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Role of induced electrical polarization to identify soft ground/fractured rock conditions

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ABSTRACT

This study attempted to evaluate the role and effectiveness of induced polarization (IP) along with electrical resistivity to identify soft ground/fractured rock. Theoretical studies as well as laboratory-scale experiments were conducted for this purpose. The theoretical study involved deriving the functional relationship between chargeability and influential variables. This was followed by performing a sensitivity analysis using the derived relationship to reveal that the size of narrow pores (r_1) exerted the greatest influence on the chargeability followed by the salinity of the pore water (C_0). In the laboratory test, a small-scale fractured rock zone was modeled using sandstone as a parent rock. The chargeability and resistivity were measured by changing the size of the joint aperture filled with tap water and/or sea water, the location of the fractured zone, and the thickness of the soil layer in a soil-rock multi-layered ground. The experimental study modeled the jointed zone between competent sandstone layers and indicated that the chargeability was mostly controlled by the size of the narrow pore (r_1) of the surface sandstone and not by the porosity of the jointed zone. Hence, it was concluded that the chargeability did not significantly depend on the fractured characteristics of the jointed rock. It could be difficult to clearly distinguish as to whether the low resistivity value is caused by the sea water intrusion or by the increase in porosity of the fractured ground. However, the IP exploration can be effectively utilized to identify sea water intrusion since the chargeability decreased as the salinity of pore water increased. The experimental study on a soil-rock multi-layered ground indicated that the measured chargeability was controlled by the percentage of current flow that passed through the competent rock as well as by the narrow pore size of the rock itself. In conclusion, the ground condition could be easily identified by measuring the IP in conjunction with the electrical resistivity, and this increased the reliability of identifying the existence of sea water, layered ground, and/or the fractured rock.

1. Introduction

Induced Polarization (IP) is a geophysical phenomenon that represents either the voltage attenuation in the ground after turning off an injected current in the time domain or the frequency variation of the resistivity of the ground in the frequency domain. In simple terms, the IP effect reflects the degree to which the rock/soil can store electric charge when an electric current passes through it in a manner analogous to a leak capacitor (Kiberu, 2002). The pioneering study by Schlumberger (1920) involved the discovery of an IP response for the first time. Following this, there were no further significant developments for several decades until the fore-mentioned study was rediscovered by Bleil (1953), Wait (1958), and Marshall and Madden (1959). Bleil (1953) revealed that the IP phenomenon in a mineralized zone and/or in an electrolyte containing metallic minerals was generated at the surface of minerals, and this phenomenon was the same as that occurring in the polarized electrode. Wait (1958) attempted to theoretically estimate the IP in the frequency domain. He suggested that an IP response could be defined in terms of resistivities measured at low frequency as well as at high frequency. Marshall and Madden (1959) explained the IP effect based on membrane polarization in which metallic minerals were not present. In the studies that followed, the IP was diversely utilized in field explorations for petroleum, groundwater resources, and environmental studies such as the mapping of an intruded saline water area (Roy and Elliott, 1980; Seara and Granda, 1987). Additionally, attempts were made to identify the causes of IP in the ground without the presence of metallic-type minerals (Fridrikhsberg and Sidorova, 1961; Titov et al., 2004). These studies proposed a capillary model and explained that the rise of residual voltage that occurred from the

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variation of ionic mobility was caused by piled-up positive ions at the narrow pore throat (capillary pore) within the granular particles.

An electrical resistivity survey is frequently utilized for site investigations during the design stage of a construction project. However, the IP is rarely used in the geotechnical engineering field. In this study, the role and effectiveness of the IP in conjunction with the electrical resistivity was examined from a geotechnical engineering viewpoint to identify the soft ground/fractured rock conditions by conducting theoretical studies and laboratory experiments. In the theoretical study, the relationship between the chargeability and variables affecting chargeability was derived. A sensitivity analysis using the derived relationship was performed to identify the main factors that significantly influenced the chargeability. In the laboratory experiment, a fractured rock zone was modeled on a small scale using sandstone as a parent rock. Chargeability and resistivity were measured at the ground surface by changing the size of the joint aperture both with and without the existence of the clay gouge within the joint, changing the water salinity levels, and changing the location of the fractured zone separate from the ground surface. In addition, the thickness of the soil layer (that exhibited lower chargeability than the sandstone layer) was varied to perform tests on the soil-rock multi-layered ground. Finally, chargeability variations measured from the laboratory tests were compared with those obtained from the derived theoretical relationship. Finally, the study verified the effectiveness of IP along with the electrical resistivity to identify the fractured rock conditions and/or the multi-layered ground conditions.

2. Theory

2.1. Induced polarization in the ground

The phenomenon of IP in the ground without the presence of metallic minerals is primarily caused by accumulating positive ions (cations) at a narrow pore channel (see Fig. 1). In natural ground conditions with pore water, positive ions within pore fluid are attracted to the negatively charged surface of the rock and/or soil and form a positively charged layer (Kiberu, 2002). The positively charged layer at the narrow pore channel and/or the narrow pore throat itself hinders the flow of ions and causes an increase in positive ion concentrations that generates a potential difference across the pore throats.

2.2. Time domain method

The IP value can be measured either by the time domain IP method or by the frequency domain IP method. The time domain IP method uses direct current (DC), while the frequency domain IP method uses alternating current (AC) and the apparent resistivity is measured at different AC frequencies. However, in theoretical terms, the time domain IP and frequency domain IP are identical to each other because the equations to estimate the two IP methods can be transformed into each other by using Fourier transform. In this study, the time domain IP method was adopted to simultaneously measure the electrical resistivity and the IP value by injecting a DC into the ground.

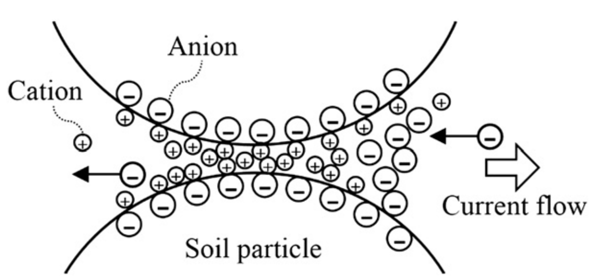

Fig. 1. Accumulation of cations at the narrow pore channel.

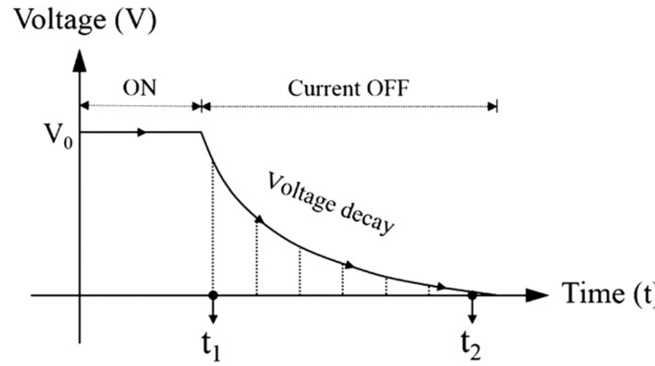

Fig. 2. Voltage decay curve in time domain IP.

In the time domain method, an electrical current that flows into the ground is abruptly turned off. The attenuating voltage is then measured for a given time to estimate the apparent chargeability in order to determine the polarization characteristics of the ground. The electric potential difference created between the potential electrodes does not abruptly disappear when the current is switched off. However, it starts to decrease slowly (see Fig. 2), and this is a phenomenon that occurs due to the resultant voltage caused by the piled-up cations inside the ground.

Fig. 2 indicates a general voltage decay curve to measure the time domain IP. Specifically, V_0 denotes the voltage while current is injecting into the ground. The current is then switched off, and the voltage decay $V(t)$ between the time interval t_1 and t_2 is measured. From Fig. 2, the chargeability, m that represents the polarization characteristics can be expressed as follows:

$$m = \frac{1}{V_0}\int_{t_1}^{t_2} V(t)\, dt \tag{1}$$

2.3. Derivation of chargeability relationship

Fridrikhsberg and Sidorova (1961) proposed a capillary model to explain the IP effect within ion conductive soil/rock. This model explains that the IP phenomenon in the ground occurs when cation concentrations increase as the cations accumulate at the narrow pore throats where the current passes through. In other words, a local ion concentration gradient is produced in areas of variation of the pore radius. Fridrikhsberg and Sidorova (1961) derived an expression for the magnitude of the IP in terms of the chargeability (denoted as m) based on the

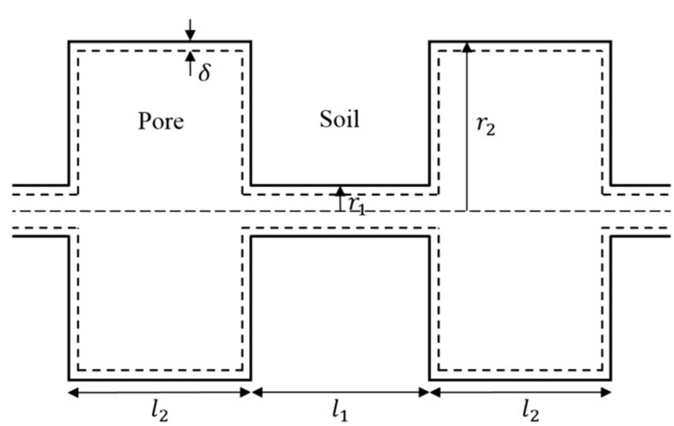

Fig. 3. Schematic view of a 'slit' sequence representing interconnected pores.