Monitoring of ground condition into road decrepit slopes by seismic and electric prospecting

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A large number of shotcrete slopes that were constructed in Japan during the 1970's are now more than 30 years old, and there has been a significant degree of deterioration. Therefore, it is important to develop a method for monitoring the stability and the durability of these slopes. In this paper, we propose a technique that converts seismic velocity and electric resistivity data to porosity and saturation, which is then used to monitor weathering and groundwater fluctuation behind the slope. The evaluation results of this methodology confirm that the distribution of porosity and saturation of rock mass around the evaluated slope arrived at by this conversion system agree with those of the actual rock mass conditions evaluated using boring samples. In addition, it was possible to monitor the signs of seasonal variation and weathering in the ground by performing monitoring using this methodology over a period of multiple years.

1. INTRODUCTION

Slope stabilization structures made with shotcrete were constructed in large numbers in Japan in the 1970's. As more than 30 years have passed since their original construction, a variety of problems have come to light, such as cavitations behind the concrete lining, and slope failures caused by weathering of the natural ground. Currently slope management is conducted primarily by road patrols and road facility inspections to prepare disaster prevention records regarding aged slopes. If further investigation of a particular slope is found to be required, a geophysical exploration is conducted to review countermeasures to be taken against defects. When designing prevention works for a slope, it is necessary to know the engineering properties of the rock behind the slope. Therefore, geophysical parameters such as seismic velocity must be reliably converted to engineering properties so that geophysical methods can be used more effectively in evaluating the slope. In many cases, a single geophysical property, such as resistivity, is not sufficient to accurately estimate the engineering properties of rocks. For these reasons, Kusumi and Nakamura (2007) devised a technique that can convert in-situ seismic velocity and resistivity to porosity and water saturation distributions (hereafter referred to as "conversion analysis"). In this study, using this conversion analysis methodology we tried to monitor the thickness of weathered rock and the degree of moisture build up in a more accurate manner, with a focus on seismic and electrical explorations that are considered to be effective in assessing the weathering of the natural ground behind the slope and variations in ground water levels.

2. GEOLOGICAL CONDITIONS OF THE SLOPE

The geophysical data for the analysis in this study was acquired at a shotcrete slope (A-district) and a non-supported slope (B-district) of a national highway as shown in Figure 1. In geological terms, the overall slope consists of a sandstone layer, alternating sandstone-shale strata, and a basalt lava layer, which are located in the Tanba strata formed during the Triassic and Jurassic periods of the Mesozoic era. Figures 2 and 3 show the locations of the investigation, which are near the south side of the national road. The overall slope is comparatively large-scale, with dimensions of about 200m in length and about 50m in height. The shotcrete slope is located in the eastern part of the overall slope, and the non-supported slope is located in the western part of it. On the surface of the shotcrete, there are many cracks due to aging, and a lot of vegetation can be seen protruding from the cracks along with associated swelling.

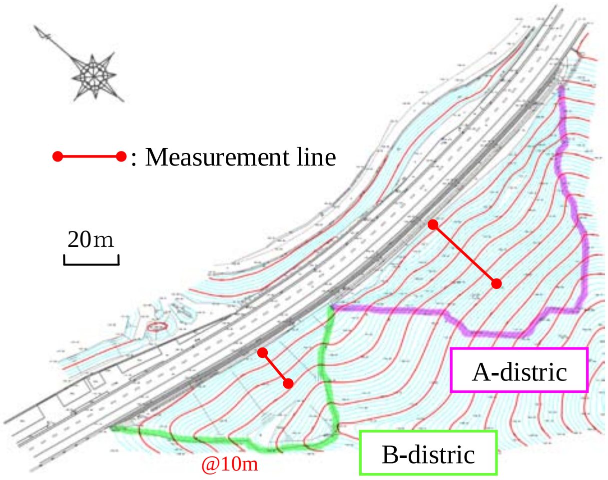


Figure 1. Topographic features of the slope

Figure 2. View of A-district (shotcrete slope)

Figure 3. View of B-district (non-supported slope)

3. OUTLINE OF CONVERSION ANALYSIS

There have been several studies regarding the empirical relations between geophysical parameters such as seismic velocity and resistivity, and engineering properties such as porosity. Wyllie's time average equation (1956) and Archie's law (1942) are two of the well known relations. Conversion analysis uses Wyllie's equation, which relates seismic velocity to porosity and water saturation as shown in Equation 1, and Archie's law, which relates resistivity to porosity and water saturation as shown in Equation 2.

$$\frac{1}{V_P} = \frac{(1-\phi)}{V_m} + \frac{\phi \cdot Sr}{V_f} + \frac{\phi \cdot (1-Sr)}{V_a} \qquad (1)$$

$$\rho = a \cdot \rho_w \cdot \phi^{-m} \cdot Sr^{-n} \qquad (2)$$

where V_p = seismic P-wave velocity of rock mass; V_m = seismic P-wave velocity of the intact piece; V_f = seismic P-wave velocity of the pore water; V_a = seismic P-wave velocity of the pore air; ρ = resistivity of rock mass; ρ_w = resistivity of water; ϕ = porosity; Sr = saturation; a, m, n = constants (these are called "conversion parameters").

It is well known that Wyllie's equation can only be applied to seismic waves of higher frequency. We have tested its applicability in a physical model experiment and found that it approximately holds true in our field data (Nakamura et al., 2003).

Regarding Archie's law, recent studies (for example, Chiba and Kumata, 1994) have shown that a modified version of Archie's law based on the parallel circuit model as given in Equation 3 should be used for rocks with more conductive materials than water, such as clay. Therefore in this study Equation 3 is employed instead of Equation 2 in the conversion analysis.

$$\frac{1}{\rho} = \frac{1}{F \cdot \rho_w} + \frac{1}{\rho_c} \qquad (3)$$

where F = formation factor ($=a \cdot \rho_w \cdot \phi^{-m} \cdot Sr^{-n}$), ρ_c = resistivity of conductive solids distributed in the rock.

Equations 1 and 3 can be also expressed by the following simultaneous equations for a rock model divided into small elements as shown in Figure 4.

$$Vp = f(\phi, Sr) \qquad (4)$$

$$\rho = g(\phi, Sr) \qquad (5)$$

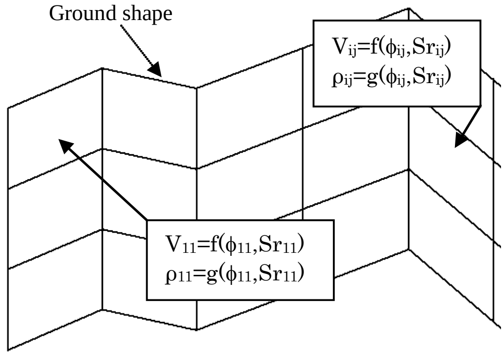


Figure 4. The cell-based rock mass model for conversion calculations

In the conversion analysis, these simultaneous equations are solved with the optimization method. Input values used for the conversion analysis are the resistivity distributions obtained by electrical or electromagnetic prospecting and the seismic velocity distribution obtained by seismic prospecting. In the calculation, the rock mass is divided into cells as shown in Figure 4 and porosity and water saturation as unknowns assigned for each cell are estimated from seismic velocity and resistivity measurement values (Nishikata et al., 1998).

The calculation to obtain geophysical data is performed with the flowchart shown in Figure 5. Seismic P-wave velocity and resistivity values are first assigned to each cell in the rock mass model. The known parameters and constants in Equations 1 and 3 are then set up. They are the P-wave velocity of the intact rock piece (V_m), the P-wave velocity of the pore water (V_f), the P-wave velocity of the pore air (V_a) in Equation 1, and the constants (a, m, n) indicating the ground quality in Equation 3. The simultaneous equations are then solved to obtain porosity and saturation values for each cell. The volumetric water content is calculated by multiplying porosity by water saturation.

Conversion parameters are usually estimated from laboratory tests of rock core samples obtained in the boreholes at the site. If there is no available data for the site, conversion parameters from the database we have developed (Kusumi and Nakamura, 2007) are employed.

Porosity estimated by conversion analysis is used for the rock mass classification by setting up the threshold of the porosity, which is determined based on the positional data obtained using the boring data. Saturation estimated by conversion analysis is used for the evaluation of groundwater level and water channel. Through this process of conversion analysis, it is possible to perform a more quantitative evaluation of the results of seismic and resistivity explorations, which previously were evaluated individually and qualitatively.

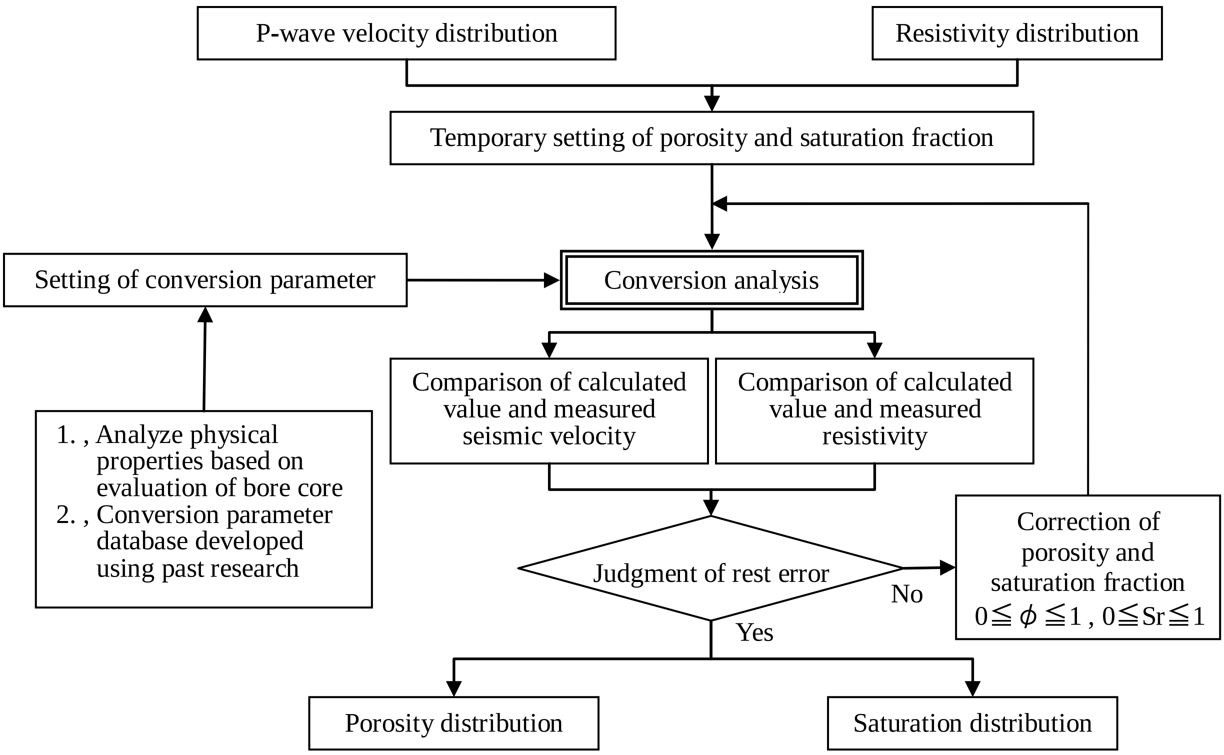


Figure 5. System flow for evaluation of geological structure using the conversion method

4. GEOPHYSICAL DATA USED IN THE ANALYSIS

At the investigation sites, seismic tomography and resistivity tomography were carried out between the ground surface and the boreholes. Investigation was conducted a total of 4 times, once in the summer and once in the winter for 2 years. Resistivity tomography at the A district indicated that the resistivity near ground level had decreased significantly due to the influence of metal bodies behind the shotcrete. Therefore, the evaluation by the conversion analysis was carried out using the results of the B district.

The results of the 2 tests that were performed during the 2 winter investigations are shown in Figure 6 and 7. The interval of the receiver and/or electrode was 1m. As a seismic source, a sledge hammer was used on the ground, and in addition, a water hammer was used on the borehole. From these figures, it can be seen that seismic velocity of 1,000 m/sec or less is distributed around several meters in depth at the slope. Furthermore, seismic velocity at the deepest layer reaches about 3,000 m/sec. A comparison of the 2 winter investigations shows that there was hardly any difference in the seismic velocity distribution.

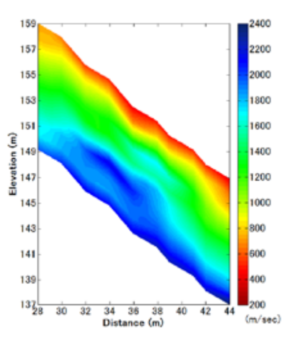
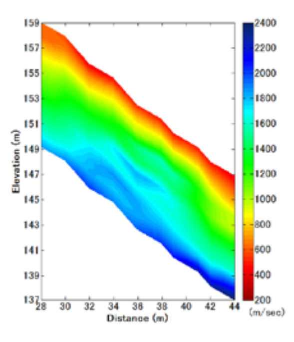
P-wave velocity	
2008/Winter	2009/Winter
	

Figure 6. Results of seismic prospecting

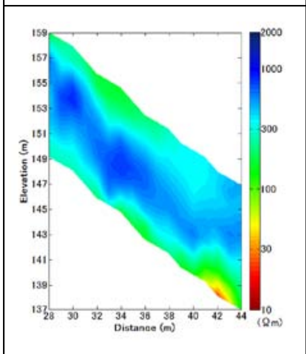
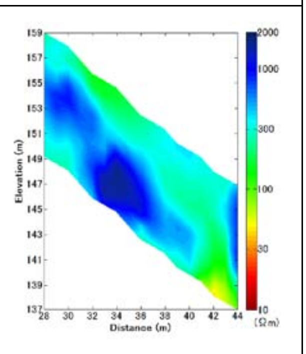
Resistivity	
2008/Winter	2009/Winter
	

Figure 7. Results of electric prospecting

On the other hand, from the resistivity distribution, it can be seen that a range of high resistivity zones are spread in middle area. In contrast, the deeper interior of the rock has lower resistivity. According to the boring information, it is estimated that alternating sandstone-shale strata exist in the low resistivity area, and green rock exists in the high resistivity area. In the comparison of the resistivity distribution of the 2 winter investigations, there was an increase in the contrast between high resistivity and low resistivity.

5. CONVERSION PARAMETERS USED IN THE ANALYSIS

(1) Setting the conversion parameters

The conversion parameters are set by measuring resistivity and seismic P-wave in an indoor experiment, using a boring core test piece in a considering point. The relational expressions of resistivity used for the conversion analysis is a formula created when calculating the relations of resistivity and saturation, and that of resistivity and porosity from the measuring results of the indoor experiment.

The resistivity increases exponentially as the saturation decreases, the relational expression of the two is shown as follows.

$$\rho = \alpha \cdot Sr^{-n} \qquad (6)$$

Where ρ = resistivity of rock mass; α = resistivity in the state of saturation; Sr = saturation; n = constant (one of conversion parameters).

And from the relation between the resistivity and the porosity in the state of saturation, we obtained the relational expression as follows.

$$\alpha = a \cdot \rho_w \cdot \phi^{-m} \qquad (7)$$

Where ρ_w = resistivity of water; ϕ = porosity; a, m = constants (the other of conversion parameters).

Therefore, it is possible to set the constants (a, m, n), which are conversion parameters by calculating these relations. The fact that there is a good relation between the points that are made by plotting the figures of the P-wave velocity obtained in the indoor experiment and a theoretical curve made by Wyllie's formula makes it possible to set the conversion parameters on the P-wave velocity. For example, Figure 8 and 9 show some results of the indoor experiment.

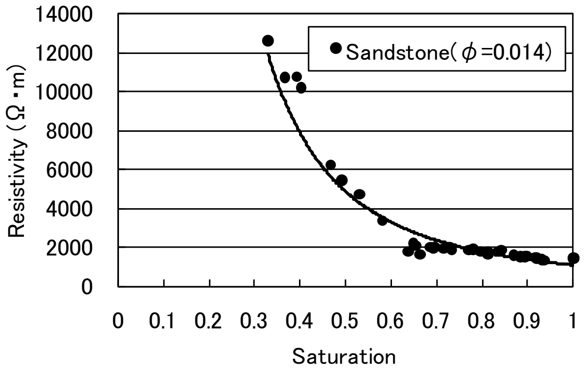


Figure 8. Example of relationship between resistivity and saturation

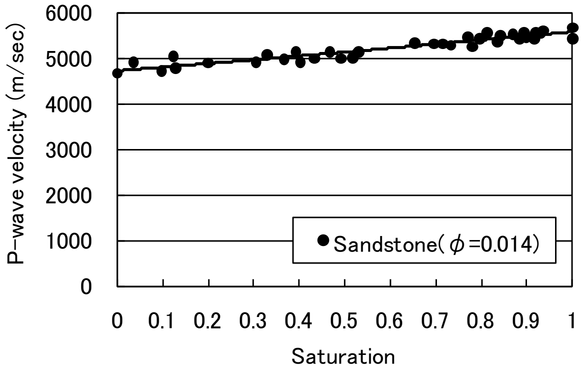


Figure 9. Example of relationship between P-wave velocity and saturation

(2) List of conversion parameters

The conversion parameters were decided in this research by evaluating the physical properties of boring cores from the considering point. Table 1 shows the conversion parameters of the rock types used in this conversion analysis.

6. RESULTS OF EVALUATION BY CONVERSION ANALYSIS

The results calculated by conversion analysis are shown in Figure 10. A comparison of the porosity indicates that there was a higher level of porosity around the ground level in winter 2009 than winter 2008. So, it can be inferred that there was significant weathering of this part of the slope. Also, there appears to be less saturation around the ground level in winter 2009 than in winter 2008. In addition, winter 2009 exhibits a decrease in the saturation near the middle 10m in depth of the figure. From this fact, it would be possible to estimate the location of the water channel right after the rainfall.

Table 1. The conversion parameters of the rock types used in this conversion analysis

Type of rock		Sandstone	basalt	Alternating sandstone-shale strata
Conversion parameter	a	0.10	0.43	0.08
	m	1.61	1.04	1.32
	n	2.53	1.64	1.72
P-wave velocity	V_m (m/sec)	4,100	6,400	5,700
	V_f (m/sec)	1,500	1,500	1,500
	V_a (m/sec)	330	330	330
Resistivity	ρ_w (Ωm)	50	50	50
	ρ_c (Ωm)	3,800	2,800	1,300

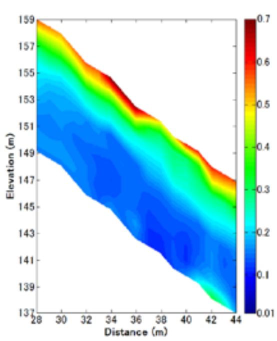
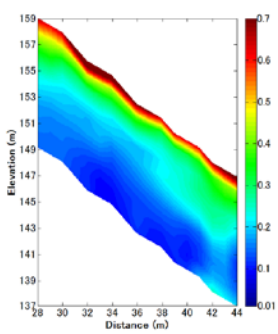
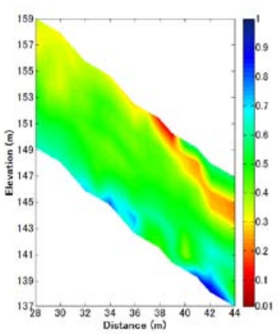
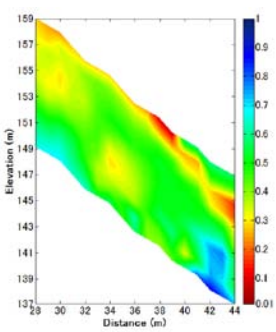
Porosity		Saturation	
2008/Winter	2009/Winter	2008/Winter	2009/Winter
			

Figure 10. Results of conversion analysis

7. CONCLUSION

In this study, data obtained by seismic prospecting and resistivity prospecting was used to verify the applicability of conversion analysis to calculate the porosity and the saturation fractions that can be in turn used as an effective tool to evaluate the soundness of aging slopes. The porosity distribution data that was obtained by conversion analysis tended to roughly correspond with the rock class division of the boring results. Moreover, a change in porosity over time was detected, which suggests the usefulness of this methodology for monitoring the progression of weathering.

Regarding the saturation distribution data obtained by conversion analysis, there was a tendency for the area where the saturation fraction is high to roughly correspond to the location of groundwater. This indicates that conversion analysis is an effective technique for estimating the position of the water channel.

It was found that metal bodies within the shotcrete slope had a strong influence on the resistivity distribution of the ground level, and as a result it was determined that evaluation by conversion analysis could not be carried out. It is expected that future improvement in the measuring method will make it possible to eliminate this sort of interference.

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