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Mechanisms at the origin of size effects in coarse soils and rockfills

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ABSTRACT: The reliability of small-scaling techniques for coarse soils and rockfill materials have remained a subject of great interest in geotechnical research and practice. However, researchers have often reported contradictory experimental trends of size effects on mechanical behavior. This paper summarizes extensive research conducted by the authors aimed at elucidating the mechanisms underlying size effects in coarse granular materials. Based on comprehensive large-scale drained triaxial compression laboratory tests, the effects of several factors are systematically studied: material intrinsic parameters (grading, particle shape and particle crushing strength), specimen characteristics (sample size, representative element volume) and testing boundary conditions. The analyses identify the sources of size effects in small-scale triaxial specimens, aiming to clarify the limitations of small-scale testing techniques. This understanding is essential to prevent optimistic estimates of soil properties, ensuring safe and reliable geotechnical designs of large structures such as rockfill dams, railway ballast platforms, and mine waste rock piles.

KEYWORDS: coarse soils, rockfills, small-scaling, size effects, particle crushing, grain shape, shear strength.

1. INTRODUCTION

The mechanical characterization of coarse-grained materials (CGMs) has always been a subject of great interest in the geotechnical community (Holtz and Gibbs, 1957; Marsal, 1967; Leps, 1970; Barton and Kjærnsli, 1981; Indraratna et al., 1998; Varadarajan et al., 2003; Bard et al., 2012; Ovalle et al., 2014, 2020). To ensure the construction of reliable geotechnical structures, accurate mechanical characterization of CGM is essential. However, CGMs contain oversized particles that exceed the capacity of conventional laboratory testing devices, including the largest triaxial equipment ever reported (Leussink, 1960; Marsal, 1967; Marachi et al., 1972; Verdugo and de la Hoz, 2007; Hu et al., 2011; Ning et al., 2025). This constraint requires the use of small-scaling techniques by reducing the maximum particle size (d_{max}). If the available testing device can handle a coarsest particle of size $d_{max\text{-}lab}$, the maximum size in the field ($d_{max\text{-}field}$) is reduced by the scaling factor $F = d_{max\text{-}field} / d_{max\text{-}lab}$. For a given specimen size, $d_{max\text{-}lab}$ is defined by testing standards (i.e. ASTMD7181), which requires a minimum aspect ratio $\alpha = D/d_{max\text{-}lab} = 6$ to guarantee a representative element volume (REV), where D is the diameter of the cylindrical triaxial specimen.

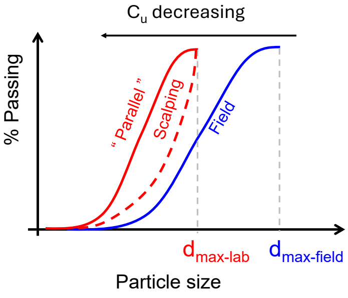


Figure 1. PSD small scaling techniques.

As shown in Figure 1, a small-scale particle size distribution (PSD) is generated through grading techniques, such as scalping and parallel grading, among others. It is important to note that small-scale materials always become more uniformly graded than the field sample. Indeed, when employing "parallel" grading, fines are not added to the finer fraction of the scaled sample to enforce parallelism, thus the coefficient of uniformity ($C_u = d_{60}/d_{10}$) reduces. Nevertheless, it is well established that the critical friction angle is not sensitive to the PSD, provided that the characteristic particle shape, surface roughness and mineralogy remain consistent across grain size fractions (Yang and Luo, 2019; Polanía et al., 2023). Accordingly, if these intrinsic properties are confirmed to remain unchanged during the scaling process, the critical strength of the field material could be reliably captured in small-scale specimens.

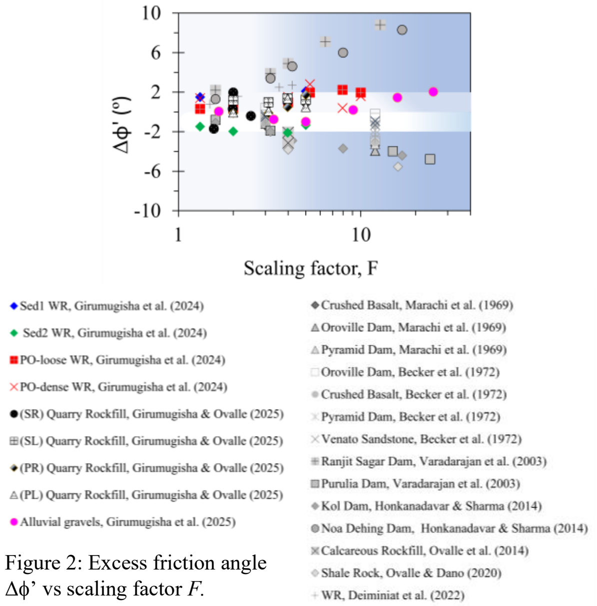


Figure 2: Excess friction angle Δϕ' vs scaling factor *F.*

Figure 2 presents an extensive compilation of data produced by the authors and recovered from literature, where drained triaxial compression tests were carried out at different F on cylindrical specimens of diverse $d_{max\text{-}lab}$, from 10 to 200 mm, and D from 70 to 1000 mm. For a given material tested at different scales (i.e., different d_{max} and D) but equivalent state conditions, the internal friction angle (ϕ') is compared with that of the coarsest specimen in its set. Then, the excess of ϕ' is obtained as $\Delta\phi' = \phi'_{coarsest} - \phi'$, and plotted against F in Figure 2 (note that the coarsest specimen in a set has $F=1 \Rightarrow \Delta\phi'=0$). The results indicate that low values of F are associated with relatively low $\Delta\phi'$, typically within a margin of ±2°. However, as F increases, the scatter in ϕ' becomes more pronounced, suggesting that the mechanical response of CGMs is increasingly compromised in small-scale specimens when F exceeds approximately 3. In practice, however, this threshold is difficult to achieve. Field-scale CGMs can easily reach $d_{max\text{-}field}$ ~1 m, making it impossible to test scaled specimens with $F \leq 3$. Moreover, size effects do not always follow a unique trend, as $\Delta\phi'$ displays both positive and negative values for different materials. Therefore, a small-scale specimen could give either conservative or optimistic values of ϕ'.

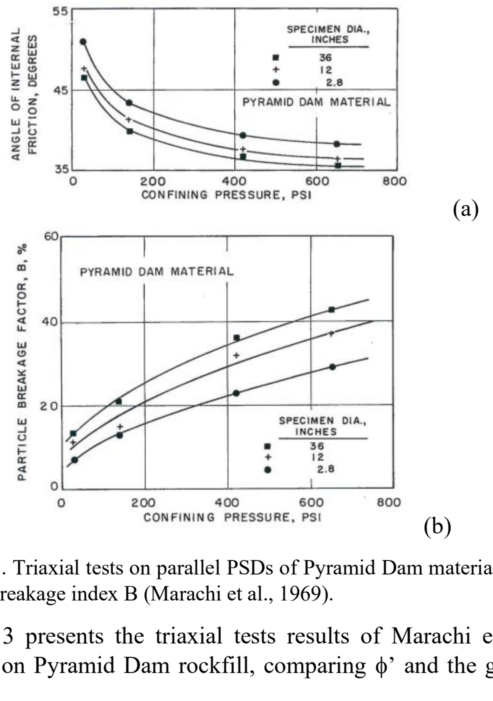
Size effects can also manifest as variations in material stiffness, stress–strain dilatancy and shear strength (Marachi et al., 1972; Verdugo and de la Hoz, 2007; Hu et al., 2011; Ovalle et al., 2020; Girumugisha et al., 2026), primarily due to changes in the intrinsic properties of the original material. Extensive research has indicated that such variations are primarily due to the coupled effects of several factors, including intrinsic material properties, state conditions, and testing configurations (Ovalle, 2013; Osses et al., 2023; Girumugisha, 2025), as discussed in this paper.

The main objective of this study is to identify the sources of size effects in coarse soils and rockfills. The paper is based mainly on a comprehensive dataset of approximately 200 laboratory tests conducted by the authors in recent years, as well as selected data from literature. The experiments include drained triaxial compression using cells that accommodate specimens with height-to-diameter (H/D in mm) ratios of 110/70, 100/100, 150/150, 300/150, 375/250, 600/300, 800/800, 1500/1000 and 2000/1000, allowing to cover the wide range of the scaling factors F shown in Figure 2.

2. SOURCES OF SIZE EFFECTS

2.1. *Effects of particle crushing*

Fracture in brittle solids, such as rock aggregates and cobbles, occurs through the propagation of existing cracks within the material. As the probability of finding these cracks increases with the specimen size, a size effect arises: the larger the volume of the particle, the lower its fracture strength. This effect promotes higher amount of particle crushing in coarser granular materials. With increasing grain crushing, the material becomes less dilatant and the peak shear strength decreases (Frossard et al., 2013; Ovalle et al., 2014).



(a)

(b)

Figure 3. Triaxial tests on parallel PSDs of Pyramid Dam material: (a) ϕ'; (b) breakage index B (Marachi et al., 1969).

Figure 3 presents the triaxial tests results of Marachi et al. (1969) on Pyramid Dam rockfill, comparing ϕ' and the grain breakage index B (as defined by Marsal, 1967) of specimens having diverse d_{max}=0.5 to 6 in. (d_{max}=70 to 914 mm) and parallel PSDs. Respectively, the specimens tested had D=2.8 to 36 in. (D=70 to 914 mm), and the aspect ratio was α~6 for all cases. Visibly, the coarser the material, the lower ϕ' (Figure 3a) and the higher B (Figure 3b), which is consistent with size effects on fragmentation strength at the grain scale.

Figure 4 shows the results on a shale rockfill reported by Ovalle and Dano (2020). Three samples with d_{max}=10, 40 and 160 mm (STV0, STV1 and STV2 in Figure 4a) were tested in triaxial specimens of D=70, 250 and 1000 mm, respectively, all with α~6, C_u=5 and parallel PSDs. Figure 4b shows the point load test strength index (I_S) of the rock particles, exhibiting a marked size effect on grain crushing strength. As expected, the results of the drained triaxial tests exhibited size effects due to grain crushing: as size increases, ϕ' decreases (Figure 4c) and B increases (Figure 4d).

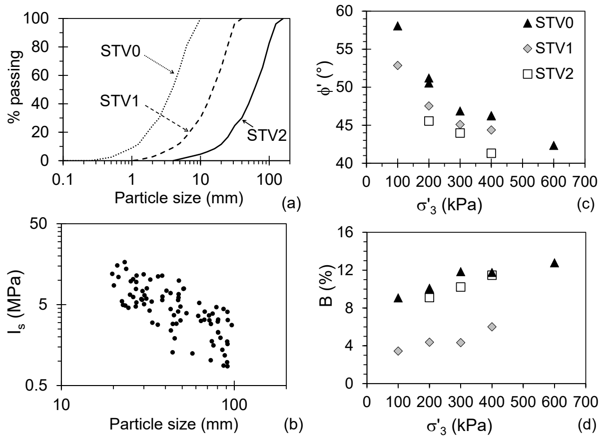


Figure 4. Triaxial tests results on STV material: (a) PSDs; (b) grain crushing strength I_S; (c) ϕ'; (d) B (Ovalle and Dano, 2020).

To account for size effects due to grain crushing, theoretical scaling laws have been proposed in the literature, such as the pioneering study of Frossard et al. (2011). These works link the grain crushing strength and its dependence to size to the shear strength envelope (Frossard et al., 2011; Ovalle et al., 2014) or the plastic work upon compression and shearing (Yin et al., 2017).

2.2. *Grain size-shape correlations*

In many rockfills, particle size and shape are correlated, with finer fractions often exhibiting more elongated shapes than coarser ones, or vice versa (Linero et al., 2017). As a result, grading-based scaling techniques may produce small-scale specimens with characteristic grain shapes that differ from those of the original coarse material. Given the strong influence of particle shape on the stress–strain behavior of granular soils (Cavarretta et al., 2010), these variations might affect the representativeness of small-scale samples (Linero et al., 2019; Carrasco et al., 2023). For instance, Figure 5a shows the evolution of the grain aspect ratio (c/a, where c and a are the shortest and largest dimensions of a grain, respectively) across different grain sizes of the shale rockfill materials shown in Figure 4a: STV0, STV1 and STV2. As c/a decreases in finer size fractions, the grains become more elongated and scattering in the shape descriptor increases. Figure 5b presents the average c/a values (in black), together with the retained PSDs (in red) of three samples at different size scales. Clearly, the finer material STV0 has more elongated particles than the coarser STV2. This observation, together with size effects on crushing strength shown in Figure 4d, might be the source of the strong size effects in shear strength presented in Figure 4c, where STV0 is consistently more resistant than STV1 and STV2.

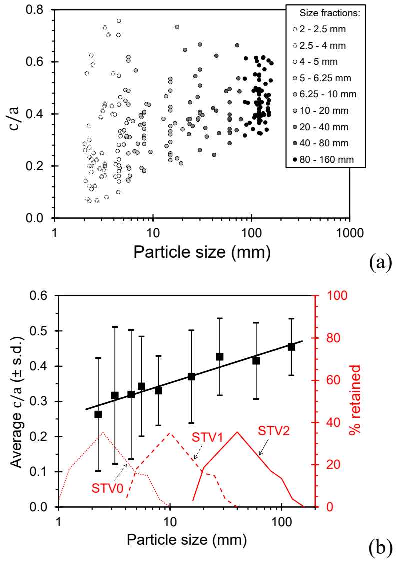
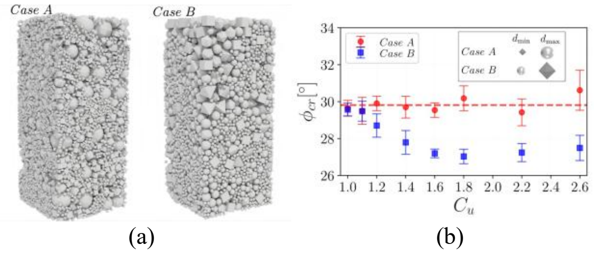


Figure 5. Particle size-shape correlation of STV rockfill: (a) c/a ; (b) average c/a vs retained PSDs (Ovalle and Dano, 2020).

To validate the effect of grain size-shape correlations, Carrasco et al. (2025) carried out numerical 3D Discrete Element Method (DEM) simple shearing simulations on granular samples with varied PSDs (C_u from 1 to 2.6) and particle shape distributions, where grain sizes and shapes can be precisely controlled to isolate their effects. As shown in Figure 6a, two cases were compared: Case A with rounded coarser grains and angular fines; Case B with angular coarser grains and rounded fines. Therefore, for a given PSD, the same grain shapes are present in Cases A and B, but their distributions across grain sizes differ. As shown in Figure 6b, critical ϕ' is highly sensitive to variations in grain shape distribution, even when the PSD is held constant. This observation is analogous to the grain shape effects observed in small-scale specimens, where grading alterations may inadvertently modify the characteristic grain shape. Consequently, to ensure the representativeness of small-scale samples, the distribution of particle shapes across grain sizes should always be verified.



(a) (b)

Figure 6. Particle size-shape correlation in DEM numerical tests (Carrasco et al., 2025).

2.3. *Effects of specimen aspect ratio α=D/dmax*

With the aim of testing the coarsest material possible, most of the authors reporting data on coarse granular materials have used a minimum α ≈ 6, in accordance with international standards from USA (ASTM D7181), Germany (DIN 18137), United Kingdom (BS 1377) and Japan (JGS 0530). However, several studies have demonstrated that this value results in low repeatability of test results, thus a REV cannot be ensured with such a low α (Amirpour Harehdasht et al., 2019; Cerato et al., 2006; Deiminiat et al., 2022; Quiroz-Rojo et al., 2024).

To assess the effects of α on coarse materials, Girumugisha et al. (2024) reported a comprehensive experimental program in mine waste rock, varying α through with specimen sizes D=150 and 300 mm, and d_{max}=5 to 50 mm. The PSDs of the three materials tested (Sed1, Sed2 and PO) are shown in Figure 7. Figure 8 exhibits the critical shear strength for 57 drained triaxial tests performed by Girumugisha et al. (2024), on specimens with α varying between 4 and 30, where ϕ' values are normalized by the corresponding friction angle at α=12, and the same confining pressure. The results confirm that the critical ϕ' remains unchanged with different gradings. Despite international testing standards recommendations, the results from this extensive dataset indicate that stable results are only consistently achieved for α ≥ 12.

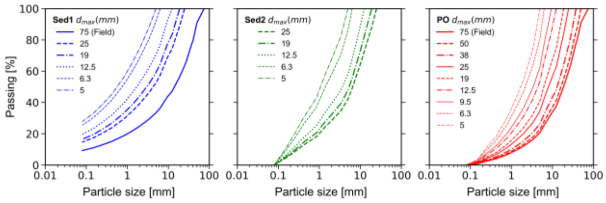


Figure 7. PSDs used by Girumugisha et al. (2024).

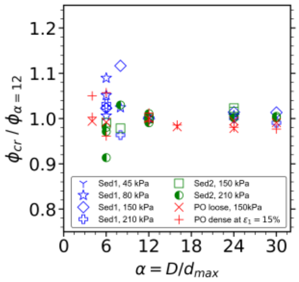


Figure 8. Effect of α on the normalized ϕ' (Girumugisha et al., 2024).

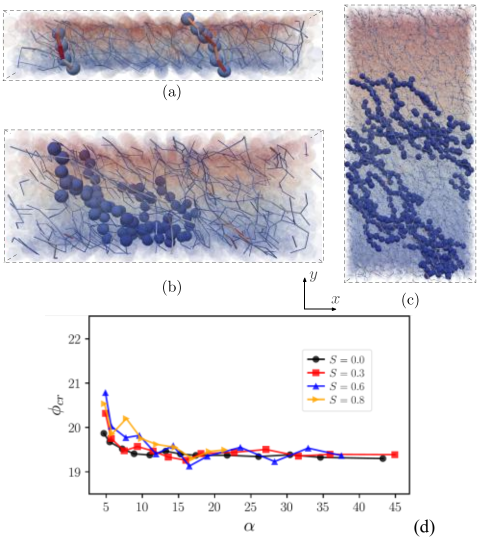


Figure 9. Screenshot of numerical DEM specimens with (a) α=5, (b) α=20, and (c) α=43, highlighting in dark blue the local rigid structures during shearing. (d) Evolution of ϕ' vs α; S is the PSD in numerical samples: S=(d_{max}-d_{min})/(d_{max}+d_{min}) (Cantor and Ovalle, 2025).

The strong effect at low α values has been further supported by DEM numerical tests carried out by Cantor and Ovalle (2025), which carried out numerical simple shear tests on specimens having α from 5 to 43. Micromechanical analyses of their DEM simulations reveal significant stress heterogeneity at low values of α. The study identifies the formation of column-like structures within the samples, which carry a substantial portion of the external load. At low α (Figure 9a and b), these structures can span the specimen height, forming continuous force chains that connect the specimens' boundaries. In contrast, when the specimen is sufficiently large (Figure 9c), such columns no longer bridge the boundaries, leading to reduced stress concentration at the walls and stable results of the shear strength, as shown in Figure 9d for $\alpha \geq 12$. The results pf Cantor and Ovalle (2025) also confirm that the critical ϕ' is not sensitive to the PSD.

Despite the significant differences in the materials studies in the laboratory tests of Girumugisha et al. (2024) and the numerical test of Cantor and Ovalle (2025), both studies identify that $\alpha < 12$ does not ensure a REV; similar observations were reported by Quiroz-Rojo et al. (2024) on triaxial shearing using DEM.

2.4. *End restraint effects*

Studies have shown that drained triaxial compression in CGMs can be influenced by the top and bottom rough platens, which might restrict free dilation of the soil specimens (Bishop and Green, 1965; Al-Hussaini, 1970). These kinematic constraints compromise test reproducibility as heterogeneous strain fields and shear strain localization are prevalent. Several practices to mitigate these artefacts include the utilization of large specimen slenderness values given by a height-to-diameter ratio H:D ≥ 2 (Taylor, 1941; Mozaffari et al. 2022), and/or end lubrication to allow for free dilation during shearing (Rowe and Barden, 1964; Duncan and Dunlop, 1968; Hettler and Vardoulakis, 1984; Wightman et al., 2024).

While most testing standards have been developed based on data from fine-grained soils and sands, experimental evidence of end restraint effect on coarse soils remains limited. Given that coarse, angular soils typically exhibit high $\phi' \sim 40^\circ$ or greater (Marsal, 1967; Marachi et al., 1969; Leps 1970; Ovalle et al., 2020), it is reasonable to assume that frictional interactions at the specimen boundaries may exert a significant influence on the material response.

Girumugisha (2025) carried out drained triaxial compression tests on rockfill specimens of H=300 mm and D=150 mm, at confining stresses of 100 and 400 kPa, comparing the results with standard rough platens and enlarged lubricated platens. They used small-scale samples from a rockfill material having $d_{max\text{-}field}$=90 mm, prepared by scalping and parallel grading, as shown in Figure 10a and 10b, respectively. Figure 11 presents typical stress-strain curves for materials with d_{max}=12.5 mm, tested with rough (R) and lubricated platens (L). The first letter in the legend indicates the scaling method (Scalping or Parallel), the second letter designates the end platen configuration (R or L), and the number is the confining stress in kPa. It can be observed that tests with standard rough ends overestimate the shear strength and dilation, indicating that end restrain effects in H:D=2 rockfill specimens are not negligeable.

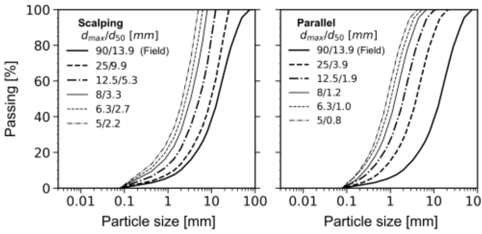
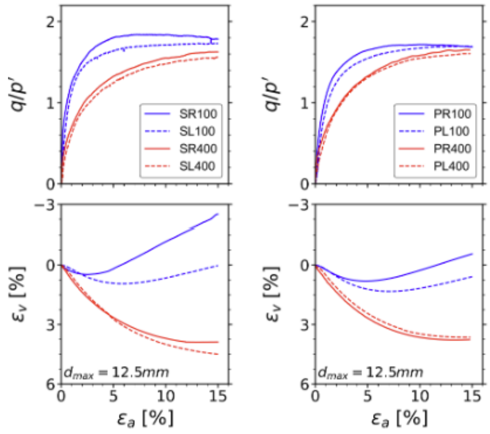


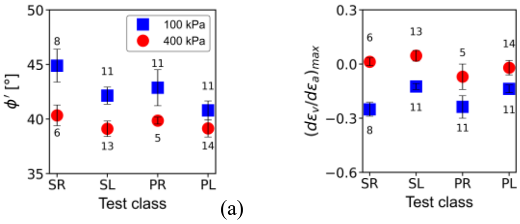
Figure 10. PSDs used by Girumugisha (2025): (a) scalping and (b) parallel grading.



(a) (b)

Figure 11. Stress-strain curves of tests with standard rough (continuous lines) and lubricated ends (dashed lines) at 100 (blue) and 400 kPa (red), respectively: (a) scalped PSDs; (b) parallel PSDs (Girumugisha, 2025).

The results of Girumugisha (2025) are summarized in Figure 12, depicting the average results from 79 tests conducted under varying grading conditions (S and P), end configurations (R and L), and confining pressures (100 and 400 kPa). Specimens with rough ends consistently exhibit higher mean values of ϕ'. The difference in ϕ' between 100 and 400 kPa is notably reduced in PL tests, suggesting that both lubrication and better grading contribute to more stable results. Concerning the maximum dilatancy rate $(d\varepsilon_v/d\varepsilon_a)_{max}$, end friction effects are evident primarily at 100 kPa.



(a) (b)

Figure 12. Mean values and standard deviations from 79 tests (Girumugisha, 2025): (a) ϕ', (b) $(de_v/de_a)_{max}$; bars are the standard deviations and numbers indicate the number of tests.

The high shear strength of rockfill materials is largely attributed to the kinematic constraints arising from interlocking among highly angular grains. In coarse, angular materials, these constraints may be further amplified by end restraint, potentially leading to an overestimation of their contribution to stress–dilatancy behavior. Such mechanisms may account for the pronounced end restraint effects frequently observed in rockfill specimens, particularly those with an aspect ratio of H:D=2, where these effects are generally negligible in fine-grained soils and sands.

2.5. *Effects of grading*

As discussed previously, small scaling alters the PSD, resulting in more uniform gradations in small-scale samples (Figure 1). This shift affects the packing conditions. Upon shearing, small-scale specimens undergo increased grain rearrangement, resulting in enhanced dilatancy. Consequently, small-scale samples often display a more optimistic dilative response compared to well-graded, field-scale materials (Girumugisha et al. 2026). This effect does not arise from particle size, but from grading, and has been comprehensively studied in sands (Ahmed et al., 2023; Basson et al., 2024).

Recent experimental work by Girumugisha et al. (2026) illustrates the effects of small-scaling and grading on the stress-strain behavior of coarse alluvial gravel. The scaled PSDs and photos of the particles are presented in Figure 13. Drained triaxial tests were performed under σ_3'=100 and 600 kPa, on specimens with distinct sizes D=100, 150 and 800 mm, all with a slenderness ratio H:D=1 and lubricated ends.

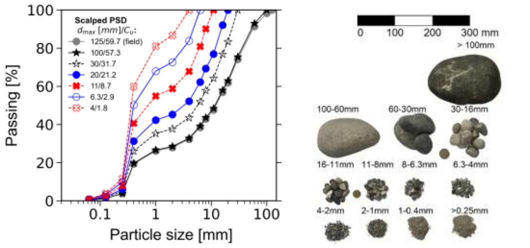


Figure 13. PSDs of coarse and small-scaled alluvial gravels; colors denote different specimen sizes (modified from Girumugisha et al., 2026).

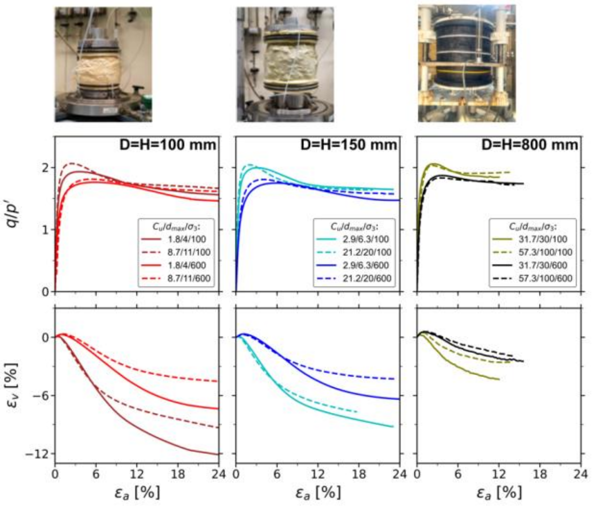


Figure 14. Stress-strain curves of coarse and small-scaled alluvial gravel, tested using three distinct specimen sizes, σ_3' and C_u (modified from Girumugisha et al., 2026).

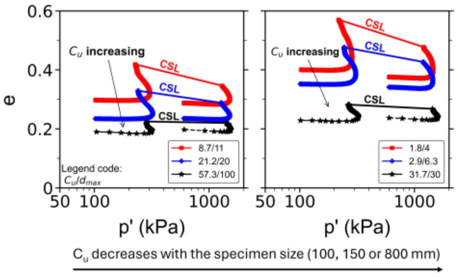


Figure 15. Grading effects on critical state line in coarse and small-scaled alluvial gravels (modified from Girumugisha et al., 2026).

The resulting stress-strain responses are presented in Figure 14, organized from left to right according to increasing specimen size. For each size and σ_3'; two distinct C_u values are examined for each specimen size D. All tests in Figure 14 exhibited a peak strength followed by limited strain softening at large strains. Within a given specimen size, better graded samples (i.e., higher C_u, shown with dashed lines) demonstrated similar higher peak stress ratios (q/p'; $q = \sigma_1' - \sigma_3'$ and $p' = (\sigma_1' + 2\sigma_3')/3$), but lower volumetric dilatancy. For better visualization, Figure 15 presents the estimated critical state lines (CSL) in the $e - p'$ space, where e is the void ratio. Decreasing C_u causes the CSL to shift upward to higher e values, indicating looser packing in small-scale specimens. In contrast, better graded materials achieve denser initial packing, as finer particles effectively fill the voids between coarser particles, leading to lower e values at critical state.

3. CONCLUSIONS

Based on comprehensive studies of triaxial small-scaling in coarse granular materials, the following conclusions and recommendations for practitioners are provided:

- Since generating small-scale samples of a coarse granular soil implies altering its particle size distribution, it is mandatory to characterize the reference densities at each scale to compare the stress-strain behavior under equivalent relative density (i.e. state) conditions.
- In general, small-scale specimens exhibit lower amount of particle crushing than the original coarser material, resulting in lower compressibility and higher peak strength in finer samples. This size effect on crushing could lead to optimistic mechanical parameters for design, which can be addressed using existing theoretical solutions.
- It is crucial to measure the characteristic grain shapes across all grain sizes involved in scaled granular samples. If grain shapes strongly differs throughout different size fractions, the reliability of small-scaling techniques might be questionable.
- The minimum specimen aspect ratio $\alpha = D/d_{max} \geq 6$ recommended by worldwide standards does not consistently ensure a REV with reliable testing repeatability. Recent research recommends $\alpha \geq 12$, however, further comprehensive testing is needed to validate these results and potentially revise widely used standards.
- End platen lubrication should be systematically applied in triaxial tests on coarse rockfills, even in H:D = 2:1 specimens, where end restraint effects are typically negligible in fine-grained soils and sands.
- Due to grading effects, small-scale specimens at equivalent relative densities exhibit higher dilatancy and critical state void ratio than the original coarse soil. However, provided that the characteristic particle shape remains unchanged over all size fractions, small-scale specimens provide a reliable basis for assessing shear strength at critical state.

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