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Effect of Specimens' Height to Diameter Ratio on Unconfined Compressive Strength of Cohesive Soil

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Abstract: The undrained shear strength (Su) and cohesion (Cu) of cohesive soils are frequently determined using an unconfined compression test. However, the test results are heavily dependent on specimen size. This causes uncertainty in geotechnical analyses, constitutive models, and designs by overestimating or underestimating the shear strength of cohesive soils. Therefore, the study aims to assess the effect of the height-to-diameter ratio on the unconfined compressive strength (UCS) of cohesive soil. The soil specimen was tested on a compacted cylindrical specimen at the maximum dry density and optimum moisture content with a height to diameter (H/D) ratio of 1–3 for 38, 50, and 100 mm specimen diameters. Disturbed sample specimens were considered for the laboratory program. Accordingly, the standard Proctor compaction test determines soil classification and compaction characteristics. The unconfined compression test was performed for undisturbed and compacted remolded states of various diameters of cohesive soil specimens to investigate the strength variation with the specimen variation in H/D ratio. The laboratory test results revealed that cohesive soil's unconfined compression strength value drops rapidly with height-to-diameter ratios and the soil specimens' diameter increases. However, the UCS value was stable at H/D ratio from 1.75 to 2.25. As the specimens' diameter and H/D ratio increased, the peak UCS value axial strain decreased. Similarly, the gap between the axial strains of peak UCS value for the smallest and the most significant H/D ratio decreased with increase in the specimens' diameter.

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Keywords: Height to diameter ratio; Unconfined compression strength; UCS scale effect.

1 Introduction

The unconfined compression test is the simplest, most affordable, and most commonly used test for investigating the shear strengths of cohesive and semi-cohesive soils in the total stress state in either undisturbed or compacted state. Nevertheless, for cohesionless or coarse-grained soil, it is challenging to determine undrained shear strength using an unconfined compression test due to the absence of cohesive behavior of those soil materials [1]. Moreover, the test applies to soils during construction operations and design phases where the rate of construction is fast and the time to drain pore water pressure is too limited [2]. Accordingly, the result estimates the short-term bearing capacity for foundations and the short-term stability of slopes of fine-grained soils. Similarly, it is of great significance to compare the shear strengths of soils from a site to quickly establish soil strength variability cost-effectively and determine the stress–strain characteristics under rapid (undrained) loading conditions.

The unconfined compression test is an effective and conventional means of cohesive soil shear strength determination in terms of total stress. However, the specimen's size affects the unconfined compression test result. Therefore, the size of a specimen is essential in determining the unconfined strength of cohesive soil, which increases or decreases the test result [3]. Thus, the fluctuation of an unconfined compressive test result overestimates or underestimates the shear strength of cohesive soil's parameters. This leads to various engineering decisions, which raises the problem of safety, economy, and risk in geotechnical engineering during the design, construction, and maintenance phases. This also increases the construction costs for the maintenance of failed structures because of the overestimated shear strength of the soil.

The specimen size of unconfined compressive strength (UCS) is the sample specimen's height-to-diameter (H/D) ratio. The H/D ratio of the unconfined compression soil test differs in different institutional manuals and design codes. According to the ASTM D2166 [4] standard, the H/D ratio of the cylindrical sample specimen is recommended to be between 2.00 and 2.50, with a diameter greater than 33 mm [5-6]. A British standard method of soil testing (BSI 1377-7) [7] employs an H/D ratio of 2.0, with a diameter ranging from 35 to 100 mm [8]. Japan's Geotechnical Society suggests a specimen diameter of 35 mm and a height of 80 mm. Turkish Standards Institution (TS 1900-2) recommends that the aspect ratio of the unconfined compression test specimen's diameter should be between 38 and 50 mm, with H/D ratio of 2.00 [9]. Braja [10] also suggested that the H/D ratio of an UCS test sample specimen should be between 2.00 and 3.00 [10], as mentioned in [1]. However, a recent study shows that the minimum aspect ratio of the unconfined compression test (i.e., 1.00) also gives a representative test result for zero end platen frictions [3]. This indicates that depending on the original formation and stiffness of soil in different countries the sample will fail in different manner during the unconfined compression test. Therefore, there is no joint agreement among the standard codes on the various building code recommendation values of specimen diameters and H/D ratios [1].

The size of the sample specimen's unconfined compression test should have enough H/D ratio to avoid restrained end-loading endplate effect and side buckling effect. If the specimen's H/D ratio is small, the whole specimen is restrained by the friction of the end-loading plate and it develops the potential for the interference of failure planes, which increases the UCS of a soil sample by preventing the formation of the weakest failure plane. On the other hand, if the specimen is long, it tends to buckle and develops bulging local failure. Consequently, this decreases the UCS of the soil specimens [3, 11, 12]. Still, designs lead by personal and experience judgment, and there is no better agreement yet among countries' laboratory standards, manuals, and building codes. Following this, the test value varies, posing a problem in designing foundations' footing and other geotechnical applications [13]. Moreover, the size of the specimen is essential for determining cohesive soil shear parameters [14]. Different studies assessed the effect of specimen size on unconfined compression tests in the last few decades.

Ang and Loehr [15] conducted an unconfined compression test for four different specimen sizes of reinforced silty clay soil. The reinforced silty clay soil was compacted at maximum dry density and optimum moisture content. The authors suggest that the test's specimen size intensely affects the UCS of the cohesive soils at maximum dry density and optimum moisture content. Hogaki [16] introduced a new procedure for the unconfined compressive test on a small-sized sample specimen (15 mm diameter and 35 mm height). The small size varied by 10% of the mean unconfined compression strength (q_u) value from the ordinary diameter (35 mm diameter and 80 mm height). Then, the researcher concluded that, since the variation of q_u value was in the range of 15%–17%, as indicated by [17], a small specimen could be used instead of a specimen of large size.

According to [2, 16], due to the decreasing friction between the specimen and the specimen head plate, the H/D ratio of 1.00 represented an internal frictional angle and cohesive value, whereas an H/D ratio of 2.00 achieved much greater shear strength parameter values. For zero endplate and specimen friction, it is also revealed that the minimum aspect ratio of 1.0 can effectively reduce failure halfway between the sample specimens [3].

Güneyli and Rüşen [1] conducted unconfined compression tests, considering the effect of the H/D ratio. In this article, cylindrical soil samples with H/D ratios of 0.5–3 were prepared from four types of clay soils using a constant 48 mm diameter. Accordingly, the test results of the unconfined compression tests conducted on the compacted clay soils decreased linearly with increasing H/D ratios. This reduction indicates that the aspect ratio of the cylindrical specimen is a crucial factor to consider when measuring the compressive strength of a soil specimen in an UCS test.

Wang *et al.* [3] came up recently with a deep study on the specimen size end effect of strength and mode of failure for remolded earthen soil samples in UCS tests. From the authors' investigation, it was found that as the H/D ratio rises, the failure mode of the samples changes from tensile to shear modes and the defects become visible in the middle of the specimens. Peak strain, elastic modulus, and residual stress also change with various H/D ratios. The end-friction interface effect becomes smaller as the H/D ratio exceeds 1.0.

Despite the consensus in the literature that specimen size impacts the cohesive soil's UCS, the authors of [2, 16] agree that the presence of compacted soil specimens impacts the results of an unconfined compression test. The size effect, however, has little impact on the quantity of moisture content when there is a high water content (more than the optimal water content).

The authors of this paper investigate the effect of the H/D ratio of cohesive soil specimens on unconfined compression test results, which substantially impact geotechnical design in the practical design and construction industry. On the other hand, several research studies have investigated the influence of the specimen's H/D ratio on soil shear strength characteristics, such as the UCS test. Most previous studies, however, focused on the influence of the H/D ratio on the constant diameter of sample specimens. As a result, the current study investigates the influence of the H/D ratio on the diameter and height of cohesive soil specimens, and a statistical correlational model is developed between the H/D ratio and unconfined compressive strength.

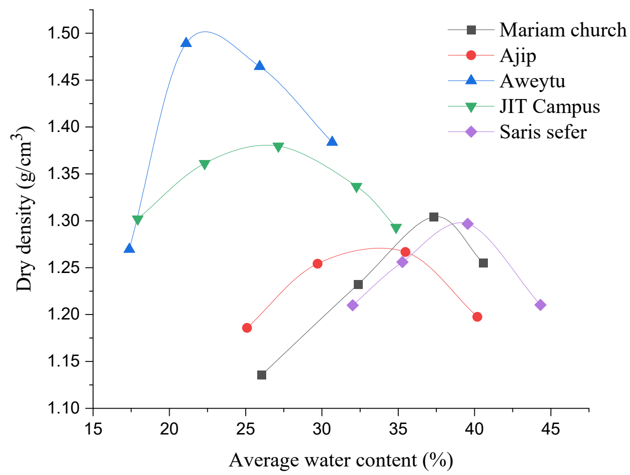

Figure 1: Graph of standard Proctor compaction curves.

2 Materials and Methods

2.1 Material properties

The cohesive soil specimens were collected from five test pits at a depth of 3 m from the ground level in Jimma Town, Ethiopia (i.e., from Aweytu, Ajip, Mariam Church, Saris, and Jimma Institute of Technology [JIT] campus). According to the Unified Soil Classification System (USCS) soil classification system, the collected cohesive soil from all test pits was fine grained. The fine-grained material collected from the Aweytu test pit was a gray-colored, low-plasticity clay soil (CL). The soil sample collected from the Ajib and JIT campus test pits was a black-colored, high-plasticity clay soil (CH). Moreover, the soil samples collected from Mariam Church and Saris Sefer test pits were red-colored, high-plasticity silty soil (MH).

The soil specimens' maximum dry density and optimum moisture content were determined using the Proctor compaction test. This study conducted a standard Proctor test for all test pits. The specimens used for this test were air-dried and passed through a sieve of size 4.75 mm. In order to fully wet the specimens, they were soaked for about 4 hours and then compacted by 2.45 kg rammers from a 30.5 cm height of drops in three layers. For each layer, the soil was compacted by dropping the 2.45 kg rammer 25 times using a mechanical compactor machine according to the ASTM D698-07 [22] standard.

The relationship between dry density and moisture content of all test pits is shown in Figure 1. The collected cohesive soils' maximum dry density and optimum moisture content were determined from the plotted curve. Accordingly, the specimens' maximum dry densities ranged from 1.27 to 1.51 g/cm^3. The optimum moisture content varied from 23% to 39%, as shown in Table 1.

The index properties of the soils, including the classifications according to the American Association of Highway and Transportation Officials (AASHTO) and Unified Soil Classification System (USCS) soil classification standards, are summarized in Table 1.

2.2 Unconfined compression test

This research aims to demonstrate the framework of unconfined compression test results affected by the H/D scale ratio. The specimen size selection is usually done according to user preference and past experiences, which are subjective in real-world conditions to apply for practical design, analysis, and modeling. Therefore, these thought triggers are investigated in the subsequent section. This experiment was designed to evaluate the impact of the specimen's H/D ratio on the UCSs of cohesive soils. The diameters of compacted (remolded) sample specimens were selected to be 38, 50, and 100 mm. The diameters of the specimen were chosen as per ASTM D 2166 [4] and BSI 1377-7 [7] as well as the availability of these size on the market. Each specimen's diameter had H/D ratio of 1.00, 1.25, 1.50, 1.75, 2.00, 2.25, 2.50, 2.75, and 3.00. The test was conducted on a compacted (remolded) sample specimen. The remolded specimens were prepared based on their respective maximum dry density and optimum moisture content according to ASTM D2166 [6]. A compacted soil specimen is more homogeneous and has minor defects and voids. Accordingly, it gives a uniform UCS and deformations.

To evenly wet all the soil particles, the samples were soaked for roughly 24 h at their optimum moisture content. The soaked soil materials were covered by plastic to protect them from water evaporation. The soil samples

Table 1: Summary of index properties, classifications, and compaction parameters of the soils tested.

Parameters	Pit sites				
	Ajib	**Aweytu**	**Saris Sefer**	**JIT campus**	**Mariam Church**
Liquid limit, %	79	49	72	86	75
Plastic limit, %	32	22	36	28	49
Plastic index, %	47	27	36	58	26
Percentage of course soil, %	0.0	10.7	0.0	0.0	0.2
Percentage of sandy soil, %	16.7	33.6	1.6	2.7	1.6
Percentage of fine soil, %	83.3	55.7	98.4	97.3	98.1
Soil classification					
USCS	CH	CL	MH	CH	MH
Group name	High-plasticity clay soil	Low-plasticity clay soil	High-plasticity silty soil	High-plasticity clay soil	High High-Plasticity plasticity silty
AASHTO	A-7-5	A-7-6	A-7-5	A-7-6	A-7-5
Group name	Clayey soil	Clayey soil	Clayey soil	Clayey soil	Clayey soil
Standard Proctor compaction test					
Optimum moisture content, %	34	23	26.5	39	37.5
Maximum dry density, g/cm^3	1.27	1.51	1.38	1.3	1.31

were remolded at their maximum dry density after being uniformly wet.

The unconfined compression soil test specimens were remolded using their respective specimens' diameters of molds (i.e., 38, 50, and 100 mm specimen diameters). Trials were used to determine the number of layers and blows required to remold the sample specimens.

The remolded specimens were extruded from the lubricated molds using a hydraulic extruder and their height was trimmed according to their H/D ratio, as shown in Table 2. The dry density and the moisture content of the remolded specimens were checked. The difference between the remolded specimens' water content and their optimum moisture content varied from 0.56% to 0.75%. Also, the difference between the remolded specimens' dry density and their maximum dry density was from –0.02 to 0.02 g/cm^3. However, since the difference was slight, it was considered negligible [3]. The strain rate of the unconfined compression testing was adopted according to earlier studies [1, 16]. The strain rate was taken at 1% per minute as stated in the Japanese geotechnical standard [5] for all specimen heights to decrease the strain rate effect on the unconfined compression test result.

As shown in Table 2, the unconfined compressive test was performed at the H/D ratio of 1.00, 1.25, 1.50, 1.75, 2.00, 2.25, 2.50, 2.75, and 3.00 for each specimen's diameter of 38 mm, 50 mm, and 100 mm. The height of the specimens for each diameter ranged from 38 to 300 mm. Accordingly, the UCS values for the remolded cohesive soil specimens were determined from the five test pits at three different soil specimen diameters and nine H/D ratios for their respective diameter.

2.3 Data processing and analysis

The dry density and the moisture content of the remolded soil specimens prepared at different H/D ratios were compared with the optimum moisture content and maximum dry density. The soil specimens' dry density, water content, diameter, and height before and after the test were similar with a negligible variance. Then, the determined UCS value corresponding to its H/D ratio was appropriated for the data analysis. For the test results having a wide gap between those control points, another trial was conducted until the variance was reduced.

Table 2: Specimens' height for each diameter, with respect of their H/D ratio at stain rate of 1%/min.

H/D ratio	Specimen's diameter					
	38 mm		50 mm		100 mm	
	Height (mm)	Strain mm/min	Height (mm)	Strain mm/min	Height (mm)	Strain, mm/min
3.0	114	1.14	150	1.50	300	3
2.75	104.5	1.05	137.5	1.38	2750	2.75
2.5	95.0	0.95	125	1.25	250	2.50
2.25	85.5	0.86	112.5	1.13	225	2.25
2.0	76.0	0.76	100	1.00	200	2.00
1.75	66.5	0.67	87.5	0.88	175	1.75
1.5	57.0	0.57	75.0	0.75	150	1.50
1.25	47.5	0.48	62.5	0.63	125	1.25
1.00	38.0	0.38	50.0	0.50	100	1.00

The optimum aspect ratio was determined by analyzing the UCS values and stress-strain curves of the remolded cohesive soil specimens for the different specimen diameters with their corresponding H/D ratios. The recommendation of an appropriate aspect ratio of specimens was evaluated according to consistency peak UCS values among the series H/D ratio of 38, 50, and 100mm diameters. When the aspect ratio of specimens increases, the peak UCS value difference between the successive aspect ratios decreases and becomes more stable [3,18]. The change in UCS value among the successive H/D ratio of the specimens is greater for too small and too large aspect ratios of the specimens. Therefore, an appropriate H/D ratio was selected according to the UCS uniformity. For the unconfined compression test sample specimen, the inclined failure planes do not intersect each other along the entire length of the sample specimens of the appropriate specimen size [2]. However, the failure pattern varies with the H/D ratios of the test sample specimens. For a small H/D ratio, the whole sample is restrained by the friction of the end-loading plates [11].

Consequently, the bulging failure mechanism occurs [19]. On increasing the aspect ratio, stress distribution inside the sample will become more uniform [3]. Therefore, the failure mechanism will be changed. The buckling effect is another issue if the H/D ratio increases due to the slenderness effect [11]. As a result, a complex failure mechanism will happen [1]. Accordingly, the failure mechanism of the specimens was assessed to determine the appropriate H/D ratio of UCS values. Then, according to the failure mechanism, the UCS value uniformity, the characteristics of the stress–strain graph, axial strains of the peaks, and the UCS values of the H/D ratios for each diameter were evaluated and validated with previous studies done in similar soil types.

2.4 Statistical analysis for predicting unconfined compression strength value

A single linear regression analysis was conducted to evaluate the effect of the H/D ratio on the UCS of the cohesive soils using Microsoft Excel-2016, OriginPro-2021, and SPSS-25 data modeling software. UCS equations were then derived for the selected H/D ratio for specimens' sample diameters, which applies to the study area. A Statistical Distributions test, Shapiro-Wilk normality test, scatter plot, and Pearson correlation coefficient (R) were used to evaluate the quality of the data collected.

3 Results and Discussion

3.1 Effect of H/D ratio on UCS

Figure 2 shows the effect of the H/D ratio on the UCS test, varying the H/D of the soil specimens. From the result, it is observed that as the height and diameter of the soil specimen increase, the UCS of the soil decreases. With H/D ratios from 1.00 to 1.75 and from 2.5 to 3, the difference in UCS value of the cohesive soil specimen between consecutive H/D ratios was steeply decreased. Compared to the other consecutive H/D ratios, the difference between the UCS values of the specimens measured from the H/D ratio of 1.75–2.25 was considerably smaller. This was also similar for all the sample specimens' diameters, as shown

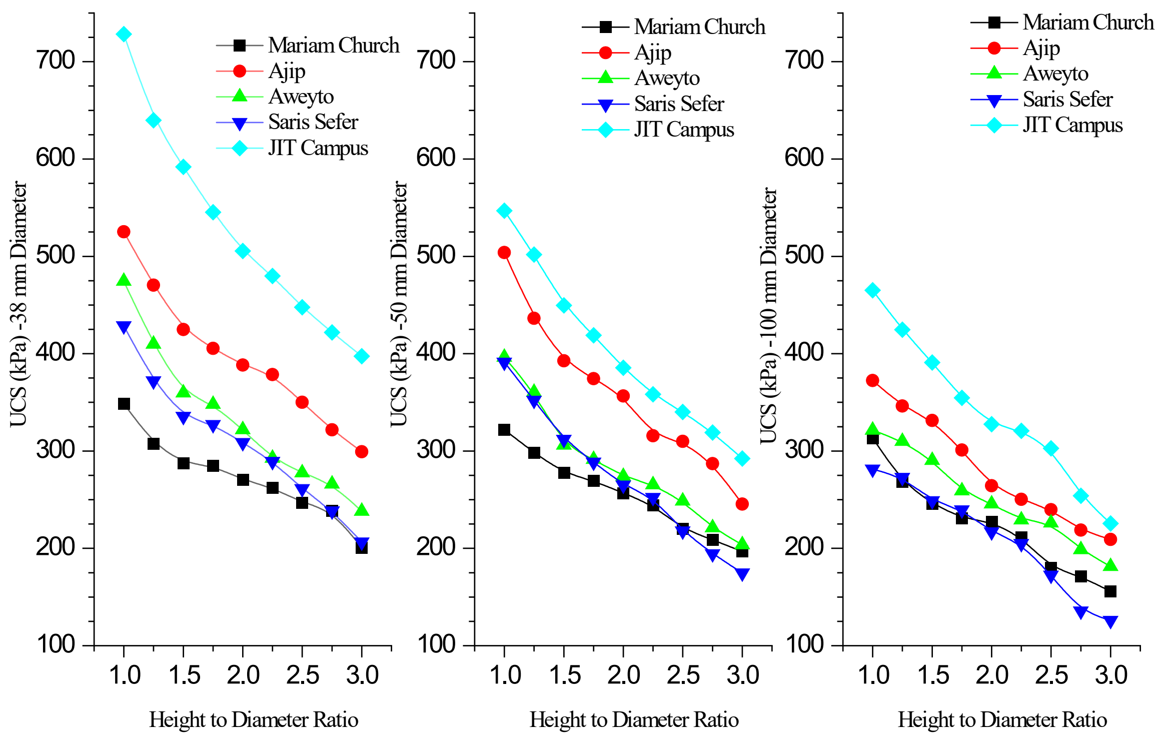

Figure 2: Peak value of unconfined compressive strength for specimens with diameter of 38, 50, and 100 mm with their respective H/D ratio.

in Figure 3, which is the same as [1] investigated earlier. The peak UCS value of all test pits at a small H/D ratio was the highest because the whole specimen is restrained by the friction of the end-loading plate and develops the potential for the interference of failure planes, which increases the UCS of a soil sample by preventing the formation of the weakest failure plane. From an H/D ratio of 2.50 to 3, the peak UCS values rapidly decreased and attained the smallest values due to the buckle effect, developing bulging local failures.

The peak value of UCS for each consecutive H/D ratio decreased as the diameter of specimens increased. Micro-defects and voids increased as the specimen's diameter increased. Compaction homogeneity and moisture content uniformity also started to decline. For these reasons, an increase in specimen diameter results in a fall in the UCS value. Despite the difficulty in transporting and drilling, large-sized soil sample specimens might represent the actual soil specimens in the field. This difference in the UCS value of the cohesive soil from the smallest specimen diameter to the largest specimen diameter was relatively smaller than that mentioned in [14, 20]. Both studies were conducted on specimen size effects using the triaxial test. The effect of confining pressure can explain the observed difference.

Figure 3 shows the variation in percentage for the peak UCS in each H/D ratio from their mean or average values of 38 mm, 50 mm, and 100 mm specimen diameter of all test pits. The sample specimen's UCS value of 2.0 H/D ratio was the one that comes closest to the average value for all specimens' diameter. However, the difference in the average value of UCS increased as the H/D ratio was far from the H/D ratio of 2 to both 1 and 3. The polynomial fit curve trend lines illustrated that, generally, the closest UCS value of the specimen to the mean value was at a 2 H/D ratio for all test pits. This property was also mentioned in [3], and the result was similar. According to the laboratory test result in the study, the UCS value is stable from 1.75 to 2.25 H/D ratio. The end platen and slenderness (buckling) effect decrease among these H/D ratios. Hence, the test result becomes close to the mean value of UCS for the cohesive soils tested at different specimen sizes.

3.2 Stress–strain curve scale effect of UCS

Figures 4–8 show the relation of stress–strain of unconfined compression test results for the test pits of Ajib, Aweytu, JIT, Mariam Church, and Saris Sefer, respectively. The peak UCS values were attained at the

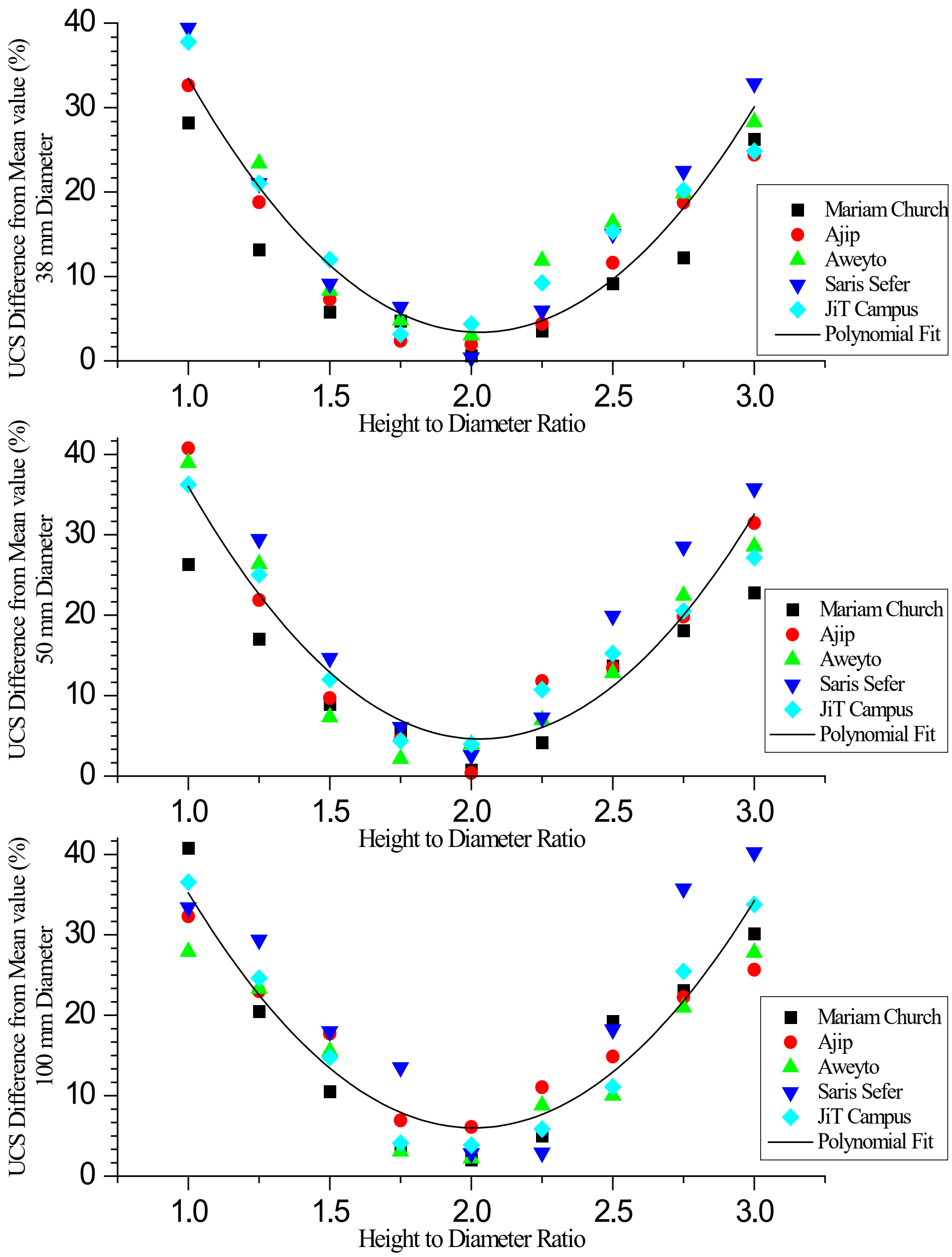

Figure 3: Percentage of UCS difference from the mean value for 38, 50, and 100 mm specimen diameters.

significant axial strain in the smallest H/D ratio. However, for a small H/D ratio, the specimen's stress–strain curve experienced small axial stresses at the early axial strains. When the height of the specimen was too short, the whole specimen was restrained by the friction of the end-loading plates [11]. This reveals that the axial stress grows to a peak and is slightly constant.

However, as the specimen's H/D ratio increased (from 1.75 for 38 mm and 1.50 for 50 mm specimen diameter), the curve was slightly linear at the initial axial strain, and then the slope decreased until the peak reached the UCS value. Having reached the peak UCS value, the curve rapidly dropped as the H/D ratio was increased. Specifically, from the H/D ratio of 2.50, the stress–strain curve was slightly linear, with less steeply slope until the peak strength was attained and the curve became sharp. Hence, the endplate effect was reduced by the specimen's height starting from 1.5 to 1.75 H/D ratios and above. However, the axial stresses rapidly dropped from 2.25 to 2.50 H/D ratios due to the increase in local defects and buckling effects. This is similar to that reported in previous studies [1,3,11].

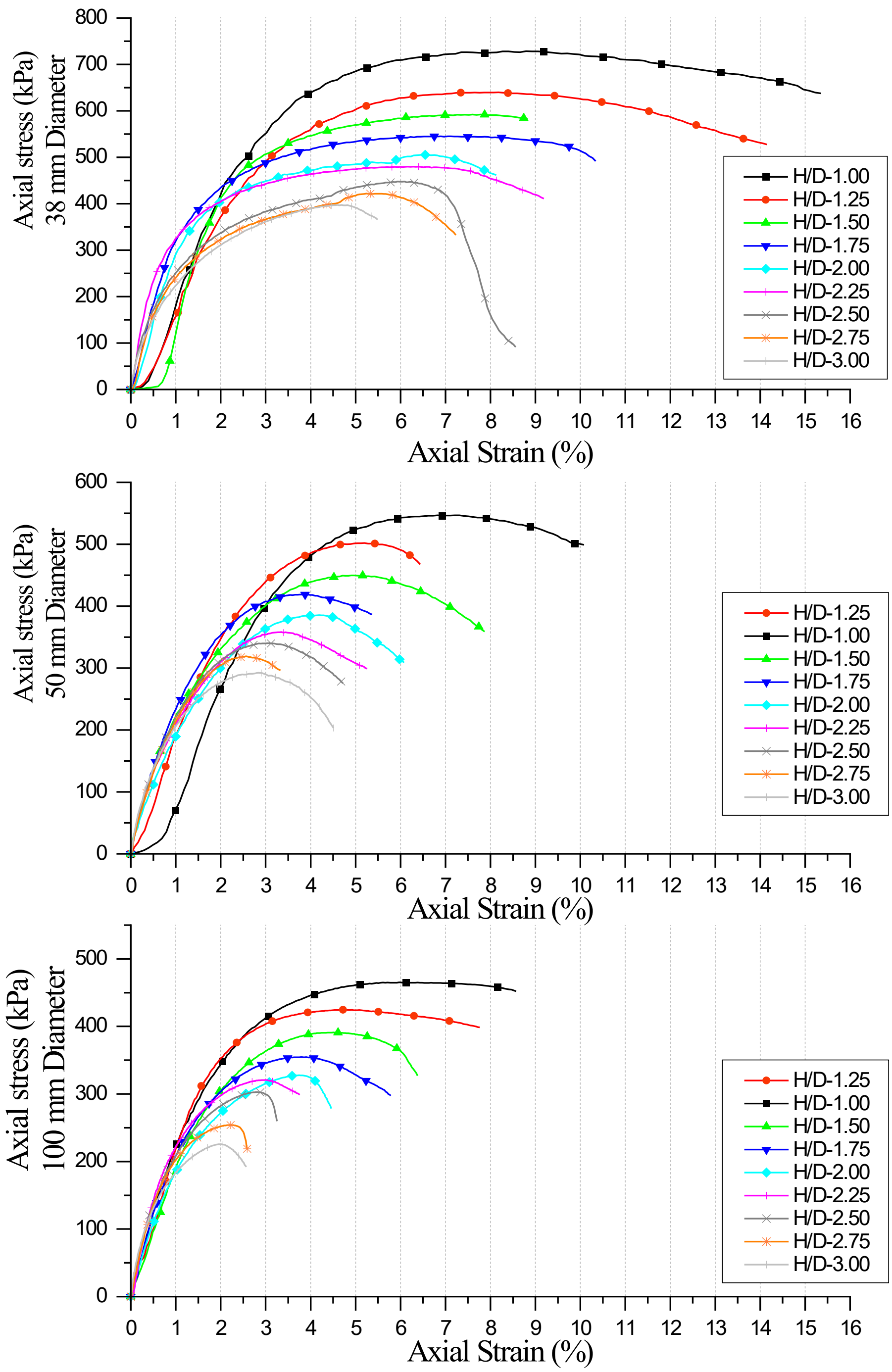

Figure 4: Stress–strain curves for 38 mm, 50 mm, and 100 mm specimen diameters of Ajip test pit from top to bottom.

The effect of specimen's diameter for a stress–strain curve is shown in Figures 5–9. As the H/D ratio increased, the axial strain of peak UCS decreased, and the sharpness of the curve increased for 38 mm specimen diameter. However, 50 and 100 mm specimen diameters showed relatively minor differences compared to the 38 mm diameter of the specimen.

The characteristics of the stress–strain curves in the successive specimens' H/D ratio becomes consistent as increased as the specimen's diameter. For instance, the 38 mm diameter specimen's peak UCS strain varied from 11.5% to 4.4%, while the strain value varied from 6% to 2% and from 4.7% to1.8% for specimen diameters of 50 and 100 mm, respectively. The peak UCS stress–strain curve of 38 mm specimen diameter was a smooth curve for an H/D

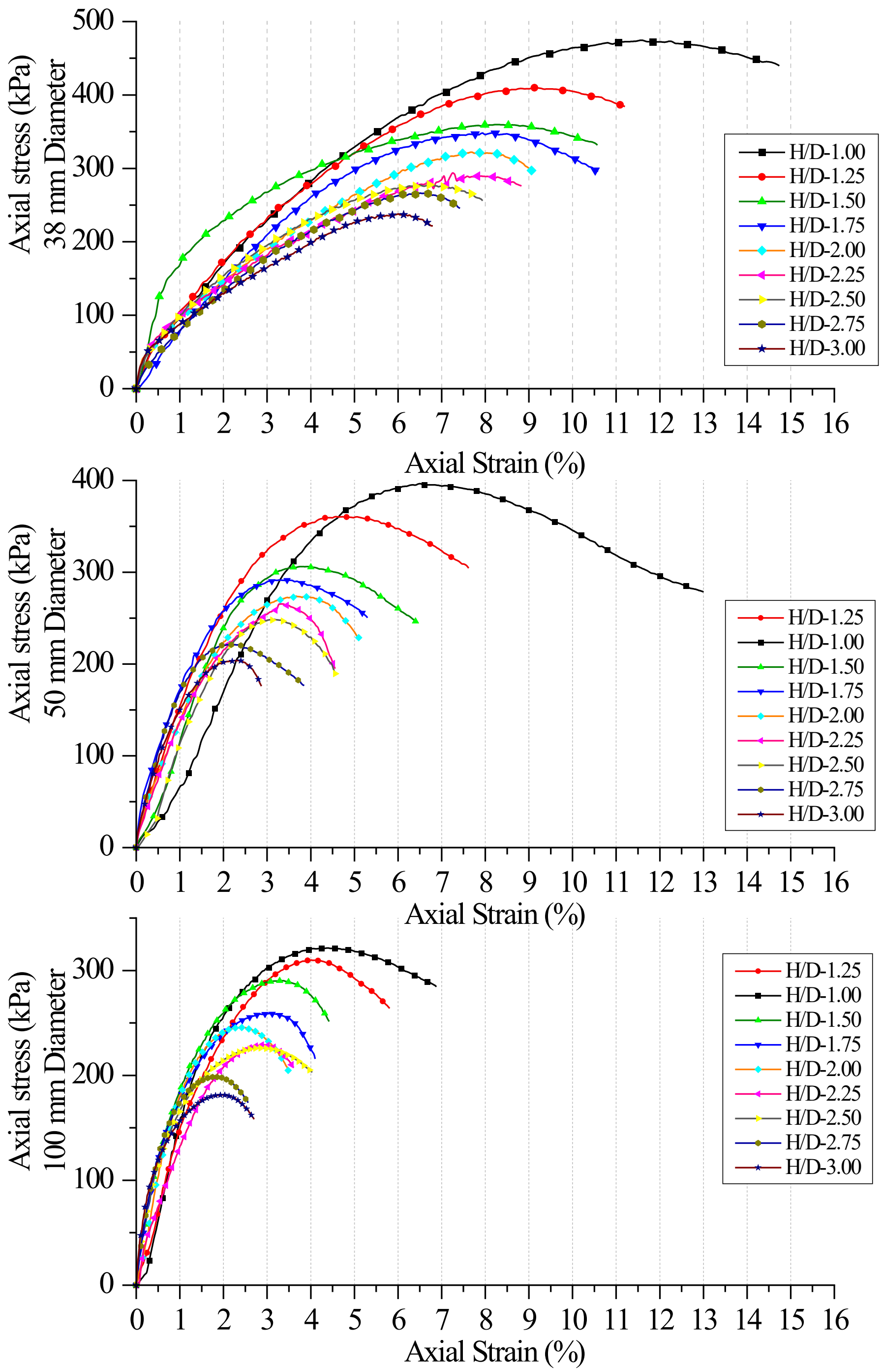

Figure 5: Stress–strain curves for 38 mm, 50 mm, and 100 mm specimen diameters of Aweytu test pit from top to bottom.

ratio from 1.00 to 1.75 for all test pits. In contrast, it was a sharp curve for an H/D ratio from 2.5 and above. The stress–strain curves were sharp for 50 and 100 mm diameter, starting from H/D ratios of 2. Therefore, the highest diameter specimen exhibited complex stress–strain curves compared to those of smaller diameter specimens. In this study, the stress–strain curve of 38 mm diameter experienced both ductile and brittle behaviors, while those of 50 and 100 mm specimen diameters possessed a brittle failure with localized shear failures before the development of one or more failure planes. Accordingly, the effect of the endplate decreased on increasing both the specimen diameter and H/D ratios. Thus, the behavior of the stress–strain curves of the unconfined compression test changed from ductile to brittle behavior as the H/D ratio and diameter of the specimen increased.

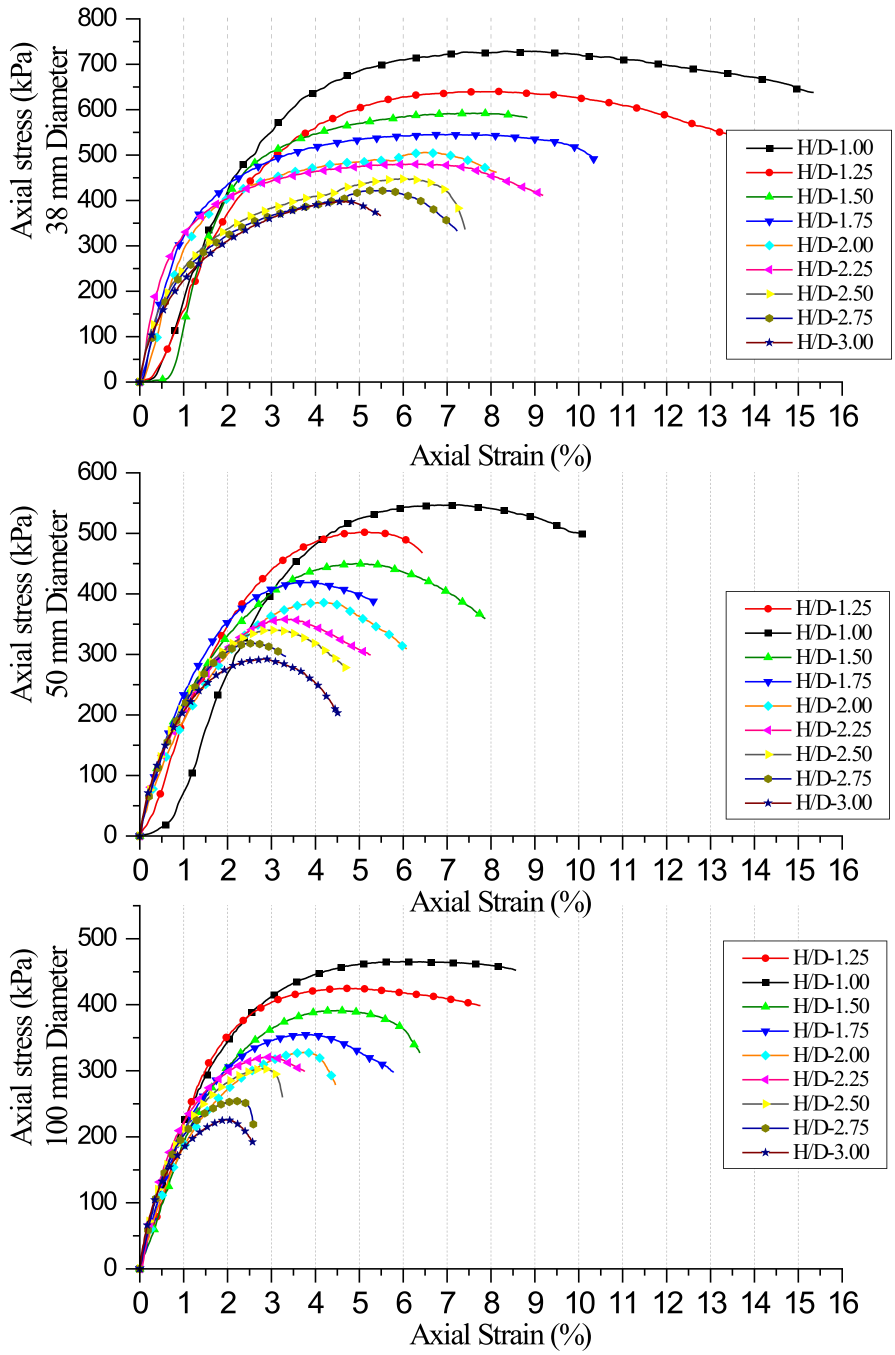

Figure 6: Stress–strain curves for 38 mm, 50 mm, and 100 mm specimen diameters of JIT campus test pit from top to bottom.

3.3 Effect of specimen's H/D ratio on the failure pattern

3.3.1 Failure pattern of 38-mm-diameter specimen

Figure 9 shows the failure pattern of a 38-mm-diameter specimen for various H/D ratios. The failure pattern of the axially compressed cohesive soil specimen varied as the specimen's H/D ratio increased. The observed failure crack was vertical for the H/D ratio of 1.00–1.50, and the crack extended from end to end of the entire specimen length. That is categorized as splitting tensile failure. However, the crack length and the inclination slope reduced as the H/D ratio increased from 1.75 to 2.25. The failure crack of high-plasticity clay soil specimen (CH) (for Ajip and JIT campus test pits) extended from nearly the top to the near bottom of the specimen and is classified as a shear failure pattern. For (test pits of Aweytu) low-

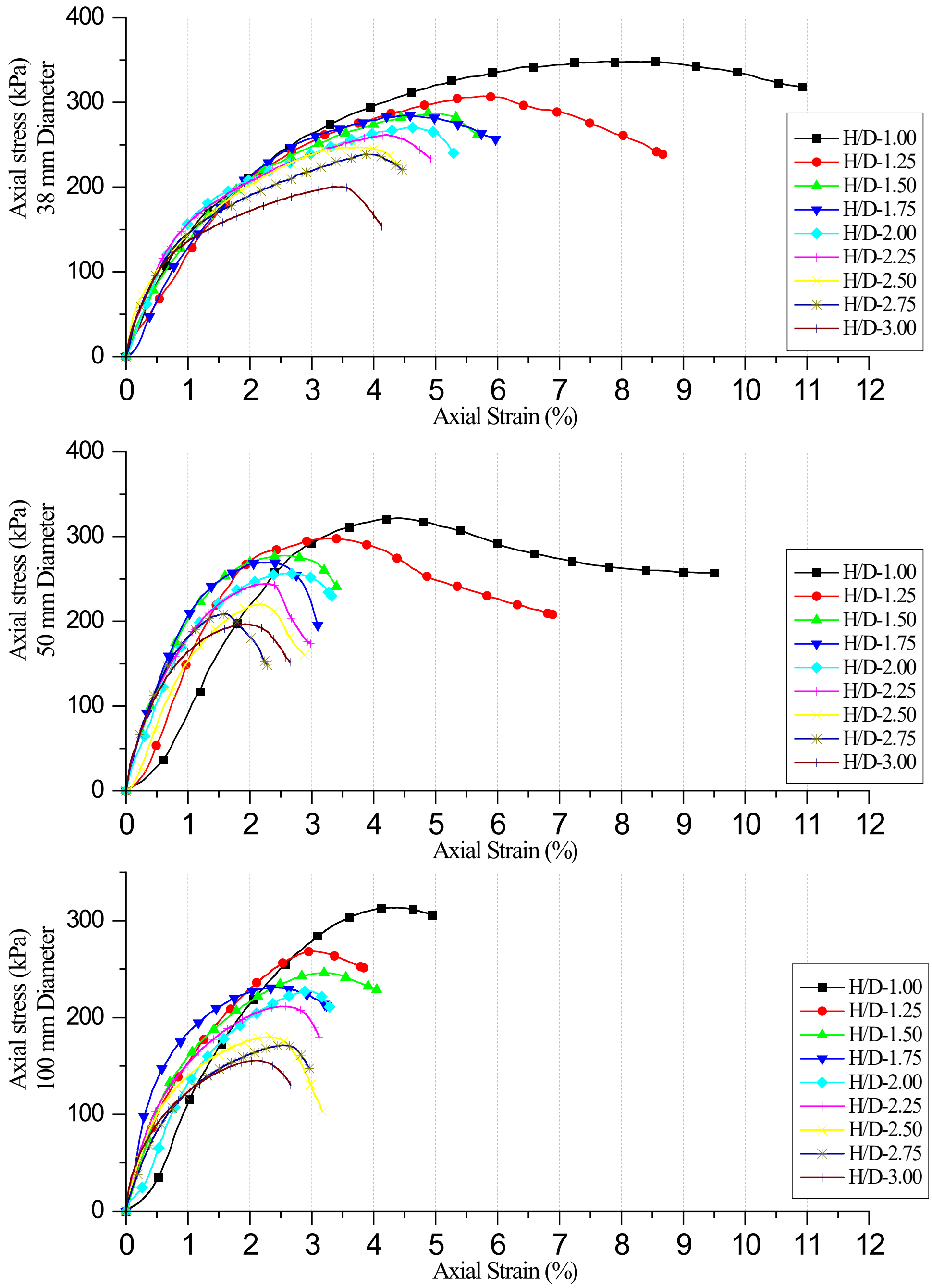

Figure 7: Stress–strain curves for 38 mm, 50 mm, and 100 mm specimen diameters of Mariam Church test pit from top to bottom.

plasticity clay soil (CL), Mariam church, and Saris Sefer high-plasticity slit soil (MH), the failure crack started from the top of the specimen and extended to the bottom of the specimen. However, it was not intersecting the lower edge of the specimen. Accordingly, the failure pattern was both tensile shear and shear failure.

The failure crack of the H/D ratio from 2.50 to 3.00 exhibited local failures at the top or middle of the specimens. The failure patterns of these H/D ratios were a mix of local splitting tensile, local tensile shear, local shear, and buckling. In this range, the failure pattern was observed as quite complex, as mentioned in previous studies such as [1] and [3]. According to the deformation characteristic in this study, for an H/D ratio from 1.00 to 2.00, the deformation was observed throughout the entire length. Though, the deformation of the specimens for these of H/D ratio greater than 2.00 were locally deformed. The specimens were laterally bulged up to an H/D ratio of 1.75.

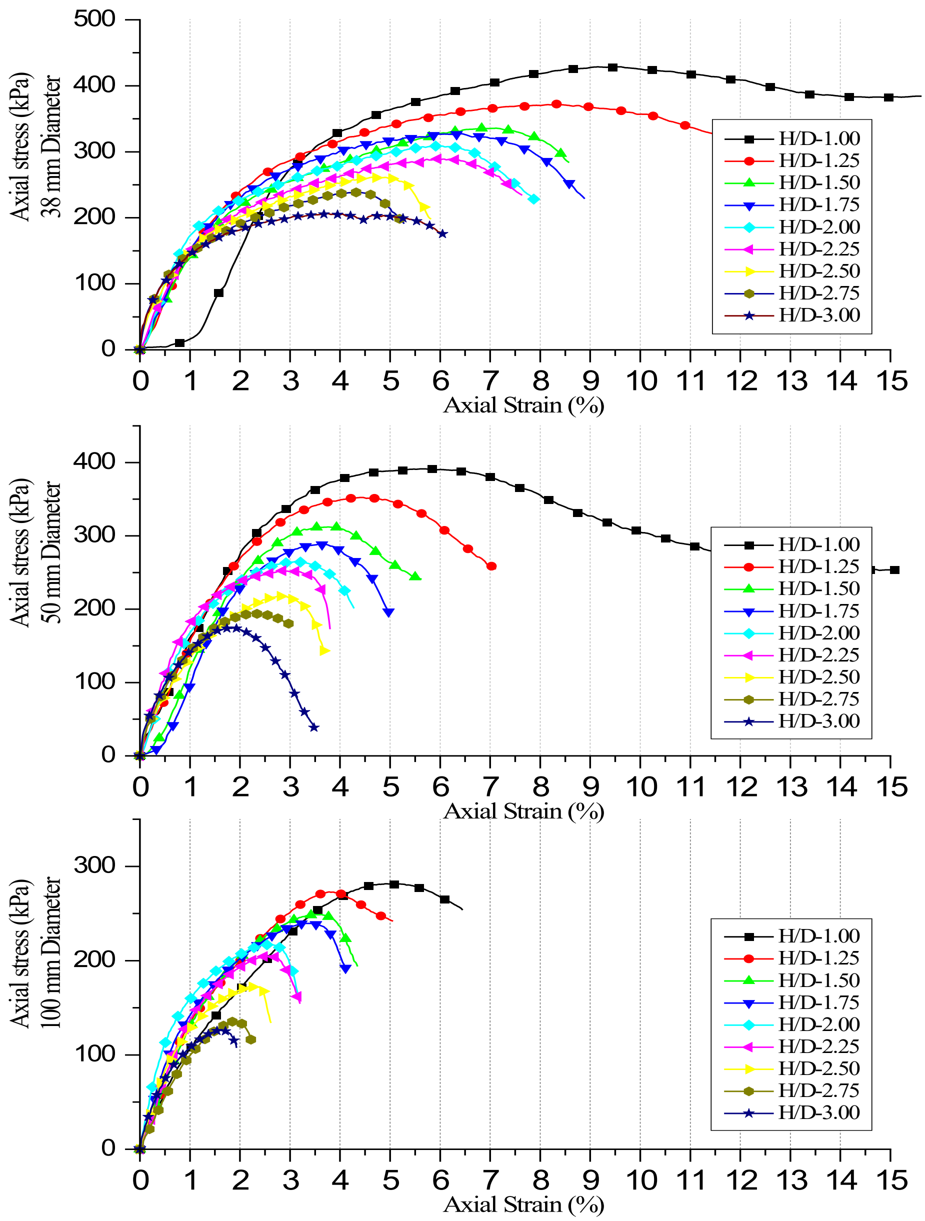

Figure 8: Stress–strain curves for 38 mm, 50 mm, and 100 mm specimen diameters of Saris Sefer test pit from top to bottom.

However, the bulging length decreased with increasing diameter of the specimens and their respective H/D ratio.

3.3.2 Failure pattern of 50-mm-diameter specimen

Figure 10 shows the failure pattern of specimens for various H/D ratios for a 50-mm-diameter specimen. For 50 mm specimen diameter, the tensile shear failure pattern started from an H/D ratio of 1.50. The tensile shear failure changed to shear failure for high-plasticity slit soil (MH) specimens for an H/D ratio from 1.75 to 2.50, for high-plasticity clay from 1.75 to 2.25 H/D ratio, and for low-plasticity clay soil (CL) specimens from 1.50 to 2.00 H/D ratio. For the low-plasticity clay soil (CL) and high-plasticity slit soil (MH), the specimens were deformed throughout their length from 1.00 to 2.50 H/D ratio. For soil specimens with high-plasticity clay soil (CH), specimens' deformation was throughout their entire length up to 2.00 H/D ratio. Nevertheless, for 2.75 and 3.00 H/D ratios, the specimens only deformed in some portion of their height. In contrast, the bulging characteristic of the cohesive soil specimen with 50-mm diameter decreased from an H/D ratio of 1.75 to 01.50.

Figure 9: Failure pattern of 38 mm specimen diameter: (a) Ajip, (b) Aweytu, (c) JIT campus, (d) Saris Sefer, and (e) Mariam Church.

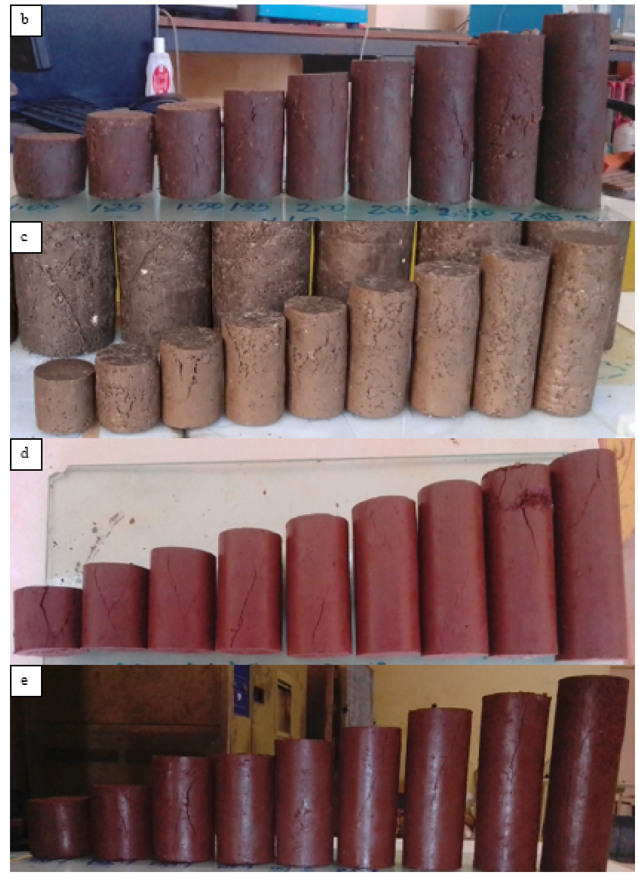

Figure 10: Failure pattern of 50 mm specimen diameter: (a) Ajip, (b) Aweytu, (c) JIT campus, (d) Saris Sefer, and (e) Mariam Church.

3.3.3 Failure pattern of 100-mm-diameter specimen

Figures 11 and 12 show the failure pattern of 100-mm-diameter specimen for various H/D ratios. At an H/D ratio of 1.00, the failure pattern for all test pits was splitting tensile, except for high-plasticity clay. The failure pattern of soil specimens of low to high plasticity was tensile shear failure at an H/D ratio of 1.25, shear failure from 1.50 to 2.25, and a mix of local failure patterns from 2.75 to 3.00. At the same time, the failure pattern of soil specimen from the Mariam Church test pit (high-plasticity slit soil [MH]) was tensile failure at an H/D ratio of 1.25, shear failure at an H/D ratio from 1.50 to 2.25, and shear and splitting tensile failure at an H/D ratio from 2.50 to 3.00. The soil specimen of JIT campus test pit (high-plasticity clay soil [CH]) showed bulging failure at an H/D ratio from 1.00 to 1.25, shear failure at an H/D ratio from1.50 to 2.25, and local shear failure at an H/D ratio from 2.50 to 3.00. According to the authors ‘ opinions, this difference may be observed due to the soil specimen test pits’ plasticity behavior and compaction uniformity.

In general, the specimen’s 50 and 100 mm diameters gave more reliable and representative UCS test results than 38 mm diameter, based on the uniformity of deformations, characteristics of failure patterns, and behavior of stress–strain curves observed in this study. Therefore, a greater diameter of the specimen accurately represents the soil strength in the field, as described in [14].

The peak unconfined compression strength of cohesive soil tested at an H/D ratio of 2.00 was most similar to the mean test result observed across all specimen diameters. This H/D ratio deformed consistently. Compared to other specimens’ H/D ratios, the stress–strain curve from H/D ratios of 1.75 to 2.25 was neither horizontal nor sharp. As a result, conducting an unconfined compression test at an H/D ratio of 2.00 yields a consistent and representative UCS of cohesive soil in specimens with diameters of 38, 50, and 100 mm. This H/D ratio is also recommended in [3] for 50-mm-diameter sample specimens and is within the range of the test standard given in [22].

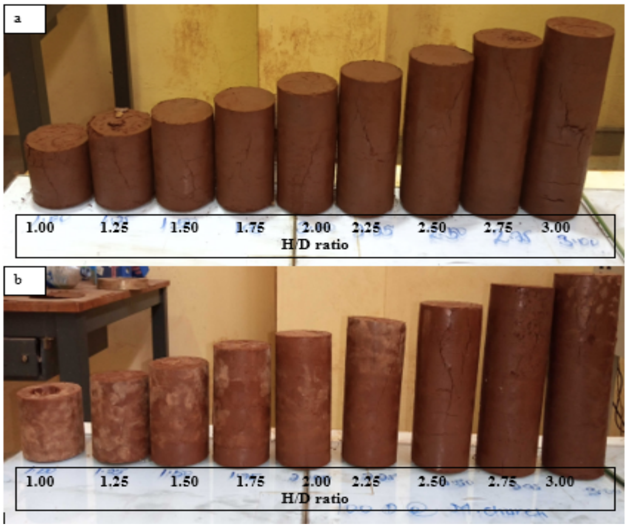

Figure 11: Failure pattern of 100 mm specimen diameter: (a) Saris Sefer and (b) Mariam Church.

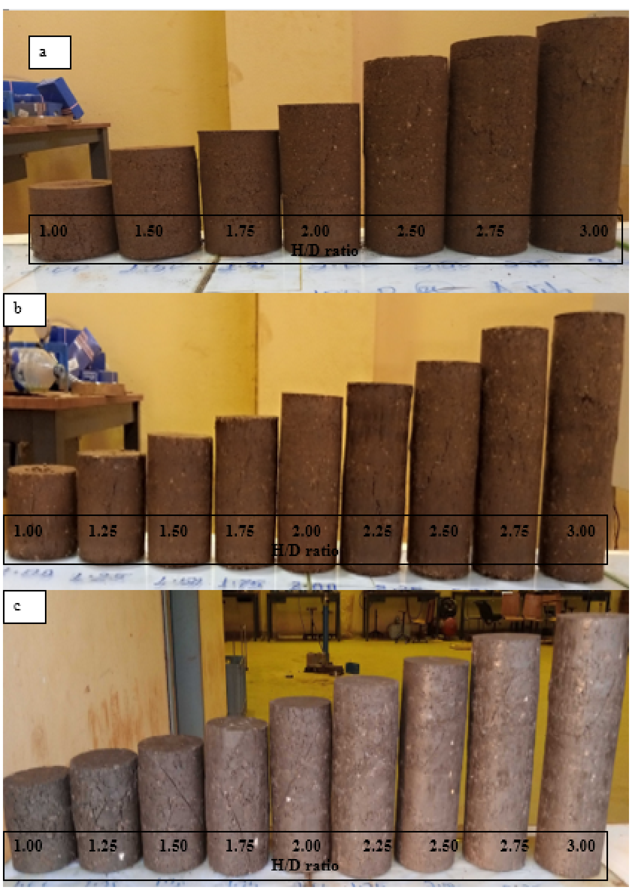

Figure 12: Failure pattern of 100 mm specimen diameter: (a) Ajip, (b) Aweytu, (c) JIT campus.

3.4 Regression analysis between the dependent variable (peak UCS value at H/D ratios of 2) and the predictors (H/D ratio)

3.4.1 Statistical data distribution, Shapiro–Wilk normality tests, scatter plots, and Pearson correlation coefficient (*R*) analyses

To perform regression analysis, the data were assessed using the statistical distribution, Shapiro–Wilk normality tests, scatter plots, and Pearson correlation coefficient (*R*). Accordingly, detailed analyses of these parameters are discussed in the subsequent sections.

3.4.1.1 Statistical data distribution result

Tables 3–5 shows the descriptive statistics of the peak UCS value of the five test pits for 38, 50, and 100 mm specimen diameters, respectively. These descriptive statistics results showed that the values of skewness and kurtosis over their standard error were in the range of –1.96 to +1.96. Therefore, the collected data were normally distributed data.

3.4.1.2 Normality test result

The two widely used normality tests are the Kolmogorov–Smirnov and the Shapiro–Wilk tests. Although it can handle sample sizes as large as 2000, the Shapiro–Wilk test is more suitable for small sample sizes (50 samples). For this reason, the Shapiro–Wilk test was employed as our numerical method of determining normality.

Table 6 shows that the significance levels (Sig.) are greater than 0.05 for all the test pits on Shapiro–Wilk analysis. This demonstrates that our data were normally distributed.

3.4.1.3 Scatter plot strategy

In this study, the H/D ratio of specimens with diameters of 38, 50, and 100 mm was used to represent the predictive (independent) variables, while the UCS was used as the dependent variable (dependent). OriginPro-2021 was used to create a scatter plot before starting the regression analysis using the test results. This allowed us to visually examine the relationships between the dependent and predictor variables and identify the model that best matched the test results.

Table 3: Descriptive statistics of the peak UCS value for specimens of diameter 38 mm.

	Number of observations	Minimum (kPa)	Maximum (kPa)	Mean (kPa)	Std deviation	Skewness	Skewness std error	Kurtosis	Kurtosis std error
Mariam Church	9	200.54	348.63	271.96	42.55	0.177	0.717	0.649	1.400
Ajip	9	299.33	525.21	395.97	71.13	0.527	0.717	-0.046	1.400
Aweytu	9	238.07	474.49	332.04	75.12	0.776	0.717	0.114	1.400
Saris Sefer	9	206.53	428.74	307.54	68.45	0.308	0.717	-0.111	1.400
JIT campus	9	397.37	728.32	528.64	108.76	0.682	0.717	-0.293	1.400

Table 4: Descriptive statistics of the peak UCS value for specimens of diameter 50 mm.

	Number of observations	Minimum (kPa)	Maximum (kPa)	Mean (kPa)	Std deviation	Skewness	Skewness std error	Kurtosis	Kurtosis std error
Mariam Church	9	196.73	321.97	254.91	41.74	0.132	0.717	-0.909	1.400
Ajip	9	245.42	503.90	358.01	79.63	0.529	0.717	0.005	1.400
Aweytu	9	203.80	396.40	285.28	62.33	0.627	0.717	-0.180	1.400
Saris Sefer	9	174.75	391.34	272.07	71.92	0.313	0.717	-0.757	1.400
JIT campus	9	292.35	546.82	401.37	85.46	0.525	0.717	-0.755	1.400

Table 5: Descriptive statistics of the peak UCS value for specimens of diameter 100 mm.

	Number of observations	Minimum (kPa)	Maximum (kPa)	Mean (kPa)	Std deviation	Skewness	Skewness std error	Kurtosis	Kurtosis std error
Mariam Church	9	155.66	313.46	222.71	50.06	0.434	0.717	-0.176	1.400
Ajip	9	209.21	372.44	281.48	58.61	0.338	0.717	-1.415	1.400
Aweytu	9	181.44	321.42	251.30	48.41	0.130	0.717	-1.134	1.400
Saris Sefer	9	126.06	281.43	210.98	56.46	-0.386	0.717	-1.181	1.400
JIT campus	9	225.62	465.21	340.70	77.48	0.142	0.717	-0.629	1.400

Analysis of the scatter plots of the peak UCS for all test pits is shown in Figure 13. This figure shows that there is a real indication of the points lying randomly spread as a straight or nearly straight line.

3.4.1.4 Correlation analysis and result (Pearson correlation coefficient, *R*)

The most popular method for determining a linear correlation is the Pearson correlation coefficient (R). The intensity and direction of the relationship between two variables are expressed as a number between –1 and 1.

In Tables 7–9, there is sufficient evidence to conclude that there is a significant (Sig.) linear relationship between the peak UCS value of all test pits and the H/D ratio because the correlation coefficient is significantly different from zero.

Table 6: Shapiro–Wilk normality test.

	38 mm specimen diameter			50 mm specimen diameter			100 mm specimen diameter		
	Statistic	**Degrees of freedom**	**Sig.**	**Statistic**	**Degrees of freedom**	**Sig.**	**Statistic**	**Degrees of freedom**	**Sig.**
Mariam Church	0.989	9	0.995	0.974	9	0.926	0.968	9	0.879
Ajip	0.974	9	0.925	0.977	9	0.946	0.936	9	0.538
Aweytu	0.952	9	0.709	0.956	9	0.759	0.959	9	0.784
Saris Sefer	0.988	9	0.994	0.974	9	0.925	0.935	9	0.532
JIT campus	0.953	9	0.725	0.958	9	0.776	0.981	9	0.969

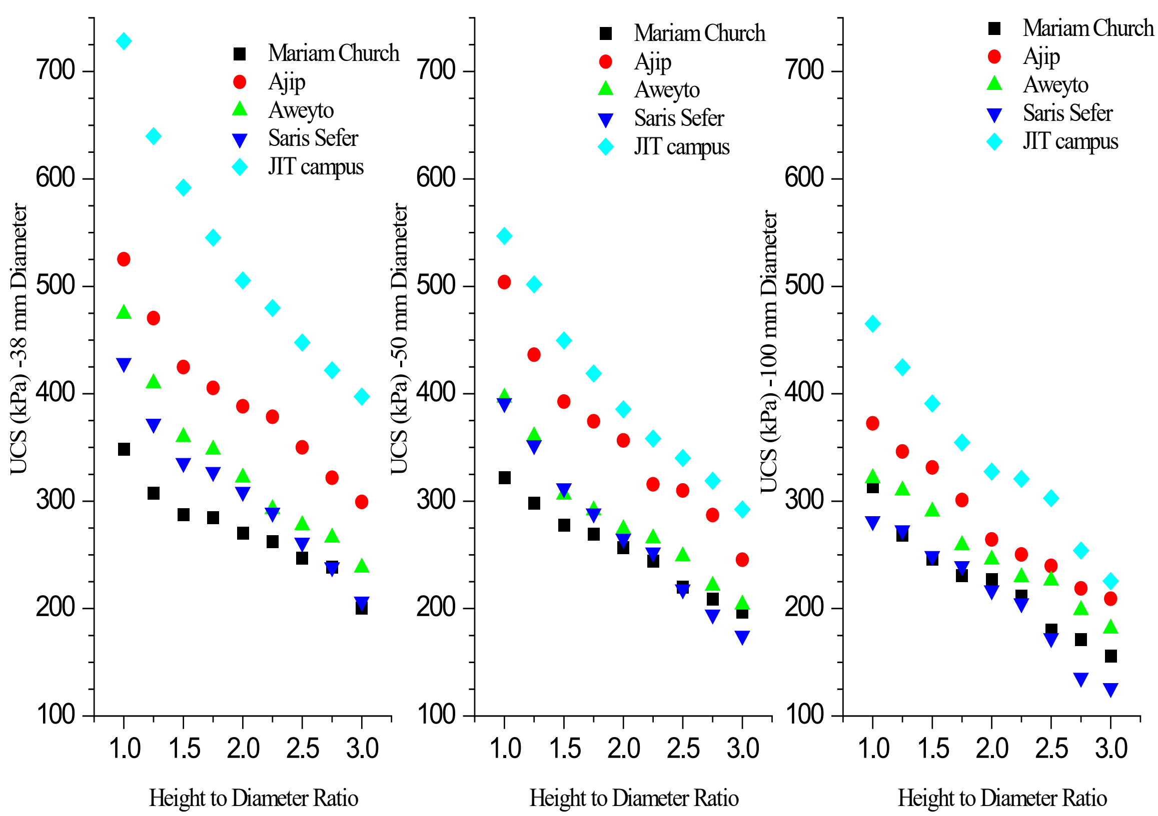

Figure 13: The scatter plot of UCS versus H/D ratio for 38, 50, and 100 mm specimen diameter from left to right.

3.4.2 Regression analysis

This study set a correction factor to the optimum H/D ratio (i.e., 2.00) for specimens with diameters 38, 50, and 100 mm. As a result, the best fit line and least square regression were determined for cohesive soil specimens with low-plasticity clay soil (Aweytu test pit), high-plasticity clay soil (Ajip and JIT campus test pits), and high-plasticity silt soil (Saris Sefer and Mariam Church test pits) in all specimen diameters. To perform regression analysis, the data were assessed with statistical distribution, Shapiro–Wilk normality tests, scatter plots, and Pearson correlation coefficient (*R*). The results showed normally distributed data, with a strong correlation between the peak UCS value and the cohesive soil specimens' H/D ratio of all specimens' diameters.

As a result, for 38, 50, and 100 mm specimen diameters, the ratio of peak UCS of different H/D ratios (i.e., from 1.00 to 3.00) to 2.00 H/D ratio ($UCS/UCS_{2.00}$) is plotted in Figures 14–16, respectively. For these plotted

Table 7: Significance level (Sig.) and Pearson correlation coefficient (*R*) of UCS value for 38 mm specimen diameter.

		Height to diameter ratio	UCS of Mariam Church test pit	UCS of Ajip test pit	UCS of Aweytu test pit	UCS of Saris Sefer	UCS of JIT campus test pit
Height to diameter ratio (H/D)	*R*	1	-0.968**	-0.979**	-0.970**	-0.984**	-0.979**
	Sig.		0.000	0.000	0.000	0.000	0.000
	n	9	9	9	9	9	9
UCS of Mariam Church test pit	*R*	-0.968**	1	0.984**	0.977**	0.993**	0.971**
	Sig.	0.000		0.000	0.000	0.000	0.000
	n	9	9	9	9	9	9
UCS of Ajip test pit	*R*	-0.979**	0.984**	1	0.991**	0.996**	0.992**
	Sig.	0.000	0.000		0.000	0.000	0.000
	n	9	9	9	9	9	9
UCS of Aweytu test pit	*R*	-0.970**	0.977**	0.991**	1	0.988**	0.995**
	Sig.	0.000	0.000	0.000		0.000	0.000
	n	9	9	9	9	9	9
UCS of Saris Sefer test pit	*R*	-0.984**	0.993**	0.996**	0.988**	1	0.986**
	Sig.	0.000	0.000	0.000	0.000		0.000
	n	9	9	9	9	9	9
UCS of JIT campus test pit	R	-0.979**	0.971**	0.992**	0.995**	0.986**	1
	Sig.	0.000	0.000	0.000	0.000	0.000	
	n	9	9	9	9	9	9

n – number of valid observations for the variable
**Correlation is significant at the 0.01 level (two-tailed)

Table 8: Significance level (Sig.) and Pearson correlation coefficient (*R*) of UCS value for 50 mm specimen diameter.

		Height to diameter ratio	UCS of Mariam Church test pit	UCS of Ajip test pit	UCS of Aweytu test pit	UCS of Saris Sefer	UCS of JIT campus test pit
Height to diameter ratio (H/D)	*R*	1	-0.994	-0.978	-0.973	-0.993	-0.986
	Sig.		0.000	0.000	0.000	0.000	0.000
	n	9	9	9	9	9	9
UCS of Mariam Church test pit	*R*	-0.994	1	0.983	0.981	0.997	0.987
	Sig.	0.000		0.000	0.000	0.000	0.000
	n	9	9	9	9	9	9
UCS of Ajip test pit	*R*	-0.978	0.983	1	0.989	0.988	0.991
	Sig.	0.000	0.000		0.000	0.000	0.000
	n	9	9	9	9	9	9
UCS of Aweytu test pit	*R*	-0.973	0.981	0.989	1	0.992	0.992
	Sig.	0.000	0.000	0.000		0.000	0.000
	n	9	9	9	9	9	9
UCS of Saris Sefer test pit	*R*	-0.993	0.997	0.988	0.992	1	0.995
	Sig.	0.000	0.000	0.000	0.000		0.000
	n	9	9	9	9	9	9
UCS of JIT campus test pit	*R*	-0.986	0.987	0.991	0.992	0.995	1
	Sig.	0.000	0.000	0.000	0.000	0.000	
	n	9	9	9	9	9	9

n – number of valid observations for the variable
**Correlation is significant at the 0.01 level (two-tailed)

Table 9: Significance level (Sig.) and Pearson correlation coefficient (*R*) of UCS value for 100 mm specimen diameter.

		Height to diameter ratio	UCS of Mariam Church test pit	UCS of Ajip test pit	UCS of Aweytu test pit	UCS of Saris Sefer	UCS of JIT campus test pit
Height to diameter ratio (H/D)	*R*	1	-0.979	-0.988	-0.992	-0.987	-0.990
	Sig.		0.000	0.000	0.000	0.000	0.000
	n	9	9	9	9	9	9
UCS of Mariam Church test pit	*R*	-0.979	1	0.965	0.965	0.958	0.979
	Sig.	0.000		0.000	0.000	0.000	0.000
	n	9	9	9	9	9	9
UCS of Ajip test pit	*R*	-0.988	0.965	1	0.989	0.960	0.983
	Sig.	0.000	0.000		0.000	0.000	0.000
	n	9	9	9	9	9	9
UCS of Aweytu test pit	*R*	-0.992	0.965	0.989	1	0.972	0.993
	Sig.	0.000	0.000	0.000		0.000	0.000
	n	9	9	9	9	9	9
UCS of Saris Sefer test pit	*R*	-0.987	0.958	0.960	0.972	1	0.974
	Sig.	0.000	0.000	0.000	0.000		0.000
	n	9	9	9	9	9	9
UCS of JIT campus test pit	*R*	-0.990	0.979	0.983	0.993	0.974	1
	Sig.	0.000	0.000	0.000	0.000	0.000	
	n	9	9	9	9	9	9

n – number of valid observations for the variable
[**]Correlation is significant at the 0.01 level (two-tailed)

Table 10: Model summary of UCS/(UCS at 2 H/D ratio)-38 mm diameter and H/D ratio.

Model summary[b]				
Model	***R***	***R*²**	**Adjusted *R*²**	**Std error of the estimate**
1	0.963[a]	0.928	0.926	0.053191

[a]Predictors: (constant), H/D ratio
[b]Dependent variable: UCS/(UCS at 2 H/D ratio)-38 mm diameter

Table 11: Coefficients of UCS/(UCS at 2 H/D ratios)-38 mm diameter and H/D ratio.

Coefficients[a]						
Model		**Unstandardized coefficients**		**Standardized coefficients**	*t*	**Sig.**
		B	**Std. Error**	**beta**		
1	(Constant)	1.596	0.026		61.838	0.000
	H/D ratio	-0.288	0.012	-0.963	-23.469	0.000

[a]Dependent variable: UCS/(UCS at 2 H/D ratio)-38 mm diameter

graphs, linear regression lines were fitted to the resulting data for the cohesive soils which were collected from five test pits at different locations in Jimma Town.

Accordingly, the general correction formula for the H/D ratio of 2.00 for specimen diameters of 38, 50, and 100 mm is given as

$$\frac{\mathrm{UCS}}{\mathrm{UCS}_{2.00}} = a - b\left(\frac{H}{D}\right) \tag{1}$$

where a-$b(H/D)$ is the correcting factor for UCS of cohesive soil at H/D ratio of 2.

By rearranging equation (1), we obtain

$$\mathrm{UCS}_{2.00(\mathrm{corrected})} = \frac{\mathrm{UCS\ (measured)}}{a-b(\frac{H}{D})} \tag{2}$$

where $\mathrm{UCS}_{2.00}$ is the corrected UCS (kPa) at H/D ratio of 2.00 for specimen diameters of 38, 50, and 100 mm, UCS is the measured UCS (kPa) within $1.00 \le H/D \le 3.00$, H is the specimen height, D is the specimen's diameter, "a" is the intercept, and "b" is the slope of linear regression fit lines.

Table 12: Model summary of UCS/(UCS at 2 H/D ratios)-50 mm diameter and H/D ratio.

Model summary[b]				
Model	*R*	R^2	Adjusted R^2	Std error of the estimate
2	0.969[a]	0.938	0.937	0.0540444

[a]Predictors: (constant), H/D ratio
[b]Dependent variable: UCS/ (UCS at 2 H/D ratio)-50 mm diameter

Table 13: Coefficients of UCS/ (UCS at 2 H/D ratios)-50 mm diameter and H/D ratios.

Coefficients[a]						
Model		Unstandardized coefficients		Standardized coefficients	*t*	Sig.
		B	Std error	beta		
2	(Constant)	1.658	0.026		63.201	0.000
	H/D ratio	-0.318	0.012	-0.969	-25.509	0.000

[a]Dependent variable: UCS/ (UCS at 2 H/D ratio)-50 mm diameter

Table 14: Model summary of UCS/(UCS at 2 H/D ratios)-100 mm diameter and H/D ratio.

Model summary[b]				
Model	*R*	R^2	Adjusted R^2	Std error of the estimate
3	0.970[a]	0.941	0.940	0.0540500

a. Predictors: (constant), H/D ratio
b. Dependent Variable: UCS/(UCS at 2 H/D ratio)-100 mm Diameter

Table 15: Coefficients of UCS/(UCS at 2 H/D ratios)-100 mm diameter and H/D ratios.

Coefficients[a]						
Model		Unstandardized coefficients		Standardized coefficients	*t*	Sig.
		B	Std error	beta		
3	(Constant)	1.671	0.026		63.699	0.000
	H/D ratio	-0.328	0.012	-0.970	-26.238	0.000

[a]Dependent variable: UCS/(UCS at 2 H/D ratio)-100 mm diameter

The correlation coefficients, the intercept (a), and the slope (b) values are summarized in Table 16.

The correlation coefficients, the intercept (a), and the slope (b) values are summarized in Table 16.

The single linearly regression fitted lines in Figure 14 (38 mm specimen diameter), Figure 15 (50 mm specimen diameter), and Figure 16 (100 mm specimen diameter) show that there is a strong negative correlation between

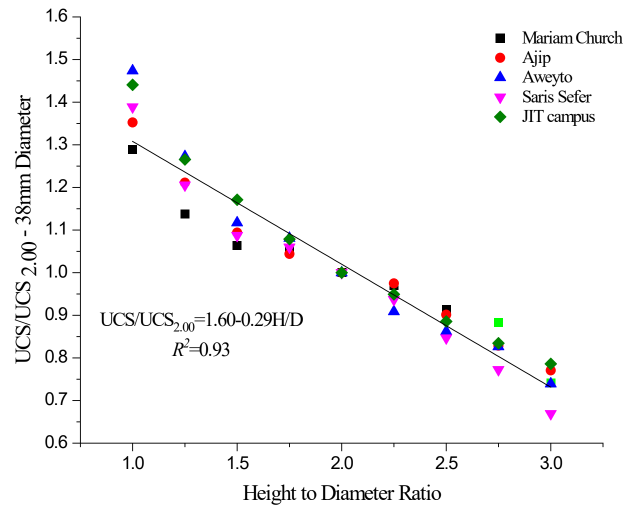

Figure 14: Plot of $UCS/UCS_{2.00}$ versus height to diameter ratio for a specimen diameter of 38 mm.

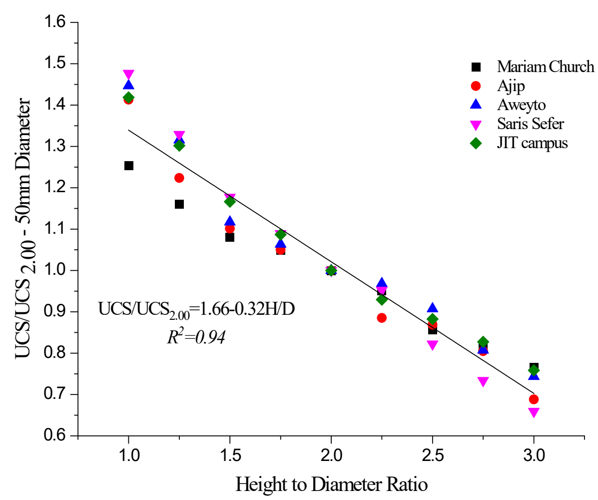

Figure 15: The plot of $UCS/UCS_{2.00}$ versus height to diameter ratio of 50 mm specimen diameter.

UCS(measured)/$UCS_{2.00}$ ratio and H/D ratio. Table 10-15 shows that, details of the statistical output indicated that the relationship developed between UCS and H/D ratio of all specimens' diameters was significant (i.e., *P*-value (Sig.) = 0.000 < 0.05).

3.4.3 Validation of regression model

3.4.3.1 Regression model accuracy

Finding a line with the lowest prediction error across all data points is the goal of linear regression. The performance of the model in regression analysis is assessed using the metrics mean squared error (MSE), mean absolute error

Table 16: Regression equations of $UCS(measured)/UCS_{2.00}$ ratio for different specimen diameters versus H/D ratio.

Specimens' diameter	Regression equations	R^2	Sig.	Correlation state	Equation number
38 mm	$UCS_{2.00}$=(UCS(measured))/(1.596-0.288(H/D))	0.928	0.000	Strong	3
50 mm	$UCS_{2.00}$=(UCS(measured))/(1.658-0.318(H/D))	0.938	0.000	Strong	4
100 mm	$UCS_{2.00}$=(UCS(measured))/(1.671-0.328(H/D))	0.941	0.000	Strong	5

Table 17: Regression model accuracy for the developed equations.

Specimens' diameter of regression equations	MAE	MSE	RMSE	MAPE
38 mm	13.44	289.05	16.70	3.84%
50 mm	12.53	215.77	14.64	4.15%
100 mm	11.21	232.69	14.86	4.42%

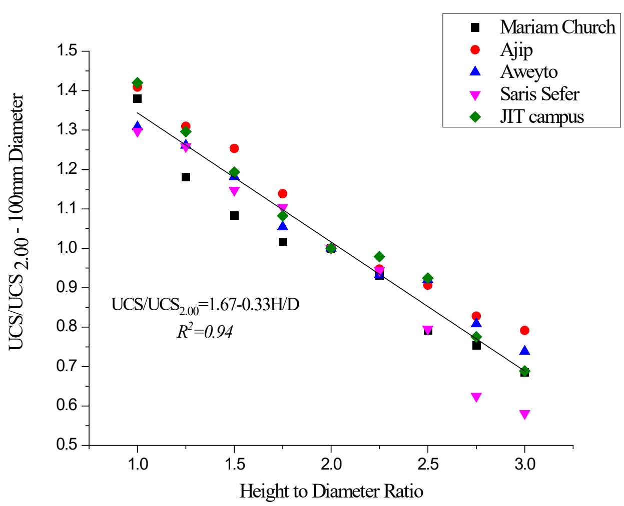

Figure 16: The plot of $UCS/UCS_{2.00}$ versus height to diameter ratio of 100 mm specimen diameter.

(MAE), root mean square error (RMSE), and mean absolute percentage error (MAPE). These values are described in Table 17.

3.4.3.2 Comparison of the developed corrective formulas with measured UCS value for 2 H/D ratio

The corrective formulas of UCS from the developed model are determined and compared to the actual UCS value of H/D ratio of 2 for the three diameters of specimens. Thus, the variations of UCS value measured at 2 H/D ratio and the corrected values for the different aspect ratios are calculated as

$$\text{Variation} = \frac{\text{Measured UCS@2}(\frac{H}{D})\text{ratio} - \text{Corrected UCS @ different}\frac{H}{D}\text{ratio}}{\text{Measured UCS@2}\frac{H}{D}\text{ratio}} * 100 \quad (6)$$

where variation is the variation in percentage between the measured laboratory and predicted UCS of the sample specimens for 2 H/D ratios, a UCS@2(H/D) ratio is the laboratory measured UCS at 2 H/D ratios (kPa), and corrected UCS @ different H/D ratios is the predicted value for UCS from different 1 H/D ratio to 3 H/D ratios at 2 H/D ratios (kPa).

The variations in percentage between the measured and predicted UCS values for the H/D ratio of 2 were determined using equation (6). The calculated values were 3.62%, 3.69%, and 6.18% for specimens with diameters of 38, 50, and 100 mm, respectively.

4 Concluding remarks

Based on the study and experimental data, the scale effect of specimen size on the UCS of cohesive soil was assessed from a series of laboratory tests by changing the H/D ratio of different specimens' diameters and heights. In addition, several literature reviews and user preference gap knowledge were pointed out to draw the following conclusions in connection to the experimental work:

- The tendency to decrease the UCS value with increasing H/D ratio is not affected by the diameters of the cohesive soil specimens. The UCS value linearly decreases with increasing H/D ratio in all diameters of the specimens. Similarly, the peak value of UCS for each consecutive H/D ratio decreases with the increase in specimens' diameter.
- The stress–strain curve of the small diameter changed from ductile to brittle state behavior with the increment of the H/D ratio. Although the diameter increases, the curves of the series H/D ratios are governess by brittle behavior. The axial strains of the peak UCS value also decrease with the increase in both specimens' diameter and their respective H/D ratios. Similarly, the difference in axial strains between the smallest and the largest H/D ratios decreases with the increase in specimens' diameter.

- The failure patterns of axially compressed cohesive soil specimens alter as the diameters and H/D ratios increase. In this study, we found different failure patterns of shear, tensile and splitting failure at different diameters over the range of H/D variation.
- From 1.00 to 3.00 consecutive H/D ratios, the closest to the mean UCS value was 2.00 in all specimen diameters. Correspondingly, according to the uniformity of deformations, failure patterns, and the behavior of stress–strain curves, an unconfined compression test at a 2 H/D ratio gives a consistent and representative UCS of cohesive soil in 38, 50, and 100 mm specimen diameters.
- For specimens with diameters of 38, 50, and 100 mm, equations with strong correlation coefficients were developed to convert the measured UCS values from 1.00 to 3.00 H/D ratios to the standard UCS value at a 2.00 H/D ratio.

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