Analysis of Rockslide and Engineering Slide via Integration between Rock Mechanical and Geophysical Parameters

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Abstract. The measurement of rock mechanical parameters is an essential step to assess rockslide and engineering slide to support the design of any underground project. Traditionally, such parameters are obtained by the number of drilling tests. However, such tests suffer from efficiency in terms of time, cost, and data coverage. In addition, drilling methods need more equipment and cannot be performed in steep topographic areas. Thus, the use of geophysical methods, such as electrical resistivity tomography (ERT), is noninvasive, user friendly, and cost effective. In this work, we introduce a new approach that involves the empirical integration of rock mechanical and geophysical parameters. Our novel approach provides an efficient alternative to the borehole tests for the estimation of rock mechanical parameters, such as the rock mass integrity coefficient ($K_v$). This approach gives insights into the subsurface for the assessment of rockslide and engineering slide. The subsurface is mapped with different types of rock mass, such as crushed, poorly integral, and fresh bedrock or integral rock. This approach reduces a significant number of borehole tests and assesses the rock mass quality with more than...
90% accuracy compared with traditional approaches. Our novel approach is applicable in most cases.

1. Introduction

The continuous development of rock engineering structures, including infrastructure facilities and water conservancy projects, has increased the engineering disasters [1]. For the successful progress of a project in a rock mass construction, the rock mass quality of engineering geology must be evaluated. The design assumptions of engineering structures mainly depend on the analysis of rock mass quality [2]. Moreover, such assessment reveals the engineering geological conditions of the rock mass and thus provides insights into rockslide and engineering slide. Additionally, during construction, the rock mass quality evaluation helps to establish applicable theoretical criteria and disaster prevention and control process. For underground engineering surveys, designs, and safety construction, an accurate assessment of rock mass quality is important. Such studies are the main research topic in geotechnical engineering and rock mechanics [3].

Rock mass quality evaluation serves as a basis for classification of rock mass characteristics [4]. The rock mass integrity coefficient (Kv) is used to assess the strength of rock mass and thus presents the general stability and quality of engineering rock mass. This coefficient is one of the important indices in rock mass classification and rating of rock mass integrity. However, this integrity coefficient is obtained via conventional boreholes and hence difficult to acquire in frequent drilling tests. Additionally, boreholes techniques are costly, time consuming, require more equipment, cannot be carried out in steep topographic areas, and only provide the information about a single point [5]. Therefore, the evaluation of rock mass quality in geotechnical engineering is a challenging task for engineering geologists and experts. Meanwhile, the use of geophysical methods is noninvasive, inexpensive, and user friendly and provides a large coverage [6]. A relation exists between geophysical and rock properties, such as uniaxial compressive strength, modulus of elasticity, Schmidt hardness, slake durability index, porosity, and density [7,8,9]. Geophysical parameters, such as electrical resistivity and seismic velocity, have a correlation with rock mechanical parameters, including rock mass integrity coefficient and rock quality designation; these geophysical parameters decrease with the increase in the number of fractures/joints [10,11].

In this work, a noninvasive geophysical method called electrical resistivity tomography (ERT) was performed along three profiles in an accelerator-driven system in South China (Figure 1a). The rock mass integrity coefficient obtained from four borehole tests was correlated with the electrical resistivity acquired from three ERT profiles. Such correlation was used to obtain the empirical equation so as to provide the two-dimensional (2D) and 3D mapping of rock mass integrity coefficient over the entire area at great depths.

2. Methodology

In the ERT survey, electric current was measured via a pair of current electrodes, where as the potential difference was measured using another pair of potential electrodes. Then, the following equation was used to obtain the apparent resistivity:

\[
\rho = \frac{K \Delta V}{I}
\]  
(1)
where \( \rho \) is the apparent resistivity calculated in \( \Omega \) m, \( \Delta V \) shows the potential difference in volts, \( K \) is the geometric factor of the electrode array, and \( I \) is the electric current in ampere. The apparent resistivity measured in the field is not the true resistivity of subsurface materials. The true resistivity was acquired using an inversion program of the software. In this work, ERT measurements were acquired by ABEM Lund Imaging System (Lund University, Sweden) using a pole-dipole array along three geophysical profiles. In the pole-dipole array, a remote pole was used at an “infinite” equivalent distance away from the array to obtain the apparent resistivity data [12]. The asymmetric effects of the pole-dipole array were removed by the integration of two independent measurements of forward and reverse pole-dipole along each profile. The signal quality was enhanced via stacking with a maximum number of 10 times. The apparent resistivity measurements along profile 1 were acquired using 261 electrodes for the electrode interval of 5 m and a profile length of 1300 m in the SE-NW direction. The ERT profile 2 was obtained using 65 resistivity data points, 5 m electrode spacing, and 320 m spread length in the SW-NE direction, whereas profile 3 was attained with 61 resistivity measurements, 5 m electrode interval, and 300 m profile spacing in the SW-NE direction. Finally, the inverse computation analysis of the optimized method using Res2dinv was performed to acquire pseudo-sections of true resistivity [12].

The rock mass integrity coefficient was obtained in three boreholes up to 40 min depth using the following equation:

\[
K_v = \left( \frac{V_{pm}}{V_{pr}} \right)^2 \quad (0 \leq K_v \leq 1) \tag{2}
\]

Where \( K_v \) is the rock mass integrity coefficient, \( V_{pm} \) shows the rock mass acoustic P-wave velocity in km/s, and \( V_{pr} \) is the intact rock velocity in km/s. The intact rock velocity \( V_{pr} \) was acquired from the core samples, whereas the rock mass acoustic velocity \( V_{pm} \) was measured via in situ measurement. The rock mass acoustic velocity depends on the structural characteristics, rock composition, joint cementation, rock mass discontinuity, and groundwater occurrence. Hence, the rock mass integrity coefficient \( K_v \) was used in the comprehensive evaluation of the rock mass integrity in hard rock investigations.

The rock mass integrity coefficient provides the evaluation of the rock mass strength at four well points up to a maximum depth of 40 m. To assess the subsurface for the analysis of rock mass quality for large depths (i.e., 100 m) and large coverage over the entire area, we correlated the integrity coefficient with ERT. For this purpose, the true/inverted resistivity of specific ERT data points (i.e., four data points) near the boreholes were correlated with the rock mass integrity coefficient obtained from the boreholes at different depths. Via the correlation between boreholes lithology, \( K_v \), and resistivity, the following empirical equation was obtained (Figure 1b):

\[
y = 0.181 \ln(x) - 0.6998 \tag{3}
\]

Where \( y \) shows the rock mass integrity coefficient, and \( x \) presents the resistivity. The inverted resistivity of all ERT data points was used in the above equation to obtain \( K_v \) over the entire area at large depths. Equation (3) was used to obtain \( K_v \) for the highly weathered rock (crushed), partly weathered rock (poorly integral) and fresh bedrock (integral) (Figure 1b).
3. Results and Discussions

3.1. Rock mass integrity coefficient from boreholes

In this work, four boreholes were made to acquire the rock mass integrity coefficient ($K_v$) to assess the rock mass quality/strength for rockslide and engineering slide at the specific borehole location. The results of rock mass integrity index coupled with the borehole lithology suggest that the highly weathered or crushed rock had $K_v$ values less than 0.35, partly weathered or poorly integral rock delineated via $K_v$ ranging from 0.35 to 0.55, and fresh or integral bedrock with $K_v$ as low as 0.56 and as high as 1.00 (Table 1). The rock mass integrity index was obtained from the core samples of three boreholes for the 40 m depth only, hence providing low coverage for the evaluation of rock mass quality at four well points for the shallow depth only. However, the investigated area has a highly heterogeneous setting of hard rock, which changes from point to point throughout the study area. Thus, more boreholes were drilled to cover the entire site. However, the project budget limited the drilling of numerous boreholes. Therefore, an alternative approach that can be used to assess the rock mass quality of the...
entire study area before the construction of engineering structures was applied. This problem was solved by using a noninvasive ERT survey along three profiles. Then, the ERT data were correlated with the $K_v$ of boreholes to map $K_v$ over the entire area.

3.2. Correlation between ERT and $K_v$

The 2D ERT pseudo-section was obtained along each geophysical profile. The ERT maps were integrated with the borehole lithology. Based on the calibration between the electrical resistivity of ERT and lithological logs of boreholes, the subsurface layers were delineated with a specific range of resistivity. The first layer was delineated as the highly weathered or crushed rock with resistivity values less than 400 $\Omega$m, the second layer underlying the top layer was assessed as the partly weathered or poorly integral rock with resistivity between 400–1000 $\Omega$m, and the final layer below the second layer was interpreted as the fresh or integral bedrock with resistivity greater than 1000 $\Omega$m (Table 1). The resistivity of four ERT data points near the boreholes were correlated with the rock mass integrity index of the same boreholes at different depths with a maximum of 40 m depth. Resistivity values less than 400 $\Omega$m were inputed in Equation (3) to obtain a $K_v$ less than 0.35 for the highly weathered or crushed rocks. A resistivity between 400–1000 $\Omega$m was used in the same equation to obtain $K_v$ values in the range of 0.35–0.55. Similarly, Equation (3) was used for resistivities greater than 1000 $\Omega$m to obtain $K_v$ values greater than 0.55 for the fresh or integral bedrock.

| Resistivity ($\Omega$m) | $K_v$ | Rock mass quality         |
|------------------------|-------|----------------------------|
| <400                   | <0.35 | Highly weathered or crushed|
| 400-1000               | 0.35-0.55 | Partly weathered or poorly integral |
| >1000                  | >0.55 | Fresh or integral          |

3.3. 2D mapping of $K_v$

The apparent resistivity data acquired from the ERT survey were processed and plotted as 2D maps of the inverted resistivity via the inversion program of the software (Figure 2a). The electrical resistivity values along the ERT profiles 1–3 ranged between 0–105000 $\Omega$m over the entire investigated area. Based on the empirical correlations between the rock mass integrity index and the electrical resistivity of ERT, the 2D map of $K_v$ was obtained for each profile (Figure 2b). The 2D maps of the rock mass integrity coefficient assessed the subsurface with $K_v$ ranging from 0 to 1. The rock mass quality/strength of the subsurface was delineated via 2D interpreted maps of $K_v$, such as the top layer of crushed or highly weathered rock with $K_v$ less than 0.35, the second layer of poorly integral or partly weathered rock with $K_v$ between 0.35–0.55, and the bottom layer of integral or fresh bedrock with $K_v$ ranging between 0.55 and 1.00 (Figure 2c).
3.4. Integration of 2D $K_v$ maps

The 2D $K_v$ map for each profile was obtained. To determine the exact location of the $K_v$ maps, we integrated the three 2D $K_v$ maps (Figure 3a). The 2D $K_v$ map of profile 1 was oriented in the SE-NW direction, whereas the 2D $K_v$ maps of profiles 2 and 3 were oriented to the SW-NE direction. Similarly, the interpreted 2D $K_v$ maps of the rock mass qualities were integrated (Figure 3b). The integrated 2D $K_v$ maps suggest that the average thickness of the crushed or highly weathered layer was 20 m, the average thickness of the poorly integral or partly weathered layer was 10 m, whereas the fresh bedrock was revealed at an average depth of 30 m. The integrated maps also revealed five deep weathered or poorly integral zones with a depth of more than 70 m. Two such zones were delineated along profile 1 at 250 and 870 m distances, one deep weathered/fault zone was interpreted along profile 2 at 100 m distance, and another fourth such zone was revealed at 50 m distance along profile 3 (Figure 3b).
identified deep weathered or fault zones provide unsuitable places for the construction of engineering structures. Thus, such zones should be avoided in the construction of engineering infrastructures in the investigated area.

Figure 3. (a) Integration of 2D $K_v$ maps of the three profiles; (b) delineation of rock mass quality based on (a).

3.5. 3D mapping of $K_v$

To obtain further insights into the subsurface for the evaluation of rock mass quality over the entire study area, we plotted the obtained $K_v$ values as a 3D map (Figure 4a). Near the surface, $K_v$ showed low values, where a sits values increased with depth, except for three deep weathered/fault zones where $K_v$ remained low. Figure 4b shows the 3D mapping of the interpreted $K_v$.

Figure 4. (a) 3D mapping of $K_v$ of profiles 1–3; (b) evaluation of rock mass strength based on (a).
The 3D $Kv$ interpreted map suggests that most of the top surface was covered with the highly weathered or crushed rock, whereas the rock quality improved with depth. Meanwhile, one deep weathered/faults zone was identified in the SE direction, and two were detected in the SW direction (Figure 4b). The most suitable places for the construction of deep engineering infrastructures were found at 0–200, 300–800, and 900–1300 m in profile 1, at 0–50 and 150–320 m in profile 2, and 0–25 and 100–300 m in profile 3.

4. Conclusions

The rock mass integrity coefficient ($Kv$) is an important rock mechanics parameter used to evaluate the quality and strength of rock mass in any hard rock area. Traditionally, this parameter is obtained from core samples of drilling. However, drilling is expensive and may not be carried out in steep topographic areas. Therefore, an alternative approach that is not only cheaper but can also provide large coverage with the 2D and 3D mapping of $Kv$ over the entire area is necessary. In this work, we introduced a new and integrated approach of ERT and several borehole data. In this innovative approach, we determined useful correlations between the $Kv$ obtained from several boreholes and the electrical resistivity of ERT. Then, the empirical equation for different types of rock was obtained, and $Kv$ was mapped over the entire area via 2D and 3D mapping. This approach can reduce a significant number of expensive drilling tests and provide more coverage of $Kv$ over the entire area for the assessment of rock mass quality. In this work, the top layer was assessed as the highly weathered or crushed rock with resistivity less than 400 $\Omega$m and $Kv$ less than 0.35, the second layer belonged to the partly weathered or poorly integral with a resistivity between 400–1000 $\Omega$m and $Kv$ ranging from 0.35 to 0.55, and the bottom layer was fresh bedrock or integral rock with resistivity greater than 1000 $\Omega$m and $Kv$ greater than 0.55 but less than 1.00.

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