直交画像解析による割石質量推定のための新しい実用的方法

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【Research Article】

A New Practical Method for Estimating the Mass of Quarried Stones by Analysis of Orthogonal Images

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Abstract

A new practical method is presented for estimating the volumes and masses of quarried stones from their projected areas and is compared with two conventional methods based on the intermediate axis and three characteristic dimensions. The projected areas are obtained from two horizontal orthogonal images of the stones taken by a camera with the aid of a measuring frame. The parameter of each prediction equation for the new method and the two conventional methods was fitted to data obtained from a sample of 100 small crushed stones. The results indicate that the new method is the most accurate and precise, with a range of −23% to 30% in relative error for 95% prediction intervals. Full-scale validation using large quarried stones of 1.16 to 3.01 tons showed that the new method successfully predicted the masses of quarried stones within the accuracy range expected from regression analysis, while the method that relies solely on the three characteristic dimensions resulted in predictions that were beyond the acceptable range of error.

1. Introduction

Quarried stones of irregular size and shape are used for marine coastal structures such as rubble mound breakwaters and stable substrates for macroalgae. To ensure hydrodynamic stability under design wave conditions, the stones must be of sufficient mass. These stones are typically very heavy and their masses are therefore estimated by measuring their dimensions rather than direct weighing. However, it is not easy to define or measure the size of quarried stones in most cases due to their irregular shape and large volume, leading to significant errors in the estimate.

There are primarily three different methods to determine the dimensions of quarried stones. The first method (Method I) defines the long axis as the maximum length of the stone. The intermediate axis is then defined as the maximum width perpendicular to the long axis. The maximum thickness of the stone perpendicular to the plane of the long and intermediate axes is then recorded. The second method (Method II) places a stone on a horizontal plane such that the maximum projected area is directed downward. The maximum height is taken to be the thickness of the stone. In the top view, the long axis is defined as the length of the stone and the short axis as the maximum width perpendicular to the long axis (Fig. 1). The third method (Method III) defines the three characteristic dimensions as the axial dimensions of the smallest imaginary rectangular box that encloses the stone.

The U.S. Army Corp Engineers[1)] adopts Method I to determine the size of stones. The Riprap Design and Construction Guide (RDCG)[2)] of the British Columbia Ministry of Environment, Lands and Parks in Canada expresses the mass of riprap stones based on a sphere with diameter equal to the intermediate axis. The Japanese Industrial Standard (JIS) A 5006[3)] provides a formula to estimate the mass of rubble from the product of the three orthogonal dimensions defined by Method II. The European standard EN 13383 adopts Method III to define the shape of armor stones.

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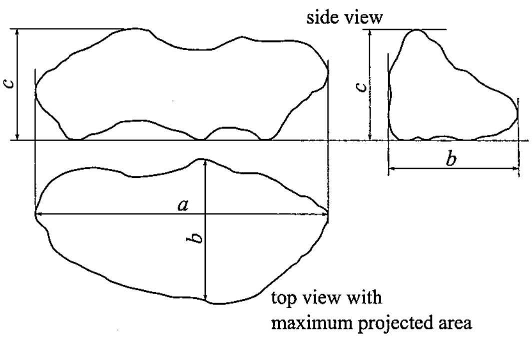

Fig. 1 Definition of the length, width, and thickness of rubble in the JIS.

Determining the dimensions of quarried stones involves some subjective judgment, particularly because the directions of the three axes for large stones may be difficult to visualize[4]. In addition, the estimate of the volume of irregular stones from only a single dimension or all three characteristic dimensions may be considerably inaccurate. No information is available regarding the accuracy of these methods.

The objective of this study was to examine the accuracy of the conventional methods and to propose a more accurate alternative for estimating the volume of quarried stones based on their lengths or areas. The new, empirical method is based on photography, which enables objective analysis and practical field applications. Crushed stones, acting as scale models of large quarried stones in the field, were used to establish the equations for volume estimation in the laboratory. The proposed technique was validated via a field experiment.

2. Materials and Methods

1) Equations for estimating mass of stones

For a stone of volume V (m^3), the mass is given by

$$M = \rho_s V \tag{1}$$

where M is the mass (kg) and ρ_s is the bulk density (kg/m^3) of the stone. The RDCG proposes a simple method for estimating V as the volume of a sphere with a diameter equal to the intermediate axis dimension determined by Method I. In other words, $V = \pi D^3/6$, where D is the intermediate dimension(m). However, it may not be easy to visually define the three orthogonal dimensions of quarried stones according to Method I due to their three-dimensional and irregular configurations. In the present study, the more practical Method II was used to determine the three orthogonal dimensions(m) of stones: the length a, the width b, and the thickness c. The values of a and b can be readily measured in the top-view image projected onto the ground. The single dimension method of the RDCG may then be revised as follows:

$$V = \alpha(\pi/6)\, b^3 \tag{2}$$

where α is a correction factor determined empirically for the possible bias in the assumption of equivalent sphere. Alternatively, a more accurate estimate of the stone volume may be obtained by the product of the three orthogonal dimensions:

$$V = k_1 abc \tag{3}$$

where k_1 is an empirically determined constant. If the stone is ellipsoid, $V = (\pi/6)abc$ and therefore, $k_1 = \pi/6 \approx 0.52$. The JIS A 5006 standard specifies a value of $k_1 = 0.25$ for rubbles. However, the k_1 value was re-examined in this study because it appeared to be too small even though rubbles have irregular geometries that include concave surfaces.

The proposed formula for the volume of quarried stones is based on the projected areas whereas the conventional methods described above are based on the lengths or axis dimensions. The projected areas carry more information than the lengths and can easily be obtained by photography. From dimensional analysis, the stone volume may be estimated from the following relationship:

$$V = k_2 (A_f A_s)^{3/4} \tag{4}$$

where k_2 is the parameter to be empirically determined and A_f and A_s are the projected areas of stones from the front and side views, respectively, defined by Method III. To measure the size of quarried stones, they should be placed on a flat ground with their largest surface directed downward. The length, width, and height of the stones can then be readily determined using Method II. However, the definition of the long and short axes may be inappropriate for the blocky rocks that frequently appear in a quarry. Therefore, orthogonal views for determining the front and side projected areas are defined as the side views of the smallest imaginary box that encloses the stone, as in Method III.

The projected areas of the stones are estimated from two orthogonal photographic images captured by a camera oriented perpendicular to the front and side surfaces of the imaginary box. A measuring rod or board is placed on a hypothesized plane (referred to here as the "measuring plane") over the surface of the box. A photograph is then taken to obtain projection coordinates in two-dimensional images (**Fig. 2**). The lengths determined by the projection coordinates correspond to those projected onto the measuring plane and not to the real coordinates, as shown in **Fig. 2**. The projected lengths and areas are distinguished using prime notation. In the front-view image, the length L'_f varies with the ratio of the average distance between the focal point of the camera and the projected outline of the stone, d_s, to the average distance between the focal point of the camera and the measuring plane, d_p (**Fig. 2**). A better estimate of L_f may therefore be obtained by multiplying it by a factor of r_1:

$$r_1 = \frac{d_s}{d_p} = \begin{cases} 1-\gamma L_s/d_p, & \text{when the measuring plane is placed on the rear side of stones} \\ 1+\gamma L_s/d_p, & \text{when the measuring plane is placed on the front side of stones,} \end{cases} \tag{5}$$

where L_s is the orthogonal width of stones in the photographing direction and γ is the correction coefficient, which is assumed to be 0.5 on average. In the side-view image, a better estimate of L_s may be similarly obtained by multiplying it by a factor of r_2:

$$r_2 = \begin{cases} 1-\gamma L_s/d_p, & \text{when the measuring plane is placed on the rear side of stones} \\ 1+\gamma L_s/d_p, & \text{when themeasuring plane is placed on the front side of stones.} \end{cases} \tag{6}$$

Therefore, the projected areas should be altered as follows:

$$A_f = r_1^2 A'_f,\ A_s = r_1^2 A'_s \tag{7}$$

The coefficient γ can vary from 0 to 1 depending on the shape of the stone, as indicated by **Fig. 2.** The ratios L_f/L'_f and L_s/L'_s (where L'_s is the projected width of the stone) can vary with different r_1 and r_2, respectively, particularly when the distance from which the photograph is taken is small relative to L_s and L_f, respectively. The relative distance should ideally be large enough to satisfy the assumption that $r_1 = r_2 = 1$ but this may often be constrained for large quarried stones, thereby requiring a modification for the closer shot.

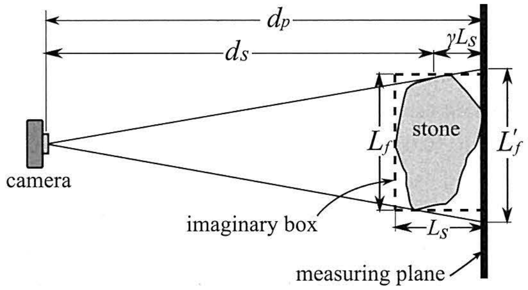

Fig. 2 Schematic of the method of photographing the projected areas of stones. The front-view image capturing is depicted. The orthogonal- and side-view images may be obtained in a similar manner. The measuring plane can be deployed on the front side (not shown here) or rear side of the stone.

2) Determination of model parameters and model testing using crushed stones

Fig. 3 shows the 100 angular-shaped crushed stones that were used to examine the relationship between the volume and dimensions and the volume and projected areas of quarried stones. Thinly shaped (c/b < 0.5) and narrow (a/b > 3) stones were not included in order to satisfy the requirement of JIS for rubble. The stones were granite with a very low porosity. Their bulk densities can therefore be assumed to be the same as the density determined using the water-immersion method:

$$\rho_s = \frac{\rho_w M}{M - M_w} \tag{8}$$

where ρ_w is the mass density of water (kg/m³), M is

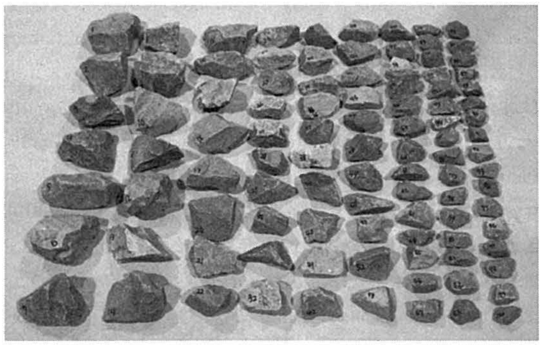

Fig. 3 Photograph of the 100 crushed stones used for the determination of model parameters and for model testing.

the mass of the dry stone in air (kg), and M_w is the mass of the stone in water (kg). The masses were measured using an electronic balance with a precision of 10^{-5} kg (0.01g). The stone volume, V, was then calculated using $V = M/\rho_s$.

To determine the stone size, each stone was placed horizontally on a table with its largest surface directed downward. The stone's length, width, and height were then determined using Method II. In addition, two orthogonal-view photographs of the stone perpendicular to the front and side surfaces of an imaginary box enclosing the stone with a minimum volume were taken, with a measuring board having a 10×10 mm grid deployed vertically on the rear side of the stone. The images were captured twice at different distances. First, to obtain data for the regression of the coefficients α, k_1, and k_2 in Eqs. 2–4, images were taken through a telescope from a distance d_p with $d_p/L_f > 25$ (d_p = 1.5–2.25 m, depending on the stone length; **Fig. 2**) so that the enlargement of the projection image at different photographing distances was negligibly small (<2%). Such a relatively great photographing distance is ideal but may often be impractical for large quarried stones. For example, 1-m long stones need a photographing distance of 25 m or more. To examine the improvement of the mass prediction at closer shots as a result of the modification of the projected areas A_f and A_s by Eqs. 5 and 6 with γ = 0.5, the same 100 stones were photographed again from a shorter distance. d_p was set to 0.70 m and therefore, d_p/L_f and d_p/L_s ranged 4.7–22.6 in the orthogonal directions.

The photographic images were analyzed to obtain the projected areas A'_f and A'_s and the projected lengths L'_f and L'_s of the stones using the image analysis software AreaQ[5]. The actual lengths and areas were obtained by transforming the distorted image coordinates into real-world projection coordinates using reference points with known coordinates on the measuring board. The values of L'_f and L'_s obtained from the image analysis were used to calculate the factors r_1 and r_2 using Eqs. 5 and 6. Any discrepancy between the results and the actual lengths could be ignored because the error introduced would be very small.

The linear least-squares regression method was then applied to Eqs. 2–4. Because the scatter-plot of residuals against the predictions of V showed that the variance was heteroscedastic, the data were log-transformed to meet the assumption of homogeneity of variance. The 95% prediction intervals (PI) for the back-transformed V-values were calculated from the standard errors of the regressions (SER) as $10^{\pm 1.984 \times \mathrm{SER}}$, where the factor 1.984 is the 95th percentile of the t-distribution with $n-1$ (or 99) degrees of freedom. The log-transformed regression equations include only single parameters for the intercept. Together with the homogeneity of variance, this means that the PI is identical to the range of the relative errors of the predictions from the regression models. All statistical analyses were performed in R[6].

3) Full scale validation with large quarried stones

To validate the applicability of the empirically developed method to large quarried stones, full-scale testing was conducted at a stone stockpile area in Anan, Tokushima, Japan, on June 2, 2014. We used ten quarried granite stones classified as 2–3 ton stones, which are usually employed for the establishment of kelp beds in

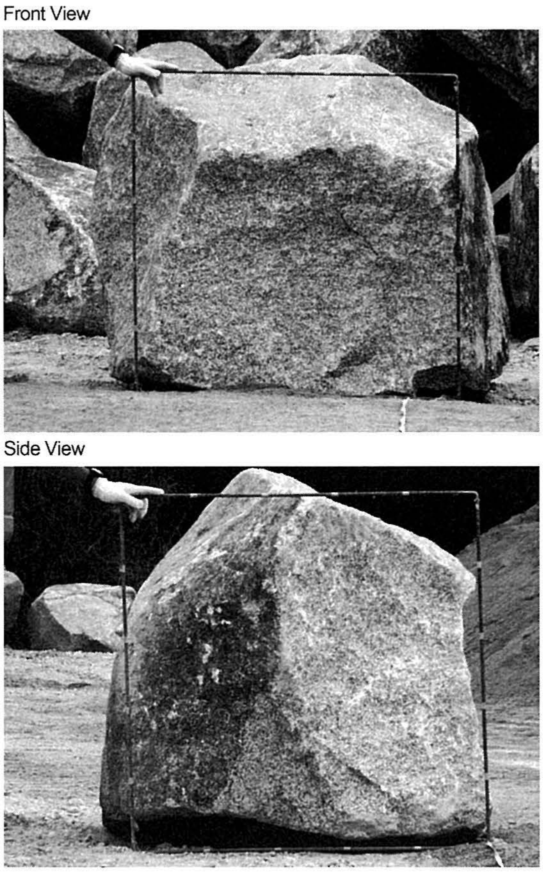

Fig. 4 Example of photographs of a large quarried stone with the 1 × 1 m measuring frame.

the Tokushima Prefecture. The stone masses were directly measured with a load cell (KDC-H-40T, Kamacho Scale Co., Ltd., Takamatsu, Japan) and ranged from 1160 to 3010 kg. The samples were placed on a horizontal flat ground with their largest surface oriented downward and the three dimensions were determined visually using a measuring rod according to Method II. The measured lengths, widths, and heights ranged between 0.96–1.53 m, 0.69–1.31 m, and 0.79–1.20 m, respectively. A measuring plane was constructed using a 1-m square frame made of 1-cm diameter stainless steel bars marked with adhesive tape at 20 cm intervals. Two orthogonal photographic images for each stone with the frame placed vertically on the front side of it were taken by a camera at a distance of d_p = 10 m (**Fig. 4**). The A'_f and A'_s were obtained using AreaQ. The A_f and A_s were then calculated using Eqs. 5–7. The volume predictions of the quarried stones were obtained by Eq. 4 with a k_2 estimate from the regression analysis for crushed stones. The stone mass was then calculated using Eq. 1 with a mean (± standard error) mass density of 2592 (±4.8) kg/m^3, which was determined using four debris samples (1.513–2.836 kg dry mass) collected from the same stockpile of quarried stones using the water immersion method.

3. Results

1) Model parameters and testing using crushed stones

The results of the regression analyses of Eqs. 2–4 are summarized in **Table 1**. The log-log plots of the stone volume versus the volumetric predictor, $\pi b^3/6$, abc and $(A_f A_s)^{3/4}$ are shown in **Fig. 5**. The single dimension method of Eq. 2 has a relatively low precision. The α-estimate in Eq. 2 suggests that the method of RDCG may overestimate the actual volume or mass by an average of approximately 30%. In contrast, the regression of Eq. 3 resulted in a higher precision, reflecting the increased information in the predictors. The k_1 estimate was 0.37, which is smaller than the value of 0.52 for an ellipsoid but significantly larger than the value of 0.25 in JIS, as expected. This may be attributed to the concave shape of the crushed stones and suggests that the JIS formula may result in a significant underestimation. The equation should therefore be revised as follows:

$$V = 0.37abc \tag{9}$$

The projected areas method (Eq. 4) provided an even more precise prediction. The 95% PI in **Table 1** indicated that 95% of the relative errors in the volume prediction from the regression models of Eqs. 2–4 can be expected to lie within ranges of −55% to 124%, −26% to 36%, and −23% to 30%, respectively.

Fig. 6 shows a comparison of the measured masses of the crushed stones to the masses predicted by the unmodified and r_1, r_2-modified projected areas in the images shot at relatively short distances. The predictions by Eq. 4 agreed reasonably well with the measurements, with the errors reduced slightly by the modification. The mean relative error in the modified predictions was 12.2% while that in the unmodified predictions was 14.2%. The number of the data points outside the 95% PI was reduced from 12% to 8% by the modification. Consequently, the equation for estimating the volume of stones in the proposed method is

$$V = 0.71[(1-0.5L'_s/d_p)^2(1-0.5L'_s/d_p)^2 A'_f A'_s]^{3/4} \tag{10}$$

2) Full scale validation with large quarried stones

Fig. 7 shows log-log plots of the measured masses of large quarried stones versus the masses predicted by the proposed method (Eq. 10). The predictions from the modified version of the JIS method (Eq. 9) are also included. The latter method underestimated the stone mass, mostly with errors beyond the 95% PI, although the value of k_1 increased to approximately 1.5 times that of the original method. This suggests that the accuracy of the JIS method may be sensitive to the shape of the stones or the subjective measurement of the three

Table 1 The results of the regression analysis

Equation	Parameter estimate (±95% CI)	SER	95% PI
Eq. 2	$\log_{10}\alpha = -0.156 \pm 0.035$ ($\alpha = 0.698$)	0.1766	0.446–2.240
Eq. 3	$\log_{10} k_1 = -0.433 \pm 0.013$ ($k_1 = 0.369$)	0.0666	0.738–1.356
Eq. 4	$\log_{10} k_2 = -0.149 \pm 0.011$ ($k_2 = 0.710$)	0.0568	0.771–1.298

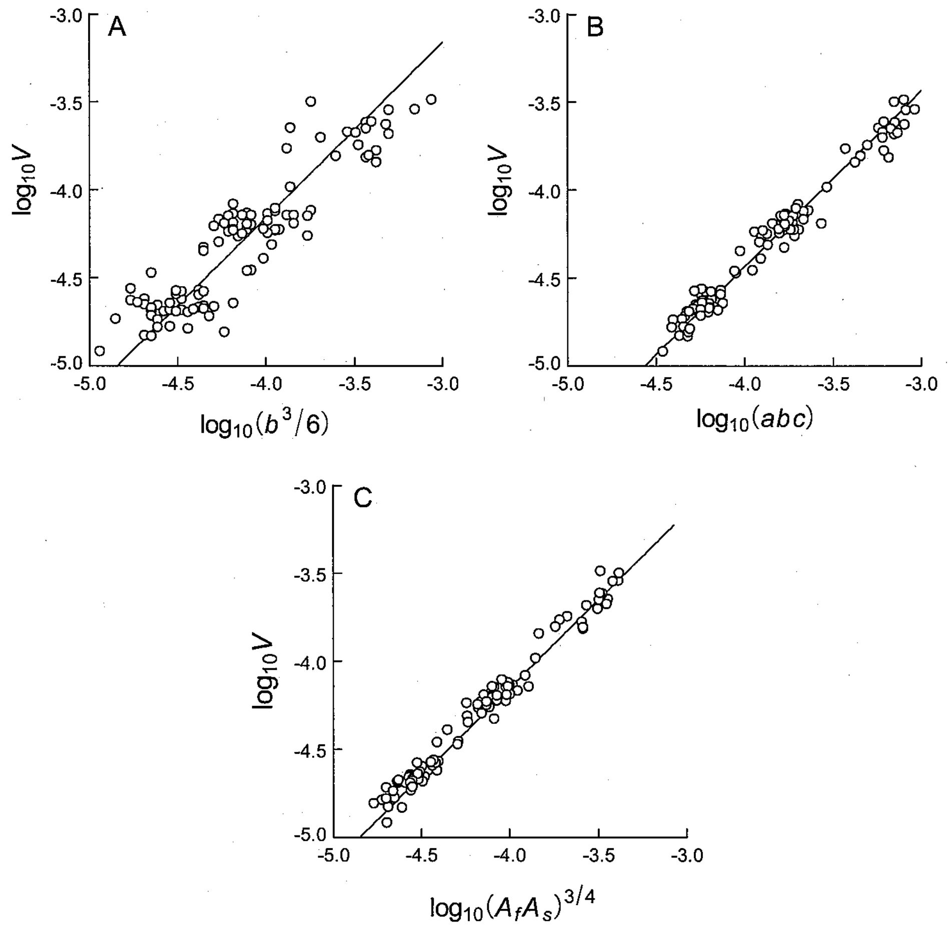

Fig. 5 The relationships between the volume and three volumetric variables (A: $\pi b^3/6$, B: abc, C: $(A_f A_s)^{3/4}$) for crushed stones. The lines represent $y = x$ + intercept, where the intercepts of the regression lines in plots A, B, and C are the estimates of $\log_{10}\alpha$, $\log_{10}k_1$, and $\log_{10}k_2$, respectively, which are listed in **Table 1**.

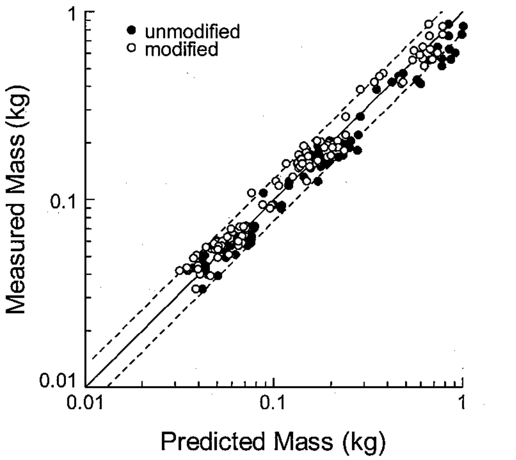

Fig. 6 A comparison of the predicted and measured masses of crushed stones from unmodified (A'_f and A'_s) and modified (A_f and A_s) projected areas. The solid line represents $y = x$ and the dashed lines represent the 95% prediction intervals.

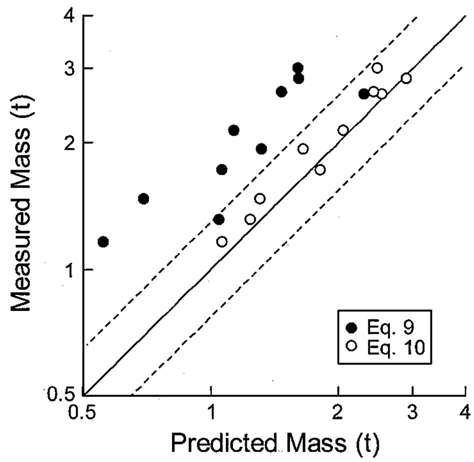

Fig. 7 Log-log plots of the predicted versus measured masses of large quarried stones. The solid line represents $y = x$ and the dashed lines represent the 95% prediction intervals of Eq. 10.

orthogonal dimensions of large stones. In contrast, the proposed projected areas method successfully gave reasonable predictions within the 95% PI for all samples. The ratios d_p/L_f and d_p/L_s ranged from 6.1 to 12.0.

4. Discussion and conclusions

The conventional methods for estimating the volume and mass of quarried stones of irregular shape rely fully on only one or three characteristic lengths determined by the subjective judgment of their orthogonal axes[4]. The results of the present study showed that the single dimension method had significantly poor precision; the prediction may be greater than 200% or less than 50% of the actual value. The precision of the prediction can be significantly improved by using three orthogonal dimensions, as found in the regression of Eq. 3. However, the regression equation (Eq. 9) developed with data of crushed stones resulted in apparent underestimation for the masses of large quarried stones. It should be noted here that the equation provides an approximately 1.5 times greater estimate than the original JIS formula. The observed impermissible errors in the prediction by Eq. 9 indicated the variability in the relationship between the dimensions and volume of stones. This is probably due to the shape of the stones, thus indicating a poor reliability of methods that rely solely on the three characteristic lengths. In contrast, the projected areas method (Eq. 10) successfully gave reasonable predictions within the permissible range, even though some quarried stone samples had blocky shapes that were underrepresented in the crushed stones sample. It was therefore concluded that the projected areas method can be a robust and reliable alternative to the conventional methods.

The accuracy and precision are important in predicting volumes not only for defining the tolerance requirements for classifying quarried stones by mass but also for evaluating their stability against wave actions. JIS specifies an error tolerance of 10% in mass for rubbles of size classes greater than 100 kg[3]. However, the observed accuracy for the modified version of the JIS method (−26% to 36% for the 95% PI) and the projected areas method (−23% to 30% for the 95% PI) indicated that it is difficult for either method to meet the required accuracy. It would be more realistic to expect that the error of the mass estimate could be as high as 30% even for the new method proposed in this study.

Accessibility is another important factor for practical use. Orthogonal dimensions have typically been used to estimate stone masses because of the fact that they can be readily determined visually. At the present time, projected areas can also be easily determined using a digital camera and image analysis software. Therefore, the projected areas method can also be readily available. A possible problem that limits the application of this method is taking photographs of stones under appropriate conditions. A reasonable estimate from this method can only be expected if the two orthogonal-view images of the smallest imaginary box that encloses the stone are taken from a distance, at least approximately five times greater than its length. Further study is needed to examine the accuracy of the prediction under different conditions.

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【研究論文】

直交画像解析による割石質量推定のための新しい実用的方法

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和　文　要　旨

割石の体積及び質量を投影面積から推定する新しい実用的方法を提示し，中間の長さの軸長と三軸長に基づく従来法二法と比較する。投影面積は，測定枠を参照としてカメラで撮影した石の二方向の水平直交画像から取得する。新しい方法と従来法二法の各予測式のパラメータは100個の小さい砕石のサンプルデータに当てはめた。その結果，新しい方法が最も正確度と精度が高く，石の体積の95%予測区間は相対誤差で−23%から30%の範囲であった。1.16〜3.01tの大きい割石を用いた実物大実証試験により，三軸長のみに基づく方法による予測は誤差の許容範囲を超えてしまったのに対して，新しい方法は割石の質量を回帰分析から期待される誤差範囲で予測できることが示された。

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