# GEOPHYSICAL CHARACTERIZATION OF MARINE CLAYS
# - FROM GEOTECHNICAL PARAMETER ESTIMATION TO PROCESS MONITORING -

GYE-CHUN CHO[i], ILHAN CHANG[ii], TAE-MIN OH[iii] and HAK-SUNG KIM[iii]

**ABSTRACT**

Marine clays are soft soil deposits having complicated mineralogy and formation characteristics. Thus, characterization of its geotechnical behavior has been a main issue for geotechnical engineers. Nowadays, the importance and applications of geophysical exploration on marine clays are increasing significantly according to the accuracy, efficiency, and reliability of geophysical survey technology. For marine clays, seismic survey is effective for density and elasticity characterization, while electro-magnetic wave provides the information about the fluid conductivity phenomena inside soil. For practical applications, elastic wave technology can evaluate the consolidation state of natural marine clay layers and estimate important geotechnical engineering parameters of artificially reclaimed marine deposits. Electrical resistivity can provide geophysical characteristics such as particle cementation, pore geometry shape, and pore material phase condition. Furthermore, nondestructive geophysical monitoring is applicable for risk management and efficiency enhancement during natural methane gas extraction from gas hydrate-bearing sediments.

**Key Words :** Marine clay, Geophysical characterization, Elastic wave, Shear wave, Electro-magnetic wave, Geotechnical engineering parameters, Gas hydrate.

## 1 INTRODUCTION

Marine clays are soft soil deposits having complicated mineralogy and formation characteristics. Therefore, prediction and evaluation on the geotechnical behavior of marine clays has been a concern for geotechnical engineers during a long history. Since Terzaghi (1923) introduced the one-dimensional consolidation theory, notable improvements have been introduced to improve understandings on the behavior of marine clays (e.g., Mikasa 1963, Gibson et al. 1967, Pane and Schiffman 1997, among others).

In field tests, settlement monitoring, pore pressure measurement, and cone penetration tests with pore pressure measurements (CPTu) are commonly used for in-situ exploration. However, the settlement tendency is discordant with the degree of pore pressure dissipation (Schiffman et al. 1984) and settlement monitoring cannot capture the local variation of the consolidation process. In addition, pore pressure measurement is associated with adverse factors stemming from the installation and control of the pore pressure gages, leading to unsatisfactory results (Tanaka and Sakagami 1989); although the CPT is suitable for exploring the behavior of soft ground, especially marine clay (Lunne et al. 1997), the pore pressure dissipation testing in CPTu is time-consuming and thus cannot easily be applied to wide marine sites. Accordingly, an alternative method of estimating geotechnical engineering parameters in marine clays is required.

Recently, the importance and effectiveness of geophysical exploration are emphasized to become an alternative of insecure conventional geotechnical site evaluation methods. Geophysical exploration provides a relatively rapid and cost-effective means of deriving areally distributed information of the geological and geotechnical condition of the earth (Kearey et al. 2001).

Generally, the most widely used geophysical survey methods are seismic, gravity, magnetic, and electrical technology. The type of physical property to which a method responds clearly determines its range of applications (Kearey et al. 2001).

For marine clay deposits, both seismic and electro-magnetic methods are applicable for reliable prospection. Seismic technology is suitable for density and elasticity characterization, while electro-magnetic method provides information about the conductivity characteristic of soil.

In this paper, current geophysical characterization applications on Korean marine clays are introduced and summarized. The results show that geophysical exploration provides reliable estimation results on geotechnical parameters and in-situ stability monitoring of marine clay deposits.

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## 2 ELASTIC WAVE-BASED CHARACTERIZAION

### 2.1 Elastic Wave and Soil

#### 2.1.1 Elastic Wave and Particulate Material

Elastic wave (usually, compressive wave P- and shear wave S- in continuous medium) is a type of mechanical wave which propagates through elastic or viscoelastic materials. Generally, the elasticity of the material dominates the propagation behavior of elastic waves (Graff 1975). Thus, the elastic wave propagation tendency (velocity or attenuation) becomes a reliable indicator to evaluate the elasticity of materials.

Soil, which is a particulate material, is commonly considered as a viscoelastic medium. Thus, the propagation of small-strain elastic waves is sufficient to evaluate the state of particulate material without fabric and structure disturbances (Santamarina et al. 2001). Generally, four material properties - bulk modulus B; shear modulus $G$; mass density $\rho$; and intrinsic attenuation $\alpha$ - are known as governing parameters for the elastic wave behavior in particulate materials.

However, soil is a multi-phase material which is a combination of solid particles and fluid (air or liquid) voids. Therefore, the existence of void fluids alter the elastic wave propagation phenomenon in soil. For instance, in saturated soil, the P-wave velocity is affected by the bulk modulus of fluid ($B_f$), porosity ($n$), and the bulk modulus of soil particles ($B_g$) (Ishihara et al. 1998), while the S-wave velocity only depends on the stiffness of particle skeleton and the mass density of soil (Cho and Santamarina 2001). Generally, the stiffness of particle skeleton is determined by the state of confining stress. In the case where capillary forces are much smaller than skeletal forces (S-waves for all saturation conditions and P-waves for unsaturated condition), the elastic wave velocity and confining effective stress relationship can be expressed as (Santamarina et al. 2001):

$$V = \alpha \left( \frac{\sigma'_o}{1\text{kPa}} \right)^{\beta} \tag{1}$$

#### 2.1.2 Shear Wave and Soil

Marine clay is a type of clay found in coastal regions, formed by natural or artificial sedimentation and deposition processes. Generally, marine clay has a weak and unstable structure affected by physical effects (temperature, pH, ionic concentration, self-weight consolidation, etc.) during its formation (Palmer et al. 1987). Meanwhile, as most marine clay deposits exist below the sea level, the void fluid condition can be considered as fully saturated with sea water. Thus, shear wave (S-wave) is recommended for geophysical characterization on marine clay to avoid the effect of void fluids, because the shear wave propagates only through soil skeletons, which means that shear wave velocity is sufficient to evaluate the soil composition and effective stress condition (Hardin and Richart 1963; Klein and Santamarina 2003).

The shear wave velocity (Eq. 1) of infinite (zero lateral strain condition, $K_0$) marine clay deposits can be expressed in terms of the vertical effective stress as follows (Santamarina et al. 2001):

$$V_s = \alpha_1 \left( \frac{\sigma'_m}{1\text{kPa}} \right)^{\beta} = \alpha_1 \left( \frac{(1+K_0)\sigma'_v}{2\text{kPa}} \right)^{\beta} = \alpha \left( \frac{\sigma'_v}{1\text{kPa}} \right)^{\beta} \tag{2}$$

where $\sigma'_m$ is the mean effective stress of the horizontal and vertical effective stresses, $\sigma'_v$ is the vertical effective stress, $K_0$ is the coefficient of earth pressure at rest, and $\alpha$ and $\beta$ are experimentally correlated parameters. According to Chang and Cho (2010), $\alpha$ and $\beta$ parameters remain constant for a normally consolidated condition. Therefore, it is available to evaluate the vertical effective stress state of marine clay using the shear wave velocity data. Detail examples are as follows.

### 2.2 Practical Applications

#### 2.2.1 Consolidation State Evaluation of Marine Clay

A marine clay deposit memorizes its stress history (i.e. maximum pre-consolidation stress, $\sigma'_p$). In fact, the stress relationship between the stress history and current effective stress state ($\sigma'_o$) in field determines the geotechnical behavior (especially consolidation state) of marine clay. The pre-consolidation effective stress ($\sigma'_p$) is generally defined to be the inflection point of the void ratio-effective stress (e-log $\sigma'$) curve determined by a laboratory consolidation test (Casagrande 1936). However, it is a challenge to evaluate the current effective stress state ($\sigma'_o$) reliably due to the presence of excess pore water pressure in field. Thus, shear wave velocity (Eq. 2) becomes an alternative to evaluate the current in-situ effective stress, by avoiding the effects of existing pore fluids and excessive pore pressure.

For a normally-consolidated (NC) state, the expected in-situ effective stress when the primary consolidation process ends at a certain depth z can be estimated by integrating the density profile of overburden soils as:

$$\sigma'_{nc} = \int_o^H \gamma' dz = \int_o^{h_w} \rho_t \cdot g dz + \int_{h_w}^H (\rho_{sat} - \rho_w) \cdot g dz \tag{3}$$

where $\gamma'$ is the effective unit weight, $H$ is the overburden depth, $h_w$ is the ground water table depth, $\rho_w$ is the water density (1 g/cm$^3$), and $g$ is the acceleration of gravity (9.81 m/s$^2$). Thus, the expected in-situ shear wave velocity under the NC condition

($V_{s\text{-}nc}$) can be estimated from Eqs 2 and 3:

$$V_{s-nc} = \alpha\left(\frac{\sigma'_{nc}}{1\text{kPa}}\right)^{\beta} \tag{4}$$

In such a case, the experimentally determined parameters $\alpha$ and $\beta$ are valid for the clay specimen which represents a clay deposit at the sampled location.

The main idea for the in-situ consolidation state evaluation using shear wave velocity is to compare the expected in-situ shear wave velocity under the NC condition (estimated by laboratory test; Eq. 4) to the real in-situ shear wave velocity ($V_s^{field}$). Therefore, the in-situ shear wave velocity profile is required for this presented concept. The in-situ consolidation state can then be evaluated as follows (Chang and Cho 2010).

NC (Normally-Consolidated) State

When $V_s^{field} \approx V_{s\text{-}nc}$, the site is determined as the NC state, where the current in-situ effective stress ($\sigma'_o$) is expected to be approximately equal to the expected effective stress under the NC condition ($\sigma'_{nc}$), in Eq. 4.

UC (Under-Consolidation) State

When $V_s^{field} < V_{s\text{-}nc}$, the site can be defined as UC state, which indicates that the current in-situ effective stress is lower than the expected effective stress under the NC condition. However, the final destination of the in-situ effective stress after complete excess pore pressure dissipation will become $\sigma'_{nc}$. In this case, the degree of consolidation ($U_z$) can be evaluated by dividing the current effective stress value by the expected final effective stress value ($\sigma'_{nc}$):

$$U_z = \frac{\sigma'_o}{\sigma'_{nc}} = \frac{\left(V_s^{field}/\alpha\right)^{1/\beta}}{\sigma'_{nc}} \tag{5}$$

OC (Over-Consolidated) State

When the wave velocity relationship is $V_s^{field} > V_{s\text{-}nc}$, it is expected that the site has undergone stress unloading, desiccation, or diagenetic cementation processes. While the diagenesis may require a long geologic time scale, the unloading stress history of the site is presumed to be the most likely cause of the higher $V_s^{field}$ within an engineering time frame. Thus, when $V_s^{field} > V_{s\text{-}nc}$, the site is likely to be in the OC state.

The $\sigma'_{nc}$-$V_{s\text{-}nc}$ relationship for a certain site can be evaluated by performing a shear wave velocity measurement based laboratory consolidation test on undisturbed specimens sampled from the site of interest. Fig. 1 shows the laboratory consolidation test equipment. While step loading is performed, the final shear wave velocity data for each loading step are collected to evaluate the $\alpha$ and $\beta$ parameters of Eq. 4. Finally, the consolidation state becomes evaluable as mentioned previously. Practical examples are shown in Fig. 2.

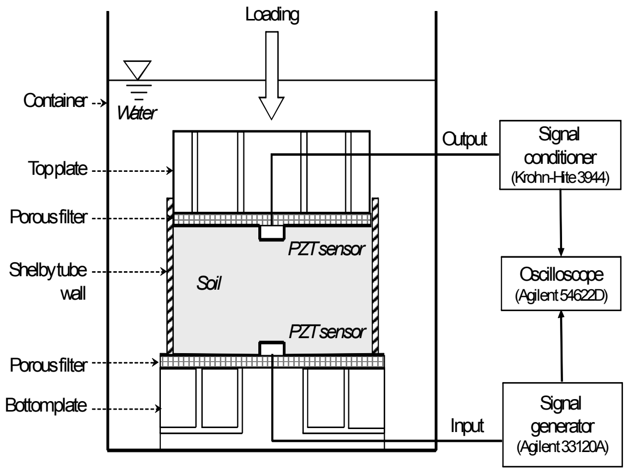
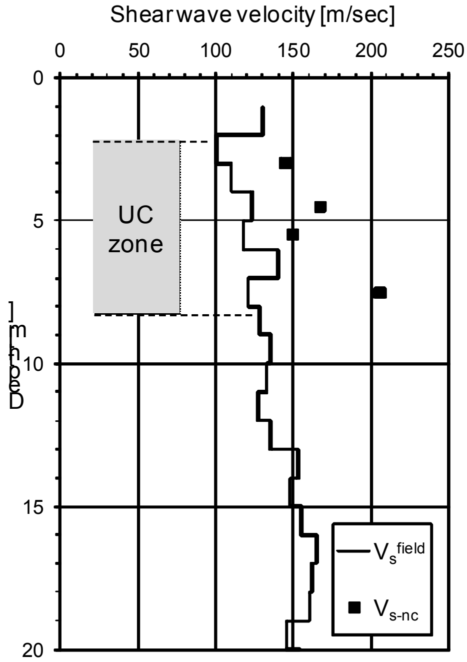



Figure 1. Laboratory consolidation test setup for shear wave velocity measurement.

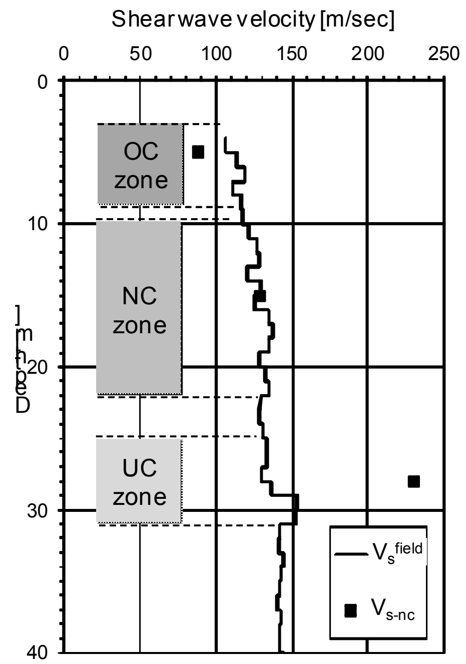
### 2.2.2 Design Parameter Estimation of Reclaimed Marine Clay

The consolidation behavior of reclaimed clay can be categorized as large strain deformation. Findings from previous studies (Mikasa 1963, Gibson et al. 1967, Gibson et al. 1981, Pradhan et al. 1995, Pane and Schiffman 1997, among others) indicate that the effective stress and the void ratio are important geotechnical engineering parameters for the characterization of large strain consolidation behavior. The consolidation characterization of dredged and reclaimed clay deposits is important for the prediction of their long-term settlement and strength when an additional load is applied. However, existing in-situ consolidation characterization methods of reclaimed clay cannot adequately estimate changes of the effective stress and void ratio during a consolidation process. Therefore, Chang and Cho (2010) suggested a laboratory simulation method to represent the in-situ reclamation process and estimate important geotechnical engineering parameters using shear wave velocity measurements.

Generally, once clay is dredged and reclaimed, sedimentation occurs first. The self-weight consolidation subsequently occurs below the transitional boundary between the free-fall settling and consolidation (Imai 1980; Been and Sills 1981). In the case of kaolinite-type clay, which is the most common marine clay type in Korea, the self-weight consolidation process is particularly significant for the characterization of reclaimed deposits. In this case, clay particles become stabilized because they are irreversible. Thus, the final effective stress ($\sigma'_f$) received by an in-situ clay element after self-weight consolidation is determined by its initial location at the beginning of the formation of the soil structure, rendering a constant effective stress condition (defined as "destined effective stress condition"; Chang and Cho 2010).

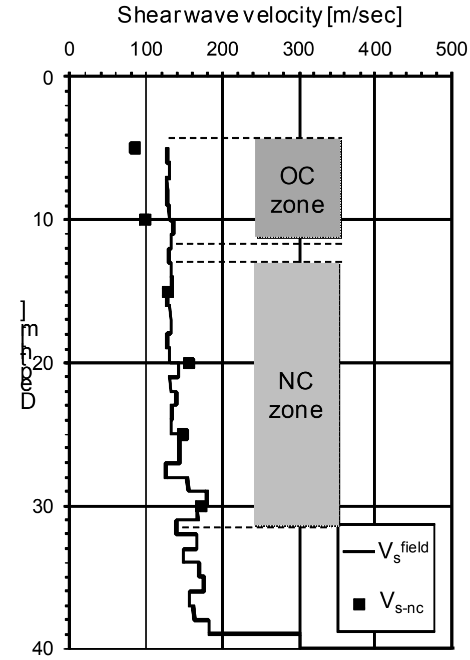



(a) Foreshore site from Incheon.




(b) Submarine deposit near Busan.

Figure 2. In-situ consolidation state evaluation results. Solid line represents the in-situ shear wave velocity profile, while solid points stand for laboratory results.




(c) Thick clay deposit from Busan.
Figure 2. *Continued.*

The in-situ conditions of reclaimed clay, including the dredged soil type, the initial water content, the local concentration of particles, and the ionic concentration, affect its sedimentation process, rendering different fabrics and structures in the clay (Imai 1980; Lee and Sills 2005). Undisturbed sampling of reclaimed clay is very difficult due to its fragility during sampling. Thus, large-scale laboratory sedimentation tests are often performed to simulate in-situ reclamation processes. However, this approach is inefficient and cumbersome. Furthermore, it is restricted to low-stress conditions (shallow depth simulation). Therefore, a new and alternative in-situ reclamation/self-weight consolidation method can be reproduced in a laboratory by performing small-scale sedimentation tests (Fig. 3) for reconstructing representative (elementary) specimens, which can be followed by conventional consolidation tests to simulate self-weight consolidation separately. Shear wave velocity based consolidation tests can then be performed on the reconstructed specimens by applying the final ("destined") effective stresses of interest at once, simulating the in-situ self-weight consolidation process.

From the laboratory consolidation test, a unique shear wave velocity – in-situ effective stress relationship (Eq. 4) is derived for a single reclaimed site. Meanwhile, a single void ratio – shear wave velocity relationship is also evaluated from strain measurements during the same laboratory procedure.

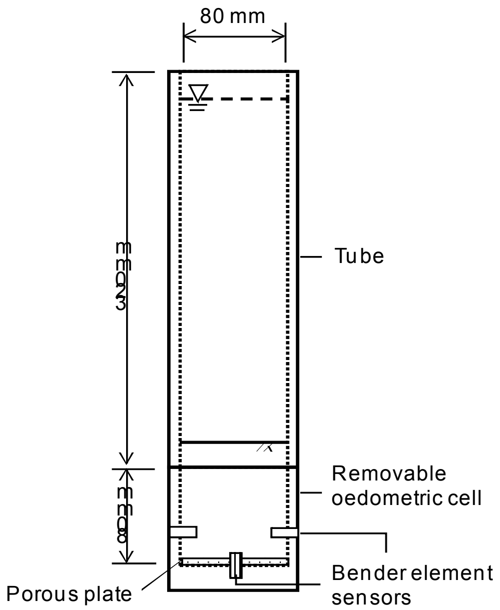



Figure 3. Sedimentation test device: Sedimentation tube with a removable oedometric cell.

Finally, geotechnical design parameters such as degree of consolidation ($U_z$), coefficient of consolidation ($C_v$), coefficient of earth pressure at rest ($K_0$), hydraulic conductivity ($k$), and undrained shear strength ($S_u$) are available to be estimated from the laboratory test results, existing large strain consolidation theories (Mikasa 1963; Been and Sills 1981; Terzaghi et al. 1996; Santamarina et al. 2001), and in-situ shear wave velocity data (Fig. 4). Details are described in Chang and Cho (2010).

Results in Fig. 4 show that the estimated geotechnical engineering parameters using shear wave velocity are consistent with those of the measured values, suggesting that shear wave velocity technique is effective for practical applications.

### 2.3 Summary

The in-situ consolidation state can be evaluated by comparing the in-situ shear wave velocity with the the expected in-situ shear wave velocity under the NC condition. The site is evaluated as over-consolidated if the in-situ shear wave velocity is higher than the expected shear wave velocity under the NC state. Otherwise it is categorized as under-consolidated. Meanwhile, the site is defined to be normally-consolidated when the in-situ shear wave velocity is close to the laboratory expected result.

The behavior of dredged and reclaimed kaolinite deposits can be characterized through a series of laboratory sedimentation and shear wave based simulation. The design parameters such as degree of consolidation, coefficient of consolidation, coefficient of earth pressure at rest, hydraulic conductivity, and undrained shear strength are estimated reliably using shear wave velocity technology.

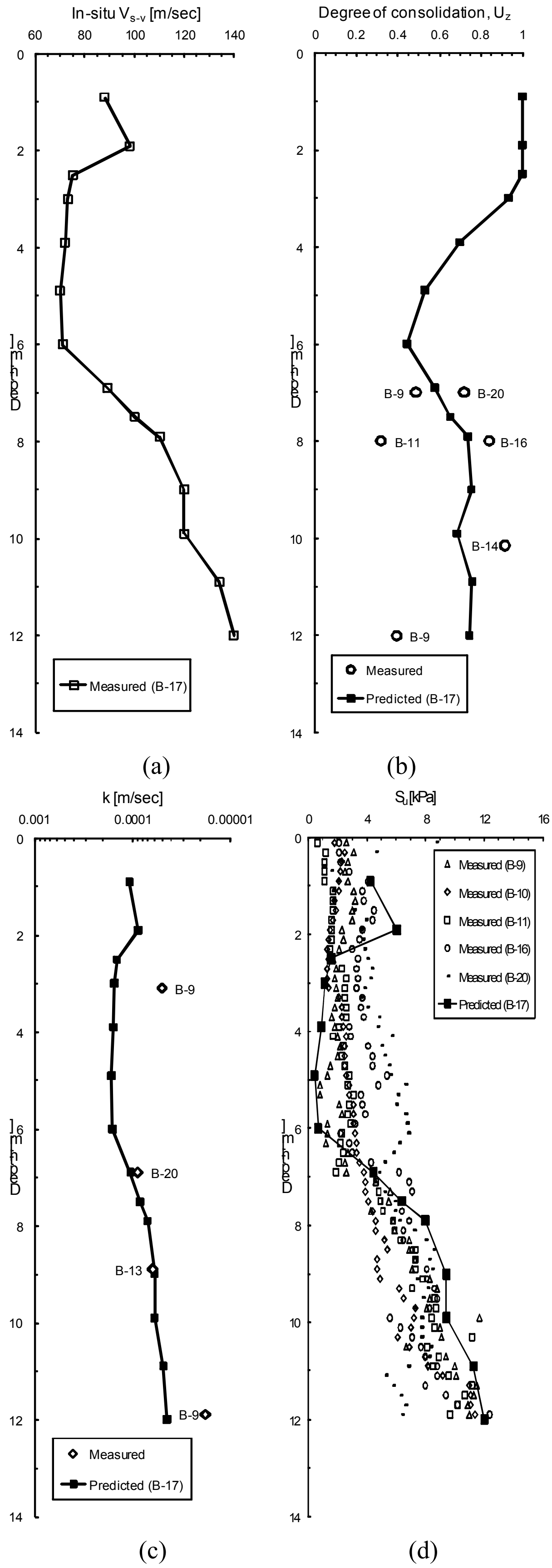



Figure 4. Comparison of the predicted geotechnical design parameters (solid lines) with the parameters measured in situ (points in b, c, and d).

## 3 ELECTRICAL RESISTIVITY-BASED CHARACTERIZATION

### 3.1 Electrical Resistivity for clay

#### 3.1.1 Electrical Resistivity

The electrical current mainly flows through the conductive phases in a material. For a particular material, the electrical current can flow through interconnected pore fluid because the pore fluid resistivity (e.g. fresh water: $1 \cdot 10^3 \Omega \cdot m$) is much lower than particle resistivity (e.g. quartz: $2 \cdot 10^{14} \Omega \cdot m$). Especially, for marine clay sediments, electrical current is clearly observed in the interconnected pore fluid due to relatively much lower pore fluid resistivity (sea water: $0.25 \Omega \cdot m$). The current flow rate can be defined as the magnitude of total electrical resistivity (hereafter, bulk resistivity). Thus, the bulk resistivity is strongly affected by porosity and pore fluid's resistivity. The bulk resistivity tends to decrease with increasing porosity and decreasing pore fluid's resistivity due to improvement of connectivity of conductors.

#### 3.1.2 Electrical resistivity models

Many researchers developed the new or modified resistivity models to verify the bulk resistivity behavior with porosity and various conducting phases such as Waff model (Waff, 1974), Modified brick-layer model (Schilling et al., 1997), or Modified Archie's model (Glover et al., 2000). However, if the conducting phase is regarded as only pore fluid, Archie's law (Archie, 1942) can be one of the simplest but most robust model for controlling parameters and providing insightful information on overall pore geometry (Winsauer et al., 1952; Jackson et al., 1978; Kwader, 1985; Worthington, 1993) Archie's law assumes that bulk resistivity is mainly influenced by pore fluid resistivity, degree of saturation, and porosity. No chemical or thermal interactions between different phases are taken into account in the model. The model considers interconnected pore fluid as a conductor. The general Archie's law at full saturation is as follows:.

$$\rho_{bulk} = a \cdot \rho_f \cdot n^{-m} \tag{6}$$

where $\rho_{bulk}$ is the bulk resistivity, $\rho_f$ is the pore fluid resistivity, $n$ is the porosity, $\alpha$ is the pore geometry coefficient, and $m$ is the cementation exponent.

### 3.2 Application

It is difficult to obtain the geophysical characteristics of marine clay sediment using conventional boring methods because of high cost as well as specimen disturbance during coring. The electrical resistivity survey can be conducted as a rapid and nondestructive geophysical method. Electrical resistivity analysis can provide geometry information to process monitoring.

#### 3.2.1 Measurement of Electrical Resistivity in Laboratory testing

An apparatus is designed for measuring the electrical resistivity of specimens with decreasing porosity by vertical loading. The apparatus consists of a cylinder shape cell, a water chamber, a top cap, a bottom cap, a signal generator, and circuit for voltage potential measurement (Fig. 5).

Electrical current of the one-dimensional field can flow only through the specimen via two electrodes. Signal generator is used to apply power supplyand alternating current (a constant frequency). Potential difference of voltage ($\Delta V$) was measured at two points to indirectly obtain the electrical current.. First measurement is for the potential difference ($\Delta V_1$) by both soil's resistance ($R_{soil}$) and an installed resistor's resistance. Second measurement is for the potential difference ($\Delta V_2$) by only soil's bulk resistance ($R_{soil}$). Soil's bulk resistance ($R_{soil}$) is calculated by Ohm's law:

$$R_{soil} = \left( \frac{\Delta V_2}{\Delta V_1 - \Delta V_2} \right) R_{known} \tag{7}$$

The electrical resistivity is then obtained from electrical resistance via a shape factor ($F_s$) calibration.

$$\rho_{bulk} = F_f \cdot R_{soil} \tag{8}$$

This calibration should be needed due to geometric difference (i.e. sharp and size) between a specimen and electrodes.

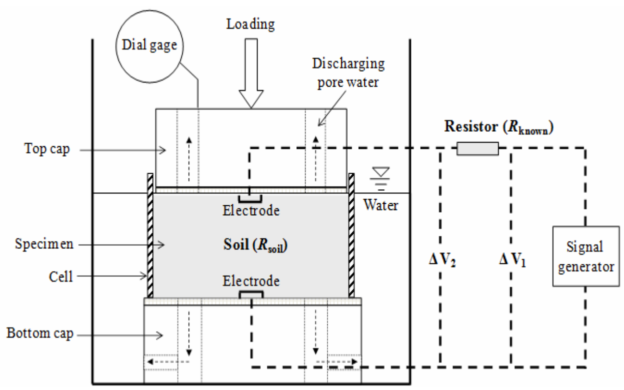



Figure 5. Apparatus for measuring electrical resistivity of soil specimen.

### 3.2.2 Characterization of marine clays

a) Particle cementation

The most useful factor in Archie's law is the cementation exponent *m*. It is recognized that this exponent is strongly related with the particle bonding condition under a fully saturated condition. Archie (1942) assumed that the exponent is dependent on the degree of cementation among particles. However, the exponent depends not only on the degree of cementation but also on the size, shape, and packing condition of particles. The exponent *m* increases with decreasing connectivity of the pore fluid (Jackson et al., 1978; Kwader, 1985; Glover et al., 2000). Especially, Jackson et al. (1978) presents that flat-like particle shape characterized for tested clays may also induce higher *m* values because the exponent increase as particle shape becomes less spherical. Full connectivity of the pore fluid is achieved when *m*=1.

An experimental result of the marin clay shows that the exponent values are approximate 7 (Fig. 6a). However, the values of natural sands are reported in the range 1.4 to 1.6 (Archie, 1942; Taylor-Smith, 1971). In addition, for slightly consolidated sands, Kwader (1985) found that values of *m* are 1.3 to 1.4. Thus, it is clear for clays to have much higher *m* values compared with sandy soils. This phenomenon may explain that clays have much poorer connectivity (i.e. lower permeability or higher tortuosity) than sandy soils. Silty sand specimen result (Fig. 6b) can support this phenomenon by comparison of relationship between clay portions and exponent values of the specimens. A1 exponent (*m*=2.72) is observed as higher than sandy soils (*m*=1.3 to 1.6) and lower than clay specimens (*m*≈7). Although this analysis has limitation due to unknown ratio of the clay component, the increasing exponents are observed with increasing portion of clay constituents which induce the poor connectivity among pores (i.e. sand < silty sand < clay).

b) Pore geometry shape

The empirical constant *a* is representative as pore geometry coefficient. Originally, Archie (1942) assumed that *a*=1, but was later found that this had to be modified in many cases. If clay is subjected to more harsh condition for electrical current flow due to more complicated pore geometry, the exponent can be out of 1. Keller and Frischknecht (1966) suggests that *a*<1 for intergranular type porosity and *a*>1 for fracture type porosity which is broadly referred by previous studies (Jackson et al, 1978; Kwader, 1985).

Silty sand specimen result, shown as Figure 6(b), shows 0.14 of pore geometry coefficient which supports Keller and Frischknecht's suggest (1966) "intergranular type porosity" for sandy soil. Marin clay specimen (Fig. 6a) also has 0.03 values of the coefficient. These coefficient results mean the pore geometry of clay specimens is intergranular-like.

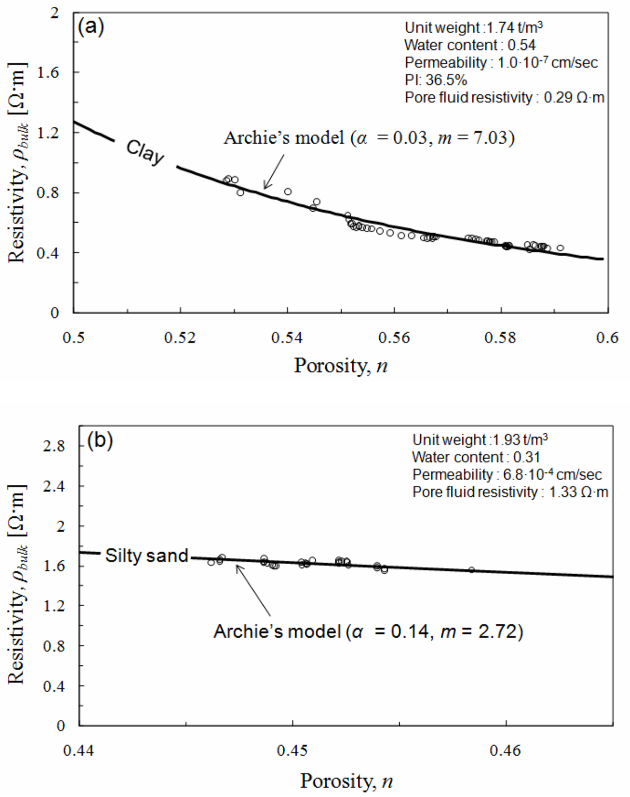



Figure 6. Bulk resistivity of marine sediments with porosity: (a) clay and (b) silty sand.

### 3.3 Summary

Electrical resistivity analysis by electro-magnetic wave can provide geophysical characteristics: particle cementation, pore geometry shape, and pore material phase condition. Changed bulk resistivity values of marine clays are reflected by changed geophysical characteristics.

● Increasing particle cementation (and decreasing pore connectivity) is monitored by increasing *m* values.
● Changing pore geometry shape is monitored by *a* values (*a*<1 for intergranular type porosity and *a*>1 for fracture type porosity).
● Changing the pore material phase is monitored by the magnitude of bulk resistivity.

## 4 GEOPHYSICAL CHARACTERIZATION OF HYDRATE BEARING SEDIMENTS

### 4.1 Importance and meaning of stability monitoring on hydrate-bearing sediment

Gas hydrate is solids comprised of water molecules forming a rigid lattice of cages with most of the cages, each containing a gas molecule which has light molecular weight. Gas hydrate is stable at low temperature and high pressure condition. Around 3.0 trillion tons of methane is trapped in hydrate form on the deep ocean floor and permafrost (Buffett 2004). Therefore, methane hydrate is considered a new energy source. A natural gas hydrate deposit of 0.6 billion tons was discovered on East-sea, Korea in 2007. This gas hydrate bearing sediments in Korea include large amount of clay particles.

Natural gas hydrate must be dissociated to extract methane from natural gas hydrate. The stiffness of gas hydrate-bearing sediments is decreases with hydrate dissociation due to the removal of bonding effect of gas hydrate between soil particles. This phenomenon could be a cause of sea floor land slide or collapse of production facility. Also, methane is about 26 times more effective on global warming than carbon dioxide (IPCC 2007). It could be a environmental disaster if methane is emitted from natural hydrate deposit to atmosphere. Therefore, continuous and reliable monitoring on the behavior and stability of natural hydrate-bearing sediments is required for natural gas hydrate extraction project.

## 4.2 Laboratory simulation

### 4.2.1 Experimental setup

The experimental setup was designed to synthesize $CO_2$-containing sediment and measure the physical properties. All the experiments were conducted in a cylindrical cell (i.e., volume 179.72 ml; internal diameter 57 mm; height 75 mm), instrumented to measure temperature, pressure, elastic wave velocities and electrical resistivity. A T-type thermocouple was mounted in the reaction cell to measure the temperature of the specimen, and the pressure was monitored by a pressure transducer. A couple of electrodes were used for electrical resistivity measurements. A couple of bender elements and a couple of PZT plate are used for elastic wave velocity measurements. The cell was submerged in a bath. The temperature of the bath was controlled between 0°C and 20°C by circulating coolant from a cooler. A couple of electrode which has a steel cap of 9.52 mm diameter is used for electrical resistivity measurement. Input voltage was 3.0 AC Volt and input frequency was 10.0 kHz.

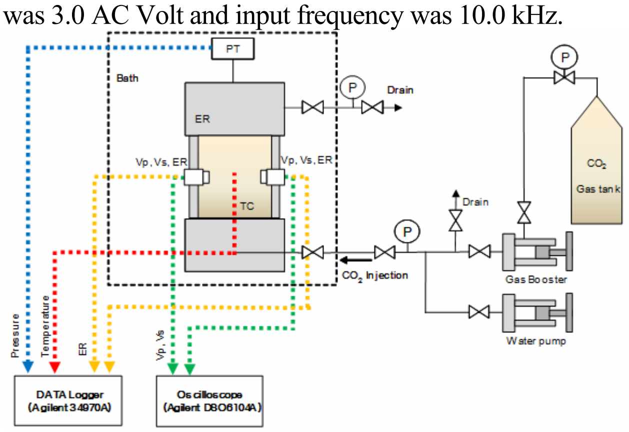
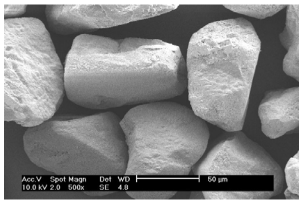
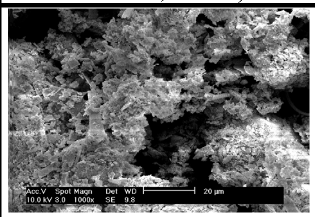



Figure 7. Experimental setup for simulation of hydrate bearing sediments (PT: pressure transducer, TC: Thermocouple, Vp: PZT plate, Vs: Bender elements, ER: Electrode).

### 4.2.2 Experimental procedure

First, the sediment specimen was slightly saturated with distilled water(water saturation was about 0.4), then $CO_2$ gas was injected with approximate 3.0 MPa to diffuse carbon dioxide into the specimen. Then the specimen was cooled from room temperature to 2.0°C. Cooled water is injected in the specimen after hydrate formation detected. Pressure, temperature, elastic wave velocities and electrical resistivity inside the system were monitored during the process.

Table 1. Used sediment specimen in this study

| Fine sand (Ottawa F110) | Marine clay (04C-6H on Ulleung Basin, East-sea, Korea) |
|---|---|
|  |  |
| $D_{50}$ = 120µm<br>$G_s$ = 2.65<br>$S_a$ ≅ 0.019$m^2$/g<br>Porosity = 0.41<br>Pore Size ≅ 190-233 nm<br>$n_{max}/n_{min}$ = 0.46/0.35<br>Sphericity = 0.7<br>Roundness = 0.7 | $D_{50}$ = 3.04µm<br>$G_s$ = 2.61<br>$S_a$ ≅ 61.55m2/g<br>Porosity = 0.40<br>Clay fraction = 10.7%<br>PL = 51.24%<br>LL = 87.95%<br>PI = 36.71% |

## 4.3 Results and analysis

Hydrate was formed with temperature decreasing at constant pressure. There was a peak on temperature because hydrate formation is exothermic reaction. Electrical resistivity and elastic wave velocities were increased suddenly by hydrate formation.

Electrical resistivity of gas hydrate is around $10^4$~$10^5$ times higher than electrical resistivity of water. Therefore electrical resistivity was increased by hydrate formation due to relatively high electrical resistivity of gas hydrate. Electrical resistivity of East-sea specimen was 10 times lower than electrical resistivity of F110 sand specimen. This is due to high ionic concentration of marine clay.

Bulk modulus of gas hydrate structure I is around 5.6 GPa. (Makogon 1997) This is higher value than bulk modulus of water, 2.2 GPa. Moreover, gas hydrate enhances the soil skeleton structure by its bonding effect. Therefore elastic wave velocity is increased by hydrate formation. Both of specimens show some difference on elastic wave velocities due to their difference on void ratio and material properties.

Meanwhile, there are differences on time and temperature for hydrate formation. In East-sea specimen, hydrate is formed more easily than in F110 sand specimen. This is due to chemical inhibitors such as NaCl (Makogon 1997).

### 4.4 Summary

Nondestructive monitoring is required for risk management and enhancement of production effectiveness of natural gas hydrate extraction project. Electrical resistivity and elastic wave velocity should be measured for this purpose. It is required that research on these geophysical properties with soil type, hydrate saturation and effective stress for field application.

## 5 CONCLUSIONS

Geophysical exploration is a rapid, cost-effective, and accurate method to characterize geological and geotechnical properties of marine clays. Seismic, especially elastic wave technology is effective on stress-strain characterization. The in-situ consolidation state can be evaluated by comparing the in-situ shear wave velocity with the the expected in-situ shear wave velocity under the NC condition.

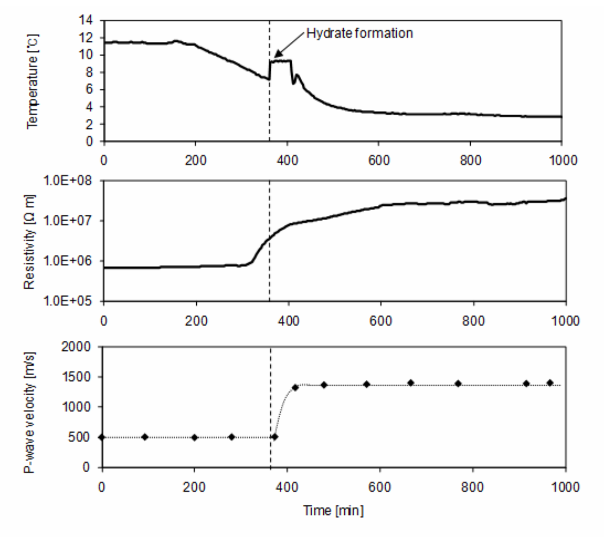



Figure 8. Electrical resistivity, and elastic wave velocity values with temperature change and hydrate formation on F110 sand specimen.

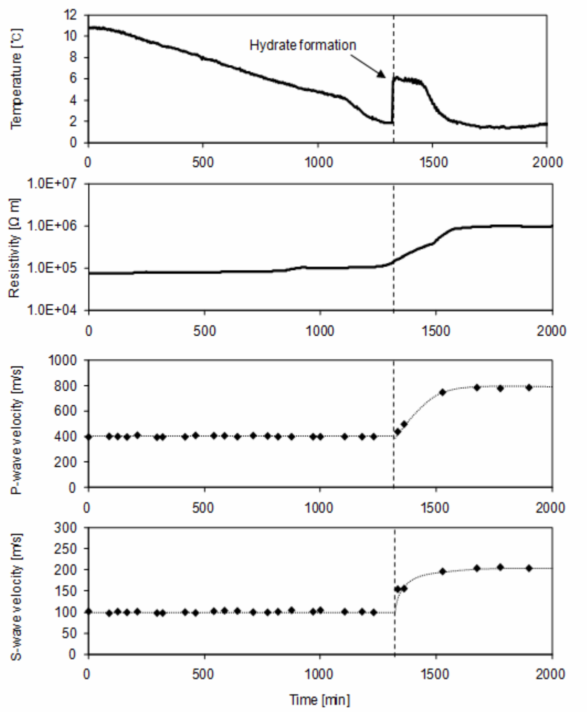



Figure 9. Electrical resistivity, and elastic wave velocity values with temperature change and hydrate formation on East-sea specimen.

The behavior of dredged and reclaimed kaolinite deposits can be characterized through a series of laboratory sedimentation and shear wave based simulation. The design parameters such as degree of consolidation, coefficient of consolidation, coefficient of earth pressure at rest, hydraulic conductivity, and undrained shear strength are estimated reliably using shear wave velocity technology.

Electrical resistivity analysis by electro-magnetic wave can provide geophysical characteristics such as particle cementation, pore geometry shape, and pore material phase condition. Changed bulk resistivity values of marine clays are reflected by changed geophysical characteristics.

For further application, nondestructive geophysical monitoring is applicable for risk management and enhancement of production effectiveness of natural gas hydrate extraction project. Electrical resistivity and elastic wave velocity are reliable indicators to monitor the stability of gas hydrate embedded marine deposits during gas hydrate dissociation (production).

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