THE JOURNAL OF THE ACOUSTICAL SOCIETY OF KOREA VOL.23, NO.4E 2004. 12 pp. 140~145

Ultrasonic Characterization of Fluid Mud: Effect of Temperature

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

(Received September 16 2004; accepted November 15 2004)

Abstract

A laboratory study was carried out to investigate the change of ultrasonic velocity as a function of temperature for fluid mud (i.e., suspension). Pulse transmission technique with ultrasonic wave was used for ultrasonic velocity measurement. The five samples for fluid mud were prepared for concentration range of 30.6% (1.24 g/cm^3 in density), 23.3% (1.19 g/cm^3), 11.5% (1.10 g/cm^3), 7.8% (1.08 g/cm^3), and 3.8% (1.05 g/cm^3) by weight. The ultrasonic velocity in fluid mud was investigated to increase (approximately 2.83 to 4.95 m/s/°C) with increasing temperature, due to the effect of viscosity and compressibility of water with changing temperature. But the increasing rate tends to decrease at temperature higher than 30°C, caused by the effect of viscosity. The concentration of fluid mud more affect to the ultrasonic velocity at higher temperature range than that at lower temperature. Overall the temperature effect on the ultrasonic velocity in fluid mud was a similar rate as for distilled water and seawater, suggesting fluid mud significantly depends on the behavior of water.

***Keywords**: Ultrasonic characterization, Fluid mud, Effect of temperature*

I. Introduction

Fluid mud layers often develop near the seabed (water/sediment interface) and consist of high-concentration (from 10 to 100 g/l) suspension. They have been recognized at the various environments from shallow sea to deep sea and are interesting subjects for study[1-4]. They are also maintained by frequent and strong sediment resuspension events driven by surface waves and tides in the muddy environments[5]. Fluid mud layer can contribute significantly to the total load of suspended sediment despite the small thickness (less than a few centimeters) of this layer when compared with the total water depth[2,6].

The waters in the bottom boundary layers (BBL) can be stratified due to the presence of this layer through the coupling effect of the high concentration of resuspended sediment and the water density. Hydrodynamic characteristics of the stratified BBLs are significantly different than those in well-mixed BBLs. In some resuspension events in turbid tidal estuaries and coastal seas, sediment is abnormally concentrated within a thin wall layer that is overlain by a thicker with much smaller concentration[7].

Ultrasonic velocity of fluid mud layer has been studied in numerous modeling research works, but with its property assumed rather than measured. Thus, the validity of the theoretical models used depends on the validity of the constitute laws they assumed[8]. The effects of temperature on ultrasonic velocity have been reported in a few cases[9-11]. The studies are limited not fluid mud layer but sediments or sedimentary rocks. Recently, new technique to detect suspension and sediment layer above seafloor *in situ*

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

Table 1. Concentration, physical properties, and mean grain size for five fluid mud samples. (FM: Fluid Mud, HC: High Concentration, MC: Middle Concentration, LC: Low Concentration).

	Concentration (% by weight)	Density (g/cm^3)	Grain density (g/cm^3)	Porosity (%)	Water content (%)	Mean grain size (ϕ)
FM-1	30.6	1.24	2.71	84.0	71.9	10.2
FM-2	23.3	1.19	2.71	89.0	79.5	10.2
HC	11.5	1.10	2.71	95.3	91.7	10.2
MC	7.8	1.08	2.71	97.6	95.6	7.45
LC	3.8	1.05	2.71	98.7	99.7	7.83

has been developed[12]. This technique uses signal analysis based on acoustic propagation in mixtures of solid particles and fluid. Provided ultrasonic velocity of fluid mud layer with temperature is available, such information can be an aid to detect exactly the boundary between suspension and sediment layers.

The aim of this paper is to measure directly ultrasonic velocity of fluid mud layer in a laboratory and to investigate its change with temperature.

II. Experiments and Apparatus

Five different fluid mud samples (Table 1) were prepared in the laboratory to investigate ultrasonic velocity. Mud fraction of sediments was sorted using a sieve (4ϕ) in the laboratory. Five fluid mud layers at water bath and mass cylinder were artificially formed as adding seawater.

Mean grain size of mud samples was measured by a Micromeritics Sedigraph 5000ET. Physical properties (porosity, water content, and density) by gravimetric method[13] were determined from mass and volume of the same specimens. Sample weight was measured by using electronic balance. Sample volume was determined for both wet and dry samples by using a manual pycnometer (Model 1350). The helium gas was kept under pressure of 18 psi (1 psi = 0.07 kg/cm^2). The mass and volume of the evaporated pore-water salts were calculated for a standard seawater salinity (35‰) and seawater density (1.024 g/cm^3) at laboratory conditions.

Ultrasonic velocities were measured as a function of temperature in fluid mud by the pulse transmission technique[14] using Hamilton Frame. The measurement system includes pulse generator (Tektronix TM 502A, PG 508/50 MHz), digital oscilloscope (Tektronix TDS 3012), and a Hamilton Frame modified (Fig. 1). The condition of pulse generator was set as following: period= 0.2 ms (5 kHz), duration= 10 µs, transition time= 50 µs. A pair of piezoelectric transducer of 1 MHz was used for driving signal. The velocities were measured with changing temperature from 0~ to ~35°C.

III. Results

Ultrasonic velocity and physical properties for five different fluid mud samples were measured. Mean grain size is also analyzed. The results are listed at Tables 1 and 2. Physical properties for the samples are

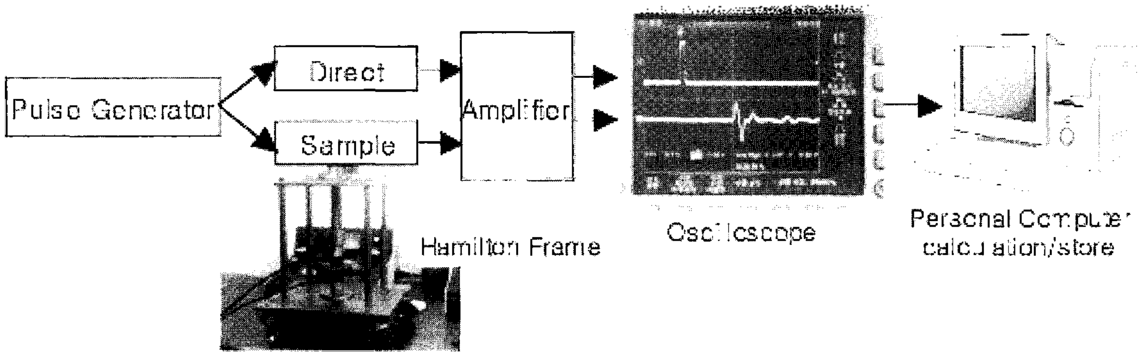


Fig. 1. Schematic diagram of the experimental set-up for measuring ultrasonic velocity of fluid mud. Hamilton frame is used.

Table 2. Ultrasonic velocity with changing temperature for five samples.

Fluid Mud-1		Fluid Mud-2		High Con.		Middle Con.		Low Con.	
Temp. (°C)	Velocity (m/s)	Temp. (°C)	Velocity (m/s)	Temp. (°C)	Velocity (m/s)	Temp. (°C)	Velocity (m/s)	Temp. (°C)	Velocity (m/s)
5.0	1433	1.1	1406	5.3	1424	6.3	1402	2.5	1434
6.0	1433	2.0	1415	6.3	1430	7.9	1430	3.0	1434
7.0	1435	3.0	1420	7.3	1432	8.5	1438	4.0	1438
8.0	1436	4.0	1425	8.3	1435	9.5	1447	5.2	1441
9.0	1441	5.0	1430	9.3	1439	10.5	1453	6.0	1446
10.0	1444	6.0	1434	10.3	1441	11.5	1458	7.0	1450
11.0	1447	7.0	1438	11.3	1443	12.5	1461	8.9	1436
12.0	1452	8.0	1443	12.3	1447	13.5	1464	9.0	1437
13.0	1455	9.0	1445	13.3	1450	14.5	1466	10.0	1442
14.0	1458	10.0	1449	14.3	1453	15.5	1473	11.1	1445
15.0	1461	11.0	1452	15.3	1456	16.5	1474	12.3	1447
16.0	1465	12.0	1456	16.3	1458	17.5	1482	13.0	1449
17.0	1469	13.0	1459	17.3	1462	18.5	1483	14.0	1452
18.0	1473	14.1	1461	18.3	1464	19.6	1482	15.0	1456
19.0	1475	15.0	1463	19.3	1465	20.5	1488	16.1	1457
20.0	1480	16.0	1466	20.3	1466			17.0	1460
21.0	1483	17.0	1469					18.0	1463
22.0	1488	18.0	1470					19.0	1466
23.0	1491	19.0	1474					20.0	1469
24.0	1495	20.0	1477						
25.0	1498								
26.0	1500								
27.0	1504								
28.0	1507								
29.0	1508								
30.0	1513								
31.0	1514								
32.0	1515								
33.0	1517								
34.0	1517								
35.0	1519								

also displayed (Fig. 2).

Ultrasonic velocity of fluid mud 1 sample (FM-1) is systematically increased from 1433 m/s at 5°C to 1519 m/s at 35°C (Table 2). Density, porosity, and water content of the sample are 1.24 g/cm^3, 84.0%, 71.9%, respectively (Table 1; Fig. 2). The velocity of fluid mud 2 (FM-2) is increased from 1406 m/s at 1.1°C to 1477 m/s at 20°C (Table 2). Density, porosity, and water content are 1.19 g/cm^3, 89.0%, 79.5%, respectively (Table 1; Fig. 2). In case of high concentrated sample (HC), the velocity is increased from 1424 m/s at 5.3°C to 1466 m/s at 20.3°C (Table 2). Density, porosity, and water content are 1.10 g/cm^3, 95.3%, 91.7%, respectively (Table 1; Fig. 2). Middle and low concentrated samples (MC and LC) show from 1402 m/s at 6.3°C to 1488 m/s at 20.5°C, from 1434 m/s at 2.5°C to 1469 m/s at 20.0°C, respectively (Table 2). Density, porosity, and water content of middle concentration sample are 1.08 g/cm^3, 97.6%, 95.6%, respectively (Table 1; Fig. 2). Density, porosity, and water content of low concentration sample are 1.05 g/cm^3, 98.7%, 99.7%, respectively (Table 1; Fig. 2).

IV. Discussion

The speed of sound determined from the elasticity and density of the medium varies in the ocean and depends on various factors in the sediments[14]. The three main environmental factors affecting the speed of sound in the ocean are salinity, pressure, and temperature. Several sound velocity models are now available in the literature[14,15-18]. The sound speed equation developed by Clay and Medwin[14] is as below.

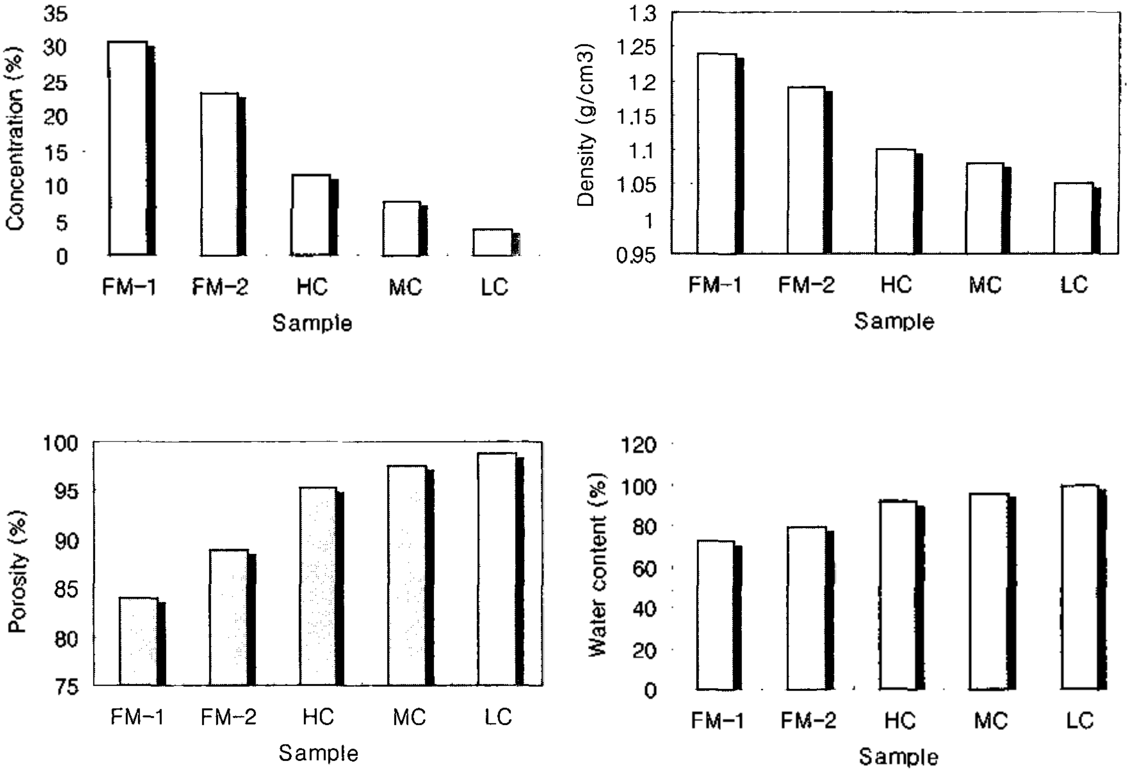


Fig. 2. Concentration and physical properties for five samples. (FM: Fluid Mud, HC: High Concentration, MD: Middle Concentration, LC: Low Concentration)

$c=1449.2+4.6T-0.055T^2+0.00029T^3+(1.34-0.010T)(S-35)+0.016z$

where,

T= temperature in °C

S= salinity in parts per thousand (‰)

z= depth in meters

This equation has accuracy within 0.6 m/s, provided accurate temperature, salinity, and depth data are available. The equation is also valid for $0 \leq T \leq 35$°C, $0 \leq S \leq 45$‰ and $0 \leq z \leq 1000$ m.

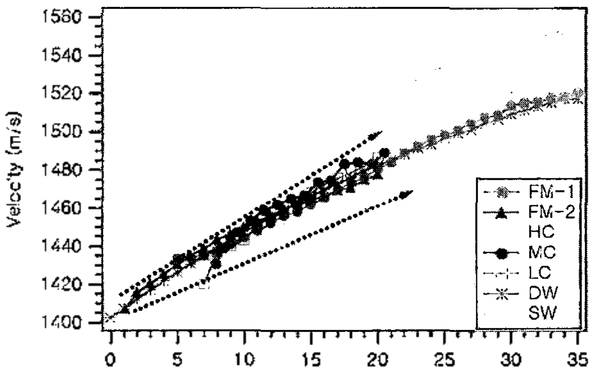


Fig. 3. Velocity with temperature for five samples, distilled water, and seawater. Initials are the same as Figure 2. Arrows indicate the difference of velocity with concentration increase with increasing temperature.

A change of salinity will cause a small correspondding change in density with a resulting change in bulk modulus, causing variation of sound speed (1.3 m/s/‰). Density of distilled water and seawater changes about 4% and 6% between 0°C and 100°C, respectively, while calcite and quartz density changes by 0.08%, 0.36% between 20°C and 100°C, respectively[19]. Pressure is more important factor than salinity, causing a change in bulk modulus and density, and results in an increase of sound speed with depth (0.017 m/s/m)[20]. But, the consideration of salinity and pressure is beyond the scope of this study.

Temperature, the most important factor affecting sound speed leads to decrease in sound speed (approximately 3 m/s/°C in seawater)[14,17,18], caused

Table 3. Velocity changing rate per 1°C for five samples, distilled water, and seawater.

	Changing rate of velocity per 1°C (m/s)
FM-1	3.21
FM-2	3.46
HC	2.83
MC	4.95
LC	4.58
Distilled water	3.30
Seawater	3.0

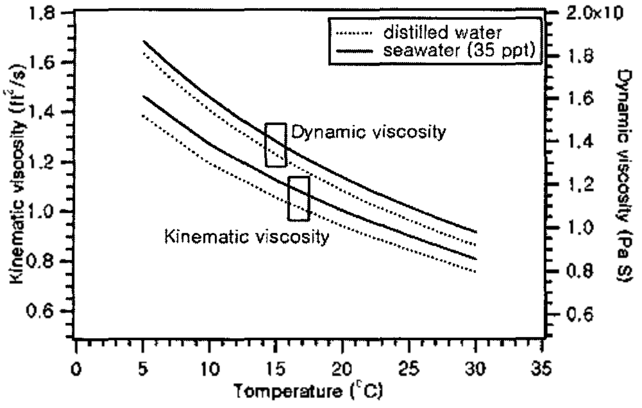


Fig. 4. Kinematic and dynamic viscosity with temperature at distilled water and seawater.

by the decrease of bulk modulus with decreasing temperature, although density increases. In this study, there are various rates of changing velocity (between 2.83 and 4.95 m/s/°C) with increasing temperature (Fig. 3; Table 3). All samples except for HC sample are greater than that (3.0 m/s/ °C) in seawater.

Ultrasonic velocity is significantly slower (approximately 30 to 50 m/s) in five samples than that in seawater (Fig. 3). In contrast, it is a very similar to the distilled water. This may be because the samples behave as a viscoelastic material with small elasticity and high viscosity before complete sedimentation[21]. The variation patterns with increasing temperature are similar to those of seawater and distilled water. But the changing rate of velocity with temperature is clearly different from five samples (Table 3). The temperature effect on water compressibility is considerable, whereas it is small for mineral particles (e.g., quartz and calcite)[22]. As temperature drops from 50°C to 0°C, the compressibility of pure water and seawater increased by 20.5%, while it decreased by about 2.2% for quartz and calcite [18,23]. From 50°C to 100°C, the compressibility of pure water increases again, it is not known in seawater. The compressibility is a reciprocal parameter of bulk modulus causing the increase of velocity. From higher temperature than 30°C, the increasing rate of compressibility slightly decreases[19], resulting from the decrease of viscosity[23]. Viscosity (i.e., kinematic and dynamic) decreases with increasing temperature, but it is not a linear (Fig. 4). As shown in the Figure 4, the magnitude of the slope tends to decrease more at higher temperatures. This pattern was observed on the curve of Figures 3 and 5, suggesting the decrease of

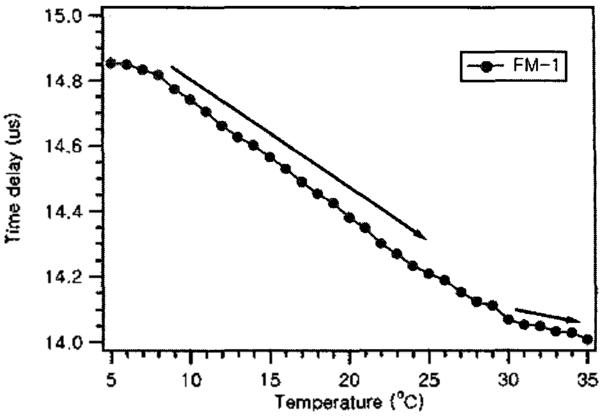


Fig. 5. Time delay with temperature at FM-1. Note that the slope decreases from the higher temperature than 30°C.

increasing rate of the velocity with increasing temperature from the boundary of 30°C. In particular, the difference of velocity with concentration in five samples increases (from approximately 10 to 20 m/s) with increasing temperature (see the arrows of Figure 3), caused by the change of viscosity and compressibility. Therefore, this study suggests velocity conversion as a function of temperature should be carefully considered.

V. Conclusion

Ultrasonic velocity as a function of temperature was measured in fluid mud with various concentrations. The velocity for all samples was increased with increasing temperature, and the velocity difference tends to increase at a higher temperature than that at lower temperature, caused by the change of viscosity and compressibility of water depending on temperature. But the temperature effect on the velocity of fluid mud was a similar rate as for distilled and seawater. This suggests that the viscosity and compressibility of fluid mud (i.e., suspension) significantly depends on the behavior of water. More experiments, however, are needed to further investigation for the characterization of ultrasonic velocity in fluid mud.

Acknowledgements

This work was supported by grant No. (R08-2003-000-10406-0) from the Basic Research Program of the Korea Science & Engineering Foundation.

References

1. M.M. Nichols, G.S. Thompson, and R.W. Fass, "A field study of fluid mud dredged material: its physical nature and dispersal", Tech. Rep. D-78-40, U.S. Army Engineering Waterway Experiment Station, Vicksburg, M.S. 1978.
2. J.T. Wells, "Dynamics of coastal fluid muds in low moderate, and high tide range environments", Can. J. Fish. Aquat. Sci. 40 (Suppl. 1), 130-142, 1983.
3. R. Kirby, "Suspended fine cohesive sediment in the Severn Estuary and Inner Bristol Channel", U.K. Rep. ETSUSTP-4042, Atomic Energy, Harwell, 1986.
4. J.P.Y. Maa, K.J. Sun, and Q. He, "Ultrasonic characterization of marine sediments: a preliminary study", Mar. Geol., 141, 183-192, 1997.
5. A. Sheremet, and G.W. Stone, "Observations of waves of over muddy seabed", J. Geophys. Res., 2004.
6. J.T. Wells, J.M. Coleman, and W.J. Wiseman, "Suspension and transportation of fluid mud by solitary waves", Proc. 16th Coastal Eng. Conf., ASCE 2, 1932-1952, 1978.
7. X.H. Wang, "Tide-induced sediment resuspension and the bottom layer in an idealized estuary.", J. Physical Oceanogr., 32, 3113-3131, 2002.
8. J.R. Silva, and P.L. Hir, "Response of stratified muddy beds to water waves", Coastal and Estuarine Fine Sediments Processes. In: McAnally, W.H. and Mehta, A.J., (eds.), 2001 Elsevier Science B.V.
9. D.S. Hughes, J.H. Cross, "Elastic wave velocities at high pressures and temperatures", Geophysics, 16, 577-593, 1951.
10. D.S. Hughes, J.L. Kelly, "Variation of elastic wave velocity with saturation in sandstone", Geophysics, 17, 739-752, 1952.
11. G. Shumway, "Sound velocity vs. temperature in water-saturated sediments", Geophysics, 23, 494-505, 1958.
12. H. Eden, V. Muller, and D. Vorrath, D, "Exact detection of suspension and sediment layer-A new surveying technology", Sea Technology, September Issue, 5pp. 2001.
13. R.E., Boyce, "Appendix I. Physical property methods. In: Initial Reports Deep Sea Drilling Project 15", edited by Edgar N.T., and J.B. Saunders, Washington, DC: US Government Printing Office, pp. 1115-1128, 1973.
14. C.S. Clay, and H. Medwin, "Acoustical oceanography: principles and applications", John Wiley & Sons, New York, pp. 544, 1977.
15. W.D., Wilson, "Equation for the speed of sound in seawater", J. Acoust. Soc. Am., 32, pp. 1357, 1960.
16. C.C. Leroy, "Development of simple equations for accurate and realistic calculations of the speed of sound in seawater", J. Acoust. Soc. Am., 46, pp. 216-226, 1969.
17. V.A. Del Grosso, "New equation for the speed of sound in natural waters (with comparison to other equations)", J. Acoust. Soc. Am., 56, pp. 1084-1091, 1974.
18. C.T. Chen and F.J. Millero, "Speed of sound in seawater at high pressures", J. Acoust. Soc. Am., 62, pp. 1129-1135, 1977.
19. F. Birch, J.F. Schairer, and H.C. Spicer, "Handbook of physical constants", GSA, Special paper 36, 1942.
20. X. Lurton, "An introduction to underwater acoustics: principles and applications", Springer, Chichester, UK, pp. 345, 2002.
21. F. Birch, "The velocity of compressional waves in rocks up to10 kilobars", J. Geophys. Res., 65, 1083-1102, 1960.
22. D. Grosso, "The velocity of sound in sea water at zero depth", U.S.N.R.L. Report 4002, 1952.
23. UNESCO, "Algorithms for computation of fundmental properties of seawater" UNESCO, Paris, France, UNESCO Tech. Papers in Marine Science 44, 1983.

[Profile]

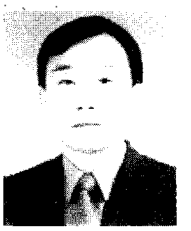
◆ **Gil Young Kim**

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, Busan, Korea, where he is currently research professor.

◆ **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.

◆ **Jeong Chang Kim**



Jeong Chang Kim received the B.S. and M.S. degree in fisheries oceanography from National Fisheries University of Pusan in 1975 and 1990, respectively, and completed a doctor's course in fisheries oceanography from Jeju National University in 1996. He has been working at Pukyong National University as an associate professor and caption of oceanography research vessel "Tamyang" since 1993 His research interests are the improvement of researching gear of ORV and the replacement of updated new measuring equipments.