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Effects of small scaling on the stress dilatancy response of coarse gravel soil

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ABSTRACT
Stress strain behavior of oversized soils is usually assessed after tests on small-scale specimens, where grading is altered due to size restrictions imposed by the available testing devices. It is well known that particle size distribution (PSD) has a strong effect on the mechanical behavior of granular soils, however, most studies reported on this topic are related to sands. This study presents an experimental study of triaxial shearing on coarse soil at different size specimen scales. The scope is to evaluate the impact of small scaling through scalping grading on the stress strain behavior of coarse alluvial gravels. Conventional triaxial compression tests were performed on specimens of 100, 150 and 800 mm in diameter. Grading and size effects are presented and discussed. The results show that dilatancy strongly increases when reducing the specimen size, and the critical state line shifts to higher void ratios. This outcome is due to PSD and packing properties, because small scale specimens are more uniformly graded than coarser ones. The paper addresses the implications of small scaling in gravelly materials.

RÉSUMÉ
Dans la pratique, la caractérisation mécanique des matériaux graveleux est généralement réalisée sur des éprouvettes de petite taille, dans lesquels la dimension maximale des particules est réduite afin de permettre leur mise en place dans les appareils d'essai standard. Cette adaptation implique une modification de la granulométrie initiale, dont l'influence sur le comportement contrainte-déformation est bien connue. Toutefois, la majorité des études sur les effets de la granulométrie ont été menées après des essais sur des sables, et l'impact de la réduction d'échelle sur les sols graveleux reste encore marginalement compris. Cet article présente une étude expérimentale sur la réponse au cisaillement d'un sol grossier à différentes échelles d'éprouvettes. L'objectif principal est d'évaluer l'influence des méthodes de réduction d'échelle sur le comportement en déformation des sols grossiers. La technique de granulométrie tronquées a été utilisée pour préparer les éprouvettes. Des essais triaxiaux ont été réalisés à l'aide de cellules standards et de très grande taille, capables d'accommoder des éprouvettes de 100, 150 et 800 mm de diamètre. Les effets de la granulométrie et de la taille des éprouvettes sont présentés et discutés. Les analyses montrent que la dilatance diminue fortement avec la taille de l'éprouvette, tandis que la ligne d'état critique se déplace vers des indices des vides plus denses. Ces différences sont principalement liées à la granulométrie et aux propriétés de compacité —les éprouvettes réduites étant plus uniformément granulés que celles de grande taille. L'article présente des perspectives pratiques sur les effets liés à la réduction d'échelle et de leurs implications pour la caractérisation des matériaux graveleux.

1 INTRODUCTION

Assessing the material mechanical behavior is crucial to any geotechnical engineering design involving coarse granular materials. However, the oversized particles contained in such materials are challenging or impossible to handle, even when utilizing the largest triaxial (Brauns and Reith, 2000; Marachi et al., 1972; Marsal, 1967; Ning et al., 2024; Ovalle et al., 2014; Verdugo and de la Hoz, 2007) or direct shear (Barton and Kjærnsli, 1981; Girumugisha et al., 2024; Linero et al., 2020; Matsuoka et al., 2001) devices reported.

Commonly, practitioners use small-scale specimens prepared through grading scaling methodologies. The particle size distribution (PSD) is altered by removing the coarse fraction having a characteristic size $d > d_{max}$ (where d_{max} is the size of the coarsest particle), based on the minimum specimen aspect ratio defined as the characteristic specimen size to d_{max} (Quiroz-Rojo et al., 2024). In scalping, the most common small-scaling method, all the material presenting $d \leq d_{max}$ is sieved to generate a new PSD (Deiminiat and Li, 2022; Ovalle et al., 2023; Zeller and Wullimann, 1957). Thus, the coefficient of uniformity ($C_u = d_{60}/d_{10}$) of the small-scale specimen decreases. However, uncertainties persist regarding the reliability of scaling methods in capturing the behavior of oversized materials (Cantor and Ovalle, 2023; Deiminiat et al., 2022).

It is widely reported that the PSD impacts the stress-strain behavior of granular soils. Along shearing under given state conditions, uniformly graded soils exhibit higher volumetric strains than well-graded ones (Ahmed et al., 2023; Manmatharajan et al., 2023; Ning et al., 2020; Yang and Luo, 2018). As the uniformity coefficient increases, fine particles fill the pores in well-graded PSD and the critical state line (CSL) shifts towards lower void ratios in the mean

effective stress space (Biarez and Hicher, 1997; Li et al., 2013; Muir Wood and Maeda, 2008). However, the constraints of small scaling of coarse gravelly soils are often overlooked by practitioners, and the impacts on geotechnical designs are typically neglected or covered by conservative factors of safety.

This paper assesses the impact of small scaling on deformation characteristics of coarse gravelly soil. Monotonic triaxial tests were conducted on dense terrace alluvial gravel specimens generated through scalping grading. The tests were carried out using triaxial devices with diameters of 100, 150, and 800 mm. The discussion addresses practical insights into the effects of small scaling on dilatancy response, and its implications for the characterization of gravel materials.

2 EXPERIMENTAL METHODS

2.1 Alluvial gravels

Nearly 15 tons of terrace alluvial gravel materials were sampled from the field site in Switzerland close to Basel. The field PSD has a d_{max}=125 mm and the following characteristic grading properties: $C_u = 60$ and curvature coefficient $C_c = d_{30}^2/(d_{10} \times d_{60}) = 1.5$, classifying as well graded gravels with sands (GW) (ASTM D2487-17). The characterization also shows a specific gravity G_s=2.67 and particle shapes classifying as subrounded to well-rounded particles.

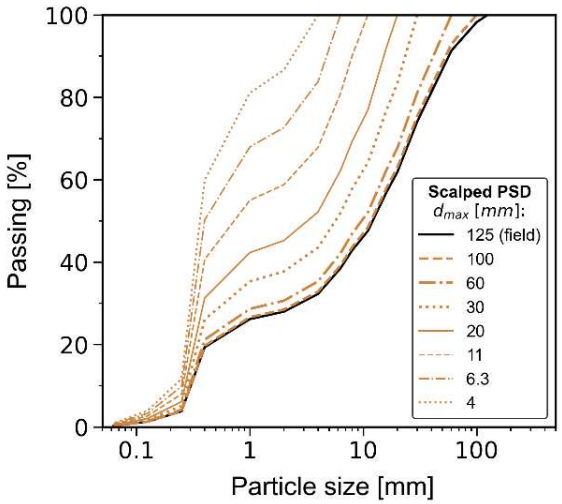


Figure 1. PSDs of the small-scale specimens prepared through scalping.

2.2 Small scaling methodologies

To account for the effects of specimen size and grading on characteristic mechanical properties, the alluvial gravel material was scaled down at d_{max}= 100, 60, 30, 20, 11, 6.3 and 4 mm using scalping grading technique. Grading was set based on the triaxial sample diameter (D), to get a minimum sample aspect ratio D/d_{max} of 8 (ASTM D7181-20, DIN 18126). Three distinct triaxial devices were utilized, accommodating small specimens (S) with D=100 mm, medium specimens (M) with D=150 mm and large specimens (L) with D=800 mm. The prepared specimen PSDs are depicted in Figure 1 and the details of the S, M and L specimens are presented in *Table 1*.

Table 1. Details of the triaxial specimens tested.

Specimen ID	D (mm)	d_{max} (mm)	C_u (-)	e_o (-)	σ_3' (kPa)	e_{cr} (-)
S1	100	4	1.8	0.430	100	0.570
S2		6.3	2.9	0.370	100	0.499
S3		11	8.7	0.322	100	0.419
S4		4	1.8	0.411	600	0.477
S5		6.3	2.9	0.359	600	0.406
S6		11	8.7	0.321	600	0.346
M1	150	6.3	2.9	0.380	100	0.476
M2		11	8.7	0.316	100	0.356
M3		20	21.2	0.258	100	0.329
M4		6.3	2.9	0.376	600	0.427
M5		11	8.7	0.270	600	0.305
M6		20	21.2	0.266	600	0.288
L1	800	30	31.7	0.252	100	0.282
L2		60	49.3	0.233	100	0.244
L3		100	57.3	0.212	100	0.230
L4		30	31.7	0.260	600	0.268
L5		60	49.3	0.218	600	0.232
L6		100	57.3	0.220	600	0.222

2.3 Triaxial testing on S and M specimens.

As shown in *Table 1*, 6 S and 6 M tests were carried out at σ_3' =100 and 600 kPa. All the specimens had a slenderness ratio (height-to-diameter, H:D=1) and comprised lubricated-enlarged caps and bases (see Figure 2a). The tests consisted of consolidated drained triaxial on saturated dense samples. S and M specimens were prepared at a dense state (Index density, $I_D = 90\%$) by mounting six and eight distinct layers of homogeneous dry material, respectively. The compaction was achieved using standard Proctor hammer blows to attain the targeted thickness. Due to the different PSDs, the achieved initial void ratios (e_o) varied between 0.40 to 0.29 in S specimens, and 0.35 to 0.23 in M specimens. The specimens were flushed with CO_2 and water for a minimum of 1-2 hours, after which saturation commenced by gradually raising the back pressure. The Skempton coefficient was $B \geq 0.95$. The Isotropic consolidation stage consisted of maintaining a desired σ_3' until the volumetric strain (ε_v) stabilization. Lastly, the shear stage was performed at constant vertical strain rates of 0.10 and 0.14 mm/min for S and M specimens, respectively, by recording the deviatoric stress $q = \sigma_1' - \sigma_3'$ up to an axial deformation of $\varepsilon_a = 24\%$.

2.4 Triaxial testing for L specimens.

Six (6) L consolidated drained triaxial tests were performed on scalped specimens with σ_3' =100 and 600 kPa. Similarly, the specimens consisted of H:D=1 with lubricated-enlarged platens, as shown in Figure 2b. A 5 mm thick membrane was then installed in the mold. A thin Karlsruhe sand layer was added at the bottom drainage in the center to improve the saturation. 8 distinct homogeneous layers were mounted, each weighing

around ~ 110 kg. The compaction was done for each layer using a vibrating tamper until a thickness of 10 cm was reached. The initial packing of the specimens was between e_o= 0.23 and e_o=0.19 ($I_D \sim 90\%$). A 2 cm thick layer of Karlsruhe sand was added on top of the last layer to level the top surface and minimize asperities. Finally, the top cap was positioned and vacuum (~ 90 kPa) was applied to hold the specimen after mold removal. The initial measurements of the specimen height at three positions were taken, as well as the diameters at the top, middle and bottom levels. Furthermore, 3 circumference bandages (Figure 2c) were added on the top, middle and bottom of the sample, to track radial strain measurements (ε_r). Figure 2c also shows 3 vertical displacement extensometers positioned for ε_a measurements. The final installation step is shown in Figure 2d.

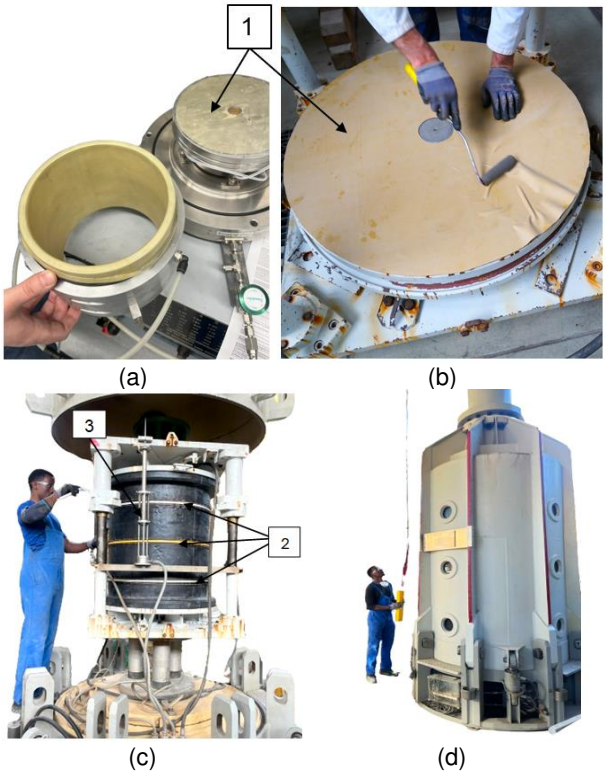


Figure 2. Specimen preparation: (a) S and M specimens showcasing the greased rubber sheet installation for lubrication (1); (b) L specimen (D=800 mm) base platen; (c) circumference bandage and extensometer installation (2 and 3); (d) L specimen ready for testing.

Upon completion, the cell was filled with water and the vacuum was gradually removed, while simultaneously applying a cell pressure of 100 kPa to hold the specimen. The saturation commenced by filling water inside the specimen for 24 hours, from bottom to top using a burette system, until it flew out via a clear vinyl hose. At this point, the "full saturation" was assumed. L specimens were subsequently consolidated at the desired pressure, after which shearing proceeded at a constant rate of 0.4 mm/min. The readings from the circumference bandages were done manually every 5 min, and data were updated in the computer until $\varepsilon_a \sim 15\%$. More details of the experimental set up can be found in Girumugisha et al. (2025).

3 RESULTS AND DISCUSSIONS

Figure 3 illustrates the stress strain response for all the specimens tested, S, M and L. The stress ratio (q/p'; where $p' = (\sigma_1' + 2\sigma_3')/3$ is the mean stress) is plotted against ε_a; the volumetric dilatancy (ε_v vs ε_a) is also shown in the same figure. The results are categorized by the specimen size (S, M and L) and arranged by σ_3' =100 kPa (*left-hand)* and 600 kPa (*right-hand).*

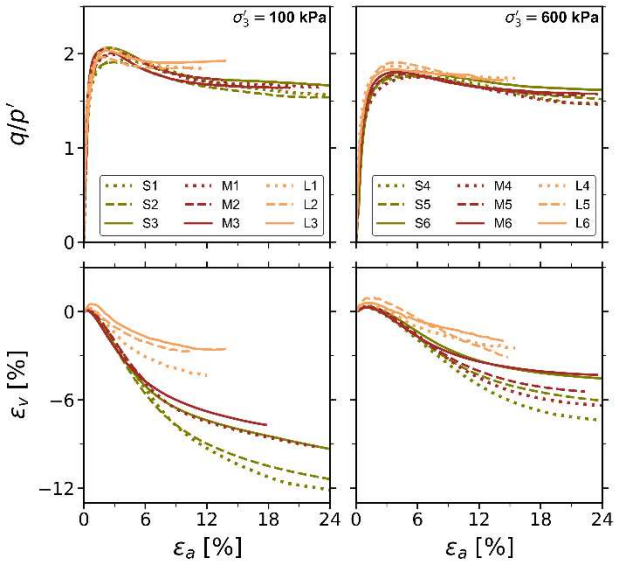


Figure 3. Stress-strain results on S, M and L specimens at σ_3' =100 kPa (*left)* and 600 kPa (*right):* volumetric deformations are plotted at the bottom subplots, respectively.

Peak internal friction angles are between 47º and 50º, without a clear trend across specimen sizes. As expected in dense specimens, peak strength behavior is observable around $\varepsilon_a \sim 3\%$, followed by softening towards critical state conditions at large strains. At any given characteristic ε_a and σ_3', S specimens exhibit the highest ε_v values, indicating more dilative behavior. On the other hand, L specimens show lower dilatancy as ε_a increases. M specimens provide an intermediate response between the two scales S and L. For instance, considering ε_v obtained in L specimens at σ_3'=100 kPa as reference values at $\varepsilon_a = 12\%$ (post peak), S and M specimens exhibit around 60% and 50% higher ε_v , respectively. The difference is reduced at $\sigma_3' = 600$ kPa about roughly 45% on both S and M scales.

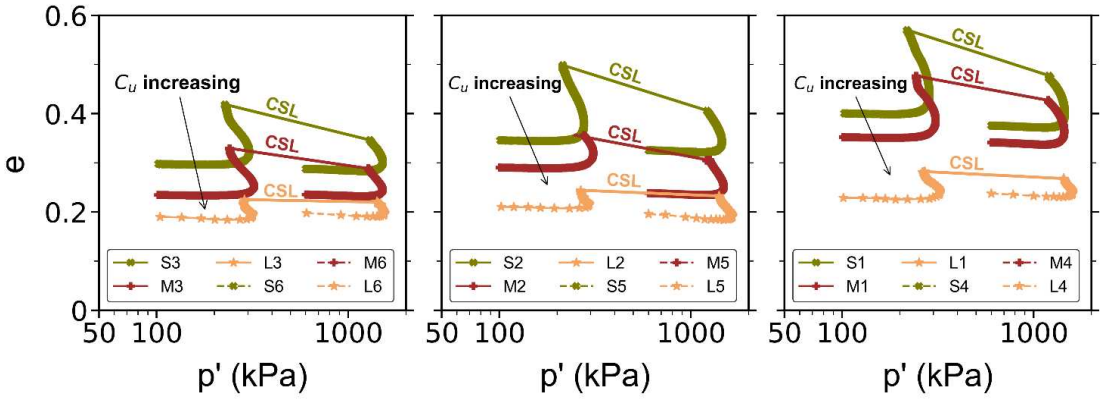


Figure 4. Critical state lines (CSL) of S, M and L specimens: C_u decreasing for a given specimen size from *left* to *right.*

This trend is consistent with the earlier discussed specimen size effect. That is, S specimens with poorly graded PSDs mobilize higher dilatancy compared to M and L specimens with more well graded PSDs. The enhanced packing in well-graded PSDs by fine fractions filling the voids inhibits particle rearrangement during shear. On the other hand, at σ_3' =600 kPa dilating behavior is reduced, suggesting that high confining pressure can moderate scale effects.

Despite the challenges to attain the critical void ratios (e_{cr}) in triaxial compression, they were assumed at the final volumetric deformations reached on a given specimen. Figure 4 illustrates the variation of the critical state line (CSL) in the $e - p'$ space. For a given subplot, the results are arranged by specimen size tested, with C_u increasing from S to L specimens. In addition, for any given specimen size, C_u decreases from *left* to *right* subplots. S specimens with lower C_u values show the highest CSL position due to the high dilative behavior. As C_u increases in L specimens, the CSL shifts downward to lower void ratio ranges. This behavior is consistent with the grading effects reported in sandy materials and suggests that the specimen size effect is more linked to grading than the size itself.

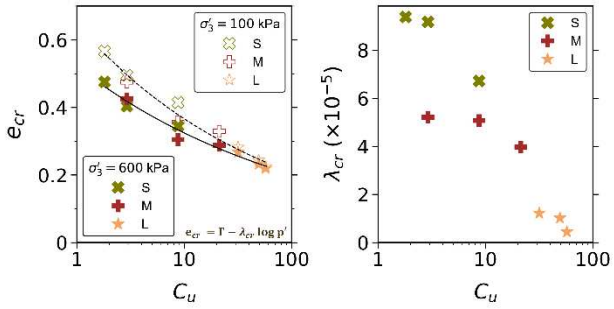


Figure 5. Critical state parameters analysis on S, M and L specimens: e_{cr} estimates (*left)* and CSL slope λ_{cr} (*right).*

CSL parameters are analyzed as a function of C_u in Figure 5. The variation of e_{cr} is shown on the *left* plot and the CSL slope (λ_{cr}) on the *right* one. Consistent with the position of the CSL, L specimens exhibit lower e_{cr} values compared to M and S specimens. The latter observation is sustained by the *right* plot, showing that λ_{cr} decreases with specimen size (associated with higher C_u). Smaller specimens exhibit 4-5 times steeper CSL slopes compared to larger specimens.

4 CONCLUSIONS

An experimental program was carried out on several specimens to assess the impact of small scaling on the dilatancy of coarse terrace alluvial gravel materials. Triaxial monotonic testing on saturated dense specimens consisted small specimens of diameter D=100 mm (S), medium M (D=150 mm) and large L (D=800mm).
The main conclusions are as follows:

- The volumetric strain behavior is affected by the specimen size. For a given axial strain, S specimens exhibited markedly higher volumetric deformations, particularly at low confining stress (σ_3' =100 kPa).
- The critical state line (CSL) showed higher critical void ratios and steeper slopes (high compressibility) in smaller specimens. The differences reached 4-5 times higher between S and M to L specimens.
- Thorough analyses suggest that the trends observed are more related to gradation (C_u) than specimen size. Namely, poorly graded S and M specimens showed overestimated dilative response compared to well graded L ones.

In summary, this study highlights the importance of considering specimen scales when interpreting triaxial test results on coarse materials. Small specimens may overestimate dilative tendencies, potentially leading to non-conservative design assumptions in engineering practice. The findings support the need for larger or scale-appropriate specimens when assessing the mechanical behavior of materials with oversize particle sizes and gradation.

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