Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering– Rahman and Jaksa (Eds)
© 2022 Australian Geomechanics Society, Sydney, Australia, ISBN 978-0-9946261-4-1

Experimental study on the shear strength of medium-coarse rockfill

Etude expérimentale sur la résistance au cisaillement des enrochements moyennement grossiers

Mauro Muñiz-Menéndez & José Estaire
Laboratorio de Geotecnia, CEDEX, Spain, mauro.muniz@cedex.es

ABSTRACT: The most common size of direct-shear-boxes are 60x60 mm; and 100x100 mm, and 150x150 mm boxes are not rare. The international test standard ISO 17892-10:2018 limits the maximum particle size that can be tested in a direct-shear box to 1/12.5 of the box side. This limit makes it impossible to test soils larger than fine gravel (2 – 6.3 mm according to ISO 14688-1:2017). For this reason, the available data on shear strength for coarse to very-coarse soils are very scarce. Since the early '80s, there is a large shear-box (1000 x 1000 mm) at the CEDEX – Laboratorio de Geotecnia, which has been widely employed for the study of rockfills for ports and dams, as well as of rail ballast and other coarse granular materials. All the data collected over these 40 years, together with some data taken from the literature, have been joined in a single database of around 100 samples. The analysis of these data allows to deepen the knowledge of the behaviour of coarse granular materials: shear criterion, average parameters, relation among parameters, etc.

RÉSUMÉ: Les dimensions les plus courantes des boîtes à cisaillement direct sont les boîtes de 60x60 mm; 100x100 mm et 150x150 mm ne sont pas aussi très rares. La norme de test internationale ISO 17892-10:2018 limite la taille maximale des particules que vous pouvez tester dans une boîte à cisaillement direct à 1 / 12,5 du côté de la boîte. Cette limite ne permet pas de tester un sol plus grand que le gravier fin (2 - 6,3 mm selon ISO 14688-1:2017). Pour cette raison, les données réelles de résistance au cisaillement pour les sols grossiers à très grossiers sont très rares. Au CEDEX – Laboratorio de Geotecnia il existe depuis le début des années 80 une grande boîte de cisaillement (1000 x 1000 mm) largement utilisée pour l'étude des enrochements des ports et des barrages, ainsi que des ballasts ferroviaires et autres matériaux granulaires grossiers. Toutes les données collectées sur ces 40 ans et certaines données de la littérature sont réunies dans une seule base de données avec près de 100 données. L'analyse de cette quantité de données permet d'approfondir la connaissance du comportement des matériaux granulaires grossiers: critère de cisaillement, paramètres moyens, relation entre paramètres, etc.

KEYWORDS: shear strength; rockfill; non-linear criterion; large shear-box.

1 INTRODUCTION.

The study of coarse granular materials is hindered by the extremely large sample size required to perform tests in this type of material. Since the size of the test equipment must be excessively large, there are very few equipment with the necessary characteristics to test these materials in the world.

In some projects, the solution proposed was the use of large in situ tests (Barton & Kjaernsli, 1981). This solution may be highly suitable for large projects, with a sufficient budget, and in the later phases of the project when the construction works have already begun and the machinery and materials are available. In more modest projects or in the early or design phases, these in situ tests are unviable.

Since the '90s, CEDEX – Laboratorio de Geotecnia (Madrid, Spain) has a 1x1-m shear box where numerous samples of coarse rock materials have been tested. The analysis of the data obtained over the years, together with the data published in literature, allow drawing some general conclusions about the behaviour of this type of materials under shear stress conditions that may be really useful in the geotechnical design of harbour works, dams, railways, etc.

2 METHODS AND MATERIALS

2.1 *Large direct-shear box*

The most common size of direct-shear-boxes are 60x60 mm. The 100x100 mm, and 150x150 mm boxes are not rare.

The international test standard ISO 17892-10:2018 limits the maximum particle size that can be tested in a direct shear box to 1/12.5 of the box side. This limit makes it impossible to test soils larger than fine gravel (2 – 6.3 mm according to ISO 14688-1:2017). For testing coarse to very-coarse soils, the use of large shear-boxes (> 500 x 500 mm) is required, but there are only a few large shear boxes around the world. Table 1 collects some of the large shear boxes described in the literature.

Most of the results used in this study come from tests carried out in the large shear box of our geotechnical laboratory (Figure 1 and Figure 2). This device has a shear plane of 1000 mm x 1000 mm. This equipment was own designed and built in the early '90s and, since then, several updates and modifications have been made.

Figure 1. Lateral view photography of the CEDEX large direct shear box

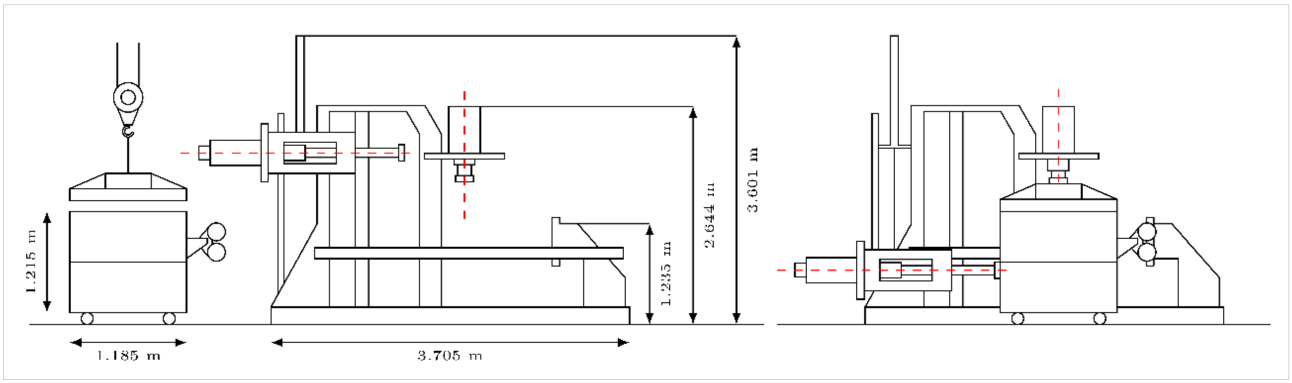

Figure 2. Scheme of the CEDEX large direct shear box

Table 1. Large direct shear boxes across the world

Institution	Shear plane L x W (mm)	Reference
School of Engineering, University of Wales, UK	3000x1500	(Davies & Le Masurier, 1997)
City University of London, UK	1500x1000	(Tanghetti et al., 2019)
University of Oxford, UK	1000x1000	(Pedley, 1990)
Department of Civil Engineering, University of Manitoba, Canada	1000x1000	(Krahn et al., 2007)
School of Civil Engineering, Purdue University; USA	1000x1000	engineering.purdue.edu
SGI Testing Services, LLC, USA	810x790	www.sgilab.com
Jaroslav Cerni Institute for Development of Water Resources, Serbia	800x800	(Andjelkovic et al., 2018)
National Institute for Rural Engineering, Japan	800x500	(Matsushima et al., 2007)
Indian Institute of Technology Roorkee, India	750x750	(Srivastava et al., 2019)
Istituto Sperimentale Modelli Geotecnici, Italy	700x700	http://www.ismgeo.it/

With the current configurations, both the normal and shear loads are applied by two servo-controlled hydraulic pistons with a load capacity of 1 MN each. The shear rate can be controlled from 0.5 to 45 mm/min, and the maximum shear displacement is 250 mm. The vertical displacement is measured by 4 LVDT transducers located close to the four corners of the box cup. This location allows the measurement, not only of the vertical displacement of the cup, but also of its tilt. The resolution of the transducers is 0.1 mm. Both the control and the data collection are performed by means of the software PCDK2, a multichannel controlling system coded by Servosis, S.L. This system records the vertical and horizontal forces applied by the pistons, the horizontal displacement, and the displacement of the four vertical sensors at an acquisition rate of 0.1 Hz. The datalogger allows a data acquisition rate as fast as several kHz.

The specimen is placed in the shear box by vertical discharge (Figure 3). Some compaction can be made by means of the vertical actuator or a small jackhammer compactor. This shear box does not allow the immersion of the specimens in water, so all the tests are carried out in dry specimens, or in specimens with their natural water content, but not in saturated specimens.

In addition to the direct shear test, it is also possible to perform other kinds of tests in this equipment, such as pull-out tests for geosynthetics.

Figure 3. Sample placing by vertical discharge

2.2 *Rockfill samples*

As can be observed in Figure 4, most of the materials tested in this shear box are granular rock materials coarse to medium in size. These materials are studied to be used, for instance, in harbour backfills, embankment dams or railway infrastructures.

According to the standard ISO 14688-1:2017, regarding the dimensions of this box, materials with grain sizes up to 8 cm could be tested. However, over the years, coarser materials were tested, reaching sizes up to 20 cm.

From a petrological point of view, the samples tested differ greatly, of which limestones, quartz sandstones and granites, either natural or crushed gravel, stand out because these are the most common materials in Spain.

Within the rock materials tested, those used as ballast in conventional and high-speed railway lines must be highlighted. Given the strength, deformability and durability characteristics demanded for the rail ballast, this material only comes from extremely hard rocks with a shear strength of the aggregates that stands out from the rest of materials, as will be seen below. The specific weight values of the material tested usually range from 14 to 20 kN/m^3, depending on the type of material and the compaction degree reached.

This equipment has also been used to carry out tests in other materials that are present in many geotechnical projects such as recycled materials (e.g. shredded tyres). It has also been studied the shear strength in the interface between rockfill and concrete elements such as harbour caissons or railway sleepers against ballast. However, these materials will not be commentated on in this article.

Figure 4. Some examples of the materials tested at CEDEX's facilities

3 RESULTS

In this article, 55 direct shear tests performed at CEDEX laboratory are compiled, each one composed of at least 3 specimens (more than 200 specimens in total) tested at different normal loads (σ_n). The results of these tests, analysed together, are shown in Figure 5. Beyond the data variability due to the great variety of lithologies and grain size distributions tested, if a linear failure criterion—Mohr-Coulomb type— is assumed, an average friction angle (ϕ) of about 45° is observed, without cohesion (c).

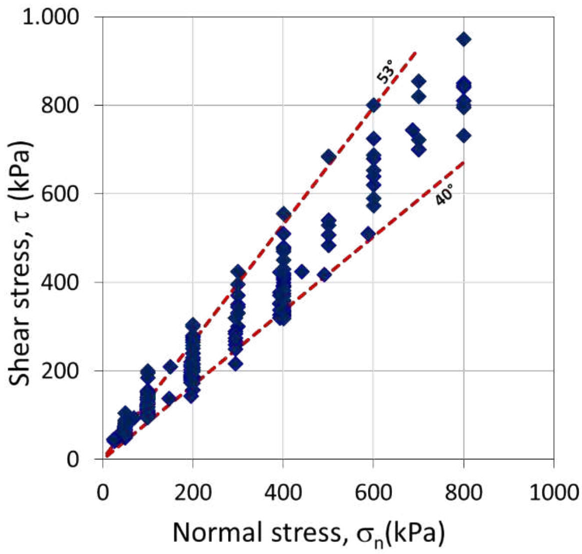

Figure 5. Shear stress (τ) vs normal stress (σ_n) on the large shear tests performed at CEDEX

If the friction angle (ϕ) of each point is represented separately as a function of the normal stress of the test (Figure 6), a general trend can be observed: the friction angle seems to decrease with an increasing normal stress. This would indicate that the behaviour of these materials is not completely linear.

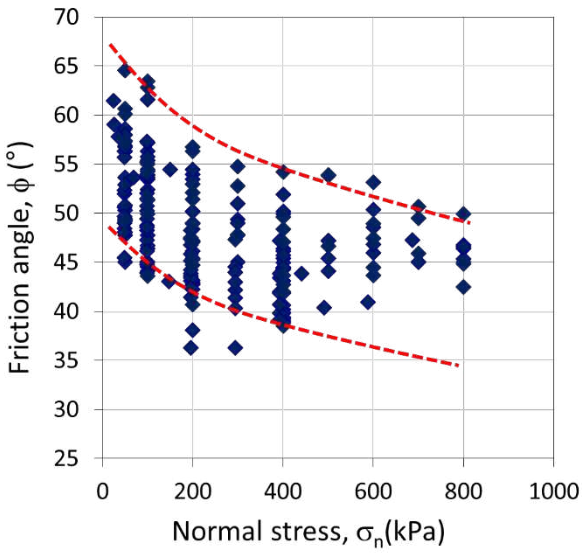

Figure 6. Friction angle (ϕ) vs normal stress (σ_n) on the shear tests

4 DISCUSSION

A previous study of the data obtained in CEDEX carried out by Estaire & Olalla (2006) analysed the goodness of fit of different failure criteria. The best fit was obtained with a power law failure criterion (R^2 = 0.99). R^2 high values, although somewhat lower than with the previous criterion, were also obtained for linear

Mohr-Coulomb criteria either with cohesion (R^2 = 0.96) or cohesionless (R^2 = 0.98). This had been already indicated by De Mello (1977), who proposed the power law criterion for these materials. Figure 7 shows, as an example, a complete test, which consists of four test points performed at different normal stresses (50, 100, 200 and 400 kPa). This test was interpreted assuming a non-linear parabolic failure criterion according to Eq. 1:

$$\tau = \mathbf{a}\, \sigma_n^{\mathbf{b}} \quad (1)$$

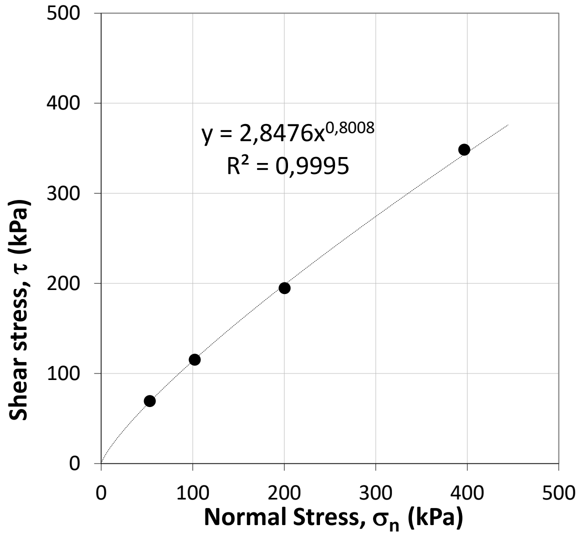

Figure 7. Power law fit for a large direct shear test performed at CEDEX facilities

The non-linear behaviour of this type of materials is described by several authors, who propose the use of non-linear criteria such as that of De Mello (1977) or other similar ones (Barton, 2013; Estaire & Olalla, 2006; Frossard et al., 2012; Indraratna, 1994; Ovalle et al., 2014). In view of the data presented in this work, the non-linearity of these materials seems to be demonstrated, the fit obtained with a parabolic criterion being better than with linear criteria. This behaviour could be due to the breakage of grains, although this study has not delved into the reason for this behaviour, but rather into the pure description of it.

Along with the data from the tests carried out at CEDEX, other data collected from the literature were analysed (Boakye, 2008; Charles & Soares, 1984; Marsal, 1967, 1973; Ovalle et al., 2014). These data come from both direct shear and large triaxial tests, and the data provided by Marsal, which have been included in numerous works related to rockfills over the years, are especially noteworthy.

Another phenomenon that was observed in the analysis of the collected results as a whole is the existence of a dependency in the value of the parameters **a** and **b**. This relationship is shown in **Error! Reference source not found.**Figure 8 with a suggested trend based on our experience. In this case, the criterion was made non-dimensional-since the parameter **a** of the criterion is dependent on the units (Indraratna et al., 1999) in which the shear stresses (τ) and normal stresses (σ_n) are expressed (see Eq. 2).

$$\frac{\tau}{P} = \mathbf{a}\left(\frac{\sigma_n}{P}\right)^{\mathbf{b}} \quad (2)$$

where τ is the shear resistance, P is the atmospheric pressure, **a** and **b** are the fitting parameters of the power law criterion, and σ_n is the normal stress used in the test.

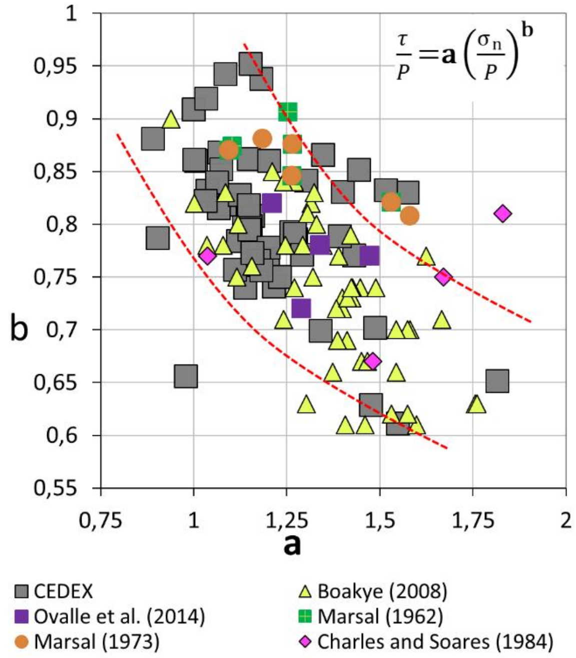

Figure 8. Relation between **a** and **b** parameters of the power law criterion (non-dimensional form) of the results published by different authors.

Parameter **a** varies between 0.75 and 2, while parameter **b** varies between 0.6 and 1. As a general trend, it is observed that the higher the value of the parameter **a**, the lower the value of **b**. This would indicate that the non-linearity of the strength of the material is more pronounced for stronger materials.

If, instead of using a dimensionless failure criterion, a fitting function is used on the values of shear stress and normal stress expressed in kPa (common unit in the interpretation of these tests), the effect of the units maximizes enormously—although artificially—the correlation between the two parameters. Although part of the correlation is due to artificial causes, it can help to verify the validity of the test results (Figure 9).

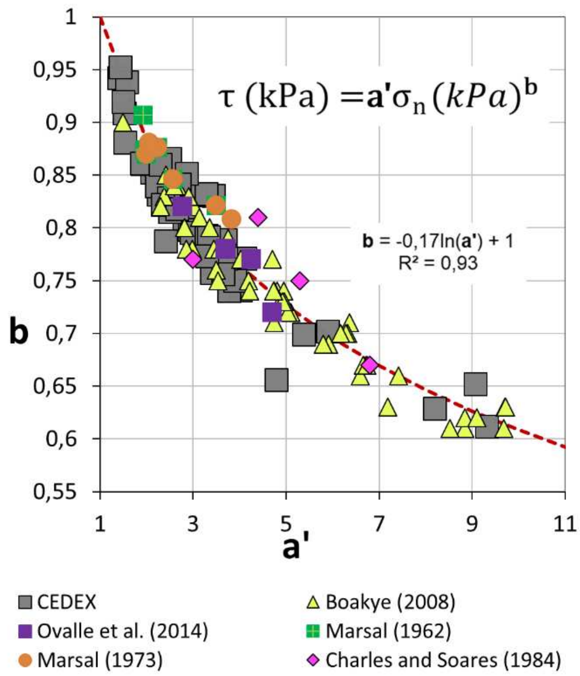

Figure 9. Relation between **a'** and **b** parameters of the power law criterion (stresses expressed in kPa) of the result published by different authors.

It can be observed how both the values obtained in the CEDEX direct shear box and those published by other authors show a very good correlation (R^2 = 0.93). The correlation represented in Eq. 3 and 4 can be used to verify future test results.

$$\mathbf{b} = -0.17 \cdot \mathrm{Ln}(\mathbf{a'}) + 1 \quad (3)$$

$$\tau = \mathbf{a'}\, \sigma_n^{-0.17 \cdot \mathrm{Ln}(\mathbf{a'})+1} \quad (4)$$

5 CONCLUSIONS

The empirical study of the shear strength of coarse granular materials is an engineering challenge, given the large volumes required to perform a representative test. Apart from expensive and difficult to perform in situ tests, there are few existing facilities in the world that are capable of testing these materials. In this article, the large direct-shear box from the CEDEX-Laboratorio de Geotecnia in Madrid (Spain) has been presented.

In this work, one of the largest data-sets on shear strength tests of coarse granular materials present in the literature has been analysed. Most of them were obtained directly by the CEDEX laboratory, while others were compiled from renowned scientific articles on the subject.

In view of the data, it can be concluded that the behaviour of coarse granular materials is clearly non-linear in terms of their shear strength. The results analysed are better adjusted to the power law criterion ($\tau = \mathbf{a} \cdot \sigma_n^{\mathbf{b}}$) proposed by De Mello (1977) than to other linear Mohr-Coulomb criteria. Within these linear criteria, the cohesionless interpretation (c' = 0) seems to better represent the behaviour of these materials than an interpretation without null cohesion (c' > 0).

The parameters of the criterion proposed by De Mello were analysed for all the collected tests. A clear relationship was found between the parameters **a** and **b** of the criterion, and it can be concluded that, in general, the higher the strength of the material (higher value of **a**) the less linear its behaviour is (lower value of parameter **b**).

If these parameters are analysed with the non-dimensionless data, using the data in kPa, a regression function is obtained that can be used as a guide to validate the results of the tests.

6 ACKNOWLEDGEMENTS

The authors would like to acknowledge all the lab technicians who participate in the performance of this large shear tests at CEDEX - Laboratorio de Geotecnia (J.L. Gómez, Ó. Tello, J.A. Casado, J.L. Toledo, M. Pintado, A. Guerrero). The authors also acknowledge Raquel Fuertes, Msc. for her help with the translation and proofreading of the manuscript.

7 REFERENCES

Andjelkovic, V., Pavlovic, N., Lazarevic, Z., & Radovanovic, S. (2018). Modelling of shear strength of rockfills used for the construction of rockfill dams. *Soils and Foundations*, *58*(4), 881–893. https://doi.org/https://doi.org/10.1016/j.sandf.2018.04.002

Barton, N. (2013). Shear strength criteria for rock, rock joints, rockfill and rock masses: Problems and some solutions. *Journal of Rock Mechanics and Geotechnical Engineering*, *5*(4), 249–261. https://doi.org/10.1016/j.jrmge.2013.05.008

Barton, N., & Kjaernsli, B. (1981). Shear strength of rockfill. *Journal of the Geotechnical Engineering Division*, *107*, 873–891.

Boakye, K. (2008). *Large in Situ Direct Shear Tests on Rock Piles at the Questa Min, Taos County, New Mexico* [New Mexico Institute of Mining and Technology, NM, USA]. https://books.google.es/books?id=LK-TNwAACAAJ

Charles, J. A., & Soares, M. M. (1984). Stability of compacted rockfill slopes. *Géotechnique*, *34*(1), 61–70. https://doi.org/10.1680/geot.1984.34.1.61

Davies, M. C. R., & Le Masurier, J. W. (1997). Soil/Nail Interaction Mechanisms from Large Direct Shear Tests. In *Ground improvement geosystems Densification and reinforcement* (pp. 492–499). https://doi.org/10.1680/gigdar.26056.0062

De Mello, V. F. B. (1977). Reflections on design decisions of practical significance to embankment dams. *Geotechnique*, *27*(3), 281–355. https://doi.org/10.1680/geot.1977.27.3.281

Estaire, J., & Olalla, C. (2006). Análisis de la resistencia de escolleras mediante ensayos de corte directo en caja de 1 x 1 m. *Ingeniería Civil*, *144*, 73–79.

Frossard, E., Hu, W., Dano, C., & Hicher, P.-Y. (2012). Rockfill shear strength evaluation: a rational method based on size effects. *Geotechnique*, *62*(5), 415–427. https://doi.org/10.1680/geot.10.P.079

Indraratna, B. (1994). Implications of non-linear strength criteria in the stability assessment of rockfill dams. In *International conference on soil mechanics and foundation engineering (13 ; New 1994-01-05)* (pp. 935–938). A.A. Balkema, Rotterdam.

Indraratna, B., Haque, A., & Aziz, N. (1999). Shear behaviour of idealized infilled joints under constant normal stiffness. *Géotechnique*, *49*(3), 331–355. https://doi.org/10.1680/geot.1999.49.3.331

Krahn, T., Blatz, J., Alfaro, M., & Bathurst, R. (2007). Large-scale interface shear testing of sandbag dyke materials. *Geosynthetics International - GEOSYNTH INT*, *14*, 119–126. https://doi.org/10.1680/gein.2007.14.2.119

Marsal, R. (1967). Large Scale Testing of Rockfill Materials. *Journal of the Soil Mechanics and Foundations Division*, *93*(2), 27–43. https://doi.org/10.1061/JSFEAQ.0000958

Marsal, R. (1973). Mechanical properties of rockfill. In Hirschfeld & Poulos (Eds.), *Mechanical properties of rockfill. Embankment-Dam Engineering, Casagrande Volume* (pp. 109–200). John Wiley & Sons, Incorporated.

Matsushima, K., Mohri, Y., Aqil, U., Yamazaki, S., & Tatsuoka, F. (2007). Mechanical Behavior of Reinforced Specimen Using Constant Pressure Large Direct Shear Test. In H. I. Ling, L. Callisto, D. Leshchinsky, & J. Koseki (Eds.), *Soil Stress-Strain Behavior: Measurement, Modeling and Analysis* (pp. 837–847). Springer Netherlands. https://doi.org/https://doi.org/10.1007/978-1-4020-6146-2_63

Ovalle, C., Frossard, E., Dano, C., Hu, W., Maiolino, S., & Hicher, P.-Y. (2014). The effect of size on the strength of coarse rock aggregates and large rockfill samples through experimental data. *Acta Mechanica*, *225*(8), 2199–2216. https://doi.org/10.1007/s00707-014-1127-z

Pedley, M. J. (1990). *The performance of soil reinforcement in bending and shear*. Oxford University, UK.

Srivastava, L. P., Singh, M., & Singh, J. (2019). Development of Large Direct Shear Test Apparatus for Passive Bolt Reinforced Mass. *Indian Geotechnical Journal*, *49*(1), 124–131. https://doi.org/10.1007/s40098-018-0306-6

Tanghetti, G., Goodey, R. J., Divall, S., McNamara, A. M., & Mckinley, B. (2019). Design and development of a large shear box for testing working platform material. In *ECSMGE - 2019. XVII European Conference on Soil Mechanics and Geotechnical Engineering*. https://openaccess.city.ac.uk/id/eprint/21985/