Determing Liquid Limit and Plastic Limit of Clay Soils by Electrical Surface Conduction and Diffuse Double Layer Thickness

Md Farhad Hasan 1,2,⁎ and Hossam Abuel-Naga 1

1 Department of Civil Engineering, La Trobe University, Melbourne, VIC 3086, Australia; h.aboel-naga@latrobe.edu.au
2 Department of Energy, Environment and Climate Action, Victoria State Government, Melbourne, VIC 3083, Australia
⁎ Correspondence: farhad.hasan@agriculture.vic.gov.au

Abstract: The aim of this study was to propose a new approach to determine the liquid limit and plastic limit of clay soils by considering electrical conductivity (EC) measurements. The proposed method included incorporating a new parameter, F, which is the ratio of the volumetric water contents of diffuse double layer (DDL) water and free water. In addition, the EC parameter, σ, was considered as the ratio of electrical surface conductivity and electrical conductivity of water. The changes in the thickness of DDL (χ) were also assessed to obtain corresponding equations to establish a connection with clay mineralogy, water content, and specific gravity in the final prediction. Three-dimensional surface analyses were conducted to find a correlation among F, σ, and χ to identify an appropriate method to predict liquid limit and plastic limit. The study was conducted with 39 different types of samples, and the outcomes from the EC approach were validated against the conventional methods. Overall, the coefficient of determination, R² = 0.90, and Lin’s concordance correlation coefficient, (LCCC) = 0.91, were obtained for liquid limit prediction, whereas R² = 0.64 and LCCC = 0.80 were obtained for plastic limit determination.

Keywords: liquid limit; plastic limit; electrical conductivity; diffuse double layer; volumetric water content; clay mineralogy

1. Introduction

Clay-rich soils require rational treatment in geotechnical engineering to implement any structural designs safely. These soils exhibit substantial characteristics due to their differences in mineralogy [1,2], degree of saturation [3], water content [4,5], micropore structures [6], particle size distribution [7], temperature [8], and level of anisotropy [9,10]. Without analysing those geotechnical properties efficiently, any construction site may experience a detrimental impact. In general, clay-rich soils behave as semisolids within a particular range of water content, and this range defines the physical properties of corresponding soils. Therefore, it is significant to determine the clay soil properties associated with water contents prior to any constructional development.

Atterberg Limits are determined to classify and demonstrate the characteristics of cohesive soils, like clays, which have different water contents. It was first introduced by Albert Atterberg in 1911 [11,12] and was later refined by Arthur Casagrande and Karl Terzaghi, two pioneers of soil mechanics. Some of the important applications of Atterberg Limits can be highlighted, as these measurements help determine soil deformability, expansion capability, soil strength, and hydraulic conductivity. Atterberg Limits (ASTM D4318) [13] consist of three measurements of water contents of clay soils, namely shrinkage limit, liquid limit, and plastic limit. Liquid limit and plastic limit are major geotechnical properties, as these measurements indicate how much water can be retained in a specific clay sample.
before it goes through a transition from a plastic state to a liquid state. In other words, the liquid limit is defined as the states where clay soils start to behave like liquid, while the plastic limit is described as a state featuring a specific water content where the soil goes through the transition from ductile (tough) to brittle (loss of toughness) [14,15]. This transition is a gradual change; therefore, the determination of the transition boundary is inherently arbitrary [15].

Liquid limit could vary in a wider range based on the properties of the clays. For example, bentonite clay possesses a surface area almost 40 times greater than that of kaolin clay [9,16]. As a result, filling the bentonite pores will require a greater amount of water. In addition, interparticle forces also influence the variations in the liquid limit of clays. There are two major standards to determine the liquid limit of clays, namely the fall cone test [17] and the Casagrande test [18,19]. Both of those methods are in practice across the globe. However, they have often been criticised as tedious and erratic, and they rely on manual operators [20,21]. Meanwhile, the plastic limit of clays is determined by the conventional thread-rolling test. There is no standard device or scientific measurements involved in it, and it is also highly dependent on the judgement of the operators. The method has been described as having poor reproducibility [14,22]. Both liquid limit and plastic limit tests require measuring the water content of each sample by oven-drying overnight. Therefore, there is a need to identify a scientific approach to determine the liquid limit and plastic limit of clays through a direct measurement without depending on the operator’s judgement within a comparatively shorter timescale. Some recent developments have been made to find an alternative to the Atterberg limit estimation by the utilisation of spectroscopy [23,24], data-driven prediction models developed by artificial intelligence [25,26], and hygroscopic water content [27], to name a few. However, the consideration of spectroscopy may not seem an ideal solution in the geotechnical industry if there is a lack of understanding of electromagnetic radiation, wavelengths, and associated functional ability. In other words, highly skilled operators may be required to include more practicality regardless of recent success. Meanwhile, the inclusion of hygroscopic water content [27] provided another unique pathway, and this is an indication that the conventional liquid limit and plastic limit determination could be replaced by investigating soil–water interactions further in a systematic fashion. A review of the recent trend by O’Kelly [28] suggested that an alternative method to determine the Atterberg limit remains a topic of paramount importance.

Electrical conductivity (EC) of clay soil is strongly correlated with clay mineralogy, Atterberg limits, anisotropy, degree of saturation water content, cation exchange capacity, void ratio, etc. EC has been considered by geotechnical engineers to comprehensively characterise subsurface grounds (for example, electrical resistivity tomography) [16,29–31]. Since the liquid limit and plastic limit of clay soils are unique and contain specific water contents, it is possible to implement an EC approach to determine those metrics. Several discussions already exist in the literature that aimed to establish the connection between EC and clay properties [8,9,16,30]. In the past, soil was considered to be an insulated material, and the EC measurements were dependent on the clay–water interaction within the suspension and pore water conduction only [32–34]. However, those concepts have been improved recently with the concepts of clay mineralogy. Clay–water interaction can be further discussed by considering the surface conduction layer, which is known as the diffuse double layer (DDL). The electrical properties of the DDL are controlled by the pore water salinity and surface charge of clay particles [8]. This DDL can form an effective solid by surrounding each clay particle, which is electrically conductive. Therefore, the consideration of effective solids has significantly improved the understanding of EC measurements of clay soils by incorporating both free water and DDL water. Since the liquid limit and plastic limit are unique water contents for each clay sample, the surface conduction of clay particles can be correlated with the volumetric water contents of free water and DDL water in each clay sample. Different clay samples can have the same liquid limit or plastic limit; however, the EC values will be different due to variations in the
mineralogy, and the integration of electrical surface conduction parameters along with the volumetric water contents could be sufficient to predicting the liquid limit and plastic limit.

This study aimed to propose an alternative method for determining the liquid limit and plastic limit of clay soils. A new parameter, F, has been introduced, which is the ratio of the volumetric water contents of DDL and free water in each clay sample. Later, a mathematical expression was derived by incorporating F with DDL thickness (χ) and specific gravity (Gs) that can determine the water contents of each clay at the liquid limit and plastic limit. In total, 39 different clay soils were considered. The outcomes of the liquid limits and plastic limits of each sample were compared qualitatively and quantitatively with at least one conventional test result, and overall, good accuracy was obtained. The findings from this study have the potential to present an alternative method to the conventional liquid limit and plastic limit tests by introducing improved experimental methods.

2. Materials and Methods

2.1. Mathematical Formulation

In the past, each solid clay particle was considered to be an insulator, while EC measurement relied on the conductive fluid pathway. However, the definition of conductive fluid required sufficient clarifications. The presence of water within a soil–water mixture can be divided into two parts, namely free water and DDL water. Each clay particle and its surrounding DDL forms a single conductive unit called an effective clay particle [8,9]. Therefore, the total volume of saturated clay (Vc) can be written as the following [8]:

\[ V_c = V_{fw} + V_s^e \]  

(1)

In Equation (1), \( V_{fw} \) and \( V_s^e \) are the volumes of the free water and effective solid, respectively. These volumes are different from the total volume of water, \( V_w \), and volume of solid, \( V_s \), and can be expressed as follows [8,9,16]:

\[ V_{fw} = V_w - V_{DDL}^w = [n - (1 - n)(\chi - 1)]V \]  

(2)

\[ V_s^e = V_s + V_{DDL}^w = (1 - n)\chi V \]  

(3)

where,

\[ \chi = \frac{V_s^e}{V_s} \]  

(4)

\[ n = \frac{V_v}{V} \]  

(5)

\[ n_e = \frac{V_{fw}}{V} \]  

(6)

\[ \chi = \frac{1 - n_e}{1 - n} \]  

(7)

As per Equations (2)–(7), \( V_{DDL}^w \) and \( V_v \) are the volumes of DDL water and void, respectively; n is the porosity, and \( n_e \) is the effective porosity. Both volumes of free water (\( V_{fw}^l \)) and effective solid (\( V_s^e \)) can be determined from Equations (2) and (3), respectively. The parameter \( \chi \) represents the ratio of \( V_s^e \) and \( V_s \), and, based on the definition of the effective solid, \( V_s^e \geq V_s \). Therefore, \( \chi \geq 1.0 \) can indirectly express the overall size of DDL water per unit volume of clay [8,9,16]. It can also be inferred from Equation (4) that \( \chi \) is unitless. In order to determine \( \chi \), the electrical conductivity of two different diluted clay-water systems in terms of their n value (\( n_1, n_2 \)) should be measured experimentally (for example, 1g clay/L distilled water and 2g clay/L distilled water in identical \( \sigma_{FW} \)).
Within this work, $\sigma_{\text{mix}}$ is the electrical conductivity of the diluted clay-water suspension. It can be measured as the following [9,16]:

$$\sigma_{\text{mix}} = \frac{\sqrt{(1-n)\chi}}{\sigma_s} + \left(1 - \sqrt{(1-n)\chi}\right)\sigma_{\text{Fw}}$$  \hspace{1cm} (8)

Equation (8) represents the expression to incorporate the EC of effective clay particle ($\sigma_s$) and DDL thickness ($\chi$). With two different measurements, Equation (8) can be divided into two different $\sigma_{\text{mix}}$ ($\sigma_{\text{mix1}}$ and $\sigma_{\text{mix2}}$), and $\chi$ can be determined by back-calculation as the following [8,9,16]:

$$\chi = \frac{(N_2 - N_1)\sigma_{\text{mix1w}}\sigma_{\text{mix2w}}}{\sigma_{\text{Fw}}(N_2)^2\sigma_{\text{mix1}} - (N_1)^2\sigma_{\text{mix2}} + \sigma_{\text{Fw}}\left((N_1)^2 - (N_2)^2\right)}$$  \hspace{1cm} (9)

Further descriptions on the derivation can be found in the appendices of Hasan et al. [9].

The volumes of water ($V_w$) at liquid limit and plastic limit comprise volumes of DDL water ($V_{\text{DDLw}}$) and free water ($V_{\text{FWw}}$). Therefore, the volumetric water contents can be expressed as Equations (10) and (11):

$$\theta_{\text{FW}} = \frac{V_{\text{FWw}}}{V_w}$$  \hspace{1cm} (10)

$$\theta_{\text{DDL}} = \frac{V_{\text{DDLw}}}{V_w}$$  \hspace{1cm} (11)

where, $\theta_{\text{FW}}$ and $\theta_{\text{DDL}}$ are the volumetric water contents of free water and DDL water, respectively.

A new parameter $F$ was introduced in this study, which can be determined as the following:

$$F = \frac{\theta_{\text{DDL}}}{\theta_{\text{FW}}}$$  \hspace{1cm} (12)

Therefore, $F$ from Equation (12) at the liquid limit and plastic limit can be expressed as the following:

$$F_{\text{LL}} = \frac{\theta_{\text{DDL}}}{\theta_{\text{FW}}}$$  \hspace{1cm} (13)

$$F_{\text{PL}} = \frac{\theta_{\text{DDL}}}{\theta_{\text{FW}}}$$  \hspace{1cm} (14)

Since liquid limit and plastic limit are the measurements of water contents, the water contents of DDL ($W_{\text{cDDL}}$) and free water ($W_{\text{cFW}}$) can be combined to calculate water contents at liquid limit and plastic limit. The final equations, therefore, can be expressed as:

$$W_{\text{cLL}} = W_{\text{cFW}} + W_{\text{cDDL}}$$  \hspace{1cm} (15)

$$W_{\text{cPL}} = W_{\text{cFW}} + W_{\text{cDDL}}$$  \hspace{1cm} (16)

By combining the expressions in Equations (2)–(7), $W_{\text{cDDL}}$ can be determined as:

$$W_{\text{cDDL}} = \frac{(x - 1)V_sY_w}{G_sV_sY_w} = \frac{(x - 1)}{G_s}$$  \hspace{1cm} (17)

Therefore, $W_{\text{cFW}}$ can be expressed by incorporating Equations (13) and (14):

$$W_{\text{cFW}} = \frac{(x - 1)}{F_{\text{LL}}G_s}$$  \hspace{1cm} (18)
In Equation (17), \( \gamma_w \) is the specific weight of water that varies in different temperatures, and \( G_s \) is the specific gravity.

Now Equations (15) and (16) can finally be expressed as the following:

\[
W_{cLL}^c = \frac{(\chi - 1)}{F_{LL} G_s} + \frac{(\chi - 1)}{G_s} = (1 + \frac{1}{F_{LL}}) \left( \frac{\chi - 1}{G_s} \right)
\]  

(20)

Similarly, for plastic limit:

\[
W_{cPL}^c = \left( 1 + \frac{1}{F_{PL}} \right) \left( \frac{\chi - 1}{G_s} \right)
\]  

(21)

The current study relied on Equations (20) and (21) to determine the liquid limit and plastic limit of soils, respectively. A simpler way to determine \( F \) will be discussed prior to the presentation of the outcome.

2.2. Tested Clay Samples and Properties

In total, 39 different clay samples were considered in this study. Kaolin was the only laboratory-based clay, and its geotechnical properties were collected from the suppliers. The rest of the 38 samples were natural clay soils collected from different locations in Australia. The values of \( \chi \) of the clay soils varied from 1.01 to 1.25. The liquid limit and plastic limit of the considered clay samples varied from 29% to 96% and 21% to 50%, respectively. The validation of the liquid limit test was conducted through comparison with either Casagrande, the fall cone results, or both. The EC plastic limit test was validated against the results from the thread-rolling test.

The plasticity range for the ASTM soil classification system (ASTM D2487) [35] is shown in Figure 1. The plasticity index (PI) is the difference between the liquid limit and the plastic limit of the soil. The U-line in Figure 1 is the upper boundary of the liquid limit and plasticity index values, and it is used to determine any classification error. Meanwhile, the A-line separates clay from silt, and therefore provides information on classification of soils tested in this study. The abbreviations are explained in Table 1 for further clarifications. The positions of both U-line and A-line were determined by the Equations (22) and (23) (ASTM D2487), as follows:

A-line: Horizontal at PI = 4 to LL = 25.5, then PI = 0.73 (LL − 20)  
U-line: Vertical at LL = 16 to PI = 7, then PI = 0.9 (LL − 8)  

(22)  
(23)

Table 1. Soil Classification System (ASTM D2487). Only relevant soils are included in the chart.

<table>
<thead>
<tr>
<th>Major Divisions</th>
<th>Classification Types</th>
<th>Group Symbols</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silts and clays with LL &lt; 50%</td>
<td>Inorganic silts and very fine sands, rock flour, silty or clayey fine sands with low plasticity</td>
<td>ML</td>
</tr>
<tr>
<td></td>
<td>Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays</td>
<td>CL</td>
</tr>
<tr>
<td></td>
<td>Organic silts and organic silt-clays of low plasticity</td>
<td>OL</td>
</tr>
<tr>
<td>Silts and clays with LL &gt; 50%</td>
<td>Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic soils</td>
<td>MH</td>
</tr>
<tr>
<td></td>
<td>Inorganic clays of high plasticity, fat clays</td>
<td>CH</td>
</tr>
<tr>
<td></td>
<td>Organic clays of medium to high plasticity</td>
<td>OH</td>
</tr>
</tbody>
</table>
Figure 1. The plasticity range according to the ASTM soil classification system (ASTM D2487) of clay soil samples considered in this study. PI and LL indicate the plasticity index and liquid limit, respectively.

According to Figure 1 and Table 1, the clay soils considered in this study covered a diverse range. The dominance of the CH, MH, and OH groups was observed. In most cases, clay soils with liquid limits lower than 20% are rare. It was not achievable to collect at least one clay sample within the CL-ML range. However, most of the natural soils have a liquid limit between 40% and 100%. So, the samples from the present study covered a good range of liquid limit in terms of availability.

3. Results and Discussions
3.1. Determination of F by Back-Calculation and Resampling Approach
3.1.1. Model Calibration and Internal Validation

As the mathematical formulation suggests, F is an important parameter to predicting the liquid limit and plastic limit of clay soils by EC approach. Equation (3) describes the mathematical definition; however, it was essential to simplify the determination of F with a simpler measurement. In order to determine F for both the liquid limit and plastic limit, a back-calculation approach was considered. This approach consisted of determining $F_{\text{LL}}$ and $F_{\text{PL}}$ of soils with known liquid and plastic limits. A 3D surface analysis was performed to predict F in soils as a function of the EC surface conduction parameter and size of DDL, namely $\sigma = (\sigma_s/\sigma_w)$ and $\chi$ [8,9]. Here, $\sigma_s$ [8,9] and $\sigma_w$ are the electrical conductivities of solid clay and free water, respectively. As mentioned earlier, $\chi$ is the thickness of the diffuse double layer (DDL) of the clay particles. The parameter $\chi$ is the ratio of volumes of the effective solid (clay particle and DDL) and only solid (clay particle without DDL). Therefore, $\chi$ is directly related to the thickness of DDL and $\chi \geq 1$ [8,9]. According to Equation (8), $\chi$ is a vital candidate to consider when developing a method to determine F. Since EC is also a function of water content and clay mineralogy, among many other physico-chemical properties, $\sigma$ can be considered to predict the liquid limit and plastic limit of clay soils. It is noteworthy to mention that $\sigma_w$ will remain constant in the process, as the Atterberg limit was determined using distilled water. Therefore, the role of $\sigma_s$ in F determination was emphasised. Therefore, $\chi$ along with $\sigma$ to determine a unique F was finally considered to ensure a more precise determination.

The overall contours after the surface analyses have been shown in Figure 2 for both $F_{\text{LL}}$ (Figure 2a) and $F_{\text{PL}}$ (Figure 2b). Some of the points were found outside the boundary
of the contours, and those were only visible with a rotational view. This could be one of the reasons for a reduction in \( R^2 \) for \( F_{PL} \) (Figure 2b).

\[
F_{LL} = -0.5 + \sigma + 0.52\chi \\
F_{PL} = -1.141 - 7.6\sigma + 1.148\chi
\]

3.1.2. Independent Validation

Before considering Equations (24) and (25) as the final equations to determine \( F_{LL} \) and \( F_{PL} \), the independent validation was conducted seven times, with equations to determine \( F_{LL} \) and \( F_{PL} \) being obtained and validated each time. The determination of F involved considering 34 random samples out of 39 for the model calibration, and the remaining 5 samples for the validation. The selection of 34 random samples was repeated at least 20 times before the model development to avoid biased outcomes. For each model development, internal validation was also conducted based on the contour development and how well the points were.

In the independent validation, the coefficient of determination \( (R^2) \) was found to be within an acceptable range with \( 0.91 \leq R^2 \leq 0.95 \) for \( F_{LL} \), and \( 0.90 \leq R^2 \leq 0.95 \) for \( F_{PL} \). Figures 3 and 4 demonstrate the independent validation, including surface contours and validations of \( F_{LL} \) and \( F_{PL} \) values, respectively. The \( R^2 \) values on the contours represent the fitting accuracy of the measured values. On the other hand, Lin’s concordance coefficient correlation (LCCC) on each validation plot demonstrates the agreement between the F values from proposed equations and back-calculation from the soils with known liquid limits. In general, \( 0.3 \leq LCCC \leq 0.97 \) and \( 0.17 \leq LCCC \leq 0.98 \) were obtained for \( F_{LL} \) and \( F_{PL} \), independent validations, respectively. LCCC < 0.4 was considered to be a poor prediction in this study, and this could be attributed to the lower density and improper distribution of fitted points in the contour development. For example, Batch 2 of Figure 3 exhibited LCCC = 0.3 and, by observing the contour, it can be deduced that approximately 17 points were available on the contours, which was less than 50% of the total sample size. Batch 1 of Figure 3 demonstrated LCCC = 0.86 (including one overlap), and the contour contained almost 90% of the measured data. Therefore, the independent validation of that corresponding batch produced high accuracy.
Figure 3. Cont.
Figure 3. Cont.
Figure 3. Independent validation to assess the accuracy of FLL prediction in seven batches. Each batch contains the surface developments (left) and independent validations (right). Straight lines through the points are the regression lines (red), and the other straight lines starting from the origin are the 1:1 lines.

A similar pattern in the outcome was also observed in terms of FPL prediction in Figure 4. In some cases, some overlaps of FPL were observed (Batch 1, 4, 5) due to some soils possessing similar characteristics in terms of volumetric water contents. Batch 2 of Figure 4 produced LCCC = 0.17, which was a poor outcome. However, by comparing with the contour, it can be observed that barely 12 points were found within the fitting surface, and therefore, the validation yielded inadequate accuracy. An exception can be seen in Batch 4 of Figure 4, where the number of well-fitted points was still lower than 50%, yet LCCC was found to be 0.98. This could be explained by emphasising the sample distribution on the contour, which contained quantitatively higher values of σ and χ at the end. Therefore, the prediction was highly accurate in the independent validation.

3.2. Final Test Results

After establishing the procedure to determine F for both the liquid limit and plastic limit determination for clay soils, final tests were conducted and compared with at least one conventional method to assess the accuracy of the prediction. The liquid limit outcomes from EC were compared with the two most popular liquid limit methods, namely the fall cone test and Casagrande method. The plastic limit-EC results were compared with the thread-rolling test. In all cases, great agreements were achieved.

Table 2 shows the comprehensive outcome of the present study along with relevant comparisons. In some cases, the outcome from the Casagrande method was not available as the supplier relied on the fall cone test only. Through a quick observation, it can be stated that EC has enormous potential to be an alternative to the current conventional methods of determining liquid and plastic limits.
Figure 4. Cont.
Figure 4. Cont.
Figure 4. Independent validation to assess the accuracy of F_{PL} prediction in seven batches. Each batch contains the surface developments (left) and independent validations (right). Straight lines through the points are the regression lines (red), and the other straight lines always starting from the origin are the 1:1 lines.

Table 2. Results of the present study along with quantitative comparisons.

<table>
<thead>
<tr>
<th>No.</th>
<th>Samples</th>
<th>$\sigma_s$ (S/m)</th>
<th>$\chi$</th>
<th>F_{LL}</th>
<th>F_{PL}</th>
<th>G_s</th>
<th>LL (%)</th>
<th>Cone</th>
<th>Casagrande</th>
<th>EC</th>
<th>PL (%)</th>
<th>Thread-Rolling</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Kaolin</td>
<td>0.0034</td>
<td>1.07</td>
<td>0.12</td>
<td>0.11</td>
<td>2.58</td>
<td>63</td>
<td>74</td>
<td>74</td>
<td>35</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>Dermosol</td>
<td>0.0011</td>
<td>1.1</td>
<td>0.06</td>
<td>0.16</td>
<td>2.6</td>
<td>63</td>
<td>59</td>
<td>58</td>
<td>31</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>Chromosol</td>
<td>0.0032</td>
<td>1.05</td>
<td>0.04</td>
<td>0.08</td>
<td>2.59</td>
<td>53</td>
<td>58</td>
<td>58</td>
<td>28</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>Vertosol</td>
<td>0.0009</td>
<td>1.07</td>
<td>0.06</td>
<td>0.11</td>
<td>2.58</td>
<td>58</td>
<td>49</td>
<td>49</td>
<td>28</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>Red mud</td>
<td>0.0020</td>
<td>1.09</td>
<td>0.07</td>
<td>0.15</td>
<td>2.6</td>
<td>59</td>
<td>50</td>
<td>51</td>
<td>30</td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>Expansive</td>
<td>0.0025</td>
<td>1.18</td>
<td>0.1</td>
<td>0.22</td>
<td>2.57</td>
<td>74</td>
<td>77</td>
<td>77</td>
<td>39</td>
<td>39</td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td>Red mud-2</td>
<td>0.0018</td>
<td>1.06</td>
<td>0.05</td>
<td>0.09</td>
<td>2.62</td>
<td>53</td>
<td>47</td>
<td>47</td>
<td>27</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>8.</td>
<td>Flowerdale</td>
<td>0.0007</td>
<td>1.02</td>
<td>0.03</td>
<td>0.11</td>
<td>2.56</td>
<td>32</td>
<td>29</td>
<td>29</td>
<td>27</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>9.</td>
<td>Coburg-2</td>
<td>0.0007</td>
<td>1.07</td>
<td>0.06</td>
<td>0.11</td>
<td>2.62</td>
<td>56</td>
<td>50</td>
<td>-</td>
<td>28</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>10.</td>
<td>Coburg-3</td>
<td>0.0007</td>
<td>1.06</td>
<td>0.05</td>
<td>0.09</td>
<td>2.55</td>
<td>53</td>
<td>51</td>
<td>-</td>
<td>28</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>11.</td>
<td>Craigieburn-1</td>
<td>0.0062</td>
<td>1.25</td>
<td>0.11</td>
<td>0.19</td>
<td>2.6</td>
<td>80</td>
<td>96</td>
<td>-</td>
<td>43</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>12.</td>
<td>Craigieburn-2</td>
<td>0.0008</td>
<td>1.12</td>
<td>0.08</td>
<td>0.12</td>
<td>2.65</td>
<td>65</td>
<td>62</td>
<td>-</td>
<td>32</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td>13.</td>
<td>Wantirma</td>
<td>0.0047</td>
<td>1.22</td>
<td>0.11</td>
<td>0.07</td>
<td>2.59</td>
<td>78</td>
<td>90</td>
<td>-</td>
<td>29</td>
<td>34</td>
<td></td>
</tr>
<tr>
<td>14.</td>
<td>Wollert-1</td>
<td>0.0022</td>
<td>1.15</td>
<td>0.09</td>
<td>0.02</td>
<td>2.62</td>
<td>69</td>
<td>69</td>
<td>-</td>
<td>17</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td>15.</td>
<td>Wollert-2</td>
<td>0.0015</td>
<td>1.17</td>
<td>0.07</td>
<td>0.34</td>
<td>2.6</td>
<td>64</td>
<td>62</td>
<td>-</td>
<td>45</td>
<td>42</td>
<td></td>
</tr>
<tr>
<td>16.</td>
<td>Jae</td>
<td>0.0045</td>
<td>1.22</td>
<td>0.11</td>
<td>0.14</td>
<td>2.61</td>
<td>77</td>
<td>92</td>
<td>-</td>
<td>35</td>
<td>34</td>
<td></td>
</tr>
<tr>
<td>17.</td>
<td>Officer</td>
<td>0.0007</td>
<td>1.11</td>
<td>0.04</td>
<td>0.47</td>
<td>2.63</td>
<td>51</td>
<td>57</td>
<td>-</td>
<td>41</td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>18.</td>
<td>BH1</td>
<td>0.0006</td>
<td>1.08</td>
<td>0.06</td>
<td>0.14</td>
<td>2.58</td>
<td>59</td>
<td>55</td>
<td>-</td>
<td>29</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td>19.</td>
<td>S16</td>
<td>0.0069</td>
<td>1.3</td>
<td>0.13</td>
<td>0.4</td>
<td>2.61</td>
<td>94</td>
<td>94</td>
<td>-</td>
<td>40</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>20.</td>
<td>S17</td>
<td>0.00078</td>
<td>1.031</td>
<td>0.12</td>
<td>0.45</td>
<td>2.56</td>
<td>73</td>
<td>72</td>
<td>-</td>
<td>25</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>21.</td>
<td>S18</td>
<td>0.00079</td>
<td>1.031</td>
<td>0.11</td>
<td>0.445</td>
<td>2.56</td>
<td>75</td>
<td>74</td>
<td>-</td>
<td>24</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>22.</td>
<td>S1</td>
<td>0.0062</td>
<td>1.23</td>
<td>0.13</td>
<td>0.2</td>
<td>2.56</td>
<td>71</td>
<td>73</td>
<td>-</td>
<td>45</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td>23.</td>
<td>S2</td>
<td>0.00077</td>
<td>1.031</td>
<td>0.09</td>
<td>0.22</td>
<td>2.56</td>
<td>71</td>
<td>73</td>
<td>-</td>
<td>36</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>24.</td>
<td>S3</td>
<td>0.00072</td>
<td>1.03</td>
<td>0.04</td>
<td>0.07</td>
<td>2.56</td>
<td>53</td>
<td>59</td>
<td>-</td>
<td>27</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td>25.</td>
<td>S4</td>
<td>0.00088</td>
<td>1.038</td>
<td>0.11</td>
<td>0.3</td>
<td>2.61</td>
<td>72</td>
<td>75</td>
<td>-</td>
<td>36</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td>26.</td>
<td>S5</td>
<td>0.00069</td>
<td>1.015</td>
<td>0.05</td>
<td>0.11</td>
<td>2.55</td>
<td>59</td>
<td>60</td>
<td>-</td>
<td>30</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>27.</td>
<td>S6</td>
<td>0.00266</td>
<td>1.21</td>
<td>0.12</td>
<td>0.3</td>
<td>2.62</td>
<td>75</td>
<td>81</td>
<td>-</td>
<td>39</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>28.</td>
<td>S7</td>
<td>0.00534</td>
<td>1.228</td>
<td>0.13</td>
<td>0.3</td>
<td>2.61</td>
<td>77</td>
<td>84</td>
<td>-</td>
<td>42</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>29.</td>
<td>S8</td>
<td>0.00225</td>
<td>1.12</td>
<td>0.12</td>
<td>0.3</td>
<td>2.6</td>
<td>75</td>
<td>78</td>
<td>-</td>
<td>40</td>
<td>42</td>
<td></td>
</tr>
<tr>
<td>30.</td>
<td>S9</td>
<td>0.00382</td>
<td>1.214</td>
<td>0.12</td>
<td>0.31</td>
<td>2.6</td>
<td>76</td>
<td>84</td>
<td>-</td>
<td>41</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>31.</td>
<td>S10</td>
<td>0.00136</td>
<td>1.17</td>
<td>0.10</td>
<td>0.25</td>
<td>2.58</td>
<td>72</td>
<td>73</td>
<td>-</td>
<td>38</td>
<td>38</td>
<td></td>
</tr>
</tbody>
</table>
Table 2. Cont.

<table>
<thead>
<tr>
<th>No.</th>
<th>Samples</th>
<th>σs (S/m)</th>
<th>X</th>
<th>FLL</th>
<th>FPL</th>
<th>Gs</th>
<th>LL (%)</th>
<th>Casagrande</th>
<th>EC Cone</th>
<th>EC Thread-Rolling</th>
<th>PL (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32.</td>
<td>S11</td>
<td>0.00083</td>
<td>1.035</td>
<td>0.06</td>
<td>0.12</td>
<td>2.55</td>
<td>62</td>
<td>67</td>
<td>-</td>
<td>31</td>
<td>29</td>
</tr>
<tr>
<td>33.</td>
<td>S12</td>
<td>0.00149</td>
<td>1.22</td>
<td>0.16</td>
<td>0.4</td>
<td>2.6</td>
<td>79</td>
<td>86</td>
<td>-</td>
<td>42</td>
<td>39</td>
</tr>
<tr>
<td>34.</td>
<td>S13</td>
<td>0.00081</td>
<td>1.034</td>
<td>0.05</td>
<td>0.11</td>
<td>2.55</td>
<td>59</td>
<td>62</td>
<td>-</td>
<td>30</td>
<td>31</td>
</tr>
<tr>
<td>35.</td>
<td>S14</td>
<td>0.00125</td>
<td>1.16</td>
<td>0.07</td>
<td>0.16</td>
<td>2.57</td>
<td>65</td>
<td>69</td>
<td>-</td>
<td>42</td>
<td>36</td>
</tr>
<tr>
<td>36.</td>
<td>S15</td>
<td>0.00422</td>
<td>1.217</td>
<td>0.12</td>
<td>0.3</td>
<td>2.6</td>
<td>77</td>
<td>84</td>
<td>-</td>
<td>34</td>
<td>39</td>
</tr>
<tr>
<td>37.</td>
<td>Bendigo</td>
<td>0.0021</td>
<td>1.01</td>
<td>0.02</td>
<td>0.02</td>
<td>2.59</td>
<td>39</td>
<td>33</td>
<td>40</td>
<td>23</td>
<td>33</td>
</tr>
<tr>
<td>38.</td>
<td>Clyde North</td>
<td>0.0035</td>
<td>1.02</td>
<td>0.024</td>
<td>0.03</td>
<td>2.65</td>
<td>40</td>
<td>48</td>
<td>49</td>
<td>23</td>
<td>32</td>
</tr>
<tr>
<td>39.</td>
<td>Coburg-1</td>
<td>0.0008</td>
<td>1.07</td>
<td>0.05</td>
<td>0.16</td>
<td>2.64</td>
<td>55</td>
<td>52</td>
<td>-</td>
<td>32</td>
<td>32</td>
</tr>
</tbody>
</table>

3.3. Validation of EC Outcomes

The results obtained from the EC approach to predict both liquid limit and plastic limit have been validated with fall cone and thread-rolling tests, as shown in Figures 5 and 6, respectively. Overall, $R^2 = 0.90$ and $LCCC = 0.91$ were obtained for liquid limit prediction, and $R^2 = 0.64$ and $LCCC = 0.80$ were observed for plastic limit prediction.

![Figure 5](image_url)  
Figure 5. Validation of EC approach with fall cone test for all the tested soils. LL = liquid limit. Straight line through the points is the regression line (red), and the other straight line from the origin is the 1:1 line.

According to Figure 5, the majority of the measured values from the EC approach were in close agreement with the conventional fall cone test, with some underestimation and overestimations in both lower and higher ends. $LCCC = 0.91$ was a great outcome, considering that 39 different clay soils with diverse physico-chemical characteristics were part of this study. The level of underestimated liquid limit predictions at 80% or higher was the primary reason behind reducing the accuracy of the EC approach. However, there was also a possibility that the measurement of the fall cone was not entirely correct at liquid limits greater than 80%, and this could be behind the inaccurate prediction beyond the 80% liquid limit range. Nevertheless, both the $R^2$ and LCCC values shown in Figure 5 demonstrated that EC approach was quite close to the fall cone values.
Figure 6. Validation of EC approach with thread-rolling test for all the tested soils. PL = plastic limit. Straight line through the points is the regression line (red), and the other straight line from the origin is the 1:1 line.

Meanwhile, Figure 6 depicts the level of agreement between the EC approach and thread-rolling tests for identical soil samples. While the $R^2$ value was 0.64, the LCCC outcome can be described as quite significant and positive. The $R^2$ value depends on the regression trend, and, based on Figure 6, the distribution of sample values was heavily dominated in between 30% and 45% of plastic limits. Unlike liquid limits of clay soils, plastic limits do not possess a wider range. Therefore, the $R^2$ value might have been decreased. However, as LCCC demonstrates how close the measured points are to the 1:1 line, and because LCCC = 0.80 was achieved, the EC approach to predicting the plastic limit of soils can still be considered to be a promising method.

3.4. Consideration of Fall Cone as Benchmark

Due to a limited sample amount, it was not feasible to produce the result for the missing data via the Casagrande method in Table 2. However, both the fall cone and Casagrande methods have been attributed to producing identical results for clay soils with a liquid limit < 100%, and this boundary should cover most of the natural soils. In fact, most of the inconsistency between the fall cone and Casagrande method is observed for clay soils with liquid limit > 70% [36–38]. Therefore, the absence of data from the Casagrande method did not raise any concern in validating the present study. The final comparison of liquid limit outcome was made with the fall cone test being considered as the benchmark.

The shear strength of soil at the liquid limit consists of viscous and frictional shear resistance. Therefore, it is not pragmatic to think of a device which can determine both components simultaneously [39]. The liquid limit by the Casagrande method accentuates the predominant viscous shear resistance in order to obtain the final outcome through the number of blows. Meanwhile, the fall cone test is fundamentally designed to focus on the frictional shear resistance. It has been mentioned that the Casagrande method is well-suited for soils that have a higher liquid limit (for example, more than 100%), and in terms of lower liquid limit, fall cone can be more accurate [40]. Finally, Ozer [41] showed that a soil with liquid limit < 70% can have around 2% difference in the outcome of an identical sample if a comparison is made between the fall cone and Casagrande method. The findings from this study also support this statement, and therefore the fall cone was considered as the benchmark for accuracy assessment in regard to EC. Figure 7 represents such findings. Both $R^2$ and LCCC were found to be 0.99 for the selected sample, which further cemented
the accuracy of the aforementioned discussion. However, it should be mentioned here that the focus of this study was not to identify the appropriate suite between the fall cone and Casagrande; therefore, further discussion on this has not been elaborated upon.

![Graph](image)

Figure 7. Agreement of liquid limit values for identical clay soils between fall cone and Casagrande tests. Straight line through the points is the regression line (red), and the other straight line from the origin is the 1:1 line.

3.5. Limitation of the Study and Future Recommendations

Although the EC approach to determine the liquid limit and plastic limit of clay soils has been proven to be accurate, with great future potential, the study can be further improved by increasing the sample number. The determination of F is significant in this study, and the accuracy of the surface analysis should improve if the number of samples can be increased, particularly in the plastic limit prediction. This will ensure a better fit on the surface, and the equation will be more accurate and precise.

Furthermore, the current study did not consider any clay soil sample with a liquid limit greater than 100%. However, this does not significantly downgrade the quality of the present study. It is a well-known fact that most of the natural soils have liquid limit less than 100%. Fundamentally, the EC approach was able to predict liquid limits below 100% with acceptable accuracy. Nevertheless, the potential of the EC approach would have further increased if it could have predicted the liquid limit of clays with high plasticity, such as bentonite. Bentonite is a laboratory-based clay with a high swelling capacity, and it possesses a larger DDL. The liquid limit of bentonite may vary from 100% to 600%; as a result, prediction of the liquid limit, and other clay soils with liquid limits > 100%, through the EC approach needs to be investigated. A machine learning approach could be a great option which would consider all the relevant parameters and predict F more accurately, leading to a possibly much-improved prediction of the liquid limit and plastic limit of clay soils.

4. Conclusions

A new approach to determine the liquid limit and plastic limit of clay soils has been proposed in this study by considering electrical conductivity parameters. The method considered the electrical surface conduction (σs) of solid clay particles and incorporated the variations in diffuse double layer (DDL) thickness (χ) to present liquid limit and plastic limit measurement techniques. Multifarious numerical analyses have been conducted to determine a new parameter (F), which was the ratio of volumetric water contents of DDL water and free water. The obtained equations to predict F were validated through
resampling approaches, and overall good agreements were observed. Finally, the liquid limit and plastic limit values obtained through the EC approach were compared with conventional fall cone and thread-rolling tests, respectively. For liquid limit prediction, $R^2 = 0.90$ and LCCC = 0.91 was achieved, whereas for plastic limit, $R^2 = 0.64$ and LCCC = 0.80 were gained. The outcome of this study proposes an alternative approach to determine liquid limit and plastic limit of clay soils by an on-spot, single-point measurement, whereas the conventional methods take almost 24 h to obtain the final result. The present study considered clay soils with liquid limits between 29% and 96% (fall cone) and plastic limits between 24% and 50% (thread-rolling), which covered the majority of the natural clay soil range. Although the equations to determine $F$ were validated with 39 samples across different batches, any new clay soil would require an accurate determination of $F$ by incorporating $\sigma (=\sigma_s/\sigma_w)$ and $\chi$ to predict the liquid limit and plastic limit by the EC technique within the aforementioned ranges.

**Author Contributions:** Conceptualization, M.F.H. and H.A.-N.; methodology, M.F.H. and H.A.-N.; software, M.F.H.; validation, M.F.H. and H.A.-N.; formal analysis, M.F.H. and H.A.-N.; investigation, M.F.H. and H.A.-N.; resources, M.F.H. and H.A.-N.; data curation, M.F.H.; writing—original draft preparation, M.F.H.; writing—review and editing, H.A.-N.; visualization, M.F.H. and H.A.-N.; supervision, H.A.-N.; project administration, H.A.-N.; funding acquisition, H.A.-N. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding. The work was carried out when the first author was pursuing a PhD and was financially supported by the La Trobe University Research Fellowship.

**Data Availability Statement:** All data are provided in a tabular format. Further information can be provided upon request, subject to approval from the institution.

**Conflicts of Interest:** The authors declare no conflicts of interest.

**References**

28. O’Kelly, B.C. Review of recent developments and understanding of Atterberg limits determinations. *Geotechnics* 2021, 1, 59–75. [CrossRef]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.