Abstract — The undrained shear strength occurs when the soil is quickly loaded without pore pressure dissipation. This parameter is measured by field and laboratory tests. Frequently, field tests present undrained shear strength quicker and in a larger amount than laboratory tests, even though there is an application of empirical formulation in some of these values. The present research aims to determine the undrained shear strength by the Fall Cone test, which was developed in Sweden by John Olsson between 1914 and 1922. To assess the applicability of the Fall Cone, the undrained shear strength was determined by additional tests, some of which are unconsolidated undrained triaxial and laboratory vane test. The materials of the research were 16 Brazilian soil samples with varying geotechnical properties and offshore sampling. The Fall Cone test is agreeable with traditional tests, besides being a simplistic and quick method. To conclude, the equipment can be considered as an option to complement and assist undrained shear strength evaluations from soft soils.

Index Term — Undrained shear strength. Fall Cone test. Offshore samples. Triaxial tests.

I. INTRODUCTION

The presence of soft clays deposits along the Brazilian coast encourages their study since the determination of the characteristics of this type of soil is fundamental for the lease of industrial and urban infrastructure [4]. For the determination of geotechnical parameters in soft soils some situations should be considered, such as natural variability of the field, acquisition of experimental data, stability and settlement analysis, as well as strength, deformability, and hydraulic conductivity parameters [15]. Baixada Fluminense and Baixada Santista are some of the deposits studied for project and research purposes [2].

At the laboratory to estimate undrained shear strength the following tests can be used: unconsolidated undrained triaxial, unconfined compression, fall cone and mini vane test. Fall cone and mini vane test have advantages such as simplicity, response speed and low cost in which the measurements of undrained shear strength are obtained, allowing a greater number of tests in a given sample when compared with the classic tests.

Between 1914 and 1922, John Olsson, member of the Geotechnical Commission of the Swedish Railways developed a device to determine the consistency of clays [3]. The Swedish fall cone was created to obtain in a simple and fast way the values of liquid limit and undrained shear strength, which has encouraged many countries, such as Canada, Sweden, and England, to adopt it as standardized equipment [14].

One of the practical advantages of Fall cone is that the test can be performed in a few minutes, obtaining the result of shear strength through a simple formulation and allowing quick identification of clay for indices and physical properties [3]. In the laboratory vane test, the influence of time can interfere with the results in two distinct ways, first in the delay between the insertion of the vane and the beginning of the rotation, and the speed of rotation [11]. The unconsolidated undrained triaxial test (UU) is defined as quick because there is no drainage in the course of the test and has no stage of consolidation, therefore the time factor depends mainly on the selected shear rate.

The present work aims to estimate undrained shear strength by the Fall Cone test and evaluate its applicability in Brazilian soils samples for undisturbed and remolded conditions. At the remold condition, there were realized tests in different recipients to verify the interference of the dimensions at the results. Afterwards, a comparative evaluation of undrained shear strength results was made to verify if the obtained results were consistent when compared to classic tests and formulations.

II. MATERIALS AND METHODS

The Fall cone test was developed to perform the Atterberg limits (liquid limit and plastic limit), sensitivity of clays and undrained shear strength for undisturbed and remolded samples. To undisturbed samples, the results depend on the quality of sample. Due to possible effects of anisotropy and saturation degree, undrained shear strength can vary, and this encountered value is not a $S_o$ representative of field [1].

The Fall cone test consists of measuring the penetration that a cone under precise conditions of weight and angle penetrates vertically into a previously prepared soil sample. Only the tip of the cone touches the horizontal surface of a sample and the cone is released under its own weight [7]. Then, the cone penetration is measured. The test is considered undrained because the cone penetration happens quickly and there is no time to dissipate the pore water pressure [12].

The procedure used to perform the test was ISO 17892-6 –
Geotechnical investigation and testing – Laboratory testing of soil – Part 6: Fall cone test. Each test was determined by 3 points, each point distant from each other 25 millimeters. The equipment is represented in the following figure.

![Fall cone equipment](image)

Fig. 1. Fall cone equipment

The calculation of the undrained shear strength proposed by Hansbo (1957) considers that the shear strength of soil in kPa is proportional to the mass of cone (Q) and inversely proportional to the square of the penetration, the K coefficient depends on the cone opening angle, also shear rate and sensitivity of the clays. The equation used by ISO 17892 standard acknowledges 0.80 and 0.27 as K values to 30° and 60° cones respectively and multiplicate the formulation by the acceleration of gravity (g = 9.81 m/s²).

\[ S_u = K \cdot g \cdot \frac{Q}{P^2} \]  
Eq. 1

The "cone type" parameter was evaluated to define which cone is most applicable to Brazilian soil samples. And, also verify a suitable correlation with the more usual tests in the practice of geotechnical engineering in the country. Three types of the cone were used to determine undrained shear strength in undisturbed and disturbed samples: mass of 100 grams and angle of 30° denominated Cone 1, mass of 60 grams and angle of 60° denominated Cone 2 and mass of 10 grams and 60° angle designated as Cone 3.

Another relevant parameter for the Fall Cone's evaluation, it is the size of the receptacle in which occurs the placement of remolded sample because this receptacle varies according to the standard considered. The aim has evaluated the influence of dimension on the results of undrained shear strength. In the present study, four types of receptacle were considered: the sampler itself, ISO 17892-6, the container considered by Karlsson (1981) and the cylindrical aluminum container used in previous work by the author. The containers’ dimensions are presented at the table below.

<table>
<thead>
<tr>
<th>Receptacle</th>
<th>Diameter (mm)</th>
<th>Height (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampler</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>ISO 17892-6</td>
<td>55</td>
<td>40</td>
</tr>
<tr>
<td>Karlsson (1981)</td>
<td>50</td>
<td>25</td>
</tr>
<tr>
<td>Clemente (2015)</td>
<td>70</td>
<td>22</td>
</tr>
</tbody>
</table>

The samples used are undisturbed and have been collected in a region near Baixada Fluminense. It has various geotechnical properties and depths varying from 0.91 to 12.40 meters. To have a good range of results in the present work, tests had executed on 16 samples. Table II presents the properties of the selected samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Moisture content (%)</th>
<th>Specific weight (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>48.0</td>
<td>1.74</td>
</tr>
<tr>
<td>2</td>
<td>50.4</td>
<td>1.64</td>
</tr>
<tr>
<td>3</td>
<td>53.9</td>
<td>1.67</td>
</tr>
<tr>
<td>4</td>
<td>122.2</td>
<td>1.36</td>
</tr>
<tr>
<td>5</td>
<td>88.0</td>
<td>1.48</td>
</tr>
<tr>
<td>6</td>
<td>74.9</td>
<td>1.48</td>
</tr>
<tr>
<td>7</td>
<td>90.9</td>
<td>1.49</td>
</tr>
<tr>
<td>8</td>
<td>79.7</td>
<td>1.47</td>
</tr>
<tr>
<td>9</td>
<td>45.8</td>
<td>1.73</td>
</tr>
<tr>
<td>10</td>
<td>44.3</td>
<td>1.74</td>
</tr>
<tr>
<td>11</td>
<td>43.9</td>
<td>1.75</td>
</tr>
<tr>
<td>12</td>
<td>38.3</td>
<td>1.81</td>
</tr>
<tr>
<td>13</td>
<td>52.0</td>
<td>1.68</td>
</tr>
<tr>
<td>14</td>
<td>34.0</td>
<td>1.80</td>
</tr>
<tr>
<td>15</td>
<td>46.3</td>
<td>1.74</td>
</tr>
<tr>
<td>16</td>
<td>48.6</td>
<td>1.72</td>
</tr>
</tbody>
</table>

The samples were identified according to the Unified Soil Classification System (USCS) as C – clay and M – silt. It was not observed neither odor nor characteristic color of organic matter and for this reason, the influence of organic content was not considered in the evaluation. In the figure below, samples were plotted on a plasticity chart.

![Plasticity chart](image)

Fig. 2. Plasticity chart
For the undisturbed condition, the following tests were performed: Fall Cone test, unconsolidated triaxial test (UU) and laboratory vane test, also no other containers were considered so that there was no remolding of the sample.

In the remolded samples only the Fall Cone test and laboratory vane test had been executed.

III. RESULTS

The first aspect evaluated for the undisturbed condition will be the undrained shear strength and the test penetration for the three cone types. The undrained shear strength was calculated by equation 1 with the application of a correction factor (μ) according to the liquid limit performed by the Fall Cone method. The trendline that best fits the undrained shear strength versus penetration plots for the undisturbed condition was the potential trend line. In the figure below is presented the results for this condition. Considering all the results obtained, the R² value was 0.3412, indicating an inconsistent adjustment. However, when analyzed individually, the lines for each cone have adequate R² values, above 0.97, showing a good correlation between the obtained results.

Comparing the results obtained with classic tests, it was observed that the results obtained by the Cone are larger than the results obtained by the laboratory vane test and unconsolidated undrained triaxial test (UU). Considering the UU test results for Cone 2 and 3, the trend lines were very close to each other and above the ideal line. In some cases, such as the results of Cone 2 compared to laboratory vane test results, the undrained shear strength by the Cone becomes 50% greater than by the laboratory vane test.

As for the undisturbed condition, when analyzed by cone, the trend lines for each cone have consistent R² values, above 0.99, showing a good correlation between the obtained results. Recalling that for each cone are being considered all the results obtained by the containers studied.

The comparison between the results of the Fall Cone test and laboratory vane test show that the obtained values by the Fall Cone are lower than the ones obtained by the laboratory vane test, except for the tests using Cone 3 performed at the sampler. In certain situations, the values show good convergence and in others, the results indicate considerable variability.

IV. DISCUSSION

For the undisturbed condition, it can be observed that each cone generates a differentiated slope of the others, confirming
that the penetration is inversely proportional to the undrained shear strength as presented by Hansbo (1957). The variance between the penetrations for the three cones for the same sample are not constant, because of the anisotropy of the soils and the parameters of opening angle and mass of each cone. In the case of the tested samples, the cone that best fits were Cone 1 (100 grams) because it reached a range of 3.17 to 13.17 mm. Cone 2 (60 grams) had a range of values from 1 to 5 millimeters and cone 3 obtained the smallest range of values from 0.5 to 2 millimeters. If consideration of the ISO17892-6 (5 - 20 mm) penetration range had been validated, cone 2 and 3 would not be the most appropriate options for material characterization. It can be said that the lower penetrations show undrained shear strength inconsistent with reality.

Among the Cone 1 and 2 results, there is always a cone that best fits the value found by the UU triaxial tests, due to the consistency characteristics of the sample and the mass of the cone used. The UU triaxial tests and Fall Cone tests show less compatibility than expected. Lemos (2014) also compared the results obtained through the UU triaxial test and Fall Cone, and the overall results did not show good correspondence. The conclusion was that if the correct consideration was given to the sample characteristics and test methodology, it would be possible to achieve more consistent results.

The Cone 1 (100 grams and the opening angle of 30 °) was the best option for the remolded condition. Besides, Cone 1 agrees with the ISO17892-6 penetration range recommendation. In Cone 2, some values fit the range provided by the standard, but not all of them. Cone 3 is below the minimum accepted by the standard. As for the undisturbed condition, the smaller penetrations can be unreliable and indicate overrated undrained shear strength values. A different inclination of the curve is also observed for each type of cone, confirming again that the penetration is inversely proportional to the values of undrained shear strength [5].

In the remolded samples, the variations between the penetrations for the three cones for the same sample are irregular. But for this condition, the values demonstrate a pattern of behavior: the penetration difference between the values of Cone 1 and 2 is of at least 1.3 times the difference between the values of Cone 2 and 3. When evaluated the penetrations in the different containers studied for the same Cone and sample, the values are similar, varying around 2 millimetres for penetrations of up to 10 millimetres. For larger penetrations, the values produce differences of up to 4 millimetres.

By comparing the results of the Cone and laboratory vane test, mostly the values obtained for the cone are smaller than the values for the vane test. The lines closest to the ideal were the results obtained by the Cone 3 in the ISO container and the sampler, and by the Cone 2 in the sampler. Cone 1 had the lowest correlations among the evaluated ones.

V. CONCLUSION

In this experimental work, the inverse proportional relation of the undrained shear strength and the penetration proposed by Hansbo in 1957 was confirmed. The calculation of the determination of undrained shear strength by the formula of ISO17892-6 tends to overestimate the resistance values due to the low penetrations. Thus, it demonstrates values that are inconsistent with reality and should be used with caution. The lightest cones for these materials had low penetrations of the order of 0.5 to 3.8 millimetres and throughout the scale of the equipment, it can be considered as inaccurate values.

The mass of the Cone affects the results: the larger the mass of the cone, the higher the penetration range reached. For the studied materials, it was the Cone 1 that has the best fit at the undisturbed and remolded conditions.

The height/diameter ratio (H / D) of the containers considered in this research influences subtly the undrained shear strength in the remolded condition due to penetration variations. The penetration values for the same sample were close or similar but did not indicate critical interference at the undrained shear strength result.

It has been shown that the Cone tests are compatible with the conventional tests as unconsolidated undrained triaxial and laboratory vane test, depending on the selected cone. The type of cone applied should always be considered in the assessment. For a quick evaluation of the undrained shear strength, the Cone test is simple and a fast method to perform. It allows a greater number of test points in the same sample and a small amount of material is necessary for its execution. For those reasons and observing the differences in values for the classic tests, the use of Cone can be a complement to the classic tests.

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REFERENCES


