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Uniaxial compressive strength and point load index of volcanic irregular lumps

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1. Introduction

Point load strength index (PLSI) test has been found useful in rock strength classification for engineering practice such as slope stabilization works, tunneling construction, design of mining support, and foundation. The testing procedure of the PLSI has been standardized by both the International Society for Rock Mechanics (ISRM)[1] and the American Society for Testing Materials (ASTM).[2] The point load strength test can be applied axially or diametrally to rock cores, or to irregular lumps. The point load strength is affected by size and shape, thus, the results of all three methods have been proposed to correct to a standard size of 50 mm (call PLSI or $I_{s(50)}$).[1,2] However, Bieniawski[3] reported that the standard deviation of PLSI for irregular lump test is larger than that of the PLSI on rock cores. Turk and Dearman[4] found that size effect of irregular lumps can be quite different from those for PLS test on rock cores. Consequently, the diametral and axial PLS tests are generally more preferable for rock strength estimation than the irregular lumps PLSI test.[5–9]

In Hong Kong, point load strength corrected to sample size of 50 mm ($I_{s(50)}$) was included in Geoguide 2[10] as a standard field index test for rock strength classification. The PLSI was adopted as a strength parameter in estimating allowable bearing capacity in rock strata in the code of practice for foundations design by the Building Department.[11] In 2013, Building Department of Hong Kong imposed a condition on "Large Diameter Bored Piles"[12] that each pile design on rock needs to be substantiated by the result of at least one test of either uniaxial compressive strength (UCS) or PLSI ($I_{s(50)}$). However, there is a problem that for brittle rocks (in particular for volcanic strata), retrieval of intact borehole rock samples for conducting either UCS, axial PLSI or diametral PLSI test could become difficult if not impossible. It is because rock cores from brittle rock may be fractured during the drilling process. Without an intact rock core, none of the UCS, axial PLS or diametral PLS test could be carried out. Although the Geoguide 2[10] does include the case of testing irregular lumps, apparently the use of irregular lumps has not been adopted regularly in Hong Kong in daily practice. If irregular rock fragments or lumps extracted from borehole can be used to find $I_{s(50)}$ and the corresponding UCS through correlations, the problem can be solved. Indeed, the use of irregular specimens for rock strength is found particularly important in this situation. Matsumoto et al.[13] and Nishimura et al.[14] proposed to use PLSI test for irregular rock lumps found at tunnel sites in Japan. For such tunnel projects, no rock cores were readily available. Therefore, there is a need to standardize the use of PLSI tests on irregular lumps in Hong Kong. The Hong Kong Polytechnic University was invited by the Housing Department, Hong Kong Special Administrative Region Government to investigate the correlation between uniaxial compressive strength and point load strength index of irregular lumps of rocks. This paper is a result of such collaboration.

The point load compression test for irregular lumps was actually proposed before the point load test for rock cores. The idea of testing of irregular rock lumps was originally proposed in Russia in 1960 by Protodyakonov.[15] The main advantage of this test is that no sample preparation (such as cutting and grinding) is needed. However, the original proposal by Protodyakonov[15] was to compress an irregular

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rock lump between two flat loading platens. The contact between the irregular lump and the loading platen may be more than one point. Hobbs[16] adopted this method to parallel-sided slabs of sedimentary lumps and suggested that the strength should not be restricted to a single orientation and size effect must be taken in consideration. As discussed by Broch and Franklin[17], the irregular lump test was subsequently followed up by Diernat and Duffaut[18] and Duffaut[19]. They found that if the size of granite lumps is halved, the strength could be doubled. These studies laid the foundations for size effect correction that subsequently used in ISRM.[1] Hiramatsu and Oka[20] proposed to estimate the point load strength by applying conical point contacts instead of flat platens. This test is now known as the Point Load Strength Test (PLST). Reichmuth[21,22] proposed the application of PLST to rock cores, both axially and diametrally. The diametral PLSI test was adopted by the US Bureau of Mines in 1965 as one of the ten index tests for rocks and the diametral PLSI test was found best correlated with uniaxial compressive strength (UCS).[23] In addition, Broch and Franklin[17] concluded that the scattering of point load index is less than that of uniaxial compressive strength.

In 1985, the International Society for Rock Mechanics published a standard procedure for PLST which is still widely adopted today.[1] The point load strength for irregular lumps should be evaluated as:

$$I_s = \frac{P}{D_e^2} \tag{1}$$

where P is the applied load at failure and D_e is the equivalent diameter defined as

$$D_e^2 = \frac{4A}{\pi} = \frac{4WD}{\pi} \tag{2}$$

where W is the width of the specimen, D is the distance between platen contact points. Data for different diameters of D_e should be obtained for each type of rocks to establish the correction factor to yield PLSI ($I_{s(50)}$) with reference to 50 mm diameter size. In case such data are not available, the point load strength index can be estimated by using the size correction [1,2,24–26]:

$$I_{s(50)} = F\ I_s = \left(\frac{D_e}{50}\right)^{0.45} I_s \approx \sqrt{\left(\frac{D_e}{50}\right)}\ I_s \tag{3}$$

where D_e is in mm. For tests near the standard 50 mm size, error is negligible by using the approximate expression $F=(D_e/50)^{0.5}$.[1,2] The above size correction factor was, however, obtained for cores on diametral and axial PLS test.

Turk and Dearman[4] studied the size and shape effect on PLSI test by conducting 66 irregular lumps of dolerite from England, with size ranging from 12.5 to 50 mm. The irregular specimens were prepared by hammering. They obtained an exponential power of 0.926 for the size correction factor F, and this value agrees roughly with that of Panek and Fannon.[27] This illustrates that size effect of irregular lumps can be quite different from those for PLS test on rock cores. Panek and Fannon[27] conducted PLS test on about 500 irregular rock samples of iron formation, metadiabase, and ophitic basalt, with size ranging from 25 mm to 270 mm. These fragments were obtained from the rock piles after blasting in the mine. For metadiabase, the penetration of loading conical platen at breakage failure was in the order of 15% of the original size D. Panek and Fannon[27] suggested that tests with such excessive penetrations should be rejected as invalid. Assuming an ellipsoidal shape for rock lumps, the following formula for size and shape effects was obtained [27]:

$$\frac{P}{D^2} = K\,(1/D)^{0.814}(H/D)^{0.215}(L/D)^{0.123} \tag{4}$$

where D is the initial distance between the loading points, H is the intermediate axis of the fracture surface normal to D, and L is the major axis the specimen. The index for size effect is 0.814 and this differs significantly from 0.45 or 0.5 suggested in ISRM.[1] This strongly suggests that, for irregular lumps, we should establish our own size-effect correction, instead using the exponential power of 0.45 or 0.5.

The PLSI of irregular lumps has been found correlated positively with the uniaxial compressive strength (UCS) or q_u as [28]:

$$q_u = \kappa I_{s(50)} \tag{5}$$

where κ is called "correlation factor". Guidicini et al.[28] conducted PLSI tests on irregular lumps and UCS test on six different rocks and concrete (including basalt, soft sandstone, gneissic granite and concrete) and found κ=5.263, which differs significantly from 24 suggested by Broch and Franklin.[17] Guidicini et al.[28] also proposed to estimate UCS from point load data of irregular lumps as:

$$q_u = 6.35\frac{P}{D^{1.5}} \tag{6}$$

Kohno and Maeda[29] conducted a total of 3828 PLSI ($I_{s(50)}$) tests on irregular lumps and 329 UC tests for 44 different types of soft rocks found in Hokkaido, Japan. The correlation factor κ between the $I_{s(50)}$ and UCS of rocks was 16.4. For irregular gypsum lumps found in Iran, Heidari et al.[30] established the following formulas

$$q_u = 3.49 I_{S(50)} + 24.84 \tag{7}$$

Heidari et al.[30] found that the coefficient of correlation r between UCS and $I_{s(50)}$ are 0.93, 0.94 and 0.89 for axial, diametral, and irregular PLSI test respectively. Note that coefficient of correlation r =1 or r^2=1 gives a perfect fit of all data. Therefore, the correlations between the UCS and the $I_{s(50)}$ on irregular lumps are comparable to those for axial and diametral PLSI tests. Therefore, Heidari et al.[30] concluded that irregular lump test is the most useful method for determining UCS in practice because it can be conducted in the field and is simple, fast, and low cost. The correlation factor κ clearly depends on rock types.[5] Basu and Aydin[31] found that for those $I_{s(50)}$ determined from D measured after the test, the correlation between the UCS and $I_{s(50)}$ was significantly better. Therefore, correction for indentation depth appears to be important.[31] In the present study, we will use both the initial D (distance between two load points before test) and the final D' (distance between two load points at rupture) in determining the equivalent core diameter D_e for calculating $I_{s(50)}$.

The present study investigates the correlation between UCS and PLST on irregular lumps for volcanic rocks of different grain sizes and weathering grades found in Hong Kong. Both initial D and final D' are employed to determine the equivalent core diameter D_e. We also establish the size correction factor F (=$(D_e/50)^m$) for converting point load strength index to a standard size of 50 mm. Furthermore, we also compare PLSI ($I_{s(50)}$) of irregular lumps to $I_{s(50)}$ obtained from axial and diametral PLST. Once such correlation is established with confidence, engineers can correlate PLSI of irregular rock lumps to the uniaxial compressive strength.

2. Specimen preparation for irregular lumps and PLST test

In this section, we will summarize the basic information of the volcanic rocks used in the present study, preparation of irregular lumps, and the test procedure. Results of our experiments will be deferred to the next section.

2.1. Volcanic rocks used in experiments

The main focus of the present study is to establish a size correction factor for the PLST for volcanic rocks found in Hong Kong. Although more than half of the outcrops of the 1000 km square of Hong Kong is composed of volcanic tuff, most of previous experiments on rocks were conducted on granite. It is because most of the infrastructure development in Hong Kong has been concentrated within the Victoria Harbour, which is dominated by granite. In recent years, urban developments have been expanded into more areas consisting of tuff.