

UAV photogrammetry for particle size distribution (PSD) and rock fill characterization

Marco Arrieta
Independent, Fernie, British Columbia, Canada



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ABSTRACT

The availability of the UAV (unmanned aerial vehicle) technology and the advances in computer image processing has open the door to a new era with several possibilities to determine PSD using aerial photogrammetry, which has been used to great effect in topographical surveys and geological mapping for the last 5 years. It is also an alternative to conventional sieve analysis for PSD estimation. The PSD is essential to determine the mechanical properties, especially shear strength, of the materials (rock fill) stored in waste dumps. Incorrect shear strength and other mechanical parameter estimation are often the root cause of major instabilities. For large waste rock fill the PSD is fundamental to the determine the shear behavior. Traditionally, particle size distribution for coarse grained materials such as rock fill has been obtained through physical sieving. However, the size in hard rock fills can vary significantly and range from smaller particles (<20cm diameter) to blocks or boulders greater than 100cm, with the maximum size usually limited by the in-situ ground conditions and blasting performance. Essentially, the sieving process is impractical to achieve routinely considering the scale of the material and time required. This paper explores the use of UAV photogrammetry to characterize the shear strength in waste dump materials and the influence of PSD on shear strength.

Keywords : Particle Size Distribution (PSD), Unammed Aerial Vehicle (UAV), Rock Fill and Waste Dump, Barton-Kjaersly

1 INTRODUCTION

Commonly rock fill is a widely used engineering material in embankment dams, retaining walls, shoring systems and ground improvements and is defined as rock fragments with wide size of fragments including gravels (+2mm), cobbles (+60mm) and boulders (+200mm), with a limiting size of, typically, 1m, the PSD and shape characteristics are fundamental to any geotechnical design and construction, since they can greatly affect the performance of granular materials, including their strength and load-bearing capacity [1].

These are closely related to the economics for many construction projects. With rock fill structures, the PSD of the material plays a crucial role in multiple levels [2]. For instance, the compaction of the rock fill can be affected by its particle size distribution. For construction quality control, it would be usually required to ensure that the rock fill PSD meets the design criteria and is within the design envelope [3].

The construction of waste dumps and rock fill dams has given new impetus to investigation of the physical and mechanical properties of rock fill material. In most cases, triaxial testing on the prototype rock fill using conventional laboratory equipment is unattainable as the sizes of aggregates used in the field are usually too large [4]. This in turn emphasizes the need to develop appropriate methods to determine the PSD at real scale to be establish as a scaling's laws [5].

Traditionally, the particle size distribution for engineering materials is determined through physical sieve analysis using a series of screens with squared mesh [6]. With rock fill material there is no other accurate methodologies to establish PSD except visual rock gradation analyses relying heavily on the visual examination and engineer's experience for quality control during construction [7].

This method usually involves sieving of the finer fraction (i.e., up to 60mm) and physical measurements of coarser rocks using measuring tapes or other visual aids and is considered to be expensive and time-consuming and not feasible for routine quality control purpose [8].

Commonly a full-scale gradation test on a rock fill and waste dump sample would require widely field work involving engineers and field technician, dedicating up to 48 hours to complete [9]. It is recognized that this work may be completed by a field geotechnical engineer and an assistant [10]. Machinery and safe handling procedures are also required for particle sizes in excess of 200 mm (i.e., heavier particles) [11].

Thereby, there is a strong motivation to establish a safer, faster, and simpler approach to assess the size distribution of rock fill material on a routine considering the actual developments in computer and technologies [12]. With recent developments in computing and technology, image processing can be employed to determine the PSD of rock fill and waste dump materials [13].

Similar to conventional visual assessment, the image analysis technique allows researchers and practical engineers to inspect and measure visible particles within a digital photograph using computer algorithms [14]. This presents an optimization in rock fill and waste dumps for geotechnical characterization optimizing the time consuming to collect data and dedicate time to engineering analysis [15].

However, the availability of the UAV (Unmanned Aerial Vehicle) technology and the advances in computer image processing has open the door to a new era with several possibilities to determine PSD using aerial photogrammetry, which has been used to great effect in topographical surveys and geological mapping for the last 5 years [16].

It is also an alternative to conventional sieve analysis for PSD estimation. This paper explores the use of UAV photogrammetry to characterize the shear strength in

waste dump materials and the influence of PSD on shear strength.

2 STRENGTH MODEL FOR ROCK FILL, STOCKPILES, AND MINE WASTE DUMPS

Estimate the shear strength for coarse materials which contain particles of metric scale is challenging because commercial laboratory testing devices can only accommodate samples composed by a centimeter particle [17].

Due to testing limitations, the shear strength is frequently estimated using the empirical model of Barton & Kjærnsli (1981) (B–K criterion), which considers the nonlinearity of the shear strength envelope, characterizing the behavior of coarse granular materials submitted to very high loads [18].

In the B–K criterion, the shear strength is parametrized using the equivalent roughness (R) and equivalent strength (S) [19].

The B–K empirical non-linear model is represented by Equation [1]. The model is intended to be utilized for characterizing coarse materials like rock fill and blasted rocks, which typically exhibit a non-linear shear strength envelope [20].

In the B-K model, the effective friction angle of the waste rock is estimated by adding to the residual angle of friction (φ_b) a structural component of strength (which is stress-dependent), determined by the degree of roundness of the particles and the porosity of the arrangement of particles [21].

According to the expression, the friction angle is at least equal to the residual friction angle and varies in a magnitude R for a 10-fold increase of $\frac{S}{\sigma_c}$ [22].

$$\tau = \sigma_n \tan \left[R \log_{10} \left(\frac{S}{\sigma_c} \right) + \varphi_b \right] \quad [1]$$

where:

σ_n = Effective normal stress.

φ_b = Residual friction angle of the rock.

R = Equivalent roughness of waste particles.

S = Size-dependent equivalent strength of waste particles.

The parameter R is a function of particles roundness and porosity (n) of the arrangement of particles. It is determined based on the chart developed by Barton - Kjærnsli. R may vary between 0 and 15 for loose arrangements of rounded, smooth particles to dense arrangements of very angular and rough particles, respectively. The parameter S is a function of the unconfined compressive strength (UCS) of the rock and its characteristic particle size, adopted here as the median diameter by weight (D_{50}) [23]

2.1 Strength model parameters

2.1.1 PSD using UAV

Field data collection was conducted using a DJI Mavic Pro quadrotor drone, equipped with an 1/2.3" (CMOS), Effective pixels:12.35 M (Total pixels:12.71M) [24]. Mapping involved the acquisition of multiples photos with the aim to collect and determine the geometric details of the rock fill and waste dump particles [25].

A total of 3855 images were taken and analyzed including rock fill materials with particle sizes ranging from sand and gravel to boulder sizes of up to 1000mm. The images were taken remotely by a drone. The UAV is equipped with a GPS and an inertial navigation system that can records 3D spatial coordinates and the orientation of the camera.

Four vertical flights with overlap and side lap ensured coverage of the entire areas [26].

The pictures have been taken from an average distance of 30-120 m from the waste dumps and rock fill slope surface, yielding an estimated Ground Sample Distance of about 1 cm. ShapeMetriX UAV and Fragmenter packages by 3GSM GmbH has been used to generate georeferenced point clouds and high resolution digital terrain models in order to measure PSD [27].

Figure 1 shows the photographs orientation and the Figure 2 shown the PSD analysis using UAV image. Delineation of rock fill particles is rainbow scale.

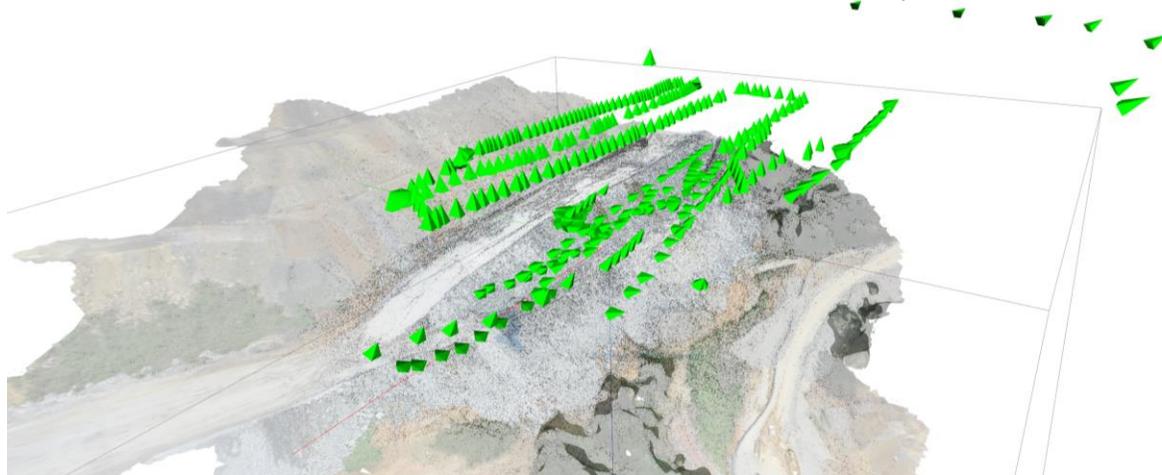


Figure 1. Location and orientation of photographs relative to point cloud.



Figure 2. Waste dump 3D model comprising >7 million points and >2.6 million mesh elements

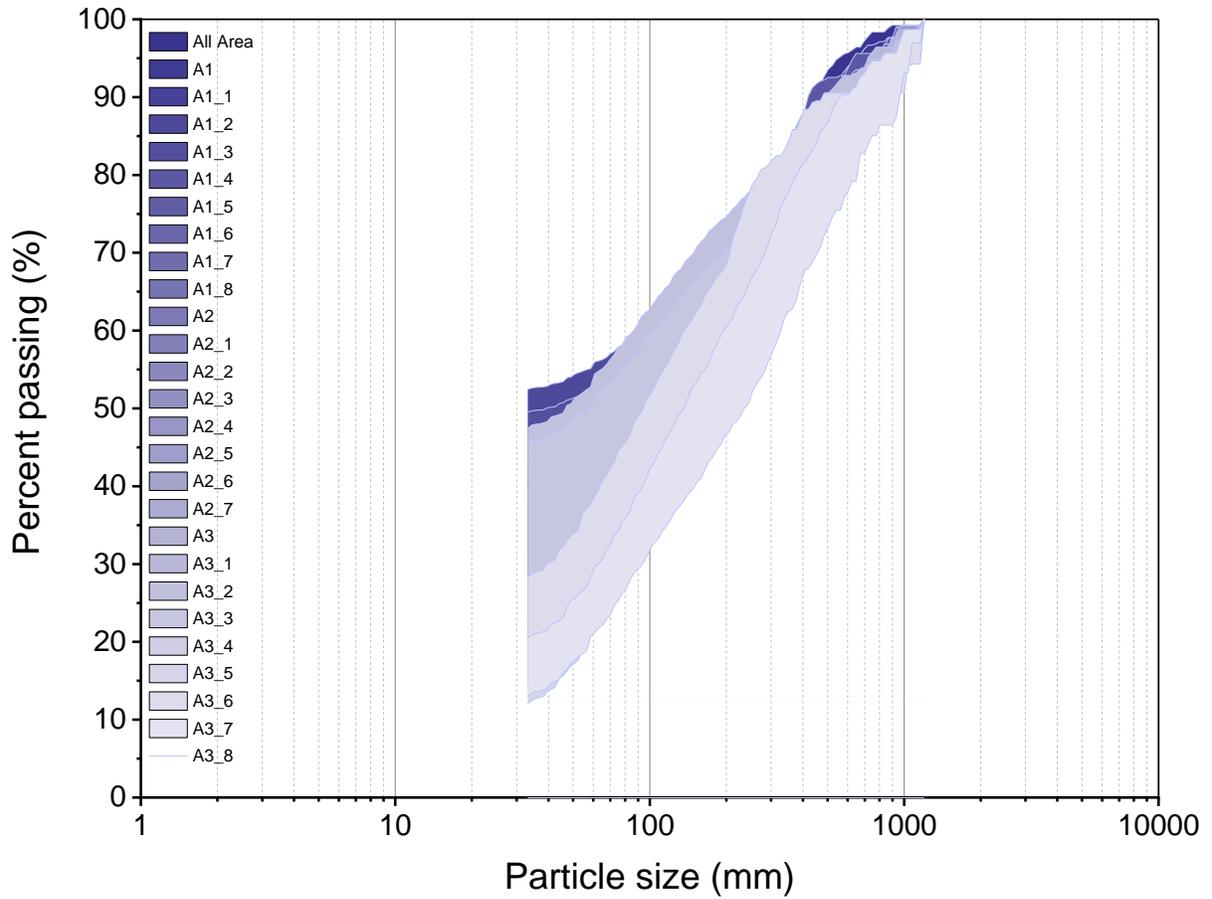


Figure 3. PSD and D_{50} at each scenario.

The PSD data assessed from these sources is shown at the Figure 3 making a comparison between the entire area and the sub-divisions. Average values are plotted to quantify the D_{50} range.

To understand the influence of variability, appropriate values and sensitivity, different ranges of PSD and D_{50} values are presented in Table 1 and Figure 4 considering the discretization process [28].

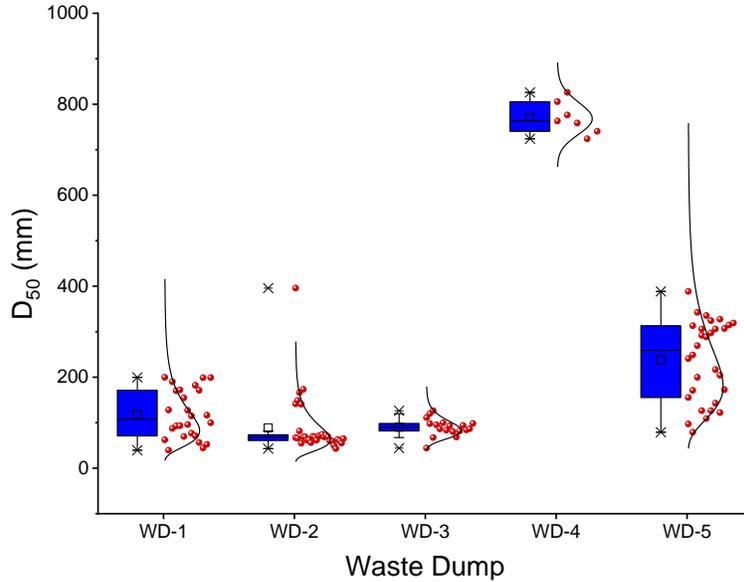


Figure 4. Characteristics of the population on D_{50} (in millimetres) by waste dump unit.

Table 1. Statistical data distribution on D_{50} (in millimetres) by waste dump unit

Site	Count	Mean	Std	Min	Perc 25%	Perc 50%	Perc 75%	Max
WD-1	26	117.9	53.4	39.3	72.3	107.3	171.0	199.7
WD-2	32	88.6	65.7	43.1	61.1	68.2	73.1	395.9
WD-3	18	89.8	19.2	44.2	82.3	89.8	98.1	126.3
WD-4	7	770.6	35.6	724.0	749.6	763.1	791.0	825.9
WD-5	30	238.1	88.8	78.9	159.3	259.0	311.6	388.5

2.1.2 Equivalent strength (S/σ_n).

The size-dependent equivalent strength is based on the waste rock UCS values and the D_{50} . The S values were assessed based on the strength assessment scheme proposed by Barton & Kjaernsli, 1981 [29] (Figure 5)

Table 2 shows the equivalent shear strength values using the mean D_{50} for each waste dump. The values have a range between 0.20 for very coarse material and 0.27 for medium materials ($D_{50} < 100\text{mm}$)

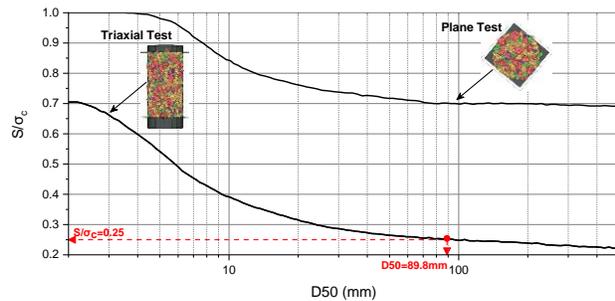


Figure 5. Equivalent strength (S) for a D_{50} of 30mm (Modified, Barton & Kjaernsli 1981)

Table 2. Equivalent strength by waste dump unit using the D_{50} mean value.

Site	D_{50} Mean	S/σ_c
WD-1	117.9	0.26
WD-2	88.6	0.27
WD-3	89.8	0.27
WD-4	770.6	0.20
WD-5	238.1	0.25

2.1.3 Residual friction angle (ϕ_b).

The residual friction angle ϕ_b can be estimated in tilting tests using dry, sawn surfaces of the parental rock. In the mining context, it is more often obtained from direct shear tests conducted on saw-cut samples selected from drill cores [30]. In this case, ϕ_b was calculated performing multiples tilt test. Table 3 shows the results and the variation of this parameter.

Figure 6 shows the distribution of the population for the ϕ_b on each waste dump. Coarse material like WD-1 (Limestone), WD-2 (Material with less than 15% fines content) and WD-3 (Rocky material) have less variation at the ϕ_b due to the minimum fine content in the composition of the material.

Table 3. Statistical data distribution on the residual friction angle (ϕ_b) by waste dump

Site	Count	Mean	Std	Min	Perc 25%	Perc 50%	Perc 75%	Max
WD-1	20	30.5	3.6	0.0	28.8	31.0	33.0	37.0
WD-2	20	36.3	1.9	22.0	35.0	36.5	38.0	39.0
WD-3	20	31.2	5.5	32.0	29.0	32.5	35.3	39.0
WD-4	20	35.8	2.4	19.0	34.0	36.0	38.0	39.0
WD-5	20	36.8	2.2	31.0	35.0	36.0	38.0	43.0

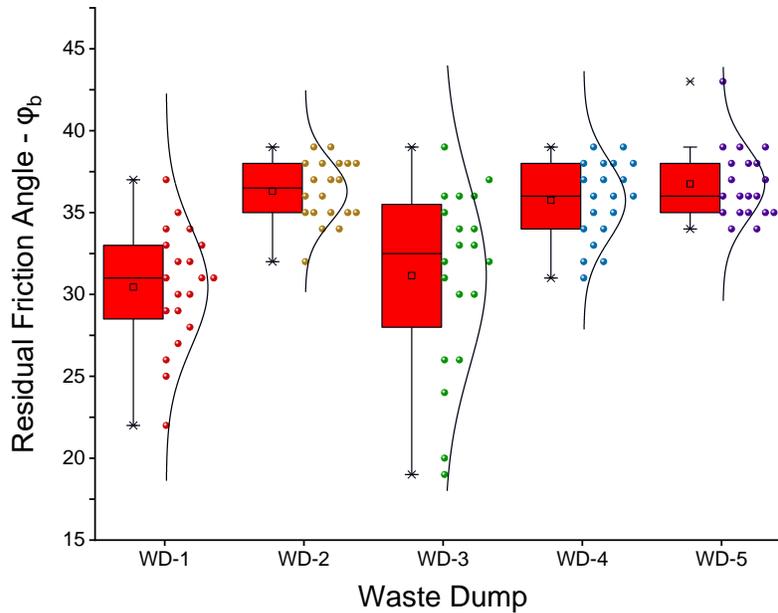


Figure 6. Characteristics of the population on the residual friction angle (ϕ_b) data by waste dump.

2.1.4 Dump porosity (n) and equivalent roughness of waste particles. (R).

The waste rock volume will expand during blasting, excavation and dumping process, and with a large range in particle size, this is typically represented as a percentage increase from the undisturbed in situ volume [31]. Segregation is also typical on dump faces during construction and material consolidation within increased loading conditions will increase density and decrease the porosity and void ratio [32].

These factors result in difficulty in the determination of porosity, with limited benchmark data available [33]. In situ assessment of the dump density for this case study was not practical. A porosity value of 25% was assumed based on the literature review and engineering judgement.

The particle shape for all the cases was considered conservatively with a smooth surface and moderate angular with and the waste porosity of 25%. Using the empirical scheme developed by Barton & Kjaernsli, 1981 presented in Figure 7 provided a roughness (R) value in the range of 6.0 and 6.4.

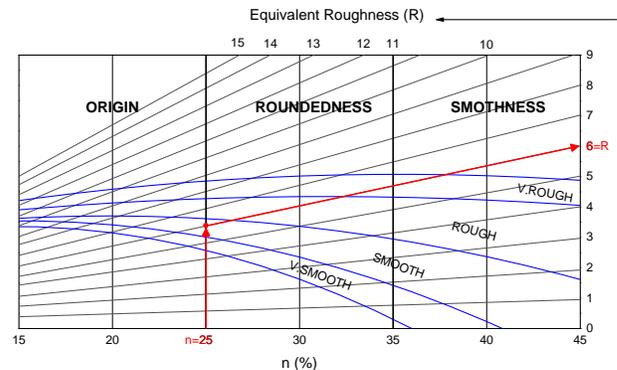


Figure 7. Empirical assessment of equivalent R parameters (Modified, Barton & Kjaernsli 1981)

2.1.5 Strength models using Barton – Kjaernsli criterion

To estimate the strength parameters for the rock fill and waste dumps the basis concept is showed in Figure 8. The base of the value corresponds to shear stress is showed at Table 4 and was calculated with the B–K criterion through

the equation [1] and using the mean values of ϕ_b and D_{50} [34].

Table 4. Input parameters for the B-K non-linear shear strength using the 1 MPa for normal stress

Site	ϕ_b (°)	R	S/ σ_n	σ_n (Mpa)	τ (MPa)	ϕ' (°)
WD-1	30.5	6.1	0.26	1.0	0.67	33.87
WD-2	36.3	6.4	0.27	1.0	0.90	42.11
WD-3	31.2	6.0	0.27	1.0	0.71	35.27
WD-4	35.8	6.3	0.20	1.0	0.87	41.07
WD-5	36.8	6.5	0.25	1.0	0.94	43.25

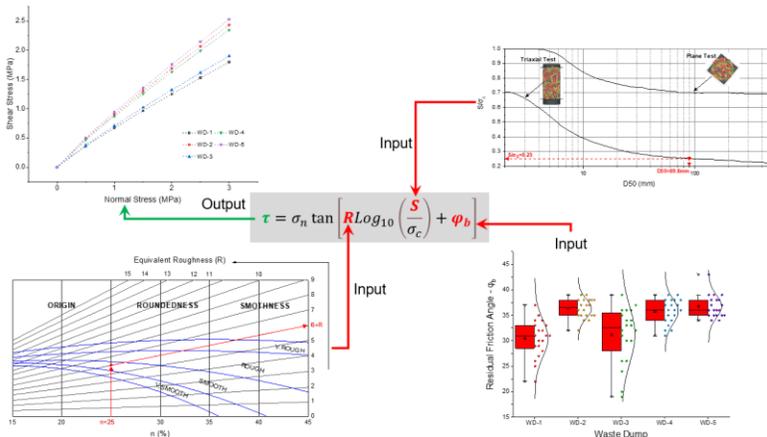


Figure 8. Basis concept and approach using B-K criterion to estimate the shear strength.

Figure 9 and Figure 10 shows 2 trends for the shear stress due to the PSD of the materials, coarse materials with a D_{50} up to 200mm average and fine waste materials with a D_{50} underneath 100mm. For coarse materials the equivalent strength relation is particular less variable than material with a fine PSD average, which means higher shear stress will obtain representing stables structures [35].

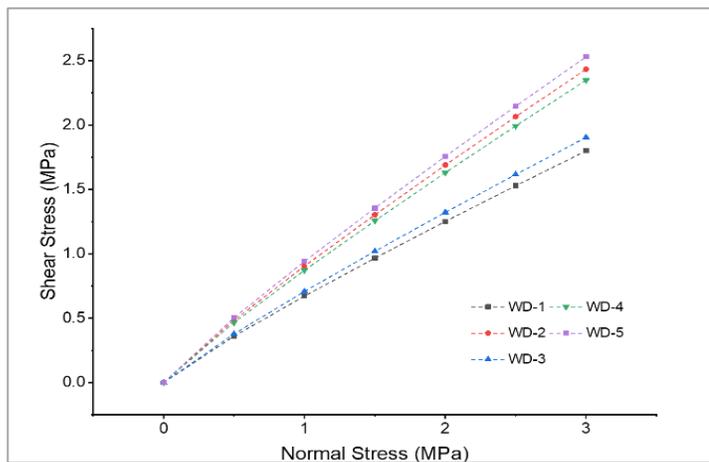


Figure 9. Non-linear shear strength envelopes using B-K criterion.

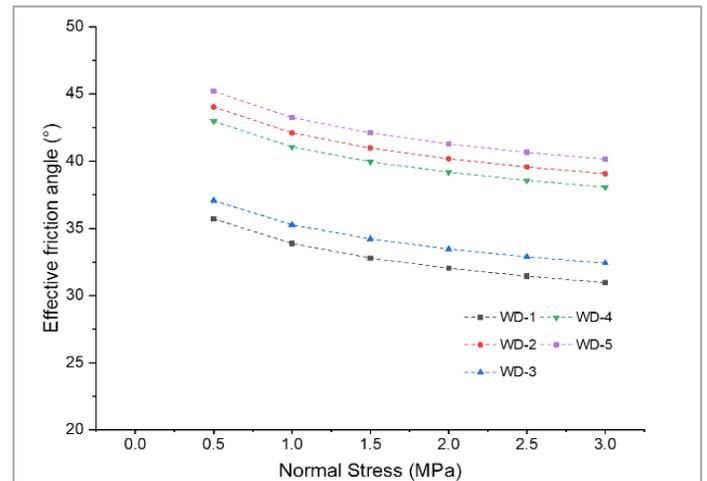


Figure 10. Shear strength of rock waste using B-K criterion

3 CONCLUSIONS

Using UAV photogrammetry to determine the PSD for a coarse materials and waste dumps, combines with the B-K nonlinear criterions to characterize the shear strength was described and illustrated with data from five rock fill and mine waste materials.

The definition of the input parameters of the model using the results of field mapping, UAV photogrammetry, tilt field determinations and judgement was described, and the evaluation of the shear strength represented by shear strength and friction angle was developed.

The availability of high-performance computers and the advances in image processing are inarguably set the new era allowing to perform PSD in the entire rock fill and waste dumps without the bias generate with the sieve analysis, obtaining accurate input data which can be used in a probabilistic analysis reducing the error at the output results.

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5 REFERENCES

[1] L. Zerui, G.-N. Behrooz and D. Mahdi, "An innovative approach to determine particle size distribution for

- rock fill material," *International Journal Of Rock Mechanics And Mining Sciences And Geomechanics*, pp. 26-35, 2015.
- [2] H. Shin and J. Santamarina, "Role of particle angularity on the mechanical behavior of granular mixtures," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 192, no. 2, pp. 353-355, 2012.
- [3] C. Dano and C. Ovalle, "Effects of particle size-strength correlation and particle size-shape correlation on parallel grading scaling of rock fill materials," *Geotechnique*, vol. 10, pp. 1-26, 2020.
- [4] G. Yang, Y. Jiang, S. Nimbalkar, Y. Sun and N. Li, "Influence of Particle Size Distribution on the Critical State of Rock fill," *Advances in Civil Engineering*, pp. 1-7, 2019.
- [5] R. Marsal, "Large scale testing of rock fill materials," *Journal of the Soil Mechanics and Foundations Division*, vol. 93, no. 2, pp. 27-43, 1967.
- [6] J. Breitenbach, "Definition of Rock fill versus Earthfill Material," *Journal of Indian Committee on Large Dams*, vol. 1, no. 1, pp. 8-12, 2012.
- [7] J. Kemeny, "Practical technique for determining the size distribution of blasted benches, waste dumps and heap leach sites," *Mining Engineering*, vol. 46, no. 11, pp. 1281-1284, 1994.
- [8] K. Grainger and G. Paine, "Development and application of a photographic fragmentation sizing assessment technique for blast analysis," *International Journal Of Rock Mechanics And Mining Sciences And Geomechanics*, p. 26–31, 1992.
- [9] N. Marachi, C. Chan and H. Seed, "Evaluation of properties of rock fill material," *Journal of the Soil Mechanics and Foundations Division*, vol. 98, no. 1, p. 95–114, 1972.
- [10] C. Ovalle, E. Frossard, E. Dano, W. Hu, S. Maiolino and P. Hicher, "Effect of size on the strength of coarse rock aggregates and large rock fill samples through experimental Data," *Acta Mechanica*, vol. 225, no. 8, p. 2199–2216, 2014.
- [11] J. Hyslip and L. Vallejo, "Fractal analysis of the roughness and size distribution of granular materials," *Engineering Geology*, vol. 48, no. 3-4, pp. 231-244, 1997.
- [12] L. Gang, Y. Liu, C. Dano and P. Hicher, "Grading-dependent behavior of granular materials: from discrete to continuous modeling," *Journal of Engineering Mechanics*, pp. 35-42, 2015.
- [13] W. Yan and J. Dong, "Effect of particle grading on the response of an idealized granular assemblage," *International Journal of Geomechanics*, vol. 11, no. 4, p. 276–285, 2011.
- [14] J. Latham, J. Kemeny, N. Maerz, M. Noy, J. Schleifer and S. Tose, "A blind comparison between results of four image analysis systems using a photo-library of piles of sieved fragments," *Fragblast*, vol. 7, no. 2, pp. 105-132, 2003.
- [15] S. Linero, L. Contreras and J. Dixon, "Estimation of shear strength of very coarse mine waste," *International Slope Stability in Mining Conference*, vol. 2, pp. 341-354, 2021.
- [16] M. Thurley, "Automated Image Segmentation and Analysis of Rock Piles in an Open-Pit Mine," *International Conference on Digital Image Computing: Techniques and Applications (DICTA)*, pp. 1-8, 2013.
- [17] N. Barton and B. Kjærnsli, "Shear strength of rock fill," *Journal of the Geotechnical Engineering Division*, vol. 107, p. 873–891, 1981.
- [18] C. Ovalle, S. Linero, E. Bard, P. Hicher and R. Osses, "Data compilation from large drained compression triaxial tests on coarse crushable rock fill materials," *Journal of Geotechnical and Geoenvironmental Engineering*, 2020.
- [19] N. Barton, "Shear strength criteria for rock, rock joints, rock fill and rock masses: Problems and some solutions," *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 5, p. 249–261, 2013.
- [20] N. Barton, "Shear Strength of Rock fill, Interfaces and Rock Joints, and their Points of Contact in Rock Dump Design," in *First international seminar on the management of rock dumps, stockpiles and heap leach pads*, Perth, western Australia, 2008.
- [21] L. Valenzuela, E. Bard, J. Campana and M. Abalon, "High Waste Rock Dumps — Challenges and Developments," in *First International Seminar on the Management of Rock Dumps, Stockpiles and Heap Leach Pads*, Perth, Western Australia, 2008.
- [22] N. Barton, "Non-linear shear strength for rock, rock joints, rock fill and interfaces," *Innovative Infrastructure Solutions*, pp. 1-19, 2016.
- [23] N. Barton, "Shear strength criteria for rock, rock joints, rock fill, interfaces and rock masses," *International Journal of Rock Mechanics and Mining Sciences*, vol. 54, pp. 297-310, 2012.
- [24] D. Zekkos, W. Greenwood, J. Lynch, J. Manousakis, A. Athanopoulos-Zekkos, M. Clark, K. Cook and C. Saroglou, "Lessons Learned from the Application of UAV-Enabled Structure-From-Motion Photogrammetry in Geotechnical Engineering," *International Journal of Geoenvironment Case Histories*, vol. 4, no. 4, pp. 254-274, 2018.
- [25] I. Colomina and P. Molina, "Unmanned Aerial Systems for Photogrammetry and Remote Sensing: A Review," *ISPRS Journal of Photogrammetry and Remote Sensing*, vol. 92, pp. 79-97, June 2014.
- [26] N. Bar, L. Borgatti, D. Donati, M. Francioni, R. Salvini and M. Ghirelli, "Classification of natural and engineered rock slopes using UAV photogrammetry for assessing stability," *IOP Conf. Series: Earth and Environmental Science*, vol. 833, 2021.
- [27] N. Bar, M. Kostadinovski, M. Tucker, G. Byng, R. Rachmatullah, A. Maldonado, M. Pötsch, A. Gaich, A. McQuillan and T. Yacoub, "Rapid and robust slope failure appraisal using aerial photogrammetry and 3D slope stability models," *International Journal of*

Mining Science and Technology, vol. 30, no. 5, pp. 651-658, 2020.

- [28] S. Linero, C. Palma and R. Apablaza, "Geotechnical Characterisation of Waste Material in Very High Dumps with Large Scale Triaxial Testing," in *Slope Stability 2007: Proceedings of the 2007 International Symposium on Rock Slope Stability in Open Pit Mining and Civil Engineering*, Perth, 2007.
- [29] S. Linero, L. Contreras and J. Dixon, "Bayesian approach to improve the confidence of the estimation of the shear strength of very coarse mine waste using Barton's empirical criterion," in *Proceedings of ICSMGE 2022: 20th International Conference on Soil Mechanics and Geotechnical Engineering*, Australia, 2022.
- [30] N. Barton, "Non-linear Shear Strength for Rock, Rock Joints, Rock fill and Interfaces," in *Sexta conferencia Raul Marshal*, Jalisco, Mexico, 2014.
- [31] B. Indraratna, L. Wijewardena and A. Balasubramaniam, "Large-scale triaxial testing of grey wacke rock fill," *Geotechnique*, vol. 43, no. 1, p. 1993, 1993.
- [32] A. Brown, "Use of soft rock fill at Evretou Dam, Cyprus," *Geotechnique*, vol. 38, no. 3, pp. 333-354, 2015.
- [33] P. Rowe, "A reassessment of the causes of the Carsington embankment failure," *Geotechnique*, vol. 41, no. 3, pp. 395-421, 2015.
- [34] P. Ramirez, C. Gonzalez and M. Alvarez, "Stability analysis of Llerin Rock fill Dam: An in situ direct shear test," *Engineering Geology*, vol. 100, no. 3, pp. 120-130, 2008.
- [35] Z. Wu, Y. Li, J. Chen, H. Zhang and L. Pei, "A reliability-based approach to evaluating the stability of high rock fill dams using a nonlinear shear strength criterion," *Computers and Geotechnics*, vol. 51, pp. 42-49, 2013.
- [36] H. Liu, F. Hussain, C. Lim Tan and M. Dash, "Discretization: An Enabling Technique," *Data Mining and Knowledge Discovery*, vol. 6, p. 393-423, 2002.
- [37] P. Domingos and M. Pazzani, "Conditions for the optimality of the simple Bayesian," *Machine Learning*, vol. 29, no. 2, p. 103-130, 1997.