Jordan Journal of Civil Engineering, Volume **18**, No. **3**, **2024**
DOI: https://doi.org/10.14525/JJCE.v18i3.11

Jordan Journal of Civil Engineering

Journal homepage: https://jjce.just.edu.jo

Determining the Dilatancy of Gravels Using a Large-size Direct Shear Test

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ARTICLE INFO

Article History:
Received: 25/3/2024
Accepted: 20/6/2024

ABSTRACT

The peak shear strength of dense coarse-grained soils is defined by the angle of the shear strength, the initial shear strength, and the angle of dilatancy. This paper mainly focuses on determining the angle of dilatancy. This parameter has been investigated by many researchers on sands or sand-gravel mixtures. The study aims to determine the dilatancy angle of various types of gravel soils using a large-size direct shear test. The results demonstrated that the dilatancy angle decreases with an increase in the normal stress. The gravels tested were separated into 8 groups based on the type of gravel, the fraction, and the shape of the grains. The relation between the dilatancy angle and the normal stress was correlated using a power function for each gravel group. The results also showed that simplified assumptions of the dilatancy angle, which are usually applied in the design of geotechnical structures, can lead to a determination of a higher value of the dilatancy angle than that determined by laboratory measurement. A simple correlation is presented, which allows for determining the angle of dilatancy from the peak and the critical angle of the shear strength in a given normal stress range.

Keywords: Angle of dilatancy, Angle of shear strength, Shear strength, Coarse-grained soil, Gravel, Direct shear test.

INTRODUCTION

The shear strength properties of gravels, which are coarse-grained materials, can be determined *in-situ* using penetration tests (Chennarapu et al., 2018; Ganju et al., 2018; Mihalik et al., 2023) or under laboratory conditions. The tests for a standard sample size (Taqieddin, 2017; Khatri et al., 2017) are replaced by the tests for a large-size sample (Bulko et al., 2023; Kharanaghi and Briaud, 2020; Hamidi et al., 2009; He et al., 2022) in these cases. Based on the type of geotechnical construction, it is possible to use natural (fluvial) gravel, which consists of pebbles, or crushed gravel (artificially modified), which consists of crushed gravel fragments. In geotechnical structures, such as road and railway embankments, base layers, gravel beds, gravel ribs or stone columns, crushed gravel is preferred instead of pebble gravel due to its better compaction (Stacho and Sulovska, 2017). Based on the soil mechanics theory (Atkinson, 2007), the dense, coarse-grained material can be defined by the peak and critical shear strength properties, while the loose coarse-grained materials are *de facto* defined only by the critical shear strength properties. Therefore, the shear strength properties are mainly defined by the peak angle of the shear strength φ'_p and the critical angle of the shear strength φ'_c. However, crushed gravel and quarry stone can show significant initial shear strengths in the peak as well as in the critical stress state ($t'_{0,p}$ and $t'_{0,c}$), which some research has stated as a cohesion or an apparent cohesion c' (Aquil et al., 2005; Soleimanbeigi and Likos, 2019). In the peak shear strength of dense coarse-grained material, dilatancy, which is defined by the angle of dilatancy y', can play a significant role.

In general, the dilatancy of soil was first investigated by Reynolds (1885). After Poorooshasb and Roscoe (1961) presented a laboratory study of the stress-dilatancy relationship of sands, many researchers continued to develop the theory of stress-dilatancy behavior (Bolton, 1986; Hamidi et al., 2009; Vermeer and de Borst, 1984; Simone and Houlsby, 2006; Patil et al., 2018). These studies were based on laboratory tests of sand, which are less demanding on the size of the test equipment. The laboratory tests can be executed using triaxial test equipment with adequate large-cell (Strahler et al., 2015; Patil et al., 2018) or large-size direct shear test apparatus (Simoni and Houlsby, 2006; Hamidi et al., 2009; Yunatci and Cetin, 2022). The dilatancy angle can be evaluated using different methods (Patil et al., 2018; Simoni and Houlsby, 2006; Hamidi et al., 2009).

A comprehensive analysis of the dilatancy of a sand-gravel mixture was presented by Simoni and Houlsby (2006). They analyzed the results of the tests in terms of the friction and dilatant contributions to the strength of the mixtures as a function of their relative density; however, they executed the tests at a constant pressure of about 90 kPa to avoid crushing the grains. Crushing of grains is not significant or can be ignored for normal stresses of below 150 kPa (Bolton, 1986); however, for normal stresses of above 150 kPa, significant crushing of grains can occur (Hamidi et al., 2009). Crushing of grains can be significant in the case of poorly-graded coarse-grained materials and crushed gravel or quarry stone (Danesh et al., 2019; Estaire and Santana, 2018; Stacho and Sulovska, 2019). The dilatancy is not constant, but it decreases with an increasing normal stress in these materials. The results of the laboratory tests, which describe the decreasing dilatancy angle with an increased normal stress, have been presented by many researchers (Pavlik and Racansky, 2019; Hamidi et al., 2009; Strahler et al., 2015; Patil et al., 2018). The effect of the shape of the grain on the stress and dilatation parameters was investigated by Arda and Cinicioglu (2021).

Cited studies are focused mainly on the analysis of the dilatancy angle of sand or sand-gravel mixtures; however, studies aimed at determining the dilatancy angle of "pure" gravel have not yet been processed to such an extent. The study presented aims to analyze the results of shear strength tests on different types of gravel soils and is focused on determining their dilatancy angle. Well-graded and poorly-graded gravel, poorly-graded quarry stone, gravel with fine content and silty gravel were tested using a large-size direct shear test apparatus. The aim was to define the value of the dilatancy angle for the coarse-grained materials selected as a function of the normal stress, in a range of normal stress up to 200kPa. Thanks to the study results, the findings have both practical and scientific uses.

Testing Procedure and Methodology Applied

The tests were executed using the SHEARMATIC 27-WF 2304 direct shear test apparatus. The apparatus scheme is shown in Fig. 1. The shear box had dimensions of 300 x 300 mm and a height of 200 mm. The samples were tested under three different normal (vertical) stresses; i.e., 50, 100, and 200 kPa or 50, 100, and 150 kPa, respectively. Each test consisted of two steps; i.e., compression of the sample and the shear testing. The sample's compression was performed quickly (within 60 minutes) because only the coarse-grained gravels were tested. The horizontal movement speed in the shear test was set at a range of 0.1-0.5 mm/min, depending on the type of the sample. The maximum horizontal movement was about 60 mm, which equals a strain of 20 %. Some photos from the testing can be seen in Fig. 2. The methodology for determining the peak and critical shear strength parameters has already been described in detail by Stacho and Sulovska (2022). The principle of determining the dilatancy angle from the direct shear test results is plotted in Fig. 3. The normal stress affects the dilatancy angle, as demonstrated. The angle of dilatancy was determined by the following equation (Atkinson, 2007; Simoni and Houlsby, 2006):

$$\tan\psi = -\frac{\mathrm{d}\varepsilon_{yy}}{\mathrm{d}\gamma_{yx}} = \frac{\mathrm{d}_v}{\mathrm{d}_u} \quad (1)$$

where ε_{yy} and γ_{yx} are the vertical compressive and shear strains, while d_v and d_u represent the vertical deformation and shear displacement.

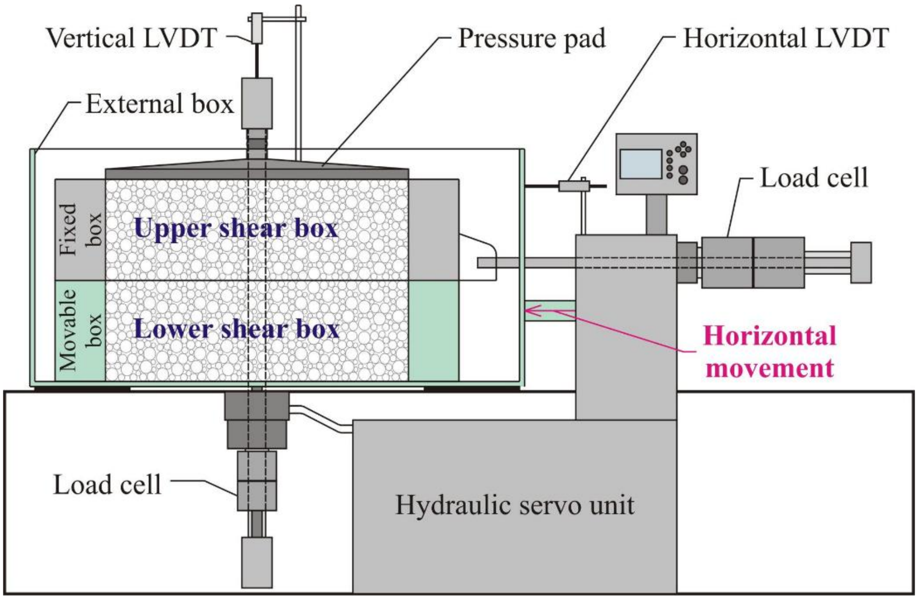

Figure (1): Scheme of the direct shear test apparatus used

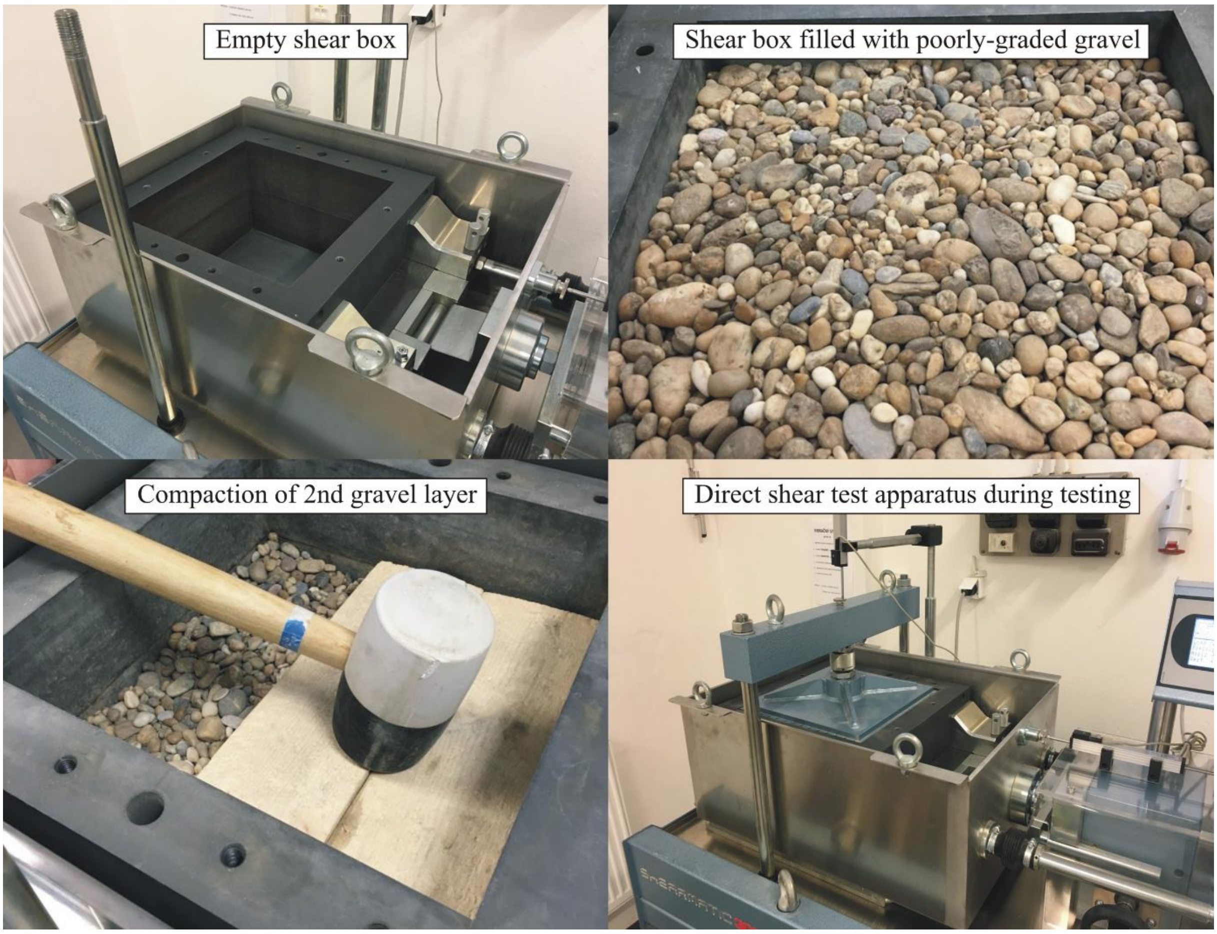

Figure (2): Photos from testing using a large-size direct shear test apparatus

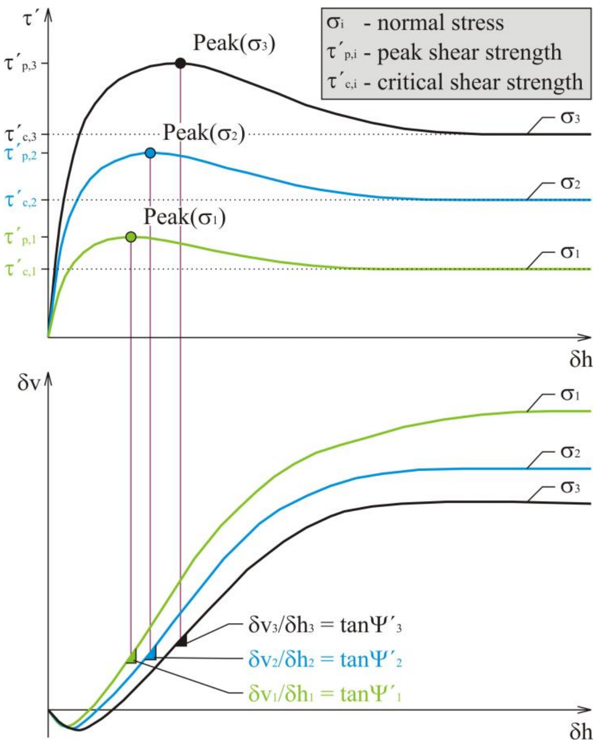

Figure (3): The angle of dilatancy determined from the results of the direct shear test

The sample materials tested were divided into separate groups, depending on the type of soil classification (GW - well-graded gravel, GP – poorly-graded gravel, G-F - gravel with fine fraction, and GM - silty gravel), the fraction (grain-size distribution range), and the shape of grains (pebbles or crushed). The samples were separated into the following groups: GW-crushed, GW - pebble, GP - 8-20 mm crushed fraction, GP - 0-20 mm crushed fraction, GP-pebble, GP - quarry, G-F, and GM. The soils were classified according to STN 72 1001: 2010 classification of soils and rocks (2010).

Evaluation of the Results of the Dilatancy Angles Measured

The results of the tests are summarized in Table 1. The peak and the critical angles of the shear strength (φ' and φ'_c) are given. The values of the measured dilatancy angles are given for each sample; i.e., ψ'_1 for σ_1 = 50 kPa, ψ'_2 for σ_2 = 100 kPa, and ψ'_3 for σ_3 = 150 or 200 kPa. The results showed that the angle of dilatancy decreased with increasing the normal stress.

Table 1. Summary of the direct shear test results

Material type	Sample	Soil symbol	Fraction	Angle of shear strength		Angle of dilatancy		
				Peak	Critical			
				φ'	φ'_c	ψ'_1	ψ'_2	ψ'_3
GW - crushed	Sample 1.1	GW	0 - 16	46.73	38.36	24.37	18.01	14.95
	Sample 1.2	GW	0 - 16	50.78	38.60	24.64	18.92	14.08
	Sample 1.3	GW	0 - 16	52.22	43.08	26.30	19.86	16.44
GW - pebble	Sample 2.1	GW	0 - 16	42.40	34.10	16.66	14.95	13.66
	Sample 2.2	GW	0 - 16	45.92	35.78	17.00	15.30	13.50
	Sample 2.3	GW	0 - 16	48.48	38.35	17.18	15.82	14.47
	Sample 2.4	GW	0 - 16	49.04	42.20	18.17	16.81	15.97
GP - crushed 8-20 mm	Sample 3.1	GP	8 - 20	50.10	43.20	22.12	20.54	19.64
	Sample 3.2	GP	8 - 20	50.42	41.24	23.16	20.12	19.34
	Sample 3.3	GP	8 - 20	51.87	43.14	21.39	19.89	18.78
GP - crushed 0 - 20 mm	Sample 4.1	GP	0 - 20	49.76	39.81	18.46	17.09	14.65
	Sample 4.2	GP	0 - 20	47.05	37.48	18.51	17.21	15.98
	Sample 4.3	GP	0 - 20	51.19	41.96	19.80	16.90	15.50
	Sample 4.4	GP	0 - 20	51.78	43.10	17.88	17.68	15.64
GP - pebble	Sample 5.1	GP	0 - 20	41.60	36.80	12.70	10.92	7.36
	Sample 5.2	GP	0 - 20	44.60	40.00	12.20	9.40	8.50
	Sample 5.3	GP	0 - 20	48.51	43.74	12.84	10.86	8.36
GP - quarry	Sample 6.1	GP	4 - 16	41.60	35.99	16.88	12.17	8.88
	Sample 6.2	GP	4 - 16	43.65	36.14	18.13	12.56	8.97
	Sample 6.3	GP	4 - 16	44.67	36.44	18.75	13.35	9.14
G-F	Sample 7.1	G-F	0 - 16	49.14	43.18	14.41	12.50	8.96
	Sample 7.2	G-F	0 - 16	49.38	44.44	14.87	12.89	9.66
	Sample 7.3	G-F	0 - 16	51.80	44.16	14.80	11.91	10.30
GM	Sample 8.1	GM	0 - 16	45.79	41.00	15.60	11.00	8.30
	Sample 8.2	GM	0 - 16	45.85	40.27	15.37	11.60	8.20
	Sample 8.3	GM	0 - 16	45.96	39.90	14.90	11.90	8.00

The relationship between the angle of dilatancy and normal stress is plotted in Fig. 4 for each group of gravels. Two trend functions were applied to interpret the dilatancy angle-normal stress dependency; i.e., the linear and power functions. The formulae expressing the dependency between the dilatancy angle and the normal stress with an adequate determination coefficient are stated in Table 2. According to the results, the power function can be expected to be more precise.

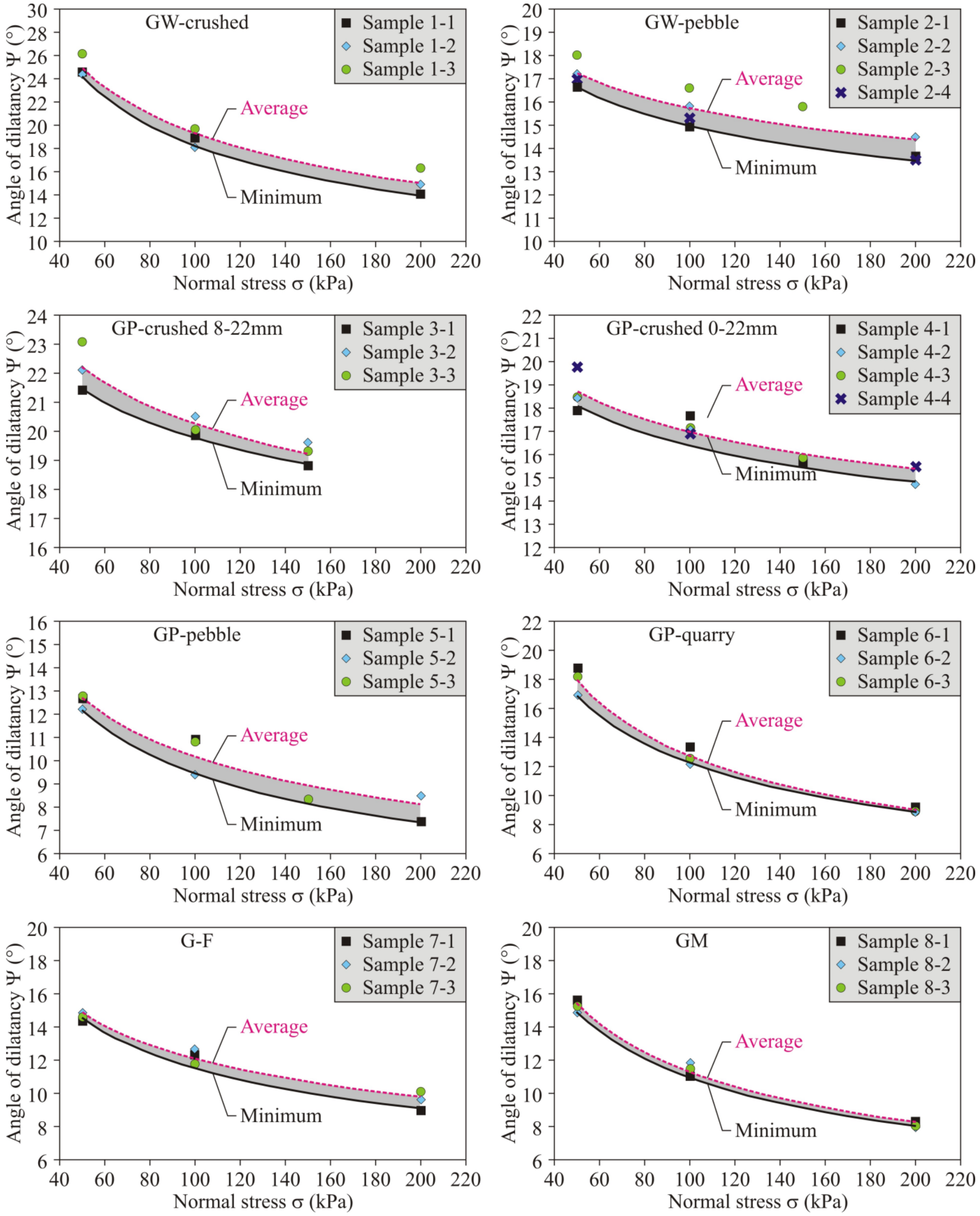

Figure (4): Evaluation of dilatancy angles for the types of gravels given

Table 2. Expressing the dependency between the dilatancy angle and the normal stress

Material type	Dependency expression - Linear function			
	Minimum		Average	
	Formula	R^2 (-)	Formula	R^2 (-)
GW - crushed	26.335 - 0.0644x	0.898	26.991 - 0.0622x	0.896
GW - pebble	17.385 - 0.0201x	0.945	17.912 - 0.0182x	0.947
GP - crushed 8-20 mm	21.939 - 0.0165x	0.924	22.686 - 0.0183x	0.846
GP - crushed 0-20 mm	19.005 - 0.0217x	0.999	19.552 - 0.0209x	0.983
GP - pebble	13.22 - 0.0306x	0.923	13.74 - 0.0291x	0.970
GP - quarry	18.525 - 0.0504x	0.917	19.768 - 0.0563x	0.919
G-F	15.885 - 0.0354x	0.980	16.089 - 0.0329x	0.984
GM	16.4 - 0.0437x	0.930	16.956 - 0.0455x	0.949
Material type	Dependency expression - Power function			
	Minimum		Average	
	Formula	R^2 (-)	Formula	R^2 (-)
GW - crushed	$113.53x^{-0.396}$	0.997	$103.24x^{-0.364}$	0.995
GW - pebble	$30.129x^{-0.152}$	0.999	$27.7x^{-0.13}$	0.999
GP - crushed 8-20 mm	$30.77x^{-0.094}$	0.995	$33.031x^{-0.103}$	0.962
GP - crushed 0-20 mm	$31.828x^{-0.144}$	0.941	$32.005x^{-0.137}$	0.993
GP - pebble	$50.648x^{-0.365}$	1.000	$44.435x^{-0.32}$	0.994
GP - quarry	$103.21x^{-0.463}$	1.000	$125.27x^{-0.497}$	1.000
G-F	$55.949x^{-0.343}$	0.987	$48.981x^{-0.304}$	0.986
GM	$86.39x^{-0.449}$	0.999	$90.581x^{-0.452}$	0.997

For each gravel group, two different power trend functions were plotted (Fig. 4). The first function was adopted as an average of the values given. The second function was achieved by only minimum values of the dilatancy angles for the normal stresses given, which permitted getting the minimum value of the dilatancy angle's distribution envelope. The minimum distribution of the dilatancy angle for each group can be recommended as adequate concerning its safety for its practical application in the design of geotechnical structures.

According to the findings, crushed gravels that are poorly or well-graded have larger dilatancy angles than poorly or well-graded pebbles. In the cases of crushed gravel, the angle of dilatancy decreases more significantly with increasing the normal stress than in the case of pebble gravels; this tendency is shown in Fig. 4 and by the equations stated in Table 2.

Comparison of the Measured and Estimated Dilatancy Angles

The angle of dilatancy is not only necessary to determine and know the properties of the coarse-grained materials given, but also to determine the correct input parameters of these materials for the precise design of geotechnical structures. In a practical application, when analytical calculations or numerical modeling is used for a geotechnical design, dense or very dense gravels have an angle of the shear strength significantly greater than 30° (Drusa et al., 2016; Hadri et al., 2021; Vlcek et al., 2023). In these cases, the coarse-grained material's dilatancy angles can be determined using Equation (2), e.g. Drusa et al. (2019):

$$\Psi = \varphi - 30° \quad (2)$$

where φ represents the peak angle of the shear strength. This simplification is also often used in the calculation of complex geotechnical structures when different types of advanced material models are taken into account (Drusa et al., 2016; Kolenak and Slavik, 2023; Sulovska and Stacho, 2021). This simplification has been applied by many researchers based on the theoretical assumptions stated in detail by, e.g. Bolton (1986). However, as the results have shown, the dilatancy angle is not a constant value. The difference between a simplified estimation of the dilatancy angle and the value of the dilatancy angle measured by the present testing was compared in Fig. 5. The parameter $\Delta\psi'$, which represents this difference, was computed using lowing Equation (3):

$$\Delta\psi' = \psi'_i - (\varphi' - 30°) \quad (3)$$

where ψ'_i is the dilatancy angle for the normal stress given (Table 1). The graphs (Fig. 5) show green columns (the safe side) when the measured value is higher than the one estimated (according to Equation 2) and red columns (the unsafe side) when the measured value is lower than the estimated one. For the types of gravel given, the estimated value of the dilatancy angle is usually greater than the measured value except in some cases (plotted by the green columns).

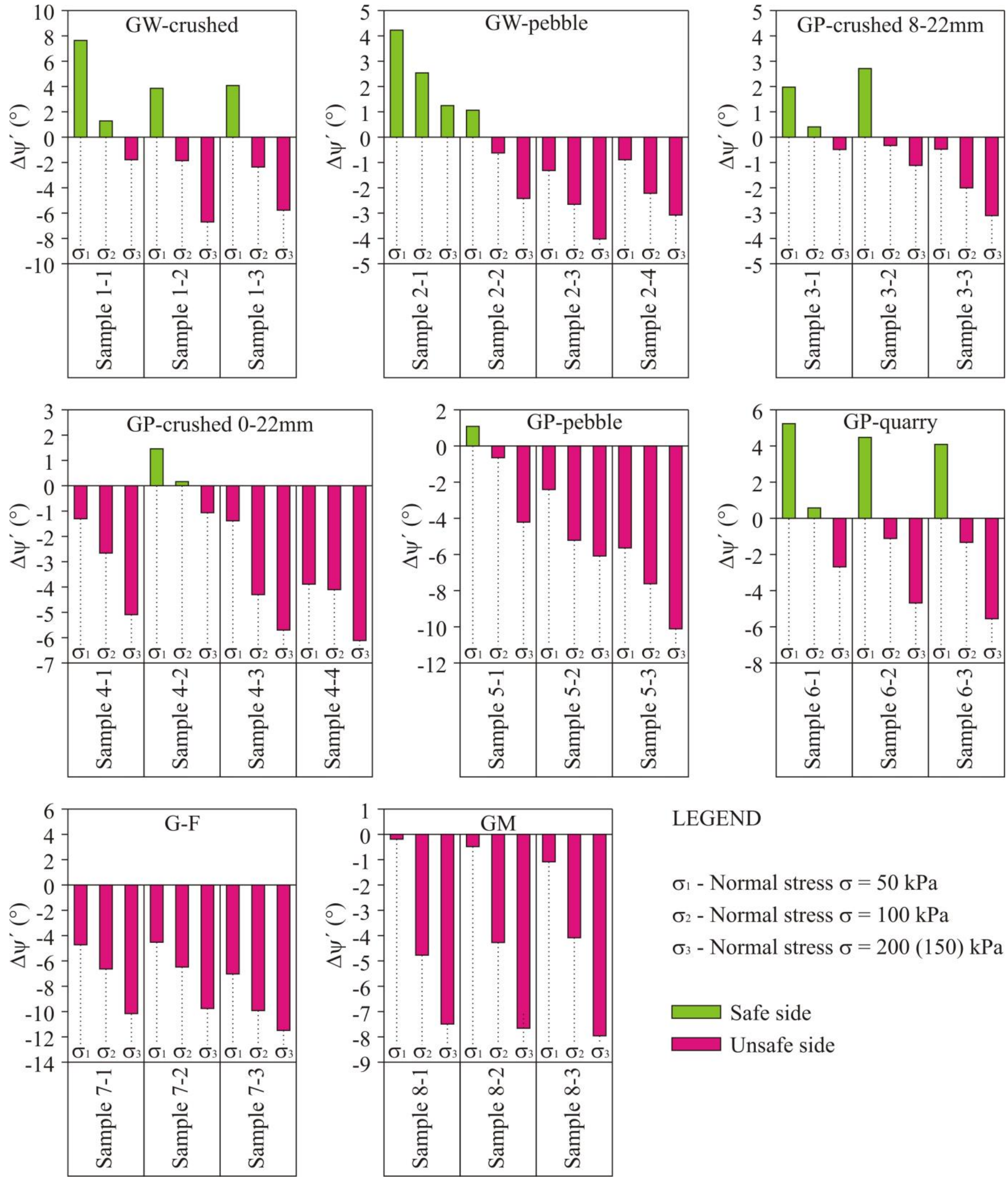

Figure (5): Differences between measured and estimated dilatancy angles for the types of gravels given

For low normal stresses (about 50 kPa), the measured dilatancy angles are greater or similar to the estimated dilatancy angles; however, for stresses above 200 kPa, the measured dilatancy angles are significantly lower than the estimated dilatancy angles. Zhao and Cai (2010) dealt with the non-linearity of the dilatancy angle in their numerical modeling of rocks. It must also be stated as a fact that the angle of the shear strength is not a constant value for the given coarse-grained materials tested (Kharanaghi and Briaud, 2020; Liu et al., 2015) and that the Mohr-Coulomb linear failure criterion is only an approximation of the non-linear behavior. However, the results of the laboratory tests showed that while the angle of the shear strength can be considered constant in the range of normal stresses (0 - 200 kPa) with sufficient accuracy (Stacho and Sulovska, 2019), the angle of dilatancy changes significantly in the range of these stresses, see e.g., Fig. 4. In summary, the results show that when designing geotechnical constructions, it is necessary to determine the shear strength parameters of the gravels input concerning the amount of stress to which the sub-soil (material) will be exposed.

DISCUSSION

The results of shear tests on types of gravel can be successfully interpreted using flow rules. Based on the theoretical background (Rowe, 1962), a simplified empirical correlation for sand (Bolton, 1986) can be stated as:

$$\varphi'_{ps} = \varphi'_{cv,ps} + 0.8\,\psi' \qquad (4)$$

where φ'_{ps} is the peak angle of the shear strength in the plane strain, and $\varphi'_{cv,ps}$ is the constant volume angle of the shear strength in the plane strain. The theoretical background explaining the difference and determination of the parameters of the shear strength in the plane strain and direct shear was well described by Simoni and Houlsby (2006). They also expressed Bolton´s equation for the results of the direct shear test in the following way:

$$\varphi'_{peak,ds} = \varphi'_{cv,ds} + b\,\psi'_{max} \qquad (5)$$

where $\varphi'_{peak,ds}$ (φ' in Table 1) is the peak angle of the shear strength determined in the direct shear, and $\varphi'_{cv,ds}$ (φ'_c in Table 1) is the constant volume angle of the shear strength in the direct shear. Their results showed that the value of the *b*-coefficient decreased with increasing the fractions. However, they executed tests at a constant pressure of about 90 kPa; so, they did not report the dependence between the normal stress and the dilatancy angle, which occurs for the types of materials given. The results presented showed that the *b*-coefficient values are lower than 0.8, which can be appropriately applied to sand. The determined values of the b-coefficients correspond with the b-coefficient values presented by Simoni and Houlsby (2006). In addition, the presented results indicated a decrease in the dilatancy angle with increasing the normal stress (Fig. 4).

The same methodology was applied in the given study to determine the *b*-coefficient for the coarse-grained gravels tested. The results are plotted in Fig. 6 as a function of the normal stress. The *b*-coefficient is non-linearly increased with increasing the normal stress and varied between 0.31 and 0.63, depending on the type of gravel. Using Equation (6), it is possible to determine the value of the dilatancy angle for a given type of gravel in the specified range of normal stress obtained from the laboratory testing results.

$$\Psi'_i = \frac{\varphi' - \varphi'_c}{b}. \qquad (6)$$

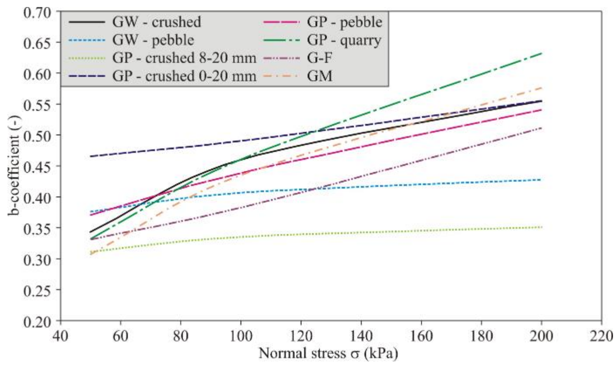

Figure (6): Relationships between *b*-coefficient and normal stresses for the types of gravels given

CONCLUSIONS

The results of the large-size direct shear tests were analyzed by focusing on determining the angle of dilatancy. The gravels tested were divided into separate groups depending on their type; i.e., well-graded gravel, poorly-graded gravel, gravel with a fine fraction, and silty gravel, the grain size, and the shape of grains. The tests were performed within the normal stress range of 50 to 200 kPa. The results showed that the dilatancy angle decreases with an increase in the normal stress. The power trend function was applied as the most accurate function to interpret the dependency of the dilatancy angle on the normal stress. Two types of power functions; i.e., the average and minimum, were adopted to interpret the dilatancy angle, depending on the normal stress. The dilatancy angles measured in the laboratory were compared with those determined by the simplified assumptions usually applied in the design of geotechnical structures. The results showed that the measured values are lower than the estimated values; thus, for the given types of gravels tested, it can be recommended to determine the dilatancy angle using laboratory testing instead of a simplified assumption. A simple relation between the shear strength parameters was adopted to determine the dilatancy angle as a function of the normal stress when the peak and the critical angles of the shear strength are known. The testing results showed that the dilatancy angle depends on the normal stress and needs to be correctly defined based on the type of material and the stress to which the sub-soil will be exposed for the proper geotechnical design.

Data Availability

All the results of the laboratory tests used in the study appear in the article submitted. The individual measurements are available at any time from the authors of the paper upon reasonable request.

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