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Comparison of Different Methods for Conducting Multistage Direct Shear Tests

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Abstract **-** Large-scale direct shear tests are frequently used to determine the shear strength of coarse-grained or mixed-grained soils. Standard practice requires carrying out at least three singlestage tests, each at a different normal stress on a new specimen. Although this ensures reliable shear parameters, it demands considerable material volume and lengthy testing times. As an alternative, multistage direct shear testing applies multiple shear phases to a single specimen, significantly reducing sample volume and laboratory time. However, each additional shear phase may alter the soil structure and affect subsequent peak shear strengths, especially in dense or overconsolidated soils. This study systematically compares singlestage and multistage direct shear tests on a mixed-grained soil with high gravel content. Five distinct multistage methods (MSA–MSE) were evaluated, varying in shear displacement and normal stress reset conditions. Specimens were compacted to medium-dense to dense conditions with water contents close to the optimum value determined by the standard Proctor test. Comparisons of the defined secant slope S_{10-50} (calculated between 10% and 50% of the peak shear stress), the dilation angle, peak shear strength, and shear parameters (friction angle and cohesion) highlight how methodological differences influence the choice of testing method. The results reveal that methods involving full shear displacement reset between stages (MSB and MSC) provide shear strength parameters closely matching those from singlestage tests. In contrast, methods without full reset (MSA and MSD) or with reversed loading sequences (MSE) produced lower peak shear strengths and distorted shear parameters due to cumulative disturbance or induced overconsolidation. These findings highlight the essential role of controlling both displacement history and loading sequence to ensure reliable parameter interpretation in multistage testing.

Keywords**:** multistage direct shear, coarse-grained soils, dilatancy, peak shear strength, friction angle, cohesion.

1. Introduction

The direct shear test is a well-established laboratory method to determine the shear strength of soils under different normal stresses. Traditionally, at least three singlestage direct shear tests are performed, each at a constant normal stress on a new specimen, to derive shear strength parameters (cohesion c' and friction angle ϕ'). However, when dealing with coarse soils containing gravel-sized particles, large-scale direct shear apparatuses (e.g., 30 × 30 cm shear boxes) are required by standards to accommodate the maximum grain size. Such large-scale tests typically involve high costs due to expensive equipment, extensive logistical efforts for obtaining large volumes of material, and labour-intensive handling, preparation, and testing procedures. To address these challenges, researchers have increasingly investigated multistage direct shear techniques, where a single specimen undergoes multiple shear phases at successively higher normal stresses [1-3]. Although multistage methods are well established in triaxial testing, especially in rock mechanics [4-8], their application to direct shear testing remains less common. In dense or overconsolidated soils, careful management of each phase is crucial to avoid inducing excessive shear zone damage, for example by imposing stricter termination criteria or limiting peak overshoot [1], [9].

Nevertheless, multistage direct shear testing carries added complexity: since each prior shear phase may affect subsequent peak behavior, controlling and interpreting the results can be challenging. In light of these advantages and drawbacks, this study compares five different multistage direct shear test methods (MSA–MSE) on a mixed-grained soil. Particular emphasis is placed on how the sequence of unloading and reloading steps applied after each shear phase, before proceeding to the next loading stage, influences the measured shear strength parameters.

2. Material and Equipment

The tested soil (designated G-1) is a mixed-grained material obtained by removing all particles larger than 20 mm. The grain size distribution, determined according to DIN EN ISO 17892-4:2017-04 [11], indicates a composition of gravel, sand, and approximately 14% fines ($d \leq 0.063$ mm), as shown in Fig. 1. Based on DIN 18196:2023-02 [12], the soil is classified as a clayey Gravel (GT), while according to DIN EN ISO 14688-1:2020-11 [13], it is identified as si'saGr. Consistency limits evaluated in accordance with DIN EN ISO 17892-12:2022-08 [14] show that the fine fraction corresponds to a high-plasticity clay (TA). Table 1 provides a summary of the properties of the tested material.

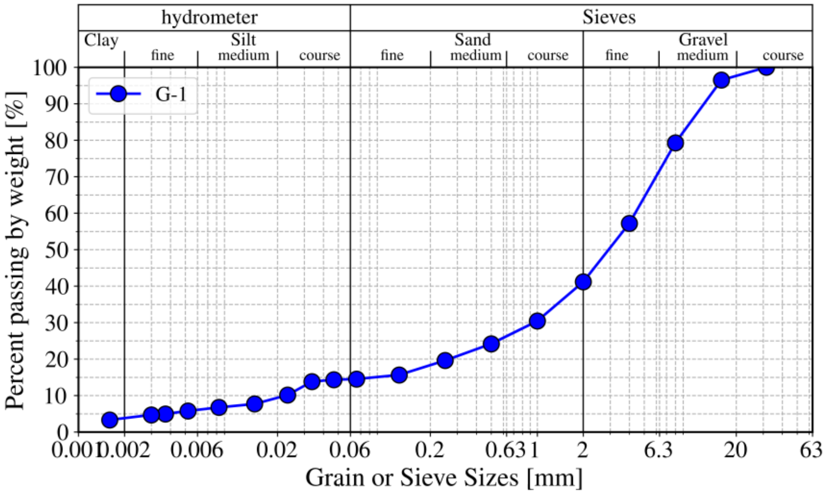


Fig. 1: Grain size distribution of tested material

Table 1: Classification properties of tested material

Soil	Soil group	G_s [g/cm³]	D_{50} [mm]	C_U [-]	C_c [-]	LL [%]	IP [%]	ρ_{pr} [g/cm³]	w_{opt} [%]
G-1	GT	2.609	3.10	195.87	9.01	70.0	39.6	1.741	16.3

GT: clayey gravel; G_S: specific gravity of the solid particles; D_{50}: median grain size, C_U: coefficient of uniformity, C_C: coefficient of curvature, LL: liquid limit, IP: plasticity index, ρ_{pr}: maximum dry density determined via standard proctor compaction, w_{pr}: optimum water content corresponding to ρ_{pr}.

Due to the relatively large gravel content, the samples were placed in a large-scale shear box (30 × 30 cm cross-section, 20 cm in height) in accordance to DIN EN ISO 17892-10:2019-04 [15] to satisfy standard requirements for the ratio of specimen size to maximum particle size. Specimens were prepared in a medium-dense to dense state with water contents close to the optimum value. To achieve this, the soil was compacted in three layers using a Proctor hammer, ensuring at least one full layer intersected the central shear plane.

The state of the specimen is expressed as the degree of compaction, D_{pr}, defined by Eq. (1), relative to the maximum dry density determined from the standard Proctor test:

$$D_{pr} = \frac{\rho_d}{\rho_{pr}} \cdot 100[\%] \tag{1}$$

where ρ_d is the measured dry density of the specimen (after compaction), and ρ_{pr} is the maximum dry density determined from the standard Proctor test.

3. Testing procedures

3.1. Overview of Multistage Direct Shear Methods

In a conventional singlestage direct shear test, each specimen is subjected to a single normal stress, consolidated until vertical deformation becomes negligible, and then sheared at a constant displacement rate until a predetermined maximum shear displacement is reached. Typically, three or more specimens, each tested at different normal stresses, are required to derive shear parameters (cohesion c’ and friction angle φ′). In contrast, the multistage direct shear method subjects one specimen to multiple normal stress levels in successive phases. Figure 2 schematically presents the five multistage direct shear methods evaluated in this study. Each method is defined by distinct sequence of unloading or adjusting shear displacement and normal stress before advancing to the next stage:

Method A (MSA): The final shear displacement from the previous stage is held constant while normal stress is increased, followed by a new consolidation at higher normal stress.

Method B (MSB): Shear displacement is returned to near zero under constant normal stress before the normal stress is increased.

Method C (MSC): Both normal stress and shear displacement are fully released to zero before the specimen is loaded to the next normal stress level.

Method D (MSD): A reverse shear is applied until shear stress approaches zero, after which normal stress is raised.

Method E (MSE): Follows the same reverse-shear sequence as Method MSD but initiates each phase at the highest normal stress and subsequently reduces normal stress.

After each adjustment sequence, the specimen is sheared under the newly established normal stress.

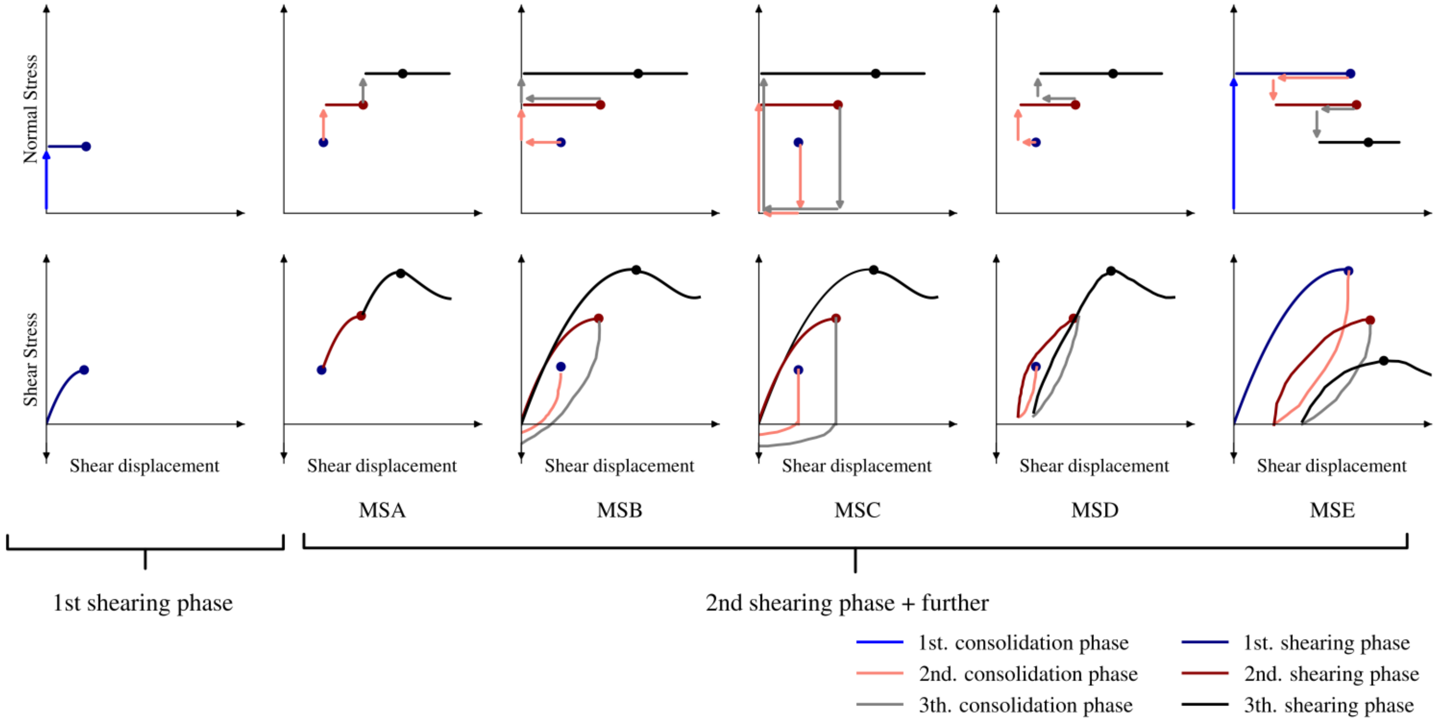


Fig2: Schematic overview of the five multistage direct-shear test methods (MSA–MSE) used in this study.

3.2. Laboratory Testing Program

Table 2 summarizes the initial conditions for the 24 tests, including singlestage (SS) and multistage methods (MSA–MSE). Each test is clearly identified by the method used (MSA, MSB, MSC, MSD, or MSE) and its corresponding number (e.g., MSA_1). The table provides detailed information including applied normal stress levels (σ'_N), initial dry density (ρ_d), initial void ratio (e_0), initial water content (w_i), initial saturation degree (S_i), water content in the shear zone after the test (w_E), initial compaction degree (D_{Pr}) and void ratio before shearing (e_{0S}). After consolidation, shearing was performed at a constant horizontal displacement rate of 0.1 mm/min.

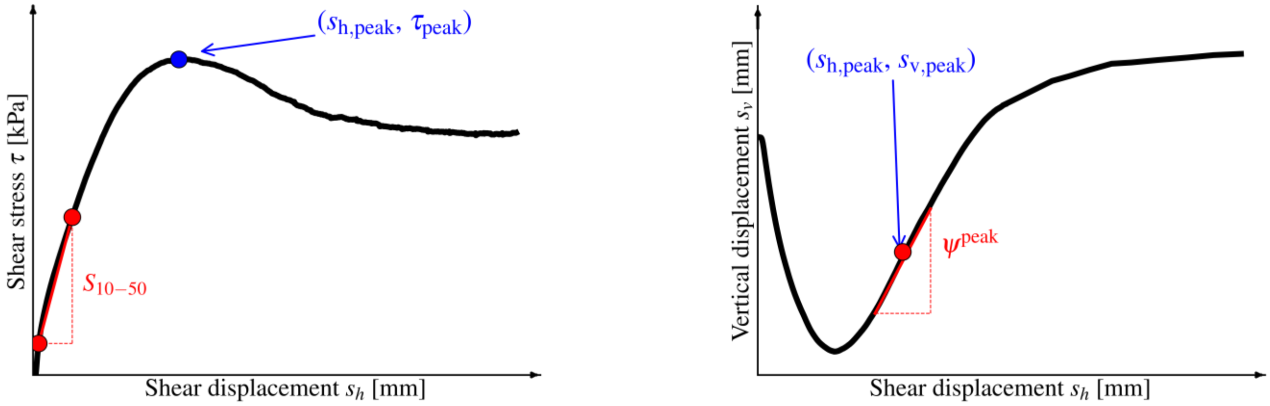
Table 2: Laboratory program of the five different multistage methods and the singlestage tests.

Test	Method	σ'_N [kPa]	ρ_d [g/cm³]	e_0 [-]	w_i [%]	S_i [%]	D_{Pr} [%]	w_E [%]	e_{0S} [-]
DS_100_1	SS	100	1.689	0.548	15.9	76.1	97.0	18.5	0.515
DS_100_2	SS	100	1.690	0.545	19.2	92.0	97.1	18.0	0.482
DS_100_3	SS	100	1.690	0.545	17.4	83.5	97.1	17.7	0.502
DS_100_4	SS	100	1.690	0.544	17.6	84.4	97.1	15.0	0.509
DS_200_1	SS	200	1.690	0.545	16.2	77.6	97.1	17.6	0.496
DS_200_3	SS	200	1.684	0.552	18.1	85.8	96.7	16.3	0.512
DS_400_1	SS	400	1.684	0.552	16.1	76.2	96.7	14.9	0.471
DS_400_2	SS	400	1.702	0.533	16.8	82.0	97.8	14.7	0.431
DS_400_3	SS	400	1.673	0.560	18.8	87.6	96.1	15.1	0.468
MSA_1	MSA	100/200/400	1.691	0.563	18.9	88,0	97.1	15.6	0.512/0.497/0.479
MSA_2	MSA	100/200/400	1.715	0.522	15.9	79,4	98.5	16.1	0.491/0.481/0.462
MSA_3	MSA	100/200/400	1.733	0.506	14.6	75,6	99.5	16.8	0.451/0.418/0.391
MSB_1	MSB	100/200/400	1.712	0.524	16.0	79,9	98.3	17.4	0.494/0.468/0.429
MSB_2	MSB	100/200/400	1.681	0.522	18.2	86,0	96.6	14.6	0.524/0.493/0.453
MSB_3	MSB	100/200/400	1.699	0.535	16.9	82,4	97.6	16.7	0.507/0.473/0.433
MSB_4	MSB	100/200/400	1.681	0.552	18.2	86,0	96.6	15.7	0.499/0.462/0.422
MSC_1	MSC	100/200/400	1.707	0.529	16.1	81,0	98.0	16.1	0.504/0.484/0.449
MSC_2	MSC	100/200/400	1.707	0.529	16.1	81,0	98.0	16.1	0.461/0.433/0.402
MSD_1	MSD	100/200/400	1.704	0.531	16.6	81,5	97.9	15.8	0.493/0.47/0.448
MSD_2	MSD	100/200/400	1.632	0.599	21.7	94,8	93.7	15.2	0.543/0.509/0.482
MSD_3	MSD	100/200/400	1.696	0.539	17.2	83,2	97.4	15.6	0.519/0.501/0.477
MSD_4	MSD	100/200/400	1.670	0.563	19.0	88,1	95.9	15.6	0.534/0.511/0.487
MSE_1	MSE	100/200/400	1.661	0.571	19.6	89,7	95.4	14.1	0.462/0.437/0.44
MSE_2	MSE	100/200/400	1.712	0.525	16.1	80,1	98.3	16.1	0.435/0.411/0.415

MSA - MSE: Multistage direct shear tests using methods A through E; SS: singlestage direct shear test; σ'_N: Normal stress; ρ_d: Initial dry density; e_0: Initial void ratio; w_i: Initial water content; S_i: Initial saturation; D_{Pr}: Initial compaction Degree; w_E: Water content in the shear zone after the test, and e_{0S}: Void ratio before shearing.

3.3. Evaluation of parameters

The initial void ratio before each shearing phase (e_{0S}) was evaluated to assess the volumetric state of the specimens and the effects of preloading in the different multistage methods. In addition, shear strength related parameters were analyzed, including the defined secant slope (S_{10-50}), calculated between 10% and 50% of the peak shear stress, the maximum dilation angle (ψ^{peak}), and the peak shear stress (τ_{peak}). Figure 3 illustrates schematically how these parameters were determined.



(a) (b)

Fig3: Schematic representation of the calculations (a) defined secant slope S_{10-50} and (b) dilation angle at peak shear stress ψ^{peak}.

4. Results and Discussion

This section summarizes and interprets the laboratory findings from direct shear tests performed at identical normal stresses (100, 200, 400 kPa) on specimens prepared at medium-dense to dense state. The analysis begins with the evaluation of the void ratio before shearing (e_{0S}), followed by a comparison of three key shear response parameters evaluated phase by phase: the defined secant slope (S_{10-50}), the dilation angle at peak shear stress (ψ^{peak}), and the peak shear stress (τ_{peak}). By directly contrasting each multistage method against its singlestage reference, this section highlights how different loading sequences affect specimen disturbance, volumetric behaviour, and peak shear stress.

4.1. Void ratio before shearing

Figure 4 shows the void ratio before each shearing phase (e_{0S}), for the different multistage methods and the singlestage tests (SS) at normal stress levels of 100, 200, and 400 kPa. Overall, all methods, including the singlestage tests, exhibit comparable void ratio variations across stress levels, with no substantial differences observed between the multistage and singlestage methods. The only notable exception is method MSE, which shows significantly lower void ratios in phases 1 and 2, due to the testing sequence starting at the higher normal stress level (400 kPa).

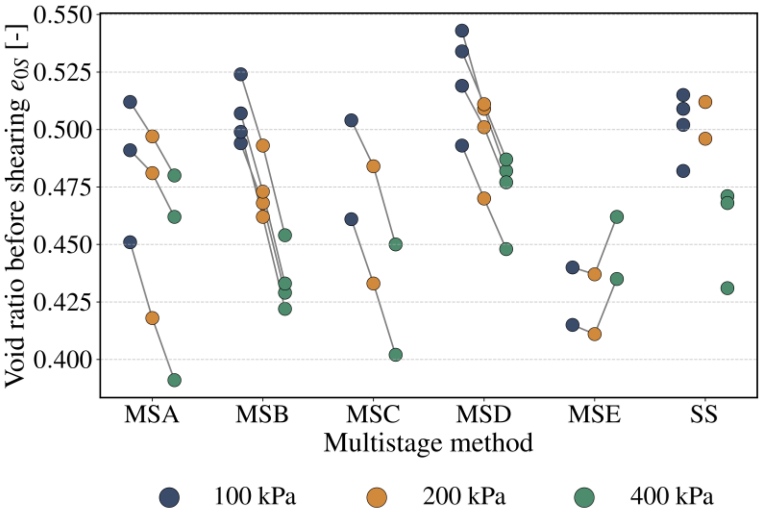


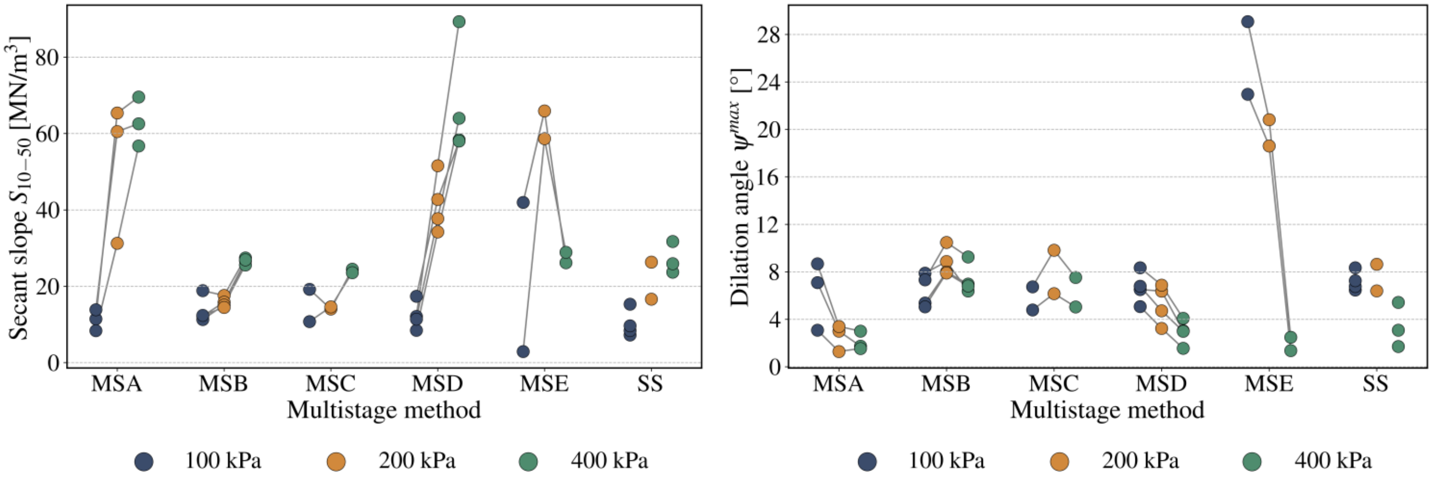
Fig.4: Comparison of the void ratio before each shearing phase among the singlestage tests (SS) and multistage methods (MSA to MSE), plotted for each applied normal stress level (100, 200, and 400 kPa).

4.2. Defined secant slope

Figure 5a illustrates the comparison of the defined secant slope (S_{10-50}) obtained from each multistage method and from the singlestage tests conducted at 100, 200, and 400 kPa. In phase 1 (blue points for methods MSA to MSD), all these multistage methods fall within the singlestage range (approximately 9–18 MN/m³). Methods MSA and MSD show a pronounced increase in S_{10-50} across the shearing phases, indicating progressive soil hardening due to cumulative shearing, as no full release of shear displacement occurs between stages. MSB and MSC exhibit an increase in secant slope that is slightly less pronounced than that observed in the singlestage tests. Method MSE shows a different behavior: the secant slope increases notably at 200 kPa but decreases sharply at 100 kPa in the final phase, which may be attributed to structural rearrangement or partial degradation of the specimen.

4.3. Dilation angle

Figure 5b shows the dilation angle at peak shear stress (ψ^{peak}) for each multistage method and for the singlestage tests at 100, 200, and 400 kPa. While most multistage methods exhibit a decreasing trend in ψ^{peak} with increasing normal stress, which is expected for granular soils under higher confinement, methods MSB and MSC deviate from this pattern: their dilation angles increase between 100 kPa and 200 kPa before decreasing at 400 kPa. Method MSD shows the most comparable behavior to the singlestage tests, with dilation angles remaining within a comparable range across all stress levels. In contrast, MSA exhibits lower dilation angles in the second and third phases, with values below 4°, indicating very limited dilative behavior. MSB and MSC exhibit dilation angles that clearly exceed those of the singlestage tests, suggesting that the unloading–reloading of shear displacement cycles involved in these methods induces significant soil hardening and enhances the dilative response. MSE, which initiates at 400 kPa, shows a markedly higher dilation angle in phase 1 (blue point) in comparison to singlestage values, reflecting its overconsolidated state resulting from the testing sequence.



(a) (b)

Fig.5: Comparison of (a) the defined secant slope S_{10-50} and (b) the dilation angle at peak shear stress ψ^{peak} for the shearing phases of the multistage methods (MSA-MSE), in comparison with singlestage (SS) tests.

4.4. Shear strength

Figure 6 presents the difference between the peak shear stress values obtained in the multistage tests (τ_{peak}^{MS}) and the corresponding average values from the singlestage tests ($\bar{\tau}_{peak}^{SS}$) at identical normal stress levels. This direct comparison highlights how each multistage procedure influences the measured shear strength. Method MSA shows consistently lower shear strengths at 200 and 400 kPa, suggesting a possible underestimation due to disturbance effects accumulated during earlier phases. A similar tendency is observed in MSD, though with slightly smaller deviations. In contrast, method MSE exhibits significantly higher shear strengths, especially at 100 kPa, which likely reflects the overconsolidated state induced by preceding loading stages. The influence of this preloading is evident in its consistently positive difference relative to the singlestage values. Methods MSB and MSC demonstrate the closest agreement with the singlestage reference across all stress levels. In both cases, the shear displacement was fully reset between phases, preserving the comparability of peak strength values and minimizing cumulative effects.

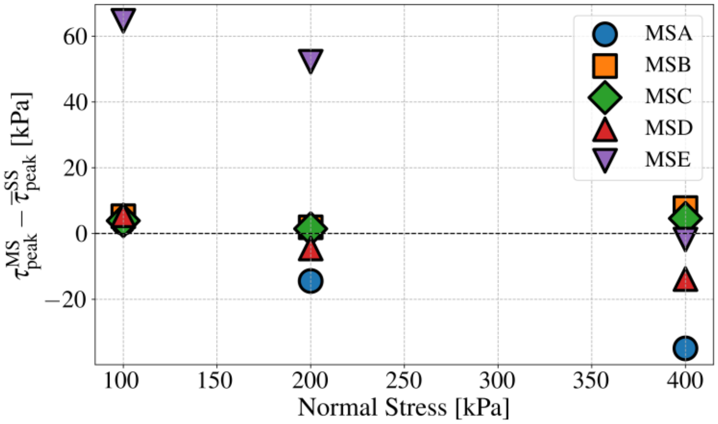
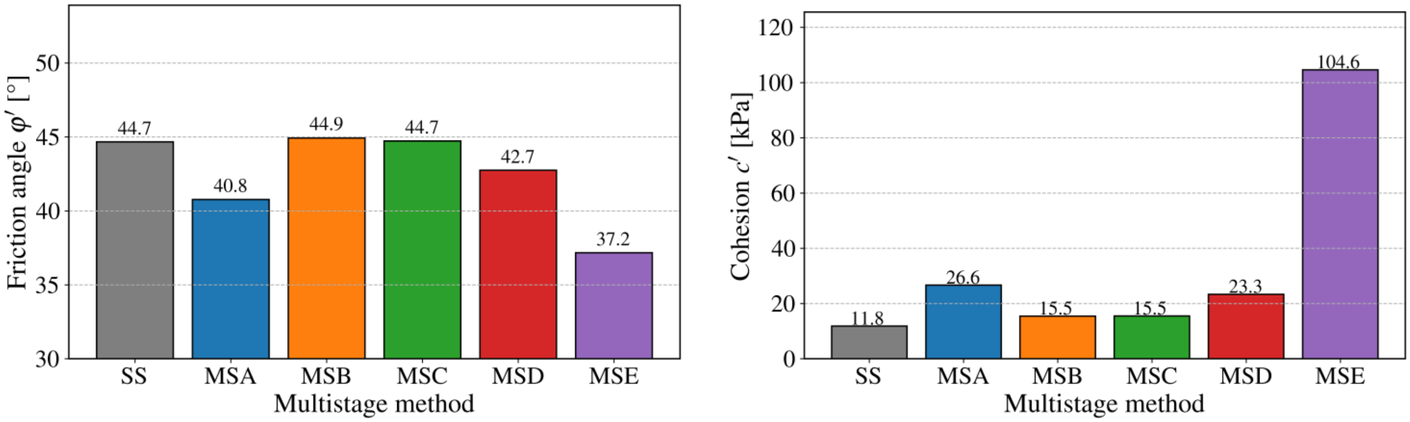


Fig.6: Difference between multistage and singlestage peak shear strength ($\tau^{MS}_{peak} - \bar{\tau}^{SS}_{peak}$) at each normal stress level.

4.5. Shear parameters

The average shear parameters, friction angle (φ‘) and cohesion (c’), obtained from the multistage methods were compared with the corresponding average values derived from singlestage tests (SS). As shown in Figure 7a, most multistage methods produced friction angles similar to or slightly lower than the singlestage reference ($\varphi'_{SS} = 44.7°$). The closest values were observed in methods MSB ($\varphi'_{MSB} = 44.9°$) and MSC ($\varphi'_{MSC} = 44.7°$), while method MSE showed a significantly lower friction angle of $\varphi'_{MSE} = 37.2°$. Regarding cohesion (Fig. 7b), clear differences can be observed among the methods. The singlestage tests resulted in an average cohesion of 11.8 kPa. Methods MSB and MSC exhibited similar values, reflecting their close agreement with the singlestage tests. In contrast, methods MSA and MSD showed higher cohesion values, while MSE presented a notably elevated cohesion of 104.6 kPa, suggesting a strong influence of the testing procedure on the derived cohesion parameter.



(a) (b)

Fig. 7: Average values of (a) friction angle and (b) cohesion obtained from singlestage tests (SS) and the different multistage methods.

4.6. Comparative Discussion of Methods

The comparative evaluation of multistage methods revealed three distinct behavioral patterns, primarily governed by the degree of shear displacement reset and the imposed loading sequence. Methods MSB and MSC, which fully reset shear displacement between phases, yielded results most similar to those of the singlestage reference tests. These methods consistently reproduced the expected secant slope and peak shear strength values, with only slightly higher dilation angles observed in later phases. Their void ratios before shearing remained comparable to those of the singlestage tests.

In contrast, MSA and MSD, which lack full displacement reset, showed markedly different behavior. Both methods exhibited a pronounced increase in secant slope due to cumulative shearing, while dilation was significantly reduced, almost completely suppressed in the later phases. Despite continued compaction across phases, peak shear strength was notably lower, especially in MSA. This mismatch indicates that accumulated shear deformation degraded the soil structure, overpowering the densification effect. MSD showed a less severe loss in strength, attributed to partial displacement recovery between stages.

The third pattern was observed in MSE, which began at the highest stress level (400 kPa), inducing a strongly overconsolidated state. As a result, phases 1 and 2 exhibited very high dilation angles, secant slopes, and peak shear strengths. Nevertheless, the derived shear parameters diverged significantly from the reference: cohesion was heavily overestimated, and the friction angle was underestimated. The distinctly low void ratios in early phases confirm that preloading history dominated the mechanical response.

These findings clearly demonstrate that cumulative shear displacement has a stronger influence on peak shear strength than void ratio alone. Particularly in MSA, even with progressive compaction, the lack of shear displacement reset led to a substantial reduction in strength. In contrast, method MSE, despite including displacement reset, showed distorted results due to the reverse loading sequence from high to low normal stress. Therefore, to ensure reliable parameter determination, both proper shear displacement reset and a progressive loading sequence (from low to high stress levels) are essential.

5. Conclusion

This study has demonstrated that multistage direct shear testing can deliver shear strength parameters comparable to conventional singlestage tests, while significantly reducing specimen volume and laboratory time for coarse and mixed-grained soils in medium-dense to dense states. However, the choice of multistage method influences both peak shear strengths and the derived shear parameters.

Among evaluated methods, MSB (complete displacement reset) and MSC (complete reset of displacement and normal stress) showed the best agreement with singlestage results, delivering consistent values for both friction angle and cohesion. In contrast, MSA (no reset) and MSD (partial reset) led to an underestimation of shear strength and distorted shear parameters, driven by cumulative structural disturbance. Method MSE, starting at a high stress level, induced overconsolidation effects that skewed results, yielding low friction angles, excessive cohesion, and misleading peak behaviour.

Notably, these results challenge a common assumption in soil mechanics: that lower void ratios necessarily yield higher shear strength. In this study, void ratio remained stable across most methods, but shear strength varied significantly, governed instead by the history of shear displacement and the sequence of applied loads.

These findings underline two key requirements for obtaining reliable and representative soil parameters in multistage testing: (1) full reset of shear displacement between phases, and (2) a progressive loading sequence from low to high normal stress. Only when both conditions are met can structural integrity be preserved and meaningful comparisons to singlestage tests be achieved. For coarse and mixed-grained soils in medium-dense to dense conditions, MSB and MSC offer the most robust compromise between testing efficiency and parameter accuracy. Future work should investigate the performance of these multistage procedures across a broader range of soil types, densities, and fine content ratios.

Acknowledgements

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