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Large scale direct shear tests on rockfill 63/180mm

Essais de cisaillement direct de grandes dimensions dans enrochement 63/180mm

J. Rocha*, P. Mengé
DEME NV, Zwijndrecht, Belgium

M. Muñiz-Menéndez
Laboratorio de Geotecnia - CEDEX, Madrid, Spain

**rocha.jose@deme-group.com*

ABSTRACT: This paper presents the results of a large-scale direct shear test campaign (1.0 m x 1.0 m x 1.2 m) performed on rockfill material, grading 63/180 mm, that was used as a foundation base for an offshore jack-up vessel. The tests were performed for normal stresses ranging between 50 kPa and 800 kPa, with the main goal of estimating the peak friction angle of the material for a normal stress of 1000 kPa. A description of the material properties is presented together with the equipment characteristics and adopted test procedures. The test results were evaluated according to the non-linear failure method proposed by De Mello (1977).

RÉSUMÉ: Cet article présente les résultats d'une campagne d'essais de cisaillement direct de grandes dimensions (1,0 m x 1,0 m x 1,2 m) réalisée sur un matériau d'enrochement, de granulométrie 63/180 mm, utilisé comme base de fondation pour un navire autoélévateur offshore. Les essais ont été réalisés pour des contraintes normales comprises entre 50 kPa et 800 kPa, avec l'objectif principal d'estimer l'angle de frottement maximal du matériau pour une contrainte normale de 1000 kPa. Une description des propriétés des matériaux est présentée avec les caractéristiques de l'équipement et les procédures d'essai adoptées. Les résultats des essais ont été évalués selon la méthode de rupture non linéaire proposée par De Mello (1977).

Keywords: Rockfill; direct shear; large scale; peak friction angle.

1 INTRODUCTION

As part of an offshore wind-farm project, rockfill with grading 63/180 mm was selected as foundation material for offshore jack-up vessels, used to load turbines and other components near a quay-wall. A minimum peak friction angle of 40 degrees under a normal stress of 1000 kPa was defined in the contract specifications.

The simplest way to determine the friction angle of a granular material is testing a sample using a shear box apparatus (Tanghetti et al., 2019). The main difficulty to perform direct shear tests in rockfill material is the large size of the particles, which does not allow for the use of conventional equipment (Marachi et al, 1969).

In order to avoid some scale effects, some limits are proposed in ASTM D3080, where the maximum diameter of the particles must be ten times smaller in comparison with the smallest shear plane, while the height of the equipment must be at least six times larger in comparison with the largest particle of the sample. Fu *et al*. (2015) tested two samples in equipment with different dimensions and got to more stringent results than the limits proposed in ASTM D3080, i.e., fifteen times for the ratio between smaller shear plane dimension and maximum particle size and ten times for the ratio between height of equipment and maximum particle size.

In the current work it was not possible to follow the limits mentioned above because of the maximum particle size of the material, 180 mm, and the target dates for the conclusion of the tests. No equipment was found available that would be compatible with the required limits and planning for the test campaign, thus it was decided to conduct the tests at Laboratorio de Geotecnia (CEDEX), in Madrid, where a large direct shear box is available. Approximately 9500 kg of material were sent to Spain from a rock quarry located in Norway for the execution of the tests.

The test results were evaluated according to the non-linear failure method proposed by De Mello (1977).

2 TESTING PROGRAM

2.1 Equipment details

The tests were performed in a large direct shear apparatus available at Laboratorio de Geotecnia - CEDEX. The shear plane has an area of 1.0 m^2 and the height of the shear box is 1.2 m.

Horizontal and vertical stresses up to 1000 kPa can be applied based on the type of material being tested. The shear force is applied by a constant horizontal displacement rate, ranging between 0.5 and 45 mm/min, until a maximum horizontal displacement of 250 mm. The vertical displacements are recorded by four transducers LVDT located on corners of the top plate.

Due to the large particle size of the rockfill it was decided to limit the vertical stress to a maximum of 800 kPa in order to guarantee a constant load during the full shearing phase. This was required because of the vertical deformations (dilatant/contractive behaviour) and response of the hydraulic system responsible for the shear force.

The control and data collection are performed by means of a multichannel controlling system. The system records the vertical and horizontal forces, and the displacements at the four transducers with an acquisition rate of 0.1 Hz.

2.2 Material properties

The rockfill material used in the testing campaign was produced in a rock quarry located in *Sogn og Fjordane*, Norway. The bedrock at the quarry consists of hard, low weathering grade rock (Devonian rock), described as a metamorphosed quartzite with presence of laminations (Figure 1).

The intrinsic properties of the rockfill material produced at the quarry are classified as excellent according to The Rock Manual (CIRIA, 2007).

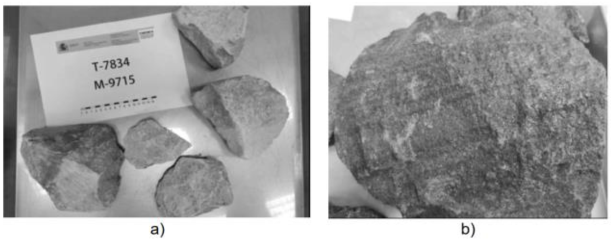

Figure 1. a) Individual particles; b) Detail of laminations.

Ten particle size distribution curves (PSDs) were performed to verify the compliance with the requirements defined in British Standard, BS EN 13383-1: 2002, for $CP_{63/180}$ materials (Figure 2).

Regarding the shape of the particles, determined by a length-to-thickness ratio larger than 3, also defined by the same standard, the material belongs to category LT_A. The broken surface was visually evaluated, and the material is defined as RO_5 according to the same standard.

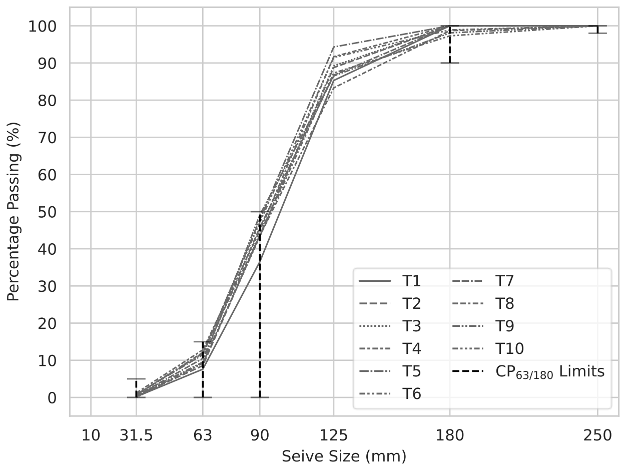

Figure 2. Particle size distribution curves.

Besides the tests and verifications described above, three specimens were cored from the biggest particles and unconfined compression tests (UCS) were performed. The dimension of the specimens and the results of the tests are summarised in Table 1.

Table 1. UCS test results.

Sample	A	B	C
Diameter (mm)	37.6	37.5	37.5
Height (mm)	92.7	93.9	92.7
Unit Weight (kN/m^3)	26.7	26.6	26.5
UCS (MPa)	125.0	128.0	92.2

2.3 Test procedures

The rockfill material will be used underwater, but this condition could not be reproduced because the shear box is not watertight. Following a request from the Client, it was decided to add water to the material during the sample preparation. For comparison purposes, one test (normal stress of 800 kPa) was executed without addition of water.

The material was placed inside the shear box in three layers, with a thickness of approximately 30 cm. The first two layers were manually installed while the last layer was installed by gravity, after cutting the sample box above the shear box.

A slight compaction was applied to the material, after the installation of each layer, by a vertical stress of 50 kPa. The main goal of this step was to guarantee the correct rearrangement between the particles. Once the installation of the third layer was completed, the required normal stress was applied, and the vertical deformations were registered.

The shear of the samples was executed with a constant rate of 0.8mm/minute and the tests were completed once a maximum horizontal displacement of 240mm was reached.

2.4 Sample conditions

Six samples were prepared following the procedures described above and tested for normal stresses between 50kPa and 800kPa.

Table 2 presents the initial conditions of the samples and Table 3 presents the sample conditions after the required normal stress was applied.

Table 2. Sample initial conditions.

Test	w (kg)	WC (%)	h_0 (mm)	γ_0 (kN/m^3)
T50	1229.5	1.30	905	13.50
T200	1405.0	1.40	996	14.03
T400	1253.0	1.50	890	14.01
T600	1236.5	1.30	890	13.80
T800	1250.0	1.50	890	13.98
T800d	1278.5	1.40	960	13.24

Table 3. Sample conditions after application of normal stress.

Test	σ (kPa)	δv (mm)	h_f (mm)	γ_f (kN/m^3)
T50	50	15.5	889.5	13.73
T200	200	24.6	971.4	14.38
T400	400	19.3	870.7	14.32
T600	600	33.7	856.3	14.34
T800	800	30.1	859.9	14.47
T800d	800	34.2	925.8	13.73

In those tables:

- w = weight of the sample in kg
- WC = water content in %
- h0 = initial height of the sample in mm
- γ0 = initial unit weight in kN/m^3
- σ = normal stress in kPa
- δv = vertical displacement in mm
- hf = final height of the sample in mm
- γf = final unit weight in kN/m^3.

3 TEST RESULTS

The results of the tests are presented in Figure 3.

As it can be seen, the difference in results between the dry test (T800d) and the equivalent wet test is negligible. The addition of water seems to produce no significant change in the behaviour of the material.

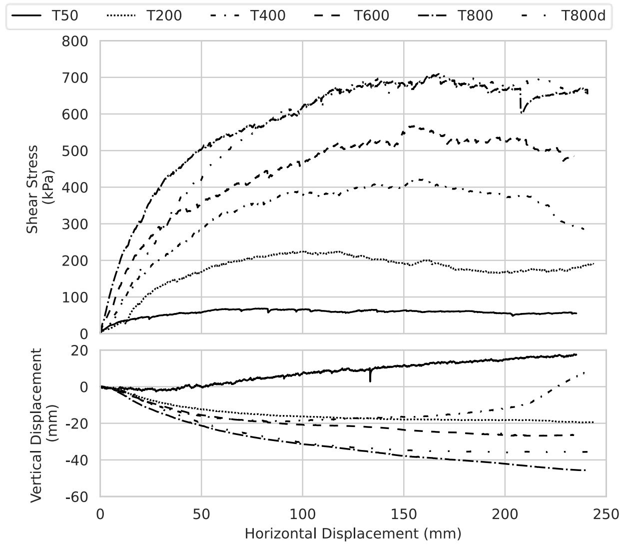

Figure 3. Shear stress and vertical displacement versus horizontal displacement.

The peak shear stresses in function of the normal stress (Figure 4) are well fitted with a non-linear regression curve, as proposed by De Melo (1977).

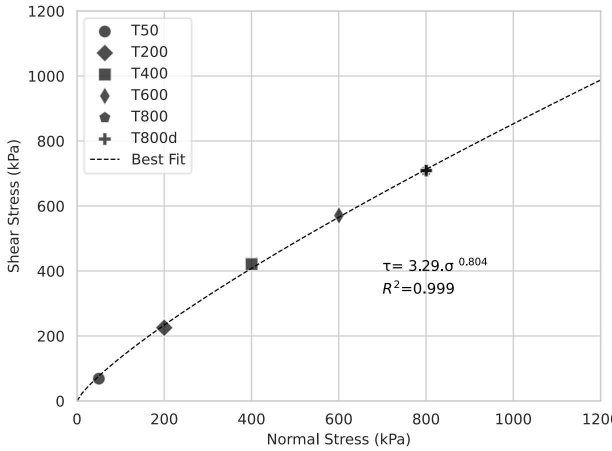

Figure 4. Peak shear stress versus normal stress.

Non-linear equation that resulted in the best fit to the test results is the following:

$$\tau = a' \times \sigma^b = 3.29 \times \sigma^{0.804} \qquad (1)$$

This result is in line with the work of several authors (Barton, 2013; Frossard *et al.* 2012; Indraratna, 1994) that have proposed non-linear failure modes for this type of material.

The constants *a'* and *b* were compared with a compilation made by Muñiz-Menéndez & Estaire (2022), including test performed at CEDEX and results published by other authors. As shown in Figure 5, the current results are in good agreement with values found in literature.

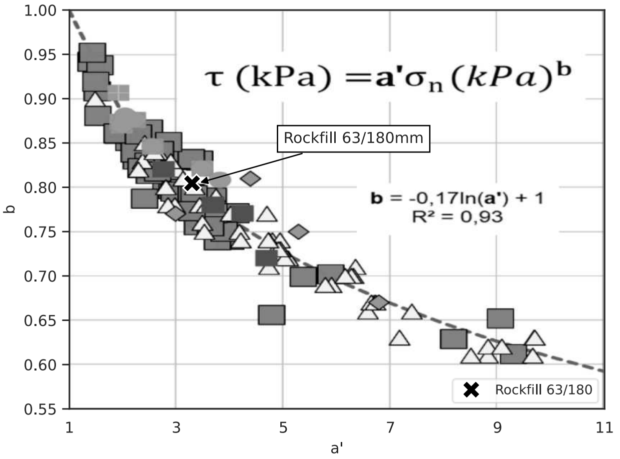

Figure 5. Relation between a' and b parameters compiled by Muñiz-Menéndez & Estaire (2022) including results of rockfill 63/180mm.

The estimated effective friction angle for a normal stress of 1000 kPa (Figure 6) was found equal to 40.5 degrees which was just above the minimum value defined in the project specifications.

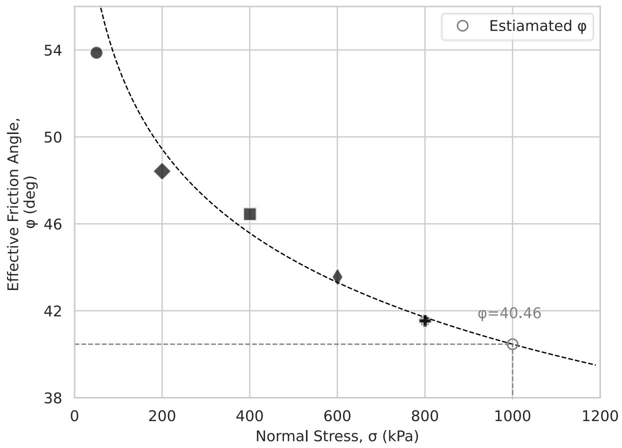

Figure 6. Estimated peak friction angle for a normal stress equal to 1000 kPa.

4 CONCLUSIONS

Six samples of rockfill, grading 63/180mm, were tested on a large-scale direct shear apparatus for normal stresses ranging between 50 kPa and 800 kPa. A non-linear regression resulted in a very good fit to the data, and a peak friction angle of 40.5 degrees was estimated for a normal stress of 1000 kPa.

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