

Multistage Direct Shear Testing in Densely Packed mixed-Grain soils

María José Toledo Arcic

Institute of Geotechnics, University of Applied Sciences Dresden, Germany, mariajose.toledoarcic@htw-dresden.de

Jens Engel

Institute of Geotechnics, University of Applied Sciences, Germany

ABSTRACT: This study investigates the application of multistage direct shear tests (MST) on mixed-grain soils with varying fines content, using the Revised Soil Classification System (RSCS) to identify the dominant grain fraction. Five ternary mixtures with fines contents ranging from 5% to 40% were tested in a densely compacted state ($D_c \approx 100\%$). Three MST methods were evaluated: MSA (no shear displacement reset), MSB (full reset), and MSC (partial reset). Results indicate that the optimal MST procedure depends on the dominant grain fraction. Coarse-dominated soils exhibit stable behaviour regardless of method, while fine-dominated mixtures demonstrate strength overestimation under MSB due to progressive hardening. Transitional mixtures showed the highest sensitivity to differences between test methods. The RSCS classification proved essential in predicting suitable MST methods, leading to efficient testing with reduced material and time requirements.

KEYWORDS: multistage direct shear test, mixed-grain soils, RSCS model, dominant grain fraction, shear strength.

1 INTRODUCTION

Mixed-grain soils pose challenges for shear strength characterisation due to their variable mechanical behaviour governed by the relative proportions of coarse and fine particles. Traditional single-stage direct shear testing requires large-scale equipment and multiple samples, particularly for coarse materials. As a more efficient alternative, multistage direct shear tests enable multiple shear phases on a single specimen. However, their suitability for mixed-grain soils remains underexplored, particularly in ternary mixtures. To clarify the underlying principle, in multistage direct shear testing (MST), several shear phases are performed sequentially on the same specimen under increasing normal stresses. After each phase, the specimen is either kept at the attained shear displacement (MSA), completely unloaded and brought back to its initial horizontal position (MSB), or partially released until negligible shear stress is reached (MSC). This procedure allows the progressive mobilisation of shear strength without the need to prepare a new specimen for each stress level. Compared with conventional single-stage tests, MST significantly reduces material demand, preparation effort and total testing time, especially for coarse or mixed-grain soils requiring large-scale equipment. This study aims to evaluate MST methods for such soils in a densely packed state and to establish guidance based on fines content and dominant grain fraction using the RSCS model.

2 MATERIALS AND METHODS

2.1 Soil mixtures and properties

Five mixtures were prepared with fines content ranging from 5.3% to 39.4%. Their grain size distributions are shown in Figure 1, and the associated soil properties are summarized in Table 1. The mixtures were initially classified using the German standard DIN 18196. Subsequently, the RSCS model by Park and Santamarina (2018) was applied to categorise each mixture according to its dominant mechanical phase: coarse (sand/gravel), transitional, or fine-grained dominated.

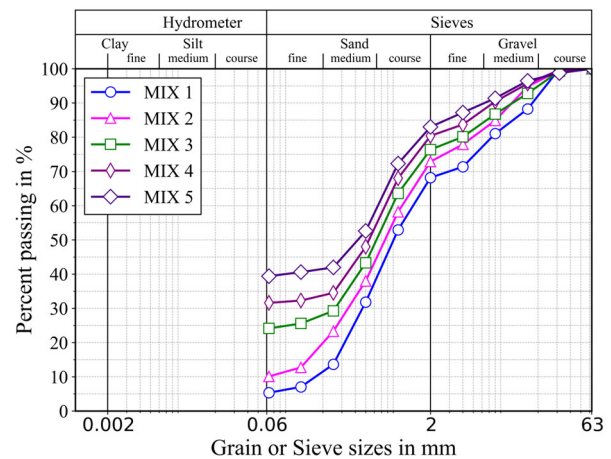


Figure 1. Grain size distribution of the tested soil mixtures.

Table 1. Soil properties of the tested mixtures.

Name	Soil Group after DIN 18196	Soil Group after RSCS model [1]	G_s [-]	ρ_{pr} [g/cm ³]	w_{pr} [%]
MIX 1	ST	S(S)	2.644	2.008	7.56
MIX 2	ST	S(S)	2.642	2.141	6.85
MIX 3	ST*	SF(F)	2.647	2.180	7.96
MIX 4	ST*	F(F)	2.633	2.125	7.89
MIX 5	ST*	F(F)	2.633	2.026	8.07

G_s = specific gravity of the solid particles; ρ_{pr} = Proctor density; w_{pr} = optimum water content. Note: The RSCS soil group column is explained in Section 2.2.

2.2 Classification of the mixtures after the RSCS Model

Based on the gravimetric–volumetric criteria proposed by Park and Santamarina (2018), the five mixtures were classified according to their load-carrying and flow-controlling components.

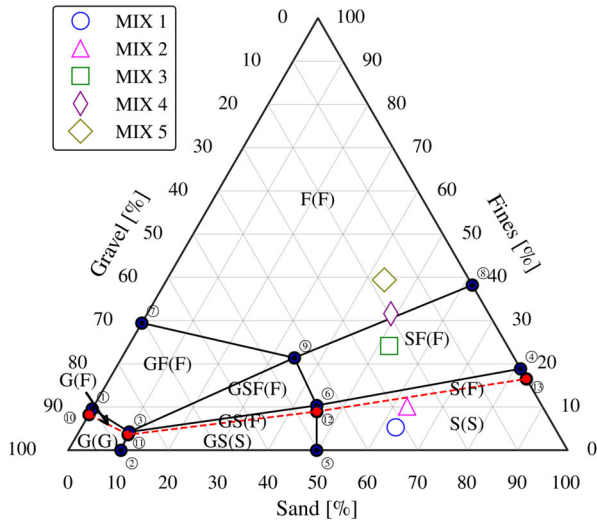


Figure 2. Classification chart after Park and Santamarina (2018) [1]. G: Gravel, S: Sand and F: fines. The first letter indicates the load-carrying component, while the letter in parentheses denotes the component that controls flow.

As shown in Table 1, MIX 1 and MIX 2 fall within the sand-controlled region (S(S)), MIX 3 corresponds to a transitional mixture (SF(F)), and MIX4 and MIX 5 are classified as fine-grained dominated (F(F)), although MIX 4 lies close to the transitional threshold.

2.3 Testing methods

Each mixture was compacted to a target state (D_c) of 100%, corresponding to its respective maximum Proctor dry density, using the optimum water content. At this preparation state ($D_c \approx 100\%$), the initial degree of saturation was approximately 80%. All specimens were then saturated prior to testing. For reference, conventional single-stage tests were also conducted on each mixture under the same stress levels. All tests were performed under drained conditions. A horizontal displacement rate of 0.1 mm/min was applied to MIX 1, MIX 2, and MIX 3, while 0.05 mm/min was used for MIX 4 and MIX 5.

A large-scale shear apparatus (30 × 30 cm) was used. Each mixture underwent single-stage tests at normal stresses of 100, 200, and 400 kPa, followed by multistage tests using three MST methods:

- MSA: constant shear displacement between phases.
- MSB: full reset of shear displacement.
- MSC: partial release by reversing shear until negligible shear stress.

The schematic of the multistage testing methods (MSA, MSB, MSC) has been presented in detail in Toledo Arcic et al. (2025).

2.4 Evaluation criterion

To evaluate the accuracy of each method, the single-stage test is used as the benchmark for comparison. Considering the inherent variability of soils, a tolerance of approximately $\pm 5\%$ in shear stress is adopted as an acceptable range within which two results can be regarded as equivalent. This criterion is used to assess whether the multistage procedures can reproduce the shear parameters typically obtained in conventional single-stage tests without a significant loss of accuracy.

3 RESULTS AND DISCUSSION

3.1 Shear behaviour in single-stage tests

Figure 3 shows the shear stress versus horizontal displacement for all mixtures at 100 kPa. Figure 4 presents the corresponding vertical displacements, highlighting the dilative response in MIX 1, MIX 2 and MIX 3 and the contractive behaviour in MIX 4 and MIX 5.

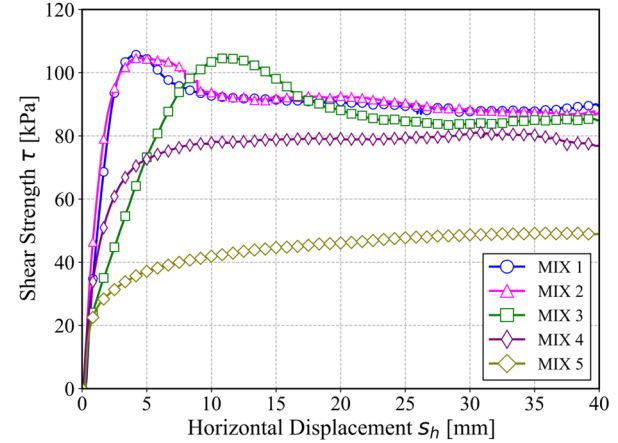


Figure 3. Shear stress vs. horizontal displacement at $\sigma'_N \approx 100$ kPa for all mixtures.

Coarse-dominated mixtures (MIX 1 and MIX 2) exhibited dilative behaviour characterised by a well-defined peak shear stress. MIX 3 showed a more gradual mobilisation of shear strength with reduced dilatancy compared to MIX 1 and MIX 2, reflecting its transitional nature. As fines content increased further (MIX 4 and MIX 5), a transition towards contractive behaviour was observed. The vertical displacement trends in Figure 4 also reveal that dilatancy increases notably from MIX 1 to MIX 2, reaching a maximum in MIX 2. This suggests that the optimal packing condition, where coarse grain voids are effectively filled by fines, occurs between 10% and 24% fines content (i.e., between MIX 2 and MIX 3). In this range, the highest shear strength and the most pronounced dilative behaviour are expected. Beyond this range, as observed in MIX 4 and MIX 5, dilatancy decreases significantly.

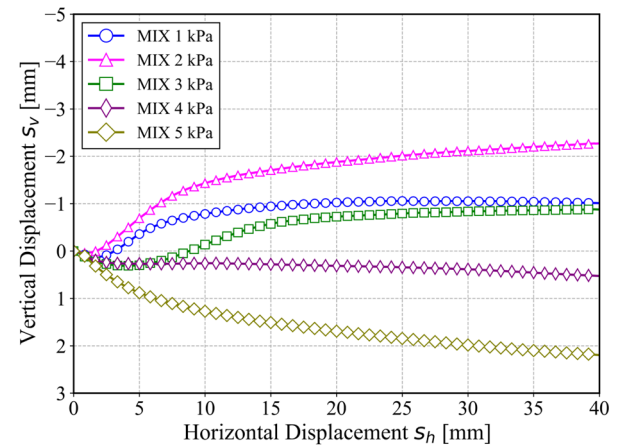


Figure 4. Vertical displacement vs. horizontal displacement at $\sigma'_N \approx 100$ kPa for all mixtures.

This behaviour aligns with the RSCS classification, which identifies the onset of the transitional zone at approximately 19% fines content until ca. 39% fines. The corresponding trend in peak shear strength with increasing fines content, derived from the failure envelopes, is illustrated in Figure 5.

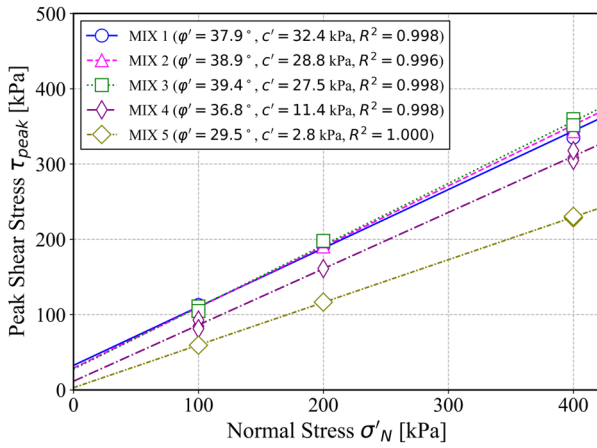


Figure 5. Peak shear stress versus normal stress for all mixtures (including angle of friction ϕ' and cohesion c').

3.2 Comparison of multistage methods

To assess the influence of the multistage methods on the determination of shear strength parameters, different methods were applied to five soil mixtures with varying fines content. This section is divided into three parts: first, the reproducibility of each method is evaluated to verify its consistency; second, the typical behaviour of selected representative mixtures is examined in detail, and finally, a comparative analysis is conducted across all tested mixtures to identify trends and differences in the resulting strength parameters.

3.2.1 Reproducibility of multistage methods

The results confirm that all three multistage methods exhibit high reproducibility, with deviations between replicates remaining within a tolerance of $\pm 5\%$ in peak shear stress, adopted here as a conservative threshold. This corresponds to variations of approximately $\pm 1.5^\circ$ in friction angle and ± 10 kPa in cohesion, depending on the soil. This threshold is considered conservative compared to the levels of variability reported in the literature.

Lutenegger and Timian (1987) reported coefficients of variation up to 42 % for cohesion and 11 % for friction angle in borehole shear tests, highlighting substantial scatter under in-situ conditions. Schwiteilo and Herle (2016) suggested that deviations below $\pm 10\%$ in peak shear strength are acceptable for evaluating test plausibility of direct shear results, particularly when structural anomalies can be excluded.

In controlled laboratory environments, lower variability is typically observed. Bareither et al. (2008) reported a standard deviation of only 0.1° in replicate direct shear tests conducted by a single operator, while inter-laboratory comparisons showed deviations of up to 18.2° . Similarly, Thermann et al. (2016) found that the choice of laboratory assistant alone could result in differences of up to 1.97° in friction angle, emphasising the role of operator consistency. These comparisons support the use of the $\pm 5\%$ criterion as a reasonable and sufficiently strict threshold for evaluating methodological reproducibility.

However, the reproducibility can still be influenced by specific aspects of the test method, depending on the method applied and the material tested. In MSB, particularly for coarse and transitional mixtures, the choice of the termination point at the end of each shearing phase significantly influences the peak shear strength mobilised in the subsequent phases. Figure 6 illustrates this effect: the main plot shows the shear stress–displacement curves for three multistage tests conducted on the mixture MIX 3 (transitional) using the MSB method. The inset highlights the relationship between the peak shear stress in the

first shearing phase ($\tau_{peak,1}$) and the fully mobilised peak in the last phase ($\tau_{peak,3}$). A clear linear trend is observed, indicating that a lower peak stress in the first phase, resulting from an early termination, leads to a reduced mobilised shear strength in the final phase. This suggests that the calculated cohesion is strongly dependent on the chosen termination point, while the friction angle remains relatively unaffected.

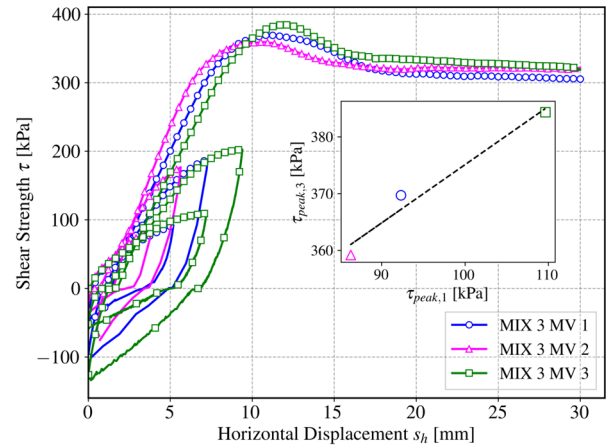


Figure 6. Influence of termination point in MSB: Example from Mixture 3 (transitional).

Conversely, MSA does not reset the shear displacement, allowing shear displacement to accumulate throughout successive shearing phases. As a result, specific effects on the test equipment may occur, such as tilting of the top cap, particularly under large cumulative displacements. This effect is especially relevant for fine-grain dominated mixtures (MIX 4 and MIX 5), where long shear displacements are required to mobilise the peak shear strength. As shown in Figure 7, a well-defined peak is not reached, and the shear strength continues to increase progressively, indicating potential top cap tilting in the final phase.

Independently of the method used, exceeding the peak strength in the early stages must be strictly avoided, as it leads to irreversible changes in the specimen and compromises the validity of the final shear strength parameters.

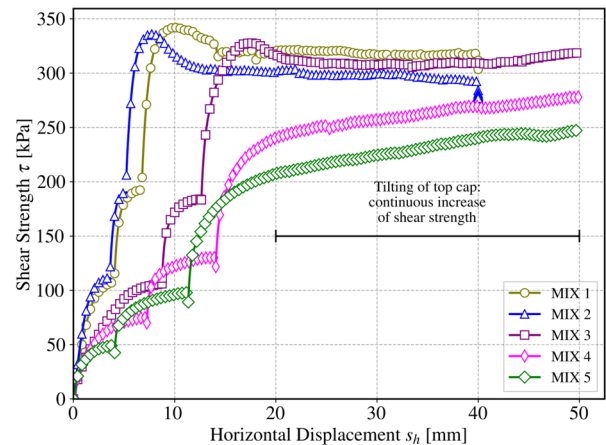


Figure 7. Shear stress vs. horizontal displacement curves for all five mixtures tested using the MSA method.

3.2.2 Behaviour in representative mixtures

The testing method is particularly evident when comparing the shear stress evolution across methods for each mixture. For transitional mixtures such as MIX 3, the MSB method results in higher shear strength values and shows a tendency towards progressive hardening with each loading–reloading phase. In

contrast, the curves obtained with the MSC method align more closely with those from the single-stage reference test. For coarse-dominated mixtures (i.e., MIX 1), however, only minor differences are observed between methods, indicating that the choice of method has little influence on the shear strength in these soils.

To illustrate these trends more clearly, Figure 8 and 9 show the results for MIX 1 under the three MST methods, along with the single-stage (SS) reference (represented by circular markers).

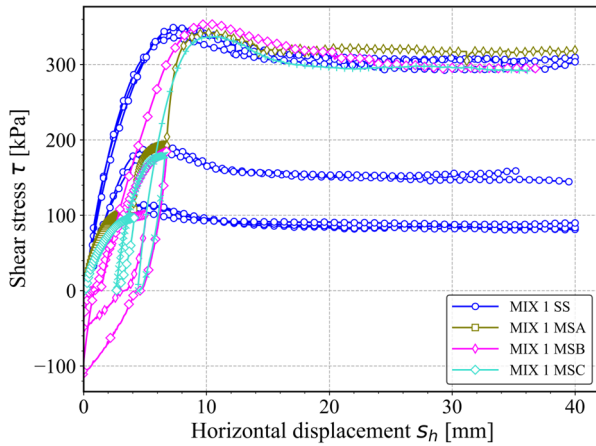


Figure 8. Shear stress vs. horizontal displacement for MIX 1.

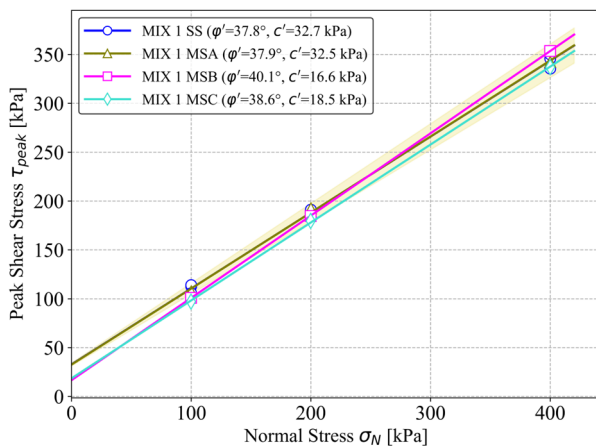


Figure 9. Peak shear strength envelopes for MIX 1.

Figure 8 shows the shear stress-displacement curves, while Figure 9 presents the peak shear strength envelopes, including the derived friction angles and cohesion values. The yellow band illustrates a $\pm 5\%$ deviation from the SS reference envelope, used as a benchmark for evaluating the agreement of multistage results. It is evident that the curves for the coarse-grain dominated mixture MIX 1 exhibit similar responses across the different methods. The MSB method leads to a slightly overestimated peak shear strength due to accumulated shear history across all phases, which results in a slightly higher friction angle (approximately 1.5°) and lower cohesion. MSA, on the other hand, yields consistent values for both friction angle and cohesion, as the constrained displacement does not significantly affect the mobilisation of peak shear strength across phases. Although MSC preserves the internal structure of the specimen and partially releases shear stress, it tends to slightly overestimate the friction angle while underestimating cohesion, compared to the single-stage (SS) reference. All three multistage methods fall within the $\pm 5\%$ deviation band, confirming the reliability of the methods for coarse-grain dominated mixtures.

In the case of the transitional mixture (MIX 3), none of the multistage methods remain within the $\pm 5\%$ deviation range, and the influence of the testing method becomes more pronounced. Figure 10 illustrates the shear stress curves for MIX 3 under the three MST procedures. MSB significantly overestimates the peak shear strength, driven by cumulative hardening over successive phases. This results in a markedly higher friction angle compared to the single-stage reference (Figure 11). In contrast, MSA underpredicts the peak due to displacement constraints and fails to capture the full strength development in later phases. MSC again proves to be the most consistent, producing curves that closely align with the single-stage behaviour in both shape and magnitude. This highlights the sensitivity of transitional mixtures to procedural differences and underscores the importance of selecting an appropriate method.

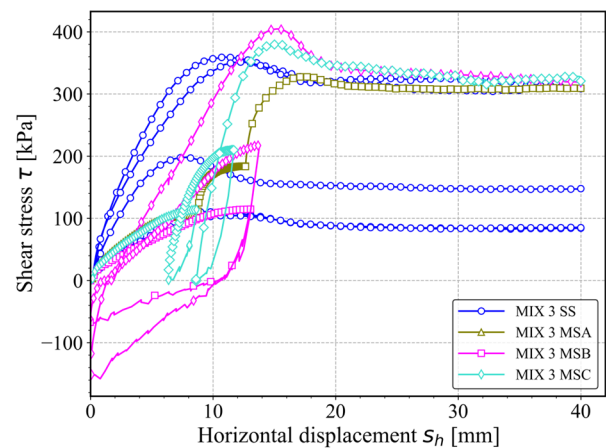


Figure 10. Shear stress vs. horizontal displacement for MIX 3.

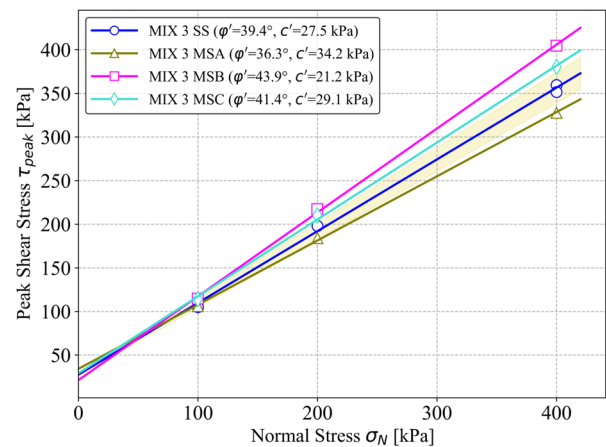


Figure 11. Peak shear strength envelopes for MIX 3.

In fine-grain dominated mixtures, such as MIX 4 and MIX 5, the influence of the testing method is more pronounced. Figure 12 shows the response of MIX 4 across the three methods. The MSB approach leads to a significant overestimation of peak strength, even more so than in the transitional mixture MIX 3. This is reflected in Figure 13, where the friction angle obtained from MSB is considerably higher than that derived from the single-stage test. In contrast, the MSA method yields values very similar to the reference in terms of both friction angle and cohesion. The MSC method behaves similarly to MSA, with both methods providing results within the $\pm 5\%$ deviation band.

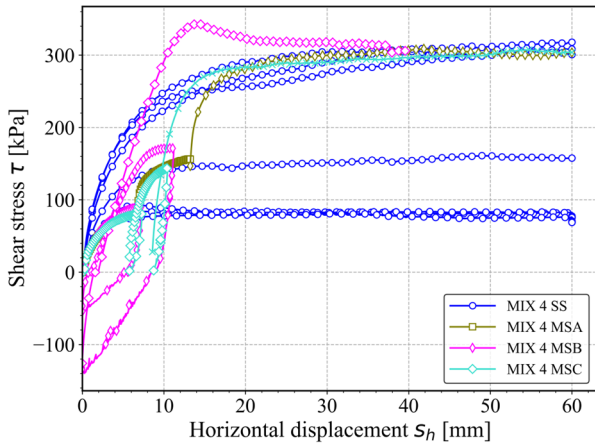


Figure 12. Peak shear strength envelopes for MIX 4.

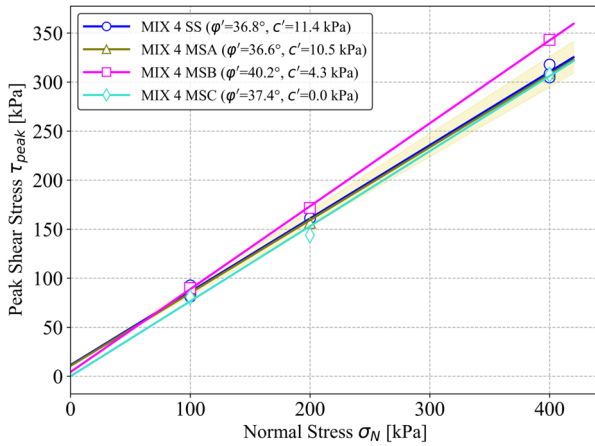


Figure 13. Peak shear strength envelopes for MIX 4.

3.2.3 Comparison across all mixtures

A comparison of the multistage methods across all tested mixtures is presented in Figure 14, which displays the relative deviation of peak shear strength obtained from each method with respect to the corresponding single-stage test. The shaded zone in the plot marks a $\pm 5\%$ range. The comparison is based on the last loading phase of each multistage test, which was performed under a normal stress of 400 kPa, and is directly compared with the single-stage test conducted at the same stress level. The relative deviation is calculated as:

$$RD (\%) = \frac{\bar{\tau}_{p,method} - \bar{\tau}_{p,SS}}{\bar{\tau}_{p,SS}} \cdot 100 \quad (1)$$

where $\bar{\tau}_{p,method}$ is the peak shear stress obtained with the corresponding multistage method, and $\bar{\tau}_{p,SS}$ is the peak value from the equivalent single-stage test.

The results reveal a clear trend: MSA and MSC consistently provide peak shear strength values within or near the $\pm 5\%$ tolerance range across all mixtures. MSB, in contrast, systematically overestimates shear strength, particularly in fine-grain dominated mixtures such as MIX 4 and MIX 5, where deviations exceed 10% and reach up to 25%. In transitional mixtures like MIX 3, MSB again falls outside the tolerance band, while MSA and MSC remain at its lower and upper boundaries, respectively. For coarse-dominated mixtures such as MIX 1, all methods perform similarly and remain within the acceptable range. Overall, MSA shows the highest consistency, followed closely by MSC, whereas MSB may be suitable for coarser soils but proves unreliable for materials with higher fines content.

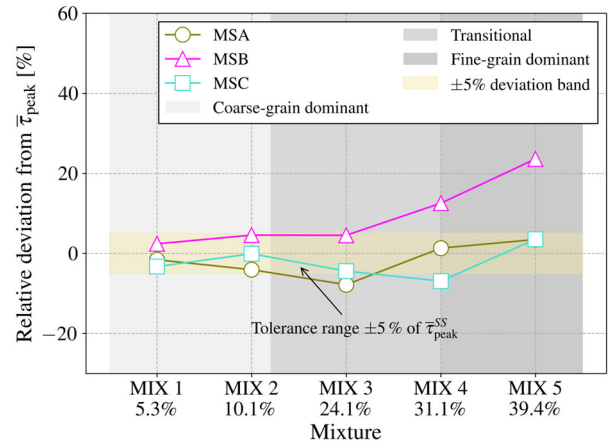


Figure 14. Relative deviation of peak shear strength obtained from multistage methods compared to the single-stage tests.

3.3 Comparison of shear strength parameters

Beyond peak shear strength, a comparison of the derived shear strength parameters, friction angle (ϕ') and cohesion (c') offers further insights into the suitability of each multistage method. Figures 15 and 16 present the values of ϕ' and c' , respectively, for all mixtures and methods, in direct comparison with the average values from the single-stage (SS) reference.

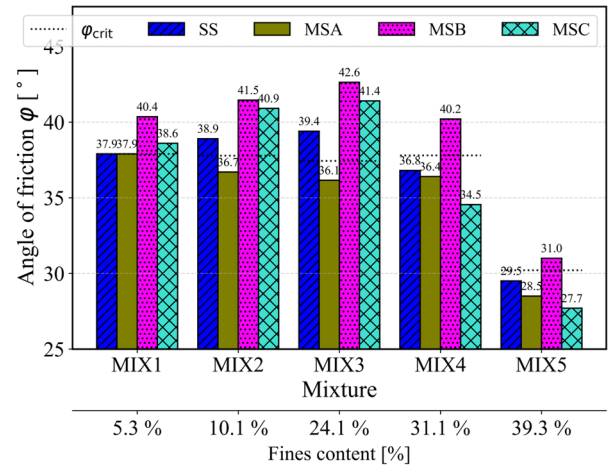


Figure 15. Comparison of the angle of friction ϕ' obtained from single-stage (SS) and multistage methods.

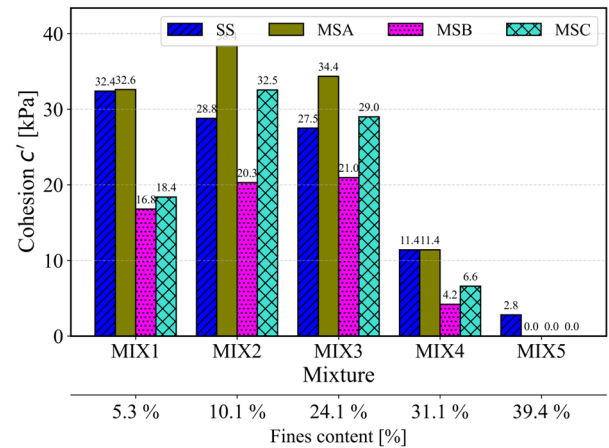


Figure 16. Comparison of the cohesion c' obtained from single-stage (SS) and multistage methods.

Figure 15 shows that the MSA method underestimates the angle of friction across all mixtures, with the largest deviations

observed in MIX 2 and MIX 3, transitional mixtures that, despite their fines content, still exhibit pronounced dilative behaviour in dense state. In contrast, MSB consistently results significantly higher values of angle of friction, particularly in the transitional mixture (MIX 3) and the fine-grain dominated mixtures (MIX 4 and MIX 5). This suggests that the MSB method is not well suited for mixtures with high fines content. For fine-dominated soils, the MSA method appears to be more appropriate. The MSC method does not show a clear trend: it tends to overestimate the friction angle in coarse-grain and transitional mixtures but underestimates it in fine-grain dominated soils. Figure 16 shows that the cohesion values derived from the multistage methods differ more markedly than the friction angles. MSA performs well in granular soils (MIX 1). However, for MIX 2 and MIX 3, which contain higher fines contents, the cohesion obtained with MSA exceeds that of the SS reference by approximately 10 kPa. This overestimation is no longer present in fine-grain dominated soils, where MSA delivers cohesion values comparable to SS. The MSB method, which consistently yields higher friction angles, results in lower cohesion values across all mixtures. The MSC method produces cohesion values similar to SS in MIX 2 and MIX 3, while slightly underestimating cohesion in MIX 1 and MIX 4. Overall, MSC appears to be better suited for transitional mixtures, providing reasonable estimates for both friction angle and cohesion.

3.4 Practical Implications and advantages of multistage testing

From a practical laboratory perspective, multistage testing reduces technical effort and material demand because only one specimen is required. In large-scale equipment (30 × 30 × 20 cm), a single direct shear test typically needs at least 25 kg of soil. Performing three single-stage tests therefore requires around 75 kg, together with the associated sampling, transport and preparation work. When an appropriate procedure is selected, the multistage methods reproduce the single-stage shear parameters within the accepted ±5 % tolerance, indicating that the loss in accuracy is minor. Economically, MST is advantageous whenever material availability or laboratory time is limited. A building-site assessor would consider MST particularly when project constraints make it impractical, expensive or unnecessary to provide several large specimens for individual single-stage tests, as comparable results can be obtained from a single sample.

4 CONCLUSIONS

This study evaluated the applicability of different multistage direct shear methods (MSA, MSB, MSC) for determining the peak shear strength and shear parameters of densely packed mixed-grain soils. Five ternary mixtures with varying fines content (5.3 % to 39.4 %) were tested using single-stage (SS) and multistage (MST) methods.

The results demonstrate that the suitability of a given multistage method strongly depends on the grain-size composition of the mixture, specifically in soils compacted to a dense state. In coarse-grain dominated soils, all methods provided results comparable to SS, although MSC showed slight underestimation in peak strength. In transitional and fine-grain dominated mixtures, however, the differences between methods became more pronounced. All three multistage methods demonstrated good reproducibility across replicates, confirming the consistency of the applied experimental procedures. The relative deviation analysis revealed that MSB systematically overestimated peak shear strength, particularly in fine-grain dominated soils, which, despite being tested in a densely compacted state, still exhibit contractive behaviour. For

these soils, MSB is especially unsuitable and therefore falls outside the ±5 % tolerance range. MSA remained within acceptable limits for most mixtures, except for the transitional mixture (MIX 3), which shows the highest compaction level, the lowest porosity at $D_c \approx 100\%$, and the most pronounced dilative behavior.

When analysing the shear strength parameters, MSA slightly underestimated friction angles, particularly in transitional mixtures, but delivered reliable cohesion values except for overestimation in MIX 2 and MIX 3. MSC delivered balanced results in transitional soils, while MSB exhibited an inverse pattern, producing high friction angles and low cohesion across all mixtures. Overall, MSC is recommended for general use because it provides a conservative approximation of the shear parameters ϕ' and c' as determined in single-stage tests. Regardless of this, MSA provides reliable peak strength parameters without resetting the horizontal displacement between the different shear phases, particularly for coarse-grain dominated materials as well as for fine-grain dominated soils that exhibit contractive behaviour. MSC is particularly well suited for densely packed transitional mixtures. MSB, although not generally necessary, may be considered for coarse-grain dominated soils when shear displacement is limited, as its reset procedure allows additional shear displacement in each stage. However, its applicability should be restricted to materials that do not exhibit significant particle crushing, since repeated loading-unloading cycles may enhance abrasion effects, which could influence the mobilization of shear strength. Furthermore, MSB should be avoided in fine-grain dominated soils, where it tends to strongly overestimate friction and underestimate cohesion.

These findings support the development of decision frameworks based on fines content and expected soil behaviour, confirming that the optimal multistage shear method is governed by the dominant grain fraction, an aspect that can be reliably predicted using the RSCS model. Future work will address how stiffness during consolidation and saturation at the end of the test influence the results.

5 ACKNOWLEDGEMENTS

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