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# Shear strength properties of Tout-Venant material from large direct shear tests.

**Loïc Gatti**, José Rocha, Patrick Mengé
*Geotechnical engineering, DEME NV, Zwijndrecht, Belgium, gatti.loic@deme-group.com, rocha.jose@deme-group.com, menge.patrick@deme-group.com.*

Sylvie Nicaise
*Laboratoire Géomécanique, INRAE, Aix Marseille Univ, RECOVER, Aix-en-Provence, France, sylvie.nicaise@inrae.fr.*

ABSTRACT: This paper investigates the geotechnical properties of a series of laboratory direct shear tests conducted under varying confining pressures (50, 100, 200, and 400 kPa) on a coarse granular material, designated GMO-Tout-Venant. The primary objective of the test campaign was to determine the friction angle of the material, a critical parameter in soil mechanics. Specimens were prepared based on material fractions, to capture reference particle size distributions, and different dry densities. Results indicated that the friction angle is significantly influenced by the grading and the density of the material. Specimens prepared at higher densities demonstrated a notable improvement in the friction angle, highlighting the importance of compaction in enhancing soil strength. Additionally, the study explored the effects of removing the fine fraction (particles up to 4 mm in diameter) from the Tout-Venant. The removal of the finer fraction resulted in higher shear stress and an increased friction angle compared to the material with the full fraction. This indicates that the absence of finer particles enhances the shear strength characteristics of the material, likely due to improved rearrangement and interlocking between the grains. The findings underscore the critical role of density/compaction and particle size distribution in determining the shear strength and friction angle of Tout-Venant, offering valuable data for geotechnical applications.

KEYWORDS: Friction angle, Direct Shear test, Tout-Venant, Large-scale.

## 1 INTRODUCTION

This paper details a large-scale testing campaign executed on a coarse granular material, originated from marine aggregates and designated GMO – Tout-Venant (GMO-TV). The material was selected as backfill material for drilled-out pin piles, as part of an offshore wind-farm project. A minimum peak friction angle of 40 degrees 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 in performing direct shear tests in coarse granular material is the large size of the particles, which does not allow for the use of conventional laboratory 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 using equipment of different dimensions and proposed more stringent criteria than the limits proposed in ASTM D3080: 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 present study, it was not possible to fulfill the previously mentioned requirements due to the material's maximum particle size of 100 mm and the availability of sufficiently large shear boxes.

The test campaign was executed at INRAE Geomechanical Laboratory in Aix-en-Provence, France, which houses a large-scale shear box that is nearly compatible with the intended testing conditions.

Direct shear tests were performed using the GMO-TV material considering its full particle size distribution for different initial densities. Additionally, the finer fraction (particles smaller than 4mm) was removed, and the tests were repeated considering the initial lowest density. The details of the specimen preparation are given under section 3.1. The peak friction angles observed during the tests were plotted according to specimen properties, such as initial density, grading curve, and confining pressures.

## 2 EQUIPMENT AND MATERIAL

### 2.1 *Equipment details*

The INRAE Geomechanical Laboratory owns a box for large-scale direct shear tests.

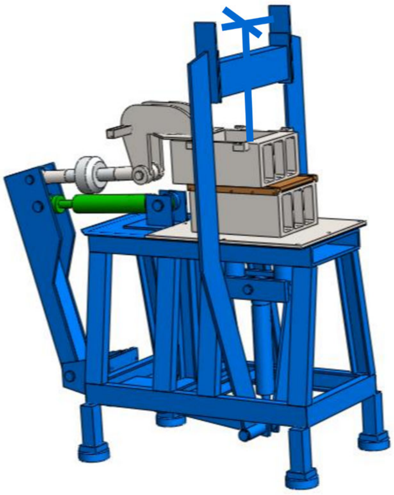

Figure 1. Illustration of the large-scale shear box at INRAE.

The Figure 1 shows an illustration of the equipment at INRAE. The box is composed of two half boxes, an upper and lower box of respectively 500 x 500 mm, and 500 x 600 mm. The total height of the box is 300 mm. The shear box has vertical and horizontal sensors, both measuring the force and the displacement. The maximum shear force applicable is 120 kN, and the maximum confining pressure is 400 kPa.

### 2.2 *Material properties*

The GMO-TV is a coarse granular material with particle sizes ranging between 0 mm and 100 mm. The grain shape is heterogeneous with a mixed angularity.

As the tests were performed on the GMO-TV in its full particle size distribution, as well as with the fine fraction removed, both PSD curves are plotted in the Figure 2. The PSD curves were established in accordance with the NF EN ISO 17892-4 standard (AFNOR, 2018). The fine fraction, defined as particles smaller than 4 mm, represents approximately 35% of the total material.

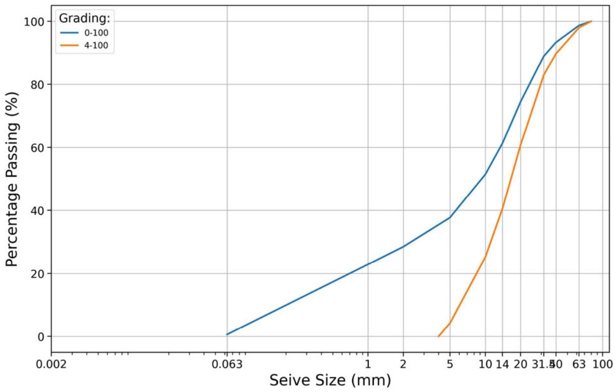

Figure 2. PSD curve of the GMO-TV material.

Since the experimental program involved two distinct particle size distributions, the minimum dry density was determined separately for each grading. This was achieved by pouring the material into the shear box and measuring its weight. The corresponding saturated density was then calculated based on the dry density.

Although the laboratory tests were conducted under dry conditions, establishing the saturated density was essential to ensure accurate interpretation of the results, given that the material was saturated under field conditions.

Table 1. GMO-TV minimum dry densities.

| Gradings<br>[mm] | Dry density<br>[kN/m³] | Porosity<br>[%] | Saturated density<br>[kN/m³] |
|---|---|---|---|
| 0 – 100 | 13.7 | 48 | 18.6 |
| 4 – 100 | 11.9 | 55 | 17.4 |

The Table 1 presents the measured dry densities for both particle size distributions, along with the corresponding porosity and saturated density values. These parameters provide a comprehensive overview of the material's characteristics under both dry and saturated conditions.

## 3 TEST PROCEDURES

### 3.1 *Specimen preparation*

To ensure the specimen accurately reflected the measured particle size distribution, the material was first divided into distinct fractions. Each fraction was weighed according to its proportion in the PSD and thoroughly mixed to create a homogeneous blend. The specimen was then constructed in five equal layers, with the weighing and mixing process repeated for each layer to maintain uniformity throughout the sample.

The total weight of each layer was 28 kg with a correspondent thickness of approximately 6 cm. The material was placed manually inside the box with a large spoon. When needed, some light compaction was applied on layer number 1, 3, and 5 to achieve the required specimen density and a flat, level top surface. The specimen was prepared in a way that the shear plane was not coincident with the planes between each layer.

The specimens were prepared at different densities depending on their grading of particles.

Table 2. Initial conditions.

| Gradings | Dry density | Saturated density | Unit |
|---|---|---|---|
| 4 - 100 mm | 15.9 | 20 | kN/m³ |
| 0 - 100 mm | 16.1 | 20 | kN/m³ |
| 0 - 100 mm | 20 | 22.5 | kN/m³ |

Table 2 summarizes the tested densities for each particle size distribution. To assess the influence of compaction, additional specimens composed of the full particle grading were prepared in a denser state. Achieving these target densities required light compaction, which was applied during the placing of the material.

### 3.2 *Direct Shear Test (DST)*

Large-scale direct shear tests were conducted in accordance with the French standard NF EN ISO 17892-10 (AFNOR, 2018). To evaluate the friction angle of the material, tests were performed under four different confining pressures: 0 kPa, 100 kPa, 200 kPa, and 400 kPa.

After preparation of the specimen, a vertical load was applied progressively over a duration of 10 minutes until the required confining pressure was achieved, and a period of stabilization was recorded during approximately 1 hour. After the stabilization period, the shear phase was performed with a shear rate of 0,5 mm/minute. The test was completed when a horizontal displacement of 50 millimeters was achieved. During the shear phase, the vertical and horizontal deformations of the specimen were recorded with LVDTs. The vertical sensors were positioned beneath the shear box, near the point where the confining pressure is applied. The horizontal sensors were aligned with the hydraulic system that applies the shear force. This setup ensured accurate measurement of deformations corresponding to the applied stresses.

## 4 TEST RESULTS

During the direct shear tests, the shear forces and the displacements were recorded. The DST results are consequently primarily plotted in terms of shear stress in function of the horizontal displacement. As the shearing was realized at four confining pressures as given in 3.2, four levels of curves can be observed. The curves giving the highest shear stresses are naturally coming from the shearing at the higher confining pressure. It can also be mentioned that the for the black curve, the 0-100mm grading at a saturated density of 20 kN/m³, has been tested at all confining pressures except the highest one (400 kPa) which explains the absence of one black curve.

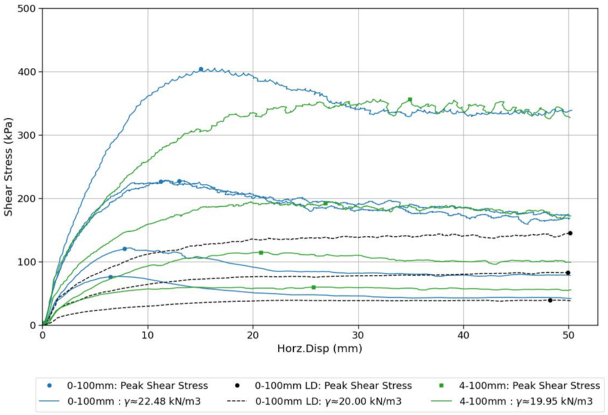

Figure 3. DST results (shear stress – displacement).

Several observations can be drawn from this Figure 3. First, the small peaks visible on the curves can be attributed to the sensitivity of the hydraulic system used to apply the loads. When comparing the test results for the fully graded material (represented by the blue and black curves), it is evident that the blue curves consistently exhibit the highest peak shear stresses. This behavior is attributed to the denser and thus more compacted material associated with the blue curves. These peaks reflect the enhanced shear strength achieved through compaction of the GMO-TV. However, at larger displacements, particularly under lower confining pressures, the blue and black curves converge, indicating similar residual shear stress values. The distinct peaks observed exclusively in the blue curves mark the maximum shear resistance prior to dilation, thereby highlighting the dilatant behavior characteristic of the denser GMO-TV.

Furthermore, when comparing different gradings at the same saturated density, thus under equivalent compaction conditions, the green curves consistently exhibit higher shear stresses than the black curves. This suggests that the absence of finer particles contributes to improved shear strength characteristics. Additionally, the green curves show peak shear stress values that are nearly equal to their residual values, indicating a slightly dilatant behavior. In contrast, the black curves display a slight gradual increase in shear stress up to the residual value, which is indicative of a contractive response.

Finally, although the green and blue curves represent the GMO-TV with different densities and different gradings, a comparison between them remains insightful. The green curves exhibit lower peak shear stress than the blue curves, reflecting the influence of reduced density. However, at large displacements, the residual shear stress of the green curves surpasses that of the blue curves, particularly under lower confining pressures. This suggests that while the denser, fully graded material (blue) initially resists shear more effectively, the coarser material (green) maintains higher residual strength over time.

In other words, the removal of fine particles leads to an increase in residual shear stress compared to the fully graded material. At the same saturated density, the slightly dilatant behavior observed in the material without fines reflects an improvement in shear strength compared to the contractive behavior of the fully graded counterpart. Moreover, even when compared to the denser, fully graded material, the absence of fines results in higher residual shear stress under lower confining pressures. These findings confirm that eliminating finer particles enhances the shear strength characteristics of the material, likely due to improved particle interlocking. Fines tend to disrupt the efficiency of force transmission by occupying voids and reducing direct contact between coarse particles. Their removal allows the coarse grains to establish a stronger and more stable contact network, which improves shear resistance (Sharma et al., 2022).

Based on the initial results, a regression analysis was performed to examine the relationship between peak shear stress and normal stress. While both linear and non-linear models were considered, the non-linear regression was ultimately selected due to its superior fit to the data. This decision was supported by the coefficient of determination ($R^2$), which was slightly higher for the non-linear model, indicating a better representation of the observed behavior. This analysis is shown in the Figure 4**.** The non-linear trend reflects the complex nature of soil shear strength, which often does not follow a strictly linear pattern.

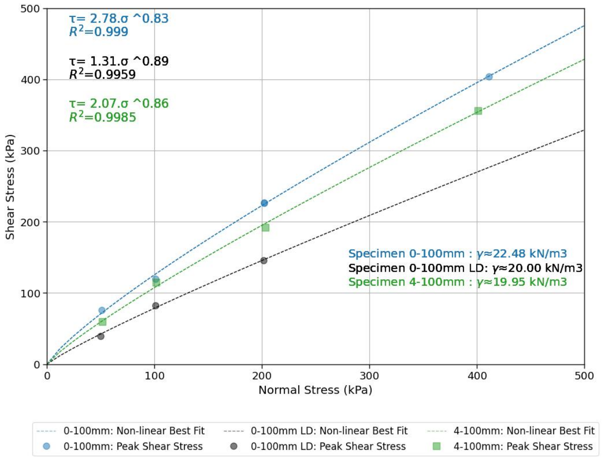

Figure 4. DST results (peak shear stress – normal stress), non-linear regression.

The non-linear equations that resulted in the bests fits to the test results follow the next structure:

$$\tau = a' \times \sigma^{b} \tag{1}$$

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

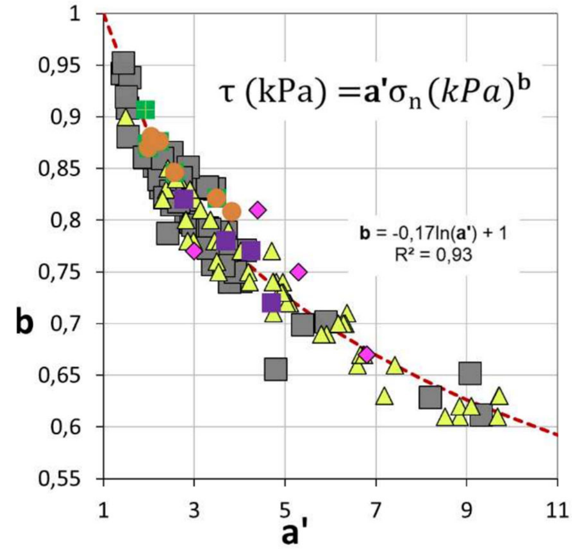

Figure 5. Relation between a' and b parameters compiled by Muñiz-Menéndez & Estaire (2022) including results of other authors.

Finally, the friction angle can be derived as shown in Figure 6. The shear strength equations obtained from the regression analysis, as presented in Figure 4, were used to extrapolate the expected friction angles for a pressure range up to 500 kPa. It was determined taking into account that the material has a cohesion equal to zero.

In fact, as it is a coarse granular soil, it is primarily composed of large particles with minimal surface area relative to their volume. These particles interact mainly through frictional contact rather than chemical or electrostatic bonding. In fact, in materials with particles up to 100 mm, the interparticle forces are dominated by mechanical interlocking and friction, not cohesion (Yang et al., 2012).

Also, several geotechnical design standards (e.g., Eurocode 7 (British Standards Institution, 2004)) recommend assuming zero cohesion for coarse, non-cohesive soils. Additionally, assuming zero cohesion simplifies analysis and aligns with conservative design principles.

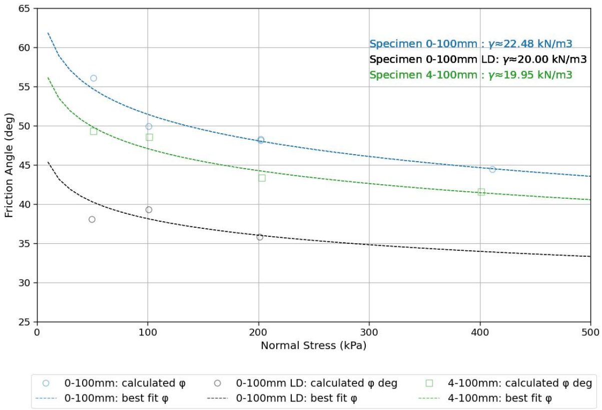

Figure 6. Estimated Peak Friction angles and best fit curves.

In general, the Figure 6 shows that the critical friction angles decrease with increasing confining pressure from 50 to 400 kPa. The observed decrease in critical friction angle with increasing confining pressure is consistent with established geotechnical behavior. As observed by Fereidooni and al. (2015), when confining pressure increases, dilatancy is suppressed, and particle interlocking becomes less effective, resulting in lower mobilized friction angles.

The blue curve exhibits the highest friction angle, clearly demonstrating that increased density, and therefore a higher level of compaction, enhances the geotechnical properties of the material. Furthermore, when comparing the fully graded material (black curve) with the variant where the fine fraction has been removed (green curve), both prepared at similar densities (20 kN/m³ for the black curve and 19.95 kN/m³ for the green), a significant increase in friction angle is observed in the absence of fines. This indicates that the removal of finer particles contributes to improved shear strength. As explained before, the likely mechanism behind this improvement is enhanced particle interlocking: fines tend to occupy voids and interfere with direct contact between coarse particles, reducing the efficiency of force transmission. By eliminating these finer particles, the coarse grains form a more robust contact network, which strengthens the material's resistance to shear, contributing to the observed increase in friction angle.

## 5 CONCLUSIONS

In conclusion, the direct shear test results clearly demonstrate the critical influence of both the density (linked to the level of compaction) and the particle size distribution on the shear strength of GMO Tout-Venant. Increased density through compaction significantly enhances peak shear stress and friction angle, while residual strength remains relatively stable. Additionally, the removal of fine particles (≤4 mm) leads to a marked improvement in shear strength and friction angle, even at similar compaction levels. This enhancement is attributed to improved particle interlocking and more efficient force transmission within the coarse-grained matrix.

Overall, these findings underscore the critical role of optimizing both compaction and particle size distribution in determining the shear strength and friction angle of Tout-Venant, or in general the mechanical performance of granular material offering valuable data for geotechnical applications.

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