Determination of Soil Plasticity

Developing Manafi Method and Apparatus

By

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The University of Adelaide

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غرض نقشیست کز ما باز ماند؛

که هستی را نمی بینم بقایی!

سعدی (۱۲۱۰-۱۲۹۲ میلادی)

The intention of this design was that it should survive;

However, I perceive no stability in existence!

Saadi (1210-1292 CE)

Abstract

Soil plasticity is one of the essential index properties required for classifying soils in geotechnical engineering practice. Determination of plasticity properties of soils is also critical for correlation with their engineering properties such as shear strength, permeability, and compressibility. However, present standard test methods for soil plasticity suffer, to different extents, from operator-dependency and inconsistency. This research aims to further develop and establish a recently introduced determination method, named the Manafi Method and Apparatus in the author's MPhil project, and obtain more precise and accurate soil plasticity determinations than from the current standard methods. This thesis by publication document presents the research outcomes. The document comprises six chapters. Except Chapters 1 and 6, Chapters 2 to 4 were written in the format of research articles. These articles have been published, accepted for publication, or submitted to journals for possible publications by the time of thesis lodgement.

The Introduction chapter presents the aims and objectives of the research project and outlines the thesis structure.

Chapter 2, entitled “A New Approach to Soil Consistency Determination”, presents research outcomes related to theory and implementation of the new testing approach. The contents reviewed and discussed the conventional quantitative methodology for soil consistency determination using standard tests. It also proposed a novel combined qualitative and quantitative research methodology for a behavioural study on soil consistency determination. A new parameter, called ‘workability’, was introduced and formulated for quantifying soil consistency. This study lays the theoretical basis for developing the novel methodology and proposed solutions to issues related to standard tests.

Chapter 3, entitled “Utilisation of Extrusion Method in Geotechnical Tests: Conception and Theoretical Analysis”, evaluates the capability of the extrusion method for soil property determinations and proposes the development of a closed-form solution for the determination of extrusion pressure using this technique. This study presents the theoretical basis

underpinning the extrusion process by extending the conventional slab analysis method to the modelling of soil extruding. In addition, the described extrusion mechanics explained reasons for some discrepancies observed in various geotechnical parameters due to the different soil deformation mechanisms among the test methods.

Chapter 4 presents the third paper, entitled “Determining Soil Plasticity Utilising Manafi Method and Apparatus”. This paper demonstrates the utilisation of the new combined qualitative and quantitative approach for soil property determinations, namely the Manafi Method and Apparatus. The proposed technique is instrumented with a new soil extrusion device to quantify the workability of soils and is calibrated to translate the workability to their liquid and plastic limits. The method is applied to seven soil samples of varying particle sizes and plasticity to determine the liquid and plastic limits, and the results are compared with those obtained by conventional methods. The outcomes suggest that the new technique provides a more precise and reliable means of soil plasticity determination in the tested samples.

Chapter 5 is the fourth paper, entitled “Effect of Particle Size on Soil Plasticity and Soil Classification”. Although the full range of particle sizes affects soil consistency, the conventional test methods and apparatuses only study the unrepresentative sub-samples containing medium sand particles of less than 425 microns. However, the novel Manafi Method and Apparatus can enhance the consistency determination method by exploring a more comprehensive range of soils containing coarser particles. Therefore, several soil samples containing various portions of coarse grains are studied. The results show that the coarse grains significantly affect soil plasticity and classification. As a result, a revision to the Unified Soil Classification System is proposed.

Chapter 6, “Conclusions and Recommendations”, summarises the research results, discusses the limitations of the study, and recommends future investigations pertinent to soil plasticity determination. The articles presented in the thesis were prepared in collaboration with two more international experts in the research field, Professor Mark B. Jaksa and Professor Nagaraj HB, forming a high standard authorship team. In addition, the research seeks to demonstrate a well-defined paradigm in favour of using the proposed method in broader soil property determinations.

Keywords: Soil Consistency, Plasticity, Workability, Liquid Limit, Plastic Limit, Atterberg Limit Tests, Manafi Method, Manafi Apparatus, Casagrande Percussion Cup Method, Fall Cone Method, Thread Rolling Method, Extrusion Method.

Statement of Originality

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint award of this degree.

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Seyed Masoud Manafi Ghorabaei

Signature: **Date:** 12/07/2022

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It was a difficult decision to leave my home country to continue my education, but I wanted to pursue my dreams and pay back my family's sacrifices with something valuable. However, the meaning of family gradually expanded for me after I got thousands of kilometres away from my immediate family. I found great friends who cared and acted as family members through happiness and sadness. I will never forget Shahram when we discussed different subjects during the breaks and walked back home after long working days at Trinity College Dublin, where this journey started.

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Table of Contents

Abstract .... *iii*

Statement of Originality .... *vi*

Acknowledgement .... *vii*

Table of Contents .... *ix*

List of Figures .... *xii*

List of Tables .... *xiv*

Chapter One - Introduction *1*

1.1 Background and Aims **2**

1.2 Research Outline **5**

1.2.1 Improvement in soil plasticity determination 5

1.2.2 Proposing a new framework for soil classification 8

1.3 Thesis Structure Layout **9**

1.4 References **11**

Chapter Two – A New Approach to Soil Consistency Determination *15*

2.1 Abstract **17**

2.2 Introduction **18**

2.3 Issues Relevant to Current Standard Methods **20**

2.4 Proposing a New Research Approach for Soil Plasticity Determination **24**

2.4.1 Test design fundamentals 26

2.4.2 Soil behaviour quantification 27

2.5 Discussion **30**

2.6 Summary and Conclusions **32**

2.7 Acknowledgments **32**

2.8 Conflict of Interest **32**

2.9 References **33**

Chapter Three – Utilisation of Extrusion Method in Geotechnical Tests: Conception and Theoretical Analysis *38*

3.1 Abstract **40**

3.2 Introduction **41**

3.3 Model Development **43**

3.3.1 Work to extrude material in deformation zone 47

3.3.2 Work to extrude material in friction zone 49

3.3.3 Work to extrude material in dead-material zone 50

3.3.4 Extruding work due to mass acceleration ... 52
3.3.5 Redundant work in extruding process ... 52
3.4 Discussion ... 53
3.5 Conclusions ... 55
3.6 Acknowledgments ... 56
3.7 Conflict of Interest ... 57
3.8 Notations ... 57
3.9 References ... 59
Chapter Four – Determining Soil Plasticity Utilizing Manafi Method and Apparatus ... 63
4.1 Abstract ... 65
4.2 Introduction ... 66
4.3 Workability ... 67
4.4 Equipment Design ... 69
4.4.1 Apparatus design concept ... 69
4.4.2 Apparatus overview ... 70
4.4.3 LL setup ... 71
4.4.4 PL setup ... 72
4.5 Laboratory Tests ... 73
4.5.1 Soil materials ... 73
4.5.2 Soil characterisation tests ... 74
4.5.3 Test results ... 77
4.5.4 *Manafi Apparatus* calibration ... 82
4.6 Validation of the *Manafi Method* ... 86
4.7 Discussion ... 90
4.8 Conclusions ... 93
4.9 Acknowledgments ... 94
4.10 References ... 94
Chapter Five – Effect of Particle Size on Soil Plasticity and Soil Classification ... 100
5.1 Abstract ... 102
5.2 Introduction ... 103
5.3 Laboratory Tests ... 107
5.3.1 Soil materials ... 107
5.3.2 Experiments and results ... 109
5.4 Discussion ... 113
5.5 Conclusions ... 118
5.6 Acknowledgments ... 119
5.7 References ... 119
Chapter Six – Conclusions and Recommendations ... 124

6.1 Research Conclusions 124
6.2 Recommendations 125
References.. 127

List of Figures

Figure 1-1: Soil plasticity variability by current standard methods and its effect on soil classification 5

Figure 1-2: Manafi Prototype. 6

Figure 1-3: Manafi Apparatus. 8

Figure 2-1: Effective parameters on soil consistency. 18

Figure 2-2: Comparison of liquid limits obtained from Casagrande and fall cone methods. .. 22

Figure 2-3: Soil characterisation process by different research approaches. 26

Figure 2-4: Movement of an object by a constant force. 28

Figure 2-5: Different resistance forces for various object materials 29

Figure 2-6: Workability variables in extrusion technique 30

Figure 3-1: Longitudinal cross-section of material extruder 41

Figure 3-2: Schematic pattern of material flow in the direct extrusion method 43

Figure 3-3: An extruder model of a single opening direct extrusion. 44

Figure 3-4: Illustration for work done on an object by a constant force. 45

Figure 3-5: One-dimensional motion of the extrusion process. 45

Figure 3-6: Longitudinal cross-section of a direct-method extruder. 46

Figure 3-7: Diagrams for the element in the deformation zone. 47

Figure 3-8: Diagram of stress for the element inside the friction zone. 49

Figure 3-9: Longitudinal cross-section of the dead-material zone. 51

Figure 3-10: A string model for determination of contact area between the dead-material and the plunger 51

Figure 4-1: Work done by a constant force on a mobilised object. 68

Figure 4-2: Different resistance forces for various object materials 68

Figure 4-3: Simplified physical model of the Manafi Apparatus. 69

Figure 4-4: Manafi Apparatus 71

Figure 4-5: Specification of liquid limit determination mould 72

Figure 4-6: Specification of plastic limit determination mould 73

Figure 4-7: Particle size distribution results 75

Figure 4-8: Standard soil plasticity determination 76

Figure 4-9: Extrusion graph samples 78

Figure 4-10: Workability graph examples (P_D–w) 80

Figure 4-11: Workability graph examples (P_D–Std. *LI*).. 85

Figure 4-12: Comparison between results obtained by the Manafi method and the standard methods 87

Figure 4-13: Normal probability plots of different methods.. 88

Figure 4-14: Box and whisker charts of precision test results 90

Figure 5-1: Soil classification based on particle size 105

Figure 5-2: Manafi Apparatus 106

Figure 5-3: Particle size distribution curves of additive sand samples 107

Figure 5-4: Particle size distribution curves of the study samples. 108

Figure 5-5: PSD comparison of samples based on principal components of clay, silt, and sand portions. 108

Figure 5-6: Workability graph examples 111

Figure 5-7: Comparison between results obtained by the Manafi method and the standard methods 113

Figure 5-8: Comparison between soil plasticity determination by the Manafi and standard methods. 114

Figure 5-9: The trend of plasticity alteration by changing the PSD and increasing the sand portion of the samples 116

Figure 5-10: Soil plasticity chart and classification. 117

List of Tables

Table 2-1: Different states and consistencies of soils 19

Table 4-1: Soil sample workability determinations around the liquid limit state. 81

Table 4-2: Soil sample workability determinations around the plastic limit state. 82

Table 4-3: Soil consistency calibration and comparison of the Manafi method with the standard method for liquid limit determination. 86

Table 4-4: Soil consistency calibration and comparison of the Manafi method with the standard method for plastic limit determination. 86

Table 4-5: Paired samples t-test results for liquid and plastic limits. 88

Table 4-6: Precision test results of the standard and Manafi methods for liquid and plastic limits. 89

Table 4-7: Comparing the accurate and estimation methods for calculating the area under the extrusion force-penetration curve. 93

Table 5-1: PSD analysis of soil samples according to BS EN ISO 14688-1 108

Table 5-2: Extrusion data and workability determinations around the liquid limit state. 109

Table 5-3: Extrusion data and workability determinations around the plastic limit state. 110

Table 5-4: Liquid limit determinations and comparison of the Manafi method with the fall cone method. 112

Table 5-5: Plastic limit determinations and comparison of the Manafi method with the thread rolling method. 112

Chapter One - Introduction

Soils are classified into various groups of similar performance and properties according to certain definite principles (Murthy 2003). Liquid and plastic limit tests are the two most common soil index tests required for soil classification and physical property determinations. However, inaccurate determination of soil plasticity may lead to a different classification of soil (Manafi 2019). In other words, different performance of soil material would be expected from an inaccurate soil plasticity determination. In many geotechnical engineering projects such as backfills and earthwork structures, it is crucial to use specific soil materials identified by strict soil classifications (i.e., ASTM D3282-15 2015). Therefore, accurate soil classification plays a significant role in geotechnical engineering. Inevitably, it is required that soil plasticity is determined accurately.

In addition, many engineering properties of soils can be estimated by the results of soil plasticity determination tests. There are many empirical correlations with important engineering parameters using Atterberg limit test results. Therefore, geotechnical engineers can estimate and assess fundamental engineering properties of soils by having the results of simple, quick, and inexpensive Atterberg limit tests. Nonetheless, the engineering parameters typically would be obtained by sophisticated, time consuming, and expensive tests. Consequently, accurate and reliable soil plasticity determination helps geotechnical engineers estimate and assess soil engineering parameters more realistically. However, current standard soil plasticity tests have several issues that may lead to different plasticity determinations (Manafi 2019). O'Kelly (2021) has recently published a useful review paper discussing the latest alternative tests to the standard methods. However, the alternative methods are not adequately suitable to replace current standard methods. The reason might lie in the simplicity and inexpensiveness of current standard methods. However, these two enchanting qualities have been obtained by trading off precision and accuracy to some extent. This research aims to develop and establish the recently proposed Manafi Method (Manafi 2017), leading to more precise and accurate soil plasticity determinations with comparable simplicity and economy to current standard methods.

1.1 Background and Aims

Various properties of soils are usually dependent on the geometry of soil particles (i.e., size and shape of particles) and consistency or relative density of soils. These properties can be expressed as index properties (Murthy 2003). Water plays a significant role in soil consistency. The absorbed water in cohesive soils enables the soil particles to roll over one another due to viscous interlayer water films. Soil consistency is a measure to evaluate the aggregate behaviour of cohesive soils. In fact, the most critical soil aggregate property of cohesive soils is the consistency (Terzaghi et al. 1996; Murthy 2003).

Consistency is a term used to indicate the degree of firmness of cohesive soils, which is expressed qualitatively by different terms from *very soft* to *hard*. The reason is that the physical properties of cohesive soils vary significantly with different water contents. Therefore, it is essential to define several limit states for these qualitative terms to identify the exact consistency state of the cohesive soil.

Atterberg (1911) studied the behaviour of clays with various water contents. He categorised the behaviour of cohesive soils into several states and introduced seven limit states. Later his methods were utilised in geotechnical engineering by Terzaghi (1926) and extended by Casagrande (1932). Their investigations led to standard procedures for determining the Atterberg limits in geotechnical engineering. The three main limit states of shrinkage limit (SL), plastic limit (PL) and liquid limit (LL) have remained in regular usage for geotechnical engineering applications.

PL and LL that outline the plastic behaviour of soils are of great importance for geotechnical engineers, which is the subject of this research. The plasticity index (PI) is the range of water contents in which soil behaves plastically, and is the difference between the water contents at the liquid and plastic limits (ASTM D653-14 2014; ASTM D4318-17e1 2017).

Soil engineering behaviour is based not only on particle size but also on the consistency property of soil (Briaud 2013). Therefore, it is required to consider soil consistency in the soil classification systems for most engineering purposes. Accordingly, the well-known engineering classification systems in geotechnical engineering (i.e., AASHTO and Unified Soil

Classification Systems) consider both particle-size distribution and Atterberg limits as criteria for soil classification.

Atterberg limit tests are easily performed for large numbers of samples, and their results provide quick assessments and correlations to critical physical and engineering properties of soil such as remoulded shear strength (Whyte 1982; Vinod et al. 2013), undrained strength ratios (Skempton 1954, 1957), Preconsolidation Pressure and Recompression Index (Nagaraj and Murthy 1985), coefficient of permeability (Carrier and Beckman 1984), critical state parameters of soil (Schofield and Wroth 1968; Nakase et al. 1988), California Bearing Ratio (Black 1962), and ratio of strength to Standard Penetration Test blow count (Stroud 1974).

Well-known national and international standards describe the plasticity determination procedures in detail (e.g., BS EN 1377-2 1990; AS 1289.3.2.1 2009; AS 1289.3.9.1 2015; AS 1289.3.1.1-2009 2017; ASTM D4318-17e1 2017). However, current standard methods have several issues that make their results unreliable in many cases (e.g., Sherwood and Ryley 1968; Sherwood 1970; Davidson 1983; Prakash 2005; Prakash and Sridharan 2006; Vardanega and Haigh 2014; O'Kelly 2015, 2016, 2017; Manafi 2019). The imprecise results are usually due to intrinsic apparatus deficiencies or limitations, and the operator's performance or judgement during the tests. Factor affecting results may originate from different base materials and various cup weights used in Casagrande apparatus, judgments about the closure of groove, different techniques of soil threading (i.e., the amount of pressure, the rate of rolling) in the thread rolling method, ambiguity in the definition of crumbling of soil thread, and etc. (Whyte 1982; Sivakumar et al. 2009; Kayabali et al. 2015b; Manafi 2017).

It is crucial to note that consistency determination of cohesive soils is the main purpose of Atterberg limit tests, and the results of these tests are indications for the transitional behaviour of cohesive soil from one state to another. In other words, identifying the qualitative terms of soil consistency is the purpose of the Atterberg limit tests. However, the inaccuracy of soil plasticity determination by current standard methods has been initiated from simplification in quantifying a complex qualitative phenomenon. The problem becomes more serious when only one parameter, like soil shear strength, is measured and becomes the criterion for determining a complex system affecting soil behaviour at different water contents. It should be noted that the combinations of many different environmental and inherent soil properties affect the consistency of soils.

Various methods produce different values because current standard tests utilise various apparatus and follow different fundamental mechanics. In addition, each method considers only some portion of the parameters affecting soil consistency. For instance, it is not appropriate to determine one particular property (i.e., soil shear strength) for the soil plasticity determination. The problem to be addressed is that current standard methods are not appropriately designed to determine soil consistency based on the meaning of the soil consistency, which is: "the relative ease with which a soil can be deformed" (ASTM D653-14 2014). Thus, it is required to study the whole behaviour of soil while its water content varies. Furthermore, other liquids such as oil in oil-contaminated soils or landfill leachate can be studied in soil plasticity determination. However, the current standard methods only consider distilled water as the liquid affecting soil consistency. Consequently, it would be possible to contemplate the valid soil consistency criterion in classifying soils and propose a suitable framework for soil classification in geotechnical engineering practice.

This PhD research project aims to develop and establish the newly-invented apparatus by Manafi (2017) as an alternative method for determining soil plasticity with higher accuracy and reliability than current standard methods. Consequently, the classification and estimation of engineering parameters of soils based on their soil plasticity determination will be more accurate and reliable. For this purpose, the following aims and objectives are considered:

1. Improving and establishing the Manafi Method and Apparatus through:
    a. Further development of the Manafi Apparatus by working on an automatic loading system, a data acquisition system, calibration based on the most appropriate extrusion ratio, and standardising the test procedure;
    b. Studying all types of clay soils [Low-plasticity Clay (CL), Intermediate-plasticity Clay (CI), High-plasticity Clay (CH), Very high-plasticity Clay (CV), and Extremely high-plasticity Clay (CE) according to BS 5930 (2015)];
    c. Investigating a wide range of mineral soils having low to very high plasticity characteristics;
    d. Mechanical analysis of the proposed apparatus.
2. Proposing a new framework for soil plasticity determination and classification by:
    a. Theorising based on a combination of quantitative and qualitative research analysis;

b. Increasing the range of particle size to cover the full range of sand portions in soil plasticity determination;
c. Providing data-driven information on mineral soils.

1.2 Research Outline

1.2.1 Improvement in soil plasticity determination

The variable soil plasticity test results obtained by current standard methods may lead to four different classifications for a particular soil, as shown in Figure 1-1 (Manafi 2019). As a result, the perception of physical and engineering parameters of the soil material will be significantly different for different classifications due to the variability of soil plasticity determinations. For instance, selecting soil material for the construction of earth structures is a susceptible process that also depends on soil classification (e.g., ASTM D3282-15 2015). Therefore, the costs of constructing earthworks might increase significantly due to procuring soil materials from a distant borrow site or improving the geotechnical properties of soil at the site in addition to the pertinent environmental consequences, only because of slight variability in their soil plasticity determinations (e.g., Di Matteo et al. 2016).

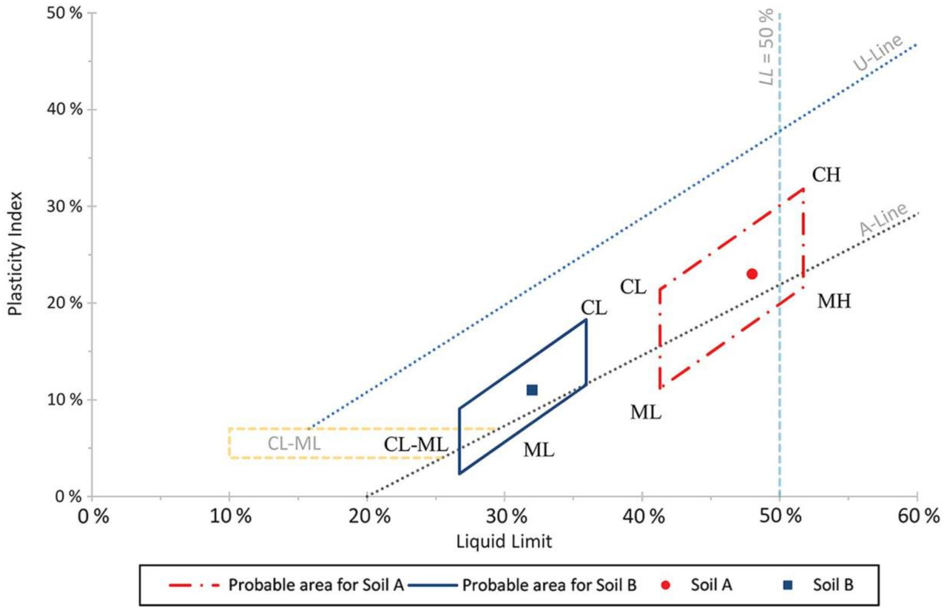

Figure 1-1: Soil plasticity variability by current standard methods and its effect on soil classification (extracted from Manafi 2019).

Recently, a new test method and an apparatus for soil consistency determination based on the nature of soil deformation, referred to as the Manafi Method and Apparatus (see Figure 1-2; Manafi 2017), were proposed. This technique makes it possible to determine the workability of soils at Atterberg limits utilising an extrusion device. The workability of soil can be calculated by determining the work required for soil deformation during the extrusion process. Accordingly, defined systems of soil deformation are correlated to specific soil consistencies (including liquid and plastic limit states).

Figure 1-2: Manafi Prototype (Manafi 2017).

The newly proposed method has several advantages over conventional methods that make it a potential alternative test method (Manafi 2017):

1. An appropriate research approach (combined qualitative and quantitative methodology) is followed in the test procedure for the soil plasticity determination;
2. Both liquid limit and plastic limit tests are attained using one apparatus and similar process;

3. Many uncertainties of conventional methods are eliminated in the proposed method due to superior apparatus design and it being less operator-dependent;
4. It is not a time-consuming test;
5. The test requires only a small soil sample;
6. The total volume of the soil specimen is tested, which increases test accuracy if any inhomogeneity is present in the soil specimen;

Although Manafi (2017) presented encouraging results utilising the method and apparatus, the study was limited to only a few mineral soil samples from three soil types of CL, MH, and CH. In addition, a specific mould with only three extrusion ratios was studied, which was not the optimum setup for regular usage in geotechnical labs. For instance, high extrusion pressures (around 500 kPa) were required to determine the PL, which made the test cumbersome for the operator considering the loading system of the apparatus.

It should be noted that any change in the design of the apparatus requires a complete calibration and data gathering process. However, considering the advantages of the newly proposed method, it is essential to comprehensively investigate the Manafi Method in order to establish it as an alternative and reliable test method for soil plasticity determination. Therefore, this research improves the Manafi Method by:

- Theorising a combined qualitative and quantitative research approach to soil consistency determination;
- Extending the mechanical analysis of the soil extrusion;
- Fabricating a precise apparatus by utilising automatic loading and data acquisition systems, as shown in Figure 1-3;
- Comprehensively studying a wide range of cohesive soils of different particle size distributions and plasticity characteristics.

Consequently, the proposed method serves as an alternative test for determining the liquid and plastic limits of cohesive soils.

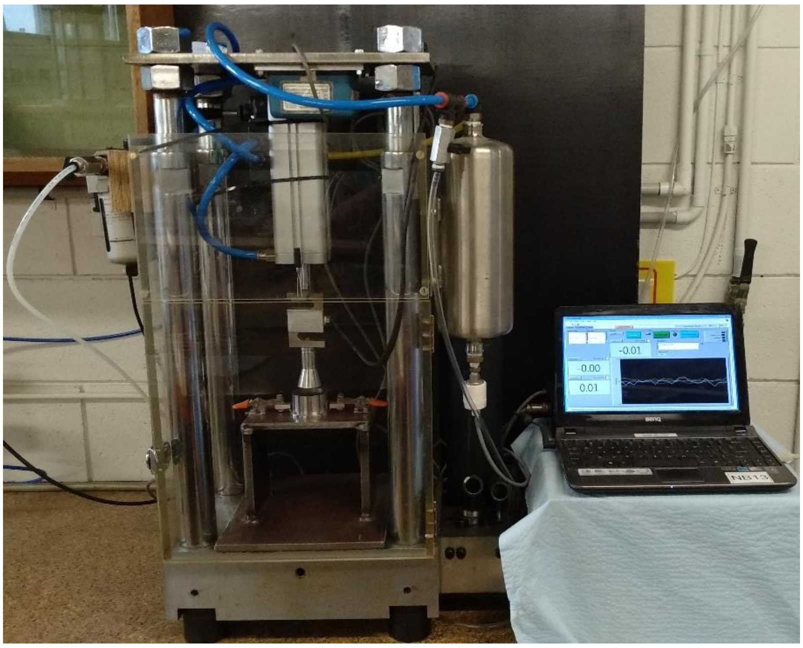

Figure 1-3: Manafi Apparatus.

1.2.2 Proposing a new framework for soil classification

One of the main problems of soil plasticity determination of current standard methods is inappropriate soil sampling procedures when several specimens are prepared from disturbed samples, and the soil particles which are coarser than 425 microns are removed through a sieving procedure (e.g., AS 1289.3.2.1 2009; AS 1289.3.9.1 2015; ASTM D4318-17e1 2017). Undoubtedly, the soil consistency is affected by the full range of soil particles, considering the effect of their specific surfaces in addition to their textures and structures. However, current standard methods are not designed to assess the coarse particles of soil samples. In addition, the conventional apparatuses are very sensitive to coarse particles in the specimen. For instance, the depth of cone penetration in the fall cone method is a function of the surface roughness of the cone and the material (Wood and Wroth 1978), which is directly affected by coarse particles. As a result, not only can soils containing particles with sand size be studied but also contaminated soils, such as oil-contaminated soils, can be investigated to enhance the soil classification systems. Therefore, it is required to propose new apparatuses and methods for considering the entire particle size distribution of soil samples for accurate consistency determinations.

Consequently, the proposed apparatus is appropriately designed to improve the accuracy of soil plasticity determination by directly measuring soil deformation and studying a broader range of particle size closer to the actual condition of the site soil. These advantages allow a new soil classification based on a combination of quantitative and qualitative research analysis (e.g., wide particle size distribution and soil workability).

1.3 Thesis Structure Layout

This thesis contains four articles written in collaboration with four international experts in the research field: Dr An Deng from the University of Adelaide, Dr Abbas Taheri from Queen's University, Canada, Professor Mark B. Jaksa from the University of Adelaide, and Professor Nagaraj Honne B. from BMS College of Engineering, India. This collaboration forms a high-standard authorship team with collectively competitive records. Consequently, this thesis is comprised of six chapters, presented in a thesis by publication format:

- Chapter One introduces the research project, expresses the research aims and objectives, and outlines the thesis structure.

- Chapter Two includes a paper entitled "A New Approach to Soil Consistency Determination". This theoretical manuscript reviews and discusses the conventional quantitative approach for soil consistency determination by standard tests. In addition, it presents a novel combination of qualitative and quantitative research methods based on a behavioural study of soil consistency determination. As a result, a new parameter, called 'workability', is defined and formulated to quantify soil consistency. The study presents a theoretical model focusing on developing a novel method for dealing with the issues related to standard tests. The details of this publication are as follows:

  Masoud S. G. Manafi, An Deng, Abbas Taheri, Mark B. Jaksa, and Nagaraj HB, 2022, "A New Approach to Soil Consistency Determination.", ready to submit.

- Chapter Three presents a published paper entitled "Utilisation of Extrusion Method in Geotechnical Tests: Conception and Theoretical Analysis". Following the proposed research approach of Chapter Two, it is necessary to decide on a soil deformation method to determine soil workability. After evaluating different soil deformation mechanisms, the soil extrusion method is chosen to develop a new geotechnical apparatus considering the compatibility and reliability of the method with the proposed approach. As part of evaluating the extrusion technique for soil property determinations, this paper develops a closed-form solution for determining the extrusion pressure. It extends the conventional slab analysis method to model the entire soil extrusion process, including the extrusion of the dead-material zone and considering the dynamic movement of the extruded material. Moreover, the different soil deformation mechanisms among the test methods explain why some discrepancies could be observed in correlating the extrusion pressures to other geotechnical parameters. The details of this publication are as follows:

> **Masoud S. G. Manafi**, An Deng, Abbas Taheri, 2022, "Utilisation of Extrusion Method in Geotechnical Tests: Conception and Mechanical Analysis." *Arabian Journal of Geosciences*, Vol. 15, No. 449, doi: 10.1007/s12517-022-09543-z.

- Chapter Four comprises an accepted paper entitled "Determining Soil Plasticity Utilising Manafi Method and Apparatus". This article presents the application of the previous theoretical papers for soil property determinations. The proposed technique is instrumented with a new soil extrusion device to quantify the workability of soils which is calibrated to translate the workability to their liquid and plastic limits, called the Manafi Method and Apparatus. The proposed method is applied to several soils with wide-range particle sizes and plasticities. The results are compared with those obtained using conventional methods. The results indicate that the proposed method is more precise and reliable than the standard methods for measuring soil plasticity. The details of this publication are as follows:

> **Masoud S. G. Manafi**, An Deng, Abbas Taheri, Mark B. Jaksa, and Nagaraj HB, 2022, "Determining Soil Plasticity Utilising Manafi Method and Apparatus." *Geotechnical Testing Journal*, doi: 10.1520/GTJ20210235.[1]

- Chapter Five presents the fourth paper entitled "Effect of Particle Size on Soil Plasticity and Soil Classification". Developing a well-designed apparatus based on the expressed theoretical concepts enables us to explore additional capabilities of the newly achieved tool to enhance soil consistency determination and, consequently, soil classification. Even though the full range of particle sizes affects the soil consistency, conventional test methods and apparatuses only assess unrepresentative sub-samples containing particles of less than 425 microns. In contrast, the Manafi Method and Apparatus allow for plasticity exploration of soils that have coarser particles. In this study, soil samples

[1] Accepted on 15 February 2022.

with various proportions of coarse grains are investigated. The results show that coarse grains significantly influence soil plasticity and classification. As a result, a revision to the Unified Soil Classification System is proposed. The details of this publication are as follows:

> **Masoud S. G. Manafi**, An Deng, Abbas Taheri, Mark B. Jaksa, and Nagaraj HB, 2022, "Effect of Particle Size on Soil Plasticity and Soil Classification.", *Geotechnical Testing Journal*, under review.

- Chapter Six, entitled "Conclusions and Recommendations", summarises the research results, discusses the limitations of the study, and suggests future investigations relevant to soil plasticity determination.

1.4 References

AS 1289.3.1.1-2009, 2017, "Methods of Testing Soils for Engineering Purposes - Soil Classification Tests - Determination of Liquid Limit of a Soil – Four Point Casagrande Method." Standards Australia, Sydney, Australia.

AS 1289.3.2.1, 2009, "Methods of Testing Soils for Engineering Purposes - Soil Classification Tests - Determination of the Plastic Limit of a Soil." Standards Australia, Sydney, Australia.

AS 1289.3.9.1, 2015, "Methods of Testing Soils for Engineering Purposes - Soil Classification Tests - Determination of the Cone Liquid Limit of a Soil." Standards Australia, Sydney, Australia.

ASTM D653-14, 2014, "Standard Terminology Relating to Soil, Rock, and Contained Fluids." ASTM International, West Conshohocken, PA, doi: 10.1520/D0653-14.

ASTM D3282-15, 2015, "Standard Practice for Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes." ASTM International, West Conshohocken, PA, doi: 10.1520/D3282-15.

ASTM D4318-17e1, 2017, "Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils." ASTM International, West Conshohocken, PA, USA, doi: 10.1520/D4318-17E01.

Atterberg, A., 1911, "Uber Die Physikalische Bodenuntersuchung Und Uber Die Plastizitat Der Tone. (on the Physical Testing of Soil and the Plasticity of Clays)." *Internationale Mitteilungen für Bodenkunde*, Vol. 1, No. 1, pp. 10-43.

Black, W. P. M., 1962, "A Method of Estimating the California Bearing Ratio of Cohesive Soils from Plasticity Data." *Géotechnique*, Vol. 12, No. 4, pp. 271-282, doi: 10.1680/geot.1962.12.4.271.

Briaud, J. L., 2013, *Geotechnical Engineering: Unsaturated and Saturated Soils*, John Wiley & Sons, Hoboken, New Jersey, p. 998 pages.

BS 5930, 2015, "Code of Practice for Ground Investigations." British Standards Institution, Milton Keynes, UK.

BS EN 1377-2, 1990, "Methods of Test for Soils for Civil Engineering Purposes. Part 2: Classification Tests." British Standards Institution, Milton Keynes, UK.

Carrier, W. D., and Beckman, J. F., 1984, "Correlations between Index Tests and the Properties of Remoulded Clays." *Géotechnique*, Vol. 34, No. 2, pp. 211-228, doi: 10.1680/geot.1984.34.2.211.

Casagrande, A., 1932, "Research on the Atterberg Limits of Soils." *Public roads*, Vol. 13, No. 8, pp. 121-136.

Davidson, D. A., 1983, "Problems in the Determination of Plastic and Liquid Limits of Remoulded Soils Using a Drop-Cone Penetrometer." *Earth Surface Processes and Landforms*, Vol. 8, No. 2, pp. 171-175, doi: 10.1002/esp.3290080208.

Di Matteo, L., Dragoni, W., Cencetti, C., Ricco, R., and Fucsina, A., 2016, "Effects of Fall-Cone Test on Classification of Soils: Some Considerations from Study of Two Engineering Earthworks in Central Italy." *Bulletin of Engineering Geology and the Environment*, Vol. 75, No. 4, pp. 1629-1637, doi: 10.1007/s10064-015-0808-8.

Kayabali, K., Üstün, A. B., and Özkeser, A., 2015b, "Refinement of the Reverse Extrusion Test to Determine the Two Consistency Limits." *Bulletin of the Mineral Research and Exploration*, Vol. 2015, No. 150, pp. 131-143, doi: 10.19111/bmre.85667.

Manafi, M. S. G., 2017, "Soil Plasticity Determination Using Manafi Method and Apparatus." MSc Thesis by Research, Trinity College Dublin, Dublin, Ireland.

Manafi, M. S. G., 2019, "Soil Plasticity Variability and Its Effect on Soil Classification." *Geotechnical Testing Journal*, Vol. 42, No. 2, pp. 457-470, doi: 10.1520/GTJ20170273.

Murthy, V. N. S., 2003, *Geotechnical Engineering: Principles and Practices of Soil Mechanics and Foundation Engineering*, Marcel Dekker, New York.

Nagaraj, T. S., and Murthy, B. R. S., 1985, "Prediction of the Preconsolidation Pressure and Recompression Index of Soils." *Geotechnical Testing Journal*, Vol. 8, No. 4, pp. 199-202, doi: 10.1520/GTJ10538J.

Nakase, A., Kamei, T., and Kusakabe, O., 1988, "Constitutive Parameters Estimated by Plasticity Index." *Journal of Geotechnical Engineering*, Vol. 114, No. 7, pp. 844-858, doi: 10.1061/(ASCE)0733-9410(1988)114:7(844).

O'Kelly, B. C., 2015, "Atterberg Limits Are Not Appropriate for Peat Soils." *Geotechnical Research*, Vol. 2, No. 3, pp. 123-134, doi: 10.1680/jgere.15.00007.

O'Kelly, B. C., 2016, "Briefing: Atterberg Limits and Peat." *Environmental Geotechnics*, Vol. 3, No. 6, pp. 359-363, doi: 10.1680/envgeo.15.00003.

O'Kelly, B. C., 2017, "Fall-Cone Strength Testing of Municipal Sludges and Residues." *Environmental Geotechnics*, Vol. 4, p. 13 pp, doi: 10.1680/jenge.15.00080.

O'Kelly, B. C., 2021, "Review of Recent Developments and Understanding of Atterberg Limits Determinations." *Geotechnics*, Vol. 1, No. 1, pp. 59-75, doi: 10.3390/geotechnics1010004.

Prakash, K., 2005, "Discussion of "Plastic Limit, Liquid Limit, and Undrained Shear Strength of Soil—Reappraisal" by Binu Sharma and Padma K. Bora." *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 131, No. 3, p. 402, doi: 10.1061/(ASCE)1090-0241(2005)131:3(402).

Prakash, K., and Sridharan, A., 2006, "Critical Appraisal of the Cone Penetration Method of Determining Soil Plasticity." *Canadian Geotechnical Journal*, Vol. 43, No. 8, pp. 884-888, doi: 10.1139/T06-043.

Schofield, A. N., and Wroth, P., 1968, *Critical State Soil Mechanics*, McGraw-Hill, London, p. 155.

Sherwood, P. T., 1970, "The Reproducibility of the Results of Soil Classification and Compaction Tests." *Road Research Laboratory Report No. LR 339*, Road Research Laboratory, Crowthorne, Berk.

Sherwood, P. T., and Ryley, M. D., 1968, "An Examination of Cone-Penetrometer Methods for Determining the Liquid Limit of Soils." *TRRL Report LR 233*, Transport and Road Research Laboratory, Crowthome, Berks.

Sivakumar, V., Glynn, D., Cairns, P., and Black, J. A., 2009, "A New Method of Measuring Plastic Limit of Fine Materials." *Géotechnique*, Vol. 59, No. 10, pp. 813-823, doi: 10.1680/geot.2009.59.10.813.

Skempton, A., 1954, "Discussion: Sensitivity of Clays and the C/P Ratio in Normally Consolidated Clays." *Proceedings of the American Society of Civil Engineers, Separate*, Vol. 478, pp. 19-22.

Skempton, A., 1957, "Discussion: Further Data on the C/P Ratio in Normally Consolidated Clays." *Proceedings of the Institution of Civil Engineers*, Vol. 7, pp. 305-307.

Stroud, M. A., 1974, "The Standard Penetration Test in Sensitive Clays and Rocks." *The European Seminar on Penetration Testing*Stockholm, Sweden, pp. 366-375.

Terzaghi, K., 1926, "Simplified Soil Tests for Subgrades and Their Physical Significance." *Public roads*, Vol. 7, No. 8, pp. 153-170.

Terzaghi, K., Peck, R. B., and Mesri, G., 1996, *Soil Mechanics in Engineering Practice*, Wiley, New York.

Vardanega, P., and Haigh, S., 2014, "Some Recent Developments in the Determination of the Atterberg Limits." *Advances in Transportation Geotechnics and Materials for Sustainable Infrastructure*, American Society of Civil Engineers, pp. 48-55, doi: 10.1061/9780784478509.007.

Vinod, P., Sridharan, A., and Deepa, K. A., 2013, "Remoulded Shear Strength at Plastic and Semi-Solid States." *Proceedings of the Institution of Civil Engineers - Geotechnical Engineering*, Vol. 166, No. 4, pp. 415-424, doi: 10.1680/geng.11.00071.

Whyte, I. L., 1982, "Soil Plasticity and Strength - a New Approach Using Extrusion." *Ground Engineering*, Vol. 15, No. 1, pp. 16-18, 20, 22, 24.

Wood, D. M., and Wroth, C. P., 1978, "The Use of the Cone Penetrometer to Determine the Plastic Limit of Soils." *Ground Engineering*, Vol. 11, No. 3.

Chapter Two – A New Approach to Soil Consistency Determination

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Overall percentage (%)	85%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
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By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);
ii. permission is granted for the candidate in include the publication in the thesis; and
iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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2.1 Abstract

It is well-known in geotechnical engineering that the behaviour of cohesive soils is intimately associated with water content. Hence, it is essential to determine soil consistency for the characterisation and classification of such soils. Present standard tests use simplified quantitative means to measure the complex qualitative phenomenon of soil consistency. The available tests are also operator-dependent and suffer result variability to some degree. Consequently, inaccurate soil classifications and imprecise estimations of engineering properties arise. This paper discusses the reasons for major issues in current standard methods regarding Atterberg limit determinations. Subsequently, the theories of a combined qualitative and quantitative research methodology are outlined for the behavioural study on soil properties, concentrating on soil consistency determination. Accordingly, a new parameter, called 'workability', is introduced and formulated to quantify the soil consistency property. The proposed approach defines the criteria for designing new alternative tests to obtain definitive results in compliance with the qualitative nature of soil consistency.

Keywords: Soil consistency, Plasticity, Atterberg limits; Quantitative approach; Qualitative approach; Workability.

Key messages of the paper:

- Discussing the parameters that affect soil consistency;
- Explaining the issues of current standard methods on soil plasticity determination;
- Clarifying the definition of soil consistency;
- Proposing a combined qualitative and quantitative research methodology for the behavioural study of soil properties, concentrating on the soil consistency determination;
- Introducing a new parameter for quantifying the soil consistency.

2.2 Introduction

Soil consistency is a property used to express how easily a cohesive soil can be deformed (e.g., soft, stiff, etc.) and to indicate the behaviour of cohesive soils with different water contents. Consistency is one of the most critical properties of cohesive fine-grained soils (Terzaghi et al. 1996; Murthy 2003). Therefore, soil consistency determination is essential for soil characterisation and classification. Soil consistency expresses the level of firmness of cohesive soils that is a qualitative phenomenon. Many different interrelated parameters affect soil consistency, as shown in Figure 2-1 (e.g., Casagrande 1932; Torrance and Pirnat 1984; Hobbs 1986; Trauner et al. 2005; Prakash and Sridharan 2006; Jeong et al. 2010; Das and Sobhan 2018).

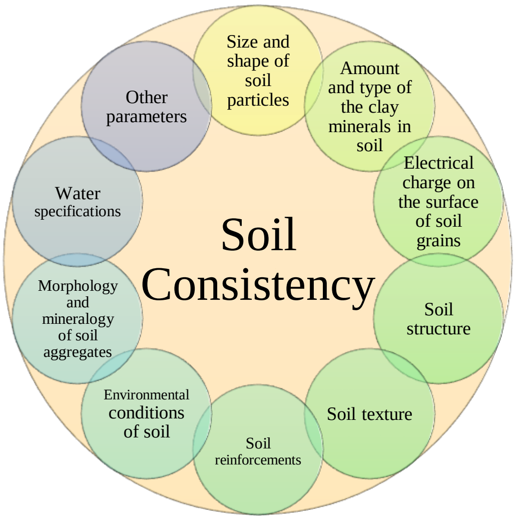

Figure 2-1: Effective parameters on soil consistency.

*Note: share of each parameter is variable for each soil.

Atterberg (1911), a chemist working in agricultural science, studied the behaviour of clays with different water contents. He categorised the consistency of cohesive soils into seven limiting boundaries. His methods were used in geotechnical engineering by Terzaghi (1926) and modified by Casagrande (1932). Their investigations led to standard procedures for the determination of the Atterberg limits. The three main limit states of shrinkage limit (SL), plastic limit (PL), and liquid limit (LL) have been extensively adopted for geotechnical engineering applications. As a result, Atterberg limits indicate the state boundaries of soils, as identified in Table 2-1.

Table 2-1: Different states and consistencies of soils (adapted from Murthy 2003).

State	Limit	Consistency
Liquid		Very soft
………………	Liquid limit (LL) …………	Soft
Plastic		Stiff
………………	Plastic limit (PL) …………	Quite stiff
Semi-solid		Very stiff
………………	Shrinkage limit (SL) ………	Extremely stiff
Solid		Hard

The plastic state, and therefore the plastic behaviour of soils, is bounded by the PL and LL. The index tests that determine these limit states provide valuable information on soil's physical and engineering properties, such as shrinkage/swelling capacity, compressibility, strength, and permeability (Sabatini et al. 2002). Since these limits provide general indications of soil behaviour (Germaine and Germaine 2009), they are used widely in soil classification. Standard laboratory tests such as the fall cone, Casagrande percussion cup, or thread rolling are available to determine the consistency values, as provided in regional standards, e.g., ASTM D4318-17e1 (2017), BS EN 1377-2 (1990), AS 1289.3.1.1-2009 (2017), AS 1289.3.2.1 (2009), and AS 1289.3.9.1 (2015). These tests are simple in their operation. The apparatuses are relatively inexpensive to purchase and maintain but suffer major to moderate reliability issues (e.g., Sherwood and Ryley 1968; Sherwood 1970; Davidson 1983; Prakash 2005; Prakash and Sridharan 2006; Vardanega and Haigh 2014; Manafi 2017, 2019). Consequently, inconsistent results obtained by conventional methods can lead to inaccurate soil classification and imprecise estimation of engineering properties (Manafi 2019). Hence, there is a need to propose alternative test methods to solve the recognised issues. O'Kelly (2021) recently published a useful review paper discussing the latest alternative tests to the standard methods. However, all of the alternative methods have been unsuccessful in replacing current standard methods.

This paper discusses the sole quantitative approach in the previous studies for soil plasticity determination. Choosing an appropriate strategy is a critical step before designing any test method. Therefore, an attempt is made to scrutinise the soil plasticity determination in the broader context of soil consistency determination. This work aims to present a new methodology for the behavioural study of soil properties, focusing on soil consistency determination. In addition, several intrinsic issues of current standard methods are highlighted to be considered in the next generation of soil plasticity determination tests. Consequently, the objectives of this study are:

- Discussing the parameters that affect soil consistency;
- Explaining the key issues of current standard methods with soil plasticity determination;
- Clarifying the definition of soil consistency;
- Proposing a combined qualitative and quantitative research methodology for the behavioural study of soil properties, concentrating on soil consistency determination;
- Introducing a new parameter for quantifying soil consistency.

Eventually, the present study is expected to contribute to our understanding of the qualitative nature of soil consistency determination, which will be crucial in the design of new alternative test methods.

2.3 Issues Relevant to Current Standard Methods

A detailed soil characterisation program needs to consider several inherent issues with the current standard methods. It should be noted that solving each issue might require a separate comprehensive study. However, this article addresses them as issues to be studied in future investigations following the newly proposed approach.

The primary approach to LL determination by standard methods is utilising the strength-based method. In this process, it is assumed that, at the LL, all soils have a particular small undrained shear strength (i.e., 1.7 kPa for the BS fall cone method (Wroth and Wood 1978) and approximately 2 kPa for the ASTM (Casagrande) percussion cup method (ASTM D4318-17e1 2017)). However, various studies report a wide range of undrained shear strengths at the LL. For instance, Prakash (2005) noted this range to lie between 0.5 to 5.6 kPa for the percussion cup method.

Various factors and uncertainties affect the results of the Casagrande (percussion cup) method. To this end, the intrinsic apparatus deficiencies or limitations include:

- Different standards use different materials for the base of the Casagrande percussion apparatus. The softer bases absorb more energy, and hence, less energy is transferred to the cup of soil, which results in higher values of LL;

- Different masses of cups adopted in the test device affect the results. ASTM D4318-17e1 (2017) uses a cup with a mass of between 185 g and 215 g. This difference in masses affects the amount of energy transferred, influencing the results obtained;
- Dimensions of the grooving tools are slightly varied. The ASTM D4318-17e1 (2017) grooving tool cuts an 8±0.1 mm deep groove, whereas the AASHTO T89-10 (2010) curved grooving tool cuts a 10±0.1 mm deep groove. Thus, this variation in the geometry of soil specimens leads to a variation in the test results.

The operator's performance and judgment also lead to variation in the results. Different techniques that operators use during the test procedure account for the majority of errors in LL determination (Sherwood 1970). Various methods of groove formation, filling the cup with soil, rate of cup drops, and judgment on the groove closure are the most critical factors that affect the LL values obtained by the Casagrande apparatus.

The fall cone method directly determines the shear strength of the soil specimen (Vardanega and Haigh 2014). Therefore, LL determination by this method is strength-based. Koumoto and Houlsby (2001) also verified the influence of the cone angle, sharpness and roughness, and shear strain rate during penetration on the results.

Compared to the Casagrande method, the fall cone method suffers fewer uncertainties in the test procedure. However, it also has several issues that make its results unreliable in some cases:

- Inappropriate assumption of specific shear strength at the liquid limit for soils (Nagaraj et al. 2019);
- Difficulty in determining the non-plastic state for some silty soils (Poulsen et al. 2012);
- Sensitivity of the results to the friction of the cone stem in the apparatuses;
- The results obtained by the fall cone method are plotted on the plasticity chart, which was initially established using the Casagrande method. The inconsistency between the LL determination methods may result in inaccurate soil classifications.

Many researchers have reported different values for the LL obtained using the percussion cup and fall cone methods (i.e., Medhat and Whyte 1986; Wasti and Bezirci 1986; Leroueil and Le Bihan 1996; Sridharan and Prakash 2000; Prakash and Sridharan 2006). Littleton and Farmilo

(1977) observed small differences between the results of the percussion cup and fall cone methods for soils with *LL*<100%. However, the percussion cup method provided higher LL values for soils with *LL*>100% (e.g., Fig. 2). The mechanics of the apparatus explain this discrepancy.

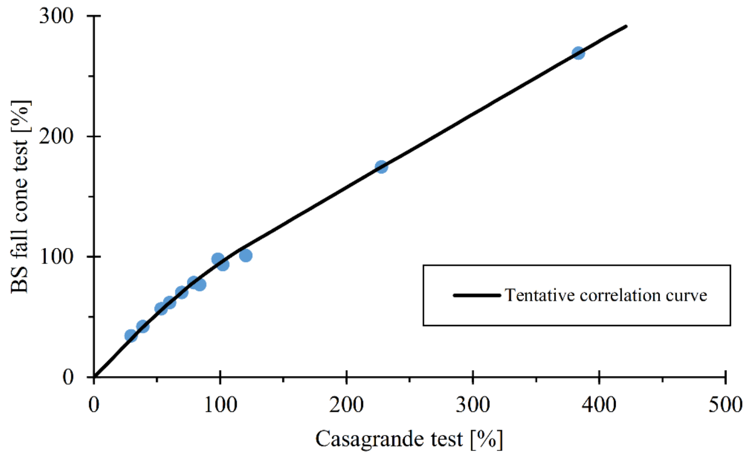

Figure 2-2: Comparison of liquid limits obtained from Casagrande and fall cone methods (adapted from Head 2006).

Researchers disagree over the preference of standard tests for LL determination. Sridharan and Prakash (1999; 2006) suggested that the undrained strength of the soil is comprised of two components: the undrained frictional resistance, which is the result of the net interparticle attractive forces due to the soil fabric, and the undrained cohesion component because of the viscous diffuse double layer water near soil particles. Consequently, the fall cone method cannot represent the plasticity property of soil as it mostly determines the undrained frictional strength of the specimen (Prakash and Sridharan 2006). However, compared to the Casagrande method, the fall cone method generally provides more consistent results due to fewer experimental and operator errors involved in the test procedures (Sherwood and Ryley 1968). This is why BS EN 1377-2 (1990) and CEN. E.N. 1997-2 (2007) prefer the fall cone test over the Casagrande cup method. Nevertheless, considering the definitions of precision and accuracy (ASTM D653-14 2014), being a more precise method does not guarantee accuracy. Therefore, the fall cone method is not necessarily the most accurate liquid limit test. In addition, the fall cone method has not been recognised as a standard test by ASTM D4318-17e1 (2017).

The plastic limit determination by thread rolling is essentially identical to that proposed by Atterberg (1911). Despite the simple test procedure, very complex strain/stress systems occur to the soil threads (such as combinations of cylindrical compression, lateral extrusion, and bar rolling distortions). These are functions of various variables, such as the ratio of hand contact to soil thread diameter, the rolling rate, the amount of applied pressure, and the friction generated between glass plate, soil, and hand (Whyte 1982). It has also been suggested that the reason for the observation of brittle failure in this test is either air entry or cavitation in the soil thread (Haigh et al. 2013; Vardanega and Haigh 2014).

Results of the standard PL test significantly depend on the operator. For instance, Sherwood (1970) reported different PL results ranging from 19% to 39% for a clay sample tested by different operators. Although there are guidelines from various sources for the test procedure, the matrix and texture of the soil might not allow the operators to follow the guidelines accurately. Besides, the test conditions are variable for every measurement. For instance, during the test, the amount of pressure differs by rolling the soil thread under fingers at joints and phalanges. The applied pressure greatly differs proportionate to soil type and its plasticity. The rolling rate varies among operators and depends on the soil type as well. Various hand textures and sizes produce different friction between the hand and the soil. Inaccurate visual measurement of the soil thread diameter is also probable. In addition, the ambiguity in the thread crumbling definition affects the operators' judgment.

Apart from laboratory test issues, current standard methods have a few other fundamental problems that prevent accurate site characterisation. Soil sampling is one of the significant issues associated with these tests. The soil used for these tests is obtained from disturbed samples. Although Atterberg limit tests are index tests, the current standard methods essentially determine the soil's shear strength. As a result, disturbed soil samples are not suitable for determining the engineering parameters of soils. In the case of LL and PL tests, it is much worse, because several specimens are prepared from disturbed samples through the sieving process that makes them fully disturbed. In this process, the structure of the soil is destroyed. In addition, soil fractions that are coarser than 425 microns are discarded prior to the tests. Consequently, the soil specimens are biased from the site's soil. Hence, it is almost irrational to correlate the test results with the site's soil. Therefore, the results of plasticity tests on disturbed samples should be interpreted by considering other in-situ test results (e.g., vane shear test). However, developing new in-situ plasticity determination tests is also suggested.

The water used in the Atterberg limit tests is also imperative. Chemistry and pH of water for preparing the homogeneous soil paste can significantly affect the results (Davidson 1983; Hobbs 1986; Yang and Dykes 2006; Asadi et al. 2011). The chemical condition of the soil and water system affects the response of remoulded soils (Rosenqvist 1953; Bjerrum 1954; Penner 1965; Torrance 1975; Torrance and Pirnat 1984). The pH of water affects the cation exchange capacity of soils. The surface of cohesive soil minerals has negative electrical charges that absorb cations and polar compounds. Hence, even the usage of distilled water, as in current test methods, may lead to a determination of soil consistency that is different from what happens in the field.

Torrance and Pirnat (1984) investigated the effect of pH on the rheology of a marine clay sample by changing the pH of the material. They showed that the shear strength of remoulded soil was pH-dependent. Ideally, water with similar specifications to the site's water should be used in the tests. If applicable, the water should be obtained from the location of the soil sample at the sample's depth, as the chemical properties might vary considerably at different depths. In addition, the viscosity and density of water vary at different temperatures, which could affect the results of Atterberg limit tests as well. Therefore, developing new in-situ plasticity determination tests might also solve these issues. As a practical remedy, the pH of soil paste after using distilled water with neutral pH should be measured and be considered in the consistency determination.

2.4 Proposing a New Research Approach for Soil Plasticity Determination

Atterberg (1911) originally defined limit states of consistency for clay soils based on soil behaviour at varying water contents. He proposed straightforward and inexpensive tests for the determination of these limits. Although his approach was appropriate for measuring soil behaviour, his tests were too rudimentary to provide accurate data. Later, Terzaghi (1926) tried to utilise his methods for soil classification, but he required more precise and reproducible results. Casagrande (1932) then sought to standardise the three main limit states of SL, PL, and LL tests for geotechnical engineering practice. The actual problem arose from quantifying the complex qualitative phenomenon of soil consistency. Designing experimental tests based on the quantitative methodology required various assumptions to simplify the qualitative process. For instance, only one engineering property, like soil shear strength, is chosen as an indication for the determination of the complex behavioural system affected by various parameters shown in Figure 2-1. Hence, although the test procedures probably are established better than Atterberg's initial tests, the sole quantitative research approach has not been suitable.

Considering the dynamic environmental conditions of the site's soil, the soil consistency determination can be classified as a 'quasi-experiment' type because there is limited or no control on determining several effective parameters (Fellows and Liu 2015). Therefore, qualitative research methods combined with quantitative methods are required. In the **quantitative research approach**, the researcher tries to detect the relationships between variables and generalise the outcomes (Van Note Chism et al. 2008). In the **qualitative research approach**, the researcher focuses on only a few parameters while concentrating on the context of the study and recognises the operator as an instrument (the analyser) of the study (Van Note Chism et al. 2008). Therefore, the effect of uncontrollable parameters on the study can be reflected by qualitative questionnaires answered by experienced operators. The main contribution of qualitative research is its ability to adapt to natural settings, which enables exploration of background, reasoning, and other internal parameters that describe the interaction of context and elements in a specific environment (Van Note Chism et al. 2008). Usage of the combined qualitative and quantitative methods encompasses the advantages of both approaches.

Figure 2-3 illustrates the process of soil characterisation by plasticity determination tests utilising the current standard and proposed approaches. The results of the PL and LL tests infer the plastic state, which in turn inform the soil consistency and hence the soil behaviour. The quantitative method is on the right-hand side of the diagram adopted by the current standard methods. On the left-hand side is the proposed combined qualitative and quantitative method, where each of the various stages needs to be considered as affecting one another. In other words, the conventional methods try to estimate and categorise soil behaviour by conducting two simplified tests that have several key issues. However, the proposed combined qualitative and quantitative approach suggests designing new reliable quantitative and qualitative tests as a part of a comprehensive investigation program considering the inter-related stages of plasticity determination and consistency examination to identify the soil behaviour.

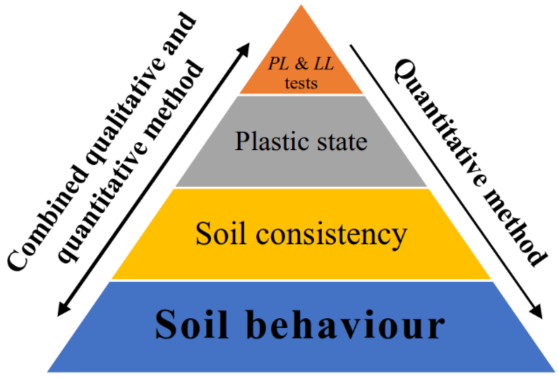

Figure 2-3: Soil characterisation process by different research approaches.

Accordingly, several quantitative and qualitative studies need to be designed for each stage to correctly estimate the soil behaviour. However, as the first step forward, this paper proposes the target parameters of the laboratory LL and PL tests to quantify the behaviour of soil specimens following the recommended method. In other words, a new criterion is introduced in this study to determine the behaviour of soil samples in laboratory tests based on the definition of soil consistency and compatible with the proposed approach as part of the comprehensive soil characterisation program.

2.4.1 Test design fundamentals

ASTM D653-14 (2014) generally defines "consistency" as "the relative ease with which a soil can be deformed". For further clarification of the meaning of consistency, the Oxford Dictionary of English defines it as "consistent behaviour" and "the quality of achieving a level of performance which does not vary greatly in quality over time" (Stevenson 2010). These definitions clarify the importance of the **soil's behaviour** in a specific system that should be monitored **over a time interval**. Consequently, it would be possible to compare the behaviour of different soils and judge the consistency of the specimen.

Oxford Dictionary of English defines the word "behaviour" as "the way in which one acts or conducts oneself, especially towards others", and provides more information with "the way in which a machine or natural phenomenon works or functions" (Stevenson 2010). These explanations show that the soil's reaction to specific conditions is the behaviour of the soil under those conditions. Although all soils react to the conditions defined by the test method, the test may not have been devised to measure the behaviour of the soil. For instance, the determination of only one parameter of soil (e.g., soil shear strength in the fall cone test) is not the determination of overall soil behaviour during the test. Moreover, tests might not have been designed well to measure the soil behaviour appropriately. For instance, different operators perform variably under the test conditions in Casagrande percussion cup or thread rolling tests. Hence, regarding soil consistency determination, it is required to design a suitable system to determine soil behaviour and standardise the soil's performance level.

The alternative test methods for determining soil consistency should coincide with the nature of soil deformation. In other words, defined systems of soil deformation correlate to specific soil consistencies (including liquid and plastic limits). Hence, a simple measurement of **deformation rate** quantifies the soil behaviour affected by the influential parameters in soil consistency. In the proposed method, considering the definition of consistency, the assumption is that although different soil types might have different values for various parameters (e.g., various shear strengths, particle size, etc., at the consistency limits), they have similar behaviour at various consistency limit states.

As a practical note, considering the current inexpensive and straightforward standard plasticity determination tests, the proposed alternative methods should have the advantages of being reliable, easy, quick, and inexpensive to challenge the present test methods.

2.4.2 Soil behaviour quantification

To benchmark the laboratory test results, it is necessary to appropriately quantify the qualitative phenomena. The proposed method is to determine the soil workability. Workability has different meanings in different areas, and it is essential to consider the context of usage [e.g., different definitions in concrete technology (Kurtz 2004), metalworking processes (Dieter and Bacon 1988), the ceramic industry and white-ware production (Wesley 2014), and backfill materials in geotechnical projects (UFC 3-220-04FA 2004)]. In general, a workable system is practical and effective, and a workable substance can be shaped by hand (Longman Group 2011). From this broad definition, it can be realised that the workability of a system is measurable by determining the system's efficiency for reaching the purpose of a particular work. Hence, the purpose of any specific project and its requirements define the concept of workability. Since soil index tests usually characterise the site's soil, the newly proposed test method should determine the general behaviour of soil when specific work applies to the soil specimen. In this regard, it is necessary to consider the meaning of 'work' in physics.

“In physics, work is done only if an object is moved through some displacement while a force is applied to it” (Serway et al. 2006). The formula for calculation of work done on an object by a constant force is:

$$W = (F\cos\theta)\Delta x \qquad \textbf{(2-1)}$$

where F is the magnitude of the force, Δx is the magnitude of the displacement, and θ is the angle between the directions of $\vec{F}$ and $\Delta\vec{x}$ (the parameters are shown in Figure 2-4).

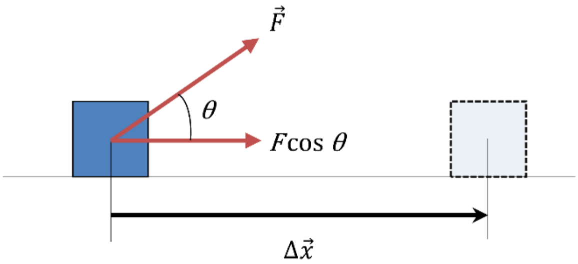

Figure 2-4: Movement of an object by a constant force.

Considering Eq. (2-1), there is no time parameter to observe the soil behaviour over a period of time. In addition, there is no direct relation to different materials of the object in the work’s formula. However, other objects might need different amounts of force to overcome the resistance against the movement of the objects, as demonstrated in Figure 2-5. The work done by F is constant for both objects in Figure 2-5(a) and (b), but the work that is exerted by the resistance force in Figure 2-5(a) is greater than in Figure 2-5(b). The difference between the net work done on objects in Figure 2-5(a) and (b) causes faster movement of the object in case (b) than the object in case (a). Actually, the net force in case (b) of Figure 2-5 ($F - F_{f(b)}$) is greater than in case (a). This will lead to an extra acceleration of the object in case (b) by assuming an identical mass in both cases, according to Newton's second law of motion. Hence, it is possible to measure the effect of resistance force by measuring the rate of work imposed on the object.

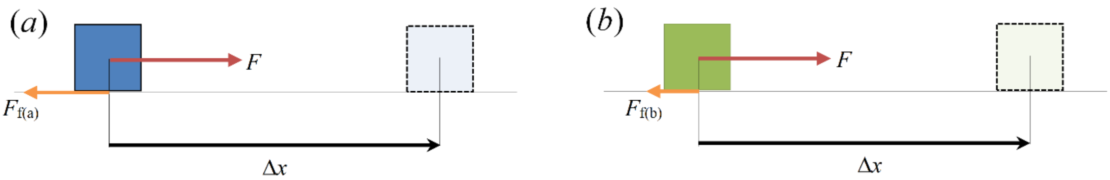

Figure 2-5: Different resistance forces for various object materials: (*a*) An object with a high resistance force against movement; (*b*) An object with a low resistance force against movement.

Power is the rate at which the work is conducted. The average power is calculated by the following formula:

$$P = \frac{W}{\Delta t} = \frac{F\Delta x}{\Delta t} = F\bar{v} \tag{2-2}$$

where Δt is the time interval, and $\bar{v}$ is the average speed of the object.

Accordingly, if there is a driving force and a variable resistance force, it will be possible to calculate the work of the resistance force by measuring the power of that specific force. The resistance in the consistency determination is the force that does work to deform the soil specimen. A specimen in a soft consistency deforms easier (or faster) than the soil in a stiffer consistency. Therefore, the deformation rate will be used to determine the work imposed and thus the workability of the soil specimen. Consequently, the consistency of the specimen can be quantified by determining the soil workability (deformation power) as the new test method.

Providing experimental data following the proposed approach requires fabricating new apparatuses and separate comprehensive laboratory tests that are out of the scope of this theoretical paper. However, this study establishes the theoretical bases of soil behaviour studies as the first step towards practical investigations on this topic.

Various soil deformation systems may be designed for the workability determination. It seems that a soil extrusion technique is well compatible with the proposed method. A soil extrusion device can deform soil specimens in a repeatable process capable of determining all variables of the workability parameter (F, F_f, Δx, and Δt as demonstrated in Fig. 6). F_f in Fig. 6 is the sum-up of all the internal resistant forces against the soil extrusion, and F is the extrusion force applied by an actuator (Manafi et al. 2022a). Therefore, the workability parameter can be obtained suitably.

Although the extrusion method has been tried for the Atterberg limit determination (e.g., Whyte 1982; Kayabali and Tufenkci 2007, 2010a), the approach used in these studies has not been appropriate, i.e., the shear strength-based approach. Consequently, discrepancies are reported (e.g., O'Kelly 2019). The data discrepancies can also be explained by comparing different soil deformation mechanisms between the extrusion method (e.g., Dieter and Bacon 1988; Saha 2000; Manafi et al. 2022a) and conventional shear strength tests (Head 2006; Head and Epps 2011, 2014). Nevertheless, the extrusion method seems suitable for the proposed approach because it determines the soil workability with low operator dependency. The authors suggest further practical studies following the soil workability determination technique (e.g., Manafi 2017).

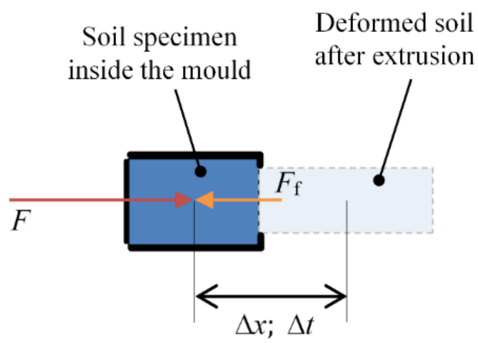

Figure 2-6: Workability variables in extrusion technique.

2.5 Discussion

"The most significant aggregate property of … cohesive soils is the consistency" (Terzaghi et al. 1996). That is why soil consistency determination is inevitable for soil classification and the correlation of results to engineering parameters such as shear strength and consolidation properties. However, soil consistency definition and determination methods have been highly controversial in geotechnical engineering. Consequently, the test results have suffered drastically in terms of precision and accuracy.

One of the main reasons for the variable results obtained by the conventional tests is the sole utilisation of the quantitative approach for the complex qualitative phenomenon of soil consistency over the past years. This study appears to be the first to propose the novel combined qualitative and quantitative method for soil consistency determination. The strength of this approach is in its capability to study the environmental and behavioural parameters in the evaluation process (as shown in Figure 2-1). In addition, there are no restrictions for using quantitative methods to assess effective parameters separately (i.e., different lab or field tests to evaluate separate parameters). However, all the assessment tools should be arranged in a comprehensive quantitative and qualitative study compatible with the qualitative nature of soil consistency.

Since the parameters in the workability determination are obtainable by a data acquisition system, i.e., by utilising load cells and displacement sensors, it will drastically reduce the operator dependency factors, which will considerably enhance the precision of soil consistency determination. In the case of soil plasticity determination, it is required to calibrate the soil workability to the particular LL and PL by the standard tests. However, considering the limitations of the conventional methods, the conventional results should be regarded as benchmarks for calibration purposes and not as decisive values. For instance, statistical analysis of the standard results for different soils can identify the variability of conventional methods at limit states (e.g., Manafi 2019). Therefore, the calibration of the workability can be done by taking into account the variability of standard results.

Three reasons prevent discussion on the accuracy of the test methods when different standard test procedures are available. First, there are no entirely accepted reference values for determining limit states. Second, there is no reference soil material to calibrate the test methods accordingly. Third, there is no precise definition of the soil conditions at the limit states. This study builds a solid foundation for future investigations by clarifying the definition of soil consistency, which is essential for benchmarking the accuracy of soil consistency determination. In addition, the theories of a systematic method for quantifying the behaviour of soil in laboratory tests are presented in this research. Accordingly, the researchers are enabled to design new apparatuses for determining the new workability parameter. Subsequent investigations will deliver reliable tools with the least operator dependency and the most compatibility with the proposed approach. Consequently, the precision and accuracy of soil consistency determination will be significantly improved. Providing experimental data following the proposed method requires separate comprehensive laboratory/field tests and fabricating new apparatuses that are out of the scope of this theoretical paper.

2.6 Summary and Conclusions

In summary, soil consistency is a qualitative phenomenon. Therefore, the behaviour of soil at different water contents needs to be examined to determine the soil consistency. This paper has highlighted the main issues of conventional plasticity tests and proposed a novel research approach combining qualitative and qualitative methodologies to comply with the nature of soil consistency. As a result, the definition of soil consistency is clarified, and the new 'workability' parameter is introduced and formulated. Accordingly, defined systems of soil deformation are correlated to soil consistency limits (including liquid and plastic limit states). Hence, the simple measurement of the workability parameter quantifies the complex qualitative soil consistency. This theoretical study provides the backbone for practical investigations to develop new alternative test methods in geotechnical engineering, particularly soil consistency determinations.

In conclusion, we have proposed an innovative approach having several potential advantages over conventional methods:

1. The test procedure follows the combined quantitative and qualitative research approach, accommodating the nature of soil consistency. Therefore, the aggregate behaviour of cohesive soils is evaluated;
2. A single test method with a similar procedure can define both the liquid and plastic limit values;
3. Determination of the workability parameter is operator-independent and reduces many uncertainties of conventional methods.

2.7 Acknowledgments

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2.8 Conflict of Interest

The authors have no competing interests to declare.

2.9 References

AASHTO T89-10, 2010, "Standard Method of Test for Determining the Liquid Limit of Soils." American Association of State Highway and Transportation Officials (AASHTO), Washington, D.C.

AS 1289.3.1.1-2009, 2017, "Methods of Testing Soils for Engineering Purposes - Soil Classification Tests - Determination of Liquid Limit of a Soil – Four Point Casagrande Method." Standards Australia, Sydney, Australia.

AS 1289.3.2.1, 2009, "Methods of Testing Soils for Engineering Purposes - Soil Classification Tests - Determination of the Plastic Limit of a Soil." Standards Australia, Sydney, Australia.

AS 1289.3.9.1, 2015, "Methods of Testing Soils for Engineering Purposes - Soil Classification Tests - Determination of the Cone Liquid Limit of a Soil." Standards Australia, Sydney, Australia.

Asadi, A., Huat, B. B. K., Hanafi, M. M., Mohamed, T. A., and Shariatmadari, N., 2011, "Chemico-Geomechanical Sensitivities of Tropical Peat to Pore Fluid Ph Related to Controlling Electrokinetic Environment." *Journal of the Chinese Institute of Engineers*, Vol. 34, No. 4, pp. 481-487, doi: 10.1080/02533839.2011.576491.

ASTM D653-14, 2014, "Standard Terminology Relating to Soil, Rock, and Contained Fluids." ASTM International, West Conshohocken, PA, doi: 10.1520/D0653-14.

ASTM D4318-17e1, 2017, "Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils." ASTM International, West Conshohocken, PA, USA, doi: 10.1520/D4318-17E01.

Atterberg, A., 1911, "Uber Die Physikalische Bodenuntersuchung Und Uber Die Plastizitat Der Tone. (on the Physical Testing of Soil and the Plasticity of Clays)." *Internationale Mitteilungen für Bodenkunde*, Vol. 1, No. 1, pp. 10-43.

Bjerrum, L., 1954, "Geotechnical Properties of Norwegian Marine Clays." *Géotechnique*, Vol. 4, No. 2, pp. 49-69, doi: 10.1680/geot.1954.4.2.49.

BS EN 1377-2, 1990, "Methods of Test for Soils for Civil Engineering Purposes. Part 2: Classification Tests." British Standards Institution, Milton Keynes, UK.

Casagrande, A., 1932, "Research on the Atterberg Limits of Soils." *Public roads*, Vol. 13, No. 8, pp. 121-136.

CEN. E.N. 1997-2, 2007, "Eurocode 7 – Geotechnical Design – Part 2: Ground Investigation and Testing." Comité Européen de Normalisation (CEN), Brussels, Belgium.

Das, B. M., and Sobhan, K., 2018, *Principles of Geotechnical Engineering*, Cengage Learning, Australia, p. 819.

Davidson, D. A., 1983, "Problems in the Determination of Plastic and Liquid Limits of Remoulded Soils Using a Drop-Cone Penetrometer." *Earth Surface Processes and Landforms*, Vol. 8, No. 2, pp. 171-175, doi: 10.1002/esp.3290080208.

Dieter, G. E., and Bacon, D., 1988, *Mechanical Metallurgy*, McGraw-Hill, Singapore, p. 751.

Fellows, R., and Liu, A., 2015, *Research Methods for Construction*, John Wiley & Sons, Ltd, The Atrium, Southern Gate, Chichester, West Sussex, United Kingdom, p. 302.

Germaine, J. T., and Germaine, A. V., 2009, *Geotechnical Laboratory Measurements for Engineers*, Wiley, Hoboken, N.J.

Haigh, S. K., Vardanega, P. J., and Bolton, M. D., 2013, "The Plastic Limit of Clays." *Geotechnique*, Vol. 63, No. 6, pp. 435-440, doi: 10.1680/geot.11.P.123.

Head, K. H., 2006, *Manual of Soil Laboratory Testing, Volume 1: Soil Classification and Compaction Tests*, Whittles Publishing, Scotland, UK.

Head, K. H., and Epps, R. J., 2011, *Manual of Soil Laboratory Testing, Volume 2: Permeability, Shear Strength and Compressibility Tests*, Whittles Publishing, Scotland, UK, p. 499.

Head, K. H., and Epps, R. J., 2014, *Manual of Soil Laboratory Testing, Volume 3: Effective Stress Tests*, Whittles Publishing, Scotland, UK, p. 424.

Hobbs, N., 1986, "Mire Morphology and the Properties and Behaviour of Some British and Foreign Peats." *Quarterly Journal of Engineering Geology and Hydrogeology*, Vol. 19, No. 1, pp. 7-80, doi: 10.1144/GSL.QJEG.1986.019.01.02.

Jeong, S. W., Locat, J., Leroueil, S., and Malet, J.-P., 2010, "Rheological Properties of Fine-Grained Sediment: The Roles of Texture and Mineralogy." *Canadian Geotechnical Journal*, Vol. 47, No. 10, pp. 1085-1100, doi: 10.1139/T10-012.

Kayabali, K., and Tufenkci, O. O., 2007, "A Different Perspective for the Determination of Soil Consistence Limits." *International Symposium on Geotechnical Engineering, Ground Improvement and Geosynthetics for Human Security and Environmental Preservation*, Bangkok, Thailand, pp. 423-432.

Kayabali, K., and Tufenkci, O. O., 2010a, "Determination of Plastic and Liquid Limits Using the Reverse Extrusion Technique." *Geotechnical Testing Journal*, Vol. 33, No. 1, pp. 1-9, doi: 10.1520/GTJ102209.

Koumoto, T., and Houlsby, G. T., 2001, "Theory and Practice of the Fall Cone Test." *Géotechnique*, Vol. 51, No. 8, pp. 701-712, doi: 10.1680/geot.2001.51.8.701.

Kurtz, J.-P., 2004, *Dictionary of Civil Engineering: English-French*, Kluwer Academic/Plenum Publishers, New York, USA p. 1515.

Leroueil, S., and Le Bihan, J.-P., 1996, "Liquid Limits and Fall Cones." *Canadian Geotechnical Journal*, Vol. 33, No. 5, pp. 793-798, doi: 10.1139/t96-104-324.

Littleton, I., and Farmilo, M., 1977, "Some Observations on Liquid Limit Values with Reference to Penetration and Casagrande Tests." *Ground Engineering*, Vol. 10, No. 4, pp. 39-40.

Longman Group. 2011, Longman Dictionary of Contemporary English (5th Edition, Electronic Version), Pearson Education.

Manafi, M. S. G., 2017, "Soil Plasticity Determination Using Manafi Method and Apparatus." MSc Thesis by Research, Trinity College Dublin, Dublin, Ireland.

Manafi, M. S. G., 2019, "Soil Plasticity Variability and Its Effect on Soil Classification." *Geotechnical Testing Journal*, Vol. 42, No. 2, pp. 457-470, doi: 10.1520/GTJ20170273.

Manafi, M. S. G., Deng, A., and Taheri, A., 2022a, "Utilisation of Extrusion Method in Geotechnical Tests: Conception and Theoretical Analysis." *Arabian Journal of Geosciences*, Vol. 15, No. 449, doi: 10.1007/s12517-022-09543-z.

Medhat, F., and Whyte, I., 1986, "An Appraisal of Soil Index Tests." *Geological Society, London, Engineering Geology Special Publications*, Vol. 2, No. 1, pp. 317-323, doi: 10.1144/GSL.1986.002.01.55.

Murthy, V. N. S., 2003, *Geotechnical Engineering: Principles and Practices of Soil Mechanics and Foundation Engineering*, Marcel Dekker, New York.

Nagaraj, H. B., Sravan, M. V., and Deepa, B. S., 2019, "Factors Influencing Undrained Strength of Fine-Grained Soils at High Water Contents." *Geomechanics and Geoengineering*, pp. 1-5, doi: 10.1080/17486025.2019.1670875.

O’Kelly, B. C., 2019, "Reappraisal of Soil Extrusion for Geomechanical Characterisation." *Geotechnical Research*, Vol. 6, No. 4, pp. 265-287, doi: 10.1680/jgere.19.00006.

O’Kelly, B. C., 2021, "Review of Recent Developments and Understanding of Atterberg Limits Determinations." *Geotechnics*, Vol. 1, No. 1, pp. 59-75, doi: 10.3390/geotechnics1010004.

Penner, E., 1965, "A Study of Sensitivity in Leda Clay." *Canadian Journal of Earth Sciences*, Vol. 2, No. 5, pp. 425-441, doi: 10.1139/e65-037.

Poulsen, R., Ibsen, L. B., and Nielsen, B. N., 2012, "Difficulties Regarding Determination of Plasticity Index of Silty Soils by Use of Casagrande and Fall Cone Methods."

Proceedings of the 16th Nordic Geotechnical Meeting, Dansk Geoteknisk Forening, Copenhagen, Denmark, pp. 199-206.

Prakash, K., 2005, "Discussion of “Plastic Limit, Liquid Limit, and Undrained Shear Strength of Soil—Reappraisal” by Binu Sharma and Padma K. Bora." *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 131, No. 3, p. 402, doi: 10.1061/(ASCE)1090-0241(2005)131:3(402).

Prakash, K., and Sridharan, A., 2006, "Critical Appraisal of the Cone Penetration Method of Determining Soil Plasticity." *Canadian Geotechnical Journal*, Vol. 43, No. 8, pp. 884-888, doi: 10.1139/T06-043.

Rosenqvist, I. T., 1953, "Considerations on the Sensitivity of Norwegian Quick-Clays." *Géotechnique*, Vol. 3, No. 5, pp. 195-200, doi: 10.1680/geot.1953.3.5.195.

Sabatini, P. J., Bachus, R. C., Mayne, P. W., Schneider, J. A., and Zettler, T. E., 2002, "Geotechnical Engineering Circular No. 5: Evaluation of Soil and Rock Properties." *Technical Manual Report No. FHWA-IF-02-034*.

Saha, P., 2000, *Aluminum Extrusion Technology*, ASM International, Materials Park, OH.

Serway, R., Faughn, J., Vuille, C., and Bennett, C., 2006, *Enhanced College Physics*, Cengage Learning, p. 118.

Sherwood, P. T., 1970, "The Reproducibility of the Results of Soil Classification and Compaction Tests." *Road Research Laboratory Report No. LR 339*, Road Research Laboratory, Crowthorne, Berk.

Sherwood, P. T., and Ryley, M. D., 1968, "An Examination of Cone-Penetrometer Methods for Determining the Liquid Limit of Soils." *TRRL Report LR 233*, Transport and Road Research Laboratory, Crowthome, Berks.

Sridharan, A., and Prakash, K., 1999, "Mechanisms Controlling the Undrained Shear Strength Behaviour of Clays." *Canadian Geotechnical Journal*, Vol. 36, No. 6, pp. 1030-1038, doi: 10.1139/t99-071.

Sridharan, A., and Prakash, K., 2000, "Percussion and Cone Methods of Determining the Liquid Limit of Soils: Controlling Mechanisms." *Geotechnical Testing Journal*, Vol. 23, No. 2, pp. 236-244, doi: 10.1520/GTJ11048J.

Stevenson, A., 2010, *Oxford Dictionary of English*, OUP Oxford, pp. 149, 372.

Terzaghi, K., 1926, "Simplified Soil Tests for Subgrades and Their Physical Significance." *Public roads*, Vol. 7, No. 8, pp. 153-170.

Terzaghi, K., Peck, R. B., and Mesri, G., 1996, *Soil Mechanics in Engineering Practice*, Wiley, New York.

Torrance, J. K., 1975, "On the Role of Chemistry in the Development and Behavior of the Sensitive Marine Clays of Canada and Scandinavia." *Canadian Geotechnical Journal*, Vol. 12, No. 3, pp. 326-335, doi: 10.1139/t75-037.

Torrance, J. K., and Pirnat, M., 1984, "Effect of Ph on the Rheology of Marine Clay from the Site of the South Nation River, Canada, Landslide of 1971." *Clays and Clay Minerals*, Vol. 32, No. 5, pp. 384-390, doi: 10.1346/CCMN.1984.0320506.

Trauner, L., Dolinar, B., and Mišič, M., 2005, "Relationship between the Undrained Shear Strength, Water Content, and Mineralogical Properties of Fine-Grained Soils." *International Journal of Geomechanics*, Vol. 5, No. 4, pp. 350-355, doi: 10.1061/(ASCE)1532-3641(2005)5:4(350).

UFC 3-220-04FA, 2004, "Backfill for Subsurface Structures." Unified Facilities Criteria UFC 3-220-04FA. US Army Corps of Engineers, NAVFAC, Air Force, Department of Defense, Technical Manual TM 5-818-4/AFM 88-5, Washington, DC, USA.

Van Note Chism, N., Douglas, E., and Hilson Jr, W. J., 2008, "Qualitative Research Basics: A Guide for Engineering Educators." *RREE, NSF DUE-0341127*.

Vardanega, P., and Haigh, S., 2014, "Some Recent Developments in the Determination of the Atterberg Limits." *Advances in Transportation Geotechnics and Materials for Sustainable Infrastructure*, American Society of Civil Engineers, pp. 48-55, doi: 10.1061/9780784478509.007.

Wasti, Y., and Bezirci, M. H., 1986, "Determination of the Consistency Limits of Soils by the Fall Cone Test." *Canadian Geotechnical Journal*, Vol. 23, No. 2, pp. 241-246, doi: 10.1139/t86-033.

Wesley, L. R., 2014, *Clays and Clay Minerals: Geological Origin, Mechanical Properties and Industrial Applications*, Nova Science Publishers, Incorporated, p. 184.

Whyte, I. L., 1982, "Soil Plasticity and Strength - a New Approach Using Extrusion." *Ground Engineering*, Vol. 15, No. 1, pp. 16-18, 20, 22, 24.

Wroth, C. P., and Wood, D. M., 1978, "The Correlation of Index Properties with Some Basic Engineering Properties of Soils." *Canadian Geotechnical Journal*, Vol. 15, No. 2, pp. 137-145, doi: 10.1139/t78-014.

Yang, J., and Dykes, A. P., 2006, "The Liquid Limit of Peat and Its Application to the Understanding of Irish Blanket Bog Failures." *Landslides*, Vol. 3, No. 3, pp. 205-216, doi: 10.1007/s10346-006-0038-z.

Chapter Three – Utilisation of Extrusion Method in Geotechnical Tests: Conception and Theoretical Analysis

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Overall percentage (%)	85%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	25/02/2022

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);
ii. permission is granted for the candidate in include the publication in the thesis; and
iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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Contribution to the Paper	Acquiring data, knowledge, analysis, and drafting.		
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Signature		Date	28/02/2022

3.1 Abstract

Extrusion method has been utilised in a variety of product-processing units such as metal casting and food processing. The process of extruding is relatively fast and reproducible, and more importantly, can benchmark shear resistance of extruded materials. These advantages have propelled researchers to practice the extrusion method to determine soil properties, e.g., Atterberg limits and shear strength. Although the mechanics behind the extrusion process remains less understood, studies have verified the feasibility of the benchmarking. This study presents the theoretical basis underpinning the extruding process by extending the conventional slab analysis method to model the entire process of extruding. The developed analytical method is original in assessing the extrusion of the dead-material zone and considering the dynamic move of extruded materials. The novel theoretical analysis enhances a more accurate estimation of extruding pressure and builds a solid foundation for developing extrusion tests in geotechnical engineering. In addition, the described extrusion mechanics explains reasons for observing some discrepant correlations to other geotechnical parameters due to the different soil deformation mechanisms among the test methods.

Keywords: Soil extrusion; Extrusion pressure; Slab analysis method; Atterberg limits; Shear strength; Laboratory tests.

Key messages of the paper:

- Developing a closed-form analysis method to estimate the extrusion pressure;
- Refining the extrusion analysis by modelling the extrusion of dead-material zone and considering the acceleration of the extrusion material;
- Justifying some discrepant results observed in correlating the extrusion pressures with other conventional tests by interpreting the unique soil deformation mechanism of the extrusion technique;
- Highlighting the capability of the extrusion method to become a standalone geotechnical test.

3.2 Introduction

The extrusion method is an established technology in manufacturing industry. The industry employs this method to transform (mainly split) raw feed materials into a variety of semi-finished or finished goods, such as cast metals, processed food, remoulded polymers, transformed pharmaceuticals and packaging materials (e.g., Dieter and Bacon 1988; Saha 2000; Guy 2001; Giles et al. 2004; Moscicki 2011). Although the equipment used by the industrial units are varied to suit different purposes, the concept of extruding remains similar. In essence, a cylindrical extruder is used to house a volume of feed-in materials to drive through an orifice or a die with the aid of a plunger. If the direction of extruding coincides with the movement of the plunger, it is a *direct extrusion*; otherwise, it is an *indirect* or *reverse extrusion*, as demonstrated in Figure 3-1. Both extrusions enable the feed-in materials to be compressed, transformed and remoulded in a defined system.

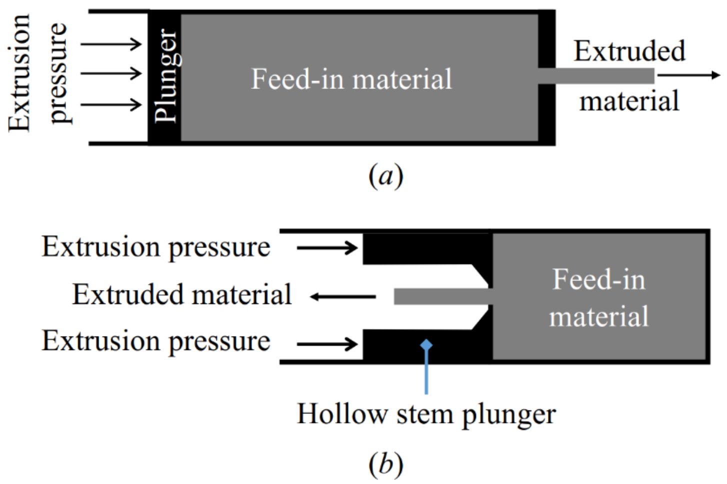

Figure 3-1: Longitudinal cross-section of material extruder: (*a*) Direct method; and (*b*) indirect method.

Albeit not a product by itself, a soil can also be extruded through an orifice. More importantly, the force that drives the process of extruding can be acquired and benchmarked against soil consistency and other soil properties, such as shear strength. Timar (1974) was the first who used the direct extrusion to determine soil plasticity. Several years later, Whyte (1982) conducted indirect extrusions and correlated the extruding force with soil consistency limits. Medhat and Whyte (1986) also attempted both the direct and indirect extrusion to determine soil consistency limits and suggested the suitability of utilising the extrusion methods for soil index properties. Kayabali and Tufenkci (2007) and Kayabali and Tufenkci (2010a) revisited the correlation proposed by Whyte (1982) and extended it based on additional test results they gathered. While they recognised the value of the extrusion technique, they pointed out result discrepancies between extrusion methods and conventional methods. They ascribed the discrepancies to operator dependency of the conventional methods.

Researchers have also extruded soils to determine shear strength. Kayabali and his teams extended their extrusion methods to undrained shear strength (e.g., Kayabali 2011a; Kayabali and Ozdemir 2013; Kayabali et al. 2015a) and drained shear strength (e.g., Kayabali et al. 2015c). Extrusion testing has also been applied to special soils, such as high plasticity kaolin–bentonite mixtures (e.g., Verástegui-Flores and Di Emidio 2014, 2015).

O’Kelly (2019) analysed the results obtained in different studies, aiming to evaluate the suitability of extrusion for soil shear strength determination. He found that the results are diverse between the studies and the consistency is suboptimal. However, the consistency evaluation neglected or at least underestimated the differences in devices, configurations, and soil types between the reviewed studies, which otherwise would have led to a better consistency. Nevertheless, it is expected to observe discrepant results obtained by various methods due to different soil deformation mechanisms.

To enhance the evaluation of the extrusion tests, one solution is to model the process of extruding and normalise it across setups. There is a range of approaches developed to normalise or analyse the process of extruding, such as the uniform energy method (Siebel 1932), slab method (Hoffman and Sachs 1953; Altan et al. 1983), slip-line method (Collins 1968; Dewhurst and Collins 1973; Hill 1998), upperbound method (Avitzur 1964; Johnson and Mellor 1973), and the perturbation method (Spencer 1961, 1962). The finite element methods were also used to simulate extruding processes of various feed-in materials (Lee et al. 1977; Argyris and Doltsinis 1979, 1981). While these analytical and numerical studies demonstrate advantages in mimicking extruding processes, discovering a closed-form solution can provide invaluable insight into the process and outweighs the other approaches (Borwein and Crandall 2013).

This paper aims to gain an insight into the mechanics behind the extruding process by developing a closed-form solution in this regard. The closed-form solution is essential for the soil property determinations using the extrusion method. The accuracy of the soil property determinations can be improved by analysing the force transfer mechanism in the extruder, for instance, by considering the effects of the soil-plunger friction and the extrusion rate on the soil deformation mechanism. Accordingly, equilibrium analyses are conducted, which are based on force, energy, and work relations. The analyses lead to an estimation of extrusion pressure as a function of soil shear strength, extruder configuration, and extrusion rate. The outcomes add to the fabrication and calibration of extruders and likely a broad acceptance of the method by the geotechnical community. It is noteworthy that the current *theoretical research* is focused on presenting the extrusion method conception and mechanical analysis. This study provides the backbone of further investigations utilising the extrusion method for soil property determinations.

3.3 Model Development

The extrusion mechanics depend on multiple factors, such as the physical and engineering properties of extruded materials and the extrusion device's configuration. A typical pattern of material flow in the direct extrusion process is demonstrated in Figure 3-2.

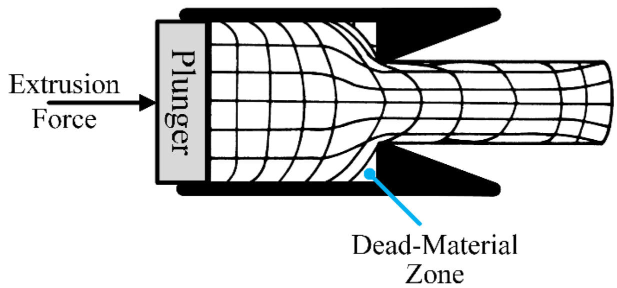

Figure 3-2: Schematic pattern of material flow in the direct extrusion method (adopted from Dieter et al. 2003).

A direct extruder model with a single opening is presented in Figure 3-3. The extruder has a length of l_0 and a circular cross-section (diameter of D_C and area of A_C). The circular opening has a diameter of D_E and an area of A_E. As $D_C > D_E$, a dead-material zone that rests in the inner corner is formed in the process of extruding. As per Saha (2000), the dead-material zone has a conical surface with a slope of α and a length of L_D. The material in the zone remains stationary until the plunger moves into the zone. Before that, shear between the stationary material and the moving material occurs on the face of the zone. The dead-material angle may be determined in practice by studying the etched cross-section of dead material after extrusion of the feed-in material prior to extrusion of the dead-material (e.g., Saha 2000) or examining the extrusion of material in 2-Dimensional laboratory models. Saha (2000) suggested expressing the dead-material angle, α, as a function of a set of parameters:

$$\alpha = f(ER,\ m,\ m',\ \bar{\sigma}) \tag{3-1}$$

where ER is the extrusion ratio (A_C/A_E), m is the factor of friction between the material and the inner wall of the extruder, m' is the factor of friction on the dead zone surface, and $\bar{\sigma}$ is the flow stress of the material. Flow stress is usually obtained experimentally using uniform compression and torsion tests (Saha 2000) and is a function of strain, $\bar{\varepsilon}$, strain rate, $\dot{\bar{\varepsilon}}$, and soil moisture content, w. For the model shown in Figure 3-3, considering the material volume consistency, $\bar{\varepsilon}$ and $\dot{\bar{\varepsilon}}$ are defined as:

$$\bar{\varepsilon} = \ ln\frac{l}{l_0} = ln\frac{A_C}{A_E} \tag{3-2}$$

$$\dot{\bar{\varepsilon}} = \frac{d\bar{\varepsilon}}{dt} \tag{3-3}$$

where l is the length of the extruded material and t is the time.

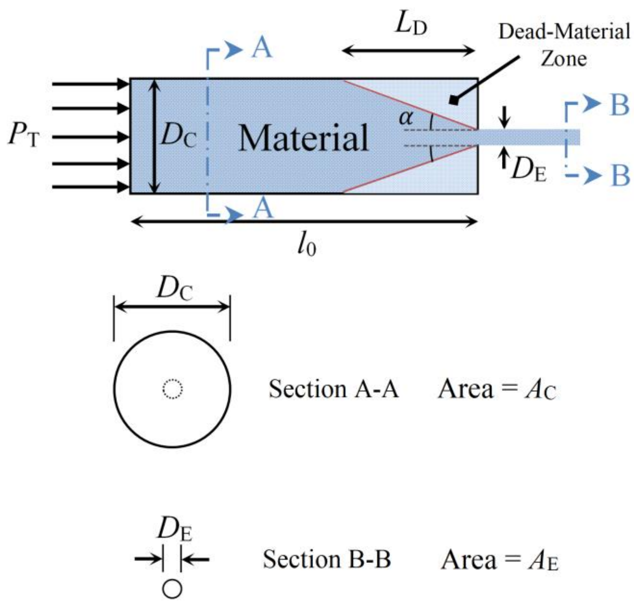

Figure 3-3: An extruder model of a single opening direct extrusion.

The extrusion process consumes energy to counteract resistance forces. Therefore, it is required to define work in physics. The work is exerted if a force is applied to an object leading to a movement by a distance. As shown in Figure 3-4, the work, W, done on an object by a constant force, F, is calculated as:

$$W = (F\cos\theta)\Delta x \qquad \textbf{(3-4)}$$

where θ is the angle between the directions of $\vec{F}$ and $\Delta\vec{x}$, and Δx is the displacement magnitude of the gravitational centre points.

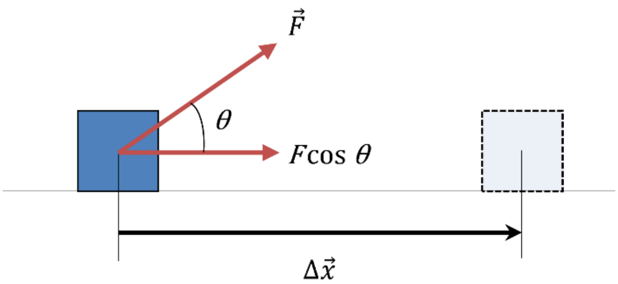

Figure 3-4: Illustration for work done on an object by a constant force.

Applying the conception of work to the process of extruding in Figure 3-5, the total work is calculated as:

$$W_{\mathrm{T}} = F_{\mathrm{T}}\,\Delta x \qquad \textbf{(3-5)}$$

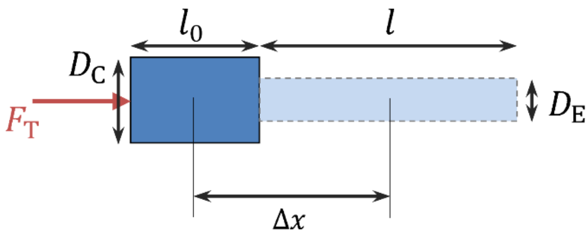

Figure 3-5: One-dimensional motion of the extrusion process.

The total extrusion pressure can also be calculated as:

$$P_{\mathrm{T}} = \frac{F_{\mathrm{T}}}{A_{\mathrm{C}}} \qquad \textbf{(3-6)}$$

The total work required for the extrusion of a material can be divided into different sub-works as:

$$W_T = W_D + W_{fC} + W_{fP} + W_R + W_{Acc} \quad \textbf{(3-7)}$$

where W_D is the plastic deformation work in the conical deformation zone, W_{fC} is the material-container walls frictional work, W_{fP} is the dead-material–plunger frictional work, W_R is the redundant work, and W_{Acc} is the acceleration work. The sub-works can be calculated by analysing the processes of extruding.

The longitudinal cross-section of a direct-method extruder is shown in Figure 3-6. In the process of extruding, the feed-in material housed in the extruder is divided into three zones, i.e., the friction, deformation, and dead material zones, respectively. Each zone is represented by a shaded slab. The dead-material zone remains relatively static in the extruding process until the plunger has fully passed the friction zone. At this moment, the plunger pushes the dead-material zone inward to the deformation zone from the apex to the base of the dead zone. Progressively, the entire volume of material is extruded.

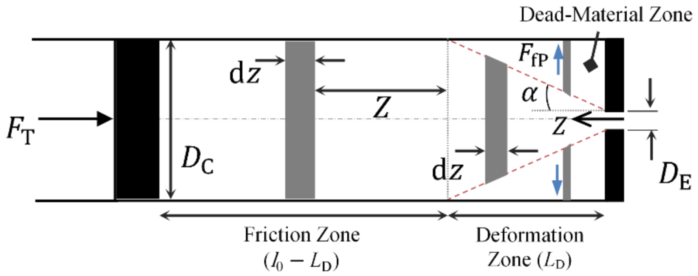

Figure 3-6: Longitudinal cross-section of a direct-method extruder.

The analyses on the friction and deformation zones are established in the literature (e.g., Dieter and Bacon 1988; Saha 2000) and adopted in this study. This paper presents two updates to the conventional slab analysis method. Consequently, a new model is presented for the extrusion of the dead-material zone. In addition, the acceleration of the extrusion material is also considered in the analysis.

The following assumptions are made: *a*) A volume of continuous material is extruded through a die; *b*) The material is extruded into a rod with a diameter of D_E; and *c*) Frictional shear stress occurs at the interfaces between the dead-material and the flowing material, the container and the flowing material, and the plunger and the dead-material.

3.3.1 Work to extrude material in deformation zone

A simplified conical deformation zone is shown in Figure 3-6. The length of the deformation zone, L_D, is expressed as:

$$L_D = \frac{D_C - D_E}{2 \tan \alpha} \tag{3-8}$$

Figure 3-7 shows the element in the deformation zone and stresses acting on the element. The stress equilibrium equation can be written as:

$$-(p_Z + dp_Z)\frac{\pi(D + dD)^2}{4} + p_Z \frac{\pi D^2}{4} + p_r \pi D\, ds\, \sin \alpha + \tau_{fF} \pi D\, ds\, \cos \alpha = 0 \tag{3-9}$$

where p_Z is the extruding pressure in Z direction, D is the diameter of the element, s is the slant height of the deformation zone, and τ_{fF} is the friction on the interface between the dead-material and the flowing material.

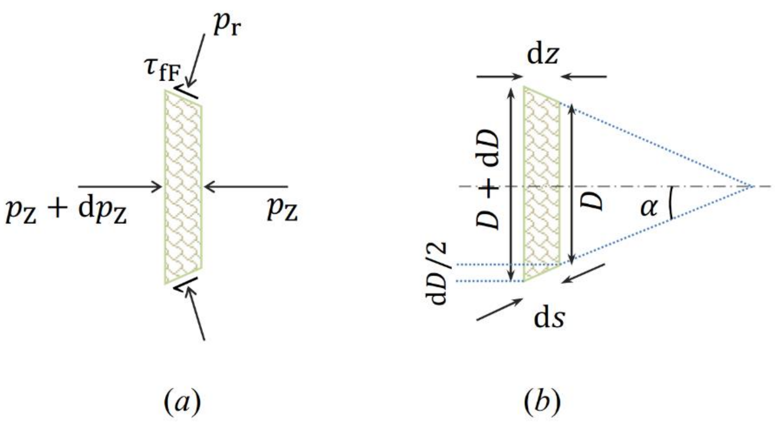

Figure 3-7: Diagrams for the element in the deformation zone: (*a*) Stress state; and (*b*) geometry.

Based on the geometry, we have:

$$ds\, \sin \alpha = dz\, \tan \alpha = \frac{dD}{2} \tag{3-10}$$

$$ds\, \cos \alpha = dz = \frac{dD}{2 \tan \alpha} \tag{3-11}$$

In addition, by applying the Von Mises' yield criterion (Saha 2000):

$$p_r = p_Z + \bar{\sigma} \tag{3-12}$$

$$\tau_{fF} = k = \frac{\bar{\sigma}}{\sqrt{3}} \tag{3-13}$$

where k is the material shear strength.

Combining Eqs. (3-9) to (3-13) and neglecting higher-order differentials:

$$\frac{\mathrm{d}p_Z}{\bar{\sigma}(1 + \frac{\cot\alpha}{\sqrt{3}})} = \frac{2\mathrm{d}D}{D} \tag{3-14}$$

Assuming constant flow stress yields:

$$\frac{p_Z}{\bar{\sigma}(1 + \frac{\cot\alpha}{\sqrt{3}})} = \ln D^2\, C \tag{3-15}$$

where C is the constant of integration and can be eliminated by substitution of the boundary conditions at $D = D_E$, $p_Z = 0$:

$$C = \frac{1}{D_E^2} \tag{3-16}$$

The equivalent diameter of the extruded material can also be written as:

$$D_E = \frac{D_C}{\sqrt{ER}} \tag{3-17}$$

Therefore, the average extrusion pressure in the deformation zone can be obtained by substitution of the value of the C constant in Eq. (3-15) as:

$$P_D = p_{Z=L_D} = 2\bar{\sigma}(1 + \frac{\cot\alpha}{\sqrt{3}}) \ln\frac{D_C}{D_E} \tag{3-18}$$

Consequently, the plastic deformation work is obtained as:

$$W_D = (P_D\, A_C)\, \Delta x \tag{3-19}$$

3.3.2 Work to extrude material in friction zone

The work to extrude material in the friction zone, or material-container frictional work, W_{fC}, is required for overcoming the resistance between the container walls and the material. The work is a function of the following parameters:

$$W_{fC} = f(p_r, m, m', m'', D_C, L, L') \tag{3-20}$$

where p_r is the radial pressure, m'' is the friction factor between the die bearing and the extruded material, L is the material length having the relative movement between the extrusion material and the container walls, and L' is the die bearing length, which can be ignored if the die has a relatively small contact area.

The diagram of stress for the element inside the friction zone is shown in Figure 3-8. The static equilibrium leads to:

$$\left[(p_Z + \mathrm{d}p_Z) - p_Z\right]\frac{\pi D_C^2}{4} = \pi D_C \, \tau_{fC} \, \mathrm{d}z \tag{3-21}$$

where τ_{fC} is the frictional shear stress at the material-container interface and can be obtained from Eq. (3-21). Hence, the friction force, F_{fC}, at the material-container interface can be obtained as:

$$F_{fC} = \pi D_C \,(l_0 - L_D)\, \tau_{fC} \tag{3-22}$$

Accordingly, the extrusion work in the friction zone can be obtained as:

$$W_{fC} = F_{fC} \, \Delta x \tag{3-23}$$

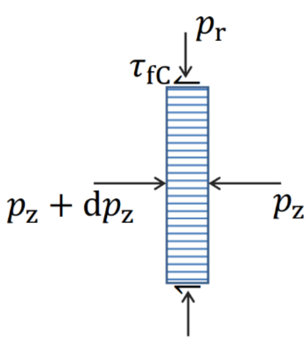

Figure 3-8: Diagram of stress for the element inside the friction zone.

3.3.3 Work to extrude material in dead-material zone

The work to extrude material in the dead-material zone, or the material–plunger frictional work, W_{fP}, is required for overcoming the sliding resistance between the dead-material zone and the plunger. The work is also a function of several parameters and expressed as:

$$W_{fP} = f(F_T, m''', D_C, L_D) \quad \textbf{(3-24)}$$

where m''' is the factor of friction between the plunger and the dead-material, which can be obtained by experiment considering the surface roughness of the plunger-extruding material, rate of extrusion, and normal stresses.

The material in the dead zone remains relatively static during the extruding process and, over time, becomes aged or oxidised where goods are extruded. Hence, industry units usually hold extruding at a safe margin to avoid extruding the dead material (Saha 2000). In this context, the extrusion analysis of the dead material is neglected in industry operations. When adapted for soil property determination, the dead material is extruded out provided it involves no product quality issue within the short period of the tests. In addition, the extruder size is relatively small for soil tests and the complete volume of the specimen is extruded. Therefore, it is required to take account of the dead-material zone in the analysis. A simple model is presented in this paper to calculate the pressure required for the extrusion of the dead-material zone.

Considering the static nature of the dead-material, it is assumed that the plunger forces the dead-material into the conical deformation zone by sliding off the material layer by layer from the apex to the base of the dead zone. In addition, it is assumed that the angle of the dead-material zone does not change in this process. Therefore, a sliding frictional force is used in the calculations. The assumptions are reasonable considering the relatively faster extrusion of the feed-in material than to the peripheral material in the extrusion of homogeneous materials (Saha 2000).

It is recognised that a portion of the extrusion work is used to transfer the dead-material zone into the conical deformation zone. Accordingly, one needs to calculate the vertical movement work of material from the dead-zone into the conical deformation zone, which comprises part of the total work required for the extrusion. Consequently, the frictional force on the plunger–dead-material interface and the displacement of the dead-material should be considered. As shown in Figure 3-9, the equivalent rectangular area of the triangular dead-material zone is developed to simplify the calculations. In this figure, B is the width of the equivalent rectangular area.

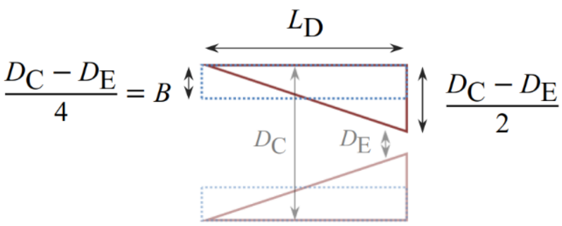

Figure 3-9: Longitudinal cross-section of the dead-material zone.

As shown in Figure 3-10, a string model is proposed to determine the contact area between the dead material and the plunger. The string model replicates the movement of the soil particles into the conical deformation zone. In the course of extruding the dead-materials, the boundary elements of the dead-material zone are in contact with the plunger. Therefore, the frictional force of the vertical movement of the material in the dead-zone can be calculated as:

$$F_{fP} = \tau_{fP}\, A_{fP} = \tau_{fP}\, \pi\, D_C\, L_D \qquad \textbf{(3-25)}$$

where τ_{fP} is the frictional shear stress between the dead-material and the plunger interface, and A_{fP} is the contact surface area between the dead-material and the plunger.

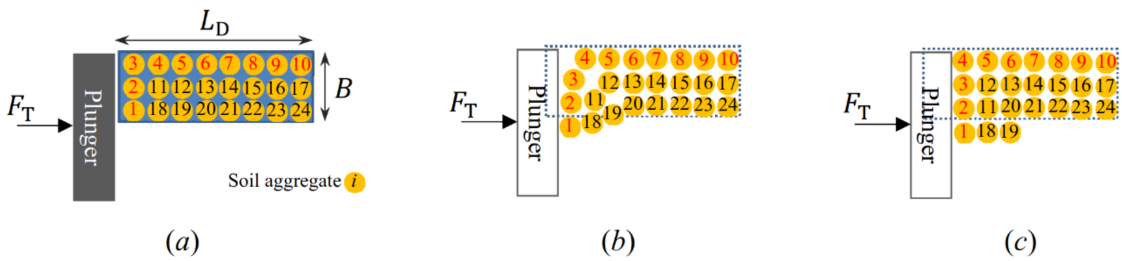

Figure 3-10: A string model for determination of contact area between the dead-material and the plunger: (*a*) Soil aggregate arrangement at the beginning of the extrusion of the dead-zone, (*b*) and (*c*) progress of sliding aggregates from the dead-zone into deformation cone.

The work that is required to move the soil material from the dead-zone into the conical deformation zone is calculated as:

$$W_{fP} = F_{fP}\, B = \tau_{fP}\, \pi\, D_C\, L_D\, \frac{D_C - D_E}{4} \qquad \textbf{(3-26)}$$

3.3.4 Extruding work due to mass acceleration

Extruding work due to mass acceleration, W_{Acc}, leads to acceleration of the material mass. If the extrusion pressure exceeds the pressure required to overcome the internal resistance forces, then the force difference accelerates the soil body in the extrusion process. The acceleration force can be obtained by applying Newton's second law of motion. The force required for acceleration of the material mass can be obtained as:

$$F_{\mathrm{Acc}} = m_{\mathrm{s}}\, a \qquad \textbf{(3-27)}$$

where m_s is the soil material mass and a is the material acceleration during the extruding process. Considering the one-dimensional motion of the extrusion process as in Figure 3-5, the acceleration of the material is calculated as:

$$\Delta x = v_0\, t + \frac{1}{2} a\, t^2 = 0 + \frac{1}{2} a\, t^2 = \frac{1}{2} a\, t^2$$

$$a = \frac{2\Delta x}{t^2} \qquad \textbf{(3-28)}$$

where v_0 is the initial velocity of the soil specimen at the start of extrusion, which is zero at the beginning of the extrusion, and t is the time of extrusion.

Accordingly, the extrusion work pertinent to the acceleration of the material can be obtained as:

$$W_{\mathrm{Acc}} = F_{\mathrm{Acc}}\, \Delta x \qquad \textbf{(3-29)}$$

3.3.5 Redundant work in extruding process

Redundant work, W_R, is related to the energy required for internal deformations of the soil material apart from the pure change in the shape of soil material in the extrusion process (Dieter 1961). The work also involves the elastic energy dissipation of the material during the extrusion process. The redundant pressure required for internal deformation work is a function of the flow stress and the angle of the dead-material zone. Considering the general pattern of material flow in the extrusion process as in Figure 3-2, shear deformations occur to the elements around the perimeter of the friction zone and on the interface of the dead-material zone. In addition, the central elements are under elongation due to the changes in the cross-sections. The difference between the calculated extrusion pressure based on the uniform plastic deformation method and the actual exerted extrusion pressure is due to the redundant work during the extrusion process (Saha 2000). The amount of the redundant force is usually determined experimentally or numerically. Alternatively, it is viable to conduct several experiments and determine the redundant work via other subworks as follows:

$$W_{\mathrm{R}} = W_{\mathrm{T}} - W_{\mathrm{D}} - W_{\mathrm{fC}} - W_{\mathrm{fP}} - W_{\mathrm{Acc}} \quad \textbf{(3-30)}$$

3.4 Discussion

The extrusion method has been used in several experimental studies for soil property determination, such as Atterberg limit states and different shear strengths (e.g., Kayabali and Ozdemir 2013; Kayabali et al. 2015c; Kayabali et al. 2016). These studies have delivered results of promoting the extrusion method as an alternative test method for the conventional methods. However, data discrepancies are unavoidable in some circumstances. Three reasons might have caused the discrepancies:

1. The inappropriate approach utilised for proposing an alternative test method [i.e., strength-based approach for soil plasticity determination (e.g., Nagaraj et al. 2012)];
2. The variability of the conventional test methods for accurate determination of soil properties (e.g., Manafi 2019);
3. The limited compatibility among the test mechanisms (e.g., different soil deformation mechanisms between the extrusion method and other shear strength tests).

The data discrepancies associated with the incompatibility of different test methods can be explained by analysing the soil deformation mechanisms in the tests. Nevertheless, the mechanics of the extrusion method had not been analysed for rationalising the probable discrepancy related to the difference in the soil deformation mechanisms. This study appears to be the first to cover this gap by proposing a closed-form solution for analysing the soil extrusion technique.

Closed-form solutions are crucial for illustrating the mechanics of methods (Hassani 2000; Borwein and Crandall 2013). Validation or justification of the proposed correlations may be done by synthesising the fundamental components of the soil deformation systems. Consequently, this paper provided an insight into the extrusion mechanics by extending the established slab analysis method (Altan et al. 1983; Saha 2000). The proposed analyses characterise the effective parameters on the soil deformation system in the extrusion technique. As a result, the difference in soil deformation mechanism in the extrusion technique with conventional tests (Head 2006; Head and Epps 2011, 2014) can explain some reasons for a part of the discrepant results obtained in the previous studies (e.g., O'Kelly 2019). In addition, the outcomes of this analysis are beneficial for the performance optimisation of extrusion devices as the effective parameters on soil extrusion are explained in this study.

The effect of material weight can be ignored in the mechanical analysis of the extrusion. Because the test involves a small volume of material and the weight of the material is relatively negligible compared to the force required for extrusion. However, depending on the design of the apparatus or considerable unit weights of the materials, it might affect the driving force (e.g., in a vertical extrusion) or the radial pressure (e.g., in a horizontal extrusion).

The updates to the slab analysis method presented in this paper involve the slip of soil grains in the dead material zone into the deformation zone and the acceleration of the extrusion material. The parameters introduced in the updates are the same type as the parameters introduced by Altan et al. (1983) in the slab analysis method. Therefore, the reliability and error in parameter measurements remain at the same level as the previously established slab analysis method.

As the soil extrusion analysis revealed, the extrusion pressure is highly affected by the extrusion setup design and the material properties. Although the developed analytical method is presented for soil extrusion tests, it can also be applied to the general extrusion process using various feed-in materials. This paper also proposed a method for calculating the extrusion pressure that may be used for adopting proper actuators in designing and calibrating new apparatuses.

Considering the mechanics of the extrusion method explained in this paper, this method provides a unique soil deformation system that may serve as a novel test method for reliable and reproducible soil property determinations. For instance, the comprehensive soil deformation process in the extrusion process may be used to study the consistency of cohesive soils based on the definition of soil consistency, "the relative ease with which a soil can be deformed" (ASTM D653-14 2014). Additionally, the soil extrusion technique can be utilised to study special geotechnical cases such as mud-rush or running soft geo-materials into underground structures. In other words, though the extrusion method can be used as an alternative method to conventional methods, it is greatly capable of introducing new standalone test methods for soil property determinations.

Although a few researchers provide considerable data on soil extrusion, little information about the details of apparatus fabrication/specification, soil sampling/specimen preparation, and test procedure are provided. Furthermore, just a few cohesive soil types with different minerals are investigated. Therefore, the knowledge of the extrusion method in geotechnical engineering is not fully established. Hence, it is required to conduct comprehensive research studies to establish the extrusion method for soil property determinations.

Considering the mechanism of soil deformation in the extrusion process, various inter-related parameters (e.g., m', α, $\bar{\sigma}$, τ_{fC}, τ_{fP}) affect the extrusion pressure. The parameters' values depend on the device geometry, extrusion rate, plunger, mould and feed-in material properties. Assessment of the effective parameters on the soil extrusion requires separate comprehensive *experimental studies* fabricating extrusion devices with sophisticated instrumentations that are out of this paper's scope. The logistic limitations prevented the authors from further practical investigations in this regard. In addition, the previous studies have not provided parameters' values and apparatus specifications to validate the conventional and the refined slab analysis methods for soil extrusion. However, this research theoretically extended the conventional slab analysis method, which builds a solid foundation for further studies on this topic.

Soil extrusion method has several advantages over the conventional geotechnical test methods such as (e.g., Timar 1974; Medhat and Whyte 1986; Kayabali 2012; Kayabali et al. 2016):

- Being quick and repeatable test with low operator dependency and high reliability;
- Simple and relatively inexpensive fabrication of the apparatus depending on the setup design;
- Requiring a low volume of a soil sample; and
- Capability to investigate different material properties with one apparatus and test procedure.

Therefore, developing new test methods based on the extrusion technique would greatly benefit geotechnical engineering practice.

3.5 Conclusions

Recently the extrusion method has been used as an alternative method to determine soil properties such as Atterberg limits and soil shear strength (e.g., Kayabali and Ozdemir 2013;

Kayabali et al. 2015c; Kayabali et al. 2016). Some of the discrepant results observed by the extrusion and standard methods may be due to the different soil deformation mechanisms among the apparatuses. Consequently, the mechanics of the extrusion technique is discussed in this paper, aiming to gain a further understanding of the extrusion process and explaining some reasons for observing discrepant results with the conventional methods. This paper extended the established closed-form analysis method developed for the estimation of the extrusion pressure (Altan et al. 1983; Saha 2000). Accordingly, a new model was developed to interpret the extrusion of the dead-material zone. In addition, the acceleration of the material during the extrusion process was taken into account to refine the calculation of the extrusion pressure. The current study was limited to the theoretical analysis of the soil extrusion technique, however, the results provide a significant first step towards further experimental investigations leading to a broad acceptance of the extrusion method in geotechnical engineering.

This paper provided an insight into the extrusion technique and explained the mechanisms involved in the extrusion process. Consequently, the discrepancies observed in previous studies related to the limited compatibility among the test methods are justified in terms of the different soil deformation mechanisms. The outcomes are also crucial for designing new extrusion test equipment.

Several researchers have stated that the soil extrusion method can examine soil properties with low operator dependency and high reproducibility (e.g., Timar 1974; Medhat and Whyte 1986; Kayabali 2012; Kayabali et al. 2016). The independent soil deformation mechanism of the extrusion method explained in this paper supports their statements if the apparatuses are well designed and fabricated. These advantages enable the extrusion method to become a prominent standalone test method as well as acting as an alternative test method to the conventional tests. Therefore, the authors recommend comprehensive investigations on this topic to reach reliable and reproducible results in soil property determinations.

3.6 Acknowledgments

The first author kindly acknowledges a postgraduate research scholarship (ASI) received from the University of Adelaide.

3.7 Conflict of Interest

The authors have no competing interests to declare.

3.8 Notations

a acceleration of the material during the extrusion process

A_C cross-sectional area of container

A_E cross-sectional area of extruded material

A_{fP} contact surface area between the dead-material and the plunger

B width of the equivalent rectangular area of the triangular dead-material zone

D diameter

D_C equivalent diameter of the container

D_E equivalent diameter of the extruded material

ER extrusion ratio

$\vec{F}$ force vector

F magnitude of force

F_{Acc} force required for acceleration of the material mass

F_{fC} frictional force at the material-container interface

F_{fP} frictional force of vertical movement of the material in the dead-zone

F_T total extrusion force

k material shear strength

l final length of extruded material

L material length having the relative movement between the extrusion material and the container walls

L' die bearing length

l_0 initial length of extrusion material

L_D length of the dead-material or deformation zones

m factor of friction between the interface of the material and the container

m' factor of friction at the dead-material zone and the flowing material interface

m'' friction factor between the extruded material and the die bearing

m''' friction factor between the plunger and dead-material zone

m_s mass of the soil material

P_D pressure required for the plastic deformation of the material

P_{fC} pressure required to overcome frictional resistance between the material and the container walls

p_r radial pressure

P_T total extrusion pressure

p_Z extrusion pressure in Z direction

s slant height of deformation cone

t time

v_0 initial velocity of soil specimen at the start of extrusion

w soil water content

W work

W_{Acc} work required for the acceleration of the material mass

W_D plastic deformation work of the material inside the conical deformation zone

W_{fC} work required to overcome frictional resistance between the material and the container walls

W_{fP} work required to overcome sliding resistance between the dead-material zone and the plunger

W_R redundant work

W_T total extrusion work

$\vec{x}$ displacement vector

α angle of the dead-material zone

Δx magnitude of the displacement

θ angle between the directions of $\vec{F}$ and $\Delta\vec{x}$,

$\bar{\sigma}$ flow stress

τ_{fF} frictional shear stress at the dead-material zone and the flowing material interface

τ_{fC} frictional shear stress at the material-container interface

τ_{fP} frictional shear stress between the dead-material and the plunger interface

$\bar{\varepsilon}$ natural strain

$\dot{\bar{\varepsilon}}$ strain rate

3.9 References

Altan, T., Oh, S.-I., and Gegel, H. L., 1983, *Metal Forming: Fundamentals and Applications*, American Society for Metals, Metals Park, OH.

Argyris, J. H., and Doltsinis, J. S., 1979, "On the Large Strain Inelastic Analysis in Natural Formulation Part I: Quasistatic Problems." *Computer Methods in Applied Mechanics and Engineering*, Vol. 20, No. 2, pp. 213-251, doi: 10.1016/0045-7825(79)90020-3.

Argyris, J. H., and Doltsinis, J. S., 1981, "On the Natural Formulation and Analysis of Large Deformation Coupled Thermomechanical Problems." *Computer Methods in Applied Mechanics and Engineering*, Vol. 25, No. 2, pp. 195-253, doi: 10.1016/0045-7825(81)90084-0.

ASTM D653-14, 2014, "Standard Terminology Relating to Soil, Rock, and Contained Fluids." ASTM International, West Conshohocken, PA, doi: 10.1520/D0653-14.

Avitzur, B., 1964, "Analysis of Wire Drawing and Extrusion through Conical Dies of Large Cone Angle." *Journal of Manufacturing Science and Engineering*, Vol. 86, No. 4, pp. 305-314, doi: 10.1115/1.3670543.

Borwein, J. M., and Crandall, R. E., 2013, "Closed Forms: What They Are and Why We Care." *Notices of the American Mathematical Society*, Vol. 60, pp. 50-65, doi: 10.1090/noti936.

Collins, I. F., 1968, "The Algebraic-Geometry of Slip Line Fields with Applications to Boundary Value Problems." *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, Vol. 303, No. 1474, pp. 317-338, doi: 10.1098/rspa.1968.0053.

Dewhurst, P., and Collins, I. F., 1973, "A Matrix Technique for Constructing Slip-Line Field Solutions to a Class of Plane Strain Plasticity Problems." *International Journal for Numerical Methods in Engineering*, Vol. 7, No. 3, pp. 357-378, doi: 10.1002/nme.1620070312.

Dieter, G. E., 1961, *Mechanical Metallurgy*, McGraw-Hill, New York, p. 615.

Dieter, G. E., and Bacon, D., 1988, *Mechanical Metallurgy*, McGraw-Hill, Singapore, p. 751.

Dieter, G. E., Kuhn, H. A., and Semiatin, S. L., 2003, *Handbook of Workability and Process Design*, ASM International, Materials Park, Ohio, USA.

Giles, H. F., Mount, E. M., and Wagner, J. R., 2004, *Extrusion: The Definitive Processing Guide and Handbook*, Elsevier Science.

Guy, R. C. E., 2001, *Extrusion Cooking: Technologies and Applications*, Woodhead, Cambridge.

Hassani, S., 2000, *Mathematical Methods: For Students of Physics and Related Fields*, Springer, New York.

Head, K. H., 2006, *Manual of Soil Laboratory Testing, Volume 1: Soil Classification and Compaction Tests*, Whittles Publishing, Scotland, UK.

Head, K. H., and Epps, R. J., 2011, *Manual of Soil Laboratory Testing, Volume 2: Permeability, Shear Strength and Compressibility Tests*, Whittles Publishing, Scotland, UK, p. 499.

Head, K. H., and Epps, R. J., 2014, *Manual of Soil Laboratory Testing, Volume 3: Effective Stress Tests*, Whittles Publishing, Scotland, UK, p. 424.

Hill, R., 1998, *The Mathematical Theory of Plasticity*, Oxford University Press, Oxford, p. 355.

Hoffman, O., and Sachs, G., 1953, *Introduction to the Theory of Plasticity for Engineers*, McGraw-Hill, New York, p. 276.

Johnson, W., and Mellor, P. B., 1973, *Engineering Plasticity*, Van Nostrand-Reinhold, London.

Kayabali, K., 2011a, "Assessment of Shear Strength at Consistency Limits - a Reappraisal." *Electronic Journal of Geotechnical Engineering*, Vol. 16 U, pp. 1679-1695.

Kayabali, K., 2012, "Estimation of Liquid, Plastic and Shrinkage Limits Using One Simple Tool." *Electronic Journal of Geotechnical Engineering*, Vol. 17 N, pp. 2079-2090.

Kayabali, K., Aktürk, Ö., Fener, M., Dikmen, O., and Harputlugil, F. H., 2015a, "Revisiting the Bjerrum's Correction Factor: Use of the Liquidity Index for Assessing the Effect of Soil Plasticity on Undrained Shear Strength." *Journal of Rock Mechanics and Geotechnical Engineering*, Vol. 7, No. 6, pp. 716-721, doi: 10.1016/j.jrmge.2015.07.003.

Kayabali, K., Aktürk, Ö., Fener, M., Ozkeser, A., Ustun, A. B., Dikmen, O., Harputlugil, F., and Asadi, R., 2016, "Determination of Atterberg Limits Using Newly Devised Mud Press Machine." *Journal of African Earth Sciences*, Vol. 116, pp. 127-133, doi: 10.1016/j.jafrearsci.2016.01.005.

Kayabali, K., and Ozdemir, A., 2013, "Use of Reverse Extrusion Method to Determine Undrained Shear Strength." *Geotech Geol Eng*, Vol. 31, No. 2, pp. 719-727, doi: 10.1007/s10706-013-9621-y.

Kayabali, K., and Tufenkci, O. O., 2007, "A Different Perspective for the Determination of Soil Consistence Limits." *International Symposium on Geotechnical Engineering, Ground Improvement and Geosynthetics for Human Security and Environmental Preservation*, Bangkok, Thailand, pp. 423-432.

Kayabali, K., and Tufenkci, O. O., 2010a, "Determination of Plastic and Liquid Limits Using the Reverse Extrusion Technique." *Geotechnical Testing Journal*, Vol. 33, No. 1, pp. 1-9, doi: 10.1520/GTJ102209.

Kayabali, K., Yilmaz, N., and Mollamahmutoglu, M., 2015c, *An Alternative Shear Strength Test for Saturated Fine-Grained Soils: Preliminary Results*, IOS Press, Buenos Aires, Argentina, doi: 10.3233/978-1-61499-601-9-407.

Lee, E. H., Mallett, R. L., and Yang, W. H., 1977, "Stress and Deformation Analysis of the Metal Extrusion Process." *Computer Methods in Applied Mechanics and Engineering*, Vol. 10, No. 3, pp. 339-353, doi: 10.1016/0045-7825(77)90077-9.

Manafi, M. S. G., 2019, "Soil Plasticity Variability and Its Effect on Soil Classification." *Geotechnical Testing Journal*, Vol. 42, No. 2, pp. 457-470, doi: 10.1520/GTJ20170273.

Medhat, F., and Whyte, I., 1986, "An Appraisal of Soil Index Tests." *Geological Society, London, Engineering Geology Special Publications*, Vol. 2, No. 1, pp. 317-323, doi: 10.1144/GSL.1986.002.01.55.

Moscicki, L., 2011, *Extrusion-Cooking Techniques: Applications, Theory and Sustainability*, Wiley-VCH; Chichester: John Wiley, Weinheim.

Nagaraj, H. B., Sridharan, A., and Mallikarjuna, H. M., 2012, "Re-Examination of Undrained Strength at Atterberg Limits Water Contents." *Geotech Geol Eng*, Vol. 30, No. 4, pp. 727-736, doi: 10.1007/s10706-011-9489-7.

O'Kelly, B. C., 2019, "Reappraisal of Soil Extrusion for Geomechanical Characterisation." *Geotechnical Research*, Vol. 6, No. 4, pp. 265-287, doi: 10.1680/jgere.19.00006.

Saha, P., 2000, *Aluminum Extrusion Technology*, ASM International, Materials Park, OH.

Siebel, E., 1932, *Metal Forming in Plastic Condition (in German)*, Verlag Stahieisen, Düsseldorf.

Spencer, A. J. M., 1961, "Perturbation Methods in Plasticity—I Plane Strain of Non-Homogeneous Plastic Solids." *Journal of the Mechanics and Physics of Solids*, Vol. 9, No. 4, pp. 279-288, doi: 10.1016/0022-5096(61)90005-9.

Spencer, A. J. M., 1962, "Perturbation Methods in Plasticity—Ii Plane Strain of Slightly Irregular Bodies." *Journal of the Mechanics and Physics of Solids*, Vol. 10, No. 1, pp. 17-26, doi: 10.1016/0022-5096(62)90025-X.

Timar, A., 1974, "Testing Plastic Properties of Cohesive-Type and Intermediate-Type Soils by Extrusion." *Acta Technica Academiae Scientiarum Hungaricae*, Vol. 76, No. 3-4, pp. 355-370.

Verástegui-Flores, R. D., and Di Emidio, G., 2014, "Assessment of Clay Consistency through Conventional Methods and Indirect Extrusion Tests." *Applied Clay Science*, Vol. 101, pp. 632-636, doi: 10.1016/j.clay.2014.09.033.

Verástegui-Flores, R. D., and Di Emidio, G., 2015, "Determination of Consistency Limits of Clay by Means of Extrusion Tests." *European Conference on Soil Mechanics and Geotechnical Engineering*, ICE, Edinburgh, UK, pp. 3431-3436, doi: 10.1680/ecsmge.60678.vol6.538.

Whyte, I. L., 1982, "Soil Plasticity and Strength - a New Approach Using Extrusion." *Ground Engineering*, Vol. 15, No. 1, pp. 16-18, 20, 22, 24.

Chapter Four – Determining Soil Plasticity Utilizing Manafi Method and Apparatus

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i. the candidate's stated contribution to the publication is accurate (as detailed above);
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iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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4.1 Abstract

Soil plasticity is one of the essential index properties required for classifying soils in geotechnical engineering practice. Determination of plasticity properties of soils is also critical for correlation with their engineering properties such as shear strength, permeability, and compressibility. However, present standard test methods for soil plasticity suffer, to different extents, from operator-dependency and inconsistency. This study introduces a new technique utilising a combined qualitative and quantitative approach for soil property determinations, namely the *Manafi Method and Apparatus.* The method is proposed as an alternative technique to determine the liquid and plastic limits of soils. The proposed technique is instrumented with a new soil extrusion device to quantify the workability of soils and is calibrated to translate the workability to their liquid and plastic limits. The method is applied to seven soils of varying particle sizes and plasticity to determine the liquid and plastic limits, and the results are compared with those obtained by the conventional methods. The outcomes suggest that the new technique provides a more precise and reliable means of soil plasticity determination in the studied samples.

Keywords: Plasticity; Liquid Limit; Plastic Limit; Soil Consistency; Soil Extrusion; Workability.

Plain Language Summary:

This paper introduces an alternative test method for soil plasticity determination highlighting the capability of the new test method and apparatus in:

- Determination of liquid and plastic limits;
- Determination of the ‘workability’ parameter for several different soil types;
- Calibration of the new apparatus for the soil plasticity determinations;
- Comparing the results obtained by the proposed and conventional methods;
- Illustrating the advantages of the proposed method.

4.2 Introduction

Soil plasticity is an essential index property used to evaluate the consistency and engineering behaviour of soils. The plasticity is usually characterised by the plastic limit (PL) and the liquid limit (LL) of the soil of interest. Standard laboratory tests, such as the Casagrande percussion cup and fall cone methods, are available to determine LL, and the thread rolling method for determining PL (e.g., BS EN 1377-2 1990; AS 1289.3.2.1 2009; AS 1289.3.9.1 2015; AS 1289.3.1.1-2009 2017; ASTM D4318-17e1 2017). PL and LL determinations lead to calculation of important indices, i.e., plasticity index (PI) and liquidity index (LI), which are paramount to soil classification.

Although the available standard test methods for soil plasticity are inexpensive and straightforward, the obtained results suffer major to moderate reliability issues, such as reporting variable results (e.g., Sherwood and Ryley 1968; Sherwood 1970; Davidson 1983; Prakash 2005; Prakash and Sridharan 2006; Vardanega and Haigh 2014; Manafi 2017, 2019). Various studies have been undertaken to propose alternative test methods to overcome issues associated with the standard tests. Soil extrusion is a relatively new test method for soil property determination. The direct and reverse extrusion methods were first attempted to determine the LL and PL of soils by Timar (1974) and Whyte (1982), respectively. Whyte proposed a shear strength-based approach, which was also implemented by Kayabali and Tufenkci (2007). Their further studies (2010a) explored the repeatability of test results and thereby sought to demonstrate the reliability of the extrusion method. However, they observed scatter in their data, which was attributed to the uncertainties associated with the standard Atterberg limit tests. Kayabali and his research group continued utilisation of the extrusion method to obtain various soil properties, including Atterberg limits (e.g., Kayabali and Tufenkci 2010b; Kayabali 2011a; Kayabali et al. 2015b; Kayabali et al. 2016), and undrained and drained shear strengths (e.g., Kayabali 2011a; Kayabali and Ozdemir 2013; Kayabali et al. 2015a; Kayabali et al. 2015c). Verástegui-Flores and Di Emidio (2014, 2015) also studied high-plasticity kaolin−bentonite samples using the extrusion method.

Although the extrusion method has been explored to determine soil limit states, the utilised approaches have not been appropriate. In the strength-based approach, it was assumed that particular shear strengths indicate the limit states (e.g., 1.7 kPa and 170 kPa for LL and PL, respectively). Therefore, an attempt was made to correlate the extrusion pressures to the shear strengths and to determine the limit states. However, extensive ranges of shear strengths have been reported at the limit states (e.g., Karlsson 1961; Dumbleton and West 1970; Whyte 1982; Harison 1990; Marinho and Oliveira 2012; Nagaraj et al. 2012; Vinod et al. 2013; Vardanega and Haigh 2014; Nagaraj and Sravan 2019). Not only do soils have different shear strength values at the limit states, but also the mechanics of the extrusion method (e.g., Dieter and Bacon 1988; Saha 2000; Manafi et al. 2022a) differ drastically from the conventional shear strength tests (such as vane shear, direct shear, and unconfined compression tests). Therefore, various parameters affect the test results, which may explain the discrepant results reported in previous studies (e.g., O'Kelly 2019).

Another approach was to correlate the extrusion pressure obtained by a specific ram speed to the results of current standard methods without considering the variability problems of standard methods (e.g., Manafi 2019). These inappropriate approaches have led to discrepant results, which has hindered recognising the extrusion method as an alternative to the standard test. To overcome these shortcomings, a new method is proposed following a combined qualitative and quantitative approach (Fellows and Liu 2015). As a result, an energy-based parameter, termed workability, is introduced to quantify and measure soil consistency. The workability parameter is obtainable using a new extrusion apparatus. This study demonstrates the implementation of the proposed method and the processes of using workability to determine LL and PL values. In the meantime, the performance of the apparatus is compared with the conventional test methods.

4.3 Workability

Workability can be quantified by determining the work rate, i.e., the energy transferred to move or deform an object over time. The formula for calculation of work, W, is:

$$W = (F \cos \theta) \Delta x \quad \textbf{(4-1)}$$

where F is the magnitude of the force, θ is the angle between the directions of force $\vec{F}$ and displacement $\Delta\vec{x}$, and Δx is the magnitude of the displacement. The parameters are shown in Figure 4-1.

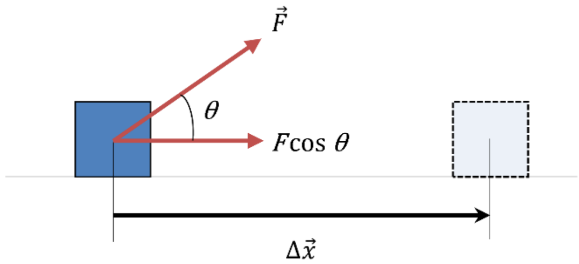


Figure 4-1: Work done by a constant force on a mobilised object.

Different objects might need different levels of force to overcome the resistance against the movement of the objects. As demonstrated in Figure 4-2, the work done by F_1 is constant for both objects in Figure 4-2(*a*) and (*b*), but the work that is exerted by the resistant force in Figure 4-2(*a*) is greater than in Figure 4-2(*b*). The difference between the net works done on the objects in Figure 4-2(*a*) and (*b*) causes more rapid movement of the object in the case of Figure 4-2(*b*) than the object in Figure 4-2(*a*). Actually, the net force in Figure 4-2(*b*), ($F_1 - F_{f2}$), is greater than that in Figure 4-2(*a*). According to Newton's second law of motion, this will lead to the additional acceleration of the object in Figure 4-2(*b*), provided the two objects have the same mass. Hence, it is possible to measure the effect of the resistant force by measuring the rate of work imposed on the object.

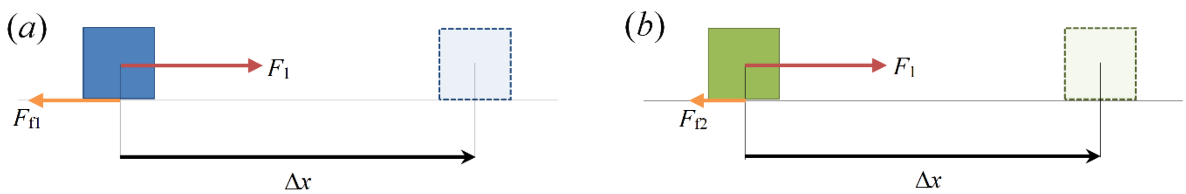


Figure 4-2: Different resistance forces for various object materials: (*a*) An object with a high resistance force against movement; (*b*) An object with a low resistance force against movement.

The work done can be used to determine the power P, that is the rate at which the work is conducted. The average power is calculated by the following formula:

$$P = \frac{W}{\Delta t} = \frac{F\Delta x}{\Delta t} = F\bar{v} \qquad \textbf{(4-2)}$$

where Δt is the time interval and $\bar{v}$ is the average speed of the object. The power P is indicative of the workability of the materials and for soils can be used to quantify consistency and plasticity.

The resistance force in the determination of soil consistency is the one that performs work to deform a soil specimen. A specimen with consistency classified in *soft* deforms easier (or more rapidly) than in *stiff*. Therefore, the deformation rate will be used to determine the work imposed, and thus, the workability of the soil specimen. The consistency of the specimen can be quantified by the determination of the soil workability. This concept has been developed into a test method known as *Manafi Method* (Manafi 2017) for measuring soil consistency. Additional effort is required to translate the method into an appropriate soil test apparatus and to calibrate it using various soil types.

4.4 Equipment Design

4.4.1 Apparatus design concept

A simplified model of the *Manafi Apparatus* is shown in Figure 4-3. By applying an extrusion force F_E on the partially confined soil specimen, the soil deforms and passes through several holes at the base of the mould. In this design, F_E overcomes the deformation force F_D to extrude downward the soil material with a mass of M_s within time t_D. In the presented model, F_E is the extrusion force applied by the actuator, and F_D is the resultant force of all the internal resistant forces during the extrusion process (Manafi et al. 2022a).

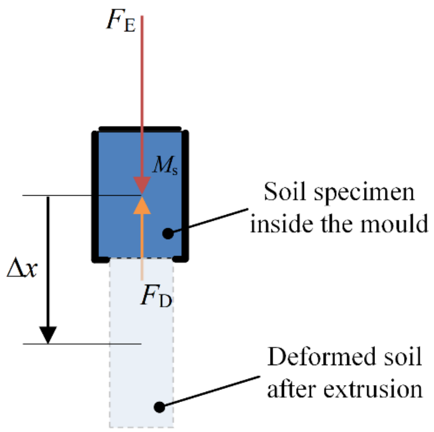


Figure 4-3: Simplified physical model of the *Manafi Apparatus*.

This model is a one-dimensional case. The resultant force ($F_R = F_E - F_D$) causes extrusion of the soil. F_D is desirable in this study, which is a measure of the soil deformation inside the apparatus. The work done by the deformation force can be measured by calculating the power. Therefore, the deformation power P_D that acts on the soil specimen can be obtained by the following equations:

$$P_D = \frac{W_D}{t_D} = \frac{F_D \Delta x}{t_D} \quad \textbf{(4-3)}$$

$$F_D = F_E - F_R \quad \textbf{(4-4)}$$

$$F_R = M_s \bar{a} \quad \textbf{(4-5)}$$

$$\Delta x = v_0 t_D + \frac{1}{2} \bar{a}\, t_D^2 \quad \textbf{(4-6)}$$

$$\bar{a} = \frac{2(\Delta x - v_0 t_D)}{t_D^2} \quad \textbf{(4-7)}$$

where W_D is the work done in deforming the soil, $\bar{a}$ is the average acceleration of the soil specimen, and v_0 is the initial velocity of the soil specimen at the beginning of extrusion.

The magnitude of the deformation force, F_D, varies with the water content of the soil specimen. A soil specimen with a higher water content requires less work to deform. Hence, it is possible to correlate a specific workability value to a particular state of consistency, including the liquid and plastic limits.

4.4.2 Apparatus overview

Throughout the extrusion process, the specimen's workability is determined and compared with the soils' calibrated workability at limit states. Consequently, the consistency limit states can be obtained by varying the samples' water content.

Figure 4-4 shows a view of the *Manafi apparatus*. The extrusion equipment comprises a metal frame and a pneumatic double-acting compact cylinder actuator. The device is equipped with an air pressure regulator and an air reservoir. The air pressure regulator is set to apply constant thrust force to the soil specimens at limit states. The apparatus also includes a load cell that is mounted behind the plunger. The load-cell is used to measure the axial force applied to the specimen during extrusion. A draw-wire displacement sensor measures the vertical movement of the plunger throughout the test. A data-acquisition system is connected to a laptop to collect the test data required to calculate the workability parameter. It is important to note that the apparatus is necessarily complex because of the nature of this research endeavour. The final operational apparatus will be more streamlined to reduce the cost of the apparatus.

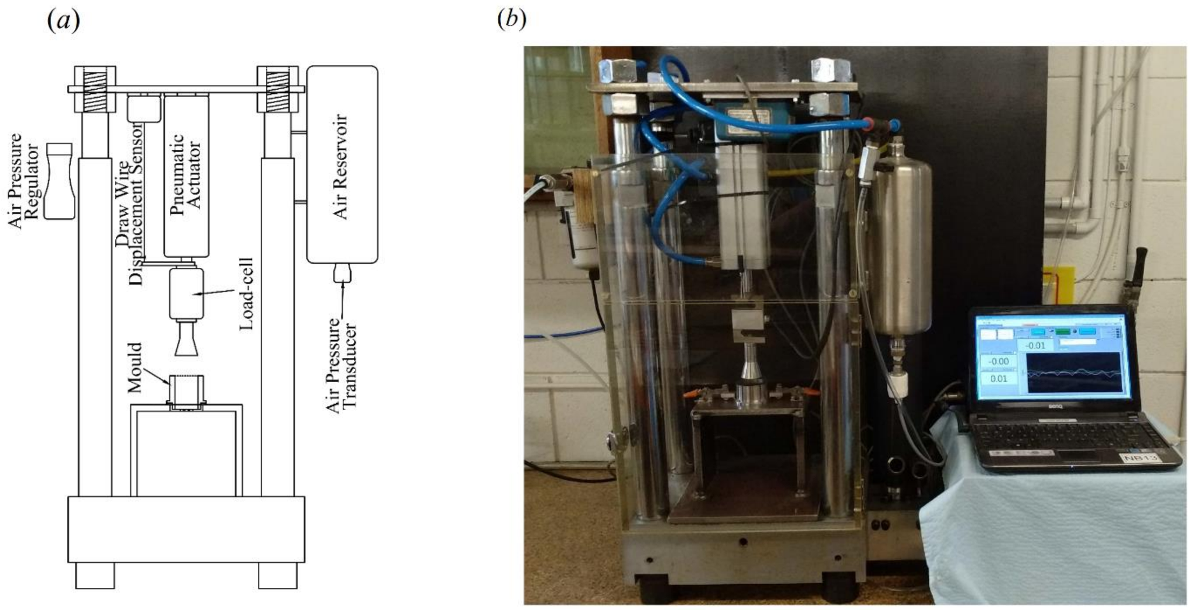


Figure 4-4: *Manafi Apparatus*: (*a*) annotated illustration; (*b*) fabricated apparatus.

The mould comprises a cylindrical container and a replaceable container base. Several container bases with different formations of holes are fabricated to provide various options of extrusion ratio (*ER*), which is defined as the ratio of the cross-sectional area of the container (A_C) to the cross-sectional area of the extruded material (A_E). The gap between the plunger and the container wall is also 520 microns. Moulds were trialled to obtain the suitable *ER*s to determine limit states while considering the apparatus's performance, the specimen's consistency, and optimised operation.

4.4.3 LL setup

The *Manafi extrusion apparatus* is used for the determination of both the LL and PL states. However, because of the sensitivity needed to measure the LL state of very soft soils, a larger volume of specimen is required, and hence a larger mould is adopted than the one used to measure the PL. As shown in Figure 4-5, the LL tests use a mould with 35 mm internal diameter, 51 mm external diameter, and 51 mm height. The container base includes three holes with a 5 mm diameter, 20 mm spacing, symmetrically distributed with a 120° internal angle and extrusion ratio of 8.35. The same technique of filling the cups in the fall cone method (AS 1289.3.9.1 2015) is applied for filling the LL mould. Trials were conducted to determine the air pressure required for the tests, and air pressure of 23 kPa was found to be suitable for LL determination, considering the actuator's constraints, operation, and test duration.

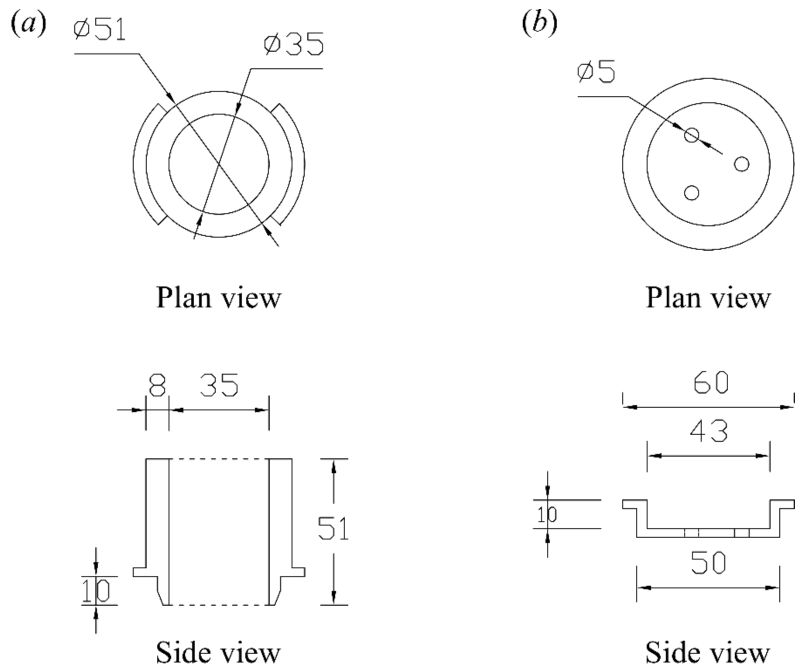


Figure 4-5: Specification of liquid limit determination mould (dimensions are in mm): (*a*) container; (*b*) container base.

4.4.4 PL setup

As the consistency of the sample becomes stiffer toward the PL, the required extrusion pressure increases. Therefore, it is required to design a mould that considers the capacity of the actuator and simplified operation. As the extrusion ratio directly affects the extrusion pressure, the aperture area of the base of the container is increased to reduce the extrusion pressure in proportion to the actuator's capacity. Consequently, as shown in Figure 4-6, the container base contains two 340 mm^2 curved slots and a centre hole with a 10 mm diameter, leading to an extrusion ratio of 1.18. In addition, to reduce the effort required to fill the container with stiff soil material, the height of the container was reduced to 36 mm. The sample preparation procedure for the PL determination is the same as for the standard PL test (AS 1289.3.2.1 2009). Consequently, a large thread of soil diameter of around 34 mm and a water content around the PL is formed and pushed into the mould by hand. Finally, the excess soil is trimmed by a straight edge spatula to make a smooth surface. After several trials, the appropriate air pressure was found to be around 484 kPa for the PL test setup.

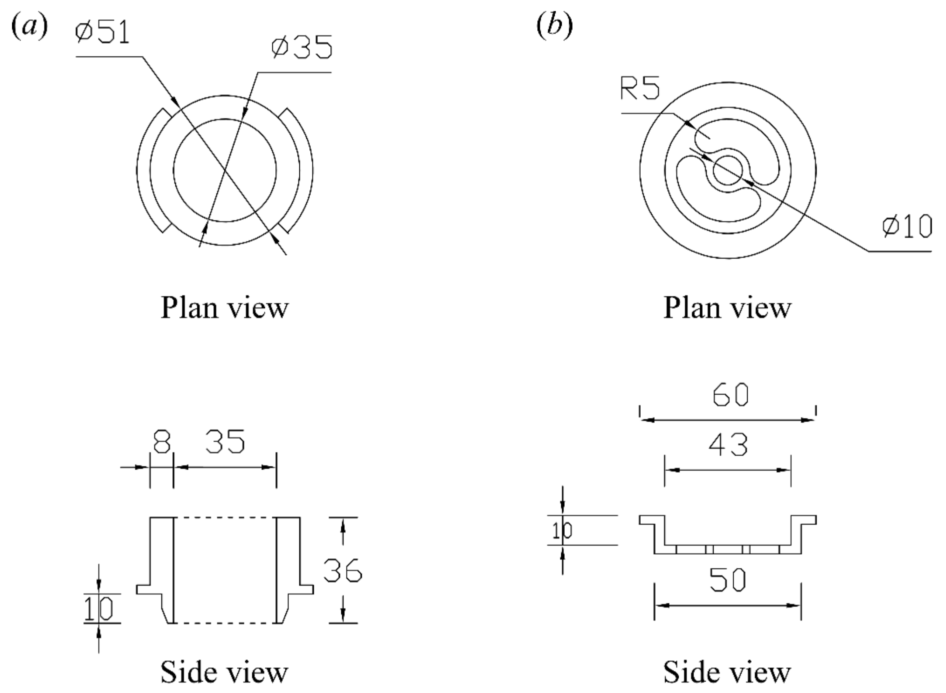


Figure 4-6: Specification of plastic limit determination mould (dimensions are in mm): (*a*) container; (*b*) container base.

4.5 Laboratory Tests

4.5.1 Soil materials

The soils applicable to Atterberg limit tests are clays, silts, clayey and silty sands (SC and SM), and some organic soils (Sabatini et al. 2002). Because of time and budgetary constraints, the experiments presented here are limited to the most common cohesive soil type, i.e., clay. However, the results will also be useful for other types of cohesive soils.

Most previous studies have focused on studying artificial soil samples obtained by mixing different fractions of industrial materials such as kaolinite or montmorillonite. Although studying several artificial samples from limited soils might be acceptable for the preliminary calibration of the new devices, the primary calibration might be biased to that particular soil mineralogy, as the mineralogy of the soil grains has a significant effect on soil plasticity and performance of the proposed apparatus. Therefore, studying various natural soils with different origins, mineralogy, and wide ranges of soil plasticity would be a proper sample size for validating new methods. However, studying various natural soils with wide plasticity ranges might be challenging considering the study limitations. This research focuses on studying various soils with different mineralogy representing different types of clays, from low-plastic to extremely high-plastic soils. In this study, natural soils from different origins, covering a wide range of particle size and cohesion, are used to validate the capabilities of the proposed method and apparatus. Considering the time, budget, logistics, and other constraints, five natural soils with different mineralogy are obtained from various locations in South Australia (Soils 1 to 5) and prepared by the wet preparation method according to AS 1289.1.1-2001 (2008). Subsequently, Soils 6 and 7 are artificially obtained from Soil 2 to study soils with different particle size distributions (PSDs) but the same mineralogy. Consequently, Soil 6 contains only silt and clay particle sizes, and Soil 7 contains 20% sand-size particles.

4.5.2 Soil characterisation tests

The tests are performed on soil samples of less than 425-microns. PSDs are determined by conducting sieving and sedimentation tests by the hydrometer method (ASTM D7928-16e1 2016). The PSDs and the percentage of the soil components are presented in Figure 4-7.

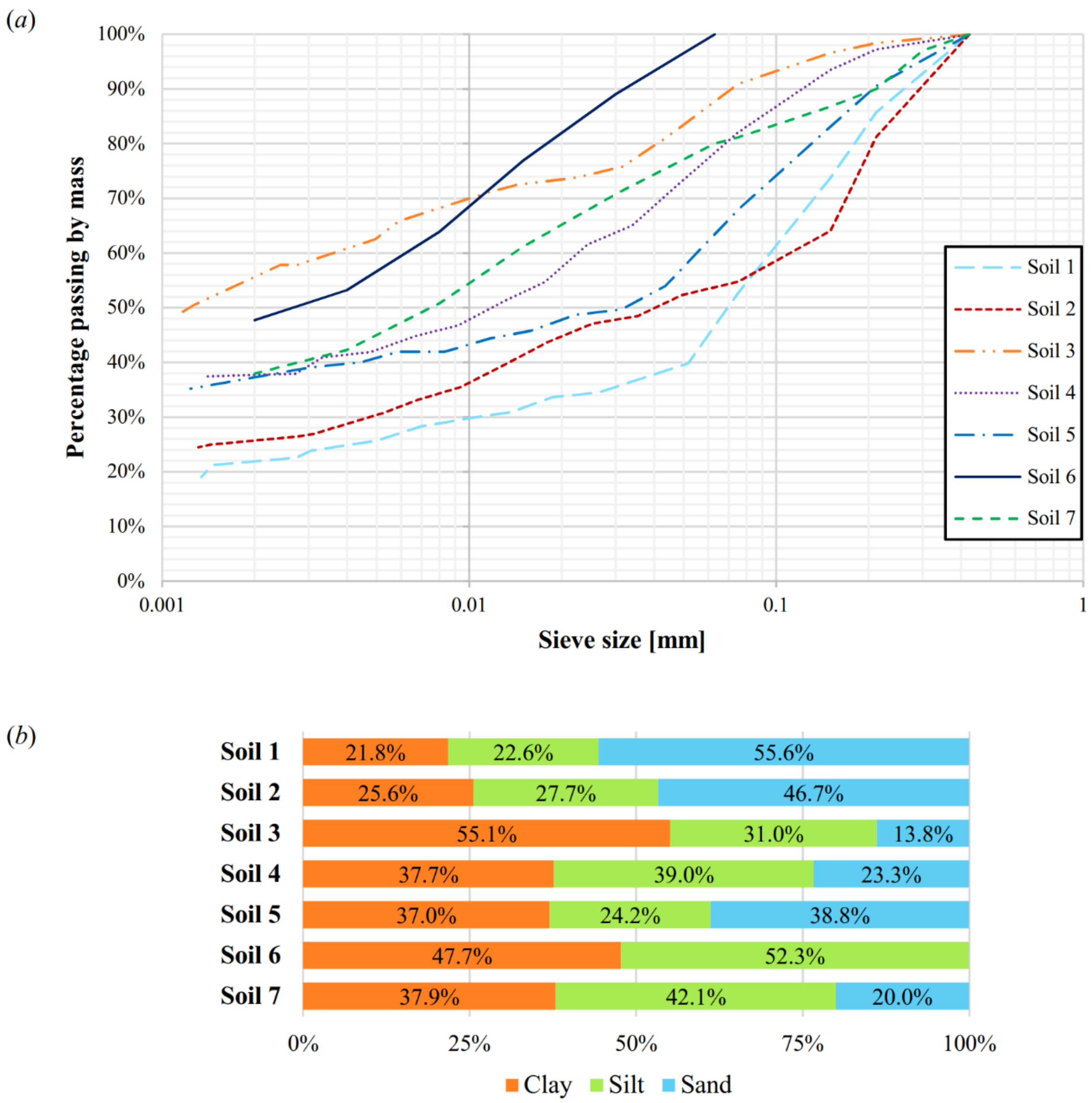


Figure 4-7: Particle size distribution results: (*a*) PSD curves;
(*b*) Soil components (according to AS 1289.3.6.1 2009).

The *LL*s and *PL*s are benchmarked with those determined based on the fall cone (AS 1289.3.9.1 2015) and thread rolling methods (AS 1289.3.2.1 2009). The variabilities of the standard values are also considered in the calibration process, as explained in the *Manafi Apparatus* calibration section. The advantage of the fall cone method over the Casagrande percussion cup method is that it provides more consistent results and is less operator-dependent (BS EN 1377-2 1990; CEN. E.N. 1997-2 2007). However, the results of both the fall cone method and the Casagrande percussion cup method are relatively close for common soil materials in geotechnical engineering (Manafi 2019). The results of the soil plasticity determination by the standard methods are presented in Figure 4-8. The results are presented to the hundredth place to enable more precise comparisons between the methods.

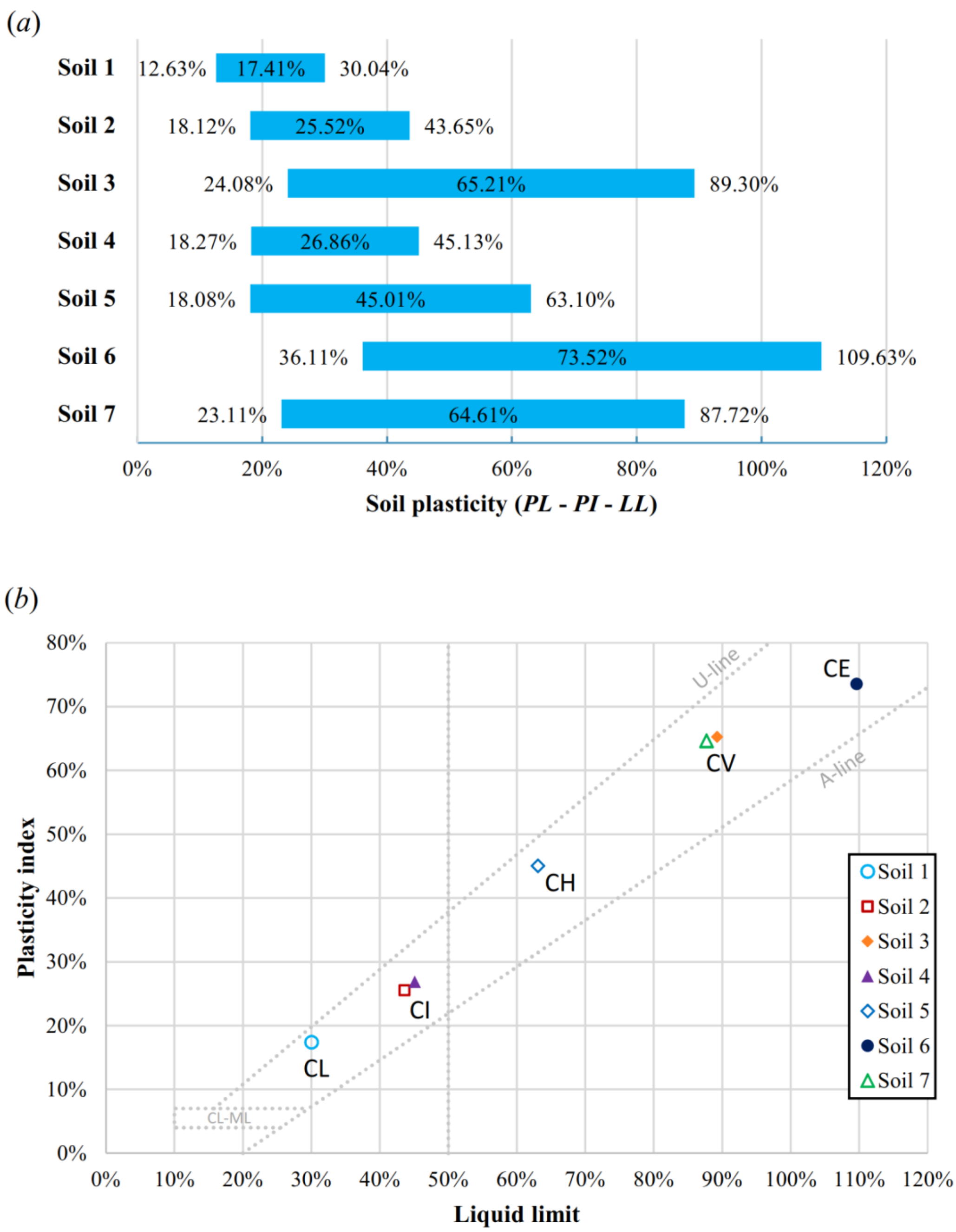


Figure 4-8: Standard soil plasticity determination: (*a*) soil plasticity results; (*b*) plasticity chart.

As shown in Figures 4-7 and 4-8, the soil samples studied in this research are representative of a wide range of plastic soils, from both PSD and plasticity range perspectives, to study at least one sample from each clay type [Low-plasticity Clay (CL), Intermediate-plasticity Clay (CI), High-plasticity Clay (CH), Very high-plasticity Clay (CV), and Extremely high-plasticity Clay

(CE) according to BS 5930 (2015)]. Therefore, a broad spectrum of clay soils is assessed and tested. Consequently, the soil samples are appropriate for calibration and validation of the proposed test method and the apparatus for the soil consistency determination.

4.5.3 Test results

The soil samples used in the present study are also tested using the proposed *Manafi method* to determine their workability at the LL and PL, which were determined by the standard methods, as described above. In this process, several soil specimens, with water contents around the limit states, are tested using the *Manafi apparatus*. Subsequently, the extrusion graph of each trial is obtained. Examples of extrusion graphs are shown in Figure 4-9, obtained by the data acquisition system, which includes the force, penetration, and the time of extrusion around the limit states. The average extrusion force and extrusion time of each trial are obtained for penetrating the height of the moulds for calculating the extrusion workability, as shown in Figure 4-9. An example of workability calculation is provided for Soil 2: water content = 41.60%, extrusion force (F_{E}) = 36.73 N, extrusion time (t_{D}) = 1.79 s, penetration depth (h_{C}) = 49.60 mm, extrusion ratio (ER) = 8.35, initial velocity of the plunger (v_0) = 0 mm/s, and mass of the specimen (M_{s}) = 84.44 g.

Considering Figure 4-3, the displacement of the specimen is calculated as:

$$\Delta x = \frac{h_{\mathrm{C}} + h_{\mathrm{E}}}{2} \tag{4-8}$$

where h_{E} is the final height of extruded soil.

Considering the constant volume of the extruding material during the extrusion process:

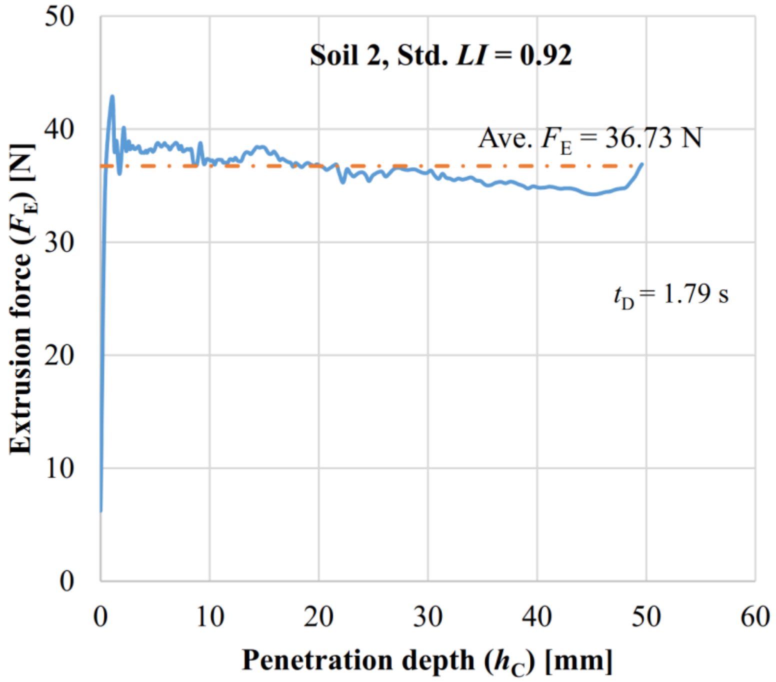
$$A_{\mathrm{C}} h_{\mathrm{C}} = A_{\mathrm{E}} h_{\mathrm{E}} \tag{4-9}$$

$$h_{\mathrm{E}} = \frac{A_{\mathrm{C}} h_{\mathrm{C}}}{A_{\mathrm{E}}} = ER\ h_{\mathrm{C}}$$

Consequently, Eq. (4-8) is written as:

$$\Delta x = \frac{h_{\mathrm{C}}(1 + ER)}{2} \tag{4-10}$$

(*a*)



(*b*)

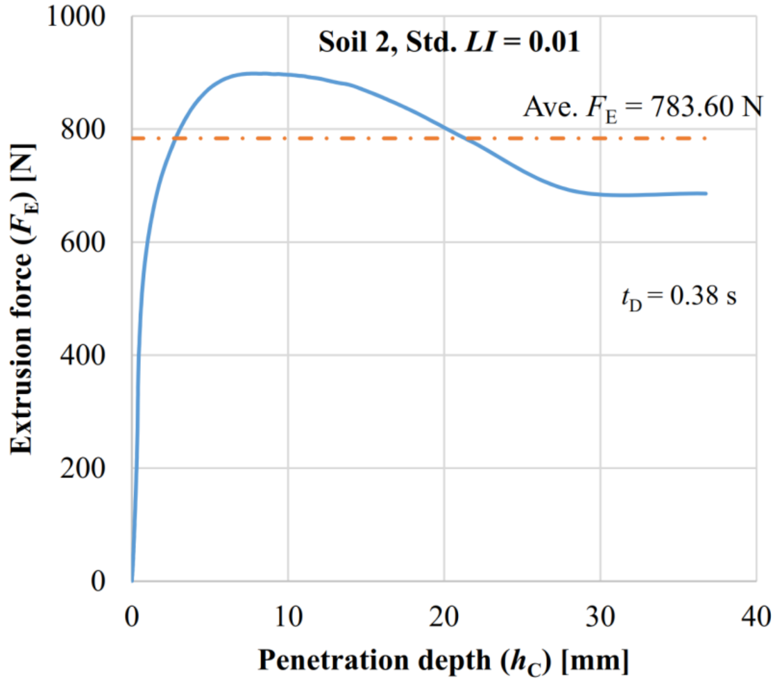


Figure 4-9: Extrusion graph samples: (*a*) for liquid limit determination; (*b*) for plastic limit determination.

Therefore: $\Delta x = \dfrac{49.60\ (1 + 8.35)}{2} = 231.88\ \text{mm}$

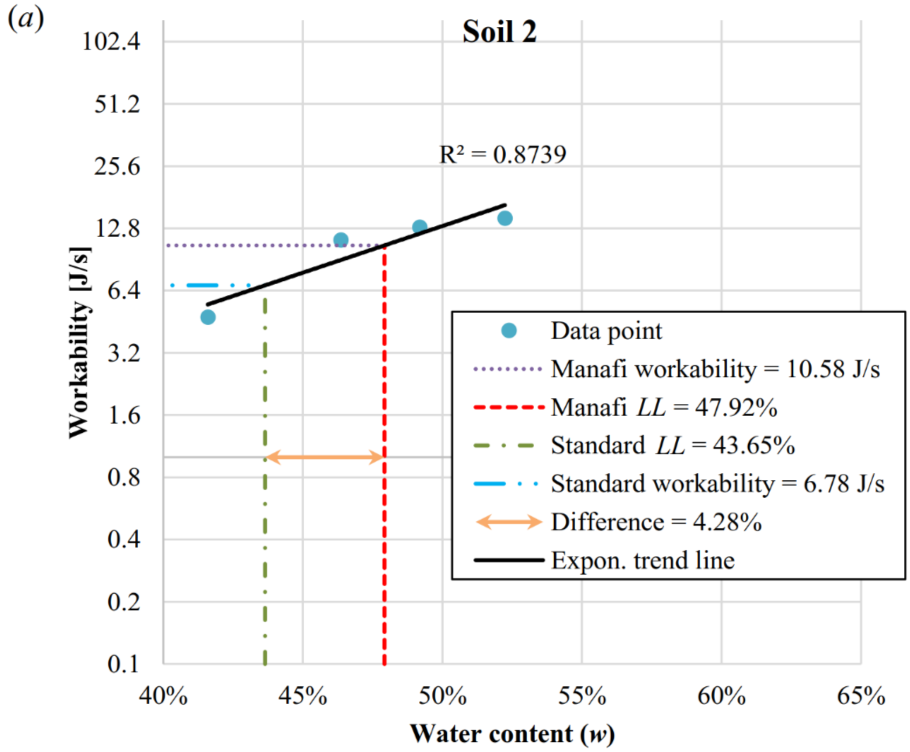
According to Eq. (4-7): $\bar{a} = \dfrac{2(\Delta x - v_0 t_\mathrm{D})}{t_\mathrm{D}^2} = \dfrac{2\,(231.88 - 0 \times 1.79)}{1.79^2} = 144.74\ \mathrm{mm/s^2}$

According to Eq. (4-5): $F_\mathrm{R} = M_\mathrm{s}\,\bar{a} = 84.44 \times 144.74 = 0.012\ \mathrm{N}$

According to Eq. (4-4): $F_\mathrm{D} = F_\mathrm{E} - F_\mathrm{R} = 36.73 - 0.012 = 36.72\ \mathrm{N}$

According to Eq. (4-3): $P_\mathrm{D} = \dfrac{F_\mathrm{D}\Delta x}{t_\mathrm{D}} = \dfrac{36.72 \times 0.23}{1.79} = 4.72\ \mathrm{J/s}$

Three or four trials around the limit states are required to obtain an appropriate workability graph. Subsequently, a semi-log graph of water content versus workability is plotted to establish the pertinent water content at the limit states (examples of which are presented in Figure 4-10; the calibration process of the *Manafi method* is discussed separately). The resulting workability measurements for each sample are presented in Tables 4-1 and 4-2.



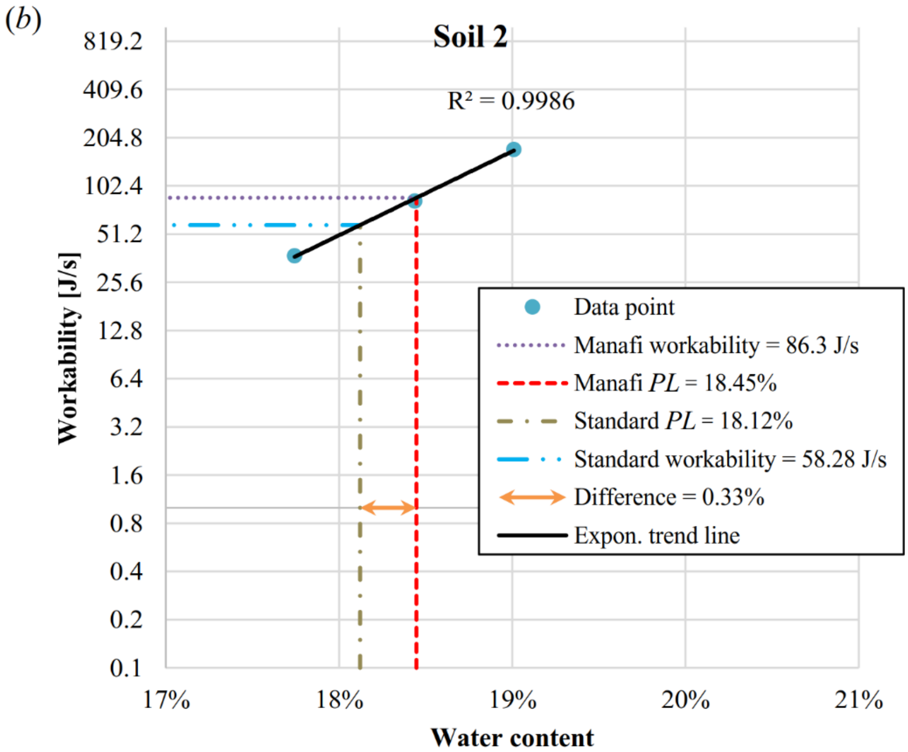


Figure 4-10: Workability graph examples (P_D–w): (*a*) liquid limit determination; (*b*) plastic limit determination.

Table 4-1: Soil sample workability determinations around the liquid limit state.

	Specimen No.	Water content [%]	Mass of specimen [g]	Extrusion force [N]	Depth of penetration [mm]	Time of extrusion [s]	Workability [J/s]
Soil 1	1	31.57	91.39	29.71	50.84	0.64	10.99
	2	33.37	89.96	26.01	50.95	0.48	12.82
	3	35.03	89.50	22.93	51.05	0.40	13.52
	4	30.97	91.17	32.65	50.15	0.89	8.59
	5	29.28	91.77	36.50	49.77	1.46	5.81
Soil 2	1	41.59	84.44	36.73	49.60	1.79	4.72
	2	46.36	83.85	28.48	50.78	0.60	11.23
	3	49.18	72.39	23.59	50.76	0.43	12.92
	4	52.24	82.32	22.36	51.23	0.37	14.29
Soil 3	1	90.72	70.33	24.92	51.11	0.44	13.44
	2	85.12	73.09	29.34	50.81	0.56	12.40
	3	93.79	71.46	23.51	50.92	0.41	13.54
	4	81.21	72.95	32.37	50.65	0.83	9.22
Soil 4	1	41.34	87.25	39.13	49.45	6.23	1.45
	2	42.18	86.47	38.18	49.56	2.28	3.88
	3	44.47	84.78	32.92	50.12	0.96	8.02
	4	46.13	84.47	30.65	50.20	0.65	11.04
Soil 5	1	59.64	78.34	31.71	50.62	0.67	11.17
	2	67.89	77.46	23.36	51.02	0.36	15.30
	3	66.03	77.43	25.50	50.95	0.41	14.70
	4	58.33	78.01	33.06	50.11	0.83	9.32
Soil 6	1	93.69	71.75	35.72	50.18	1.14	7.34
	2	101.35	70.25	30.02	50.63	0.59	12.00
	3	112.61	68.57	24.40	51.10	0.39	14.82
	4	120.91	67.83	21.18	51.35	0.33	15.19
Soil 7	1	82.39	72.74	30.40	50.48	0.83	8.63
	2	85.50	71.89	27.03	50.74	0.49	13.02
	3	91.80	70.50	23.13	51.11	0.39	14.03
	4	94.27	70.21	22.70	50.85	0.36	14.82

Table 4-2: Soil sample workability determinations around the plastic limit state.

	Specimen No.	Water content [%]	Mass of specimen [g]	Extrusion force [N]	Depth of penetration [mm]	Time of extrusion [s]	Workability [J/s]
Soil 1	1	14.41	75.53	547.53	36.73	0.12	182.51
	2	13.91	76.34	689.95	38.45	0.18	160.60
	3	13.14	76.08	777.86	36.88	0.27	115.79
Soil 2	1	19.01	71.13	567.83	39.22	0.14	173.28
	2	18.44	65.92	783.60	36.74	0.38	82.58
	3	17.74	68.00	832.63	31.81	0.77	37.49
Soil 3	1	29.40	69.16	453.49	32.31	0.08	199.26
	2	25.68	69.60	887.66	37.49	2.38	15.24
	3	26.61	71.47	796.48	37.66	0.38	86.03
	4	25.44	70.24	898.26	36.48	6.47	5.52
Soil 4	1	19.18	75.35	749.39	38.20	0.25	124.78
	2	18.38	71.46	752.38	37.86	0.25	124.15
	3	20.27	75.17	549.00	39.32	0.13	180.86
	4	18.93	74.96	665.59	36.96	0.17	157.69
Soil 5	1	20.35	72.76	699.92	38.52	0.22	133.53
	2	19.23	72.25	837.33	32.16	0.83	35.36
	3	20.51	73.94	579.94	38.65	0.14	174.40
Soil 6	1	40.00	60.34	392.15	34.15	0.09	161.93
	2	37.70	57.97	544.63	35.74	0.13	163.09
	3	34.78	58.26	580.67	37.08	0.15	156.40
	4	32.53	53.73	852.10	37.25	0.62	55.80
Soil 7	1	26.14	66.42	551.22	38.67	0.14	165.84
	2	25.50	65.76	553.42	36.69	0.12	184.31
	3	24.21	65.07	737.30	37.00	0.24	123.85
	4	23.95	60.57	814.43	37.01	0.49	67.03

4.5.4 *Manafi Apparatus* calibration

There are two main approaches available to verify the test results obtained by the new test method. The first is based on the definition of soil plasticity. By clearly defining the soil consistency at the limit states as measurable behavioural conditions, it is possible to accurately determine the water content of soils at the limit states. However, no explicit definitions for the soil plasticity and soil states are given in the literature. Although ASTM D653-14 (2014) generally defines "consistency" as "the relative ease with which a soil can be deformed", it is not possible to calibrate the new device based on this inexplicit definition.

The other approach is based on the results obtained by the accepted conventional methods, in the absence of precise definitions for the various limit states. In this approach, the results obtained from the new test method are correlated with those obtained by the present standard methods. In other words, it is desirable to obtain the same value of the parameters LL and PL as determined by the standard methods by adopting the newly proposed test method. This approach is plausible if the results of the conventional methods are accurate and definitive. However, the standard methods for soil plasticity determination have their shortcomings and variabilities (e.g., Medhat and Whyte 1986; Manafi 2019). Therefore, direct usage of this approach to calibrate the newly proposed method is suboptimal, as it suffers from the same inaccuracy issues.

The proposed method for calibrating the new apparatus is a combination of the first two approaches. It is assumed that the present standard methods can specify the limit states in a way that falls within a range of water contents around the actual limit states (considering the variability of the conventional methods). In other words, the results of the standard tests help to identify the limit states thresholds; consequently, the water contents within those thresholds that all soils have the same consistency (based on the definition) will be the actual limit states. Therefore, the calibration is not directly based on the results of the standard methods but according to the soil consistency definition. After calibrating the device, all soils with the calibrated consistency/workability are at the limit states.

An important point to note is that, although different soils have different water contents at the limit states, all soils theoretically have the same LI or consistency at the limit states (LI = 0 at the PL and LI = 1 at the LL). In other words, if the test methods are accurate, they would indicate the same soil consistency at LI = 0 or 1. This assumption enables us to compare the consistency of soils at different water contents (i.e., Soil A: LL_A = 35%, LI_A = 1; Soil B: LL_B = 53%, LI_B = 1). However, the current standard test methods have their deficiencies, and their results do not necessarily determine exact limit states but are distributed normally around the limit states (Manafi 2019). For instance, Soil A: Std. LL_A = 34%, $LI_A \approx 1$; Soil B: Std. LL_B = 54%, $LI_B \approx 1$. Accordingly, the range of each limit state can be verified by performing several tests on various soil types (Manafi 2019). Therefore, it is possible to study the consistency of the soils by evaluating their workabilities in each limit state domain. Respectively, similar workability graphs based on the standard *LI* of soils are produced, as shown in Figure 4-11. Subsequently, by considering that the standard limit states are distributed normally around the actual limit states, the calibrated workability has been calculated by a numerical method to satisfy the condition of making the average value of *LI*s of all soils as 1 for liquid limit and 0 for plastic limit. Consequently, the variability of the standard methods has been considered in the calibration process. After calibration of the device, in order to determine the limit state of any soil, it is just required to obtain the workability graph (e.g., Figure 4-10) and find the water contents pertinent to the calibrated workability.

As a result, the water content pertinent to the same workability for all soils in each limit state domain can be considered as the actual limit state following the consistency definition corresponding to the calibrated workability. To sum up, the following steps are adopted for calibration of the proposed apparatus, as presented in Tables 4-3 and 4-4:

1. Standard limit states are determined (second column in Tables 4-3 and 4-4);
2. Workability graphs around the limit states are drawn (e.g., Figure 4-11);
3. Calibrated workabilities calculated in order to determine the average value of the *LI*s of the standard methods so as to become 1 for LL and 0 for PL (columns three and four in Tables 4-3 and 4-4);
4. Limit states based on the proposed method are determined using the calibrated workabilities (see Figure 4-10; fifth column in Tables 4-3 and 4-4).

The results show that the water contents obtained by the proposed method are very close to the limit states obtained by the standard methods, which confirms the validity of the proposed method. In this study, as mentioned earlier, seven different soil samples, with *PL*s ranging from 12.63 to 36.11% and *LL*s from 30.04 to 109.63%, are investigated. As shown in Figure 4-10, the apparatus is calibrated using workabilities of 10.58 J/s to determine the liquid limit and 86.30 J/s for the plastic limit. Assuming that the studied soils are representative of the soil types (CL to CE), the apparatus is calibrated for all soils within the studied plasticity range.

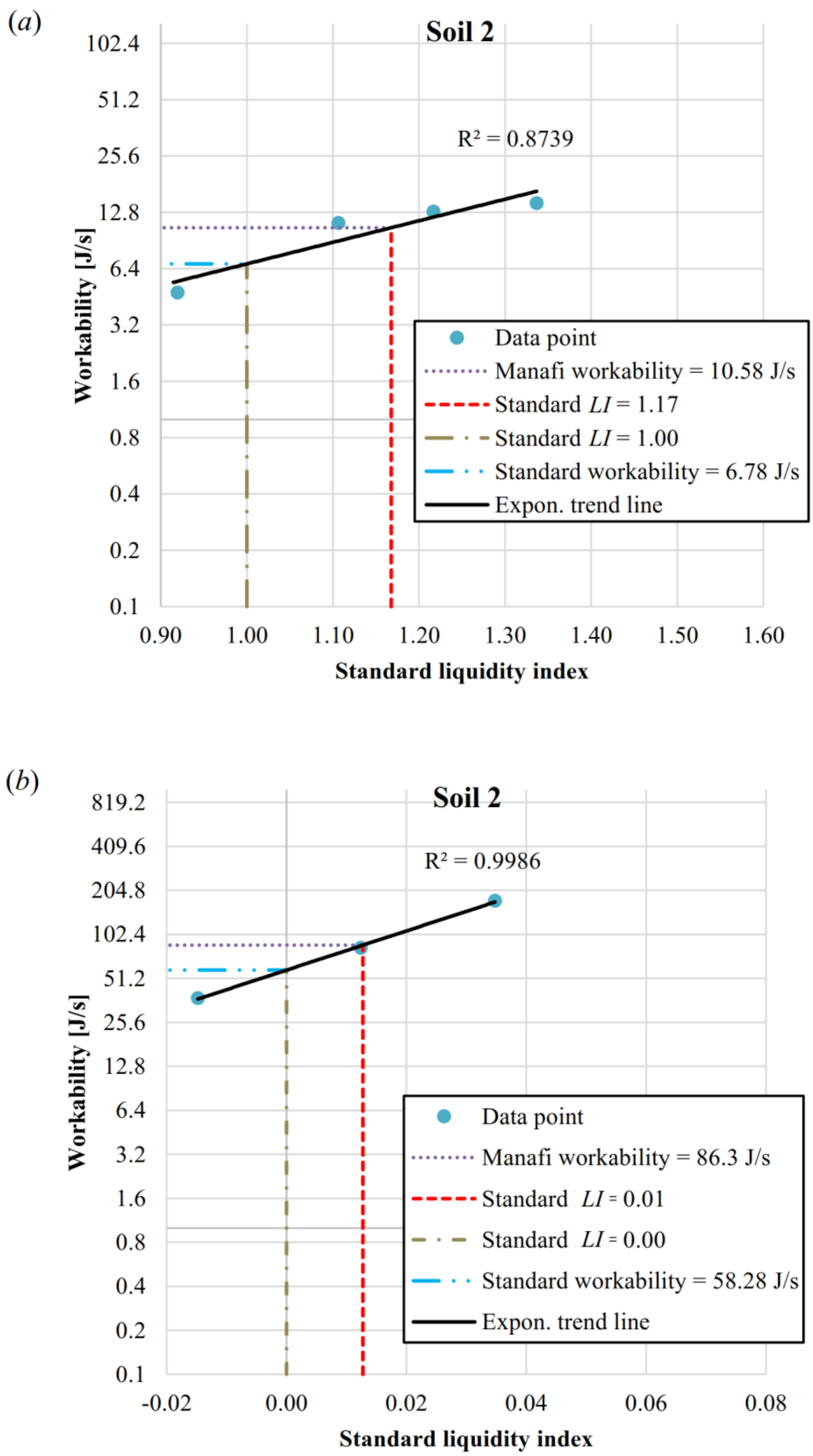


Figure 4-11: Workability graph examples (P_D–Std. *LI*): (*a*) liquid limit determination; (*b*) plastic limit determination.

Table 4-3: Soil consistency calibration and comparison of the *Manafi method* with the standard method for liquid limit determination.

Soil No.	**Fall cone method *LL* (Std. *LL*) [%]**	**Calibrated workability for *LL* (C. W_{LL}) [J/s]**	**Standard *LI* at C.W_{LL}**	***Manafi method LL* (M. *LL*) [%]**	**(M. *LL* – Std. *LL*) [%]**
1	30.04	10.58	1.14	32.50	2.46
2	43.65	10.58	1.17	47.93	4.28
3	89.30	10.58	0.91	83.27	-6.02
4	45.13	10.58	1.00	45.14	0.01
5	63.10	10.58	0.93	59.78	-3.32
6	109.63	10.58	0.90	102.62	-7.01
7	87.72	10.58	0.95	84.48	-3.24
		Average =	1.00	Average =	-1.83
				Min =	-7.01
				Max =	4.28
				Standard deviation =	4.24

Table 4-4: Soil consistency calibration and comparison of the *Manafi method* with the standard method for plastic limit determination.

Soil No.	**Thread rolling method *PL* (Std. *PL*) [%]**	**Calibrated workability for *PL* (C. W_{PL}) [J/s]**	**Standard *LI* at C. W_{PL}**	***Manafi method PL* (M. *PL*) [%]**	**(M. *PL* – Std. *PL*) [%]**
1	12.63	86.30	-0.02	12.30	-0.33
2	18.12	86.30	0.01	18.45	0.33
3	24.08	86.30	0.06	27.94	3.86
4	18.27	86.30	-0.07	16.34	-1.93
5	18.08	86.30	0.04	19.96	1.88
6	36.11	86.30	-0.04	33.41	-2.70
7	23.11	86.30	0.01	23.89	0.79
		Average =	0.00	Average =	0.27
				Min =	-2.70
				Max =	3.86
				Standard deviation =	2.23

4.6 Validation of the *Manafi Method*

The proposed method is also validated by evaluating the results obtained by the plasticity determination methods. Figure 4-12 compares the results obtained by the proposed and standard methods within the range of the investigated limit states of the soils. The coefficient of correlation (R) is a statistical measure for the strength of a relationship between variables (Mendenhall and Sincich 2016). The coefficient of determination (R^2) is another measure of the degree of correlation. Values of R^2 close to unity demonstrate strong correlations between the results obtained by the investigated methods.

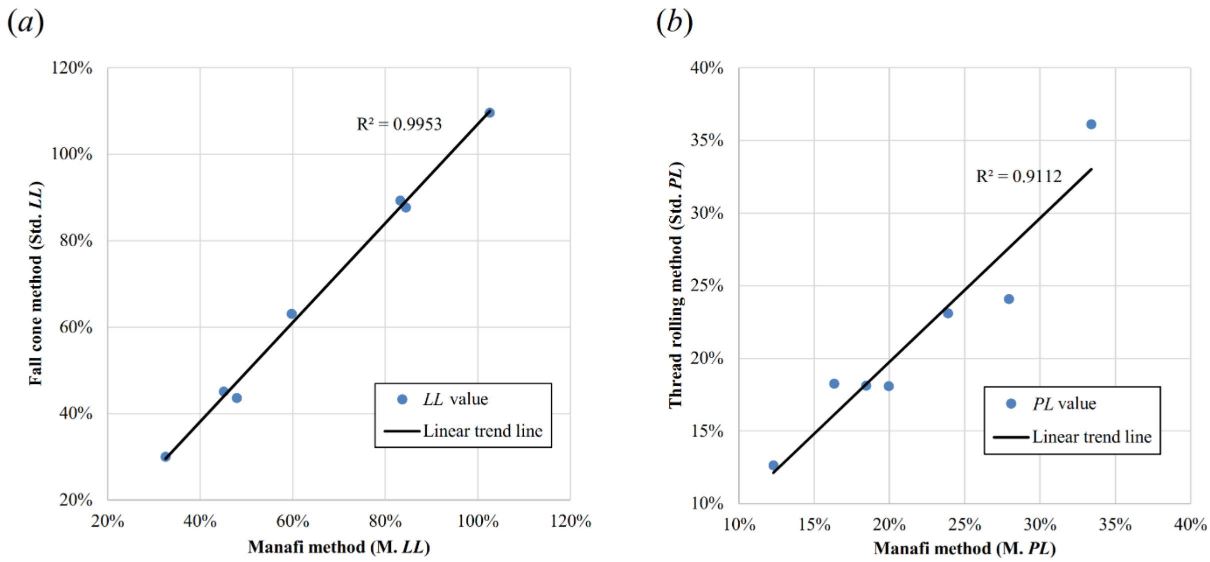


Figure 4-12: Comparison between results obtained by the *Manafi method* and the standard methods: (*a*) liquid limit; (*b*) plastic limit.

In addition, paired two-sample *t*-tests are performed for each limit state to determine the population mean intervals by different methods. Accordingly, the normal distributions of the data are examined by normal probability plots of the data. The values of R^2 shown in Figure 4-13 confirm that the data are normally distributed. Consequently, the results of the paired samples *t*-test for the *LL* and *PL* are presented in Table 4-5, considering Tables 4-3 and 4-4.

The population differences between the proposed and the standard methods, with 95% of confidence, are within the lower and upper limits of the mean interval, as presented in Table 4-5. The small population mean intervals demonstrate high interdependency of the results obtained by the proposed and standard methods. In other words, the proposed method is a reliable alternative to the present standard methods, at least for the range of soils tested.

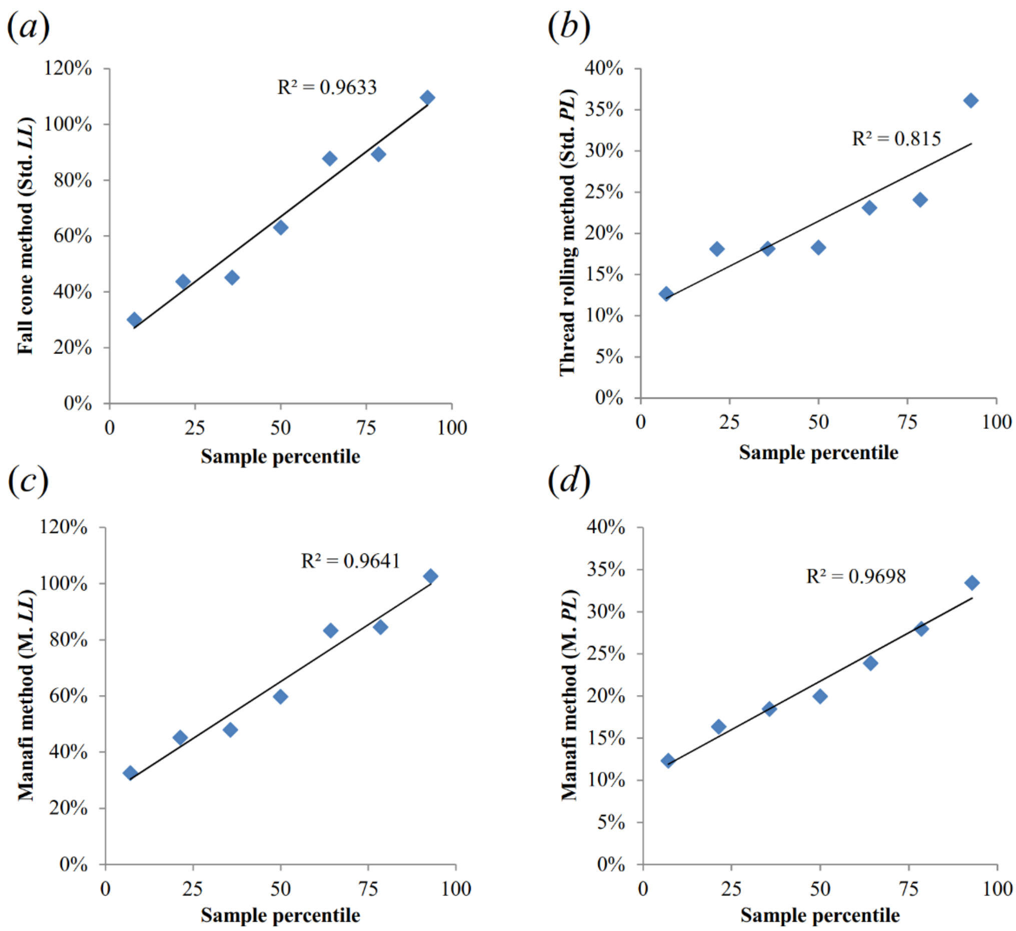


Figure 4-13: Normal probability plots of different methods: (*a*) fall cone method; (*b*) thread rolling method; (*c*) *Manafi method* for liquid limit; (*d*) *Manafi method* for plastic limit.

Table 4-5: Paired samples *t*-test results for *LL* and *PL*.

Statistics	**Liquid limit**	**Plastic limit**
Count	7	7
Average difference	-1.83	0.27%
Min difference	-7.01%	-2.70%
Max difference	4.28%	3.86%
Standard deviation	4.24%	2.23%
Confidence interval	95%	95%
Standard error	1.60%	0.84%
Degree of freedom	6	6
Critical ±t	2.447	2.447
Population mean interval (μ) lower limit	-5.75%	-1.79%
Population mean interval (μ) upper limit	2.09%	2.33%

It is understood that the term '*precision*' has several definitions in the literature. Here, the term '*precision*' implies "the closeness of agreement between independent test results obtained under stipulated conditions" (ASTM E177-14 2014). Accordingly, Soil 2 is selected to compare the precision of the standard and proposed methods. Because Soil 2 is categorised as an Intermediate-plasticity Clay (CI), it would be a suitable representative soil of the studied plasticity range from CL to CE. Therefore, the limit states of Soil 2 are determined five times by the standard and proposed methods, as presented in Table 4-6.

Table 4-6: Precision test results of the standard and *Manafi methods* for *LL* and *PL*.

Soil 2	**Fall cone method *LL* (Std. *LL*) [%]**	***Manafi method LL* (M. *LL*) [%]**	**Thread rolling method *PL* (Std. *PL*) [%]**	***Manafi method PL* (M. *PL*) [%]**
Trial 1	43.65	47.93	18.12	18.45
Trial 2	45.36	43.07	15.05	17.79
Trial 3	48.93	48.88	15.13	18.02
Trial 4	47.93	48.35	15.32	17.55
Trial 5	49.86	48.31	16.02	17.52
Average =	47.14	47.30	15.93	17.87
Range =	6.21	5.81	3.07	0.93
Standard deviation =	2.58	2.39	1.28	0.38
Standard error =	1.15	1.07	0.57	0.17

As shown in Table 4-6, the standard deviations from the proposed method are less than the corresponding values from the standard methods. In addition, as shown in Figure 4-14, the shorter ranges and interquartiles of the proposed method demonstrate reasonable estimations and a reduced data spread of the proposed method compared to the standard methods. Therefore, the proposed method offers a higher degree of precision for the determinations of the limit states than that provided by the conventional methods for the studied soil.

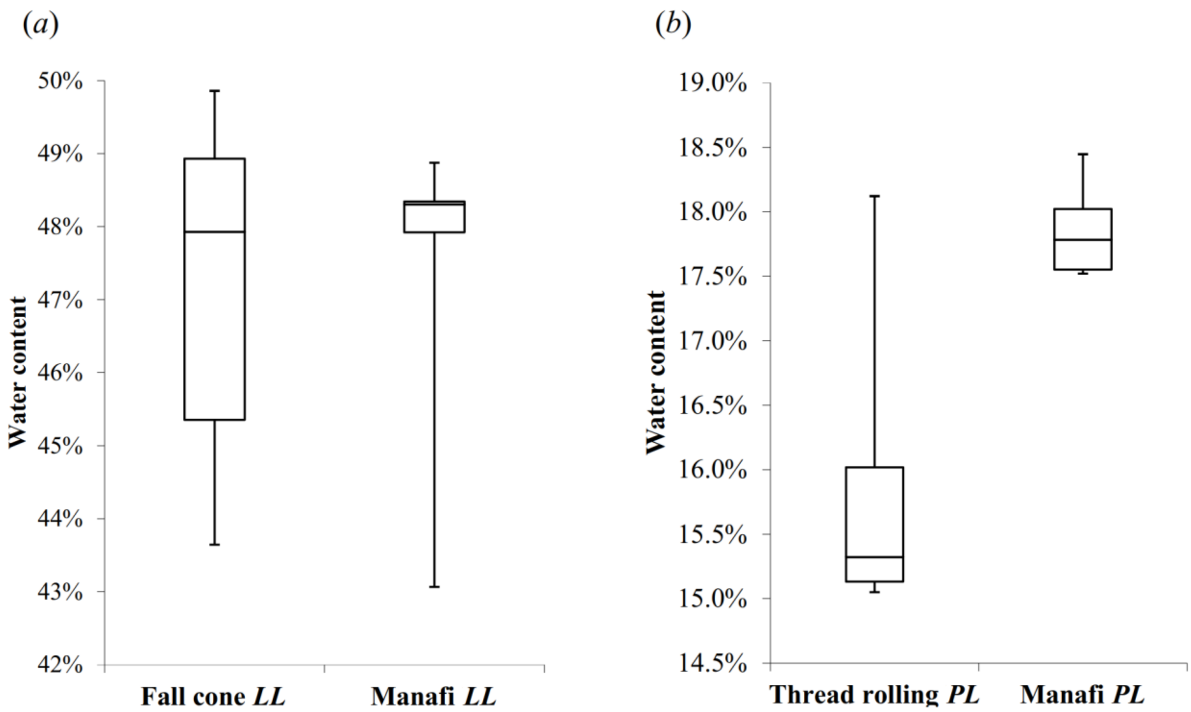


Figure 4-14: Box and whisker charts of precision test results: (*a*) LL determination; (*b*) PL determination.

The higher precision of the proposed method can also be evidenced by the trend of the results obtained within the plasticity range of the soil samples. Assuming a normal distribution of plasticity for natural soils for the studied plasticity range (Manafi 2019), the more normally distributed data set obtained by each method can be considered as the more precise method. Considering the R^2 values of the normal probability plots in Figure 4-13, the higher the R^2 value in the plots, the more normally distributed are the data sets. In other words, a higher R^2 value indicates that more consistent results can be obtained by the method. According to the values presented in Figure 4-13, the R^2 values of the proposed method exceed the counterparts obtained by the standard methods for both limit states. Hence, the proposed method provides more consistent results within the studied range of the soils' plasticity compared to the conventional methods. Therefore, more precise and repeatable results are expected to be obtained by the proposed method.

4.7 Discussion

Considering the results obtained in this study, the greatest differences between the results gained by the proposed and standard methods are in Soils 6 and 3. According to Tables 4-3 and

4-4, the greatest differences are 7.01% and 3.86% in water content for the *LL*s and *PL*s, respectively. However, considering the variability of the present standard methods (Manafi 2019), these differences are considered negligible. According to Figure 4-7, major portions of Soils 6 and 3 consists of very fine-grained particles; clay (47.7% and 55.1%, respectively) and silt (52.3% and 31.0%, respectively). These soils also have the highest liquid and plastic limits among the soils tested, which are categorised as CE and CV, respectively, according to BS 5930 (2015). These soils are usually characterised as problematic soils, and their plasticity determinations are variable using the standard methods (Manafi 2019). Hence, such discrepancies observed between the results obtained by the standard and proposed methods for these soils are understandable.

Although studying plenty of soils provides a robust interpretation of the results, the mineralogy, type and range of soil plasticity are more critical than the number of samples for validating the newly proposed method. Accordingly, seven different soils have been studied, considering the study limitations. As a result, the proposed method successfully provides an alternative soil plasticity test for the studied soil samples with different mineralogy and plasticity ranges. In addition, soils with different PSDs and the same mineralogy (Soils 2, 5, and 7) show different plasticity, which highlights the effect of PSD for reconsidering the maximum particle size (425 microns) in soil plasticity determinations.

It is infeasible to discuss the accuracy (as defined by ASTM D653-14 2014) of the plasticity determination test methods, as there is no comprehensively accepted reference value or reference soil material by which to compare the test results. However, the proposed test method and apparatus are designed based on the definition of the soil consistency by examining the relative ease of soil deformation in the test. Hence, the limit states of the soils are determined based on the particular levels of workability with the same consistencies. Therefore, the test results can be considered as accurate determinations and benchmarks for further investigations.

The proposed test involves, and hence examine, the complete volume of the soil specimen, eliminating the disadvantage of assessing only a subset of the soil specimen, as is the case with the standard methods. Examination of the whole volume of the specimen reduces the effect of the specimen's local inhomogeneity on the test results. This advantage enables one to obtain the data points of the workability graphs in only one trial. However, for instance, each data point of the penetration plot of the fall cone test requires at least two trials (BS EN 1377-2 1990;

AS 1289.3.9.1 2015). Alternatively, in the case of the PL determination by the standard methods, the test is not considered to be complete until the results of the water content determination of two trials of the thread rolling tests are within a moisture content of 0.5 % (BS EN 1377-2 1990), otherwise, the test needs to be repeated. Therefore, the number of trials in the standard methods depends on the operator's proficiency and the apparatus calibration. Consequently, the proposed method can significantly reduce the time required for the testing. For instance, a typical LL extrusion test, which involves filling the mould with soil paste, assembling the apparatus, penetration, data acquisition, cleaning the plunger, washing the mould, and preparation for the following extrusion is achieved within about 11 min. Whereas, a typical fall cone test based on AS 1289.3.9.1 (2015) for two consecutive trials of cone penetration involving filling the cup with soil paste, assembling the apparatus, cone penetration, remixing the soil paste, cleaning the cone, washing the cup, and preparation for the subsequent penetration is achieved within about 15 min. It should be noted that the typical test time by the fall cone method significantly increases if the two consecutive penetration readings differ more than 1 mm (AS 1289.3.9.1 2015), as more trials are required. Considering the requirement of the minimum four penetration values for the LL determination, the proposed method may save a significant time for at least 27% more than the standard fall cone method.

The proposed workability method is compatible with both the stress and strain controlled loading systems as it determines the workability parameter. The current apparatus is designed to provide a stress-controlled loading system. In other words, it has been tried to apply a constant force (F_E) by a pneumatic actuator via delivering a constant air pressure. However, the performance of the pneumatic actuator in very quick extrusions was limited in providing the perfect constant loading (e.g., Figure 4-9(*b*), $t_D = 0.38$ s). Notwithstanding, this does not affect the method's reliability as the actual load applied to the specimen is obtained from the load-cell mounted above the plunger and used to calculate the deformation work. In addition, the device's performance is almost identical for all soils with the same consistencies. Therefore, the apparatus has created a satisfactory constant soil deformation system for comparing soils' consistency by calculating the workability parameter.

There are two ways for calculation of the deformation work. A quick and straightforward calculation can be obtained by considering the average extrusion force as the value used in Eq. (4-4) and estimating the deformation work with an admissible precision. Otherwise, the accurate calculations should follow as below:

According to Eqs. (4-3), (4-4), and (4-10): $W_{\mathrm{D}} = F_{\mathrm{D}}\Delta x = (F_{\mathrm{E}} - F_{\mathrm{R}})\dfrac{h_{\mathrm{C}}(1 + ER)}{2}$

Therefore: $(F_{\mathrm{E}} h_{\mathrm{C}}) = \int_0^{h_{\mathrm{C}}} F_{\mathrm{E}}\, dh_{\mathrm{C}}$

where $\int_0^{h_{\mathrm{C}}} F_{\mathrm{E}}\, dh_{\mathrm{C}}$ is the area under the extrusion force-penetration curve in the extrusion graph (i.e., Figure 4-9).

To demonstrate the precision of the estimation method in calculating the deformation work, Table 4-7 compares the calculated area under the extrusion curve by both the accurate and estimation strategies. The results show that the approximation method estimates the accurate results with high precisions. Therefore, the average value of the applied load (Ave. F_{E}) is considered as the F_{E}, which also simplifies the workability calculations with decent accuracy.

Table 4-7: Comparing the accurate and estimation methods for calculating the area under the extrusion force-penetration curve.

Calculation	**Around *LL* ***	**Around *PL* ***
Accurate method (numerical integration) [mJ]	1799	28533
Approximation method (Ave. $F_{\mathrm{E}} \times h_{\mathrm{C}}$) [mJ]	1822	28793
Difference [mJ]	23	260
Percentage difference	1.3%	0.9%

* Case study of the trial presented in Figure 4-9.

The reason for choosing the stress-based approach is to reduce the cost of the next version of the *Manafi apparatus*, to be adapted for economic considerations. Several parts of the current device, such as data acquisition and loading systems, have been designed specifically for the research presented herein, which will be unnecessary when the apparatus is deployed operationally for routine soil plasticity determinations. For instance, the pneumatic loading system may be replaced by a static weight system and a lightweight loading frame to create a competitive mobile apparatus.

4.8 Conclusions

In this article, a new test method and apparatus have been examined and calibrated to determine soil consistency, referred to as the *Manafi Method and apparatus*. In this technique, the workabilities of various clay soils have been determined and correlated against their consistency limit states following a novel calibration approach.

The current research has focused on developing a more reliable method for soil plasticity determination based on the concepts of soil consistency and narrowing the limit state boundaries. The experimental results obtained by the bespoke apparatus confirm the validity of the proposed method and demonstrate that it provides more consistent results for the studied soil samples when compared against the present standard methods.

The proposed method has several advantages over the conventional techniques that make it a suitable candidate for the soil plasticity determination:

1. A reliable and consistent approach (i.e., soil consistency determination utilising a combined qualitative and quantitative approach) is incorporated in the test procedure.
2. The test is a relatively rapid. Additionally, both the liquid and plastic limit values are determined by a single apparatus and by adopting a similar testing procedure.
3. The entire volume of the soil specimen is used for the test, which reduces the effect of the sample's local heterogeneity on the test results.
4. The apparatus is relatively simple, quick, and of comparable cost with the existing standard apparatus used for the same purpose.
5. The experimental results have shown that the proposed method is more precise when compared to the standard methods of soil plasticity determination.

4.9 Acknowledgments

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4.10 References

AS 1289.1.1-2001, 2008, "Methods of Testing Soils for Engineering Purposes - Sampling and Preparation of Soils - Preparation of Disturbed Soil Samples for Testing." Standards Australia, Sydney, NSW, Australia.

AS 1289.3.1.1-2009, 2017, "Methods of Testing Soils for Engineering Purposes - Soil Classification Tests - Determination of Liquid Limit of a Soil – Four Point Casagrande Method." Standards Australia, Sydney, Australia.

AS 1289.3.2.1, 2009, "Methods of Testing Soils for Engineering Purposes - Soil Classification Tests - Determination of the Plastic Limit of a Soil." Standards Australia, Sydney, Australia.

AS 1289.3.6.1, 2009, "Methods of Testing Soils for Engineering Purposes - Soil Classification Tests - Determination of Particle Size Distribution of a Soil - Standard Method of Analysis by Sieving." Standards Australia, Sydney, Australia.

AS 1289.3.9.1, 2015, "Methods of Testing Soils for Engineering Purposes - Soil Classification Tests - Determination of the Cone Liquid Limit of a Soil." Standards Australia, Sydney, Australia.

ASTM D653-14, 2014, "Standard Terminology Relating to Soil, Rock, and Contained Fluids." ASTM International, West Conshohocken, PA, doi: 10.1520/D0653-14.

ASTM D4318-17e1, 2017, "Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils." ASTM International, West Conshohocken, PA, USA, doi: 10.1520/D4318-17E01.

ASTM D7928-16e1, 2016, "Standard Test Method for Particle-Size Distribution (Gradation) of Fine-Grained Soils Using the Sedimentation (Hydrometer) Analysis." ASTM International, West Conshohocken, PA, doi: 10.1520/D7928-16E01.

ASTM E177-14, 2014, "Standard Practice for Use of the Terms Precision and Bias in Astm Test Methods." ASTM International, West Conshohocken, PA, doi: 10.1520/E0177-14.

BS 5930, 2015, "Code of Practice for Ground Investigations." British Standards Institution, Milton Keynes, UK.

BS EN 1377-2, 1990, "Methods of Test for Soils for Civil Engineering Purposes. Part 2: Classification Tests." British Standards Institution, Milton Keynes, UK.

CEN. E.N. 1997-2, 2007, "Eurocode 7 – Geotechnical Design – Part 2: Ground Investigation and Testing." Comité Européen de Normalisation (CEN), Brussels, Belgium.

Davidson, D. A., 1983, "Problems in the Determination of Plastic and Liquid Limits of Remoulded Soils Using a Drop-Cone Penetrometer." *Earth Surface Processes and Landforms*, Vol. 8, No. 2, pp. 171-175, doi: 10.1002/esp.3290080208.

Dieter, G. E., and Bacon, D., 1988, *Mechanical Metallurgy*, McGraw-Hill, Singapore, p. 751.

Dumbleton, M. J., and West, G., 1970, "The Suction and Strength of Remoulded Soils as Affected by Composition." *RRL Report LR 306*, Road Research Laboratory, Crowthorne, Berkshire, UK.

Fellows, R., and Liu, A., 2015, *Research Methods for Construction*, John Wiley & Sons, Ltd, The Atrium, Southern Gate, Chichester, West Sussex, United Kingdom, p. 302.

Harison, J. A., 1990, "Discussion: Using the Bs Cone Penetrometer for the Determination of the Plastic Limit of Soils." *Géotechnique*, Vol. 40, No. 2, pp. 311-315, doi: 10.1680/geot.1990.40.2.311.

Karlsson, R., 1961, "Suggested Improvements in the Liquid Limit Test, with Reference to Flow Properties of Remoulded Clays." *Proceedings of the 5th International Conference on Soil Mechanics and Foundation Engineering*, Paris, France, pp. 171-184.

Kayabali, K., 2011a, "Assessment of Shear Strength at Consistency Limits - a Reappraisal." *Electronic Journal of Geotechnical Engineering*, Vol. 16 U, pp. 1679-1695.

Kayabali, K., Aktürk, Ö., Fener, M., Dikmen, O., and Harputlugil, F. H., 2015a, "Revisiting the Bjerrum's Correction Factor: Use of the Liquidity Index for Assessing the Effect of Soil Plasticity on Undrained Shear Strength." *Journal of Rock Mechanics and Geotechnical Engineering*, Vol. 7, No. 6, pp. 716-721, doi: 10.1016/j.jrmge.2015.07.003.

Kayabali, K., Aktürk, Ö., Fener, M., Ozkeser, A., Ustun, A. B., Dikmen, O., Harputlugil, F., and Asadi, R., 2016, "Determination of Atterberg Limits Using Newly Devised Mud Press Machine." *Journal of African Earth Sciences*, Vol. 116, pp. 127-133, doi: 10.1016/j.jafrearsci.2016.01.005.

Kayabali, K., and Ozdemir, A., 2013, "Use of Reverse Extrusion Method to Determine Undrained Shear Strength." *Geotech Geol Eng*, Vol. 31, No. 2, pp. 719-727, doi: 10.1007/s10706-013-9621-y.

Kayabali, K., and Tufenkci, O. O., 2007, "A Different Perspective for the Determination of Soil Consistence Limits." *International Symposium on Geotechnical Engineering, Ground Improvement and Geosynthetics for Human Security and Environmental Preservation*, Bangkok, Thailand, pp. 423-432.

Kayabali, K., and Tufenkci, O. O., 2010a, "Determination of Plastic and Liquid Limits Using the Reverse Extrusion Technique." *Geotechnical Testing Journal*, Vol. 33, No. 1, pp. 1-9, doi: 10.1520/GTJ102209.

Kayabali, K., and Tufenkci, O. O., 2010b, "Shear Strength of Remolded Soils at Consistency Limits." *Canadian Geotechnical Journal*, Vol. 47, No. 3, pp. 259-266, doi: 10.1139/T09-095.

Kayabali, K., Üstün, A. B., and Özkeser, A., 2015b, "Refinement of the Reverse Extrusion Test to Determine the Two Consistency Limits." *Bulletin of the Mineral Research and Exploration*, Vol. 2015, No. 150, pp. 131-143, doi: 10.19111/bmre.85667.

Kayabali, K., Yilmaz, N., and Mollamahmutoglu, M., 2015c, *An Alternative Shear Strength Test for Saturated Fine-Grained Soils: Preliminary Results*, IOS Press, Buenos Aires, Argentina, doi: 10.3233/978-1-61499-601-9-407.

Manafi, M. S. G., 2017, "Soil Plasticity Determination Using Manafi Method and Apparatus." MSc Thesis by Research, Trinity College Dublin, Dublin, Ireland.

Manafi, M. S. G., 2019, "Soil Plasticity Variability and Its Effect on Soil Classification." *Geotechnical Testing Journal*, Vol. 42, No. 2, pp. 457-470, doi: 10.1520/GTJ20170273.

Manafi, M. S. G., Deng, A., and Taheri, A., 2022a, "Utilisation of Extrusion Method in Geotechnical Tests: Conception and Theoretical Analysis." *Arabian Journal of Geosciences*, Vol. 15, No. 449, doi: 10.1007/s12517-022-09543-z.

Marinho, F. A. M., and Oliveira, O. M., 2012, "Unconfined Shear Strength of Compacted Unsaturated Plastic Soils." *Proceedings of the Institution of Civil Engineers - Geotechnical Engineering*, Vol. 165, No. 2, pp. 97-106, doi: 10.1680/geng10.00027.

Medhat, F., and Whyte, I., 1986, "An Appraisal of Soil Index Tests." *Geological Society, London, Engineering Geology Special Publications*, Vol. 2, No. 1, pp. 317-323, doi: 10.1144/GSL.1986.002.01.55.

Mendenhall, W. M., and Sincich, T., 2016, *Statistics for Engineering and the Sciences*, CRC Press, Taylor & Francis Group, Boca Raton, p. 1151.

Nagaraj, H., and Sravan, M. V., 2019, *A Review of Factors Affecting Undrained Strength of Fine-Grained Soils at Consistency Limits*, The Icelandic Geotechnical Society, Reykjavik, Iceland, pp. 1-8, doi: 10.32075/17ECSMGE-2019-0472.

Nagaraj, H. B., Sridharan, A., and Mallikarjuna, H. M., 2012, "Re-Examination of Undrained Strength at Atterberg Limits Water Contents." *Geotech Geol Eng*, Vol. 30, No. 4, pp. 727-736, doi: 10.1007/s10706-011-9489-7.

O'Kelly, B. C., 2019, "Reappraisal of Soil Extrusion for Geomechanical Characterisation." *Geotechnical Research*, Vol. 6, No. 4, pp. 265-287, doi: 10.1680/jgere.19.00006.

Prakash, K., 2005, "Discussion of “Plastic Limit, Liquid Limit, and Undrained Shear Strength of Soil—Reappraisal” by Binu Sharma and Padma K. Bora." *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 131, No. 3, p. 402, doi: 10.1061/(ASCE)1090-0241(2005)131:3(402).

Prakash, K., and Sridharan, A., 2006, "Critical Appraisal of the Cone Penetration Method of Determining Soil Plasticity." *Canadian Geotechnical Journal*, Vol. 43, No. 8, pp. 884-888, doi: 10.1139/T06-043.

Sabatini, P. J., Bachus, R. C., Mayne, P. W., Schneider, J. A., and Zettler, T. E., 2002, "Geotechnical Engineering Circular No. 5: Evaluation of Soil and Rock Properties." *Technical Manual Report No. FHWA-IF-02-034*.

Saha, P., 2000, *Aluminum Extrusion Technology*, ASM International, Materials Park, OH.

Sherwood, P. T., 1970, "The Reproducibility of the Results of Soil Classification and Compaction Tests." *Road Research Laboratory Report No. LR 339*, Road Research Laboratory, Crowthorne, Berk.

Sherwood, P. T., and Ryley, M. D., 1968, "An Examination of Cone-Penetrometer Methods for Determining the Liquid Limit of Soils." *TRRL Report LR 233*, Transport and Road Research Laboratory, Crowthome, Berks.

Timar, A., 1974, "Testing Plastic Properties of Cohesive-Type and Intermediate-Type Soils by Extrusion." *Acta Technica Academiae Scientiarum Hungaricae*, Vol. 76, No. 3-4, pp. 355-370.

Vardanega, P., and Haigh, S., 2014, "Some Recent Developments in the Determination of the Atterberg Limits." *Advances in Transportation Geotechnics and Materials for Sustainable Infrastructure*, American Society of Civil Engineers, pp. 48-55, doi: 10.1061/9780784478509.007.

Verástegui-Flores, R. D., and Di Emidio, G., 2014, "Assessment of Clay Consistency through Conventional Methods and Indirect Extrusion Tests." *Applied Clay Science*, Vol. 101, pp. 632-636, doi: 10.1016/j.clay.2014.09.033.

Verástegui-Flores, R. D., and Di Emidio, G., 2015, "Determination of Consistency Limits of Clay by Means of Extrusion Tests." *European Conference on Soil Mechanics and Geotechnical Engineering*, ICE, Edinburgh, UK, pp. 3431-3436, doi: 10.1680/ecsmge.60678.vol6.538.

Vinod, P., Sridharan, A., and Deepa, K. A., 2013, "Remoulded Shear Strength at Plastic and Semi-Solid States." *Proceedings of the Institution of Civil Engineers - Geotechnical Engineering*, Vol. 166, No. 4, pp. 415-424, doi: 10.1680/geng.11.00071.

Whyte, I. L., 1982, "Soil Plasticity and Strength - a New Approach Using Extrusion." *Ground Engineering*, Vol. 15, No. 1, pp. 16-18, 20, 22, 24.

Chapter Five – Effect of Particle Size on Soil Plasticity and Soil Classification

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5.1 Abstract

Soil plasticity is one of the critical index properties for soil classification. Although the full range of particle sizes affects soil consistency, the conventional test methods and apparatuses are designed based on the fallacy of limiting the plasticity property to the clay size particles of the soil matrix. Nevertheless, current standard methods only study the Atterberg limits of unrepresentative sub-samples containing medium sand particles with less than 425 microns. Recently, a new test method and an apparatus have been proposed as alternative soil plasticity tests, namely the Manafi method and apparatus. The novel device uses the extrusion method to determine a new 'workability' parameter for quantification of soil consistency. The technique can extend soil plasticity tests to soils with coarse particles. Accordingly, several soil samples containing various portions of coarse grains are studied. The results show that the coarse grains significantly affect plasticity and classification. As a result, a revision to the Unified Soil Classification System is proposed.

Keywords: Particle size; Plasticity; Soil classification; Atterberg limits; Soil consistency; Workability; Extrusion method.

Plain Language Summary:

Although the full range of particle sizes affects soil consistency, the conventional test methods and apparatuses only study the unrepresentative sub-samples containing particles of less than 425 microns. However, the novel Manafi Method and Apparatus can enhance the consistency determination method by exploring a more comprehensive range of soils containing coarser particles. Therefore, several soil samples containing various portions of coarse grains are studied. The results show that the coarse grains significantly affect soil plasticity and classification. As a result, a revision to the Unified Soil Classification System is proposed.

5.2 Introduction

It is essential to categorise soils in a descriptive way to address their prevailing behaviour. Accordingly, soils are classified into various groups that present common physical and engineering characteristics (Head 2006; BS 5930 2015; Das and Sobhan 2018). Engineering behaviour of soils is based on both soil particle size and its consistency (Briaud 2013). In fact, consistency is the most significant aggregate property of cohesive soils (Terzaghi et al. 1996; Murthy 2003). Consequently, well-known soil classification systems in geotechnical engineering consider both particle-size distribution and plasticity as criteria [e.g., Unified Soil Classification System (ASTM D2487-17 2017) and American Association of State Highway and Transportation Officials soil classification for construction purposes (AASHTO M 145-91 2008)].

The plastic limit (PL) and liquid limit (LL) define the soil's plastic state. The plasticity index (PI) determines the water content range where the soil behaves plastically and is the difference in water content between LL and PL (ASTM D653-14 2014). The plasticity determination procedures are described in various well-known national and regional standards (e.g., BS EN 1377-2 1990; AS 1289.3.2.1 2009; AS 1289.3.9.1 2015; AS 1289.3.1.1-2009 2017; ASTM D4318-17e1 2017). However, the standard methods have several shortcomings that make the results unreliable in many cases (e.g., Sherwood and Ryley 1968; Sherwood 1970; Davidson 1983; Prakash 2005; Prakash and Sridharan 2006; Vardanega and Haigh 2014; Manafi 2019; Manafi et al. 2022b). This will lead to unrealistic results that may not represent the actual characteristics of the soil in situ. Subsequently, inaccurate classification of soils may result in incorrect ground characterisation and design decisions. It may also cause the inappropriate choice of borrow sites, in addition to financial losses due to transportation costs (e.g., Di Matteo et al. 2016).

Inaccurate results are usually caused by the intrinsic deficiencies of the apparatus and inconsistencies with the operator's ability to perform the tests correctly and in a repeatable manner (Whyte 1982; Sivakumar et al. 2009; Kayabali et al. 2015b; Manafi 2019). Another major problem of the soil plasticity determination by the current standard methods is the inappropriate soil sampling procedure when several specimens are prepared from disturbed samples (e.g., BS EN 1377-2 1990; AS 1289.3.2.1 2009; AS 1289.3.9.1 2015; AS 1289.3.1.1-2009 2017; ASTM D4318-17e1 2017). Although the LL and PL tests are among the standard index and classification tests for soils (USACE EM 1110-1-1804 2001), current plasticity determination tests are often used, directly and indirectly, for determining some of the engineering parameters, especially the shear strength (e.g., Houlsby 1982; Haigh 2012; Haigh et al. 2013). It is well understood, in geotechnical engineering, that disturbed soil samples are inappropriate for determining the engineering parameters of a majority of soils. Nevertheless, heavily disturbed soil samples are used in soil plasticity determinations. Thereupon, several specimens are prepared from entirely disturbed samples, in which the structure of the soil sample is destroyed through the sieving process.

Furthermore, the inappropriate specimen preparation is worsened by removing soil particles coarser than 425 microns. Considering the specimen definition (Head 2006), it is almost unrealistic to correlate the results of Atterberg tests to the in situ soil using such heavily disturbed specimens prepared by the standard methods. The word “specimen” is defined as: “specimen (from Latin specere, to look at):

1. An example of something from which the character of the whole may be inferred.
2. A part of something taken as representative of the whole.
3. A part or portion of some substance serving as an example of the in question thing for purposes of investigation or scientific study”.

Considering the first two meanings, soil specimens studied in the standard plasticity determination tests are not representative of the soil in situ. By considering the third meaning, the standard tests seek to measure the soil plasticity, which is claimed to be the most noticeable physical property of clay soils (Casagrande 1932). Therefore, considering soil particle size ranges (as shown in Figure 5-1), the specimen should be limited to soil particles of less than 2 microns, according to BS EN ISO 14688-1:2002+A1 (2013), or less than 5 microns according to ASTM D422-63(2007)e2 (2007). Nevertheless, the soil specimens studied in the plasticity determination tests, according to BS 5930 (2015), cover the full range of silt up to some portion of medium sand. Nonetheless, there is no guarantee of confining the plastic behaviour of soils to clay size particles. For instance, the colloidal size of quartz grains does not resemble clay behaviour (Terzaghi et al. 1996). In addition, several studies show that soils with small fractions of clay size particles may demonstrate plastic behaviour categorised even in a highly plastic group; or the plasticity index may be increased by reducing the clay fraction of the soil sample (e.g., Polidori 2003, 2007; Kayabali 2011b; Kayabali and Balci 2013). These highlight the credibility of the effect of the coarse fraction of soil on its plasticity. Therefore, although the clay size fraction of the soil significantly affects the plasticity of soil, the mechanism of water absorption in the soil matrix (e.g., Das and Sobhan 2018) should be considered as the criterion for the soil plasticity property. Hence, the plasticity property of a soil should not be solely limited to the clay size particles of that soil.

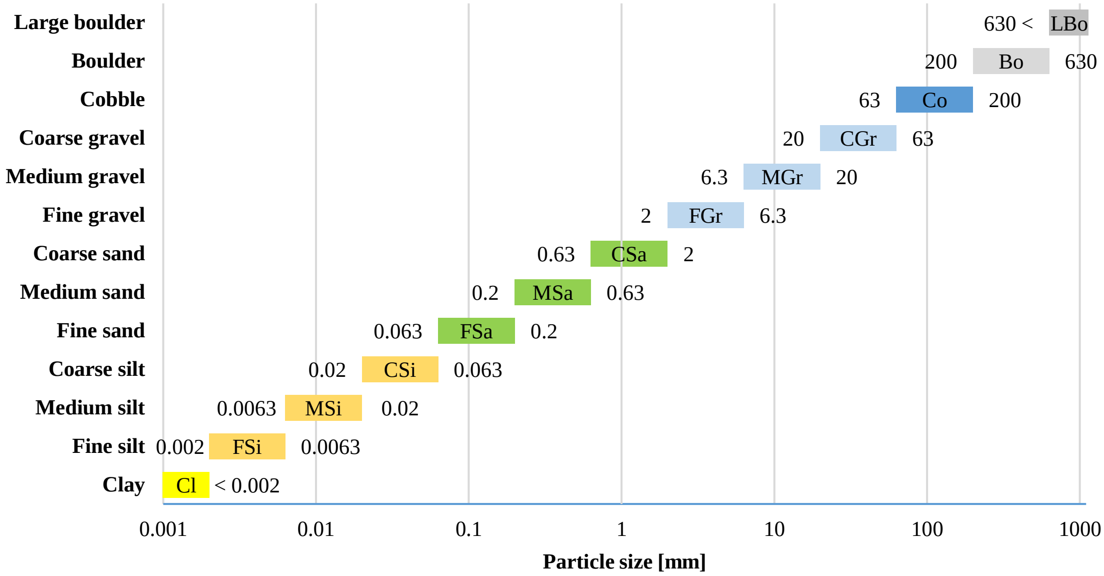


Figure 5-1: Soil classification based on particle size
[according to BS EN ISO 14688-1:2002+A1 (2013)].

Water absorption and soil consistency are usually affected by the full range of soil particles, considering the effects of their specific surface, texture, and structure. However, current standard methods are not designed to consider coarse particles larger than 425 microns. This limitation may lead to an unrealistic determination of the water absorption capacity of the soil to represent field conditions, which can be very different due to a mismatch between the compositions of the soil used in the laboratory testing as compared to that in the field. For instance, large porous stones, or coarse particles with a negative surface electrical charge, may significantly affect the water absorption capacity of the soil. Nevertheless, the effect of coarse particles on soil plasticity cannot be studied by current standard designations. In addition, the conventional apparatuses are not designed to evaluate the desired properties with the inclusion of coarse particles, and therefore, are sensitive to the presence of the coarse particles in the specimen. For instance, the depth of cone penetration in the fall cone method is a function of the surface roughness of the cone and the material (Wood and Wroth 1978), which is directly affected by particle size and shape. As another example, in the PL thread rolling method, the 3 mm diameter of the soil thread limits the maximum particle size of the soil specimen. Therefore, a new alternative test method is required to provide realistic results for characterising soils in situ without modifying their composition.

Recently, Manafi et al. (2022a; 2022b, 2022c) proposed a new alternative test method for soil plasticity determination utilising an extrusion apparatus, as shown in Figure 5-2. The authors introduced the workability parameter, which quantifies the consistency of cohesive soils. Their method removes many limitations of conventional tests, including studying the effect of coarse-grained particles on soil plasticity. Therefore, more realistic soil samples resembling the soil in situ may be studied. This research demonstrates the capability of the new test method in studying the effect of different particle sizes in specimens on soil plasticity determination. In addition, this study attempts to improve the soil sampling process compared to the standard methods by including a coarser particle size range, covering all particles up to coarse sand size, according to BS EN ISO 14688-1:2002+A1 (2013).

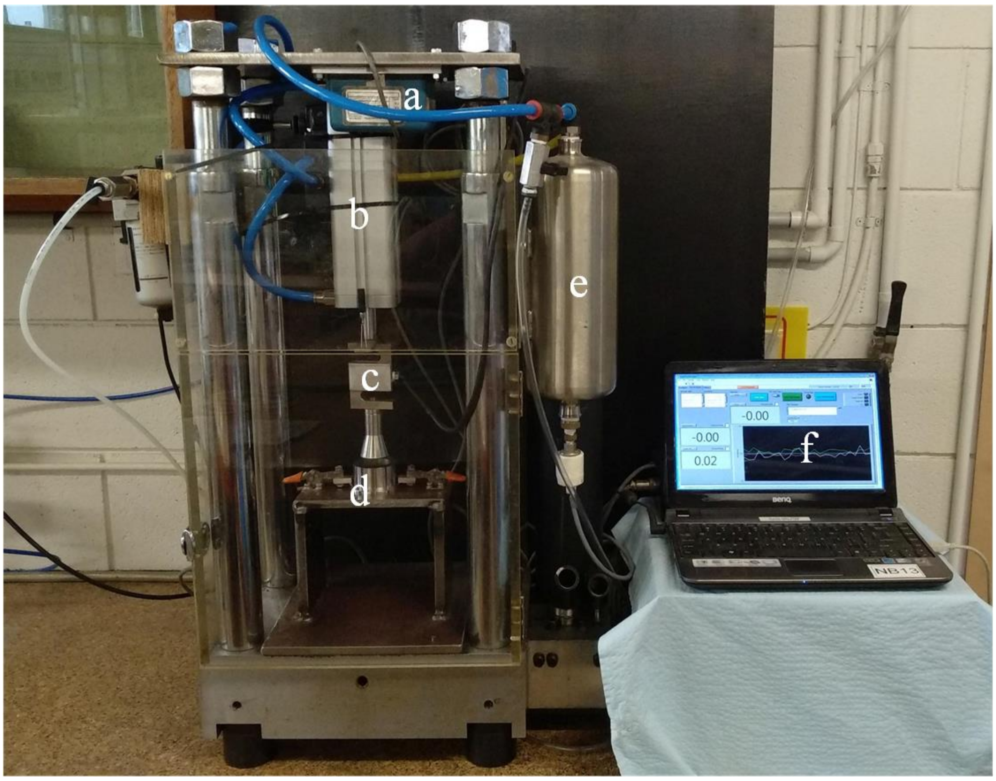


Figure 5-2: Manafi Apparatus (Manafi et al. 2022b). Main components: (a) draw wire displacement sensor; (b) Pneumatic actuator; (c) Load-cell; (d) Mould; (e) Air reservoir; (f) Data acquisition system.

5.3 Laboratory Tests

5.3.1 Soil materials

The soil plasticity determination tests are performed on a natural clay soil sample collected from Port Augusta in South Australia. The standard sample preparation follows the wet preparation method according to AS 1289.1.1-2001 (2008) to prepare the natural soil sample (S1). In order to study the effect of particle size on soil plasticity, several artificial samples, having different particle size distributions (PSDs), are produced. For this purpose, the finest soil sample is prepared by passing the standard soil sample through a 63-micron sieve to obtain a sample containing only silt and clay size particles (S2). The remaining soil samples are prepared progressively by adding proportional amounts of different types of sands, from fine to coarse sands having the PSD curves given in Figure 5-3. Consequently, soil samples covering the full range of sand fractions are obtained (S3, S4, and S5). The PSD curves of the study samples are shown in Figure 5-4. To provide a clear particle size comparison among the soils, each soil is subdivided into its components according to BS EN ISO 14688-1:2002+A1 (2013), and the results are presented in Table 5-1 and Figure 5-5.

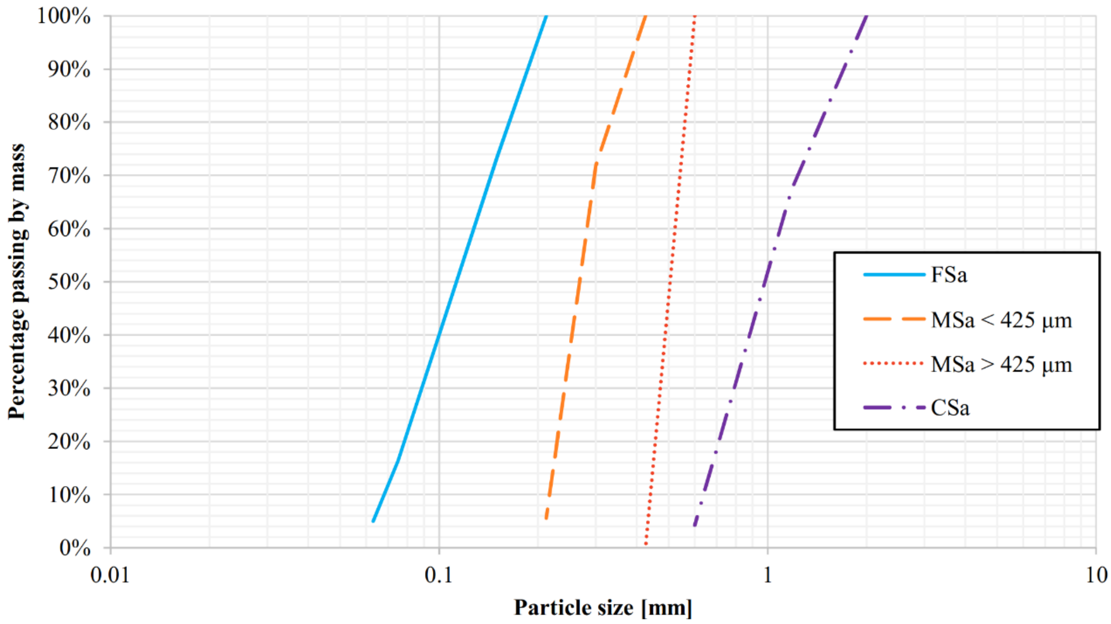


Figure 5-3: Particle size distribution curves of additive sand samples (refer to Figure 5-1 for soil classifications).

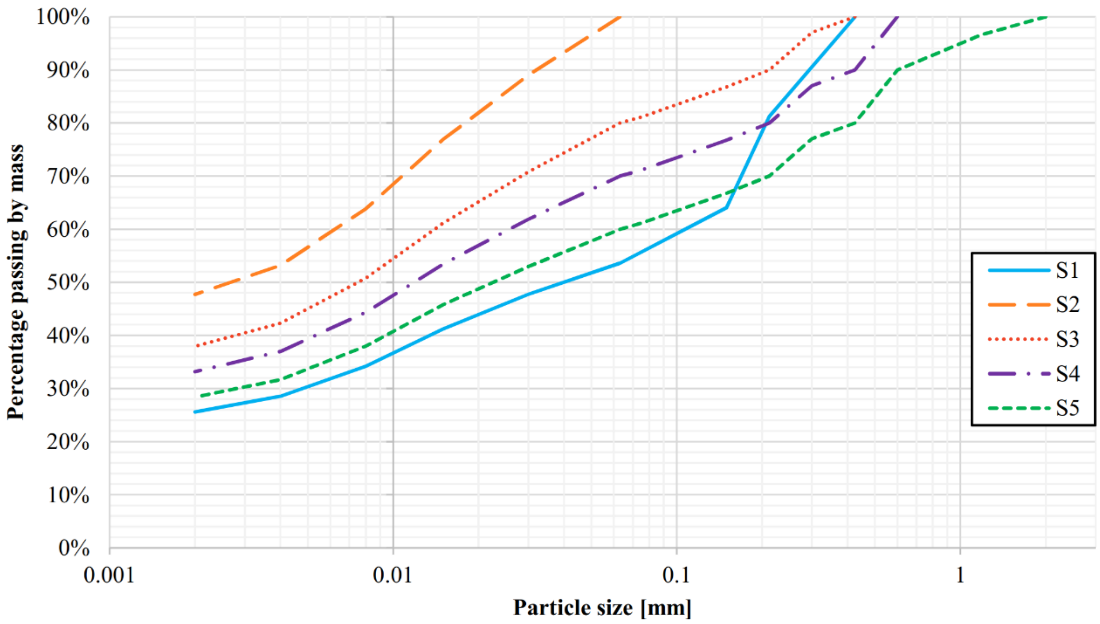


Figure 5-4: Particle size distribution curves of the study samples.

Table 5-1: PSD analysis of soil samples according to BS EN ISO 14688-1:2002+A1 (2013).

Soil Components		S1		S2		S3		S4		S5	
Sand	Coarse sand	46.4%	0.0%	0.0%	0.0%	20.0%	0.0%	30.0%	0.0%	40.0%	10.0%
	Medium sand		18.8%		0.0%		10.0%		20.0%		20.0%
	Fine sand		27.6%		0.0%		10.0%		10.0%		10.0%
Silt	Coarse silt	28.0%	9.0%	52.3%	16.7%	42.1%	15.6%	36.8%	13.7%	31.6%	11.8%
	Medium silt		12.7%		23.7%		17.8%		15.6%		13.3%
	Fine silt		6.3%		11.8%		8.6%		7.5%		6.4%
Clay		25.6%		47.7%		37.9%		33.2%		28.4%	

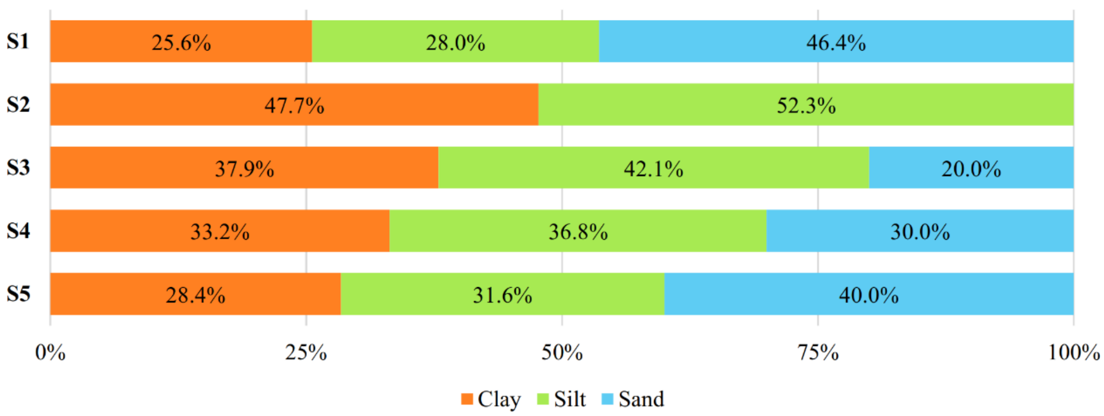


Figure 5-5: PSD comparison of samples based on principal components of clay, silt, and sand portions.

5.3.2 Experiments and results

As BS EN 1377-2 (1990) and Eurocode 7 (CEN. E.N. 1997-2 2007) prefer the fall cone method to the percussion cup method, due to it being less operator-dependent and providing more consistent results, the fall cone method was used for the LL determinations. Therefore, the soil plasticity determinations were conducted based on the standard methods (AS 1289.3.2.1 2009; AS 1289.3.9.1 2015) and the newly proposed alternative test method utilising the soil extrusion technique (Manafi et al. 2022b). The results of the Manafi method are based on the calibrated workabilities of 10.58 J/s and 86.30 J/s for the determination of liquid and plastic limits, respectively (Manafi et al. 2022b). The extrusion data of the soil samples are presented in Tables 5-2 and 5-3. An example of soil plasticity determination by the workability graph is presented in Figure 5-6. As shown in this figure, the limit states are determined by determining the water contents pertinent to the calibrated workabilities for the LL and PL in the workability graphs (Manafi et al. 2022b).

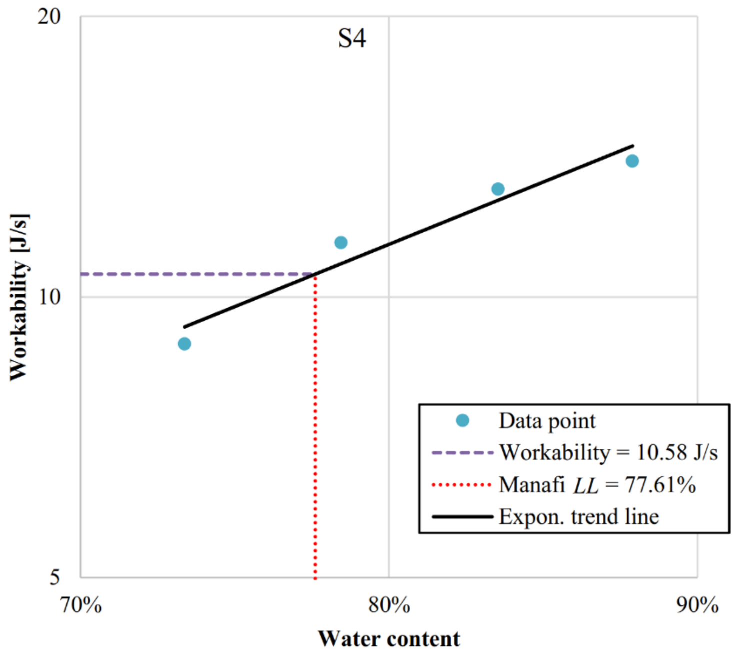
Table 5-2: Extrusion data and workability determinations around the liquid limit state.

	Specimen No.	**Water content [%]**	**Mass of specimen [g]**	**Extrusion force [N]**	**Depth of penetration [mm]**	**Time of extrusion [s]**	**Workability [J/s]**
S1	1	41.59	84.44	36.73	49.60	1.79	4.76
	2	46.36	83.85	28.48	50.78	0.60	11.23
	3	49.18	72.39	23.59	50.76	0.43	12.92
	4	52.24	82.32	22.36	51.23	0.37	14.29
S2	1	93.69	71.75	35.72	50.18	1.14	7.34
	2	101.35	70.25	30.02	50.63	0.59	12.00
	3	112.61	68.57	24.40	51.10	0.39	14.82
	4	120.91	67.83	21.18	51.35	0.33	15.19
S3	1	82.39	72.74	30.40	50.48	0.83	8.63
	2	85.50	71.89	27.03	50.74	0.49	13.02
	3	91.80	70.50	23.13	51.11	0.39	14.03
	4	94.27	70.21	22.70	50.85	0.36	14.82
S4	1	78.45	73.42	26.80	50.41	0.55	11.43
	2	83.54	72.08	23.86	50.70	0.43	13.05
	3	87.89	73.00	22.99	51.24	0.39	13.98
	4	73.38	74.08	31.86	50.90	0.85	8.90
S5	1	71.64	75.07	30.36	44.71	0.51	12.40
	2	73.94	74.90	27.84	40.55	0.43	12.20
	3	78.07	74.49	27.88	46.07	0.48	12.45
	4	84.32	73.21	24.36	49.86	0.40	14.07
	5	89.52	71.70	23.18	49.46	0.35	15.14

Table 5-3: Extrusion data and workability determinations around the plastic limit state.

	Specimen No.	Water content [%]	Mass of specimen [g]	Extrusion force [N]	Depth of penetration [mm]	Time of extrusion [s]	Workability [J/s]
S1	1	19.01	71.13	567.83	39.22	0.14	173.28
	2	18.44	65.92	783.60	36.74	0.38	82.58
	3	17.74	68.00	832.63	31.81	0.77	37.49
S2	1	40.00	60.34	392.15	34.15	0.09	161.93
	2	37.70	57.97	544.63	35.74	0.13	163.09
	3	34.78	58.26	580.67	37.08	0.15	156.40
	4	32.53	53.73	852.10	37.25	0.62	55.80
S3	1	26.14	66.42	551.22	38.67	0.14	165.84
	2	25.50	65.76	553.42	36.69	0.12	184.31
	3	24.21	65.07	737.30	37.00	0.24	123.85
	4	23.95	60.57	814.43	37.01	0.49	67.03
S4	1	22.99	67.29	846.57	37.62	0.66	52.60
	2	23.16	63.59	728.70	37.09	0.28	105.20
	3	21.85	64.79	878.64	37.70	0.93	38.82
	4	23.85	68.22	631.10	38.56	0.17	155.95
S5	1	21.05	66.87	861.48	36.10	0.65	52.14
	2	19.29	63.12	937.43	24.24	2.66	9.31
	3	21.23	66.24	504.88	36.91	0.11	184.46
	4	20.30	66.48	622.22	36.60	0.17	145.94

(*a*)



(*b*)

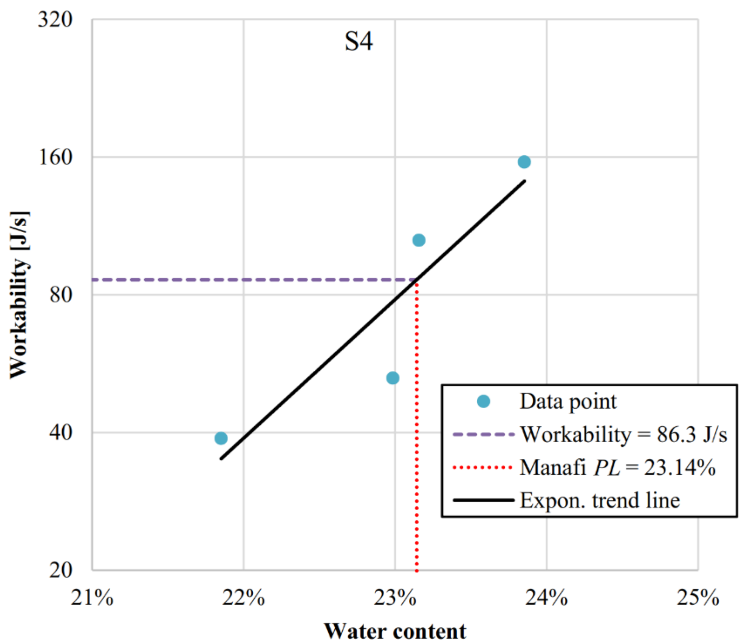


Figure 5-6: Workability graph examples: (*a*) liquid limit determination; (*b*) plastic limit determination.

Although the standard test methods limit the maximum particle size of samples to less than 425 microns, the plasticity determination tests of samples with coarser particles were also conducted using the standard methods to provide a comparison with the results of the Manafi method. Considering the maximum particle size of 2 mm in the samples, it is still possible to perform tests using the standard methods, as the fall cone apparatus is basically a shear strength determination device (Vardanega and Haigh 2014). Likewise, all soil grains are small enough to fit within the 3 mm diameter of the soil thread in the plastic limit determination by the standard method. Consequently, the results obtained by the standard and Manafi methods are presented in Tables 5-4 and 5-5. Comparisons of the results obtained by different methods are also presented in Figure 5-7. The high coefficients of determination (R^2) close to unity imply good correlations between the results obtained by the different methods. In order to provide a more precise comparison between the methods, the test results are presented in two decimal figures.

Table 5-4: Liquid limit determinations and comparison of the Manafi method with the fall cone method.

Soil ID	**Fall cone method *LL* (St. *LL*) [%]**	**Manafi method *LL* (M. *LL*) [%]**	**(M. *LL* – St. *LL*) [%]**
S1	43.65	47.93	4.28
S2	109.63	102.62	-7.01
S3	87.72	84.48	-3.24
S4	77.14	77.62	0.48
S5	67.13	61.60	-5.53
		Average =	-2.20
		Min =	-7.01
		Max =	4.28
		Standard deviation =	4.60

Table 5-5: Plastic limit determinations and comparison of the Manafi method with the thread rolling method.

Soil ID	**Thread rolling method *PL* (St. *PL*) [%]**	**Manafi method *PL* (M. *PL*) [%]**	**(M. *PL* – St. *PL*) [%]**
S1	18.12	18.45	0.33
S2	36.11	33.41	-2.70
S3	23.11	23.89	0.79
S4	20.62	23.14	2.52
S5	18.36	20.77	2.41
		Average =	0.67
		Min =	-2.70
		Max =	2.52
		Standard deviation =	2.12

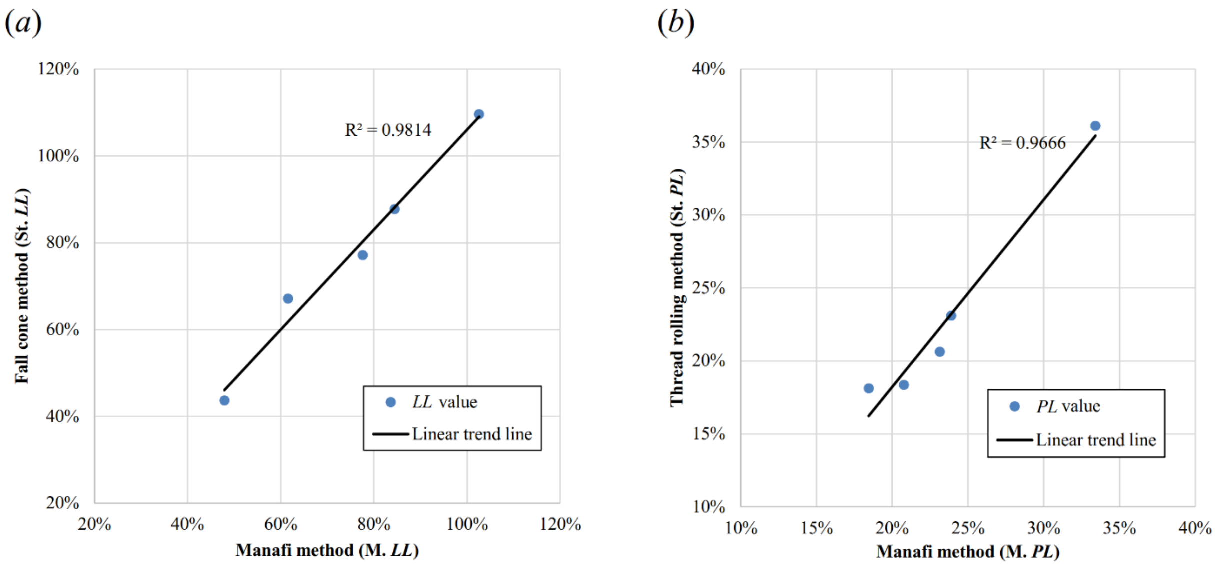


Figure 5-7: Comparison between results obtained by the Manafi method and the standard methods: (*a*) liquid limit; (*b*) plastic limit.

5.4 Discussion

This research attempts to increase the particle size range up to a limit that is still possible to perform the plasticity determination tests by the standard methods. Therefore, the full range of sand sizes according to BS EN ISO 14688-1:2002+A1 (2013) is investigated. For this purpose, the same consistencies of the soil samples are studied (with the workabilities of 10.58 J/s for LL and 86.30 J/s for PL). Figure 5-8 compares the results obtained by different methods as given in Tables 5-4 and 5-5. As shown in the figure, the results obtained by the Manafi and standard methods are similar. The greatest difference between the standard and Manafi methods is in the case of S2, with 7.01% and 2.70% water content differences for *LL* and *PL*, respectively. Figures 5-4 and 5-5 show that S2 has the finest soil particles among the samples and entirely comprises fine-grained soils (52.3% silt and 47.7% clay size particles). In addition, it is categorised as an extremely high-plasticity clay (*LL* = 102.62 %; *PL* = 33.41%; *PI* = 69.21%). Considering the variability of the standard methods in determining this type of soil (Manafi 2019), the observed difference is considered negligible.

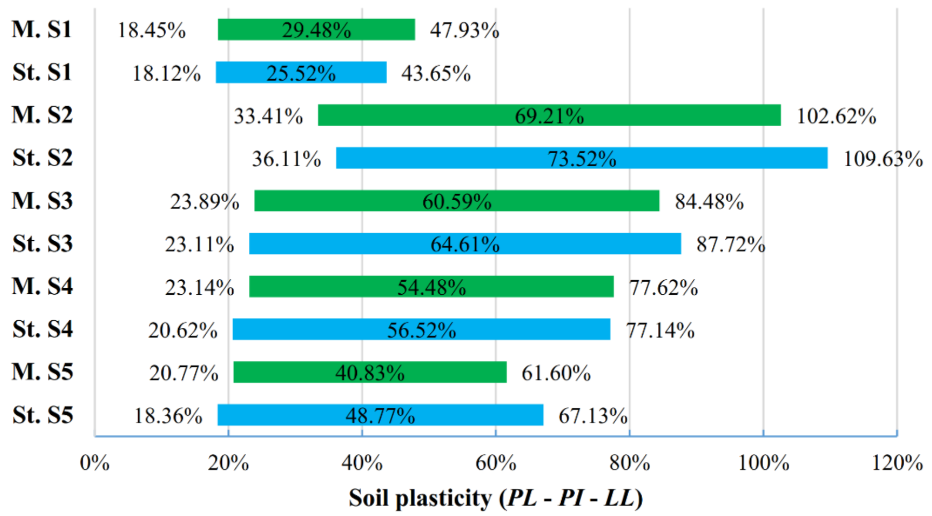


Figure 5-8: Comparison between soil plasticity determinations using the Manafi and standard methods.

It should be considered, to obtain more realistic measurements for characterising in situ soils, the sampling process requires improvement by involving a wider range of particle sizes. This research shows the capability of the proposed method for studying a broader range of particle sizes in the determination of soil plasticity. However, for further investigations, the apparatus and the mould require modifications in proportion to the maximum particle size of the specimen. For instance, larger containers with different extrusion ratios are necessary to extrude the gravel-sized particles in the soil specimen.

Studying various particle sizes of the soil samples with the Manafi method enables analysis of the effect of reduction in the specific surface on the plasticity property by increasing the soil particle sizes. Since the samples are made from a particular soil sample (S1), the type of clay is not changed in the sample production process; therefore, only the particle size distributions affect the soil plasticity determinations.

Specific surface is an effective parameter influencing the plasticity of cohesive soils. Greater negative charges are expected due to larger specific surfaces of the material, and therefore, a stronger water absorption mechanism and higher plasticity (Das and Sobhan 2018). Considering the particle size distribution of samples shown in Figure 5-4, S2 has the highest specific surface and plasticity among the studied soil samples. By progressively increasing the ratio of coarser particles (S2 to S5), the specific surface of the samples reduces, and hence, there is a consequent reduction in the plasticity of the samples (Figure 5-8), which conforms to the expected outcome.

As shown in Figure 5-9, based on the results obtained by the Manafi method, the percentage of sand significantly affects the plasticity property of the soils. Figure 5-9(*a*) shows that, by gradually increasing the sand proportion of the samples, the plasticity of the soils decreases. However, this affects the LL and PL differently, as shown in Figure 5-9(*b*). For instance, the *PL* is more affected by increasing the sand proportion to about 37% compared to the *LL*; after that, the *LL* is more affected.

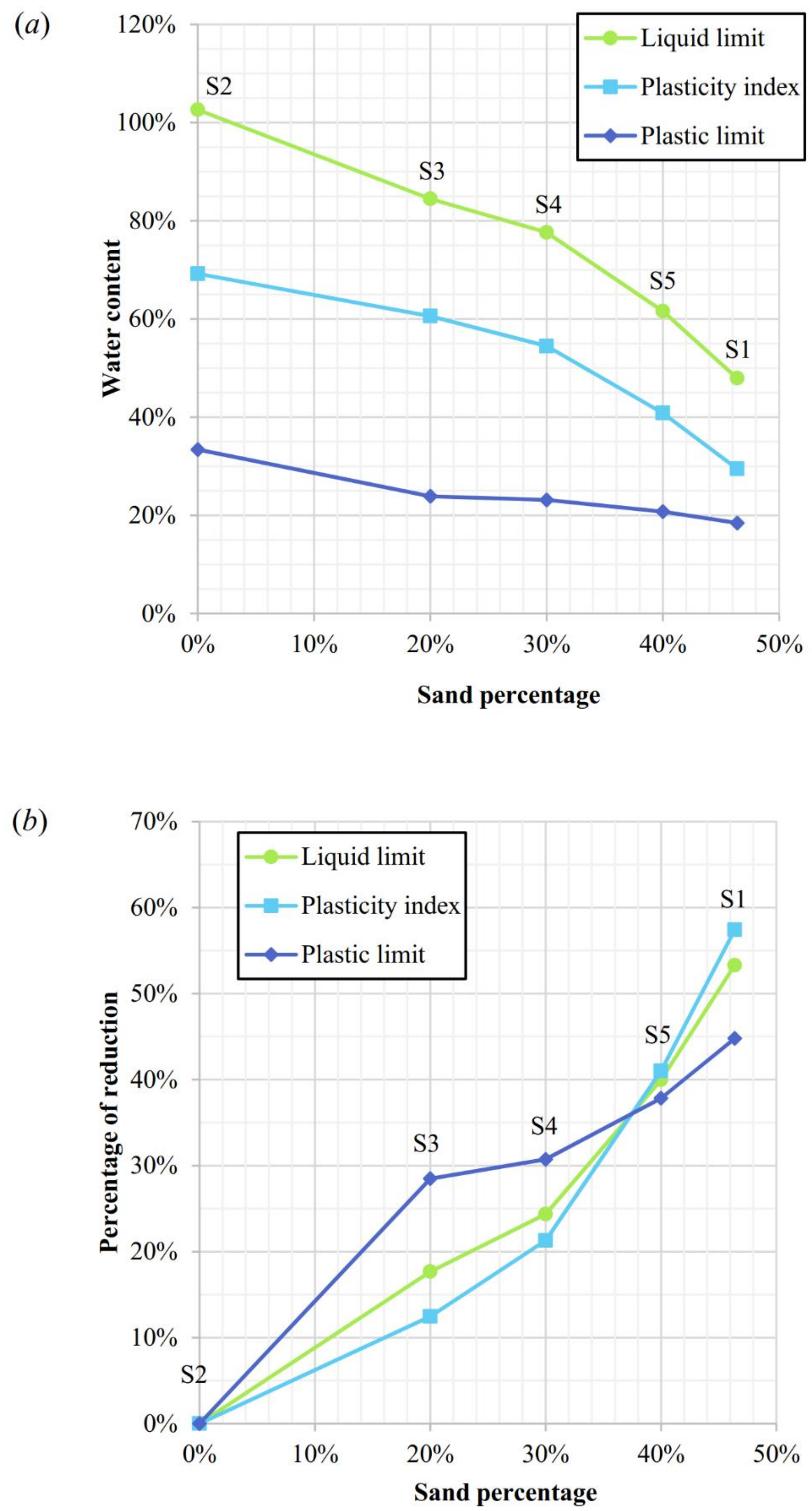


Figure 5-9: The trend of plasticity alteration by changing the PSD and increasing the sand portion of the samples: (*a*) Plasticity parameter values; (*b*) Percentage of reduction in comparison to the soil sample with no sand particles (S2).

As soil plasticity is affected by particle size, the soil classification also changes according to the plasticity chart. Figure 5-10 presents the transition of the soil classification in the plasticity chart as the proportion of sand varies. In this figure, the soil classifications are determined following BS 5930 (2015). As demonstrated in Figure 5-10, the different proportions of particle sizes affect plasticity to varying extents, which consequently affect soil behaviour and hence the soil classifications. By increasing the sand content of the soil samples (S2 to S5), both the *LL* and *PI* of the soils decrease, and therefore, the soil classes shift from Extremely high-plasticity Clay (CE) to High-plasticity Clay (CH).

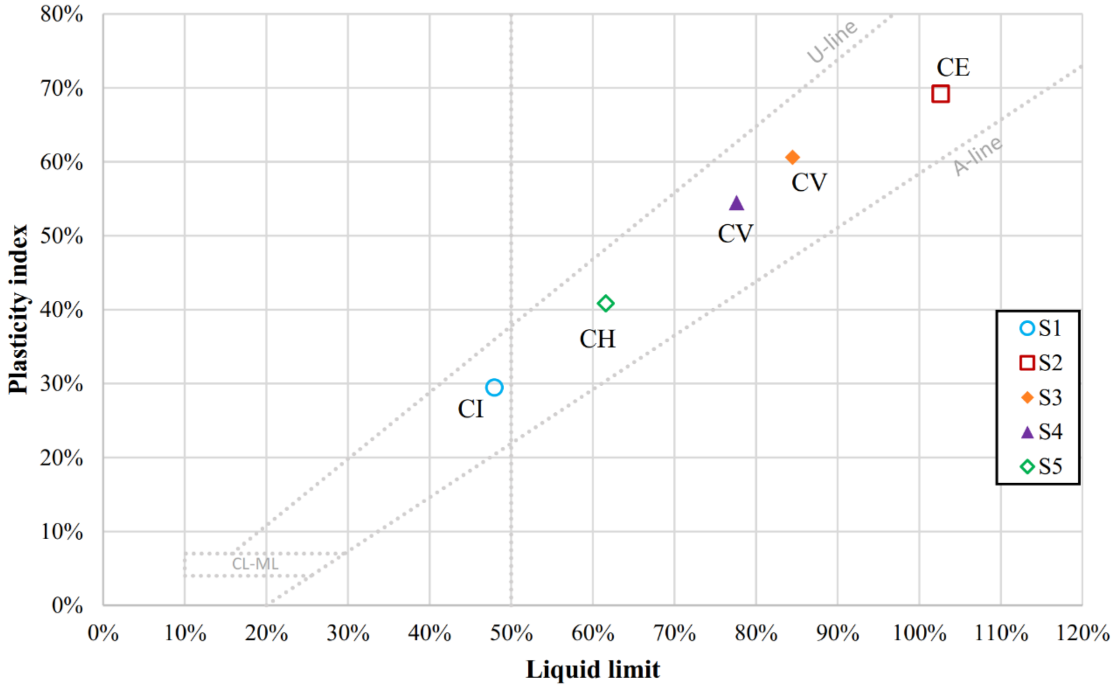


Figure 5-10: Soil plasticity chart and classification.

It should be noted that different combinations of soil particles also affect soil behaviour. For instance, comparing S1 and S5, which have roughly similar sand, silt, and clay proportions (as shown in Figure 5-5), they are categorised in different soil groups (Intermediate-plasticity Clay (CI) and High-plasticity Clay (CH) respectively) with a relatively significant difference in plasticity properties due to the different combinations of sub-particles (as presented in Table 5-1). This shows that removing a significant portion of soil particles in the sampling process by the current standard methods (i.e., particles bigger than 425 microns) leads to a less accurate estimation of the general soil behaviour.

The Unified Soil Classification System (USCS), initially proposed by Casagrande (1948), is now relatively universal in geotechnical engineering. However, there is a contradiction in the categorisation methodology for fine-grained and coarse-grained soils in the USCS (ASTM D2487-17 2017). Initially, the USCS determines whether a major part of the inorganic soil comprises fine-grained or coarse-grained particles. If the majority of the soil sample is coarse-grained, the name of the soil will be initiated by the major portion of the coarse-grained particles based on their size, (S)and or (G)ravel. However, if one considers a soil sample consisting predominantly of fine grains, the soil is not classified based on the particle size of the fine grains (silt or clay) but is categorised based on the plasticity of the soil. Therefore, if the soil of interest falls in a section above the ‘A-line’ on the plasticity chart, it will be categorised as clay; otherwise, it will be classified as silt. It is understood that this is undertaken primarily for practical reasons, as the accurate determination of the sizes of the fine grains is not as straightforward as that for the coarse grains. However, in the present study, although the major portion of the fine grains in all soil samples comprises silt-sized particles, all the soils are incorrectly categorised as clay soils. This is misleading in soil classification and affects the expected general behaviour of the soil. As a practical suggestion, the hydrometer test may be used to detect the major component of the fine-grained soils based on particle size alongside a modified plasticity chart to determine the plasticity level.

This research has demonstrated the effect of the variation of soil particles of less than 2 mm on soil plasticity. Larger particles, such as gravels, can also affect the plasticity of the soil. Hence, further research on this topic is suggested. For instance, the texture of the coarse particles and the structure of the soil matrix might significantly influence the water absorption property of the soil. However, none of these parameters is measurable by the current standard methods due to the inappropriate sampling and test procedures. Therefore, it is suggested that soil classification by the current standard methods be revised by undertaking further research, including larger particle sizes for soil plasticity determination.

5.5 Conclusions

Soil plasticity determination is a critical test for the classification of soils. The standard plasticity test methods do not consider the full range of soil particles in the sampling process. This will lead to unrealistic results that may not represent the actual characteristics of the in situ soil.

Current standard methods are not designed to include the effect of coarse particles (bigger than 425 microns) on the plasticity of soils. However, the new alternative test method proposed by Manafi et al. (2022b) enables one to study a broader range of soil particles in the soil plasticity determination. In this research work, the effect of the full range of sand particle sizes on the plasticity of a soil sample has been investigated. The results showed a significant effect of the different particle sizes and combinations of soil grains on the plasticity of the soil samples, which led to different soil classifications, from extremely plastic to intermediate plastic clays. It is also highly expected that similar effects on the soil plasticity by gravel size particles will be observed, considering the texture and structure of the coarse grains. Therefore, further investigations are planned to consider the effect of all particles on soil consistency. This will lead to the further development of alternative plasticity test methods and apparatuses.

It is suggested the USCS be revised from two aspects. First, the need for considering a more realistic soil plasticity property covering the full range of soil particles. Second, reconsidering the classification of fine grains based on the particle size as well.

5.6 Acknowledgments

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5.7 References

AASHTO M 145-91, 2008, "Standard Specification for Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes." American Association of State Highway and Transportation Officials (AASHTO), Washington, D.C.

AS 1289.1.1-2001, 2008, "Methods of Testing Soils for Engineering Purposes - Sampling and Preparation of Soils - Preparation of Disturbed Soil Samples for Testing." Standards Australia, Sydney, NSW, Australia.

AS 1289.3.1.1-2009, 2017, "Methods of Testing Soils for Engineering Purposes - Soil Classification Tests - Determination of Liquid Limit of a Soil – Four Point Casagrande Method." Standards Australia, Sydney, Australia.

AS 1289.3.2.1, 2009, "Methods of Testing Soils for Engineering Purposes - Soil Classification Tests - Determination of the Plastic Limit of a Soil." Standards Australia, Sydney, Australia.

AS 1289.3.9.1, 2015, "Methods of Testing Soils for Engineering Purposes - Soil Classification Tests - Determination of the Cone Liquid Limit of a Soil." Standards Australia, Sydney, Australia.

ASTM D422-63(2007)e2, 2007, "Standard Test Method for Particle-Size Analysis of Soils." ASTM International, West Conshohocken, PA, doi: 10.1520/D0422-63R07E02.

ASTM D653-14, 2014, "Standard Terminology Relating to Soil, Rock, and Contained Fluids." ASTM International, West Conshohocken, PA, doi: 10.1520/D0653-14.

ASTM D2487-17, 2017, "Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)." ASTM International, West Conshohocken, PA, doi: 10.1520/D2487-17.

ASTM D4318-17e1, 2017, "Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils." ASTM International, West Conshohocken, PA, USA, doi: 10.1520/D4318-17E01.

Briaud, J. L., 2013, *Geotechnical Engineering: Unsaturated and Saturated Soils*, John Wiley & Sons, Hoboken, New Jersey, p. 998 pages.

BS 5930, 2015, "Code of Practice for Ground Investigations." British Standards Institution, Milton Keynes, UK.

BS EN 1377-2, 1990, "Methods of Test for Soils for Civil Engineering Purposes. Part 2: Classification Tests." British Standards Institution, Milton Keynes, UK.

BS EN ISO 14688-1:2002+A1, 2013, "Geotechnical Investigation and Testing - Identification and Classification of Soil - Part 1: Identification and Description." British Standards Institution, Milton Keynes, UK.

Casagrande, A., 1932, "Research on the Atterberg Limits of Soils." *Public roads*, Vol. 13, No. 8, pp. 121-136.

Casagrande, A., 1948, "Classification and Identification of Soils." *Transactions of the American Society of Civil Engineers*, Vol. 113, pp. 901-930.

CEN. E.N. 1997-2, 2007, "Eurocode 7 – Geotechnical Design – Part 2: Ground Investigation and Testing." Comité Européen de Normalisation (CEN), Brussels, Belgium.

Das, B. M., and Sobhan, K., 2018, *Principles of Geotechnical Engineering*, Cengage Learning, Australia, p. 819.

Davidson, D. A., 1983, "Problems in the Determination of Plastic and Liquid Limits of Remoulded Soils Using a Drop-Cone Penetrometer." *Earth Surface Processes and Landforms*, Vol. 8, No. 2, pp. 171-175, doi: 10.1002/esp.3290080208.

Di Matteo, L., Dragoni, W., Cencetti, C., Ricco, R., and Fucsina, A., 2016, "Effects of Fall-Cone Test on Classification of Soils: Some Considerations from Study of Two Engineering Earthworks in Central Italy." *Bulletin of Engineering Geology and the Environment*, Vol. 75, No. 4, pp. 1629-1637, doi: 10.1007/s10064-015-0808-8.

Haigh, S. K., 2012, "Mechanics of the Casagrande Liquid Limit Test." *Canadian Geotechnical Journal*, Vol. 49, No. 9, pp. 1015-1023, doi: 10.1139/t2012-066.

Haigh, S. K., Vardanega, P. J., and Bolton, M. D., 2013, "The Plastic Limit of Clays." *Geotechnique*, Vol. 63, No. 6, pp. 435-440, doi: 10.1680/geot.11.P.123.

Head, K. H., 2006, *Manual of Soil Laboratory Testing, Volume 1: Soil Classification and Compaction Tests*, Whittles Publishing, Scotland, UK.

Houlsby, G. T., 1982, "Theoretical Analysis of the Fall Cone Test." *Géotechnique*, Vol. 32, No. 2, pp. 111-118, doi: 10.1680/geot.1982.32.2.111.

Kayabali, K., 2011b, "Determination of Consistency Limits: A Comparison between -#40 and -#200 Materials." *Electronic Journal of Geotechnical Engineering*, Vol. 16 T, pp. 1547-1561.

Kayabali, K., and Balci, M. C., 2013, "An Appraisal of the Problems Related to the Classification of Fine-Grained Soils." *Electronic Journal of Geotechnical Engineering*, Vol. 18 K, pp. 2251-2262.

Kayabali, K., Üstün, A. B., and Özkeser, A., 2015b, "Refinement of the Reverse Extrusion Test to Determine the Two Consistency Limits." *Bulletin of the Mineral Research and Exploration*, Vol. 2015, No. 150, pp. 131-143, doi: 10.19111/bmre.85667.

Manafi, M. S. G., 2019, "Soil Plasticity Variability and Its Effect on Soil Classification." *Geotechnical Testing Journal*, Vol. 42, No. 2, pp. 457-470, doi: 10.1520/GTJ20170273.

Manafi, M. S. G., Deng, A., and Taheri, A., 2022a, "Utilisation of Extrusion Method in Geotechnical Tests: Conception and Theoretical Analysis." *Arabian Journal of Geosciences*, Vol. 15, No. 449, doi: 10.1007/s12517-022-09543-z.

Manafi, M. S. G., Deng, A., Taheri, A., Jaksa, M. B., and HB, N., 2022b, "Determining Soil Plasticity Utilising Manafi Method and Apparatus." *Geotechnical Testing Journal*, Vol. 45, No. 4, p. 22, doi: 10.1520/GTJ20210235.

Manafi, M. S. G., Deng, A., Taheri, A., Jaksa, M. B., and HB, N., 2022c, "A New Approach to Soil Consistency Determination."

Murthy, V. N. S., 2003, *Geotechnical Engineering: Principles and Practices of Soil Mechanics and Foundation Engineering*, Marcel Dekker, New York.

Polidori, E., 2003, "Proposal for a New Plasticity Chart." *Géotechnique*, Vol. 53, No. 4, pp. 397-406, doi: 10.1680/geot.2003.53.4.397.

Polidori, E., 2007, "Relationship between the Atterberg Limits and Clay Content." *Soils and Foundation*, Vol. 47, No. 5, pp. 887-896, doi: 10.3208/sandf.47.887.

Prakash, K., 2005, "Discussion of “Plastic Limit, Liquid Limit, and Undrained Shear Strength of Soil—Reappraisal” by Binu Sharma and Padma K. Bora." *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 131, No. 3, p. 402, doi: 10.1061/(ASCE)1090-0241(2005)131:3(402).

Prakash, K., and Sridharan, A., 2006, "Critical Appraisal of the Cone Penetration Method of Determining Soil Plasticity." *Canadian Geotechnical Journal*, Vol. 43, No. 8, pp. 884-888, doi: 10.1139/T06-043.

Sherwood, P. T., 1970, "The Reproducibility of the Results of Soil Classification and Compaction Tests." *Road Research Laboratory Report No. LR 339*, Road Research Laboratory, Crowthorne, Berk.

Sherwood, P. T., and Ryley, M. D., 1968, "An Examination of Cone-Penetrometer Methods for Determining the Liquid Limit of Soils." *TRRL Report LR 233*, Transport and Road Research Laboratory, Crowthome, Berks.

Sivakumar, V., Glynn, D., Cairns, P., and Black, J. A., 2009, "A New Method of Measuring Plastic Limit of Fine Materials." *Géotechnique*, Vol. 59, No. 10, pp. 813-823, doi: 10.1680/geot.2009.59.10.813.

Terzaghi, K., Peck, R. B., and Mesri, G., 1996, *Soil Mechanics in Engineering Practice*, Wiley, New York.

USACE EM 1110-1-1804, 2001, " Engineering and Design - Geotechnical Investigations." Department of the Army, U.S. Army Corps of Engineers, Washington, DC, USA.

Vardanega, P., and Haigh, S., 2014, "Some Recent Developments in the Determination of the Atterberg Limits." *Advances in Transportation Geotechnics and Materials for Sustainable Infrastructure*, American Society of Civil Engineers, pp. 48-55, doi: 10.1061/9780784478509.007.

Whyte, I. L., 1982, "Soil Plasticity and Strength - a New Approach Using Extrusion." *Ground Engineering*, Vol. 15, No. 1, pp. 16-18, 20, 22, 24.

Wood, D. M., and Wroth, C. P., 1978, "The Use of the Cone Penetrometer to Determine the Plastic Limit of Soils." *Ground Engineering*, Vol. 11, No. 3.

Chapter Six – Conclusions and Recommendations

This chapter summarises the research outcomes on soil plasticity determined by the proposed method. Additionally, future studies are recommended for further investigations in this field.

6.1 Research Conclusions

Four theoretical and experimental research articles have been drafted following the development and implementation of the proposed Manafi Method and Apparatus. By highlighting the main concerns of conventional plasticity tests, the first paper proposes a novel approach that combines the qualitative and quantitative research methodologies to fit the nature of the soil consistency. Consequently, a new 'workability' parameter is introduced and formulated by clarifying the definition of soil consistency. Accordingly, the soil consistency limit states (including liquid and plastic limits) are correlated to the soil deformation rates and can be quantified by determining the workability parameter. The proposed approach has three main advantages over the conventional methods:

1. The aggregate behaviour of cohesive soils is assessed by a combined qualitative and quantitative methodology based on the soil consistency definition.
2. Both liquid and plastic limits can be determined by a single test method.
3. The workability parameter is calculated operator-independently, reducing uncertainties associated with conventional methods.

The mechanical analysis of the extrusion method, presented in the second paper, demonstrates the capability of this soil deformation technique for determining the soil workability. Accordingly, an extension of the established closed-form method for estimating the extrusion pressure is described in the paper. Consequently, the extrusion of the dead-material zone is interpreted by developing a new model. The extrusion pressure calculation was also refined by taking into account the acceleration of the material during the extrusion. In short, our paper explains the principles of extrusion and the processes involved in it.

The third article describes how the theories in Papers one and two can be applied to soil property determinations. Accordingly, the new soil extrusion apparatus is fabricated, and the proposed method is applied to several soils of varying particle sizes and levels of plasticity to verify the method. The proposed technique is instrumented with the new soil extrusion device to quantify the workability of soils which is calibrated to translate the workability to their liquid and plastic limits. Comparing the results with those obtained by the standard methods demonstrates the following advantages:

1. Incorporation of the appropriate combined qualitative and quantitative approach in the test procedure;
2. A relatively rapid test which determined both the liquid and plastic limits using a single apparatus;
3. The proposed test reduces the impact of sample heterogeneity on the test results by examining the entire soil specimen.
4. The test device is relatively fast and straightforward;
5. The experimental results indicate that the proposed method is more precise and reliable than the conventional plasticity determination tests.

Considering the capabilities of the new technique, one can conduct plasticity tests free of restrictions on the standard tests. One of the main issues of the soil plasticity determination by current standard tests is omitting soil grains larger than 425 microns. However, the Manafi method allows one to investigate a broader range of soil particles and make the soil sample approximating the in-situ soil. Consequently, several soil samples were characterised to examine the effect of particle size on plasticity covering a wide range of particles up to coarse sands. It was found that the different particle sizes and combinations of soil grains had a significant effect on the plasticity property, which led to different classifications for soils, ranging from *extremely plastic* to *intermediate plastic* for the soil samples tested. The results demonstrated the limitations of the unified soil classification system and suggested two practical updates accordingly: i) improving the plasticity determination by examining the full range of particles, and ii) considering the particle size distribution as a criterion in classifying the fine-grain soils, similar to classifying the coarse soils in the USCS.

6.2 Recommendations

Soil consistency is affected by many interrelated factors, from environmental conditions of the soil to operator-dependent parameters. This research was an attempt to establish the newly proposed research approach for tackling these issues. In addition, a new reliable laboratory test was developed to be compatible with the proposed methodology and have fewer limitations than on the current standard methods. However, there are still several field and laboratory issues in soil consistency determination, which are worth researching a comprehensive soil characterisation program by using the combined qualitative and quantitative approach.

Chapter 2 discusses the main issues of the soil consistency determination by current standard methods in detail. However, finding solutions for each issue requires various research projects within a comprehensive soil characterisation program. These research projects require support from national and regional standard organisations (e.g., ASTM, BS, AS, etc.) in order to develop an inclusive soil characterisation plan. For instance, the laboratory plasticity test results should be interpreted based on other test outcomes such as sieve analysis, hydrometry, mineralogy, water chemistry and pH tests, alongside qualitative surveys for considering the in-situ environmental conditions performed by experienced operators.

Considering the time and budget constraints of this research project, the soil samples were restricted to the most critical cohesive soil types, which are clay soils. Although an extensive range of soil plasticity has been investigated in this research, increasing the number of tests studying various types of soils, including silty and organic soils, can statistically increase the reliability of the proposed test method.

Several parts of the current Manafi Apparatus, such as data acquisition and pneumatic loading systems, were designed specifically for research purposes. These sophisticated and expensive parts can be saved where a simple dead-weight loading system and a timer are in place. Consequently, the testing units improved for commercial usages will be cost-competitive over the current devices.

This research proposed a unique criterion for quantifying the qualitative phenomenon of soil consistency. The concept of consistency determination is a practical requirement for many different industrial applications such as concrete technology, pottery formations, metal casting, food processing, polymer remouldings, pharmaceutical products, packaging services, and any other applications requiring material consistency. Therefore, applying the proposed method with different materials is recommended to enhance the accuracy and precision of material consistency determination in various industries.

References

AASHTO M 145-91, 2008, "Standard Specification for Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes." American Association of State Highway and Transportation Officials (AASHTO), Washington, D.C.

AASHTO T89-10, 2010, "Standard Method of Test for Determining the Liquid Limit of Soils." American Association of State Highway and Transportation Officials (AASHTO), Washington, D.C.

Altan, T., Oh, S.-I., and Gegel, H. L., 1983, *Metal Forming: Fundamentals and Applications*, American Society for Metals, Metals Park, OH.

Argyris, J. H., and Doltsinis, J. S., 1979, "On the Large Strain Inelastic Analysis in Natural Formulation Part I: Quasistatic Problems." *Computer Methods in Applied Mechanics and Engineering*, Vol. 20, No. 2, pp. 213-251, doi: 10.1016/0045-7825(79)90020-3.

Argyris, J. H., and Doltsinis, J. S., 1981, "On the Natural Formulation and Analysis of Large Deformation Coupled Thermomechanical Problems." *Computer Methods in Applied Mechanics and Engineering,* Vol. 25, No. 2, pp. 195-253, doi: 10.1016/0045-7825(81)90084-0.

AS 1289.1.1-2001, 2008, "Methods of Testing Soils for Engineering Purposes - Sampling and Preparation of Soils - Preparation of Disturbed Soil Samples for Testing." Standards Australia, Sydney, NSW, Australia.

AS 1289.3.1.1-2009, 2017, "Methods of Testing Soils for Engineering Purposes - Soil Classification Tests - Determination of Liquid Limit of a Soil – Four Point Casagrande Method." Standards Australia, Sydney, Australia.

AS 1289.3.2.1, 2009, "Methods of Testing Soils for Engineering Purposes - Soil Classification Tests - Determination of the Plastic Limit of a Soil." Standards Australia, Sydney, Australia.

AS 1289.3.6.1, 2009, "Methods of Testing Soils for Engineering Purposes - Soil Classification Tests - Determination of Particle Size Distribution of a Soil - Standard Method of Analysis by Sieving." Standards Australia, Sydney, Australia.

AS 1289.3.9.1, 2015, "Methods of Testing Soils for Engineering Purposes - Soil Classification Tests - Determination of the Cone Liquid Limit of a Soil." Standards Australia, Sydney, Australia.

Asadi, A., Huat, B. B. K., Hanafi, M. M., Mohamed, T. A., and Shariatmadari, N., 2011, "Chemico-Geomechanical Sensitivities of Tropical Peat to Pore Fluid Ph Related to Controlling Electrokinetic Environment." *Journal of the Chinese Institute of Engineers*, Vol. 34, No. 4, pp. 481-487, doi: 10.1080/02533839.2011.576491.

ASTM D422-63(2007)e2, 2007, "Standard Test Method for Particle-Size Analysis of Soils." ASTM International, West Conshohocken, PA, doi: 10.1520/D0422-63R07E02.

ASTM D653-14, 2014, "Standard Terminology Relating to Soil, Rock, and Contained Fluids." ASTM International, West Conshohocken, PA, doi: 10.1520/D0653-14.

ASTM D2487-17, 2017, "Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)." ASTM International, West Conshohocken, PA, doi: 10.1520/D2487-17.

ASTM D3282-15, 2015, "Standard Practice for Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes." ASTM International, West Conshohocken, PA, doi: 10.1520/D3282-15.

ASTM D4318-17e1, 2017, "Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils." ASTM International, West Conshohocken, PA, USA, doi: 10.1520/D4318-17E01.

ASTM D7928-16e1, 2016, "Standard Test Method for Particle-Size Distribution (Gradation) of Fine-Grained Soils Using the Sedimentation (Hydrometer) Analysis." ASTM International, West Conshohocken, PA, doi: 10.1520/D7928-16E01.

ASTM E177-14, 2014, "Standard Practice for Use of the Terms Precision and Bias in Astm Test Methods." ASTM International, West Conshohocken, PA, doi: 10.1520/E0177-14.

Atterberg, A., 1911, "Uber Die Physikalische Bodenuntersuchung Und Uber Die Plastizitat Der Tone. (on the Physical Testing of Soil and the Plasticity of Clays)." *Internationale Mitteilungen für Bodenkunde*, Vol. 1, No. 1, pp. 10-43.

Avitzur, B., 1964, "Analysis of Wire Drawing and Extrusion through Conical Dies of Large Cone Angle." *Journal of Manufacturing Science and Engineering*, Vol. 86, No. 4, pp. 305-314, doi: 10.1115/1.3670543.

Bjerrum, L., 1954, "Geotechnical Properties of Norwegian Marine Clays." *Géotechnique*, Vol. 4, No. 2, pp. 49-69, doi: 10.1680/geot.1954.4.2.49.

Black, W. P. M., 1962, "A Method of Estimating the California Bearing Ratio of Cohesive Soils from Plasticity Data." *Géotechnique*, Vol. 12, No. 4, pp. 271-282, doi: 10.1680/geot.1962.12.4.271.

Borwein, J. M., and Crandall, R. E., 2013, "Closed Forms: What They Are and Why We Care." *Notices of the American Mathematical Society*, Vol. 60, pp. 50-65, doi: 10.1090/noti936.

Briaud, J. L., 2013, *Geotechnical Engineering: Unsaturated and Saturated Soils*, John Wiley & Sons, Hoboken, New Jersey, p. 998 pages.

BS 5930, 2015, "Code of Practice for Ground Investigations." British Standards Institution, Milton Keynes, UK.

BS EN 1377-2, 1990, "Methods of Test for Soils for Civil Engineering Purposes. Part 2: Classification Tests." British Standards Institution, Milton Keynes, UK.

BS EN ISO 14688-1:2002+A1, 2013, "Geotechnical Investigation and Testing - Identification and Classification of Soil - Part 1: Identification and Description." British Standards Institution, Milton Keynes, UK.

Carrier, W. D., and Beckman, J. F., 1984, "Correlations between Index Tests and the Properties of Remoulded Clays." *Géotechnique*, Vol. 34, No. 2, pp. 211-228, doi: 10.1680/geot.1984.34.2.211.

Casagrande, A., 1932, "Research on the Atterberg Limits of Soils." *Public roads*, Vol. 13, No. 8, pp. 121-136.

Casagrande, A., 1948, "Classification and Identification of Soils." *Transactions of the American Society of Civil Engineers*, Vol. 113, pp. 901-930.

CEN. E.N. 1997-2, 2007, "Eurocode 7 – Geotechnical Design – Part 2: Ground Investigation and Testing." Comité Européen de Normalisation (CEN), Brussels, Belgium.

Collins, I. F., 1968, "The Algebraic-Geometry of Slip Line Fields with Applications to Boundary Value Problems." *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, Vol. 303, No. 1474, pp. 317-338, doi: 10.1098/rspa.1968.0053.

Das, B. M., and Sobhan, K., 2018, *Principles of Geotechnical Engineering*, Cengage Learning, Australia, p. 819.

Davidson, D. A., 1983, "Problems in the Determination of Plastic and Liquid Limits of Remoulded Soils Using a Drop-Cone Penetrometer." *Earth Surface Processes and Landforms*, Vol. 8, No. 2, pp. 171-175, doi: 10.1002/esp.3290080208.

Dewhurst, P., and Collins, I. F., 1973, "A Matrix Technique for Constructing Slip-Line Field Solutions to a Class of Plane Strain Plasticity Problems." *International Journal for Numerical Methods in Engineering*, Vol. 7, No. 3, pp. 357-378, doi: 10.1002/nme.1620070312.

Di Matteo, L., Dragoni, W., Cencetti, C., Ricco, R., and Fucsina, A., 2016, "Effects of Fall-Cone Test on Classification of Soils: Some Considerations from Study of Two Engineering Earthworks in Central Italy." *Bulletin of Engineering Geology and the Environment*, Vol. 75, No. 4, pp. 1629-1637, doi: 10.1007/s10064-015-0808-8.

Dieter, G. E., 1961, *Mechanical Metallurgy*, McGraw-Hill, New York, p. 615.

Dieter, G. E., and Bacon, D., 1988, *Mechanical Metallurgy*, McGraw-Hill, Singapore, p. 751.

Dieter, G. E., Kuhn, H. A., and Semiatin, S. L., 2003, *Handbook of Workability and Process Design*, ASM International, Materials Park, Ohio, USA.

Dumbleton, M. J., and West, G., 1970, "The Suction and Strength of Remoulded Soils as Affected by Composition." *RRL Report LR 306*, Road Research Laboratory, Crowthorne, Berkshire, UK.

Fellows, R., and Liu, A., 2015, *Research Methods for Construction*, John Wiley & Sons, Ltd, The Atrium, Southern Gate, Chichester, West Sussex, United Kingdom, p. 302.

Germaine, J. T., and Germaine, A. V., 2009, *Geotechnical Laboratory Measurements for Engineers*, Wiley, Hoboken, N.J.

Giles, H. F., Mount, E. M., and Wagner, J. R., 2004, *Extrusion: The Definitive Processing Guide and Handbook*, Elsevier Science.

Guy, R. C. E., 2001, *Extrusion Cooking: Technologies and Applications*, Woodhead, Cambridge.

Haigh, S. K., 2012, "Mechanics of the Casagrande Liquid Limit Test." *Canadian Geotechnical Journal*, Vol. 49, No. 9, pp. 1015-1023, doi: 10.1139/t2012-066.

Haigh, S. K., Vardanega, P. J., and Bolton, M. D., 2013, "The Plastic Limit of Clays." *Geotechnique*, Vol. 63, No. 6, pp. 435-440, doi: 10.1680/geot.11.P.123.

Harison, J. A., 1990, "Discussion: Using the Bs Cone Penetrometer for the Determination of the Plastic Limit of Soils." *Géotechnique*, Vol. 40, No. 2, pp. 311-315, doi: 10.1680/geot.1990.40.2.311.

Hassani, S., 2000, *Mathematical Methods: For Students of Physics and Related Fields*, Springer, New York.

Head, K. H., 2006, *Manual of Soil Laboratory Testing, Volume 1: Soil Classification and Compaction Tests*, Whittles Publishing, Scotland, UK.

Head, K. H., and Epps, R. J., 2011, *Manual of Soil Laboratory Testing, Volume 2: Permeability, Shear Strength and Compressibility Tests*, Whittles Publishing, Scotland, UK, p. 499.

Head, K. H., and Epps, R. J., 2014, *Manual of Soil Laboratory Testing, Volume 3: Effective Stress Tests*, Whittles Publishing, Scotland, UK, p. 424.

Hill, R., 1998, *The Mathematical Theory of Plasticity*, Oxford University Press, Oxford, p. 355.

Hobbs, N., 1986, "Mire Morphology and the Properties and Behaviour of Some British and Foreign Peats." *Quarterly Journal of Engineering Geology and Hydrogeology*, Vol. 19, No. 1, pp. 7-80, doi: 10.1144/GSL.QJEG.1986.019.01.02.

Hoffman, O., and Sachs, G., 1953, *Introduction to the Theory of Plasticity for Engineers*, McGraw-Hill, New York, p. 276.

Houlsby, G. T., 1982, "Theoretical Analysis of the Fall Cone Test." *Géotechnique*, Vol. 32, No. 2, pp. 111-118, doi: 10.1680/geot.1982.32.2.111.

Jeong, S. W., Locat, J., Leroueil, S., and Malet, J.-P., 2010, "Rheological Properties of Fine-Grained Sediment: The Roles of Texture and Mineralogy." *Canadian Geotechnical Journal*, Vol. 47, No. 10, pp. 1085-1100, doi: 10.1139/T10-012.

Johnson, W., and Mellor, P. B., 1973, *Engineering Plasticity*, Van Nostrand-Reinhold, London.

Karlsson, R., 1961, "Suggested Improvements in the Liquid Limit Test, with Reference to Flow Properties of Remoulded Clays." *Proceedings of the 5th International Conference on Soil Mechanics and Foundation Engineering*, Paris, France, pp. 171-184.

Kayabali, K., 2011a, "Assessment of Shear Strength at Consistency Limits - a Reappraisal." *Electronic Journal of Geotechnical Engineering*, Vol. 16 U, pp. 1679-1695.

Kayabali, K., 2011b, "Determination of Consistency Limits: A Comparison between -#40 and -#200 Materials." *Electronic Journal of Geotechnical Engineering*, Vol. 16 T, pp. 1547-1561.

Kayabali, K., 2012, "Estimation of Liquid, Plastic and Shrinkage Limits Using One Simple Tool." *Electronic Journal of Geotechnical Engineering*, Vol. 17 N, pp. 2079-2090.

Kayabali, K., Aktürk, Ö., Fener, M., Dikmen, O., and Harputlugil, F. H., 2015a, "Revisiting the Bjerrum's Correction Factor: Use of the Liquidity Index for Assessing the Effect of Soil Plasticity on Undrained Shear Strength." *Journal of Rock Mechanics and Geotechnical Engineering*, Vol. 7, No. 6, pp. 716-721, doi: 10.1016/j.jrmge.2015.07.003.

Kayabali, K., Aktürk, Ö., Fener, M., Ozkeser, A., Ustun, A. B., Dikmen, O., Harputlugil, F., and Asadi, R., 2016, "Determination of Atterberg Limits Using Newly Devised Mud

Press Machine." *Journal of African Earth Sciences*, Vol. 116, pp. 127-133, doi: 10.1016/j.jafrearsci.2016.01.005.

Kayabali, K., and Balci, M. C., 2013, "An Appraisal of the Problems Related to the Classification of Fine-Grained Soils." *Electronic Journal of Geotechnical Engineering*, Vol. 18 K, pp. 2251-2262.

Kayabali, K., and Ozdemir, A., 2013, "Use of Reverse Extrusion Method to Determine Undrained Shear Strength." *Geotech Geol Eng*, Vol. 31, No. 2, pp. 719-727, doi: 10.1007/s10706-013-9621-y.

Kayabali, K., and Tufenkci, O. O., 2007, "A Different Perspective for the Determination of Soil Consistence Limits." *International Symposium on Geotechnical Engineering, Ground Improvement and Geosynthetics for Human Security and Environmental Preservation*, Bangkok, Thailand, pp. 423-432.

Kayabali, K., and Tufenkci, O. O., 2010a, "Determination of Plastic and Liquid Limits Using the Reverse Extrusion Technique." *Geotechnical Testing Journal*, Vol. 33, No. 1, pp. 1-9, doi: 10.1520/GTJ102209.

Kayabali, K., and Tufenkci, O. O., 2010b, "Shear Strength of Remolded Soils at Consistency Limits." *Canadian Geotechnical Journal*, Vol. 47, No. 3, pp. 259-266, doi: 10.1139/T09-095.

Kayabali, K., Üstün, A. B., and Özkeser, A., 2015b, "Refinement of the Reverse Extrusion Test to Determine the Two Consistency Limits." *Bulletin of the Mineral Research and Exploration*, Vol. 2015, No. 150, pp. 131-143, doi: 10.19111/bmre.85667.

Kayabali, K., Yilmaz, N., and Mollamahmutoglu, M., 2015c, *An Alternative Shear Strength Test for Saturated Fine-Grained Soils: Preliminary Results*, IOS Press, Buenos Aires, Argentina, doi: 10.3233/978-1-61499-601-9-407.

Koumoto, T., and Houlsby, G. T., 2001, "Theory and Practice of the Fall Cone Test." *Géotechnique*, Vol. 51, No. 8, pp. 701-712, doi: 10.1680/geot.2001.51.8.701.

Kurtz, J.-P., 2004, *Dictionary of Civil Engineering: English-French*, Kluwer Academic/Plenum Publishers, New York, USA p. 1515.

Lee, E. H., Mallett, R. L., and Yang, W. H., 1977, "Stress and Deformation Analysis of the Metal Extrusion Process." *Computer Methods in Applied Mechanics and Engineering*, Vol. 10, No. 3, pp. 339-353, doi: 10.1016/0045-7825(77)90077-9.

Leroueil, S., and Le Bihan, J.-P., 1996, "Liquid Limits and Fall Cones." *Canadian Geotechnical Journal*, Vol. 33, No. 5, pp. 793-798, doi: 10.1139/t96-104-324.

Littleton, I., and Farmilo, M., 1977, "Some Observations on Liquid Limit Values with Reference to Penetration and Casagrande Tests." *Ground Engineering*, Vol. 10, No. 4, pp. 39-40.

Longman Group. 2011, Longman Dictionary of Contemporary English (5th Edition, Electronic Version), Pearson Education.

Manafi, M. S. G., 2017, "Soil Plasticity Determination Using Manafi Method and Apparatus." MSc Thesis by Research, Trinity College Dublin, Dublin, Ireland.

Manafi, M. S. G., 2019, "Soil Plasticity Variability and Its Effect on Soil Classification." *Geotechnical Testing Journal*, Vol. 42, No. 2, pp. 457-470, doi: 10.1520/GTJ20170273.

Manafi, M. S. G., Deng, A., and Taheri, A., 2022a, "Utilisation of Extrusion Method in Geotechnical Tests: Conception and Theoretical Analysis." *Arabian Journal of Geosciences*, Vol. 15, No. 449, doi: 10.1007/s12517-022-09543-z.

Manafi, M. S. G., Deng, A., Taheri, A., Jaksa, M. B., and HB, N., 2022b, "Determining Soil Plasticity Utilising Manafi Method and Apparatus." *Geotechnical Testing Journal*, Vol. 45, No. 4, p. 22, doi: 10.1520/GTJ20210235.

Manafi, M. S. G., Deng, A., Taheri, A., Jaksa, M. B., and HB, N., 2022c, "A New Approach to Soil Consistency Determination."

Marinho, F. A. M., and Oliveira, O. M., 2012, "Unconfined Shear Strength of Compacted Unsaturated Plastic Soils." *Proceedings of the Institution of Civil Engineers - Geotechnical Engineering*, Vol. 165, No. 2, pp. 97-106, doi: 10.1680/geng10.00027.

Medhat, F., and Whyte, I., 1986, "An Appraisal of Soil Index Tests." *Geological Society, London, Engineering Geology Special Publications*, Vol. 2, No. 1, pp. 317-323, doi: 10.1144/GSL.1986.002.01.55.

Mendenhall, W. M., and Sincich, T., 2016, *Statistics for Engineering and the Sciences*, CRC Press, Taylor & Francis Group, Boca Raton, p. 1151.

Moscicki, L., 2011, *Extrusion-Cooking Techniques: Applications, Theory and Sustainability*, Wiley-VCH; Chichester: John Wiley, Weinheim.

Murthy, V. N. S., 2003, *Geotechnical Engineering: Principles and Practices of Soil Mechanics and Foundation Engineering*, Marcel Dekker, New York.

Nagaraj, H., and Sravan, M. V., 2019, *A Review of Factors Affecting Undrained Strength of Fine-Grained Soils at Consistency Limits*, The Icelandic Geotechnical Society, Reykjavik, Iceland, pp. 1-8, doi: 10.32075/17ECSMGE-2019-0472.

Nagaraj, H. B., Sravan, M. V., and Deepa, B. S., 2019, "Factors Influencing Undrained Strength of Fine-Grained Soils at High Water Contents." *Geomechanics and Geoengineering*, pp. 1-5, doi: 10.1080/17486025.2019.1670875.

Nagaraj, H. B., Sridharan, A., and Mallikarjuna, H. M., 2012, "Re-Examination of Undrained Strength at Atterberg Limits Water Contents." *Geotech Geol Eng*, Vol. 30, No. 4, pp. 727-736, doi: 10.1007/s10706-011-9489-7.

Nagaraj, T. S., and Murthy, B. R. S., 1985, "Prediction of the Preconsolidation Pressure and Recompression Index of Soils." *Geotechnical Testing Journal*, Vol. 8, No. 4, pp. 199-202, doi: 10.1520/GTJ10538J.

Nakase, A., Kamei, T., and Kusakabe, O., 1988, "Constitutive Parameters Estimated by Plasticity Index." *Journal of Geotechnical Engineering*, Vol. 114, No. 7, pp. 844-858, doi: 10.1061/(ASCE)0733-9410(1988)114:7(844).

O'Kelly, B. C., 2015, "Atterberg Limits Are Not Appropriate for Peat Soils." *Geotechnical Research*, Vol. 2, No. 3, pp. 123-134, doi: 10.1680/jgere.15.00007.

O'Kelly, B. C., 2016, "Briefing: Atterberg Limits and Peat." *Environmental Geotechnics*, Vol. 3, No. 6, pp. 359-363, doi: 10.1680/envgeo.15.00003.

O'Kelly, B. C., 2017, "Fall-Cone Strength Testing of Municipal Sludges and Residues." *Environmental Geotechnics*, Vol. 4, p. 13 pp, doi: 10.1680/jenge.15.00080.

O'Kelly, B. C., 2019, "Reappraisal of Soil Extrusion for Geomechanical Characterisation." *Geotechnical Research*, Vol. 6, No. 4, pp. 265-287, doi: 10.1680/jgere.19.00006.

O'Kelly, B. C., 2021, "Review of Recent Developments and Understanding of Atterberg Limits Determinations." *Geotechnics*, Vol. 1, No. 1, pp. 59-75, doi: 10.3390/geotechnics1010004.

Penner, E., 1965, "A Study of Sensitivity in Leda Clay." *Canadian Journal of Earth Sciences*, Vol. 2, No. 5, pp. 425-441, doi: 10.1139/e65-037.

Polidori, E., 2003, "Proposal for a New Plasticity Chart." *Géotechnique*, Vol. 53, No. 4, pp. 397-406, doi: 10.1680/geot.2003.53.4.397.

Polidori, E., 2007, "Relationship between the Atterberg Limits and Clay Content." *Soils and Foundation*, Vol. 47, No. 5, pp. 887-896, doi: 10.3208/sandf.47.887.

Poulsen, R., Ibsen, L. B., and Nielsen, B. N., 2012, "Difficulties Regarding Determination of Plasticity Index of Silty Soils by Use of Casagrande and Fall Cone Methods." *Proceedings of the 16th Nordic Geotechnical Meeting*, Dansk Geoteknisk Forening, Copenhagen, Denmark, pp. 199-206.

Prakash, K., 2005, "Discussion of “Plastic Limit, Liquid Limit, and Undrained Shear Strength of Soil—Reappraisal” by Binu Sharma and Padma K. Bora." *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 131, No. 3, p. 402, doi: 10.1061/(ASCE)1090-0241(2005)131:3(402).

Prakash, K., and Sridharan, A., 2006, "Critical Appraisal of the Cone Penetration Method of Determining Soil Plasticity." *Canadian Geotechnical Journal*, Vol. 43, No. 8, pp. 884-888, doi: 10.1139/T06-043.

Rosenqvist, I. T., 1953, "Considerations on the Sensitivity of Norwegian Quick-Clays." *Géotechnique*, Vol. 3, No. 5, pp. 195-200, doi: 10.1680/geot.1953.3.5.195.

Sabatini, P. J., Bachus, R. C., Mayne, P. W., Schneider, J. A., and Zettler, T. E., 2002, "Geotechnical Engineering Circular No. 5: Evaluation of Soil and Rock Properties." *Technical Manual Report No. FHWA-IF-02-034*.

Saha, P., 2000, *Aluminum Extrusion Technology*, ASM International, Materials Park, OH.

Schofield, A. N., and Wroth, P., 1968, *Critical State Soil Mechanics*, McGraw-Hill, London, p. 155.

Serway, R., Faughn, J., Vuille, C., and Bennett, C., 2006, *Enhanced College Physics*, Cengage Learning, p. 118.

Sherwood, P. T., 1970, "The Reproducibility of the Results of Soil Classification and Compaction Tests." *Road Research Laboratory Report No. LR 339*, Road Research Laboratory, Crowthorne, Berk.

Sherwood, P. T., and Ryley, M. D., 1968, "An Examination of Cone-Penetrometer Methods for Determining the Liquid Limit of Soils." *TRRL Report LR 233*, Transport and Road Research Laboratory, Crowthome, Berks.

Siebel, E., 1932, *Metal Forming in Plastic Condition (in German)*, Verlag Stahieisen, Düsseldorf.

Sivakumar, V., Glynn, D., Cairns, P., and Black, J. A., 2009, "A New Method of Measuring Plastic Limit of Fine Materials." *Géotechnique*, Vol. 59, No. 10, pp. 813-823, doi: 10.1680/geot.2009.59.10.813.

Skempton, A., 1954, "Discussion: Sensitivity of Clays and the C/P Ratio in Normally Consolidated Clays." *Proceedings of the American Society of Civil Engineers, Separate*, Vol. 478, pp. 19-22.

Skempton, A., 1957, "Discussion: Further Data on the C/P Ratio in Normally Consolidated Clays." *Proceedings of the Institution of Civil Engineers*, Vol. 7, pp. 305-307.

Spencer, A. J. M., 1961, "Perturbation Methods in Plasticity—I Plane Strain of Non-Homogeneous Plastic Solids." *Journal of the Mechanics and Physics of Solids*, Vol. 9, No. 4, pp. 279-288, doi: 10.1016/0022-5096(61)90005-9.

Spencer, A. J. M., 1962, "Perturbation Methods in Plasticity—Ii Plane Strain of Slightly Irregular Bodies." *Journal of the Mechanics and Physics of Solids*, Vol. 10, No. 1, pp. 17-26, doi: 10.1016/0022-5096(62)90025-X.

Sridharan, A., and Prakash, K., 1999, "Mechanisms Controlling the Undrained Shear Strength Behaviour of Clays." *Canadian Geotechnical Journal*, Vol. 36, No. 6, pp. 1030-1038, doi: 10.1139/t99-071.

Sridharan, A., and Prakash, K., 2000, "Percussion and Cone Methods of Determining the Liquid Limit of Soils: Controlling Mechanisms." *Geotechnical Testing Journal*, Vol. 23, No. 2, pp. 236-244, doi: 10.1520/GTJ11048J.

Stevenson, A., 2010, *Oxford Dictionary of English*, OUP Oxford, pp. 149, 372.

Stroud, M. A., 1974, "The Standard Penetration Test in Sensitive Clays and Rocks." *The European Seminar on Penetration Testing*Stockholm, Sweden, pp. 366-375.

Terzaghi, K., 1926, "Simplified Soil Tests for Subgrades and Their Physical Significance." *Public roads*, Vol. 7, No. 8, pp. 153-170.

Terzaghi, K., Peck, R. B., and Mesri, G., 1996, *Soil Mechanics in Engineering Practice*, Wiley, New York.

Timar, A., 1974, "Testing Plastic Properties of Cohesive-Type and Intermediate-Type Soils by Extrusion." *Acta Technica Academiae Scientiarum Hungaricae*, Vol. 76, No. 3-4, pp. 355-370.

Torrance, J. K., 1975, "On the Role of Chemistry in the Development and Behavior of the Sensitive Marine Clays of Canada and Scandinavia." *Canadian Geotechnical Journal*, Vol. 12, No. 3, pp. 326-335, doi: 10.1139/t75-037.

Torrance, J. K., and Pirnat, M., 1984, "Effect of Ph on the Rheology of Marine Clay from the Site of the South Nation River, Canada, Landslide of 1971." *Clays and Clay Minerals*, Vol. 32, No. 5, pp. 384-390, doi: 10.1346/CCMN.1984.0320506.

Trauner, L., Dolinar, B., and Mišič, M., 2005, "Relationship between the Undrained Shear Strength, Water Content, and Mineralogical Properties of Fine-Grained Soils." *International Journal of Geomechanics*, Vol. 5, No. 4, pp. 350-355, doi: 10.1061/(ASCE)1532-3641(2005)5:4(350).

UFC 3-220-04FA, 2004, "Backfill for Subsurface Structures." Unified Facilities Criteria UFC 3-220-04FA. US Army Corps of Engineers, NAVFAC, Air Force, Department of Defense, Technical Manual TM 5-818-4/AFM 88-5, Washington, DC, USA.

USACE EM 1110-1-1804, 2001, " Engineering and Design - Geotechnical Investigations." Department of the Army, U.S. Army Corps of Engineers, Washington, DC, USA.

Van Note Chism, N., Douglas, E., and Hilson Jr, W. J., 2008, "Qualitative Research Basics: A Guide for Engineering Educators." *RREE, NSF DUE-0341127*.

Vardanega, P., and Haigh, S., 2014, "Some Recent Developments in the Determination of the Atterberg Limits." *Advances in Transportation Geotechnics and Materials for Sustainable Infrastructure*, American Society of Civil Engineers, pp. 48-55, doi: 10.1061/9780784478509.007.

Verástegui-Flores, R. D., and Di Emidio, G., 2014, "Assessment of Clay Consistency through Conventional Methods and Indirect Extrusion Tests." *Applied Clay Science*, Vol. 101, pp. 632-636, doi: 10.1016/j.clay.2014.09.033.

Verástegui-Flores, R. D., and Di Emidio, G., 2015, "Determination of Consistency Limits of Clay by Means of Extrusion Tests." *European Conference on Soil Mechanics and Geotechnical Engineering*, ICE, Edinburgh, UK, pp. 3431-3436, doi: 10.1680/ecsmge.60678.vol6.538.

Vinod, P., Sridharan, A., and Deepa, K. A., 2013, "Remoulded Shear Strength at Plastic and Semi-Solid States." *Proceedings of the Institution of Civil Engineers - Geotechnical Engineering*, Vol. 166, No. 4, pp. 415-424, doi: 10.1680/geng.11.00071.

Wasti, Y., and Bezirci, M. H., 1986, "Determination of the Consistency Limits of Soils by the Fall Cone Test." *Canadian Geotechnical Journal*, Vol. 23, No. 2, pp. 241-246, doi: 10.1139/t86-033.

Wesley, L. R., 2014, *Clays and Clay Minerals: Geological Origin, Mechanical Properties and Industrial Applications*, Nova Science Publishers, Incorporated, p. 184.

Whyte, I. L., 1982, "Soil Plasticity and Strength - a New Approach Using Extrusion." *Ground Engineering*, Vol. 15, No. 1, pp. 16-18, 20, 22, 24.

Wood, D. M., and Wroth, C. P., 1978, "The Use of the Cone Penetrometer to Determine the Plastic Limit of Soils." *Ground Engineering*, Vol. 11, No. 3.

Wroth, C. P., and Wood, D. M., 1978, "The Correlation of Index Properties with Some Basic Engineering Properties of Soils." *Canadian Geotechnical Journal*, Vol. 15, No. 2, pp. 137-145, doi: 10.1139/t78-014.

Yang, J., and Dykes, A. P., 2006, "The Liquid Limit of Peat and Its Application to the Understanding of Irish Blanket Bog Failures." *Landslides*, Vol. 3, No. 3, pp. 205-216, doi: 10.1007/s10346-006-0038-z.