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Robotic automated specimen preparation (RASP) technique for soil mechanics

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ABSTRACT: One hundred years after Karl Terzaghi's groundbreaking work established soil mechanics as a scientific discipline, advancements in robotic technologies offer the possibility to transform traditional soil testing methods. Conventional soil specimen preparation, while widely accepted, is inherently prone to human bias and inaccuracies, leading to variability in test results. Automated specimen preparation techniques will emerge as a promising innovation, offering enhanced reproducibility and enabling the study of soil mechanics with unprecedented precision. These methods provide a unique future opportunity to investigate micro-mechanical and fabric-related soil behavior, which are often sensxitive to small fluctuations and challenging to analyze through conventional specimen preparation techniques. Modern robotic systems can significantly reduce the influence of human variability if applied in soil mechanical laboratories. However, this has not been done so far. Therefore, this study examines robotic-aided methods for soil mechanical testing using a conventional robotic arm, with particular focus on specimen preparation. The enhanced precision is particularly evident in the consistent attainment of homogeneous and reproducible relative densities. A comparison between the robot and experienced laboratory staff and inexperienced students in the production of air-pluviated specimens highlights the advantage of the robotic-aided techniques. Preliminary findings highlight the transformative potential of robotic-aided techniques in advancing soil mechanics research. Beyond improving repeatability and precision, these techniques will allow systematic investigation of influencing factors of the overall soil behavior, such as particle arrangement and induced inhomogeneities. By providing a reliable foundation for studying soil fabric and micro-mechanical interactions, robotic-aided specimen preparation addresses longstanding challenges in soil mechanics and opens new avenues for research. The presented results show potential extensions for soil mechanical labs of the future.

KEYWORDS: Robotic-automated, specimen preparation, triaxial testing, air pluviation.

1 INTRODUCTION

Since the beginning of the establishment of soil mechanics as a scientific discipline, specimen preparation has belonged solely to manual human techniques. However, the specimen preparation has always been an important part of soil mechanical testing, due to the well-known dependence of soil behavior on the so-called fabric induced by the specimen genesis. The effect of the specimen preparation has been studied, for example, for the dry air pluviation (Mulilis et al. 1975, Vaid & Negussey 1984), moist tamping (Ladd 1974), water sedimentation, or other methods (Wichtmann et al. (2020), Mugele et al. 2025). Mulilis et al. 1975, using undrained cyclic tests, showed that the cyclic resistance ratio varies depending on the specimen preparation method. Wichtmann et al. (2020) demonstrated that the high cyclic strain accumulation behaviour under drained conditions is influenced by the specimen preparation. Mugele et al. (2025) investigated undrained monotonic tests and observed that the initial mean effective pressure relaxation depends on the specimen genesis. Nevertheless, all of these few exemplary results demonstrated the governing effect of specimen preparation methods for the testing in soil mechanics.

Therefore, the specimen preparation is a subject of continuous research effort. Different researchers and engineers try to always improve the different specimen preparation methods to mimic mainly the deposit conditions. When considering a mature method as air pulivation, different techniques have been developed, including diffusor sieves (Lagioia et al. (2006), rainfall methods, air pulivation with a single nozzle, or fluidized granular beds (Jin et al. 2019). Lagioia et al. (2006) named mainly three factors influencing dry density and homogeneity of air pluviated specimens: Fall height, depositional intensity, and uniformity of sand flow. The motion in free fall in a fluid of an isolated spherical particle can be described using

$$\mathrm{ma} = \mathrm{mg} - \mathrm{V}\rho\,\mathrm{g} - \mathrm{C_d}\,\rho\,\mathrm{A}\,\frac{\mathrm{v}^2}{2}, \qquad (1)$$

in which V and A are the volume and projected area of the particle, a is the particle acceleration, m the mass, ρ the mass density, v is the particle velocity, a is the particle acceleration, g is the gravitational acceleration, and $\mathrm{C_d}$ is the drag coefficient (Vaid & Negussey 1984). The solution of this differential equation depends not only on the height of fall, but also on the fluid, the grain size, the grain mass, and the grain shape, which symbolizes the complexity of the processes involved in specimen preparation.

Based on this literature review, it is evident that specimen preparation is an important part of soil mechanics. Unfortunately, this part of soil mechanics has not been further developed extensively. This is counterintuitive, given that industrial automation and the integration of robotics and artificial intelligence are advancing. Such approaches have been introduced in mechanical engineering over the years to automate production and line management, but only slightly in civil engineering testing. Some examples besides soil mechanics are a zero-invention and testing apparatus that has been shown by Zhou (2023) for asphalt testing. Another example presented by Hägle et al. (2025) shows the robotic-assisted milling of reinforced concrete structural members.

Only a limited number of researchers have used digitalization and automation in their soil mechanical tests so far. Jin et al. (2020) utilized a six-axis robotic system for small-scale geotechnical testing, mainly targeting terra-mechanical applications. In the same direction, at the German Aerospace Center in Bremen, a Landing & Mobility Test Facility has been established (Schröder et al. 2011). The main purpose of this facility is to study the interactions between the lander's footpad and the surface of a celestial body during a landing event. Anilkumar and Martinez (2024) have used a 6-degree-of-freedom (DOF) robotic manipulator as a platform for circumnutation-inspired penetration in sand using the robotic system as a loading device. Some recent results show how to use a robotic system for angle of repose tests and the estimation of the minimum dry density (Pucker 2025).

In this contribution, a robotic-aided specimen preparation (RASP) technique, originally proposed in Mugele et al. (2025b), is presented and compared to manual preparation. The automated specimen preparation is described, and the different influences of parameters such as fall height, nozzle diameter, and nozzle speed are discussed. The results demonstrate that the

RASP approach produces specimens that are more homogeneous than those prepared manually. By this novel method, it is also possible to document the specimen preparation process using data produced during the whole process. In addition, it also enhances our understanding of specimen generation by hand and helps to improve the homogeneity of our soil testing specimens.

2 METHODOLOGY

2.1 *Sand*

Karlsruhe Sand (KS) was used in this study. This sand has been used since the 90s (Hettler & Vardoulakis (1984), Bauer (1996), Vogelsang et al. (2013)) for different batches in different physical and laboratory element testing at the Institute of Soil Mechanics and Rock Mechanics (IBF) in Karlsruhe. KS can be classified as middle sand, poorly graded. The index properties of this sand can be found in Table 1. The grain size distribution is shown in Figure 1 beside a microscope photograph. The sand has a sub-angular grain shape, and the main mineral is quartz.

Table 1. Index properties of Karlsruhe sand (KS).

Parameter	d_{10}	d_{50}	C_u	ρ_s	$\rho_{d,max}$	$\rho_{d,min}$
Value	0.4	0.55	1.5	2.65	1.71	1.43
Unit	mm	mm	-	g/cm^3	g/cm^3	g/cm^3

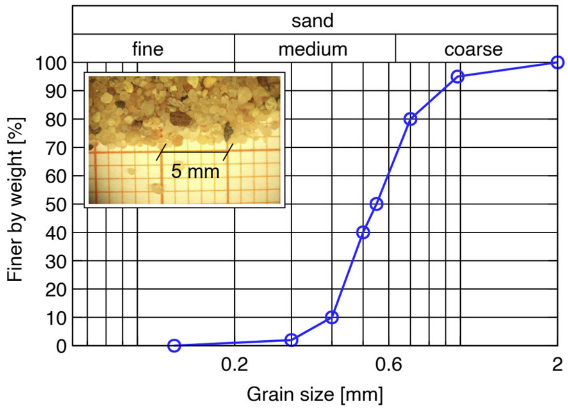

Figure 1. Sand grain size distribution of Karlsruhe sand (KS).

2.2 *Robotic System*

The robotic automated specimen preparation (RASP) method focuses on air pluviation. A robotic system is utilized, which consists of a 6-DOF robotic manipulator with a payload of 12 kg and a working radius of 1.327m (Lexium Cobot arm, Schneider Electric) with a control unit (Lexium Cobot Cabinet controller, Schneider Electric). The robotic unit can be handled by a scripting language and has a set of standardized commands, comparable to other commercial robotic systems.

For this research, a custom mould setup was used to evaluate the homogeneity across different layers of the specimen. The mould consists of stacked PVC rings, allowing measurement of the local density distribution within the specimen after preparation. Each ring has an inner diameter of 10 cm and a height of 2 cm. The total specimen height is 20 cm. The setup is shown in Figure 2.

In addition, a sand hopper stores enough Karlsruhe sand. Nozzles with different diameters have been used. Specimens have been prepared under the variation of the fall height, the nozzle diameter, the robot velocity, and the pluviation pattern.

Two distinctive patterns have been used. The concentric pattern (CP) mainly consists of concentric circles. The other pattern is the serpentine pattern (SP), which meanders through the whole specimen area. Both patterns, SP and CP, have been rotated in each layer to an angle of 17° per layer and are shown in a 3D trajectory in Figure 3. This rotation ensures that the paths of successive layers are not identical. The SP pattern was examined in detail in Mugele et al. (2025b). Therefore, the results of the CS pattern are presented in this study.

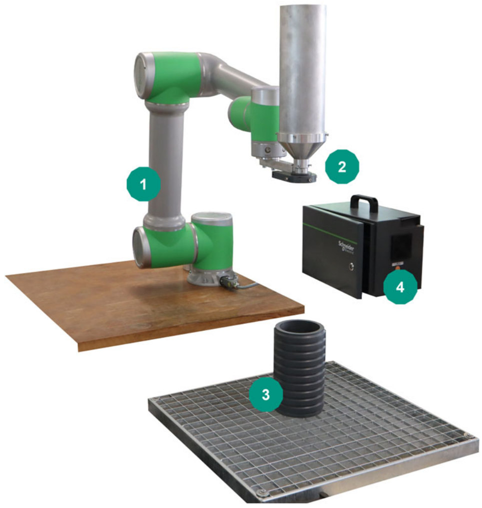

Figure 2. Robotic automated specimen preparation (RASP) setup consisting of a 1) robotic arm, 2) an adaptable nozzle with a sand hopper, 3) stackable PVC rings as specimen mould, and 4) a control unit.

To reach a constant fall height during the whole specimen preparation process, the robotic arm must move upwards during the process. The vertical movement is performed incrementally after each layer. The magnitude depends mainly on the mass flow through the nozzle and the time the robot needs for each layer. The mass flow through a nozzle depends primarily on the ratio of the nozzle diameter to the grain size of the material being considered. However, the design of the nozzle itself also plays a crucial role. The mass flow can be easily measured by determining the mass flowing through the nozzle per unit of time. For a given pattern, a larger mass flow (e.g., through a larger nozzle diameter) results in a larger vertical movement. However, the density of the specimen also influences the required value of the vertical movement, meaning that the latter can only be determined in an iterative process. The details are described in Mugele et al. (2025b).

The experimental results presented in the following were obtained from the same series of experiments as those discussed in Mugele et al. (2025b). The data serve as supplementary material to the data shown there.

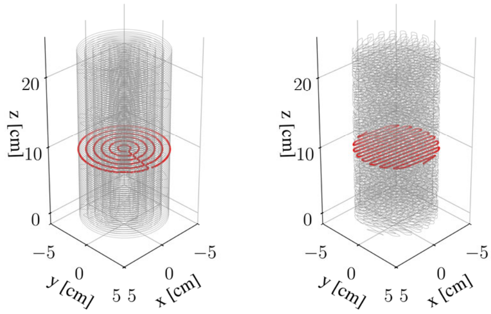

Figure 3. Pluviation patterns for the concentric (CP) pattern (top) and the serpentine (SP) pattern (bottom).

3 RESULTS FOR ROBOTIC AUTOMATED SPECIMEN PREPARATION

The RASP method is analyzed using the measured densities over the stacked rings (specimen height). Due to the procedure, the spatial homogeneity of the specimen can only be studied in the vertical direction. In the following, key factors influencing the achieved density and its distribution are discussed using the mean value of the relative density $\bar{I}_D$ and its coefficient of variation CV ignoring the top and bottom rings, thereby eliminating boundary effects. Each test was carried out twice to evaluate reproducibility.

The comparison of specimens with different fall heights (25 cm and 35 cm) is shown in Figure 4. The fall height is hereby defined as the vertical distance from the nozzle to the current deposition level. As expected from the literature (e.g., Vaid & Negussey 1984), increasing the fall height leads to an increased density. In Figure 4, the variation of the relative density between rings 2 and 9 is quite small. In the bottom ring, the density is much smaller compared to the rest of the specimen. This can be attributed to the aleatoric jumps of individual grains when the air pluviation is done on a hard surface with large grains. This effect also occurs for manual specimen preparation, and is discussed in detail in Mugele et al. (2025b). In general, the densities over the height show minor fluctuations with a coefficient of variation of $CV < 3\%$. Repeated RASP specimens show almost the same average density.

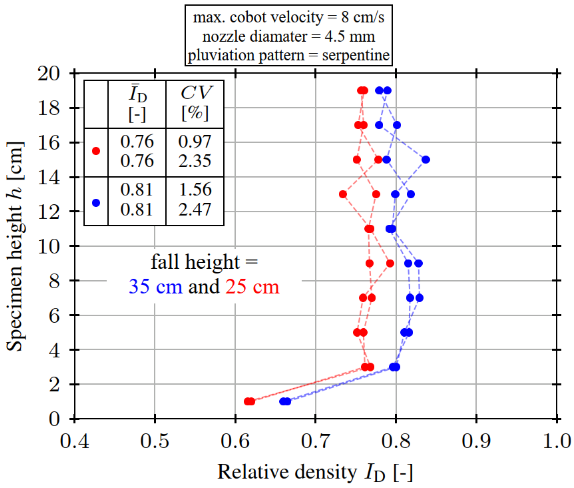

Figure 4. Vertical distribution of the relative density using RASP specimens with different constant fall heights.

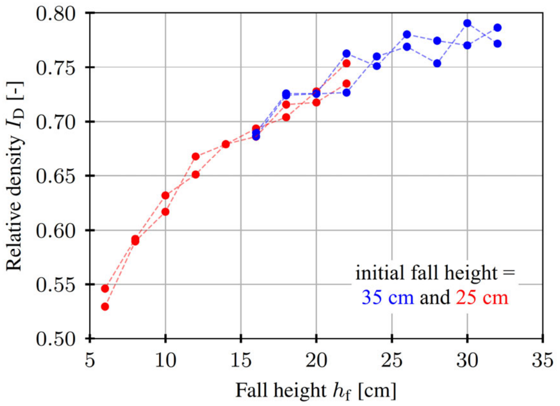

Figure 5. Relative density as a function of the fall height.

Figure 5 shows the achieved relative density as a function of the fall height. The latter data was measured by neglecting the vertical movement described above for two different initial fall heights. As the fall height decreases, the relative density decreases nonlinearly, which again illustrates the influence of the fall height on the resulting relative density.

In addition to the test shown in Figure 4 with the smaller fall height of 25 cm and a maximum cobot velocity of 8 cm/s, further specimens were prepared in Figure 6 at higher and lower maximum velocities (6 and 10 cm/s). There, a slight tendency towards a denser specimen at a faster cobot velocity can be seen. However, the effect is so small that it can be classified as insignificant.

Figure 7 shows specimens for which different nozzle diameters (6 and 4.5 mm) have been chosen. There is a strong influence on the densities achieved. The larger the nozzle diameter, the looser the specimens become, which is consistent with the literature (e.g., Vaid & Negussey 1984). As the nozzle diameter increases, the mass flow increases, and sample preparation is faster overall. In addition, with increasing nozzle diameter and identical other parameters, the vertical movement after each layer increases. It should also be noted that the nozzle diameter is limited to a minimum, as small nozzle diameters can cause the nozzle to become clogged.

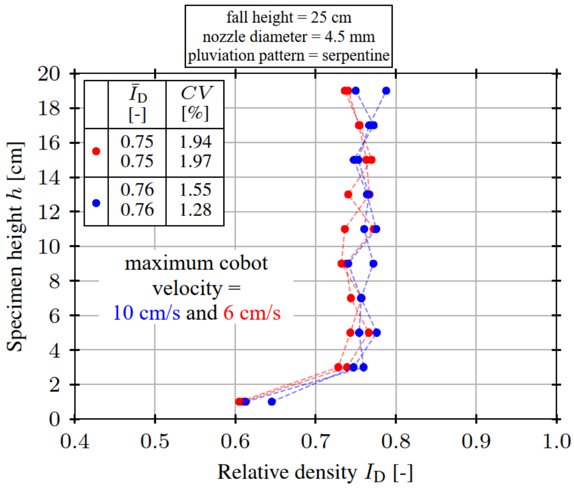

Figure 6. Vertical distribution of the relative density using RASP specimens with different maximum cobot velocities.

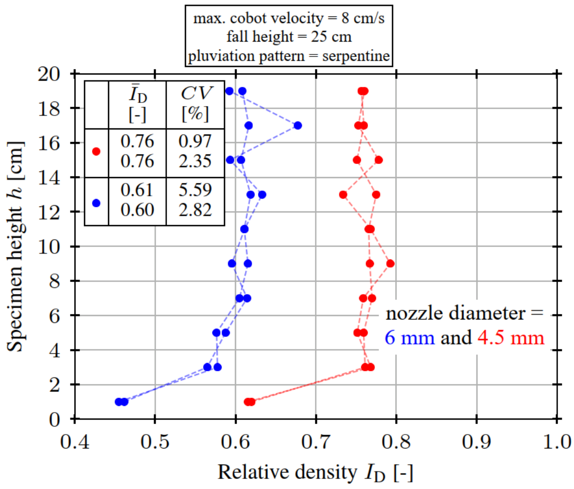

Figure 7. Vertical distribution of the relative density using RASP specimens with different nozzle diameters.

4 COMPARISON OF RASP VS. HUMAN SPECIMEN PREPARATION

The RASP method, which has been discussed previously, is compared to human specimen preparation (HSP). The shown HSP specimens have been prepared by a lab technician with more than 15 years of experience (called an expert).

The results shown in Figure 8 were obtained using two nozzle diameters of 4.5 and 6.0 mm. The desired fall height (25 cm) has been communicated to the technician, but has been challenging to maintain during the HSP process. The HSP specimens show much larger scatter than the RASP specimens. Furthermore, even experts have difficulty in repeating a specimen. As shown in Mugele et al. (2025b), with decreasing experience of the lab technicians, the deviation increases and reproducibility decreases. As an interesting observation, it can be noted that, under otherwise identical conditions, the HSP by the expert provided denser specimens than the RASP method (compare Figure 7 and Figure 8).

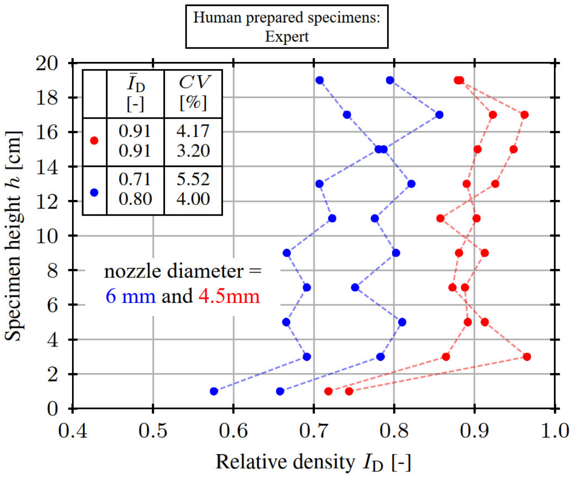

Figure 8. Vertical distribution of the relative density using HSP specimens with different nozzle diameters.

5 CONCLUSIONS

A robotic-aided specimen preparation (RASP), proposed by Mugele et al. (2025b), has been presented. Compared to the previous and conventional human specimen preparation (HSP), it can be observed that the potential impact of RASP on soil mechanical testing is huge. The RASP method can be used to produce significantly more homogeneous and reproducible samples for soil mechanical testing. It can be expected that the RASp method will significantly improve the quality of soil mechanical experiments. The authors see a huge potential for commercial and non-commercial laboratories across the world.

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