

Measurement of rock fragmentation by digital photoanalysis

Analyse photographique par méthode digitale de la fragmentation induite par explosifs

Haufwerkverteilung durch digital photographische Analyse

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ABSTRACT: The authors describe a new method for measuring the size distribution of rock fragments produced by blasting, tested during recent experimental blasting in Virginia, USA. In this method, photographs of the broken rock are digitized, apparent size distributions are measured, and corrections are made for the effect of overlapping blocks. An unfolding (correction) function, has been derived empirically from measurements on small scale samples of crushed rock. Results of this research show further potential for the investigation of correlations between rock mass characteristics, types of explosives, blasting patterns, and fragmentation.

RESUME: Les auteurs décrivent une méthode nouvelle pour la détermination de la distribution granulométrique de fragments rocheux produits par sautage. Cette méthode a été appliquée sur un site expérimental en Virginia, USA. Grâce à des photographies et à la technique digitale, la distribution des dimensions apparentes des fragments est obtenue en y intégrant une correction pour le chevauchement. C'est une correction empirique basée sur des mesures effectuées à petite échelle sur des échantillons de rocs concassés. Les résultats de cette recherche sont encourageants et indiquent un potentiel pour l'étude de corrélations entre les caractéristiques de la masse rocheuse, le type d'explosifs et de sautage et la fragmentation.

ZUSAMMENFASSUNG: Die Autoren beschreiben eine neue Methode zur Auswertung der Größenverteilung von durch Felsprengung produzierter Bruchstücke. Die Methode wurde unlängst bei Versuchsprengungen in Virginia, USA, erprobt. Photographische Aufnahmen der zersplitterten Felsmasse von unterschiedlicher Größenordnung wurden durch Digitalaufzeichnung transformiert. Die sich ergebende Größenverteilung wurde gemessen und Korrekturen für teilweise Überlagerung von Bruchstücken konnten vorgenommen werden. Eine Berichtigungsfunktion wurde von kleinen, mechanisch zerbrochenen Steinresten empirisch abgeleitet. Die Auswertung der Ergebnisse ist Richtungweisend in Hinblick auf Möglichkeiten weiterer Erforschung der Korrelationen von Felscharakteristik, Sprengmitteln, Sprengsatz Verteilung und Felszersplitterung.

1. INTRODUCTION

"Fragmentation" describes the size distribution of blocks produced by blasting. The ideal design of blast should produce a fragmentation closely matched to that required for a specific application such as for rockfill or armor stone, and reduce to a minimum the need for secondary blasting and crushing. Improved fragmentation in most applications means smaller blocks, and generally requires more drilling and more explosives. The costs, however, are offset by easier and cheaper loading, hauling, and crushing (MacKenzie 1966; Greenland and Knowles, 1969).

Because fragmentation is so closely related to the economics of the quarrying operation, it needs to be measured quickly and accurately in order to monitor blasting, and to optimize blast design, while reducing costs and environmental impact.

Currently, there are three methods for determining size distributions:

Sieving has been used extensively in scaled down blasting tests (Dick et al. 1973; Bhandari and Vutukuri 1974; Singh et al. 1980), but is prohibitively slow and expensive for full scale production blasts.

Predictions have been made from blasting parameters and rock mass properties, either using empirical formulae (Lovely 1973; Just and Henderson 1971), or from computer simulations (Gama 1984). These methods, however, do not measure the actual fragmentation.

Photographic methods have been developed in which some parameter of block size, such as length or cross sectional area, is measured on the image either manually (Carter 1977; Almone and Dowling 1983; Noren and Porter 1974) or using an image analysing computer (Gozon 1986). These methods measure only the wholly visible fragments, and not the ones overlapped by other fragments. This represents a serious sampling bias, as discussed below.

A new method of measuring fragmentation using digital photoanalysis has been developed at the University of Waterloo as part of a larger investigation to characterize rock fabric (Franklin and Maerz 1986). This method measures sizes of overlapping as well as non-overlapping fragments, and reconstructs the true size distribution. It was tested during the summer of 1986, by applying it to full scale blasting trials conducted in Virginia by E. I. du Pont de Nemours & Co. Inc.

2. MEASURING TECHNIQUES

2.1 Objectives

The process of deriving a size distribution from a photograph can be considered in four stages:

Photographic sampling: following a strategy designed to ensure that the size distributions in the photographs represent the muckpile as a whole.

Digitization of the photograph: either manually, or by an automatic process involving enhancement and edge detection.

Measurement of apparent block sizes on the photograph.

Conversion of apparent to real block size distributions.

2.2 Photographic Sampling

The muckpile is clearly heterogeneous with respect to fragment size. The largest sizes appear to have a tendency to be thrown to the forward fringes of the pile, and the smallest to cover the upper surface. Sizes appear to increase progressively from the back to the front of the pile, and lateral variations are also possible.

A photograph is a record only of a surface or section. The locations and directions of photography must be selected so that when the photographic data are extrapolated to three dimensions, they are representative of the whole muckpile. Three alternatives can be considered:

To photograph the complete muckpile from a balloon-mounted camera. Aside from the obvious practical difficulties, this method might give biased fragmentation measurements, because of the concentration of smaller fragments at the top of the muckpile.

To photograph a vertical cut through the length of the muckpile. Inevitable delays to the work of loading would hardly be welcomed by the quarry operator. Furthermore, any attempt to excavate a vertical face could easily introduce further errors because of sloughing and the plucking of larger blocks.

To photograph the broken rock product in the haulage trucks after loading from the muckpile. This method appears the least problematic, and was used in the Du Pont trials, mainly because it allowed sampling without delaying the loading and haulage operations.

Truckload samples were taken and photographed at regular intervals along the centerline of the muckpile, perpendicular to the quarry bench. This accounted for front-to-back variations. Vertical variations were averaged by getting the loader to lift a complete vertical section of the pile at each sampling point. A typical set of data, for Truck # 24 of the Du Pont blasting trials, is presented in Figs. 1 and 4.

While removing some biases, this method of sampling introduces others:

A perspective error: the closer blocks appear larger than the blocks further away.

A sorting error: the large blocks tend to slide to the bottom of the pile that forms in the



Fig. 1a: Broken rock in the haulage trucks.

TRUCK 24

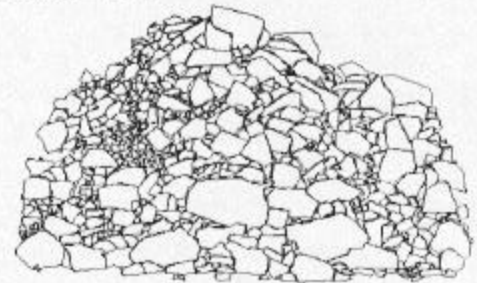


Fig. 1b: Digital image of the block profiles.

TRUCK 24 BLOCK SIZE PROFILE DESCRIPTION

MIN 0.000
MAX 0.470
D 1.70
C 0.070

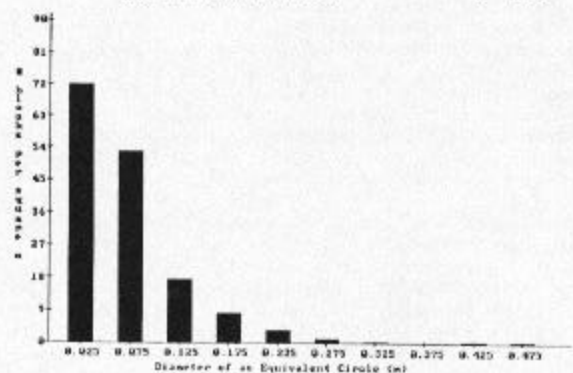


Fig. 1c: Distribution of the block diameters d_{ec} .

truck, whereas smaller ones tend to stay near the top.

An oversize error: very large blocks are not loaded into the truck.

To minimize the perspective error, photographs were taken using a telephoto lens, which flattens and compresses the depth of the image. The sorting error appears to be small and to affect the positions of blocks rather than the overall size distribution. Oversized blocks were counted separately. Research to date shows the total of these sampling errors appear to be quite small. Further studies of sampling methods and the associated errors are in progress.

2.3 Digitization

Two methods of digitization, manual tracing (vector), and automatic scanning (raster) methods are available (Franklin and Maerz, 1986).

For the Du Pont blasting trials, the manual method was used, in which photographs of the truckloads were digitized using an X-Y digitizing pad (Fig. 1b). "Profiles" of blocks, defined as the outlines of complete or partially overlapped blocks, were stored in digital form as the vertices of polygons.

In future studies, the authors expect to be making increasing use of the much faster automatic image analysis alternative. Using the manual method, each photograph took two to three hours to digitize. Techniques of image enhancement and edge detection are being developed to allow blocks to be "recognized" by the computer.

2.4 Measurement of Block Areas and Diameters

The area of each polygon (profile) was measured using the standard mensuration formula. Areas are difficult to visualize, so block sizes were expressed as the diameters " d_{ec} " of equivalent (equal-area) circles. These were then put into ten classes of equal class width, for display in the form of histograms (Fig. 1c). The frequency distributions were expressed as the number of blocks of a particular diameter class per square metre of surface on the muckpile (N_g).

2.5 Determination of True Block Size Distribution

Overview

This stage of analysis requires converting the measured distribution of diameters (d_{ec}) into a "true distribution"; the one that would be obtained if the particles were spread without overlaps. Block size must now be expressed three-dimensionally in terms of the diameter " d_{es} " of an equivalent sphere, one with a volume equal to that of the particle. This allows easy conversion to block weight or mass, as measured by sieving. We are much more concerned with weight than with numbers of fragments, particularly when considering small-sized particles.

Two methods were considered as described below, one analytical, and one empirical:

Analytical Approach

A somewhat similar problem has been studied and solved by stereologists in the fields of biology, metallography, and petrography: that of obtaining

true particle size distributions from apparent ones observed in microscopic thin or polished sections (Deffoff and Rhines 1968; Underwood 1970; Weibel 1979, 1980). In these cases, the d_{ec} of a particle sliced at random is only some fraction of a diameter through its centroid. "Unfolding functions", derived on the basis of geometric probabilities, are used to convert from d_{ec} to d_{es} distributions.

At first an attempt was made to use the same type of function to correct for the overlap in the blast fragmentation. However, when one such function, given by Weibel (1979), was applied to some of the Du Pont data, it gave results that were obviously in error.

In a test to determine why, a box was filled with several hundred styrofoam balls, taking care to avoid regular packing. The spheres were photographed (Fig. 2a), the photographs digitized, and the diameters (d_{ec}) were measured. The results showed an abundance of very large and very small profiles (Fig. 2b) rather than the profile distribution derived using methods of statistical geometry for a slice through an assemblage of spheres (Fig. 2c). The abundance of large profiles corresponded to the many spheres that were fully exposed on the surface layer of the pile, whereas the very small profiles came from highly overlapped spheres in the second and third layers, seen through windows in the upper layer.

From this simple test, it was concluded that a different unfolding model would be needed from those of classical stereology. For present purposes, a semi-empirical unfolding model was the only practical alternative.

Semi-Empirical Approach

Simulations were carried out, using particles of crushed rock up to 50 mm diameter. A log-normal diameter (d_{es}) distribution was prepared by sieving and mixing, and was dumped into a scaled-down version of the box of a truck. The simulated pile was then photographed, digitized, and the diameters (d_{ec}) measured. The d_{ec} and d_{es} distributions were then compared.

Some mechanisms observed during this procedure are as follow:

Overlap of fragments: many observed diameters (d_{ec}) are smaller than their true diameters (d_{es}): i.e. the percentage of small sizes is greater than it should be.

Missing lines: smaller sizes are missing in the photograph, by virtue of falling into holes between and behind larger fragments, or because of insufficient photographic resolution: i.e. the measured percentage of small sizes is less than it should be. Note that this tends to offset the overlap effect.

Anisotropic stacking: anisotropic (platy) shape and stacking lead to a coarsening of the photographic measurements of block area: one tends to measure the largest dimensions of the block.

Observations also suggest that a significant portion of particles found on the surface of a pile are not overlapped, especially large ones. If the diameters of all particles adjacent to the surface are determined correctly (a hypothetical situation in view of overlap), the number of fragments of any class is proportional to the mean diameter of this class (d) and to the number of these particles per unit volume (N_v), i.e.

$$N_a(d) = d N_v(d)$$

The relationship essentially follows from dimensionality considerations. The coefficient of proportionality in the above formula depends on the mean curvature of particles (Santalo, 1976) and is strictly unity for spheres.

To reflect the actual conditions of measurements the above formula must be modified to account for the fact that the area-equivalent diameters (d_{ec}) are determined instead of volume-equivalent diameters (d_{es}). An empirical unfolding function $f(d)$ is introduced as a coefficient of proportionality in the above formula that can be rewritten as follows:

$$N_a(d) = f(d) d N_v(d)$$

The function $f(d)$ was determined from a model experiment that involved a log-normal fragment size distribution. The resulting "unfolding function" is illustrated in Fig. 3.

The fact that the value of the "unfolding function" approaches unity for large particle sizes confirms an intuitive conclusion that most large particles are visible on the surface without overlap. Deviation of $f(d)$ from unity is a measure of particle overlap for a given class.

Large values of the unfolding function for smaller diameters reflect the fact that the "visible" size of particles adjacent to the surface is necessarily smaller than the true particle dimension. The procedure of determining the area-equivalent diameters on the basis of the visible portion of particles unavoidably results in over-representation of small sizes. The "unfolding function" can be used to correct this situation and to convert the measured distribution of diameters (d_{ec}) into a true distribution (d_{es}):

$$N_v(d) = \frac{1}{d f(d)} N_a(d)$$

The use of this unfolding function on samples of other sizes, shapes, or distributions essentially assumes that there are no scale effects when extrapolating from a crushed rock sample to the blast fragmentation sample; and that anisotropy, if present, of the blast fragmentation is assumed to be similar to that of the crushed rock sample.

As an example of the application of this unfolding function, Fig. 4a shows the results of converting the data of Fig. 1c to a volumetric size distribution. This may then be converted into a mass (M) distribution using the relationship:

$$M(d) = N_v(d) V(d) \rho$$

where V is the average volume of a block in the size class:

$$V(d) = \frac{\pi}{6} d^3$$

and ρ is the rock density. Fig. 4b shows the results of converting Fig. 4a to a mass distribution.

Finally, one can present these data in more familiar format, by converting the mass distribution into a cumulative percentage mass distribution as shown in Fig. 4c. This is the same as the "cumulative percent passing" used in a standard sieve analysis, used when testing soils or aggregates.

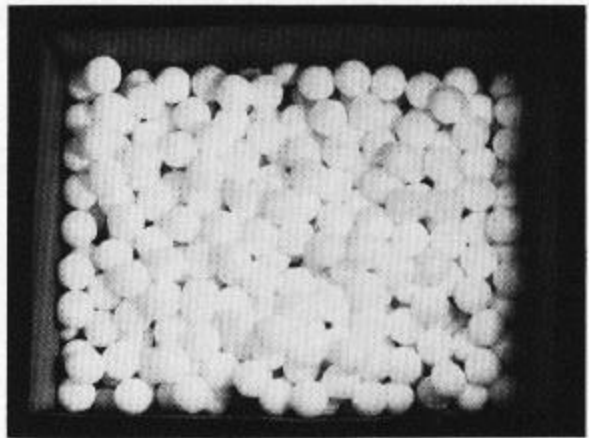


Fig. 2a: Randomly packed assemblage of spheres.

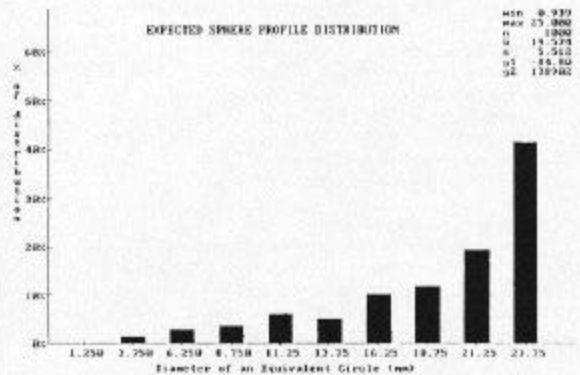


Fig. 2b: Expected d_{ec} distribution, of the spheres, based on geometric probabilities.

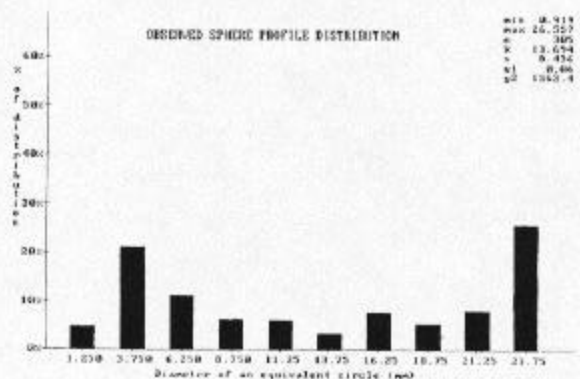


Fig. 2c: Observed d_{ec} distribution of the spheres, from the photograph.

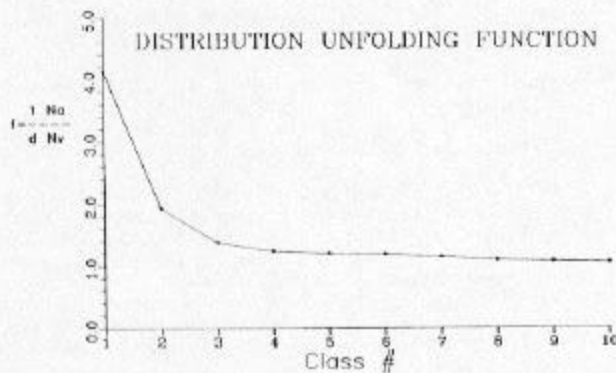


Fig. 3. Empirical unfolding function to relate d_{ec} to d_{es} .

Statistical Representation

Distributions are usually simplified by expressing them in terms of measures of central tendency (average or mean, median, mode) and of dispersion (variance or standard deviation, quartiles, coefficient of uniformity or sorting).

The two histograms of Figs. 4a and 4b show the relative abundance of blocks in each diameter class, according to their numbers and weights respectively. In this particular blast, the most common size (the "mode") was in the order of 7 cm, which was slightly greater or less than the "average" because of the non-symmetrical nature of the distribution. The mode has greater practical significance, being the size produced in the greatest quantity.

The cumulative percent distribution of Fig. 4c demonstrates the approximate log-normality of the size distribution, and is perhaps the most convenient way of visualizing both central tendency and dispersion. Central tendency is measured as the "median", different from both the mode and mean, which is the size D_{50} : half of the sample weight is smaller and half larger than this size. Dispersion can readily be measured in terms of statistics such as D_{10} , D_{25} , D_{60} , D_{75} and D_{90} , defined the same way as D_{50} . Two alternative measures are the Coefficient of Uniformity C_u (D_{60}/D_{10}) and the Coefficient of Sorting C_s (D_{75}/D_{25}). The larger these coefficients, the greater the dispersion.

3. GEOLOGY AND EXPLOSIVES

Measurements were recently made on three full scale test blasts to evaluate fragmentation. The results are to be discussed more fully elsewhere (Maerz, Franklin & Coursen, 1987). They demonstrated, however, a link between block size before and after blasting. Rock that was initially more closely jointed, as measured by photoanalysis of the benches, tended to finish up in smaller fragments. An exception was that near-surface seamy rock still yielded a disproportionate percentage of oversized blocks, because of clay-filled joints and lack of confinement.

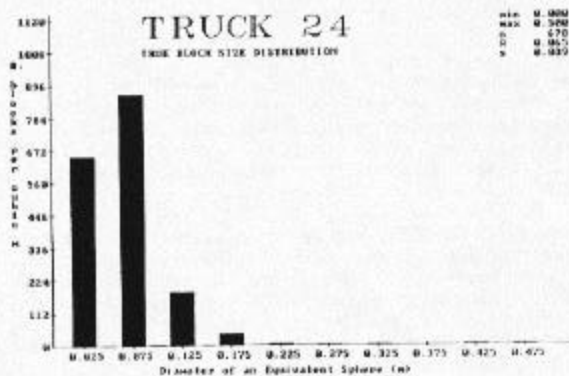


Fig. 4a: Unfolded distribution of block diameters (d_{es}).

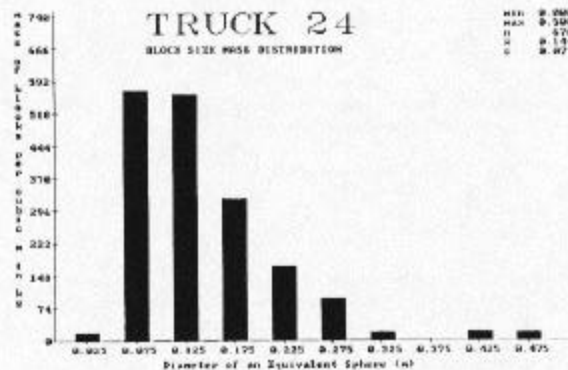


Fig. 4b: Distribution of mass in any given d_{es} class.

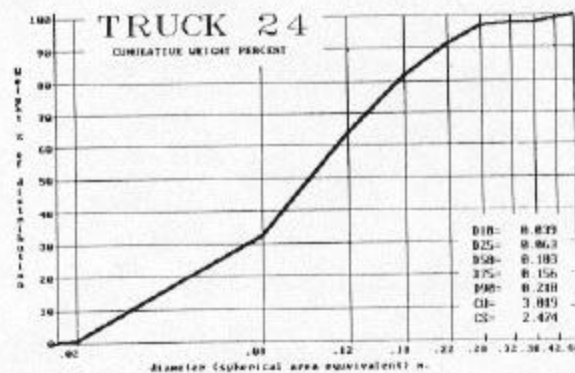


Fig. 4c: Cumulative mass distribution.

4. POTENTIAL OF THE TECHNIQUE

Despite being at an early stage in its development, the photoanalytical technique compares favorably with conventional methods of measuring fragmentation. Using the comprehensive photographic record, stored digitally, analysis can be carried out without disrupting production, and results can be re-analysed at a later date if necessary.

Methods of sampling and vector digitization have been developed and tested. Using scaled-down simulations, a semi-empirical method has been developed for correcting or "unfolding" the apparent size distribution to give a true volumetric or weight distribution of the broken rock. A start has been made in selecting and defining parameters of the size distribution, so as to adequately represent the efficiency of blasting and the quality and value of the product in its various applications.

The photoanalysis technique will, however, become much more efficient, and a really useful and practical tool, with replacement of the vector by the raster (automatic) method of digitization, and with further development of the unfolding formula, testing it for scale effects, different size distributions and block shapes.

5. ACKNOWLEDGEMENTS

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