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Accuracy of Rock Properties Measured by Knocking small-Ball Inspection on a piece of Rock

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ABSTRACT: Typical mechanical properties of rock materials include deformation modulus and uniaxial compressive strength. As a direct method for obtaining these properties, the authors have developed and applied Knocking Ball Inspection (KBI) that can quickly and easily provide the modulus of elasticity of rock in situ and in laboratory tests. However, KBI requires a certain size of rock mass to secure the striking surface and cannot be applied to sites where a rock mass cannot be sampled. Therefore, we developed Knocking Small-Ball Inspection (KSBI) that can be applied to the exploration of rock fragments by downsizing the body of the hammering ball. In this study, the measurement accuracy of KSBI was verified by comparing the modulus of elasticity obtained from KBI and KSBI for a rock block. In addition, the method of fixing rock fragments during KSBI was investigated, and the results are reported together with the verification results of the measurement accuracy.

1 INTRODUCTION

The foundation ground that supports civil structures and the excavated earth and rock in civil engineering projects exist in a wide range of conditions, from hard and consolidated rock to unconsolidated soil. Additionally, embankment structures for constructing facilities such as railways, roads, residential areas, and airports are generally made using natural materials like rocks and soils (including cement-improved soil).

The deformation and strength characteristics of the foundation and excavated earth required for the design of structures like dams and mountain tunnels are typically determined through laboratory tests using samples obtained from investigation borings or in-situ tests (Shirasagi et al., 2014). However, due to the inherent heterogeneity, discontinuious nature, and anisotropy inherent to rock masses unexpected conditions may arise during construction with limited test results. Therefore, for example, in the Tunnel Standard Specifications, visual observations and rock hammer strikes are specified for evaluating the ground conditions, including the geological conditions, degree of hardness, cracks, faults, and groundwater conditions, as well as the stability of the tunnel face. If the actual conditions deviate from the initial assumptions, adjustments such as changes in support patterns may be made considering safety and cost-effectiveness. Thus, ground evaluation during construction plays a crucial role, but it often relies on qualitative senses and sounds during visual observation and hammer strikes, making it highly subjective to the observer.

Methods such as Schmidt hammer tests, point load tests, or uniaxial compression tests can be used to quantitatively evaluate the condition of the foundation and excavated earth (Razali et al., 2023a, 2023b). However, their application is limited due to the constraints of their range of applicability and, for some of these techniques,the need for conducting tests in a laboratory setting, which can be time-consuming. Furthermore, in construction projects like dam construction where rocks or concrete aggregates are extracted from the original mountain, it is crucial to determine the quality of the rock materials. While qualitative judgments based on visual evaluations and hammer strikes have been primarily used, there is a need for the development of methods that can quantitatively and rapidly assess the quality of rock materials on-site, as parameters like specific gravity and water absorption can only provide a quantitative assessment when tests are conducted indoors.

On the other hand, for foundation soils and embankments, plate load tests and field CBR tests are commonly conducted to confirm the bearing capacity for direct foundations of structures. While these tests are highly reliable, they require load reaction devices and have long testing durations, leading to limitations in testing frequency. In addition to compaction control based on the physical properties of soil materials (density and water content), there is a need for methods that can directly manage and evaluate the mechanical performance of soil structures such as backfill behind roadbeds and bridge abutments.

Based on these considerations, in recent years, there has been an increasing demand for multi-point measurements from a quality assurance perspective. In response to this demand, a "Knocking Ball Inspection(KBI)" method has been developed, which can be applied extensively even in construction sites with significantly different measurement environments, and can evaluate the physical properties of rocks in a simple and quantitative manner. This method evaluates the elastic modulus of rock materials (in the case of KBI) or the deformation modulus of soil materials (in the case of falling ball inspection) based on the response characteristics obtained from the collision of a metallic sphere with an attached accelerometer, using the theory of sphere collision (Hertz theory). And it can measure measure with the same accuracy as the Schmidt hammer[1]. The originality lies in applying Hertz theory to a wide range of ground materials that exhibit elastic-plastic behavior by making certain modifications and assumptions to the isotropic elastic body theory of Hertz. However, in KBI, a steel ball with a diameter of 50 mm was used, and for stable inspection, the target of inspection needed to be at least 10 cm with a smooth impact surface. Therefore, small rock fragments with a diameter of less than 5 cm were excluded, and it could not be applied to crushed rock in situations like TBM construction. To address this, the steel ball diameter was downsized to 30 mm(Knocking Small-Ball Inspection (KSBI)) and compared to KBI in terms of accuracy (Figure 1).

Figure 1. Comparison KBI with KSBI

2 THEORICAL BACKGROUND

2.1 Heltz Theory

When a metallic sphere collides with a foundation, the foundation deforms in different modes depending on its characteristics. Specifically, if the foundation is soft, the contact time between the sphere and the foundation is longer compared to when the foundation is hard. This relationship is expressed by Hertz's theory of elasticity, as shown in Equation (1) and Figure 2. Equation (1) represents the relationship for "collision between a sphere and a plane," which is derived by assuming that one of the spheres has an infinitely large radius and mass in the most fundamental "collision between spheres" theory of Hertz. This method applies Equation (1) to the collision between a metallic sphere and a foundation. The contact time T when the sphere collides with a plane (foundation) is measured using an accelerometer as shown in Figure 2, and Equation (1) is used to calculate the elastic modulus (or generally the deformation modulus) E_2 of the foundation.

$$E_2 = \frac{1 - v_2^2}{\frac{\pi}{M}\sqrt{RV_0}\left(\frac{T}{a}\right)^{\frac{5}{2}} - \frac{1 - v_1^2}{E_1}} \quad (1)$$

Here, a is a constant (≒4.53), v_1 and E_1 represent the Poisson's ratio (0.3) and the elastic modulus (210 GPa) of the metallic sphere, respectively. V_2 and E_2 represent the Poisson's ratio and the elastic modulus of the foundation, respectively. M and R represent the mass and radius of the sphere, and V_0 represents the velocity of the sphere at the time of collision. We need to note that equation (1) is applicable to a perfectly elastic material. Additionally, while the values of v_1, E_1, M, and R for the sphere are known, in order to obtain the value of E_2 for the substrate from equation (1), the standard values[1] for Poisson's ratio v_2 are as follows: rock: 0.2, gravelly soil: 0.2, cement-improved soil: 0.25, sandy soil: 0.3, silt: 0.35, clay: 0.4. As for V_0 ,because of manual strike of hammer, V_0 inevitably fluctuates and V_0 is calculated by integrating the acceleration time history.

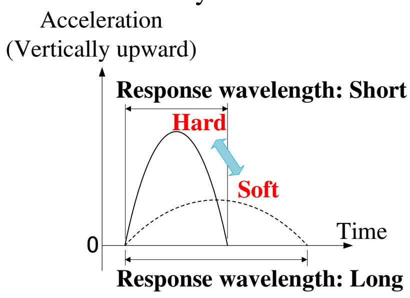


Figure 2. The concept of contact time

2.2 Equipment configuration

Figure 3 shows the system and equipment configuration of KBI. And Figure 4 shows a KBI test conducted in situ. The spherical object used for collision is replaced according to the target for evaluating the properties of rocks or soils, but there is no difference in the basic data processing based on Hertz theory. In both cases, the response characteristics at the time of collision are instantly processed by a tablet-type computer, and the validity of the data can be visually assessed immediately based on the consistency between the obtained acceleration waveform and the sine curve approximation.

Figure 5 shows example of introducing of KBI for ground evaluation in tunnel faces. Safety is highly emphasized in ground evaluation at tunnel faces, so we have improved the push rod system by attaching a small ball to the tip of the rod and using a spring to ensure distance of two meters from the tunnel face. This modification allows us to obtain results similar to those obtained by conventional hammer strikes. For both vertical and horizontal strike directions, the value V_0, which is substituted into the theoretical formula, is calculated by integrating the acceleration time history when the object is struck. Therefore, no correction is made for the difference in input energy due to the difference in strike directions between the two methods.

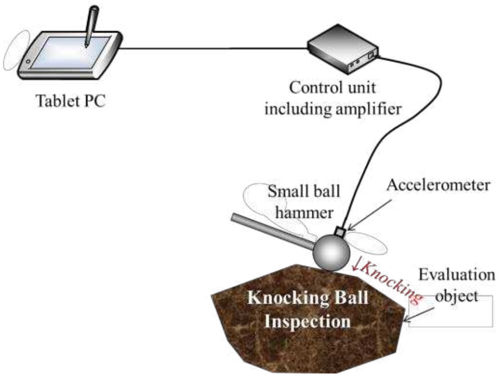


Figure 3. Equipment configuration of KBS

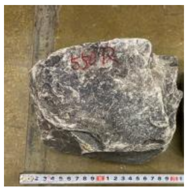
Figure 4. In situ KBI test

Figure 5. The implementation status of KBS in tunnel faces.

3 ACCURACY VERIFICATION OF KSBI

We conducted impact testing on a chart and a block of siliceous sandstone, as shown in Table 1, to compare the effects of KBI with that of KSBI on the measurement results. We performed fifteen impacts for each size at the same impact point and verified the variability of the measurement data.

Table 1. Rock block as the object of investigation

Rock Species	Chart	Siliceous Sandstone
Size	Short Side 5 cm× Long side30 cm×Thickness10 cm	Short Side 20 cm× Long side25m×Thickness10 cm
Specimen		

The results obtained from the experiment are presented in Table 2. It was observed that the average values of the elastic modulus for both types of rock blocks were generally similar, regardless of the size of the steel ball used. However, for the siliceous sandstone, the average elastic modulus for KSBI was found to be 2.2 GPa higher than that for KBI. Furthermore, the standard deviation was found to be larger for KSBI in both rock types, and the coefficient of variation was approximately 10% higher as well. These findings suggest that the impact energy of KBI is greater, resulting in a wider exploration range and less susceptibility to the influence of fine cracks in the rock. Conversely, KSBI has a narrower exploration range, which leads to increased variability due to these influences. Nevertheless, considering that there is no significant deviation in the coefficient of variation, we believe that the impact of downsizing the steel ball is minimal.

Table 2. Results of investigation for rock

Rock type	Chart		Siliceous sandstone	
Exploration Methods	KBI	KBSI	KBI	KBSI
Average elastic modulus value (GPa)	36.7	36.3	34.8	37.0
Standard deviation (GPa)	8.4	12.0	10.0	14.8
coefficient of variation	0.23	0.33	0.29	0.40

4 VERIFICATION OF THE ROCK FRAGMENT FIXATION METHOD

When conducting KBI on rock fragments, if the rock fragments are not properly secured, they may move during the impact. In such cases, the energy of the impact does not transmit well, resulting in unclear acceleration waveforms and decreased measurement accuracy. Additionally, when using a vise to secure the rock fragments during the ball impact, the rock fragments often experienced localized damage due to the force exerted by the vise.

To address this issue, a method of fixing rock fragments using mortar was devised, and the measurement accuracy during ball impact testing of rock fragments fixed with mortar was compared to that of rock blocks fixed with a vise. The mortar was made of early-strength cement and cured for one day. The samples used are a rock block (shale: 30 cm long, 20 cm wide, 10 cm thick) and a rock fragment (shale: 4 cm long and wide, 5 cm thick). The rock fragments were obtained by crushing the above-mentioned rock block. The rock fragment was placed in an acrylic empty container, and mortar was poured into the gap between the rock fragment and the container to fix it (Table 3). For the verification, a steel ball with a diameter of φ30 mm was used, and both the rock block and rock fragment were subjected to 15 impacts each.

Table 3. Results of investigation for rock block and rock fragments

Rock Species	Shale rock mass	Shale rock fragments (fixed with mortar)
Size	Short side 15 cm x long side 30 cm x thickness 10 cm	Short side 4cm × long side 4cm × thickness 5cm
Specimen		

Table 3 shows the verification results. The standard deviation and coefficient of variation for both the rock block and the rock fragment (fixed with mortar) were equivalent, indicating that using mortar as a fixing method for rock fragments can achieve the same level of accuracy as the conventional method. Therefore, even when only small rock fragments are available, it is possible to estimate the modulus of elasticity by using the mortar fixing method in conjunction with other techniques.

Table 4. Results of verification of the rock fragment fixation method

Rock type	Shale rock mass	Shale rock fragments (fixed with mortar)
Exploration Methods	KSBI	
Average elastic modulus value (GPa)	33.2	33.1
Standard deviation (GPa)	8.5	8.5
coefficient of variation	0.26	0.26

5 CONCLUSIONS

The measurement accuracy of the small ball impact test with a diameter of 30 mm was found to have slightly larger variations compared to the conventional ball impact test with a diameter of 50 mm. However, it was discovered that by using the fixation method with mortar, the same measurement accuracy as the conventional ball impact test can be achieved. In the future, data will be accumulated for various rock types to verify the correlation between the thickness and width of the rock fragments and their elastic modulus. Additionally, further investigation will be conducted to determine if the uniaxial compressive strength can be estimated from the elastic modulus.

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