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Acoustic and Elastic Properties of the Southeastern Yellow Sea Mud, Korea

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Abstract

Compressional wave velocity (Vp), shear wave velocity (Vs), elastic and physical properties, and electrical resistivity for two core sediments obtained from Southeastern Yellow Sea Mud (SEYSM) were measured and computed. The sediments consist of homogeneous mud (mostly silt and clay) with shells and shell fragments. As a result, the mean grain size is uniform (7.5-8.5ϕ throughout the core sediments. However, physical properties such as wet bulk density and porosity show slightly increasing and decreasing patterns with depth, compared to the mean grain size. The compressional (about 1475 m/s in average) and shear wave (about 60 m/s in average) velocities with depth accurately reflect the pattern of wet bulk density and porosity. Electrical resistivity is more closely correlated with compressional wave velocity than physical properties. The computed Vp/Vs and Poisson's ratios are relatively higher (more than 10) and lower (approximately 0.002) than Hamilton's (1979) data, respectively, suggesting the typical characteristics of soft and fully water-saturated marine sediments. Thus, the Vp/Vs ratio in soft and unconsolidated sediments is not likely sufficient to examine lithology and sediment properties. Relationships between the elastic constant and physical properties are correlated well. The elastic constants (Poisson's ratio, bulk modulus, shear modulus) given in this paper can be used to characterize soft marine sediments saturated with seawater.

Keywords: *Vp/Vs ratio, Physical properties, Elastic constants, Electrical resistivity, SEYSM*

I. Introduction

Physical (wet bulk density, porosity) and acoustic properties (compressional (Vp) and shear wave (Vs) velocity) and elastic constants (e.g., Poisson's ratio, bulk modulus, shear modulus) in sediments and rocks are important parameters in modeling the seafloor for underwater acoustics, geophysics, and foundation engineering [1]. In particular, the Vp/Vs ratio may be useful in indicating the presence of gas in sediments and rocks during oil exploration reflection measurements, due to a significant drop in the Vp/Vs ratio [2-3]. Gregory [3] reported that Vp/Vs in most water-saturated rocks varies from about 1.42 to 1.98, but when pore spaces are filled with gas, the Vp/Vs ratio is likely to be lowered to about 1.30 to 1.69.

Poisson's ratio determined from Vp/Vs ratio is one of elastic constants studied and the ratio is determined from transverse to longitudinal strain under an applied stress. When rigidity is zero (in a suspension of mineral particles in water), no shear wave can be transmitted and Poisson's ratio is 0.50. Poisson's ratio for most sediments and rocks is less than 0.50[4]. Poisson's ratio is of importance in studies of elasticity in earth materials, in geotechnical engineering, and in some aspects of seismic exploration for gas and oil [3].

Electrical resistivity is used to correlate geological formations and to provide some indication of reservoir content for exploitation [5]. In the case of saturated marine sediment, the resistivity changes will reflect changes in porosity and fabric and

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the presence of gas in the pore space, because the conduction of the current passing through sediments depends on the permeability of the sediment frame containing interstitial water, grain particles, and gas in the pores. Thus, the resistivity may be considered as a lithology indicator for characterizing marine sediments.

The purposes of this study are to characterize compressional and shear wave velocity, physical properties, and electrical resistivity for soft marine sediments obtained from the southeastern Yellow Sea and to provide detailed elastic constants for the sediments.

II. Materials and Methods

Two core samples (Station 1: Latitude 34°51.730', Longitude 125°42.470' Station 2: Latitude 33°38.100' Longitude 126°9.710') of mud were obtained from the Southeastern Yellow Sea during May of 2003 (Fig. 1). The core lengths at Stations 1 and 2 are about 3.5 and 3.47 m, respectively (Fig. 2).

Mean grain size was analyzed by dry sieving for the sand-sized fraction and by a Sedigrph 5100 for the silt- and clay-sized fraction. Porosity and density were determined by gravimetric method [6] from the mass and volume of the same specimens. Sample weight was determined by using an electronic balance. Sample volume was determined for both wet and dry samples by using a manual pycnometer (Model: pycnometer 1350).

The specimens' compressional wave velocity was measured with the pulse transmission technique [7]. The measurement system includes a pulse generator (Model: Tektronix TM 502A, PG 508/50 MHz), digital oscilloscope (Model: Tektronix TDS 3012), and a modified Hamilton Frame. The condition of the pulse generator was set as following: period = 0.2 ms (5 kHz), duration = 10 μs μs A pair of piezoelectric transducers of 1 MHz was used for the driving signal.

Shear wave velocity was also measured using a pulse transmission technique based on the Hamilton frame. A function generator (Model: Tektronix AFG 310) and oscilloscope (Model: Tektronix TDS 3012) were used to generate the transmitting pulse and receive the signals passed through sample. A duomorph ceramic bender transmitter and receiver, designed and constructed at the Naval Research Laboratory-Stennis Space Center [8], was used to measure shear wave velocity. The transmitter was driven by a 10 V p-p pulsed sine wave. The driving frequency was set at 500 Hz.

The four electrodes technique [9] was used to measure the electrical resistivity of the sediment sample. The measurement was conducted at the frequency of 100 Hz at room temperature (approximately 23℃ A plexiglas sample holder was used depending upon the shape of the cubic sample [10]. The sampler holder consists of an outer pair of current electrodes and an inner pair of potential electrodes. The resolution depends on significant

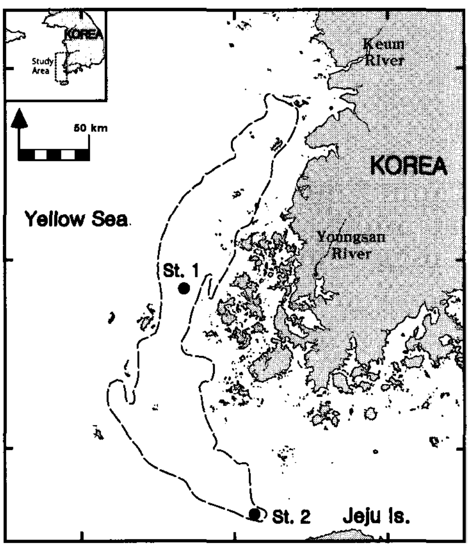

Fig. 1. Physiographic map of the study area including two piston core locations. Dotted line represents the distribution of the mud deposits (SEYSM).

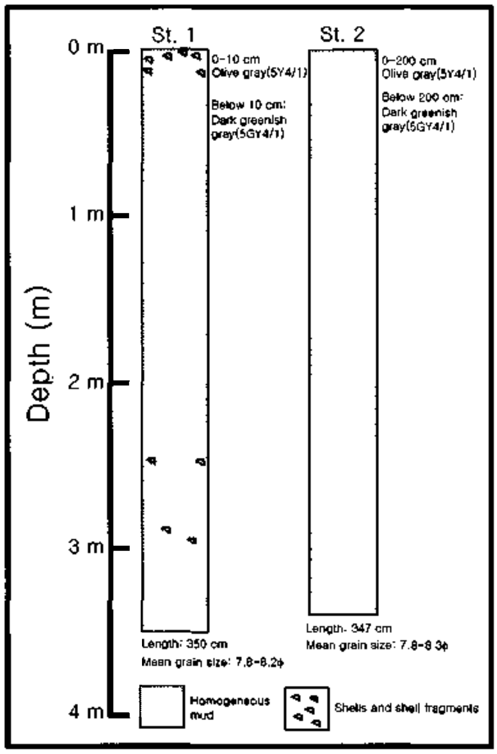

Fig. 2. Lithology of the cores. Note that the cores are mainly composed of homogeneous mud.

disturbance and contamination of the sample. The detailed descriptions for the measurement system are given in the literature reported by Seo et al. [10].

Elastic constants such as Poisson's ratio (σ bulk modulus (κ and shear modulus (μ were computed from the compressional wave velocity, shear wave velocity, and wet bulk density according to Hamilton's equation [1].

III. Results and Discussion

3.1. Sediment characteristics

The cored sediments are composed of homogeneous mud (mean grain size, 7.5-8.5ϕ with shells and shell fragments (Fig. 2, Tables 1 and 2). The mean grain size is nearly constant with depth (Figs. 3 and 4), suggesting no significant change in the sedimentary processes and environments during deposition. This sediment pattern around the study area is well known from previous reports [11, 12, 13]. According to these reports, the major source of sediment is probably the Keum River. The fine grained sediments discharged from the river are transported southward by the coastal current, resulting in a gradual southward increase in porosity and a decrease in wet bulk density and sound velocity [13]. Similarly, the mean grain size in this study shows the decreasing pattern from Station 1 (7.96ϕ to Station 2 (8.26ϕ

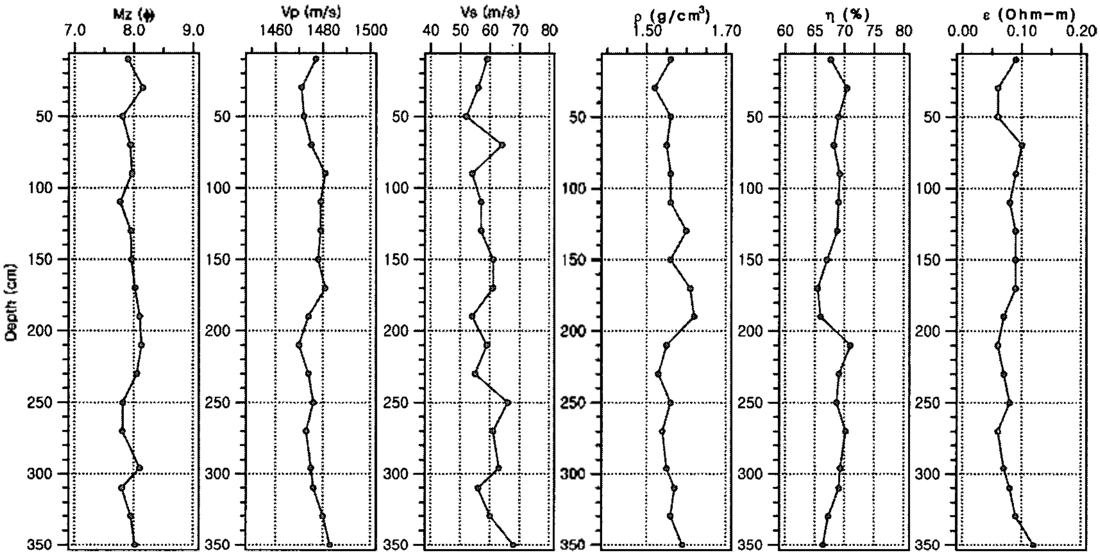

Fig. 3. Profiles of mean grain size, acoustic and physical properties, and electrical resistivity at Station 1. Wet bulk density and porosity shows a mirror image.

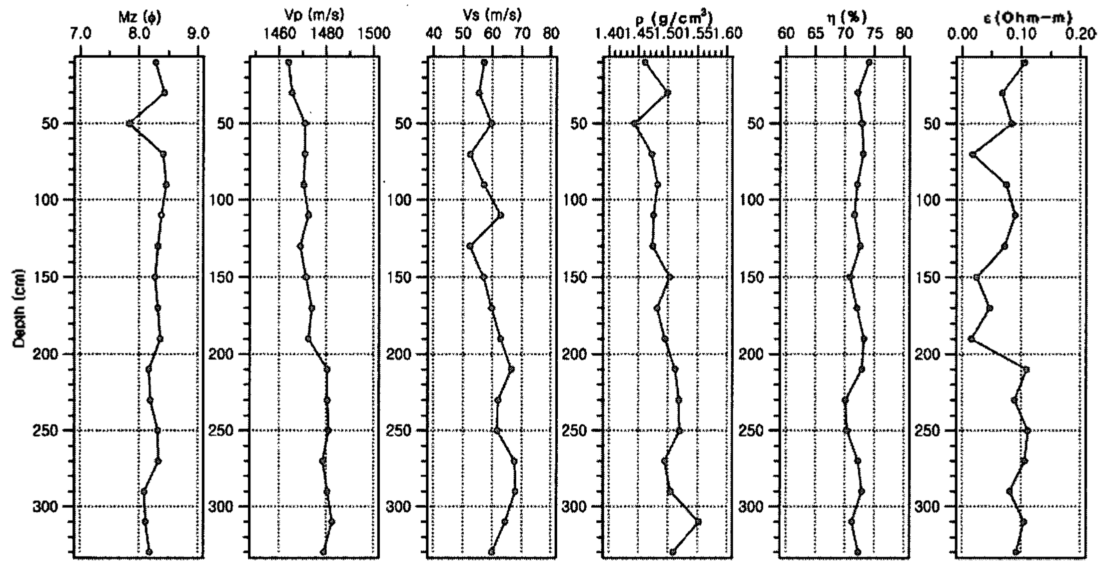

Fig. 4. Profiles of mean grain size, acoustic and physical properties, and electrical resistivity at Station 2. The compressional wave velocity is relatively correlated with electrical resistivity.

Table 1. Acoustic, physical, and elastic properties for Station 1. (Mz: mean grain size, Vp: compressional wave velocity, Vs: shear wave velocity, ρ :wet bulk density, η : porosity, ϵ : electrical resistivity, ohm-meter, σ : Poisson' s ratio, κ : bulk modulus, dynes/cm$^2 \times 10^{10}$, μ: shear modulus, dynes/cm$^2 \times 10^7$).

Depth (cm)	Measured						Computed			
	Mz (φ)	Vp (m/s)	Vs (m/s)	ρ (g/cm³)	η (%)	ε	Vp/Vs	σ	κ	μ
10	7,90	1477	59	1,56	67,7	0,09	25,21	0,4988	3,401	5,364
30	8,15	1471	56	1,52	70,4	0,06	26,33	0,4989	3,293	4,760
50	7,81	1472	52	1,56	69,0	0,06	28,48	0,4991	3,376	4,168
70	7,94	1475	64	1,55	68,2	0,10	23,14	0,4986	3,357	6,287
90	7,97	1481	54	1,56	69,2	0,09	27,34	0,4990	3,414	4,576
110	7,77	1479	57	1,56	69,0	0,08	25,81	0,4989	3,408	5,127
130	7,95	1479	57	1,60	68,8	0,09	26,07	0,4989	3,498	5,157
150	7,96	1478	61	1,56	67,1	0,09	24,04	0,4987	3,392	5,884
170	8,02	1481	61	1,61	65,5	0,09	24,14	0,4987	3,530	6,070
190	8,10	1474	54	1,62	66,0	0,07	27,11	0,4990	3,519	4,798
210	8,13	1470	59	1,55	71,0	0,06	25,06	0,4988	3,351	5,347
230	8,05	1474	55	1,53	69,1	0,07	26,60	0,4989	3,320	4,702
250	7,82	1476	66	1,56	68,7	0,08	22,52	0,4985	3,378	6,680
270	7,81	1473	61	1,54	70,2	0,06	24,09	0,4987	3,339	5,765
290	8,10	1475	63	1,55	69,3	0,07	23,43	0,4986	3,666	6,144
310	7,80	1476	56	1,57	69,1	0,08	26,21	0,4989	3,421	4,989
330	7,95	1480	60	1,56	67,3	0,09	24,59	0,4988	3,400	5,637
350	8,02	1483	68	1,59	68,4	0,12	21,75	0,4984	3,480	7,376
Avg.	7,96	1476	59	1,57	68,5	0,08	25,11	0,4988	3,402	5,491

Table 2. Acoustic, physical, and elastic properties for Station 2. (Mz: mean grain size, Vp: compressional wave velocity, Vs: shear wave velocity, ρ :wet bulk density, η : porosity, ϵ : electrical resistivity, ohm-meter, σ : Poisson' s ratio, κ : bulk modulus, dynes/cm$^2 \times 10^{10}$, μ: shear modulus, dynes/cm$^2 \times 10^7$).

Depth (cm)	Measured						Computed			
	Mz (φ)	Vp (m/s)	Vs (m/s)	ρ (g/cm³)	η (%)	ε	Vp/Vs	σ	κ	μ
10	8,28	1464	57	1,46	74,1	0,11	25,77	0,4988	3,124	4,777
30	8,43	1466	55	1,49	72,2	0,07	26,40	0,4989	3,214	4,618
50	7,83	1471	59	1,44	72,9	0,08	24,63	0,4987	3,115	5,142
70	8,41	1471	52	1,47	73,1	0,02	28,00	0,4990	3,181	4,064
90	8,46	1471	57	1,48	72,1	0,07	25,72	0,4988	3,199	4,845
110	8,38	1473	62	1,47	71,6	0,09	23,43	0,4986	3,191	5,825
130	8,32	1469	52	1,47	72,6	0,07	28,00	0,4990	3,176	4,058
150	8,27	1472	57	1,50	70,9	0,02	25,78	0,4988	3,248	4,895
170	8,32	1474	59	1,48	72,0	0,05	24,65	0,4987	3,212	5,296
190	8,36	1473	62	1,49	73,3	0,02	23,44	0,4986	3,234	5,902
210	8,17	1480	66	1,51	72,9	0,11	22,26	0,4984	3,305	6,686
230	8,19	1480	61	1,51	70,1	0,09	23,90	0,4986	3,321	5,826
250	8,32	1481	61	1,51	70,4	0,11	23,01	0,4986	3,325	5,781
270	8,33	1478	67	1,49	72,3	0,11	21,89	0,4983	3,257	6,814
290	8,09	1480	67	1,50	72,9	0,08	21,83	0,4983	3,288	6,918
310	8,11	1482	64	1,55	71,2	0,11	22,00	0,4985	3,404	6,446
330	8,18	1479	59	1,50	72,3	0,09	24,67	0,4987	3,294	5,420
Avg.	8,26	1474	60	1,49	72,2	0,08	24,54	0,4987	3,241	5,489

3.2. Sound velocity (Vp, Vs) and Vp/Vs ratio

Compressional and shear wave velocities relatively increase with depth, reflecting the variation of physical properties (Figs. 3 and 4). But the compressional wave velocity in Station 1 is higher in the upper section (90-170 cm depth) than the lower section (the interval of 190-310 cm depth). This pattern is similar to the profiles of wet bulk density and porosity (Fig. 3). This is probably due to the rapid deposition that prevents dewatering in the lower section. Shear wave velocity shows the increasing trend with some slight fluctuation (Figs. 3 and 4). The overall compressional wave velocity (about 1475 m/s in average) is lower than (Tables 1 and 2) that of Kim et al. [13] (>1520 m/s), who investigated at the adjacent area. The reasons are probably due to the difference of measurement system (an error in sample length of Kim et al. [13] and the sampled location. The sediments from Kim et al. [13] are characterized by the large amount of silt (greater than 65%) compared to this result (20-50%) (Fig. 5).

Shear wave velocity (about 60 m/s on average) is higher than what Kim and Kim [8] measured in the gassy sediments (<20 m/s), but the results of this study are similar to what Richardson et al. [14] reported for a similar sediment type (50-60 m/s). Shear speed in unconsolidated sediments is sensitive to overburden pressure or compaction. Thus shear wave velocity depends on environmental parameters such as sedimentary processes and environments, various sediment types, the presence of gas in the pores, the degree of consolidation and compaction, and burial depth [14].

Vp/Vs ratio is characterized by the high value (about 25 on average) (Fig. 5). According to Hamilton[4], the higher values (greater than 45) of Vp/Vs can be expected when Vs approaches zero in some sediments (i.e., suspension). The ratio in consolidated rocks and deep borehole sediments is less than 3 [15-16-17]. In the case of sand, the ratio is very high (very high gradient with depth) in the first few meters (ca., 5 m) below the seafloor, and then decreases (a much smaller gradient), caused by small increases of Vp with increasing pressure or depth in water-saturated sands [4]. Provided accurate Vp and Vs are measured, the Vp/Vs ratio can be used to estimate the lithology and/or the presence of gas in sediments and rocks. But there is a difficulty to apply the ratio for soft and water-saturated sediments. The reason is due to the deficiency of precise shear wave velocity, caused by the difficulty of the measurement technique and the sensitivity of the shear speed by high attenuation.

Shear wave velocity versus compressional wave velocity is correlated well (Fig. 6). In general, shear wave velocity increases with increasing compressional wave velocity, caused by the increasing of bulk modulus and shear modulus [1, 4, 18, 14, 19].

3.3. Physical and electrical properties

Wet bulk density and porosity show good mirror images (Figs. 3 and 4). Wet bulk density at Stations 1 and 2 is 1.57 and 1.49 g/cm^3 (Tables 1 and 2), respectively. Porosity at Stations 1 and 2 is 68.5 and 72.2%, respectively. These values are different from the data (approximately 65%) that Kim et al. [13] reported in this area. This is probably caused by the difference in the clay content (Fig. 5), although the area of study is similar. In this study, the clay content is greater than 50%, compared to the silt and sand contents, but is less than 30% in the data reported by Kim et al. [13]. As discussed in the previous section, wet bulk density and porosity of Station 1 are likely to be inversed at the upper and lower sections of the core (Fig. 3).

Electrical resistivity is an important variable for understanding the geological events of depositional environments, the effects of mechanical and chemical diagenesis with burial depth after deposition, and the seafloor investigation of ocean engineering and naval application [20, 18, 21]. Electrical resistivity values at Stations 1 and 2 are as low as 0.08 to 0.11 ohm-m on average

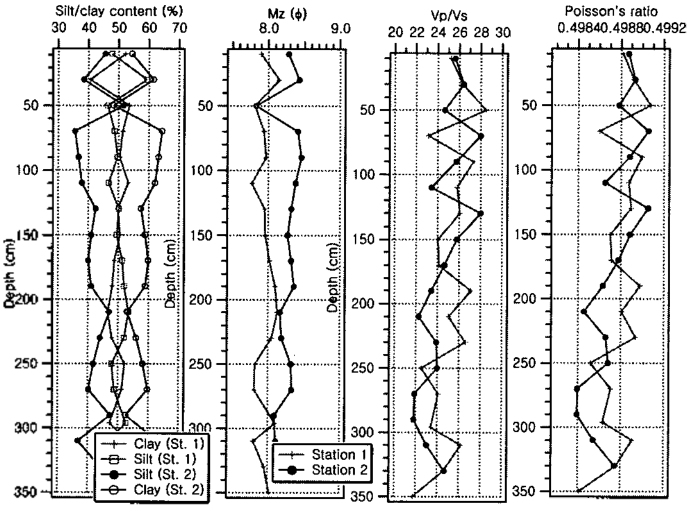

Fig. 5. Profiles of sediment texture, Vp/Vs ratio, Poisson' s ratio at Stations 1 and 2. Station 2 is characterized by the high clay content and the low silt content compared to Station 1.

(Tables land 2), indicating soft sediments saturated with seawater. The profiles are likely to reflect the variation of physical properties, and coincide well with the pattern of compressional wave velocity (Figs. 3 and 4). Electrical resistivity and compressional wave velocity is significantly affected by the microstructure and the presence of gas and/or water in the pore [21, 10]. Thus, physical and acoustic properties (esp., compressional wave velocity) can roughly be predicted using electrical resistivity.

3.4. Elastic constants

Measurement and computation of elastic constants have been gathered for marine sediments [1, 22]. The results showed that the equations of elasticity can be used to compute unmeasured elastic constants in the case of water-saturated sediments. In this study, Poisson's ratio, bulk and shear modulus were computed (Tables 1 and 2) using the Hamilton's [1] equation.

Poisson's ratio with depth shows the high values in the upper section of the cores (Fig. 5), although all values are greater than 0.49. Generally, the values greater than 0.49 are typical in the first 25 m below the seafloor, and decrease with depth as a consequence of linking Vp with Vs [4]. As shown in the Figure 5, the pattern shows the decreasing trend with depth but the gradient is very insignificant due to the similarity of sediment types with depth.

Bulk modulus is strongly dependent on porosity. Therefore it is no surprise to find that the plots of computed values of bulk modulus versus porosity or density show a good correlation (Figs. 7 and 8). As shown in Figures 7 and 8, the plotted data is well grouped by each station. This is probably responsible for the high clay content of Station 2 compared to Station 1 (Fig. 5), although the mean grain size shows insignificant difference. The computed

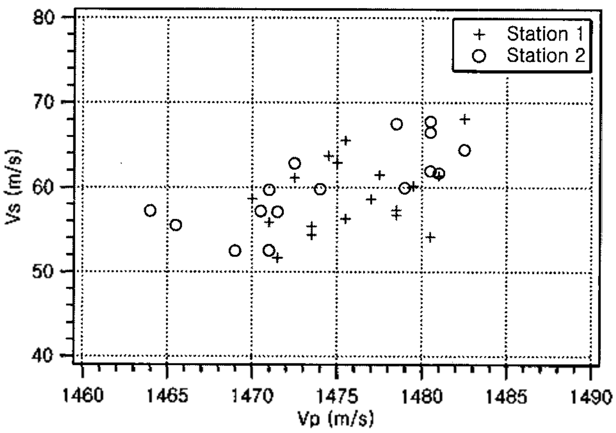

Fig. 6. Shear wave velocity versus compressional wave velocity. Note a good correlation.

bulk modulus values show a range of 3.115 to 3.666 dynes/cm^{2}x10^{10} (Tables 1 and 2). These values are relatively similar to those (<3.2 dynes/cm^{2}x10^{10}) of Hamilton [1] for the similar sediment type. But the computed shear modulus is significantly lower, between 4.058 and 6.918 dynes/cm^{2}x10^7 (Tables 1 and 2), than Hamilton's (1971) (<0.22 dynes/cm^{2}x10^{10}) for the similar sediments. This is probably due to the difference in shear wave velocity. Hamilton [1] computed the bulk modulus and shear modulus using a shear wave velocity of approximately 100 m/s, estimated with a similar sediment type. Thus, Hamilton's values (1971) could be overestimated. As reported already, the shear wave velocity measured in this study is lower (approximately 60 m/s) than Hamilton's [1], which, in turn, computes a low value of bulk modulus and shear modulus. Thus, this result cannot be directly compared with the results reported by Hamilton [1]. This study only presents the computed values of the bulk modulus and shear modulus for marine sediments. Further study is needed to provide specific and detailed elastic constants for various sediment types and sedimentary environments.

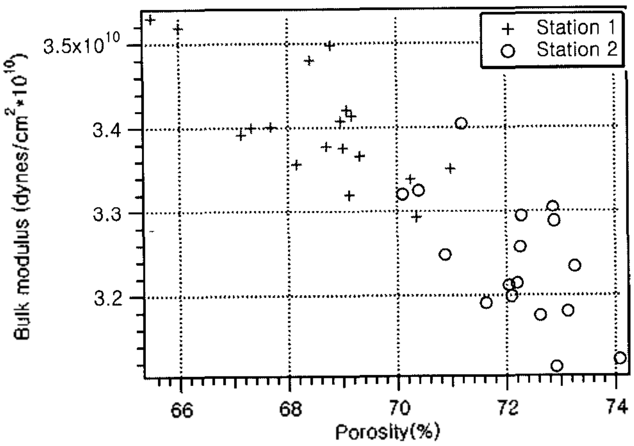

Fig. 7. Bulk modulus versus porosity. The values of Stations 1 and 2 are grouped well. Note a good inverse correlation.

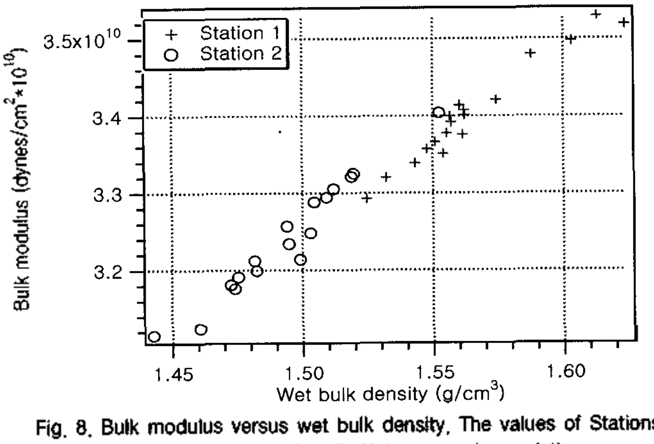

Fig. 8. Bulk modulus versus wet bulk density. The values of Stations 1 and 2 are grouped well. Note a good correlation.

IV. Conclusions

The cored sediments from Southeastern Yellow Sea Mud (SEYSM) consist of homogeneous mud (mostly silt and clay) with shells and shell fragments. The mean grain size is uniform with depth. Wet bulk density and porosity show a slightly increasing and decreasing pattern with depth, compared to the mean grain size. The compressional and shear wave velocities with depth coincide well with the pattern of physical properties. Electrical resistivity also reflects the pattern of velocity and physical properties. The computed Vp/Vs and Poisson's ratios are relatively higher and lower than the data presented by Hamilton (1979), respectively, suggesting the typical characteristics of soft marine sediments. Thus, it seems unlikely to characterize the Vp/Vs ratio for soft and unconsolidated sediments. Relationships between the elastic constant and physical properties are correlated well. The computed elastic constants can be used to characterize soft marine sediments saturated with seawater.

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