

Evaluating Soil Classification Variability in Engineering Geology and Geotechnics: A Case Study from Central Europe

Stanislav PASEKA

Authors' affiliations and addresses:

Institute of Landscape Water Management,
Faculty of Civil Engineering, Brno University of
Technology, Brno, Czech Republic
e-mail: stanislav.paseka@vut.cz

Correspondence:

Stanislav Paseka, Institute of Landscape Water
Management, Faculty of Civil Engineering, Brno
University of Technology, Brno, Czech Republic
tel.: +420541147782
e-mail: stanislav.paseka@vut.cz

Funding information:

Brno University of Technology
Grant Number: FAST-S-25-8771: Precipitation-
runoff and erosion processes in the landscape and
optimization of extensive water treatment
processes

How to cite this article:

Paseka, S. (2026). Evaluating Soil Classification
Variability in Engineering Geology and
Geotechnics: A Case Study from Central Europe.
Acta Montanistica Slovaca, Volume 31 (2), 531-
546

DOI:

<https://doi.org/10.46544/AMS.v31i2.16>

Abstract

Accurate soil classification is crucial in engineering geological investigations, as it directly impacts foundation stability, load-bearing assessments, and seepage control in geotechnical structures. This study investigates the impact of various measurement methods on soil classification, utilizing a case study in the Czech Republic, with a focus on geotechnical and underground engineering applications. Three boreholes were analysed, following international standards (EN ISO 14688-2, EN ISO 17892-4, and ČSN 73 6133), to assess particle size distribution (PSD) and consistency limits. The PSD was determined from dry and wet sieving combined with hydrometer analysis, while the liquid limit (WL) and plastic limit (WP) tests were performed using both standardised and modified techniques.

The results revealed notable variability in PSD, particularly for fine-grained fractions, influenced by sample preparation techniques and procedural inconsistencies. WL tests showed strong agreement between the standardised and custom-made cones, with deviations of less than 6.4%, while plasticity index (IP) calculations revealed differences between the in-house and accredited laboratory results, emphasizing the role of methodological precision.

The study applied both the Unified Soil Classification System (USCS) and ČSN classification frameworks, revealing that while the plasticity chart consistently distinguished clays from silts, broader soil classifications varied significantly depending on the measurement approach. These findings underscore the necessity for standardized geotechnical testing protocols to ensure reliable classifications for underground engineering, foundation design, and other environmental applications, thereby contributing to safer and more sustainable infrastructure development.

Keywords

Soil Classification, Particle Size Distribution (PSD), Consistency Limits, Geotechnical Engineering, Engineering Geology.



© 2026 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).

Introduction

Engineering geology plays a fundamental role in ensuring the stability, safety, and longevity of infrastructure. Accurate characterisation of soil properties is essential for predicting soil behaviour under various environmental conditions and in the design of structures ranging from small-scale residential foundations to large-scale infrastructure and landscape engineering projects. Comprehensive geotechnical investigations help mitigate risks associated with foundation instability, reduce maintenance costs, and prevent structural failures, which can have significant economic and environmental consequences (Malomo et al., 1983; Amadi et al., 2012). Soil classification is a cornerstone of engineering geological studies, directly influencing critical design decisions such as foundation depth, load-bearing capacity, and soil permeability, in both geotechnical and hydraulic engineering applications.

A reliable classification framework requires the integration of both laboratory and in-situ testing methods, each providing complementary insights into soil stiffness, strength, and consistency. Laboratory tests, such as liquid limit (WL) and plastic limit (WP) measurements, are particularly crucial when defining the boundaries between the solid, plastic, and liquid states of fine-grained soils. These parameters influence deformation behaviour, mechanical properties, and the effects of moisture fluctuations on long-term structural stability (Sherwood and Ryley, 1970; Houlsby, 1982). In geotechnical, mining, and hydraulic engineering, these tests are essential when assessing soil suitability for embankments, dikes, and other earthworks, where precise classification is critical to ensure stability, load-bearing efficiency, and seepage control.

This study follows internationally recognized standards, including EN ISO 14688-1, EN ISO 14688-2, EN ISO 17892-4, EN ISO 17892-12, and ASTM D2487-11. These standards provide a consistent methodological framework for determining consistency limits and particle size distribution (PSD), ensuring comparability and reproducibility across geotechnical investigations. The WL was determined using both a standardised cone penetrometer and a custom-made cone, while the WP was measured using the manual thread-rolling method. Together, these tests define the plasticity index (IP), a key classification parameter for fine-grained soils (Karlsson, 1961; Robertson, 2006; Fojtova and Marschalko, 2008; EN ISO 17892-4, 2016). PSD was analysed using both dry and wet sieving techniques, supplemented by hydrometer analysis to capture finer soil fractions.

Previous studies have highlighted the inherent variability in geotechnical testing and its impact on classification accuracy. Hrubesova et al. (2016) reported significant discrepancies between the Casagrande cup and cone penetrometer methods, particularly for high-plasticity soils, where the cone method tends to yield lower WL values. Similarly, Tanzen et al. (2016) identified operator variability as a critical factor in WP testing, emphasizing the need for methodological refinements to enhance consistency. These findings reinforce the necessity for standardised testing procedures to minimize uncertainty in soil classification.

A key challenge in engineering geology and geotechnics is the variability introduced by variations in sample preparation, operator handling, and environmental conditions. Studies by Wood (1982) and Hansbo (1957) underscored how procedural variabilities in consistency tests can significantly affect classification outcomes. This variability is particularly critical in geologically diverse regions, where soil heterogeneity presents challenges for infrastructure projects that require accurate and reproducible classification methods.

Recent advances in geotechnical research have aimed to improve the reliability and interpretability of soil classification and plasticity metrics, addressing long-standing limitations in conventional index testing. Manafi et al. (2022) developed a novel apparatus and method for determining soil plasticity, integrating both qualitative and quantitative components to enhance consistency and precision. Nugraha et al. (2020) investigated the correlation between the plasticity index and the methylene blue value in coarse-grained soils with fines, revealing a linear relationship that supports a more reliable classification of heterogeneous materials. Firincioglu and Bilsel (2023) introduced a unified model for soil plasticity potential that incorporates mineralogical and index properties, broadening the conceptual framework beyond the traditional IP. These efforts are complemented by recent studies that utilize machine learning and hybrid modeling approaches. Liu et al. (2024) employed deep learning techniques to predict Atterberg limits from routine soil properties, demonstrating high predictive accuracy across a diverse range of soil types. Nguyen et al. (2022) proposed a machine learning framework combining classification and regression for soil type identification based on plasticity characteristics. Bian et al. (2025) applied an optimized support vector machine model to classify soils based on cone penetration test data in the Kaifeng area, demonstrating that machine learning approaches can enhance the reliability and efficiency of preliminary soil classification in the absence of direct laboratory testing. Together, these studies signal a shift toward data-enriched and integrative methodologies in geotechnical classification, with the potential to reduce procedural variability and improve reproducibility in both research and practice.

This study investigates the influence of different testing methods on soil classification outcomes through a case study in the Czech Republic. The research evaluates three distinct WL determination methods: analysis by an accredited laboratory, a standardised cone, and a custom-made cone, alongside two PSD approaches (dry and wet sieving). Through a systematic comparison of these methods, the study addresses methodological uncertainties in soil classification, providing a comprehensive assessment of their reliability and practical implications.

Furthermore, the study integrates PSD and plasticity data within both the Unified Soil Classification System (USCS) and EN ISO 14688-2 frameworks, offering a dual perspective on classification. This approach enhances the understanding of how methodological choices affect geotechnical assessments and provides valuable insights for engineering geology, geotechnical investigations, and infrastructure development. The findings contribute to the optimisation of soil classification procedures, improving the reliability of geotechnical data to support informed decision-making in construction, mining, and hydraulic engineering applications.

Materials and Methods

Accurate characterisation of soil properties is a cornerstone of geotechnical engineering, essential for understanding soil behaviour and determining its suitability for construction purposes. This study combines traditional methodologies with innovative approaches, such as the use of a custom-made cone for determining the liquid limit, to evaluate their impact on soil classification outcomes. The methodology was designed to provide a comprehensive and standardized analysis of particle size distribution (PSD) and consistency limits (liquid and plastic limits), aligning with the study's goal to assess variability and reliability in soil testing.

• Particle Size Distribution Analysis

Particle size distribution (PSD) is a critical parameter in soil classification. It defines the relative proportions of the various particle sizes within a sample. The classifications of coarse-grained soils (sand and gravel) and fine-grained soils (silt and clay) depend heavily on PSD, which influences their load-bearing capacity, drainage properties, and overall soil behaviour.

In this study, PSD analysis was performed using both dry sieving and wet sieving techniques, supplemented by the Casagrande hydrometer method for finer fractions (<0.063 mm). The dry sieving method, recognized for its simplicity and speed, involves the sieving of a dry soil sample through a series of sieves with progressively smaller openings. However, its accuracy can be compromised when dealing with cohesive or aggregated soils. Wet sieving, which incorporates washing and agitation, is employed to address these limitations, particularly when separating fine particles that may adhere to larger aggregates under dry conditions. These two approaches provide a comparative analysis of PSD methodologies, highlighting their respective strengths and limitations (Craig, 2004; Das, 2017; EN ISO 17892-4, 2016).

For particles finer than 0.063 mm, sedimentation analysis using a Casagrande-type hydrometer was conducted. This method, standardised under EN ISO 17892-4, measures the settling velocity of soil particles in a fluid, calculated using Stokes' law. By converting sedimentation rates into particle size distributions, this technique delivers a continuous grain size curve for fine fractions. The combined results from sieving and hydrometer analysis were plotted as cumulative grain size distribution curves, facilitating soil classification according to the Unified Soil Classification System (USCS) and EN ISO 14688-2 standards.

• Consistency Limits

Knowledge of consistency limits is essential for understanding the deformation behavior of fine-grained soils, as they define the transitions between solid, plastic, and liquid states. This study focused on determining the liquid limit (WL), plastic limit (WP), and plasticity index (IP) using a combination of traditional and innovative methods.

Liquid Limit (WL)

The liquid limit represents the moisture content at which soil transitions from a plastic to a liquid state (Sherwood and Ryley, 1970). Two approaches were employed:

The standardised cone method, prescribed by EN ISO 17892-12, uses an 80g cone with a 30° angle that penetrates the soil sample. The WL corresponds to the moisture content at which the cone achieves a penetration depth of 20 mm.

Custom-made cone method; to explore variability, a custom-made cone was designed and used alongside the standardised device. This approach aims to assess the reliability and applicability of alternative equipment for WL determination.

Both methods were applied under controlled laboratory conditions to ensure repeatability and accuracy. The results were compared to those from an accredited laboratory, which also utilized an 80 g cone with a 30° angle for WL determination.

An alternative approach to determining the liquid limit is the Casagrande method, which employs a different principle. This method involves repeatedly dropping a soil-filled brass cup onto a hard surface until a defined groove closes after a specific number of blows. Despite its historical significance, the Casagrande method is often criticized for its susceptibility to operator-induced variability (Tanzen et al., 2016).

Plastic Limit (WP)

The plastic limit, defined as the moisture content at which soil transitions from a plastic to a semi-solid state, was determined using the traditional thread-rolling method. Soil samples were rolled into threads approximately 3 mm in diameter until crumbling occurred. While effective, this method is highly operator-dependent, introducing

variability into the results. The results from this method were compared to data provided by the accredited laboratory to evaluate potential discrepancies.

Plasticity Index (IP)

The plasticity index, a key parameter for soil classification, was calculated as the difference between WL and WP:

$$IP = WL - WP \quad (1)$$

This index quantifies the range of moisture content over which soil remains plastic, providing critical insights into soil behaviour, particularly for clay-rich soils with high compressibility and plasticity (Casagrande, 1947; Mohajerani, 1999).

• **Soil Classification Framework**

In this study, soil classification was performed according to the Unified Soil Classification System (USCS) as outlined in ASTM D2487-11, the EN ISO 14688-2 standard, and the local Czech standard, ČSN 73 6133, which is based on the European standard EN 1997-2. These frameworks incorporate PSD data and consistency limits to classify fine-grained soils. This combined approach ensures a comprehensive geotechnical profile, capturing both particle size and plasticity characteristics, which can be used to inform engineering applications.

The plasticity chart, a key tool within the USCS, is a plot of WL against IP, which distinguishes between clays and silts. Soils located above the A-line on the chart are classified as clays, while those below the A-line are identified as silts. This plasticity chart is particularly valuable for predicting soil behaviour, such as expansion, strength, and settlement, under varying moisture conditions. By delineating classifications such as low-plasticity clays (CL) and intermediate-plasticity silts (MI), the chart provides critical insights into the suitability of soils for construction or other engineering purposes.

The inclusion of a custom-made cone for WL determination represents a novel aspect of this study, offering a practical and cost-effective alternative to standardised devices. By comparing traditional methods with in-house modifications and validating the results against data from accredited laboratories, the research provides valuable insights into the variability and reliability of geotechnical testing methods. These findings underscore the importance of methodological rigor in soil classification and highlight the potential for integrating innovative approaches into standard geotechnical practices.

Case Study

The study was conducted at a selected site in the Blansko district near Brno, Czech Republic. The geomorphological setting belongs to the Bohemian-Moravian Subsystem, specifically the Bohemian-Moravian Highlands within the Hornosvratecká Highlands and its Nedvědice subunit (Czudek 1972). Regionally, the site is part of the Bohemian Massif, within the Moravian-Silesian zone, specifically the Moravicum region and its Svatka Dome.

The lithological structure of the study area includes formations from the Bílé Potok, Bíteš, and Olešnice Groups. The Bíteš Group is characterised by a variety of metamorphic rocks exhibiting mylonitic and cataclastic structures. Overlying this, the Olešnice Group contains biotite schists, graphite phyllites, and fine-grained garnet-bearing paragneiss. The Quaternary cover comprises eluvial and deluvial loams with varying rock fragment contents, transitioning into solid bedrock at deeper layers. At the borehole locations (S1, S2, and S3), the soil profiles predominantly consisted of sandy to clayey-sandy loams with a stiff consistency and admixtures of rock fragments.

The field investigation involved drilling three boreholes (S1, S2, and S3) using a manual spoon auger with a diameter of 60 mm. These boreholes provided undisturbed soil samples from two distinct depths in each profile. The samples collected were subject to laboratory analysis to determine fundamental soil properties, including moisture content and specific gravity. Moisture content was measured gravimetrically using the oven-drying method to obtain precise weight measurements of both the wet and dry samples. Specific gravity was determined using pycnometer analysis, a method that ensures accuracy in assessing the density of soil solids relative to water.

The results of these analyses are presented in Table 1, which summarizes the sample depths, average moisture content, and average specific gravity for all three boreholes. The sampling depths were selected to match those of the samples analysed by the accredited laboratory, ensuring comparability between datasets. These basic soil properties provided the foundation for subsequent analyses, including particle size distribution and consistency limits, which are essential for soil classification.

Tab. 1 Basic Soil Properties of Borehole Samples

Borehole	Depth [m]	Moisture Content [%]	Specific Gravity [g/cm ³]
S1	2,0; 2,5	11,9	2,91
S2	1,1; 1,5	15,1	2,78
S3	2,1–2,6	14,4	2,73

Results

• Own Measurements and Laboratory Comparison

To evaluate the reliability and variability of soil classification methods, comprehensive testing was conducted on samples collected from the three boreholes at the study site. These samples underwent rigorous laboratory analysis, utilizing two PSD methods (dry sieving and wet sieving, both supplemented with the Casagrande hydrometer method), two approaches for determining WL (using an original standardized cone and a custom-made cone), and a single approach for determining WP. All measurements were performed under controlled laboratory conditions to ensure repeatability and accuracy.

For comparative purposes, soil samples collected from the same locality, in close proximity to the original boreholes, were analysed by an accredited geotechnical laboratory (GTP 07/2023). To minimize potential variability, the original boreholes were accurately relocated in the field, and the comparative samples were collected in immediate proximity and from equivalent depths, with a maximum vertical offset of 0.5 m. This approach ensured that both datasets originated from stratigraphically comparable positions, although minor heterogeneity in soil composition cannot be entirely excluded even at such small distances. The laboratory employed internationally standardised procedures to determine PSD curves, liquid limits, and plasticity limits. This parallel dataset provided a benchmark for evaluating the outcomes of the in-house methods and allowed for a direct comparison of the results obtained using different techniques and equipment.

The combination of traditional and innovative approaches used in this study, particularly the incorporation of a custom-made cone for WL determination, allowed for a nuanced assessment of methodological impacts on soil classification. By comparing results across methods and against an accredited laboratory, this study highlights the practical implications of methodological variability and underscores the importance of standardisation in geotechnical practice.

• Particle Size Distribution Analysis

PSD forms the foundation of soil classification, providing essential information on the proportions of gravel, sand, silt, and clay within a soil sample. The PSD curves for the three boreholes (S1, S2, and S3) were analyzed using two in-house methods: dry sieving supplemented by the Casagrande hydrometer method, and wet sieving with a hydrometer. These methods were compared to the PSD curves provided by an accredited laboratory. The results are presented in Figure 1.

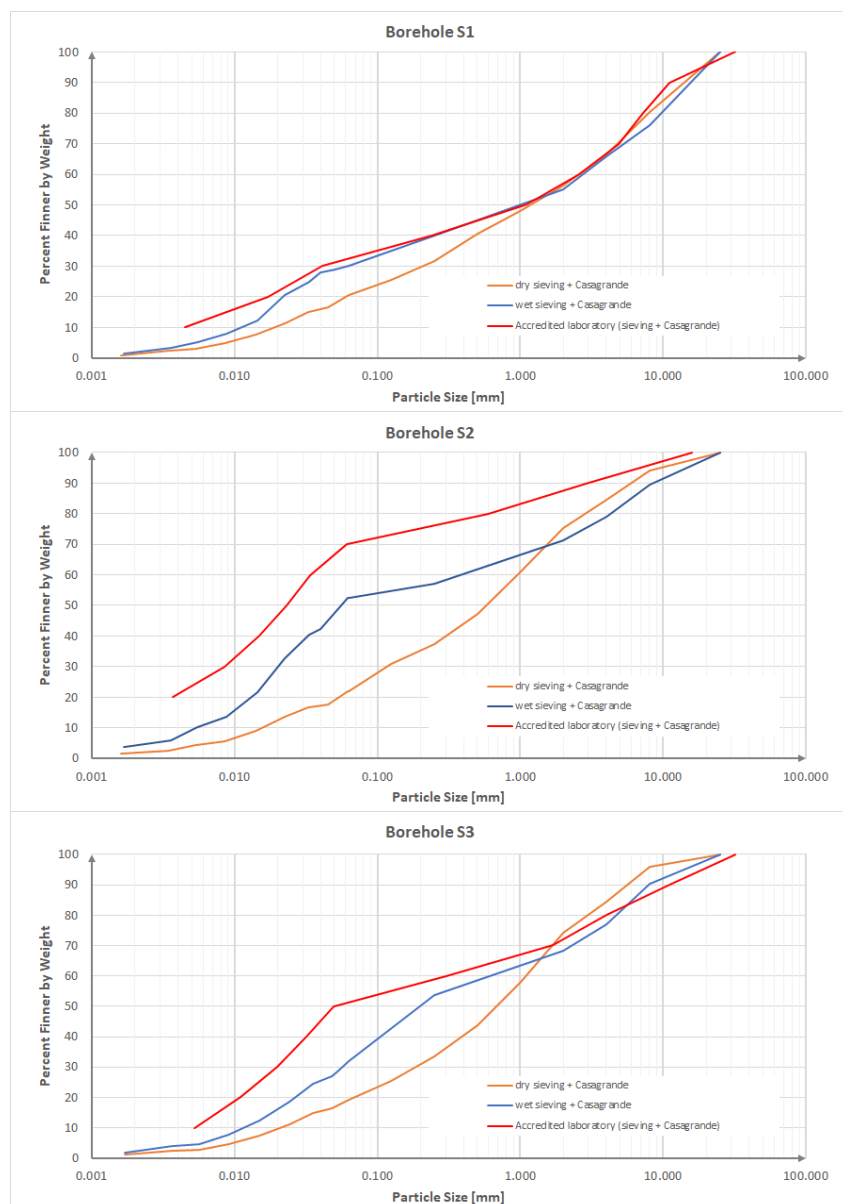


Fig. 1 Grain Size Distribution Curves for Boreholes S1, S2, and S3

The analysis revealed notable discrepancies between the in-house methods and the laboratory results, particularly for particle fractions smaller than 1 mm. These inconsistencies can be attributed to the inherent subjectivity in the handling and preparation of samples, as well as differences in procedural precision. Dry sieving, although simple and efficient, is susceptible to errors stemming from the incomplete disaggregation of soil aggregates, which can result in the underrepresentation of finer fractions. Wet sieving, by incorporating washing and agitation, more effectively separates fine particles, producing results that align more closely with laboratory standards.

Despite these improvements, variability persists due to factors such as operator technique, sample selection, and adherence to procedural standards. The random selection of representative subsamples from the bulk soil samples introduces an additional layer of variability, which can impact the observed discrepancies. In this study, each test was conducted on a 200g soil sample; however, even minor differences in the composition of these subsamples can influence the results. Such variability underscores the importance of meticulous sample preparation and strict adherence to standardised procedures.

The observed differences in PSD curves, particularly for fine-grained fractions, also highlight the subjective nature of soil preparation techniques. While the hydrometer method provides a continuous distribution of finer particles, its reliance on accurate sedimentation measurements requires careful handling and calibration. Disparities in the preparation of the suspension or inconsistencies in hydrometer readings can introduce further variability, underscoring the importance of operator skill and procedural rigor.

The cumulative PSD curves, displayed in Figure 1, offer a comparative overview of the results obtained using different methodologies. These curves illustrate the critical role of consistent and standardised testing procedures in minimizing discrepancies and ensuring reliable soil classification. By addressing these procedural challenges, geotechnical investigations can achieve greater accuracy and reproducibility, ultimately improving the reliability of engineering solutions.

• Consistency Limits

Liquid Limit (WL)

The results of the WL tests conducted on samples from boreholes S1, S2, and S3 are presented in Figure 2, which is comprised of three graphs, one for each borehole and for each of the two cone penetration methods.

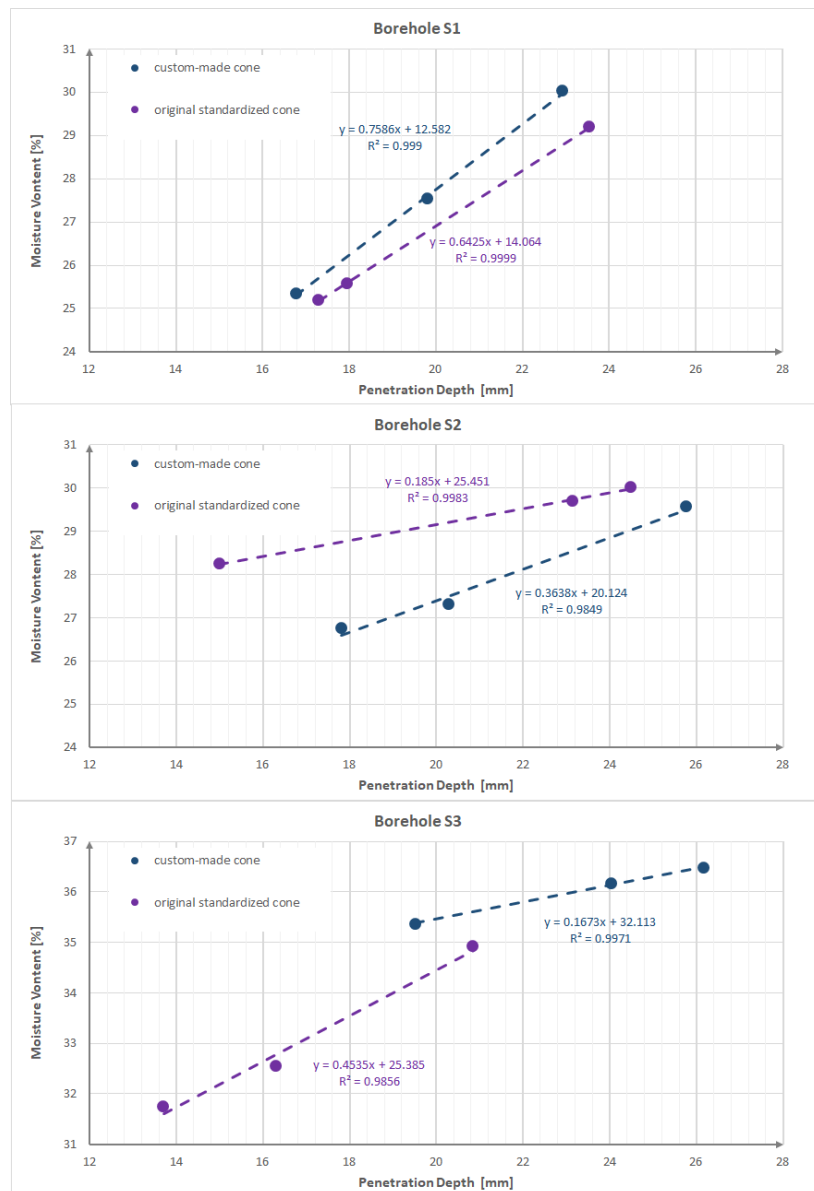


Fig. 2 WL Test Results for Boreholes S1, S2, and S3

Both test methods used to generate the data shown in Figure 2 were conducted under controlled laboratory conditions to ensure repeatability and minimize environmental influences. Each graph displays the results of measurements obtained using two different cone penetration devices: the original standardised cone and a custom-made cone. For each device, three moisture content values were measured corresponding to different penetration depths of up to 20 mm. The three measured points were fitted onto a linear regression line, from which the moisture content corresponding to a penetration depth of exactly 20 mm was calculated.

The WL values derived from both cones were compared to those obtained from an accredited laboratory, which also employed a cone penetrometer with a standardised 80g cone at a 30° angle. The WL values are summarized in Table 2.

Tab. 2 WL values for Standardised Cone, Custom-Made Cone, and Accredited Laboratory

Borehole	Standardized Cone WL (%)	Custom-Made Cone WL (%)	Laboratory WL (%)
S1	26,91	27,75	35
S2	29,15	27,40	36
S3	34,46	35,46	40

The comparison revealed minor discrepancies between the original and custom-made cones, with discrepancies of no more than 6.4%. These results suggest that the custom-made cone is a viable alternative to the standardised device for practical applications. However, the WL values from the in-house measurements across all boreholes were consistently lower than those reported by the accredited laboratory. This discrepancy highlights the inherent sensitivity of the WL determination to sample preparation, operator handling, and specific procedural differences.

The variability observed in the WL results can be attributed to differences in the uniformity of moisture distribution within the soil samples during preparation. Proper mixing and consistency in sample preparation are critical to ensure reliable results. Even minor deviations from standardised procedures, such as insufficient mixing or uneven moisture distribution, can significantly influence outcomes. This underscores the semi-subjective nature of WL testing, emphasizing the need for strict adherence to procedural guidelines to achieve consistent and reproducible results.

Plastic Limit (WP)

WP was determined using the traditional thread-rolling method, where soil is rolled into threads approximately 3 mm in diameter until they crumble. This method is highly operator-dependent, with results influenced by the individual's skill, technique, and perception during the test.

For each borehole (S1–S3), three WP measurements were conducted, and their averages calculated. These results, summarized in Table 3, showed close agreement with the laboratory measurements, with deviations of no more than 4.7%. Despite the relatively small differences, the inherent subjectivity of the WP method introduces potential variability. Operator variability, such as inconsistency in rolling speed, pressure applied, or thread formation, can affect the results. Nevertheless, the alignment between in-house and laboratory measurements suggests that the method, when performed with care and consistency, can yield reliable results.

Tab. 3 WP results from Boreholes S1–S3

Borehole	WP Meas. 1 (%)	WP Meas. 2 (%)	WP Meas. 3 (%)	Average WP (%)	Laboratory WP (%)
S1	20,66	21,01	20,70	20,79	22
S2	20,13	20,25	19,48	19,95	21
S3	26,88	25,93	26,48	26,43	27

Plasticity Index (IP)

IP was calculated as the difference between WL and WP. IP provides a measure of the range of moisture content over which the soil is plastic, reflecting its potential for deformation and compressibility. In this study, IP was calculated for three scenarios (A–C):

- (A) WL determined using the original standardised cone combined with the in-house WP measurements.
- (B) WL determined using the custom-made cone combined with the in-house WP measurements.
- (C) WL and WP values provided by the accredited laboratory.

The results, detailed in Table 4, revealed noticeable differences across the different scenarios.

Tab. 4 IP Results for Boreholes S1–S3

Borehole	IP A (%)	IP B (%)	IP C (%)
S1	6,12	6,96	13
S2	9,20	7,45	15
S3	8,03	9,03	13

The results revealed noticeable differences between the in-house measurements and those from the accredited laboratory. For all boreholes, the laboratory-derived IP values (C) are significantly higher than those obtained from in-house testing, both with the standardised cone (A) and the custom-made cone (B). The deviations are most pronounced for Borehole S2, where the laboratory IP value exceeds the in-house results by more than 5%.

A comparison between the standardised cone (A) and the custom-made cone (B) highlights minor discrepancies, ranging from 0.84% to 1.75% across all boreholes.

The laboratory-derived IP values were consistently higher than those from in-house testing. The variability in IP values can primarily be attributed to discrepancies in WL measurement. These discrepancies were likely influenced by differences in sample preparation, such as moisture mixing, or were partially due to the subjectivity of the method and the approach of the operator. The comparison between the standardised cone and the custom-made cone showed minor deviations. This agreement suggests that the custom-made cone can provide comparable

results to the standardised device under controlled conditions. These findings underscore the influence of WL variability on IP values and highlight the importance of standardised preparation and testing protocols to minimize variability and ensure reliable soil classification.

• Soil Classification and the Plasticity Chart

The PSD analysis and consistency limit tests form the basis for classifying soils using the plasticity chart within the framework of the USCS. The plasticity chart in Figure 3 provides a visual representation of soil sample classifications by plotting WL against IP. This approach enables the differentiation of clays and silts, which is essential for understanding soil behavior in engineering applications.

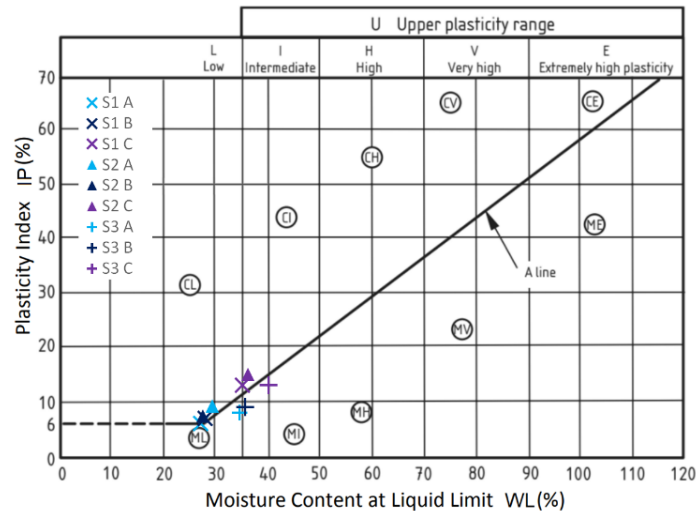


Fig. 3 Plasticity Chart for Soil Classification Based on WL and IP

The chart categorizes most of the samples from boreholes S1 and S2 as low-plasticity clays (CL), except Borehole S2C, which is classified as an intermediate-plasticity clay (CI). In contrast, samples from Borehole S3 predominantly fall into the category of intermediate-plasticity silts (MI), except for one sample, S3A, which is close to the boundary of low-plasticity silts (ML). These classifications are summarized in Table 5.

Tab. 5 Plasticity classification of soil samples from boreholes S1, S2, and S3 based on the Plasticity Chart.

Borehole	S1			S2			S3		
Scenario	(A)	(B)	(C)	(A)	(B)	(C)	(A)	(B)	(C)
Plasticity Diagram	CL	CL	CL	CL	CL	CI	ML	MI	MI

The results underscore the high degree of consistency in the classifications across the study area, reflecting the homogeneous nature of the locality. Regardless of the measurement method employed, all samples consistently placed either above the A-line (indicating clays) or below it (indicating silts) on the plasticity chart. This agreement validates the robustness of the testing methodologies used, particularly the custom-made cone, which aligned closely with the results obtained using a standardised penetrometer.

To further refine the soil classifications, the study incorporated additional analyses based on the principles of ČSN 73 6133, a Czech standard aligned with the European standard EN 1997-2. This classification approach integrates both PSD data and plasticity characteristics, offering a more comprehensive geotechnical profile. The grain size distribution curves derived from different methods - dry sieving with Casagrande testing, wet sieving with Casagrande testing, and results from the accredited laboratory - served as the primary inputs for this analysis. Simultaneously, results from the plasticity chart (Figure 3) provided crucial data to determine whether each sample lay above or below the A-line. This combined approach enabled the precise classification of the soil samples into their respective categories, as visualized in the attached triangular diagram in Figure 4.

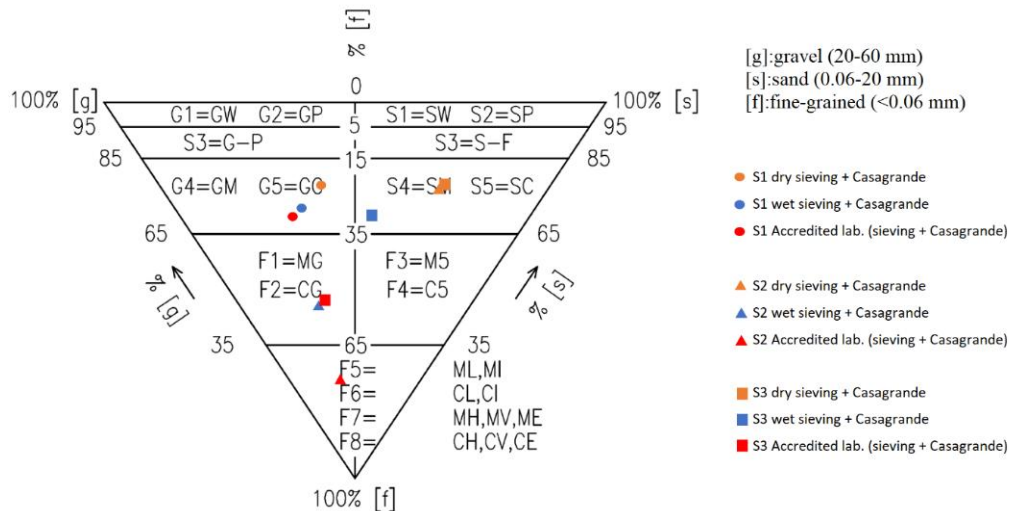


Fig. 4 Soil Classification Based on Grain Size Distribution and Plasticity Characteristics

The grain size curves indicate consistent classifications for Borehole S1 across all methods. However, significant discrepancies were observed in Boreholes S2 and S3, where the classifications varied depending on the method employed. For instance, the classifications of Borehole S2 ranged from "gravelly clayey sand" to "silty clay," while Borehole S3 varied between "gravelly silty sand" and "gravelly sandy clayey silt." These differences can be attributed to variations in the PSD curve determination methods, emphasizing the critical importance of using reliable and consistent procedures for accurate soil classification. A more detailed explanation of the soil classifications shown in Figure 4, including the symbols and classes used, is provided in Table 6. A complete overview of soil classification is given in Table 7.

Tab. 6 Soil Classification Symbols and Categories.

Category	Symbol	Class
<i>Gravelly soils ($g > s$)</i>		
Well-graded gravel	GW	G1
Poorly graded gravel	GP	G2
Gravel with fine-grained admixture	G-F	G3
Silty gravel	GM	G4
Clayey gravel	GC	G5
<i>Sandy soils ($s > g$)</i>		
Well-graded sand	SW	S1
Poorly graded sand	SP	S2
Sand with fine-grained admixture	S-F	S3
Silty sand	SM	S4
Clayey sand	SC	S5
<i>Fine-grained soils</i>		
Gravelly silt	MG	F1
Gravelly clay	CG	F2
Sandy silt	MS	F3
Sandy clay	CS	F4
Silt with low plasticity	ML	F5
Silt with intermediate plasticity	MI	F5
Clay with low plasticity	CL	F6
Clay with intermediate plasticity	CI	F6
Silt with high plasticity	MH	F7
Silt with very high plasticity	MV	F7
Silt with extremely high plasticity	ME	F7
Clay with high plasticity	CH	F8
Clay with very high plasticity	CV	F8
Clay with extremely high plasticity	CE	F8

Tab. 7 Detailed soil classification results based on ČSN 73 6133 for boreholes S1-S3 according to different PSD curves and scenarios (A-C).

Borehole	PSD - curves	Scenario	ČSN 73 6133
S1	dry+Cas.	(A)	G5=GC
		(B)	G5=GC
		(C)	G5=GC
	wet+Cas.	(A)	G5=GC
		(B)	G5=GC
		(C)	G5=GC
	Accr. Lab.	(A)	G5=GC
		(B)	G5=GC
		(C)	G5=GC
S2	dry+Cas.	(A)	S5=SC
		(B)	S5=SC
		(C)	S5=SC
	wet+Cas.	(A)	F2=CG
		(B)	F2=CG
		(C)	F2=CG
	Accr. Lab.	(A)	S5=SC
		(B)	S5=SC
		(C)	S5=SC
S3	dry+Cas.	(A)	S4=SM
		(B)	S4=SM
		(C)	S4=SM
	wet+Cas.	(A)	S4=SM
		(B)	S4=SM
		(C)	S4=SM
	Accr. Lab.	(A)	F1=MG
		(B)	F1=MG
		(C)	F1=MG

The inclusion of additional classifications based solely on PSD, as outlined in EN ISO 14688-2, highlights the influence of gravel content (2–63 mm), sand content (0.063–2 mm), and fines content (<0.063 mm) on soil categorization. The results, visualized in Figure 5 and summarized in Table 8, demonstrate that different PSD methods have a significant impact on soil classification outcomes. For example, Borehole S1 classifications ranged from "silty sand with gravel" to "clayey sand with gravel," underscoring how methodological differences shape the interpretation of soil composition.

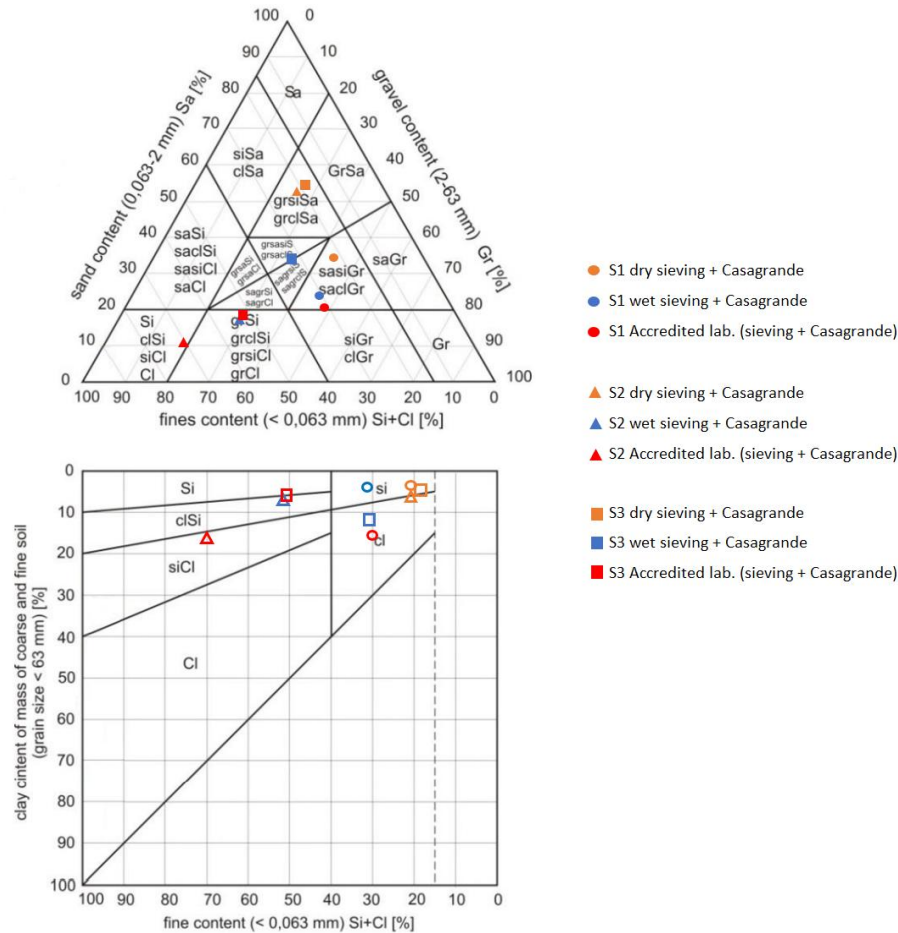


Fig. 5 Impact of Different Methods for Determining Grain Size Distribution on Soil Classification Following EN ISO 14688-2

Tab. 8 Detailed soil classification results based on EN ISO 14688-2 according to different PSD curves

Borehole	PSD - curves	EN ISO 14688-2	
S1	dry+Cas.	sasiGr	Silty sand with gravel
	wet+Cas.	sasiGr	Silty sand with gravel
	Accr. Lab.	saciGr	Clayey sand with gravel
S2	dry+Cas.	grclSa	Gravelly clayey sand
	wet+Cas.	grclSi	Gravelly clayey silt
	Accr. Lab.	siCl	Silty clay
S3	dry+Cas.	grsiSa	Gravelly silty sand
	wet+Cas.	grsaciS	Gravelly sandy clayey silt
	Accr. Lab.	grSi	Gravelly silt

These findings highlight the critical role of combining PSD analysis and plasticity data in soil classification. While significant discrepancies were observed between different PSD methods, which directly influenced soil classification outcomes, the plasticity chart demonstrated consistent results across all measurement methods. This reliability reinforces the value of the plasticity chart in differentiating soils into clays or silts, not only when using a standardized cone or a custom-made cone, but also when considering the results from in-house or accredited laboratory conditions.

The study highlights the need for robust, standardized methodologies, such as those outlined in EN ISO 14688-2, which is widely applied in geotechnical evaluations. Similarly, the ČSN standard provided complementary insights, confirming its relevance in the context of this study. By addressing both the international and national frameworks, the research highlights the close alignment in classification outcomes, reinforcing the reliability of these standards in geotechnical practice. By leveraging multiple complementary approaches, this integrated framework provides a comprehensive understanding of soil behavior, which is crucial in infrastructure design, construction, and land management applications. Future work should address the variability in PSD results by refining sample preparation techniques and reducing operator-induced inconsistencies, further enhancing the accuracy and applicability of these methods in engineering practices.

Discussion

• Evaluation of Basic Soil Properties

The initial assessment of basic soil properties, including moisture content and specific gravity, provided the fundamental dataset for subsequent analyses. The close agreement between the sampling depths in this study and those in the analysis carried out by the accredited laboratory ensured direct comparability. Maintaining consistency in sampling protocols is crucial for reducing variability across datasets, as emphasized in prior studies (Das 2017; Craig 2004). Moisture content and specific gravity significantly influence soil behaviour, affecting particle aggregation, consistency limits, and classification accuracy. These parameters are essential in the evaluation of geotechnical properties, as they directly impact the suitability of the soil for engineering projects.

• Particle Size Distribution Analysis

The particle size distribution (PSD) analysis revealed notable discrepancies between the methods employed, particularly for fine-grained fractions below 1 mm. These differences were most pronounced between the in-house methods (dry and wet sieving supplemented by hydrometer analysis) and the accredited laboratory results. Similar findings have been reported by Konert and Vandenberghe (2008), who noted that dry sieving results tend to lead to the underrepresentation of finer fractions due to incomplete aggregate disaggregation, whereas wet sieving improves particle separation and thus more accurately reflects the true PSD.

Variability in PSD results can be attributed to several factors, including differences in sample preparation, operator handling, and procedural consistency. Studies by Gee and Bauder (1986) have highlighted the sensitivity of PSD results to operator skill, reinforcing the need for meticulous adherence to protocols. While the wet sieving in this study reduced discrepancies, it did not fully eliminate them, underscoring the semi-subjective nature of PSD determination. Furthermore, inconsistencies in PSD results have direct implications for soil classification, as grain size distribution affects consistency limits and overall geotechnical behaviour.

It should be noted that the findings reported by Konert and Vandenberghe (1997) were based on a wide range of unconsolidated sediments originating from fluvial, aeolian, and lacustrine environments, while the methodological overview provided by Gee and Bauder (1986) was derived from various soil types without a specific focus on cohesive soils. In contrast, the samples analysed in this study represent cohesive soils of engineering geological relevance. While the methodological discrepancies observed in both contexts are comparable, the degree of divergence may vary depending on soil genesis and grain size composition.

• Consistency Limits: WL, WP, and IP

The WL and plastic limit (WP) tests exhibited inherent variability between the in-house and laboratory measurements. The custom-made cone produced results comparable to the standardised device, with WL deviations remaining below 6.4%. However, in-house WL values were consistently lower than those reported by the accredited laboratory, a discrepancy likely arising from variations in sample preparation and procedural execution. These findings align with previous research by Sherwood and Ryley (1970), who demonstrated that WL determination is highly sensitive to moisture content distribution and operator technique on various fine-grained soils.

Similarly, WP testing using the thread-rolling method on various fine-grained soils was influenced by operator variability, as noted in studies by Tanzen et al. (2016). Despite this, the relatively small discrepancies between the in-house and laboratory WP results suggest that adherence to standardised procedures yields reliable outcomes. The plasticity index (IP), derived from WL and WP, highlighted the cumulative discrepancies, with laboratory-derived values consistently exceeding those from in-house tests. These findings reinforce the importance of standardisation in WL and WP methodologies, as variability in either parameter directly affects IP calculations and, consequently, soil classification.

Although the studied soils are generally sandy in nature, only their fine-grained components were used for the WL and WP tests. Therefore, the comparison with studies based on various fine-grained soils remains methodologically valid.

• Soil Classification and the Plasticity Chart

Integrating PSD data with consistency limits provided a robust framework for soil classification within the USCS framework. The plasticity chart demonstrated strong internal consistency, accurately differentiating clays from silts across all testing methods. This reliability supports the use of plasticity-based classification as a key component of geotechnical assessments, as noted by Hansbo (1957). However, while the plasticity chart produced stable classifications, the broader classification based on PSD and IP varied significantly, particularly for boreholes S2 and S3. This outcome highlights the sensitivity of classification results to granulometric analysis techniques.

The consistency observed between the ČSN 73 6133 and EN ISO 14688-2 standards further supports the robustness of these methodologies. Despite variations in the PSD results, the alignment of classification outcomes

across these standards underscores their complementary nature. These findings are consistent with the work of Fojtova and Marschalko (2008), who emphasized the importance of integrating international and national standards to improve classification accuracy for clayey soils.

• Practical Implications and Future Directions

The findings of this study have significant implications for geotechnical practice, particularly in engineering geological investigations. The integration of traditional and alternative testing methods highlights the importance of robust, standardised procedures in minimizing variability and ensuring reliable soil classification. This comparative approach sheds light on how variations in sample preparation and testing methods affect classification outcomes, highlighting key reliability challenges in standard soil testing procedures. By combining PSD and plasticity data within both EN ISO 14688-2 and ČSN 73 6133 frameworks, this study provides a comprehensive basis for understanding soil behavior, which is crucial for infrastructure design, construction, and land management applications.

Future research should focus on refining sample preparation techniques to minimize operator-induced variability, particularly for PSD analysis, where inconsistencies in fine-grained fractions persist as a challenge. Additionally, exploring automated testing methods for WL and WP could further enhance reproducibility and reduce subjectivity. This study supports the use of alternative tools, such as custom-made cones, which may offer a cost-effective and accessible option in practical settings without substantially compromising accuracy. Improved soil classification methodologies extend beyond laboratory accuracy, directly influencing engineering applications such as the design of embankment dams, flood-control structures, and drainage systems. Accurate classification informs key engineering parameters, including load-bearing capacity, foundation depth, impermeability, and seepage control, all of which are critical for infrastructure resilience and environmental sustainability. For instance, in hydraulic engineering, these parameters significantly affect the longevity and safety of water management structures, as well as the sustainability of water resources (Paseka et al., 2018; Paseka and Marton, 2021).

Addressing these challenges will contribute to improved geotechnical assessments, enhancing the reliability of engineering designs and ensuring the long-term stability of critical infrastructure.

Conclusions

This study provides a systematic evaluation of soil classification methodologies, integrating particle size distribution (PSD) analysis and consistency limit testing within the frameworks of internationally recognized standards (EN ISO 14688-2 and ČSN 73 6133). By comparing in-house testing methods with results from an accredited laboratory, key insights were gained into the reliability, variability, and practical applicability of these approaches in engineering geological investigations.

The results of the PSD analysis highlighted significant discrepancies between the dry and wet sieving methods, particularly for fine-grained fractions smaller than 1 mm. Dry sieving tended to produce results that underrepresented these fractions due to incomplete aggregate disaggregation, whereas wet sieving, despite its increased labour intensity, produced results more consistent with laboratory standards. These findings highlight the critical role of sample preparation techniques and procedural rigor in ensuring accurate granulometric assessments.

In consistency limit testing, the custom-made cone provided results comparable to those of the standardized device, with deviations of less than 6.4%. However, systematic differences between in-house and laboratory WL measurements emphasize the influence of sample preparation techniques on classification outcomes. The plastic limit (WP) results exhibited a greater degree of agreement, with deviations of less than 4.7%, despite the inherently subjective nature of the thread-rolling method. Consequently, the plasticity index (IP), derived from WL and WP, reflected these cumulative methodological discrepancies, reinforcing the need for standardisation and precise procedural adherence in geotechnical testing.

The integration of PSD and plasticity data within the USCS and ČSN classification frameworks enabled a comprehensive, multi-method assessment. While the plasticity chart consistently differentiated clays from silts across all methodologies, broader soil classifications varied considerably, depending on the measurement approach, particularly for boreholes S2 and S3. These findings underscore the sensitivity of the classification results to granulometric techniques and highlight the necessity for cross-validation through complementary testing methods.

While the normative frameworks applied in this study are well-established, the novelty lies in the comprehensive and practical evaluation of the variability and reliability inherent in soil classification procedures under domestic testing conditions. This study explicitly quantifies the degree of uncertainty associated with operator influence and methodological differences, thereby providing practitioners with a clearer understanding of the precision and limitations of current laboratory and in-house methods. The results obtained are particularly relevant for soils typical of Central Europe, for which these findings offer key insights. However, it is acknowledged that soil behaviour and classification reliability may differ for other soil types and geological

contexts. By highlighting these uncertainties, the research encourages a more cautious and informed interpretation of classification results, which is essential for improving decision-making in engineering practice. This nuanced perspective on classification reliability represents a valuable contribution to both academic research and applied geotechnical engineering.

From an applied perspective, the results of this study have direct implications for foundation design, load-bearing assessments, and the evaluation of seepage control measures in hydraulic structures such as embankments and retention basins. The reliability of the soil classification is critical to the long-term stability and safety of engineered structures, particularly in regions with complex geological settings. Future research should focus on refining sample preparation protocols, enhancing procedural standardisation, and exploring automated testing methods to minimize operator variability and improve reproducibility in soil consistency assessments. Addressing these challenges will contribute to more accurate engineering geological evaluations, supporting the development of resilient infrastructure and sustainable land management strategies.

References

- Amadi, A.N., Eze, C.J., Igwe, C.O., Okunlola, I.A., & Okoye, N.O. (2012) Architect's and Geologist's View on the Causes of Building Failures in Nigeria. *Mod. Appl. Sci.*, 6, 31–38. <https://doi.org/10.5539/mas.v6n6p31>
- ASTM D2487-11. Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System); ASTM International: West Conshohocken, PA, USA, 2011.
- Bian, H.; Sun, Z.; Bian, J.; Qu, Z.; Zhang, J.; Xu, X. (2025). Assessment of soil classification based on cone penetration test data for Kaifeng area using optimized support vector machine. *Environmental Earth Sciences*, 84(2), 135. <https://doi.org/10.1038/s41598-024-84632-5>
- Casagrande, A. (1947) Research on the Atterberg Limits of Soil. *Public Roads*, 13(8), 121-130.
- Craig, R.F. (2004) *Soil Mechanics*, 7th ed.; Spon Press: London, UK.
- ČSN 73 6133. Geotechnical design of buildings – Part 1: Classification of soils and rocks. Czech Standards Institute, 2016.
- Czudek, T. (1972) Geomorfologické členění ČSR. *Studia Geographica* 23; Geografický ústav ČSAV: Brno.
- Das, B.M. (2017) *Principles of Geotechnical Engineering*, 9th ed.; Cengage Learning: Boston, MA, USA.
- EN 1997-2. European Committee for Standardization (CEN). Eurocode 7 – Geotechnical design – Part 2: Ground investigation and testing. Brussels: CEN, 2007.
- EN ISO 14688-1. Geotechnical Investigation and Testing—Identification and Classification of Soil—Part 1: Identification and Description. International Organization for Standardization: Geneva, Switzerland, 2018.
- EN ISO 14688-2. Geotechnical Investigation and Testing—Identification and Classification of Soil—Part 2: Principles for a Classification; International Organization for Standardization: Geneva, Switzerland, 2018.
- EN ISO 17892-4. Geotechnical Investigation and Testing—Laboratory Testing of Soil—Part 4: Determination of Particle Size Distribution. International Organization for Standardization: Geneva, Switzerland, 2016.
- EN ISO 17892-12. Geotechnical Investigation and Testing—Laboratory Testing of Soil—Part 12: Determination of Liquid and Plastic Limits. International Organization for Standardization: Geneva, Switzerland, 2018.
- Firincioglu, E.; Bilsel, H. (2023). A Unified Soil Plasticity Potential Model Integrating Mineralogical and Index Properties. *Applied Sciences*, 13(13). <https://doi.org/10.3390/app13137889>
- Fojtova, L., & Marschalko, M. (2008) Needs of Comparison for Liquid Limit Measurements According to Czech Standards and New Received European Legislation. *Trans. VSB Tech. Univ. Ostrava Civil Eng. Ser.* 2008, 1.
- Gee, G.W., & Bauder, J.W. (1986) Particle-size analysis. In: Klute, A. (Ed.), *Methods of Soil Analysis. Part 1: Physical and Mineralogical Methods*. American Society of Agronomy, Madison, WI, USA, pp. 383–411, 1986.
- GTP - Geotechnical survey for the Lhota u Lysic Regional Office dated 07/2023, Brno.
- Hansbo, S. A (1957) New Approach to the Determination of the Shear Strength of Clays by the Fall-Cone Test. *Proc. Roy. SGI*, 14, 7–48.
- Houlsby, G.T. (1982) Theoretical Analysis of the Fall Cone Test. *Geotechnique*, 32(2), 111–118.
- Hrubesova, E., Lunackova, B., & Brodzki, O. (2016) Comparison of Liquid Limit of Soils Resulted from Casagrande Test and Modified Cone Penetrometer Methodology. *Procedia Eng.*, 142, 364–370. <https://doi.org/10.1016/j.proeng.2016.02.063>
- Karlsson, R. (1961) Suggested Improvements in the Liquid Limit Test with Reference to Flow Properties of Remoulded Clays. In: *Proceedings of the 5th International Conference on Soil Mechanics and Foundation Engineering*; Paris, France, pp. 171-184.
- Konert, M., & Vandenberghe, J. (2008) Comparison of laser grain size analysis with pipette and sieve analysis: A solution for the underestimation of the clay fraction. *Sedimentology*. <https://doi.org/10.1046/j.1365-3091.1997.d01-38.x>

- Liu, C.-Y., Ku, C.-Y., Wu, T.-Y., & Ku, Y.-C. (2024). An Advanced Soil Classification Method Employing the Random Forest Technique in Machine Learning. *Applied Sciences*, 14(16), 7202. <https://doi.org/10.3390/app14167202>
- Malomo, S., Olorunniwo, M.A., & Ogunsanwo, O. (1983) Engineering Geological Mapping in Terrains of Tropical Weathering: An Example from Abuja, Nigeria. *Eng. Geol.*, 19, 133–148. [https://doi.org/10.1016/0013-7952\(83\)90031-5](https://doi.org/10.1016/0013-7952(83)90031-5)
- Manafi, S.; Deng, A.; Taheri, A.; Jaksa, M.B., & Nagaraj, H.B. (2022). Determining Soil Plasticity Utilizing Manafi Method and Apparatus. *Geotechnical Testing Journal*, 45(4). <https://doi.org/10.1520/GTJ20210235>
- Mohajerani, A. (1999) A Suggested Calibration for the Cone Penetrometer Liquid Limit. *Aust. Geomech.*, 34(4), 71–76
- Nguyen, M.D.; Costache, R.; Ho, S.A.; Ahmadzadeh, H.; Le, H.V.; Prakash, I.; Pham, B.T. (2022). Novel Approach for Soil Classification Using Machine Learning Methods. *Bulletin of Engineering Geology and the Environment*, 81(11), 468. <https://doi.org/10.1007/s10064-022-02967-7>
- Nugraha, A.D.; Subagio, S.; Azizi, F. (2020). The Correlation between Plasticity Index and Methylene Blue Value for Soils Containing Fines. *IOP Conference Series: Materials Science and Engineering*, 852(1).
- Paseka, S., Kapelan, Z., & Marton, D. (2018) Multi-Objective Optimization of Resilient Design of the Multipurpose Reservoir in Conditions of Uncertain Climate Change. *Water*, 10(9). <https://doi.org/10.3390/w10091110>
- Paseka, S., & Marton, D. (2021) The Impact of the Uncertain Input Data of Multi-Purpose Reservoir Volumes under Hydrological Extremes. *Water*, 13(10). <https://doi.org/10.3390/w13101389>
- Robertson, P.K. (2006) Guide to In-Situ Testing. Gregg Drilling and Testing, Inc..
- Sherwood, P.T., & Ryley, M.D. (1970) An investigation for a cone penetrometer method for the determination of liquid limit. *Geotechnique*, 20(2), 203–208. <https://doi.org/10.1680/geot.1970.20.2.203>
- Tanzen, R., Sultana, T., Islam, M.S., & Khan, A.J. (2016) Determination of Plastic Limit Using Cone Penetrometer. In *Proceedings of the 3rd International Conference on Advances in Civil Engineering*; Chittagong, Bangladesh.
- Wood, K.M. (1982) Cone Penetrometer and Liquid Limit. *Geotechnique*, 32, 152–157.