbance caused by coring technique, degassing cracks, and disturbance during handling of sample for measurement. This core revealed organic matter content which is sufficient for methane generation. In addition, a strong H_2S odor was noted from core sample and horizontal cracks identified as degassing cracks, and soupy structures caused by gas escape and high water content. Therefore, the variation of anisotropy shows complicated patterns with sediment depth (Fig. 5).

In summary, shear wave velocity trends of two cores represent a positive gradient with depth in the sediment. This suggests that the cores were normally consolidated. However, further study is needed to provide the necessary data to improve the models.

V. Conclusion

Shear wave velocity was measured from two core samples obtained in unconsolidated marine sediments of the western continental margin, the East Sea.

Time delay by system is 43.18 μs and shear wave velocity is 22.49 m/s. Shear wave velocities of station 1 range from 8.9 to 19.0 m/s, and mean velocities in horizontal and vertical direction are 12.8 m/s, 11.4 m/s, respectively. At station 2, the velocity is ranged between 8.8 and 22 m/s, and mean velocities in horizontal and vertical direction are 16.0 m/s, 15.0 m/s, respectively.

Shear wave velocities in both cores are qualitatively in agreement with the compared Richardson et al.'s model[1], although the absolute value is different. The difference may result from the factors such as the measurement frequency, sediment type, sedimentary processes and environments. Thus, this data is reported with confidence.

The sediment type of two core samples is mud (mean grain size, 8-9ϕ). Shear wave velocity with sediment depth generally increases, suggesting a condition under overburden pressure after deposited (suggesting normally consolidated sediments).

The complicated variations of shear wave velocity anisotropy with depth at station 2 are probably the result of sediment disturbance by possible gas effect.

This result will be effectively used as reference data to measure shear wave velocity and establish geoacoustic model in future.

Acknowledgements

This work was supported by grant No. (R08-2003-000-10406-0) from the Basic Research Program of the Korea Science & Engineering Foundation. The first author wishes to thank Dr. Michael D. Richardson and William C. Vaughan at Naval Research Laboratory-SSC and Dr. Joan M. Gardner at Naval Research Laboratory-DC.

References

1. M. D. Richardson, E. Muzi, B. Miaschi, and F. Turgutcan, Shear wave velocity gradient in near-surface marine sediment. In: Hovem J. M., Richardson, M. D., and Stoll, R. D. (eds.), Shear wave in marine sediments. Kluwr Academic Pub., Netherlands, 295-304, 1991.
2. D. J. Shirley, and L. D. Hampton, Shear wave measurements in laboratory sediments. *J. Acoust. Soc. Am.*, **63**, 607-613, 1978.
3. P. J. Schultheiss, Physical and geotechnical properties of sediments from the Northwest Pacific. Deep Sea Drilling Project Leg 86 Init. Repts., DSDP, **86**, 701-722, 1985.
4. M. D. Richardson, P. V. Curzi, E. Muzi, B. Miaschi, and A. Barbagelata, Measurement of shear wave velocity in marine sediments. In: Lara-Saenz, A., Ranz-Guerra, C., and Carbo-Fite, C., (eds.), Acoustics and Ocean Bottom. Second Specialized Conference, CISC Madrid, 75-84, 1987.
5. M. D. Richardson, E. Muzi, L. Troiano, and B. Miaschi, Sediment shear waves: a comparison of in situ and laboratory measurements. In: Bennett, R.H., Bryant, W.R. and Hulbert, M.H. (eds.), Microstructure of fine grained sediments, Springer-Verlag, New York, 403-415, 1990.
6. D. L. Lavoie, and A. Anderson, Laboratory measurements of acoustic properties of Periplatform carbonate sediments. In: Hovem, J. M., Richardson, M. D. and Stoll, R. D., (eds.), Shear waves in Marine sediments. Kluwer Academic Publishers, Dordrecht, The Netherlands, 111-120, 1990.
7. D. J. Shirley, An improved shear wave transducer. *J. Acoust. Soc. Am.*, **63**, 1643-1645, 1978.
8. I. W. Horn, Some laboratory experiments on shear wave propagation in unconsolidated sands. Marine Geotechnol. 31-54, 1980.
9. B. A. Brunson, and R. K. Johnson, Laboratory measurements of shear wave attenuation in saturated sand. *J. Acoust. Soc. Am.*, **68**, 1371-1375, 1980.
10. P. J. Schultheiss, Simultaneous measurement of P&S wave velocities during conventional laboratory soil testing procedures. Marine Geotechnol. **4**, 343-367, 1981.
11. M. D. Richardson, In-situ shallow-water sediment geoacoustic properties. International Conference on Shallow-Water Acoustics, Beijing, China, 21-25, 1997.
12. S. H. Danbom, and S.N. Domenico, Shear wave exploration. Tulsa, Society of Exploration Geophysicists, 1987.
13. E. L. Hamilton, Prediction of in-situ acoustic and elastic properties of marine sediments. *J. Geophysical Res.*, **76**, 579-604, 1971.
14. E. L. Hamilton, Shear wave velocity versus depth in marine sediments: A review. Geophysics, **68**, 985-996, 1976.
15. E. L. Hamilton, E. L., Acoustic properties of sediments. In: Lara-Saenz, A., Ranz-Guerra, C. and Carbo-Fite, C., (eds.), Acoustic and Ocean Bottom, Instituto de Acustica Madrid' 3-58, 1987.
16. G. M. Bryan, and R. D. Stoll, The dynamic shear modulus of marine sediments. *J. Acoust. Soc. Am.*, **83**, 2159-2164, 1988.
17. M. A. Biot, Generalized theory of acoustic propagation in porous dissipative media. *J. Acoust. Soc. Am.*, **34**, 1254-1264, 1962.
18. M. A. Stoll, Theoretical aspects of sound transmission in sediments. *J. Acoust. Soc. Am.*, **68**, 1341-1350, 1980.
19. K. B. Briggs, and M. D. Richardson, Physical and acoustic properties of surface sediments from the Venezuela Basin: a data report, Naval Ocean Research and Development Activity, Stennis Space Center, MS. NORDA Technical Note, **238**, 282, 1984.
20. G. Y. Kim, and D. C. Kim, Velocity anisotropy of unconsolidated sediment in the Ulleung Basin, East Sea, Korea. J. Acoust. Society of Korea, **20**, 87-93, 2001.
21. R. D. Stoll, Sediment Acoustics, Lecture Notes in Earth

Sciences, Springer Verlag, New York, 153, 1989.

22. B. A. Brunson, Shear wave attenuation in unconsolidated laboratory sediments. NORDA technical Note, **159**, 242, 1983.
23. B. O. Hardin, and F. E. Richart, Jr., Elastic wave velocities in Granular soils, J. Soil Mech. Found. Div., ASCE 89, SM1, 33-65, 1963.
24. S. D. Wilson, and R. P. Miller, Discussion of foundation Vibrations, In: Richart, Jr., F.E., (ed.), in Transactions ASCE 127, part 1, 913, 1962.
25. B. O. Hardin, and W.L. Black, Vibration modulus of normally consolidated clay. J. Soil Mech. Found. Div., ASCE 94 SM2, 353-369, 1968.
26. F. E. Richart, Jr., J. R. Hall, Jr., and R. D. Woods, Vibrations of soil and foundations (Prentice-Hall, Englewood Cliffs), 1970.

[Profile]

- **Gil-Young Kim**

Kim, Gil Young received B.S., M.S., and Ph.D degree in oceanography and applied geology in 1986, 1991, and 1998, respectively, from Pukyong National University, Busan, Korea. From 2001 to 2003, he worked as post-doctor researcher at Naval Research Laboratory, Stennis Space Center, MS, USA. In 2003 he joined the Research Institute of Marine Science & Technology, Korea Maritime University in Busan, Korea, where he is currently a full time researcher.

- **Dae-Choul Kim**

Kim, Dae Choul received B.S. and M.S. degree in oceanography in 1978, 1980, respectively, from Seoul National University, Seoul, Korea. He received his Ph.D degree in geology and geophysics, from Hawaii University in 1985. Since 1985, he has been with the Department of Applied Geology and Environmental Exploration Engineering, Pukyong National University, Busan, as professor.