

Deformation Behavior of Geosynthetic-Encased Columns of Marine Sand in Triaxial Compression Evaluated by an Image-Based Method

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Research Article

Keywords: Geosynthetic-encased column (GEC), Marine sand, Triaxial compression test, Image-based measurement, Bulging deformation, Ground improvement

Posted Date: October 27th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11325732/v1>

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Additional Declarations: No competing interests reported.

DEFORMATION BEHAVIOR OF GEOSYNTHETIC-ENCASED COLUMNS OF MARINE SAND IN TRIAXIAL COMPRESSION EVALUATED BY AN IMAGE- BASED METHOD

Abstract

Geosynthetic-encased columns (GECs) improve very soft ground by providing radial confinement through the encasement. Triaxial compression tests were conducted on small-scale columns of marine sand encased in a nonwoven geotextile with a tensile stiffness of 15 kN/m, and a low-cost image-based method was used to measure their deformed shape. Six tests were carried out, including an unencased column, an unsaturated encased column, three saturated repeat tests, and a saturated column consolidated under 50 kPa. The columns were photographed in air before shearing and after unloading and dewatering, and their boundary profiles were extracted using Otsu thresholding. The three repeat tests reached the termination load at axial strains of 24.3% to 25.5%, confirming the repeatability of the load-strain response. Under the same unsaturated conditions, the encasement reduced the maximum bulging by 60% compared with the unencased column, despite a termination load five times higher. However, the axial strains measured from the images were 18% to 77% smaller than those recorded by the apparatus, mainly because the columns recovered during unloading and dismantling. A correction based on the column's deformation during unloading was therefore proposed to estimate the range of the bulging at the end of loading. The corrected values preserved the ranking of the load-strain response, but a simple equilibrium check suggests that the constant-volume estimate overstates the bulging. The image-based method provided the complete deformed profile of the column at low cost, and recommendations were given for its use in triaxial studies of GECs.

24 **Keywords:** Geosynthetic-encased column (GEC), Marine sand, Triaxial compression test,
 25 Image-based measurement, Bulging deformation, Ground improvement

26 **Abbreviations**

B	Skempton pore pressure coefficient
GEC	Geosynthetic-encased column
D_r	Relative density (%)
J	Secant tensile stiffness of the encasement (kN/m)
$D_0, D(z)$	Initial diameter; width of the profile at elevation z (mm)
L/H	Position of the maximum bulging measured from the base
I-B	Image-based analysis
T-A	Triaxial apparatus
$\epsilon_{a,TA}, \epsilon_{a,IB}$	Axial strain from the triaxial apparatus and from the images (%)
$\epsilon_r, \epsilon_{r,corr}$	Radial strain measured on the images; corrected radial strain at the end of loading (%)
κ, ν_u	Correction factor; equivalent Poisson's ratio during unloading
K_p, σ_r	Passive earth pressure coefficient; radial stress provided by the encasement (kPa)
V_{i1}, V_{i2}, V_f	Initial, saturated and final states of the specimen (image codes)

27

28 **1. INTRODUCTION**

29 Construction on soft, compressible deposits remains a persistent challenge in geotechnical
 30 practice, particularly in coastal and deltaic regions, where road and railway embankments are
 31 often built over thick layers of soft clay with low undrained shear strength. Among available

ground improvement techniques, granular (stone) columns are widely used because they provide reinforcement, drainage, and densification at a relatively low cost (Barksdale and Bachus 1983; McKelvey et al. 2004). However, a granular column's load-carrying capacity depends directly on the lateral confinement mobilized in the surrounding soil. In very soft soils, typically with undrained shear strengths below about 15 kPa, this confinement is insufficient, and the column fails by excessive lateral bulging in its upper portion (Ayadat and Hanna 2005). Geosynthetic-encased columns (GECs) were developed to overcome this limitation. Wrapping the granular column in a geotextile or geogrid sleeve provides additional radial confinement through hoop tension mobilized in the encasement, allowing the column to retain its load-carrying capacity even when the surrounding soil offers little lateral support (Raithel and Kempfert 2000; Alexiew et al. 2005). Analytical design models, most notably that of Raithel and Kempfert (2000), and many successful applications in embankment and reclamation projects have made GECs a mature technology (Raithel et al. 2005; Almeida et al. 2015; Hosseinpour et al. 2019). Laboratory investigations at the element and model scales have played a central role in clarifying the system's mechanics. Triaxial and unit-cell tests on encased granular specimens have consistently shown that the encasement increases peak strength, imparts apparent cohesion to the composite, stiffens the stress-strain response, and shifts the deformation mode from pronounced local bulging toward a more uniform radial expansion (Wu and Hong 2009; Gniel and Bouazza 2009; Murugesan and Rajagopal 2010; Miranda and Da Costa 2016). Model tests on single columns and column groups have further shown that the benefit of encasement is greatest in the upper part of the column, where bulging concentrates, and that it decreases as the column diameter increases (Murugesan and Rajagopal 2010; Ali et al. 2014; Alkhorshid et al. 2019).

Two aspects of this body of work motivate the present study. The first concerns the fill material. Most published element tests were conducted on crushed stone, gravel, or standard silica sands,

whereas in many coastal regions the locally abundant granular material, and therefore economically and environmentally attractive, is marine sand obtained from dredging. Using dredged marine sand as column fill reduces demand for quarried aggregate and associated transport, and it addresses the growing scarcity of river sand in deltaic regions (Hackney et al. 2021; Nguyen et al. 2021). Nevertheless, element-scale data on encased columns of marine sand remain scarce. This work continues an ongoing research program. Pham et al. (2026) report the mechanical characterization of the same marine sand and its use in a validated three-dimensional model of a GEC-supported embankment.

The second aspect concerns deformation measurement. In routine triaxial testing, axial deformation is recorded by a displacement transducer, and the volumetric response is inferred from boundary measurements, so the specimen's actual deformed shape, particularly the bulging profile, which is the key deformation mode of granular columns, is not captured. Full-field optical techniques such as digital image correlation and photogrammetry-based reconstruction have been applied to triaxial specimens with considerable success (Bhandari et al. 2012; Zhang et al. 2015), but they generally require dedicated hardware, camera calibration through the cell fluid, or extensive post-processing, which limits their use in laboratories with standard equipment. A pragmatic alternative, adopted here, is to photograph the specimen with a consumer-grade camera in a fixed geometric arrangement and to extract the specimen boundary from the images by simple grayscale processing. When photographs are taken after the confining cell has been dismantled and the cell water removed, the optical distortion caused by the cell wall and fluid is avoided, at the cost of a change in specimen state between the end of loading and imaging. This study combines triaxial compression tests on geosynthetic-encased marine sand columns with a low-cost image-based method to measure their deformed shape. The change in specimen state between the end of loading and imaging is quantified by comparing image-based and device measurements, and a correction is proposed to estimate the

lateral deformation at the end of loading. The study then evaluates the effects of encasement, saturation, and confinement on column deformation and recommends a procedure for image-based triaxial testing of encased columns. A subsequent study will examine imaging the specimen inside the cell, which avoids the unloading stage.

2. TRIAXIAL TESTING PROGRAM

2.1. Fill material

The column fill was marine sand MR3 from Binh Thuan on the South-Central coast of Vietnam (Fig. 1). It is one of the three marine sands characterized in the companion study by Pham et al. (2026) and comes from a shallow Holocene marine deposit near the shoreline. These deposits contain large, readily accessible reserves, making them a realistic alternative to river sand (Nguyen et al. 2021).

The grain-size distributions of the three marine sands and of the reference river sand used by Pham et al. (2026) are similar. All are poorly graded sands (SE according to DIN 18196), with coefficients of uniformity C_u between 1.8 and 2.6 and coefficients of curvature C_c between 0.9 and 1.2. They satisfy the requirements of EBGeo (2011) for coarse-grained column fill. For the sample used in this study, $D_{50} = 0.35$ mm and $G_s = 2.68$ (Table 1).

Pham et al. (2026) measured the strength and stiffness parameters used in this paper. Consolidated drained triaxial tests were conducted in accordance with ASTM D7181-20 on specimens with a 39 mm diameter and 77 mm height, prepared at a bulk density of 1720 kg/m^3 and a water content of 8%, the same state as in the present study, and sheared at 0.05 mm/min under effective confining pressures of 50, 100, and 150 kPa with a back pressure of 100 kPa. The peak deviator stress at an effective confining pressure of 150 kPa ranged from 420 to 600 kPa. The marine sand samples had friction angles of 36 to 40° and Young's moduli of 25 to 32 MPa, close to those of the reference river sand (41° and 32 MPa). Their hydraulic conductivity,

measured in constant-head tests, ranged from 1.36 to 3.94 m/d, which is high enough for the column to maintain its drainage function. In the present study, all specimens were prepared at a water content of 8% and a bulk density of 1720 kg/m³, which corresponds to a dry density of 1590 kg/m³, an initial void ratio of 0.68, and a degree of saturation of about 31%. The same fill, water content, and density were used for all specimens. The two unsaturated columns, N-01-40 and E-01-200, therefore differ in the presence of the sleeve and in the termination load (Section 2.5). Table 1 lists the properties of MR3 and the preparation state of the specimens.

2.2. Geosynthetic encasement

The encasement was a nonwoven geotextile with a secant tensile stiffness J of 15 kN/m at 5% strain, determined from wide-width tensile tests in accordance with ASTM D4595 (2017). A comparatively low stiffness was selected intentionally. Circumferential strains of about 1% to 4% are required to mobilize hoop forces in field geotextile-encased columns (Alexiew et al. 2005). In contrast, stiffer geogrid encasement mobilizes hoop forces at radial strains below about 0.5% (Gniel and Bouazza 2010). A low-stiffness encasement therefore achieves the same mobilization range at radial strains large enough to be reliably resolved by the image-based measurement used in this study, while keeping the sleeve-induced confining pressure within the same order of magnitude as reported for laboratory-scale encased columns.

The sleeve was formed by rolling the geotextile into a cylinder of the required diameter and closing it with a longitudinal lapped seam. The seam is the weakest section of the sleeve: Rahman et al. (2025) measured seam stiffness at about 14% of the geotextile's. The seam and overlap were therefore designed following Wu and Hong (2009). An unbonded overlap, as used by Gniel and Bouazza (2010) for geogrid encasement, was not suitable here because it relies on interlock between the aggregate and the geogrid apertures and requires an overlap of up to a full circumference. The overlap adopted here, 11.5 mm on a 39 mm diameter specimen, corresponds to 0.30D or about 9.4% of the sleeve circumference, essentially the same overlap-

to-diameter ratio as the 20 mm overlap used by Wu and Hong (2009) on 70 mm diameter columns (0.29D). A single row of interrupted stitching at a 1 mm pitch was used (Fig. 2). This pattern provides continuous restraint along the seam without forming a rib stiff enough to alter the sleeve's vertical stiffness or cause local failure at the joint; Wu and Hong (2009) reported that a sewn seam of this type produced uniform results and did not trigger failure at the seam. The seam was placed parallel to the specimen axis, so it carried the full hoop force of the sleeve, which the stitches transferred across the overlap in shear. It was rotated away from the camera in every test so it did not appear on the boundary profiles used for image analysis. Table 2 compares the encasement adopted here with those used in related studies.

2.3. Specimen preparation

Cylindrical specimens (diameter 39 mm; height 77 mm; height-to-diameter ratio ≈ 2) were prepared in four steps: sewing the encasement sleeve, fabricating the column, de-airing, and, for saturated tests, saturation. The sewn sleeve was first placed inside the latex membrane, and marine sand was deposited in eight layers with moist tamping to achieve the target density. After specimen formation, a back pressure of 100 kPa was applied to saturated specimens (Section 4.1). Unencased reference specimens were prepared using the same procedure, omitting the encasement sleeve.

2.4. Apparatus and instrumentation

The tests were conducted in an automatic strain-controlled triaxial apparatus (Figs. 3 and 4). A 10 kN load cell measured the axial load, and a transducer with a range of 27 mm and a resolution of 0.001 mm measured the axial displacement. Data were logged every 6 seconds. Figure 3 shows a schematic of the arrangement, and Fig. 4 shows a photograph of the setup, including the camera position used for image analysis.

2.5. Testing program and procedure

The unencased column N-01-40 and the encased column E-01-200 were tested under unsaturated conditions. Three saturated encased columns (E-02-200-S, E-03-200-S, and E-04-200-S) were tested to assess repeatability, and one saturated column (E-05-500-S-P) was consolidated under an effective confining pressure of 50 kPa before shearing. Table 3 summarizes the testing program and the detailed conditions. All specimens were sheared at a constant displacement rate of 0.5 mm/min, corresponding to an axial strain rate of approximately 0.65%/min. Shearing stopped when the axial load reached the termination load (40, 200, or 500 N), so specimens in each group reached the same load level. The specimen was photographed before saturation (V_{i1}) and, for the saturated tests, after saturation and dewatering (V_{i2}). After the test, the axial load and cell pressure were removed, the cell was dismantled and drained, and the final state (V_f) was photographed under the arrangement described in Section 3. The initial and final states are illustrated in Fig. 5.

3. IMAGE-BASED MEASUREMENT OF THE DEFORMED SHAPE

3.1. Image acquisition

The photographs were taken with a mirrorless digital camera mounted on a rigid frame at a fixed distance of 75 cm from the specimen axis, with the optical axis horizontal and aligned with the specimen mid-height. A uniform dark background was placed behind the specimen to maximize contrast between the specimen silhouette and its surroundings. All images were captured with fixed exposure settings (ISO 500, f/2.8, 1/30 s) under constant artificial lighting, ensuring that all images were taken under the same conditions. A steel ruler of known dimensions, visible in every image, was used to convert pixel coordinates to millimeters. The initial images were captured before saturation (V_{i1}), and for the saturated tests, after saturation and dewatering (V_{i2}). The final image V_f was captured after unloading, dismantling the cell,

and removing the cell water, with the specimen left standing on the pedestal in the same position.

3.2. Object segmentation and boundary extraction

Fig. 6 shows the image-processing workflow. The region containing the specimen was first cropped from the original image (Fig. 7a) to remove background structures with intensities similar to the specimen, improving subsequent segmentation. The cropped region was converted to grayscale (Fig. 7b) and segmented using Otsu's global thresholding method (Otsu, 1979), yielding the binary image in Fig. 7c. Otsu's method selects the gray level that maximizes the between-class variance of the histogram, so the threshold is determined from each image itself, and no operator-defined value is required. This makes the procedure non-parametric and insensitive to small differences between images, an advantage over a fixed threshold applied to the whole series.

The binary image defines the specimen boundary. For each row of the binary image, the leftmost and rightmost foreground pixels are taken as the left and right lateral boundaries of the specimen (Fig. 7d). The two boundary profiles are obtained in pixel coordinates and converted to millimeters using the calibration described in Section 3.3.

3.3. Pixel-to-millimeter calibration

The ruler fixed to the frame and visible in each image served as the spatial reference. A strip of the ruler was cropped, converted to a binary image by thresholding, and inverted so that the graduations became the foreground (Fig. 8a to 8c). The binary strip was then projected perpendicular to the ruler to obtain a one-dimensional signal of the graduation positions (Fig. 8d):

$$P(x) = \sum_{y=ymin}^{ymax} B(x,y) \quad (1)$$

where $B(x, y)$ is the binary image, and x is the pixel coordinate along the ruler. The signal was smoothed with a Gaussian filter (Lindeberg, 1994), and the graduations were detected as peaks. Since adjacent graduations are 1 mm apart, the calibration factor s (mm/px) is the inverse of the mean pixel spacing:

$$s = 1/\bar{d}, \quad \bar{d} = (1/N) \sum (p_{i+1} - p_i) \quad (2)$$

where p_i is the pixel position of the i th graduation and N is the number of spacings. Pixel coordinates were then converted to millimeters using $x_{mm} = s \cdot x_{px}$. The calibration was repeated for each image so that a change in the camera position between tests does not affect the measured dimensions.

To verify the procedure, s was determined in two zones of the ruler, zone A_i on the horizontal arm and zone B_i on the vertical arm (Fig. 5a), for both the initial (V_i) and final (V_f) images of each test (Table 4). s ranged from 0.0588 to 0.0594 mm/px (approximately 17 px/mm) for all tests except E-05-500-S-P, for which it was approximately 3% lower (0.0571 to 0.0574 mm/px), probably due to a slight change in the camera position. Within each test, the difference between V_i and V_f did not exceed 0.5%, and the difference between the two zones did not exceed 0.9% (E-02-200-S). Over the 77 mm specimen height, these differences correspond to less than 0.4 mm and 0.7 mm, respectively. Because the initial and final images of a test are scaled separately, a 0.5% difference between them corresponds to an uncertainty of about ± 0.5 percentage points in the radial strain.

3.4. Deformation analysis

Specimen profiles obtained using the image-based method, following the procedure in Section 3.2, were processed to determine the axial and lateral deformations of each specimen. The analysis assumes that the apparatus does not deform during the test. Therefore, the rigid components, namely the top cap and the bottom pedestal, were removed from the profile (Fig.

9). The remaining profile represents the specimen boundary, including the soil, the latex membrane, the encasement, and the lateral deformation developed during loading. Because the profile includes the membrane and the encasement, thinning of the geotextile as it stretches lowers the measured width; 0.1 mm of thinning on each side reduces the radial strain by about 0.5 percentage points.

To identify these components, the image-based method was first applied to the apparatus alone to determine their dimensions. The top surface of the bottom pedestal, including the porous stone, was located at 167 to 168 mm on the reference frame. The top cap, including its porous stone, had a thickness of approximately 30.7 mm, measured from the top of the screw. Three points were then selected along each side edge of the top cap and the bottom pedestal, and a linear regression line was fitted through them. The intersections of these four lines with the two end surfaces of the specimen define the four corners of the analysis domain (A, B, A', and B' in Fig. 9). The axial deformation was obtained from the heights of the analysis domain in the initial and final images. The radial strain at each elevation z was calculated as $\epsilon_r(z) = [D(z) - D_0]/D_0$, where $D(z)$ is the width of the profile, and D_0 is the initial diameter measured in the initial image. The maximum bulging is the largest value of $\epsilon_r(z)$, and its position L/H is measured from the base of the column. Appendix A provides a detailed example of the procedure.

4. RESULTS AND DISCUSSION

4.1. Saturation and consolidation response

Figure 10 shows the pore water pressure and the cumulative volume of water entering the specimen as a function of time. The procedure comprised three stages, namely (1) saturation, (2) dewatering the cell to photograph the saturated specimen and obtain the reference volume for the image-based (I-B) analysis, and (3) re-saturation before shearing. Test E-05-500-S-P included an additional isotropic consolidation stage (4).

During stage (1), the pore water pressure stabilized at 96.7 to 99.6 kPa across all tests. Water inflow ranged from 4.10 to $5.40 \times 10^3 \text{ mm}^3$ for E-02-200-S, E-03-200-S, and E-05-500-S-P, but was only $0.96 \times 10^3 \text{ mm}^3$ for E-04-200-S. Stage (2) was highly reproducible (12.5 to 13.9 min) because it followed an identical sequence, and the constant volume recorded during this stage confirms that no water was exchanged with the specimen.

Stage (3) showed two distinct responses, as the pressure sequence was still being standardized. E-02-200-S and E-03-200-S took up an additional 5.74 and $2.63 \times 10^3 \text{ mm}^3$ of water, corresponding to 106% and 58% of the stage (1) inflow, whereas the volume of E-04-200-S decreased slightly ($-0.59 \times 10^3 \text{ mm}^3$) and that of E-05-500-S-P increased moderately ($+1.33 \times 10^3 \text{ mm}^3$). Because the pores of a saturated specimen cannot accommodate further water, this excess uptake likely accumulated between the latex membrane and the encasement. Spread over the column's lateral surface, the uptake of E-02-200-S and E-03-200-S corresponds to water layers approximately 0.6 and 0.3 mm thick, respectively. The largest uptake (E-02-200-S) coincided with the highest pore water pressure (106.5 kPa) and the longest re-saturation time (78.6 min), suggesting that the pressure sequence, rather than the sand, governed it.

In E-05-500-S-P, increasing the cell pressure by 50 kPa with the drainage closed raised the pore water pressure from 98.3 to 144.4 kPa, corresponding to a Skempton B-value of 0.92, slightly below the 0.95 commonly adopted in triaxial testing. The cumulative volume then decreased from 5.43 to $0.29 \times 10^3 \text{ mm}^3$ ($5.14 \times 10^3 \text{ mm}^3$ expelled), mostly within 12.6 min after the drainage was opened. Consolidation therefore removed excess water and may serve as a practical remedy for excess uptake, although the expelled volume also includes volumetric compression of the column.

4.2. Load-strain response

Figure 11 shows the axial load as a function of axial strain for tests terminated at 40, 200, and 500 N (Table 3). Generally, the load increases monotonically with strain, and no peak is

observed before the termination load. For the encased columns, this is consistent with the progressive mobilization of hoop tension in the encasement as the column bulges. The unencased column also showed no peak, and because all tests were stopped at a fixed load, a peak at larger strains cannot be excluded.

E-05-500-S-P exhibited the stiffest response, reaching 200 N at approximately 2.7% strain and 500 N at 25.5%, mainly due to the 50 kPa confining pressure. Conversely, the unencased column N-01-40 sustained less than 5 N up to 10% strain and only 40 N at 24.7%. At 20% strain, its load was approximately 7 times lower than that of E-01-200. Because both columns were unsaturated, this difference is attributed to the absence of encasement.

The encased columns terminated at 200 N and displayed similar curves. The three saturated repeat tests converged at large strains and reached 200 N at 24.3% to 25.5% strain, confirming good repeatability of the load-strain response. The curve of the unsaturated column E-01-200 separated from those of the saturated columns beyond about 10% strain, and it reached 200 N at 22.1%, about 12% lower strain than the saturated mean. Matric suction, which provides an apparent cohesion that is eliminated upon saturation, may explain part of this difference. However, suction was not measured, and its effect would be expected mainly at small strains. The different saturation history, including the water around the saturated columns (Section 4.1), may also contribute. This comparison assumes drained shearing of the saturated columns; undrained shearing of a dilative sand would have produced negative excess pore pressure and a stiffer, not softer, response.

4.3. Axial strain: device measurement versus image-based analysis

Figure 12 shows the axial variation for all tests measured with the triaxial apparatus (T-A) at the end of loading and with image-based (I-B) analysis after unloading and dewatering. The two measurements use different reference states. $\epsilon_{a,TA}$ is measured from the start of shearing,

after re-saturation and, for E-05-500-S-P, consolidation, whereas $\epsilon_{a,IB}$ is measured from the initial image (Section 3.4). For the T-A measurements, the change in specimen height was uniform across saturated tests terminated at 200 N, with axial variations of 24.3% to 25.5%, whereas the unsaturated column E-01-200 reached a lower value of 22.1%. The unencased column N-01-40 showed a similar axial variation (24.7%), although its termination load was only 40 N. Likewise, E-05-500-S-P deformed similarly (25.5%) under a termination load of 500 N.

In contrast, the image-based analysis showed smaller axial variations across all tests, ranging from 5.9% to 20.3%. Accounting for the encasement, the unencased column N-01-40 retained an axial variation of 20.3%, corresponding to approximately 82% of its T-A value, whereas the encased column E-01-200 retained only 15.1% (68%). This difference is attributed mainly to the column's rebound when unloaded. The axial displacement was not recorded during unloading and dismantling, so the recovery is inferred from the difference between the two measurements rather than measured directly. During loading, the encasement is stretched in the hoop direction. When the axial load is removed, the encasement's hoop tension squeezes the column radially, causing it to extend axially. N-01-40 has no encasement and was loaded to only 40 N, so it recovered the least (18%), and its device- and image-based results are in closest agreement.

Concerning the effect of saturation, E-01-200, E-02-200-S, E-03-200-S, and E-04-200-S show opposite trends between the two methods. At the end of triaxial loading, the unsaturated encased column exhibited a smaller axial variation (22.1%) than the three saturated columns (24.3% to 25.5%). After dismantling, however, the saturated columns retained only 5.9% to 9.4%, corresponding to 23% to 39% of their T-A values, compared with 68% for E-01-200. Thus, the dismantling stage before image acquisition affected the saturated columns more. One possible explanation is that saturation reduces the specimen's lateral resistance, resulting in

larger lateral strains and greater encasement stretch. When unloaded, the saturated specimen therefore contracts radially to a greater extent. This larger change is accommodated by vertical extension, reducing axial deformation relative to the end-of-loading state. Moreover, among the three saturated repeat tests, the reduction was most pronounced in E-02-200-S, which took up the most excess water during re-saturation (Section 4.1).

The discrepancy between the triaxial apparatus and image-based results was smaller for the column tested under confining pressure. E-05-500-S-P retained an axial variation of 11.9%, corresponding to approximately 47% of its T-A value, compared with 23% to 39% for the saturated columns sheared without confinement, even though the termination load was 2.5 times higher. However, this column also differed from the others in consolidation, the termination load, and the reference state of $\varepsilon_{a,IB}$. If the volume expelled during consolidation (Section 4.1) were entirely due to compression of the column, the corresponding axial strain would be about 1.9% for isotropic compression, and the retained fraction would fall to about 40%, close to that of E-04-200-S (39%). The effect of confinement on the recovery therefore cannot be isolated from this single test.

Overall, the image-based axial strain was smaller than the device value in every test. The reduction was largest for the saturated columns sheared without confinement, but the other conditions are each represented by a single test, so these trends are indicative only. Consequently, post-test images underestimate the axial deformation at the end of loading, a limitation that will be addressed by in-cell imaging in a subsequent study.

4.4. Lateral deformation

Figure 13 shows the deformed column profiles from the image-based analysis after unloading. All columns exhibited a single bulge, with width decreasing toward both ends due to restraint from the top cap and bottom pedestal. The unencased column N-01-40 displayed a pronounced barrel shape. In contrast, the encased columns remained nearly cylindrical, with a maximum

width only 4% to 13% larger than at the base, despite a termination load at least five times higher. This change from a barrel shape to nearly uniform expansion is consistent with earlier triaxial and unit-cell tests on encased columns (Wu and Hong, 2009; Gniel and Bouazza, 2009) and confirms the confining effect of the encasement, as quantified in Fig. 14.

The profiles of the saturated columns E-02-200-S, E-03-200-S, and E-04-200-S were also inclined. The axis of these columns shifted by 3.3 to 4.9 mm from the base to the top, corresponding to an inclination of 2.8° to 4.0° , whereas the other columns remained nearly vertical ($\leq 1.1^\circ$). This suggests that the saturated columns, with lower lateral resistance, were more sensitive to slight loading eccentricity or disturbance during dismantling. Local undulations of approximately 0.5 to 1.3 mm are also visible along the encased profiles, particularly near the top of E-03-200-S and E-04-200-S. These undulations are attributed to folds in the encasement and to water trapped between the membrane and the encasement (Section 4.1).

Figure 14 presents the maximum bulging, defined as the maximum radial strain along the column, and its normalized position L/H measured from the base of the column, obtained from the image-based analysis. Radial strain is calculated from the profile width relative to the initial diameter D_0 measured in the initial image. The maximum bulging position ranged from $L/H \approx 0.32$ to 0.54 . Because the profiles of the encased columns are flat over much of their height, this position is sensitive to small undulations; for E-04-200-S, the same maximum width (42.91 mm) occurs at $L/H = 0.47$ and 0.56 (Appendix A). The positions are therefore reported to about ± 0.1 . The unsaturated columns N-01-40 and E-01-200, as well as E-04-200-S and E-05-500-S-P, bulged near mid-height ($L/H \approx 0.45$ to 0.54), as expected for a triaxial specimen with similar restraint at both ends. In contrast, E-02-200-S and E-03-200-S, which absorbed excess water during re-saturation, exhibited the maximum bulging lower, at $L/H \approx 0.33$. This difference from the other columns is only slightly larger than the ± 0.1 resolution, so the

downward shift is indicative rather than conclusive. It is consistent with water trapped between the membrane and the encasement, which drains toward the base when the cell is emptied and locally inflates the lower part of the measured profile. However, E-02-200-S and E-03-200-S were also inclined, and a slight loading eccentricity could also lower the position of the maximum bulging. E-04-200-S was also inclined but bulged near mid-height, which favors the first explanation, but the cause cannot be identified with certainty. The excess water probably also increased the measured bulging. The maximum bulging of the three saturated repeat tests decreased in the same order as their excess water uptake (Section 4.1), from 7.7% for E-02-200-S to 6.6% for E-03-200-S and 6.3% for E-04-200-S. Spread uniformly, the water layers estimated in Section 4.1 (approximately 0.6 and 0.3 mm) would add approximately 3.1 and 1.4 percentage points to the measured radial strain, more than the observed differences from E-04-200-S (1.4 and 0.3 percentage points). Part of the excess water was therefore probably redistributed or drained before imaging, and the trapped water explains the ranking of the three tests only qualitatively. The difference between E-03-200-S and E-04-200-S (0.3 percentage points) is within the measurement uncertainty (Section 5.1), and E-04-200-S, whose saturation was the least certain (Section 4.1), is not a strictly water-free reference.

The triaxial apparatus does not measure the deformed shape of the column; at most, the volume change during drained shearing gives the average radial strain of a saturated columns. The image-based analysis therefore provides the only record of the bulging profile. The unencased column N-01-40 exhibited the largest bulging (22.6%), although its termination load was only 40 N. The encased columns showed markedly smaller values, ranging from 6.0% for E-05-500-S-P to 9.1% for E-01-200, which are 60% to 74% lower than those of the unencased column. This confirms the confinement provided by the encasement, which mobilizes hoop tension and restrains the sand's lateral expansion. Only E-01-200 shares the test conditions of N-01-40 (unsaturated, no confinement); for this pair, the reduction is 60%. The other encased

columns also differ in saturation history and, for E-05-500-S-P, in confinement. Because the unencased column recovered the least during unloading (Section 4.3), this comparison overstates the effect of the encasement; the corrected values are presented in Section 4.5.

However, as shown in Section 4.3, the columns recovered a considerable portion of their axial deformation during unloading and dismantling, so the measured bulging no longer reflects the state at the end of loading. This limitation is evident when the image-based results are compared with the axial strains measured by the triaxial apparatus. If the column volume remained constant, an axial strain of 22% to 26% would require an average radial strain of 13% to 16%. The maximum bulging of the encased columns (6.0% to 9.1%) is lower than this average. Taken at face value, this would mean a volumetric contraction of 7% to 16% during shearing, which contradicts the dilative response expected for a compacted sand with $\phi = 40^\circ$ at low confining stress. The contradiction arises because the two values describe different states, the axial strain at the end of loading and the radial strain after unloading. Hence, the image-based values should be regarded as a lower bound on the lateral deformation at the end of loading.

Despite this limitation, the image-based results provide valuable information. First, the deformation mode is captured: all columns exhibited a single bulge, and the location of the maximum bulge after unloading can be identified to within about ± 0.1 of the column height, which is not accessible from the triaxial apparatus. Second, the effect of the encasement is consistent with the load-strain response (Fig. 11): the unencased column bulged the most. E-05-500-S-P bulged no more than the saturated columns sheared without confinement (6.0% compared with 6.3% to 7.7%) despite a 2.5-fold higher termination load, but its difference from E-04-200-S (0.3 percentage points) is within the measurement uncertainty (Section 5.1).

4.5. Correction of the lateral deformation

Scaling the radial strain directly by the axial ratio $\lambda_a = \epsilon_{a,TA}/\epsilon_{a,IB}$ (1.22 to 4.35, Fig. 12) is not acceptable because it would require some columns to unloadinglose up to 18% of their volume during unloading, far more than the drainage of excess water could explain (Appendix B). Instead, a correction based on column deformation during unloading is proposed.

The column is assumed to be a cylinder with an initial height H_0 and radius R_0 . The axial strain $\epsilon_a = (H_0 - H)/H_0$ is positive under compression, and the radial strain $\epsilon_r = (R - R_0)/R_0$ is positive under expansion. The volume ratio is:

$$V/V_0 = (1 + \epsilon_r)^2 (1 - \epsilon_a) \quad (3)$$

Two states are compared: the end of loading (T-A), where only $\epsilon_{a,TA}$ is known, and the imaging state (I-B), where $\epsilon_{a,I-B}$ and $\epsilon_{r,I-B}$ are measured (Figs. 12 and 14). Because the strains exceed 20%, simple subtraction cannot capture the changes between these two states. They are therefore expressed as logarithmic strains, with the end of loading as the reference (Hencky 1928; Butterfield 1979). With $H = H_0(1 - \epsilon_a)$ and $R = R_0(1 + \epsilon_r)$, the axial extension and radial contraction during unloading are:

$$\Delta e_a = \ln[(1 - \epsilon_{a,I-B}) / (1 - \epsilon_{a,T-A})], \quad \Delta e_r = \ln[(1 + \epsilon_{r,T-A}) / (1 + \epsilon_{r,I-B})] \quad (4)$$

The ratio of these two increments defines an equivalent Poisson's ratio during unloading, $v_u = \Delta e_r / \Delta e_a$, which is assumed constant. The radial strain at the end of loading is then:

$$\epsilon_{r,corr} = (1 + \epsilon_{r,I-B}) \kappa - 1, \quad \text{with } \kappa = [(1 - \epsilon_{a,I-B}) / (1 - \epsilon_{a,T-A})]^{v_u} \quad (5)$$

where κ is the correction factor. From Eqs. (3) and (4), the volume change during unloading is $\Delta e_v = (1 - 2v_u) \Delta e_a$. Hence, $v_u = 0$ means no radial contraction during unloading ($\kappa = 1$) and returns the measured value, which is a lower bound. $v_u = 0.5$ means that the volume is constant during unloading. This constant volume estimate is an upper bound only if the column volume does not decrease during unloading. Draining the cell, releasing the back pressure, and the drainage of trapped water could reduce the volume of the saturated columns, which would

correspond to $v_u > 0.5$. In addition, Eq. (3) describes a cylinder of uniform radius, so applying Eq. (5) to the maximum radial strain assumes that the radial contraction during unloading is the same at every elevation. Under this assumption, the correction does not move the peak position L/H , but it cannot show whether L/H changed during unloading. A worked example is given in Appendix B.

For $v_u = 0.5$, κ ranged from 1.03 to 1.12, and the corrected maximum bulging ranged from 13.9% to 26.1%. The correction retains the effect of the encasement. The encased columns still bulged 19% to 47% less than the unencased column, and 47% less for E-01-200, the only encased column sheared under the same conditions as N-01-40. E-05-500-S-P bulged less than the saturated columns sheared without confinement (15.3% compared with 16.2% to 21.1%) despite a 2.5-fold higher termination load, although part of this difference comes from the smaller recovery of E-05-500-S-P, which may itself reflect its reference state (Section 4.3). The correction also changes the apparent effect of saturation. Before correction, the saturated columns bulged less than E-01-200 (6.3% to 7.7% compared with 9.1%), which contradicts their softer response in Fig. 11. After correction, they bulged, on average, 34% more (16.2% to 21.1% compared with 13.9%). This reversal follows from the larger axial recovery of the saturated columns, which Eq. (5) converts into a larger radial contraction for a given v_u . It is therefore a consequence of the correction, not an independent confirmation of the saturation effect discussed in Section 4.3. For E-04-200-S, the saturated column with the least excess water, the difference is 17%. The correction does not remove the water artifact in E-02-200-S and E-03-200-S, which will be examined by in-cell imaging in a subsequent study.

A simple equilibrium estimate shows how far the correction can be trusted. If the encasement acts as a linear membrane with $J = 15 \text{ kN/m}$, the radial stress it provides at a radial strain ϵ_r is $\sigma_r = J \epsilon_r / R$, with $R = R_0(1 + \epsilon_r)$. With $\sigma_1 = K_p \sigma_r$, $K_p = \tan^2(45^\circ + \phi/2)$, and the axial stress acting on the bulged cross section, the axial load is $F = K_p J \epsilon_r \pi R_0(1 + \epsilon_r)$, neglecting the membrane.

For $\varphi = 33^\circ$ to 40° and the four encased columns sheared without confinement, the uncorrected maximum bulging gives 210 to 420 N, 1.0 to 2.1 times the termination load of 200 N, whereas the constant volume estimates give 490 to 1080 N, 2.5 to 5.4 times (Appendix B, Table B2). Both exceed the measured load, which suggests that the hoop force at large strains is lower than $J = 15$ kN/m implies, for example because of the nonlinear response of the nonwoven geotextile or slip at the seam. Unless the secant stiffness of the seamed sleeve falls well below 15 kN/m at strains above 5%, the much larger ratios obtained with $\nu_u = 0.5$ indicate that the radial strain at the end of loading is closer to the lower bound than to the constant volume estimate. The corrected values therefore reproduce the ranking of the load-strain response but not its magnitude, and the tensile response of the seamed geotextile up to about 20% strain is needed to narrow the range.

5. ERROR ANALYSIS AND RECOMMENDED PRACTICE FOR IMAGE-BASED TRIAXIAL TESTING OF GECS

5.1. Sources of error and magnitude

Table 5 summarizes the main sources of error in the image-based measurement and the controls used in this study. The dominant error arises from the unloading stage, which reduces the axial deformation by 18% to 77% of the T-A value and leads to an underestimation of bulging. This error cannot be removed after the test; the correction proposed in Section 4.5 only gives a range for its effect on the lateral deformation. The other sources are smaller but not negligible. Water trapped between the membrane and the encasement changes the measured bulging by up to about 1.4 percentage points, the thinning of the geotextile by about 0.5 percentage points per 0.1 mm (Section 3.4), and the calibration and boundary errors together by about ± 1 percentage point. Differences in maximum bulging smaller than about 1 percentage point and differences in L/H smaller than about 0.1 should therefore not be interpreted.

5.2. Evidence from the six tests

Figure 15 shows the binary images of the six columns after dewatering. All columns, including the unencased column, remained standing after the cell was drained, allowing their complete profiles to be extracted. The unencased column N-01-40 shows a smooth barrel shape. In contrast, the encased columns show folds in the encasement along both boundaries, which explain the local undulations observed in Fig. 13. The inclination of the saturated columns E-02-200-S, E-03-200-S, and E-04-200-S is also visible in the images, confirming that it is a feature of the specimens rather than an artifact of the image processing.

5.3. Benefits and limits of the procedure

The results of Section 4 allow classification of the quantities obtained from the images. The deformation mode is reliable: all columns showed a single bulge, and the barrel shape of the unencased column is clearly distinguished from the nearly cylindrical shape of the encased columns. The position of the maximum bulging is less certain. It is resolved only to about ± 0.1 because the encased profiles are flat, it may have changed during unloading (Section 4.5), and it can be shifted by water trapped between the membrane and the encasement, as probably occurred in E-02-200-S and E-03-200-S. Comparisons between tests are meaningful only when the tests share the same saturation history and confinement, because these conditions also change the recovery before imaging; the ranking of the saturated and unsaturated columns, for example, reversed after correction (Section 4.5). The effect of the encasement, which is large compared with the measurement uncertainty, is the most robust comparison. In contrast, the axial and lateral deformations measured after unloading do not represent the state at the end of loading. Therefore, the axial deformation should be taken from the triaxial apparatus, and the lateral deformation should be reported as the range given by Eq. (5). Where the volume change during shearing is recorded, it should also be reported, because it gives the average radial strain at the end of loading and an independent check of Eq. (5).

Despite these limitations, the procedure has clear benefits. It provides the complete deformed profile of the column, which standard triaxial equipment does not measure. It directly shows the deformation mode, distinguishing the barrel shape of the unencased column from the nearly cylindrical shape of the encased columns. Moreover, it requires no apparatus modification and can be added to an existing test program at low cost. The procedure is therefore suitable for comparative studies of encased columns tested under the same saturation history and confinement. Still, it cannot replace in-cell or full-field techniques when the absolute strain or its evolution during shearing is required.

5.4. Recommended procedure

Based on the current results, the following procedure is recommended for triaxial tests on encased columns using image-based measurements (Fig. 16):

[1] Include an unencased reference specimen and an unsaturated companion test, both sheared and photographed under the same conditions as the saturated series.

[2] Verify saturation with a B-value check on every saturated specimen, keep the pore water pressure below the cell pressure during re-saturation, and consolidate the column under confining pressure before shearing to reduce water trapped between the membrane and the encasement.

[3] Mount the camera on a rigid support with the optical axis horizontal at mid-height. Place the ruler as close as possible to the plane of the specimen axis, and calibrate each image using its own ruler.

[4] Mark a reference meridian on the membrane so that the initial and final images show the same side of the column.

[5] Unload and drain the cell in stages, record the volume change during shearing and the axial displacement during unloading, and photograph the column immediately after draining.

[6] Report the axial deformation measured by the triaxial apparatus and the lateral deformation as the range given by Eq. (5), checked against the volume change and the tensile response of the seamed encasement. If the deformed shape at the end of loading is required, photograph the column through the cell before unloading, applying an appropriate refraction correction.

6. CONCLUSIONS

A triaxial testing procedure for geosynthetic-encased marine sand columns was combined with a low-cost image-based method to measure the specimens' deformed shape. The following conclusions are drawn.

1. The encasement markedly improved the response of the marine sand column. Under the same unsaturated conditions, at 20% axial strain, the encased column sustained about 7 times the load of the unencased column, and its maximum bulging was 60% lower in the images (47% with the constant volume estimate of the correction), even though the termination load was five times higher.
2. The three saturated repeat tests reached the termination load of 200 N at axial strains of 24.3% to 25.5%, confirming the repeatability of the load-strain response; their image-based results differed partly because their re-saturation histories differed. The unsaturated column was stiffer and reached 200 N at 22.1%, probably partly owing to matric suction, which was not measured.
3. The saturation procedure altered the specimen's state. Excess water taken up during saturation probably accumulated between the membrane and the encasement, increasing the measured bulging and possibly lowering its position, although loading eccentricity cannot be excluded. Consolidation under 50 kPa before shearing expelled more water than the excess uptake, but the amount of trapped water it removed could not be quantified.

4. The axial strains measured on the images were 18% to 77% smaller than the device values, which is attributed mainly to recovery between the end of loading and imaging; this recovery was not recorded directly. The reduction was largest for the saturated columns sheared without confinement, whereas the smaller reduction of the confined column could not be separated from the effects of consolidation and its reference state. Post-test images therefore underestimate the deformation at the end of loading.
5. The correction proposed in Eq. (5) gives a range for the lateral deformation at the end of loading, from the measured value ($v_u = 0$) to a constant volume estimate ($v_u = 0.5$), which is an upper bound only if the volume does not decrease during unloading. With the constant volume estimate, the maximum bulging ranged from 13.9% to 26.1%, and the saturated repeat tests bulged, on average, 34% more than the unsaturated encased column. This ranking follows from their larger axial recovery and is not an independent result; part of it comes from the water trapped in E-02-200-S and E-03-200-S, and a simple equilibrium check suggests that the constant volume estimate overstates the bulging.
6. The image-based method reliably captures the deformation mode and locates the maximum bulging after unloading to within about ± 0.1 of the column height. Comparisons between tests are meaningful when the tests share the same saturation history and confinement and when the differences exceed about 1 percentage point of radial strain. Absolute deformations should be obtained from the triaxial apparatus or reported with the range of Eq. (5). Imaging the column inside the cell, which avoids unloading errors, will be addressed in a subsequent study.

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List of figures

Figure 1. Sand sample used in the triaxial test

Figure 2. Sewn lapped seam of the geotextile sleeve: stitch pattern, sleeve dimensions, and overlap width

Figure 3. Schematic of the testing arrangement

Figure 4. Automatic strain-controlled triaxial apparatus and camera position

Figure 5. Photos of the initial state (a) and final state (b) of test E-01-200

Figure 6. Image processing workflow

Figure 7. Image-processing procedure: (a) cropped image; (b) grayscale image; (c) Otsu segmentation; (d) shape profile (samples from test E-04-200-S)

Figure 8. Spatial calibration from the ruler visible in the image: (a) cropped ruler region; (b) thresholded ruler region; (c) inverted binary representation; (d) one-dimensional projection of the graduations

Figure 9. Definition of the analysis domain: the top cap and the bottom pedestal are removed, and the corners A, B, A' and B' are obtained from linear regression lines fitted to their side edges

Figure 10. Pore water pressure and cumulative water volume during saturation and, for E-05-500-S-P, consolidation: (a) E-02-200-S; (b) E-03-200-S; (c) E-04-200-S; (d) E-05-500-S-P

Figure 11. Axial load versus axial strain

Figure 12. Variation of axial deformation measured by the triaxial apparatus (T-A) and by the image-based (I-B) analysis

Figure 13. Deformed profiles (left and right boundaries) of the columns after unloading obtained from the image-based analysis

Figure 14. Maximum bulging and its position along the column ($L/H = 0$ at the base) obtained from the image-based analysis

Figure 15. Binary images of specimens after dewatering: (a) N-01-40; (b) E-01-200; (c) E-02-200-S; (d) E-03-200-S; (e) E-04-200-S; (f) E-05-500-S-P

Figure 16. Recommended procedure for triaxial tests on geosynthetic-encased columns with image-based measurement.



Figure 1.

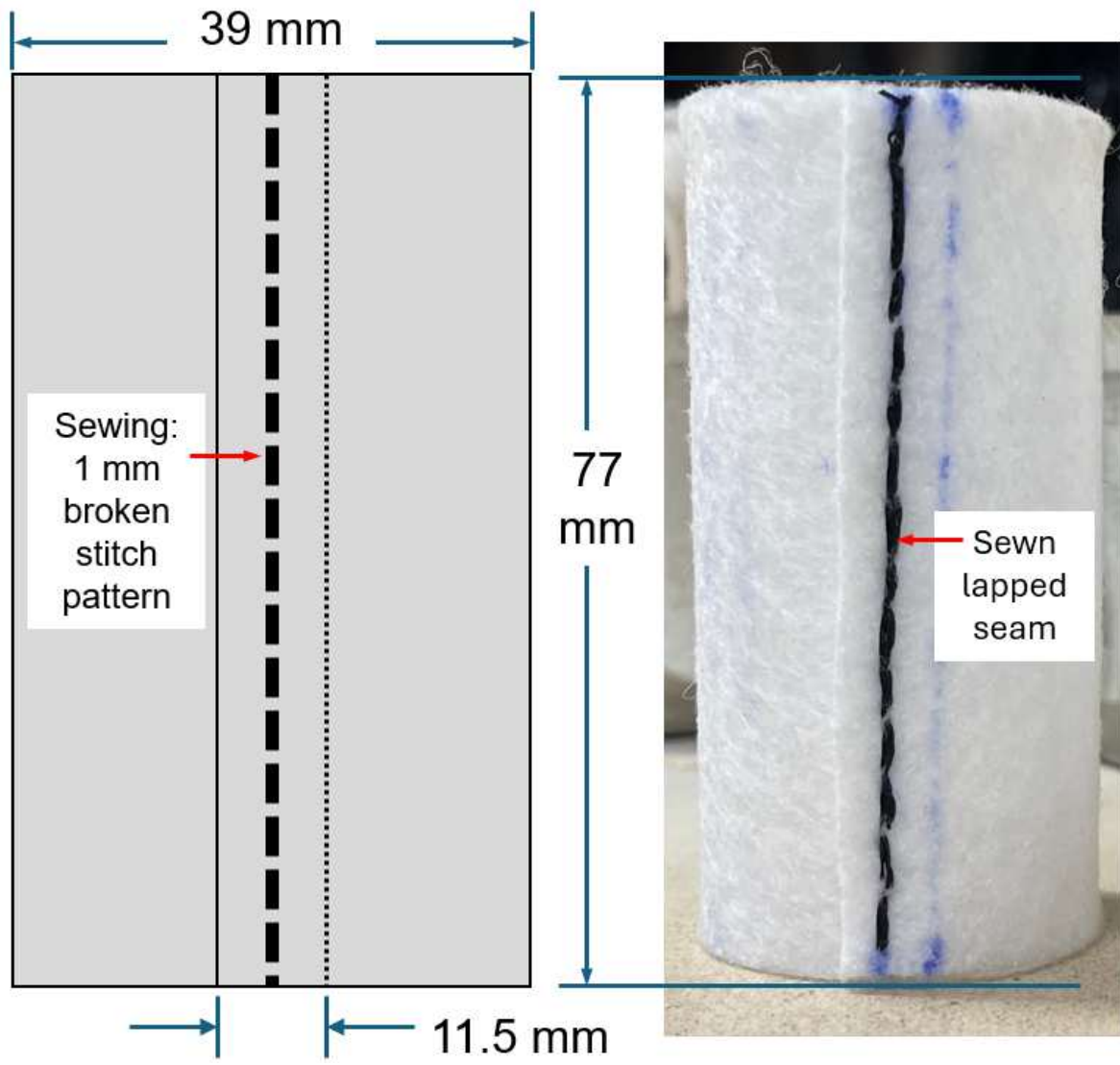


Figure 2.

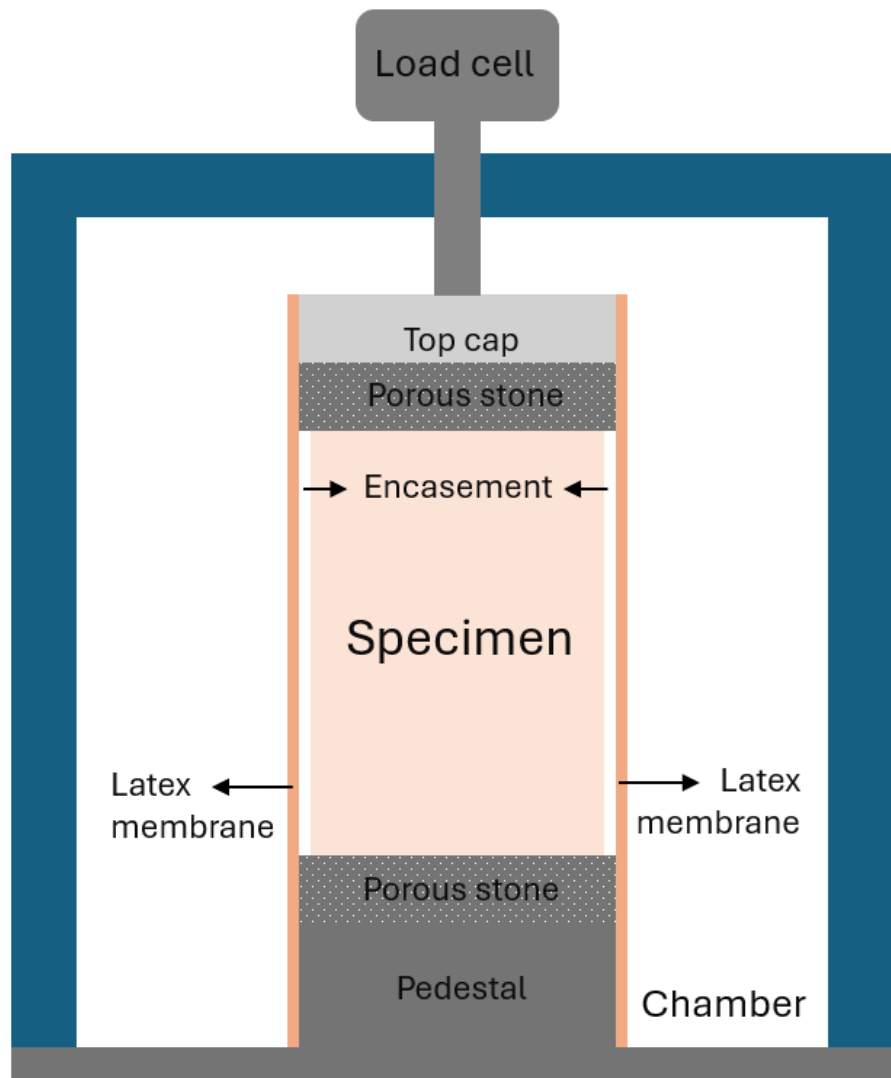


Figure 3.

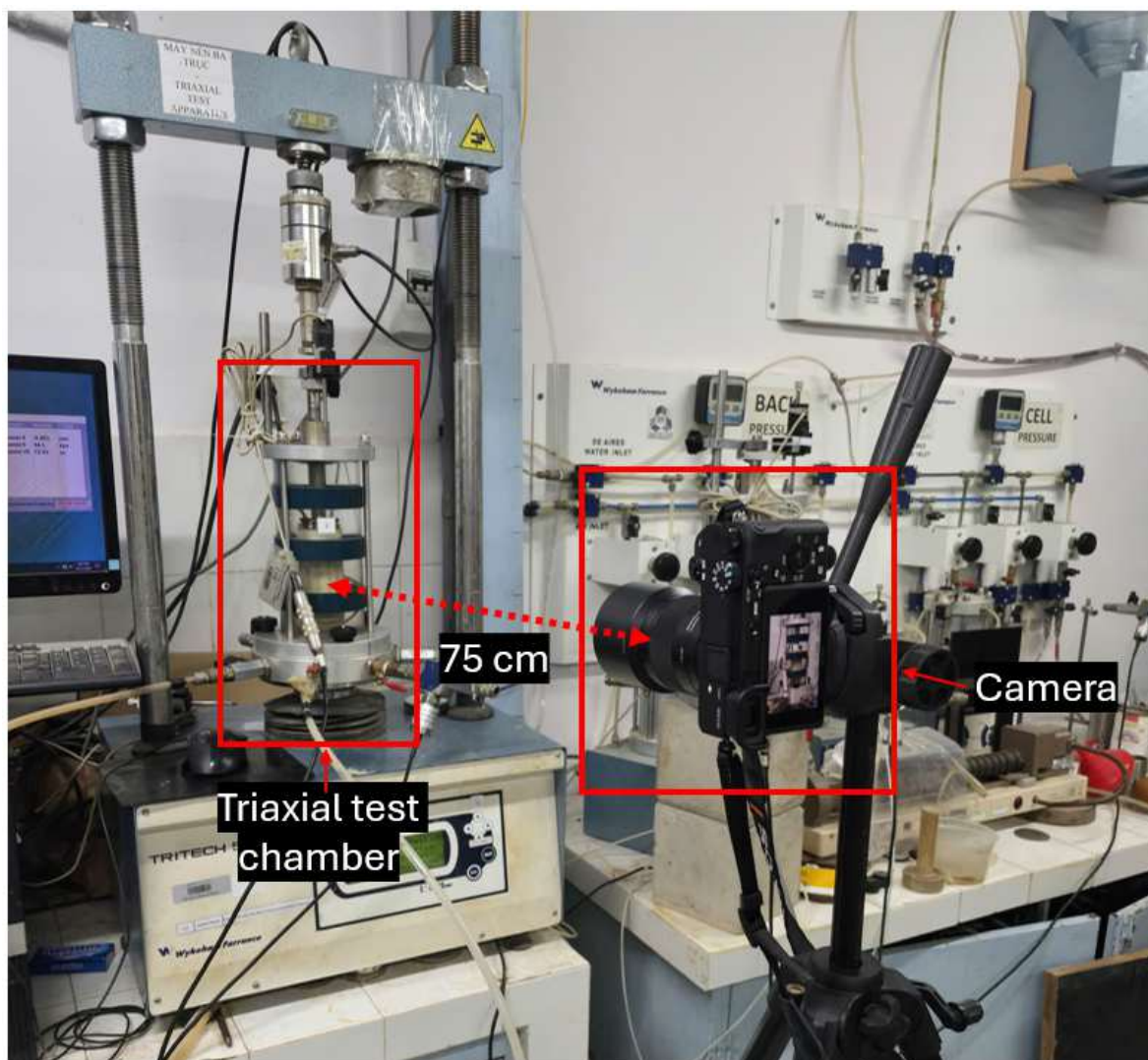


Figure 4.



(a)



(b)

Figure 5.

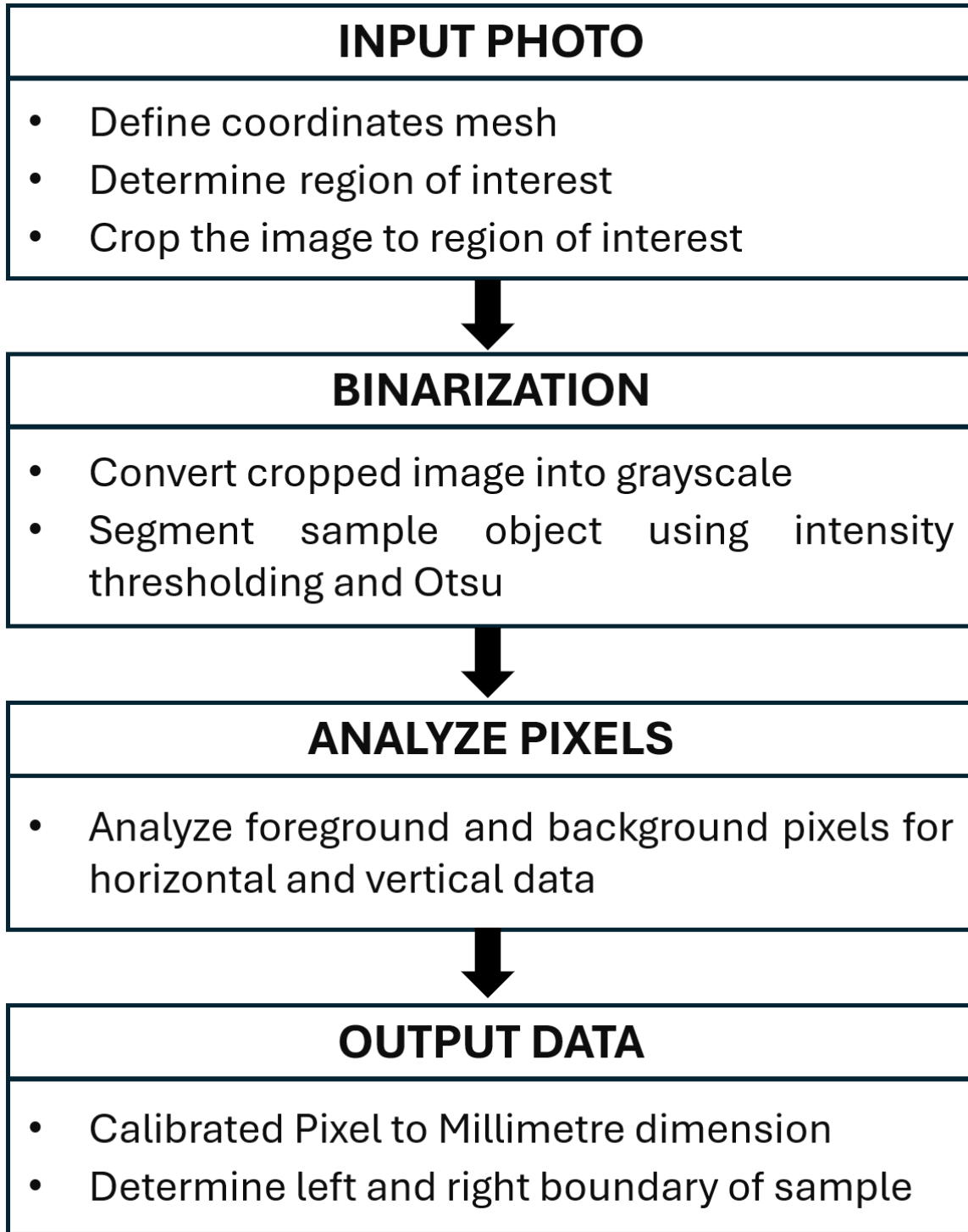


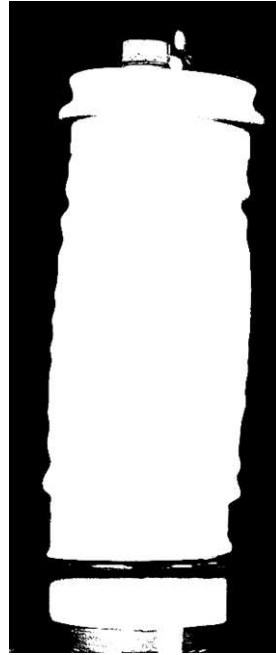
Figure 6.



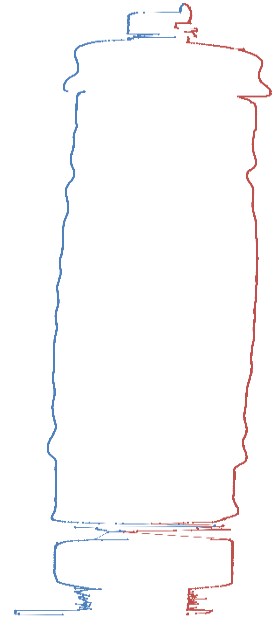
(a)



(b)



(c)



(d)

Figure 7.



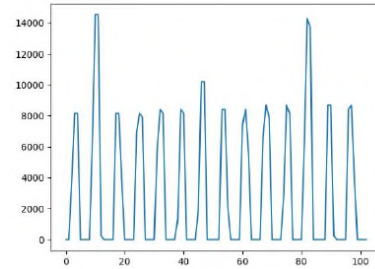
(a)



(b)



(c)



(d)

Figure 8.

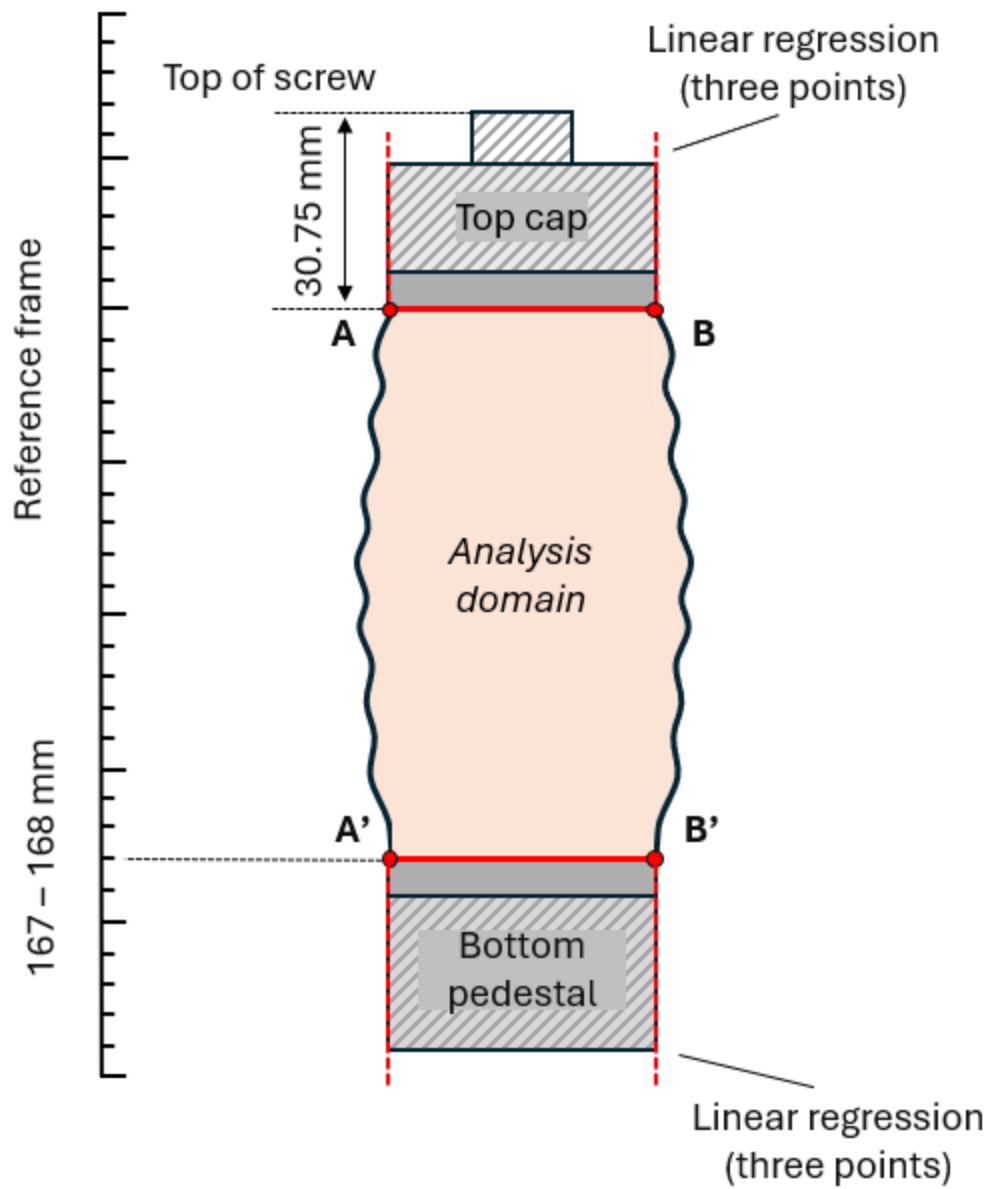
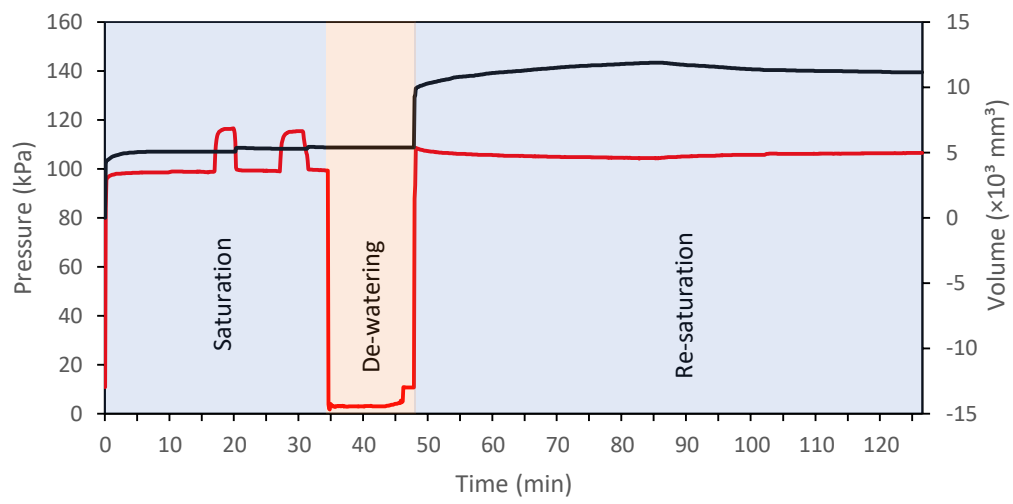
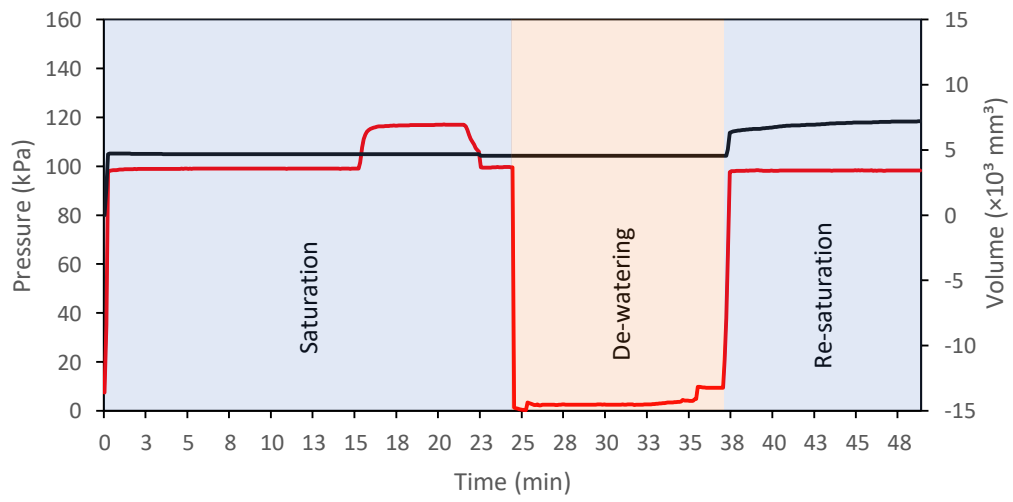


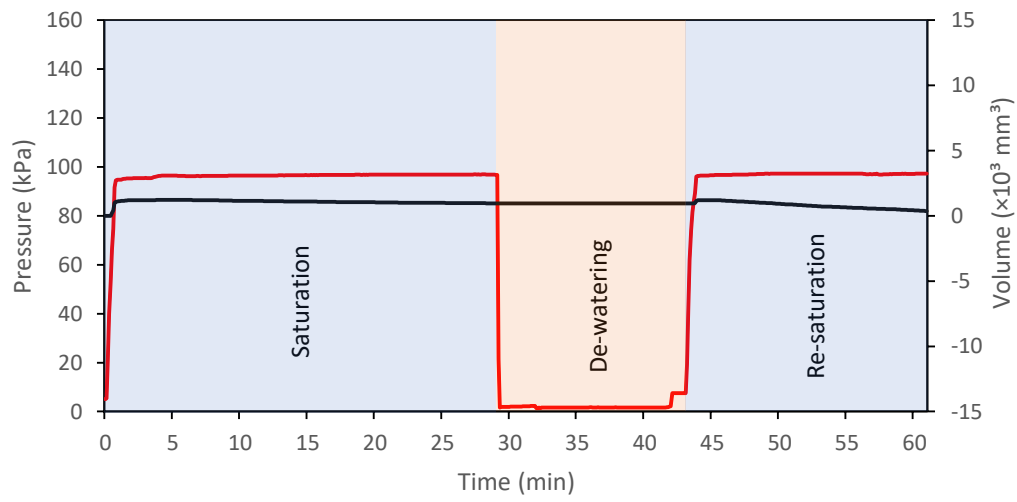
Figure 9.



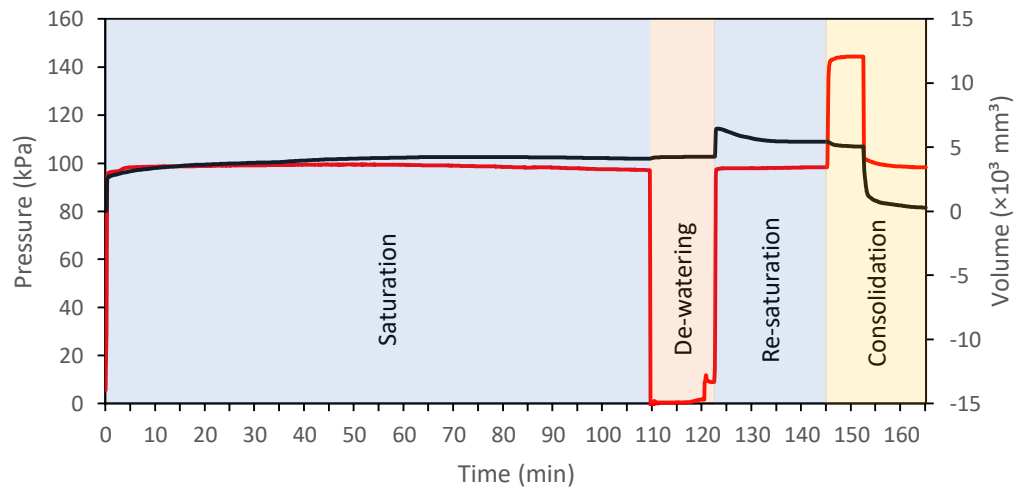
(a)



(b)



(c)



(d)

Figure 10.

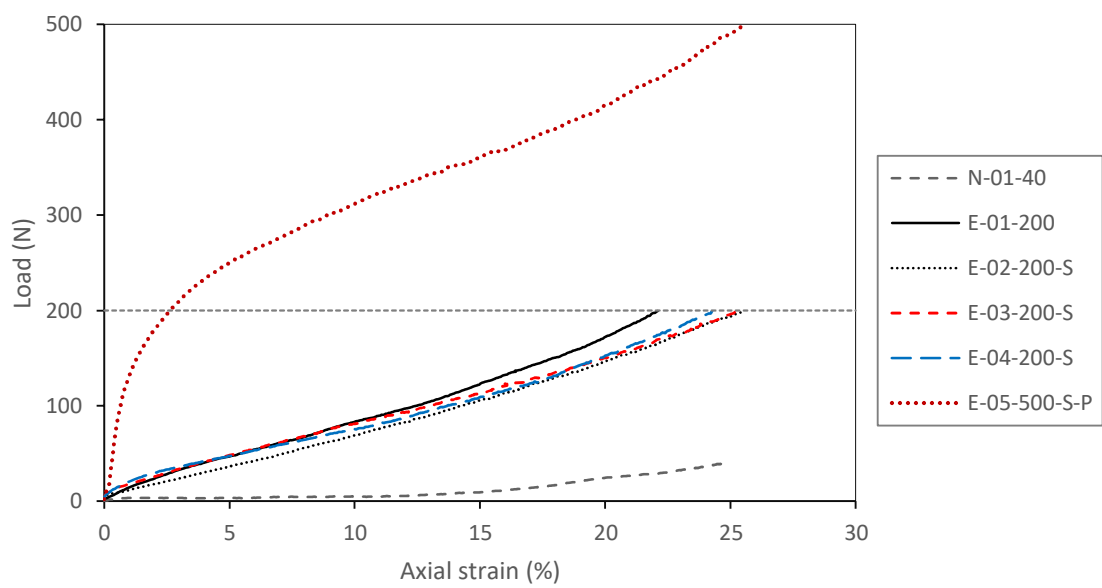


Figure 11.

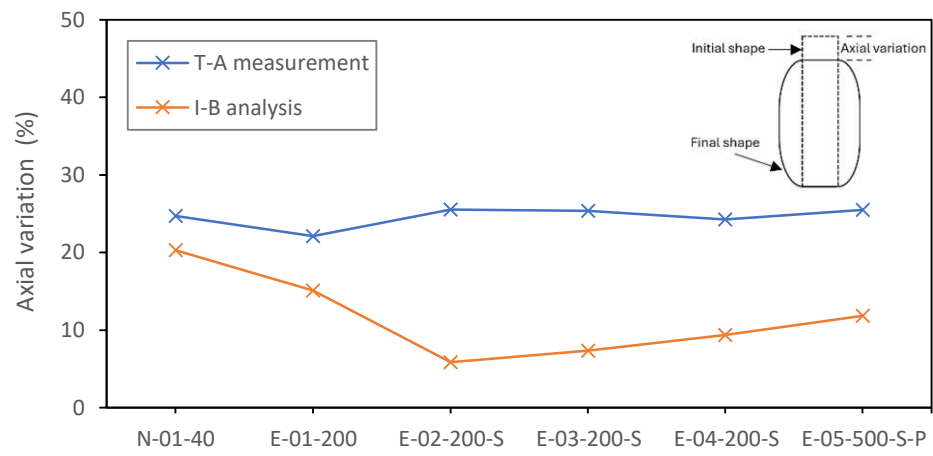


Figure 12.

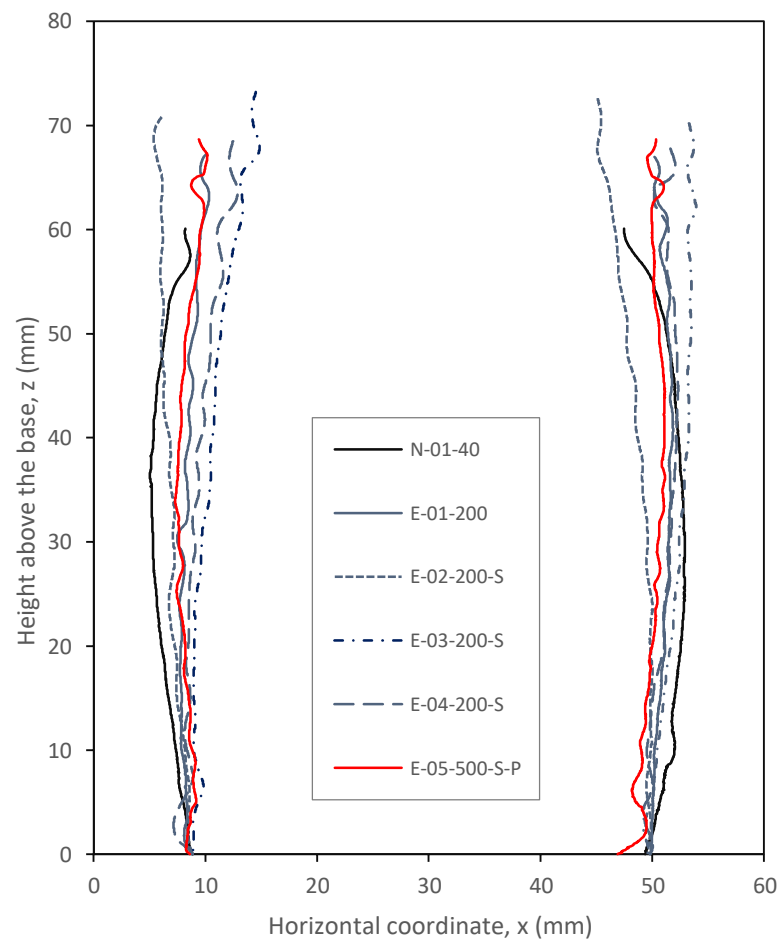


Figure 13.

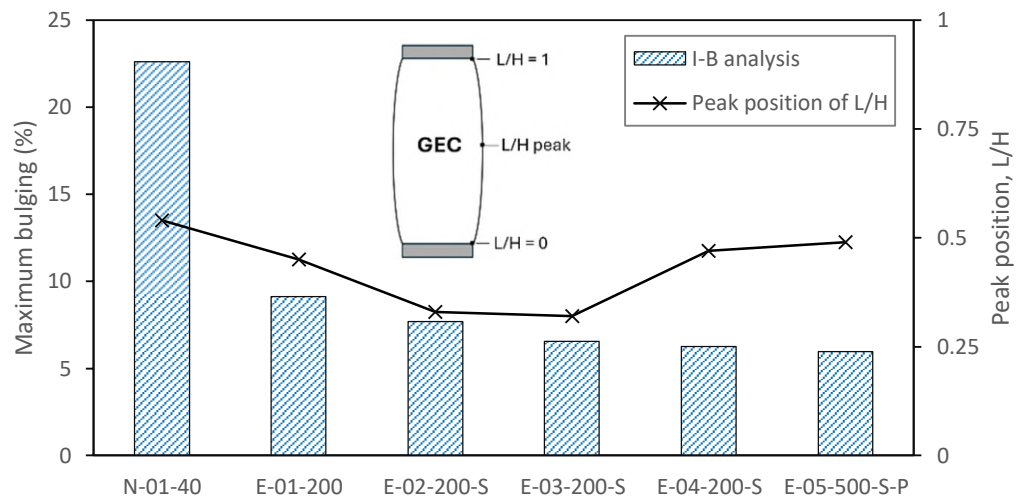
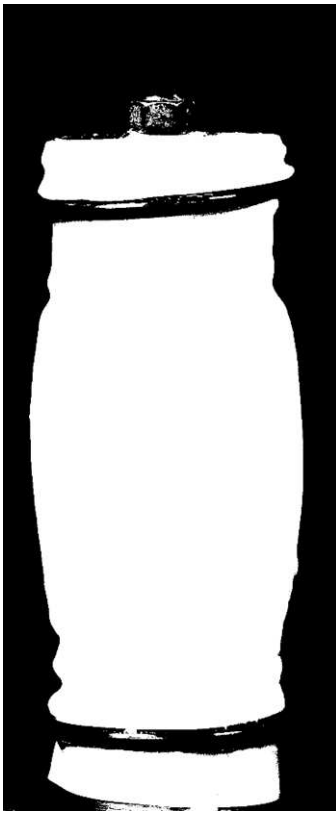
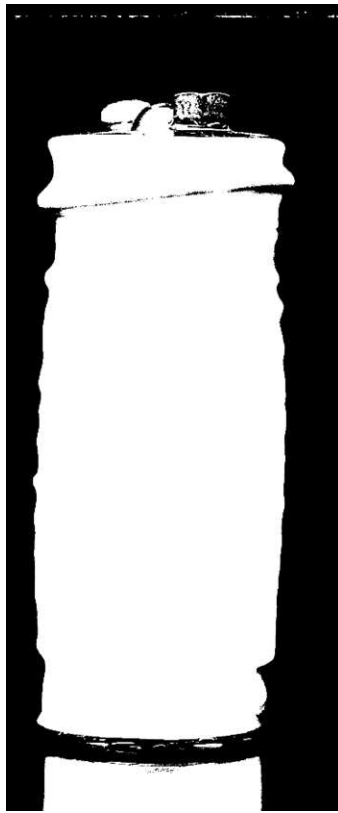


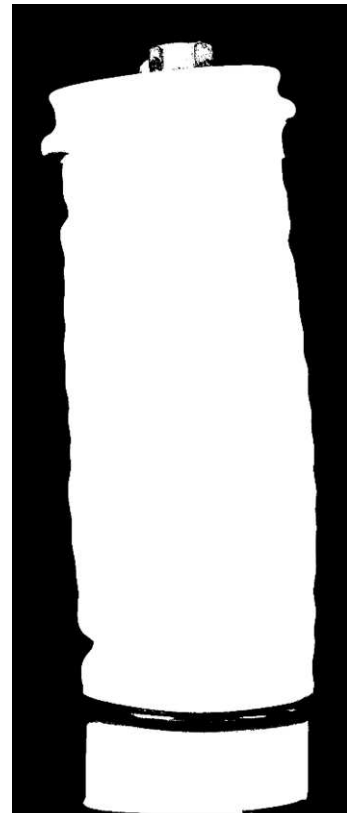
Figure 14.



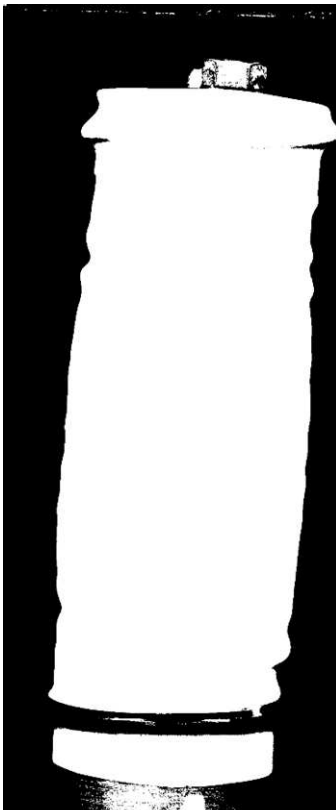
(a)



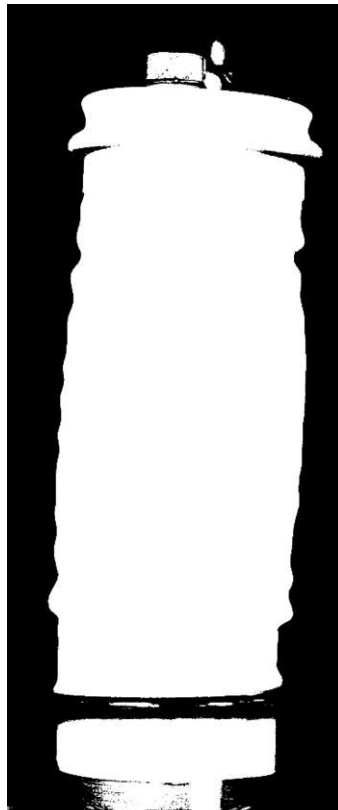
(b)



(c)



(d)



(e)



(f)

Figure 15.

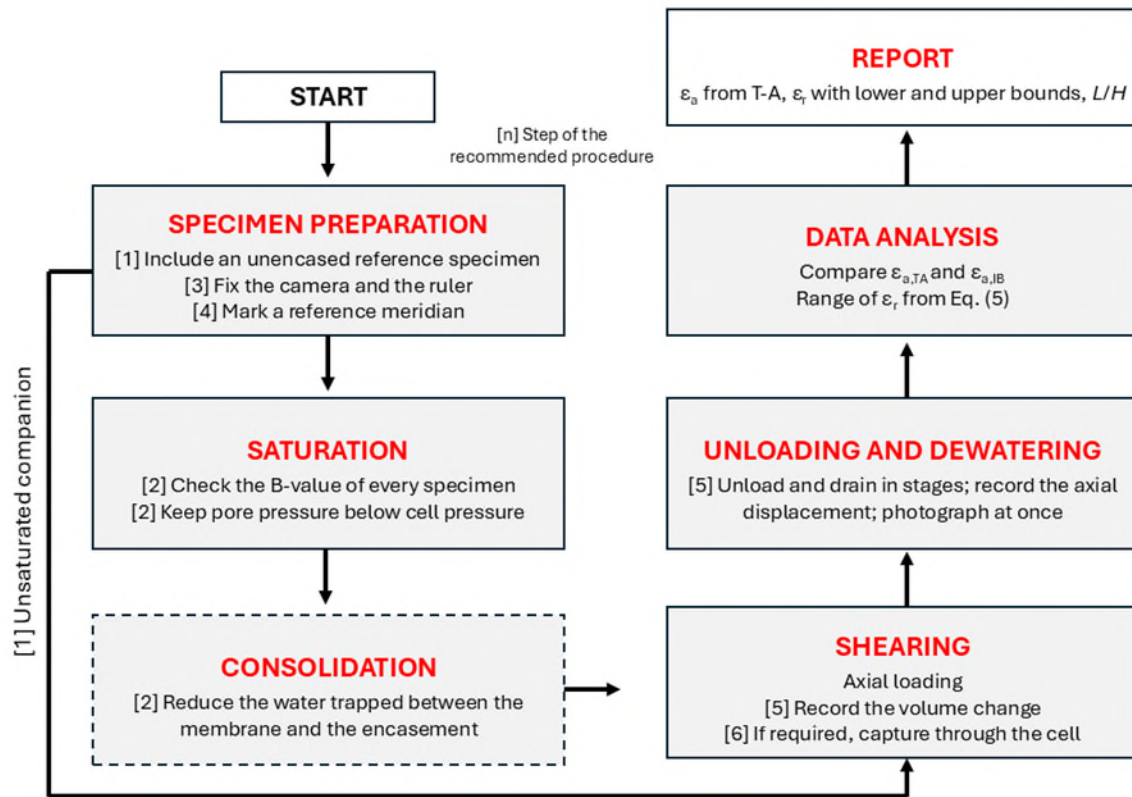


Figure 16.

List of tables

Table 1. Properties of the marine sand (MR3) and preparation state of the specimens

Table 2. Characteristics of the encasement in this study and in related studies

Table 3. Summary of the testing program

Table 4. Calibration factor (mm/px) in zones A_i and B_i for the initial (V_i) and final (V_f) images

Table 5. Sources of error in the image-based measurement of the deformed shape

Table 1.

Property	Symbol	Value	Unit
<i>Index properties (Pham et al. 2026)</i>			
Specific gravity	G_s	2.68	
Median grain size	D_{50}	0.35	mm
Soil group (DIN 18196)		SE	
<i>Preparation state of the specimens (this study)</i>			
Water content	w	8	%
Bulk density	ρ	1720	kg/m ³
Dry density	ρ_d	1590	kg/m ³
Initial void ratio	e_0	0.68	
Degree of saturation	S_r	31	%
<i>Mechanical and hydraulic properties (Pham et al. 2026)</i>			
Friction angle	φ	40	degree
Cohesion	c	1.0	kPa
Young's modulus	E	25	MPa
Poisson's ratio	ν	0.3	
Permeability	k	1.36	m/d

Table 2. Characteristics of the encasement in this study and in related studies

References	Encasement material	Tensile stiffness (J, kN/m)	Overlap dimension (mm)	Seam type
Wu & Hong (2009)	Woven geotextile	31/35/51 (5%)	20 (0.29D; D = 70 mm)	Sewn lapped seam
Gniel and Bouazza (2010)	Biaxial/uniaxial geogrid	960 to 2400 (5%)	391 to 785 (1.67D to 3.14D; D = 225 to 250 mm)	Unbonded overlap held by cable ties
Rahman et al. (2025)	Geotextiles	500 (seam: 71 at 5%)	Not reported (D = 420 mm)	Sewn seam, four-thread overlock
This study	Nonwoven geotextile	15	11.5 (0.30D; D = 39 mm)	Sewn lapped seam, 1 mm stitch pitch

Table 3.

Test code	Encasement stiffness, J (kN/m)	Termination load (N)	Saturation condition	Confining pressure (kPa)
N-01-40	0	40	Unsaturated	0
E-01-200	15	200	Unsaturated	0
E-02-200-S	15	200	Saturated	0
E-03-200-S	15	200	Saturated	0
E-04-200-S	15	200	Saturated	0
E-05-500-S-P	15	500	Saturated	50

Table 4.

Test	Zone A _i (V _i)	Zone B _i (V _i)	Zone A _i (V _f)	Zone B _i (V _f)
N-01-40	0.05893	0.05900	0.05894	0.05901
E-01-200	0.05893	0.05904	0.05888	0.05893
E-02-200-S	0.05933	0.05891	0.05941	0.05889
E-03-200-S	0.05939	0.05904	0.05911	0.05878
E-04-200-S	0.05917	0.05883	0.05924	0.05892
E-05-500-S-P	0.05712	0.05722	0.05717	0.05738

Table 5.

Source	Effect on the measurement	Likely magnitude	Control adopted here
Unloading and dewatering before imaging	Axial deformation reduced; bulging underestimated	Axial deformation reduced by 18% to 77% of the T-A value (Fig. 12)	Range of the bulging from Eq. (5), $v_u = 0$ to 0.5 (Section 4.5)
Water trapped between the membrane and the encasement	Local undulations of the profile; downward shift of the maximum bulging; larger measured bulging	Undulations of 0.5 to 1.3 mm; $L/H \approx 0.33$ instead of 0.45 to 0.54; maximum bulging of 6.6% and 7.7% instead of 6.3%	Consolidation before shearing (E-05-500-S-P) reduced the water around the column (Section 4.1)
Scale calibration	Scale error on all dimensions	Below 0.5% between V_i and V_f ; below 0.9% between zones A_i and B_i	Calibration repeated on every image (Section 3.3)
Camera geometry (working distance, offset between the ruler and the specimen plane)	Systematic scale error on absolute dimensions; strains are little affected	Below 0.1% for a working distance of 75 cm	Camera on a rigid support; same setup for V_i and V_f
Single viewing direction	Inclination and non-axisymmetric deformation not fully described	Inclination up to 4.0° (Fig. 13)	Bulging calculated from the profile width
Reflections, shadows and stray pixels	Local displacement of the boundary	A few pixels (below 0.2 mm per boundary, up to about 1	Matte dark background, fixed lighting.

		percentage point of radial strain)	
Thickness of the membrane and geotextile	Radial strain of the sand core underestimated for the encased columns	About 0.5 percentage points per 0.1 mm of geotextile thinning	None; acknowledged in Section 3.4

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [Appendix.docx](#)