

## Determination of Pre-Consolidation Pressure by Different Method

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**Abstract:** One of the most important soil problems seen on fine-grained soils is the settlement problem. The primary consolidation settlement shows itself over time with the effect of water. Also, the settlement properties of soil change depending on the stress history. In this study, silt mixtures with three different sand percentages were prepared using the slurry sludge preparation method under 50kPa load, and pre-consolidation pressures were calculated by performing the oedometer experiment on the obtained samples. Using the collected oedometer data, the pre-consolidation pressures were calculated and compared by six different methods. As a result, the results equal to the vertical stress values applied for the three mixtures were obtained by Butterfield and Tavenas methods. Sand content was effective in Casagrande, Van Zelst, and Janbu methods, but not in Butterfield, Tavenas, and Shmertman.

**Keywords:** Oedometer test; Pre-consolidation pressure; Silt; Sand content.

### 1. Introduction

The Geotechnical discipline examines a structure with billions of years of geological history. Therefore, the science that studies such a heterogeneous structure requires the solution of highly complex problems. All engineering structures are related to the soil. All kinds of engineering structures such as dwellings, service buildings, bridges, dams, roads, airports are located on or in the soil. As Richard 1995 says, “almost every structure is supported by soil or rock. Those that are not supported either fly, float, or fall” [1]. Like all objects, all soils are subjected to volume loss, i.e., vertical unit deformation, with the stress in particular, the engineering structure loads cause vertical strains in the vertical direction on soils with insufficient bearing capacity and excessive settling. But time is also an important factor in vertical unit deformations when stress is applied on clay soil. This situation causes vertical unit deformations to change in the sand for a few days and to clay soils from a few months to a few years.

Pisa tower is the first structure that comes to mind when it comes to soil problems and settlement. Its construction started in 1173, and it took approximately 200 years intermittently. The tower began to bend during construction, and after the construction was completed, the bending continued. As of 1950, the Fine Arts Palace in Mexico City has more than 3 meters of residence than the surrounding streets. The reason for this is shown as opening many water wells as the city grows. Settlement problems are seen not only under the structure but also on roads and bridge approaches. In California, 1m seating was observed in the embankment 12 years later due to the heavy approach fillings. In this context, accurate and accurate calculation of the oedometer test used to determine clay soil's settlement values is essential for its basic design [1].

Clays do not forget the loads on it in the past, and the load information is preserved in the soil structure [2]. This protected information can be calculated after obtaining the void ratio ( $e$ ) and logarithmic pressure ( $\sigma$ ) curve from the data collected after the pre-consolidation experiment. In general, the pre-consolidation pressure is calculated by the Casagrande method, Schmertmann, Janbu, Butterfield, Tavenas, Van Zelst, etc. methods also calculate it. After determining the preliminary consolidation, the condition of the clay or silt in the field is evaluated.

In Casagrande, he said that soils trapped the maximum effective stresses in their geological backgrounds in their tissues [2]. Accordingly, Casagrande developed the Casagrande method for determining the maximum effective stress (pre-consolidation pressure) [3]. Sağlamer et al. conducted oedometer experiments on samples prepared under controlled stress conditions [4]. Preliminary consolidation pressures were estimated and compared with these experiments' data by the methods given by Casagrande, Schmertmann, Janbu, Butterfield, and Tavenas.

Çetin applied preloads at different times on two different soils to evaluate whether they could record the effective stresses they exposed during faulting [5]. Later, by performing standard consolidation experiments on these samples, the Casagrande method determined preliminary consolidation pressures. He said that the total stress applied to both soils in the preload time of 2 seconds took over 60% as pre-consolidation pressure. Also, it showed

that the pre-consolidation pressures found in this way might have been recorded during the faulting of these soils 1100 years ago. Less than 4 minutes may be sufficient to record the total effective stress applied to the coarse-grained (sandy clay) unit. However, it has been determined that a minimum loading time of 5 minutes is required for the fine-grained (silt, clay) applied total stress to be recorded in its memory. He linked the time difference to the hydraulic conductivity coefficients of these two different soils.

Tan and Karagöz applied consolidation pressures to clay soil [6]. Oedometer experiments were carried out on the samples. Experimental results pre-consolidation pressures were determined by Casagrande, Butterfield, Tavenas, Burmister, and Van Zest methods. Statistical analyzes were made by comparing the determined pre-consolidation pressures with the actual pre-consolidation value. The study said that the Tavenas method is the closest result of easy, using arithmetic axis sets and reading the pre-consolidation pressure directly on the graph. They also noted that the second sensitive method was the Butterfield method.

Yılmaz et al. investigated sand and zeolite's effect on clay soil's frontal consolidation pressure [7]. They compared Casagrande and Sridharan's methods and stated that the pre-consolidation pressure values obtained were compatible with the methods. They revealed that the pre-consolidation pressure values are related to the deformation rate and uniaxial pressure values at the end of the study. Çelik and Tan investigated the determination of pre-consolidation pressure with an artificial neural network [8]. They studied an artificial neural network model was developed to determine pre-consolidation pressures in clay soils using Statistica. Researchers compared the model and graphical methods (Casagrande, Tavenas, and Butterfield) with actual (experimental) pre-consolidation pressures. They said that the artificial neural network model yielded a larger determination coefficient, lower standard deviation ratio, lower mean absolute error, and lower root mean square error.

Yıldırım and Çelebi investigated the effect of the test method and sample type on the pre-consolidation pressure on unconsolidated and undisturbed samples [9]. Experiments were carried out in one-dimensional and three-dimensional. They stated that depending on the research, the pre-consolidation pressure depends on the type of samples used in the tests, the consolidation test methods, and the methods used to find the pre-consolidation pressure. Umar and Sadrekarimi studied determining pre-consolidation pressure from laboratory tests [10]. Researchers conducted a series of 30 laboratory oedometer tests that are carried out in this study based on controlled-rate of strain and incrementally-loaded testing techniques. These test results ( $\sigma'_p$ ) are compared with the predictions of eleven methods for determining  $\sigma'_p$ . They said that a bi-logarithmic graphical approach based on the slopes of the virgin compression and recompression segments of the soil compression curve provides the most accurate predictions of  $\sigma'_p$ . Paniagua et al. investigated the practices for pre-consolidation pressure evaluation from oedometer tests [11]. Researchers determined the pre-consolidation pressure ( $\sigma'_p$ ) from high-quality oedometer test results using various interpretation methods [3, 12-15]. Researchers said that the pre-consolidation pressure was varying up to 14% between the five methods.

Another study investigated the effect of sample disturbance on the evaluation of pre-consolidation pressure of undisturbed saturated clays by using Schmertmann method [16]. This was carried out by comparing the scars estimated from the consolidation test results with the pocket penetrometer readings for the same samples. C value was obtained by pocket penetrometer, and consolidation tests got  $\sigma_c$ . From c and  $\sigma_c$  data are obtained the correlations. Researchers said that the results from consolidation tests were valid for a wide range of clay stiffness, ranging between medium stiff to very stiff clay. Also, they said that for soft clay, it could not have relied on the readings of pocket for estimating. Peri et al. investigated the behavior of oedometer tests on Yoldia clay [17]. For this purpose, primary consolidation pressures were filtered from creep using Brinch-Hansen, Taylor, and ANACONDA method. Later, the pre-consolidation pressures were determined according to Akai, Janbu, and Casagrande-Terzaghi theories. Researchers said that the pre-consolidation stress values and the consolidation curves are slightly influenced by the separation of strains method applied.

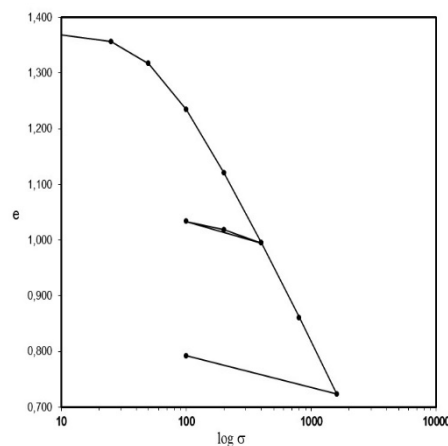
D'Ignazio et al. investigated pre-consolidation stress of clays from piezocone [18]. This purpose was used as a multivariate database consisting of numerous high-quality onshore and offshore clay data points in this paper. Correlations in the literature and available data were compared to measure uncertainties. However, despite the high quality of the data points, correlations are still affected by uncertainties. Researchers said that the correlations proposed in this study should be used only for preliminary assessment of the in-situ stress history in the absence of  $\sigma_c$ . Ali et al. investigated pre-consolidation pressure using soil index properties [19]. For this purpose, they compared pre-consolidation pressure and soil index properties. Thus, researchers suggested soil index and consolidation test data of alluvial deposits of the Bannu soil region. In new empirical correlations were derived correlations about pre-consolidation pressure  $\text{kN/m}^2$  and over consolidation ratio for deposits.

In this study, silt mixtures with three different sand percentages were obtained, and the mixes were prepared using the slurry sludge preparation method under 50kPa load. Afterward, pre-consolidation pressures were calculated by performing the oedometer experiment on the obtained samples. At the end of the study, the pre-consolidation pressures were calculated and compared using six different methods using the oedometer's data.

## 2. Pre-consolidation pressure account

It can be defined as the preliminary consolidation pressure as the largest pressure that the soil has been exposed to throughout its entire geological history. While explaining the pre-consolidation pressure that affects the soil's physical and mechanical properties, Casagrande described it as a function of adsorbed water around the clay soils [3]. At the same time, Terzaghi defined it with many changes in the soil's macrostructure [20]. On the other hand, Lambe said that it was related to ion exchange between clay and water [21]. If a soil collapse is loaded higher than the level of stress it has been subjected to in the past, the soil structure can no longer bear the increased load and begins to collapse. The mechanisms that cause pre-consolidation of soils are listed below.

- a) Change of total stress due to cover reduction, old structures, and glacier;
- b) Change in groundwater level and pressure due to artesian pressures, deep pumping (flow into a tunnel), surface drying (shrinkage), plant effect, and drying;
- c) Change in soil structure due to secondary compression;
- d) Environmental changes such as pH, temperature, and salt concentration;
- e) Chemical changes that occur due to precipitation, precipitation, and ion exchange;
- f) It can be listed as the change of unit deformation in loading [22].



**Fig. 1.** A typical oedometer test result

In Figure 1, the  $e$ - $\log$  curve obtained as a result of a typical oedometer experiment is given. The point where the slope of the consolidation curve changes is an important event in the consolidation process. The stress at this point is called the pre-consolidation pressure ( $\sigma'_p$ ). The  $\sigma'_{z0}$  value of the sample is sometimes higher than  $\sigma_{z0}$ . This means that the sample was once exposed to higher stress. While conducting consolidation analysis, the pre-consolidation pressure ( $\sigma'_p$ ) and the effective vertical stress ( $\sigma'_{z0}$ ) are compared. The effective vertical stress is determined using total stress and pore water pressures, while pre-consolidation stress is determined from laboratory test data. When these values are determined, it is determined whether the soil is normally or over-consolidated clay. Accordingly, the formula to be used in the consolidation settlement is selected:

- a)  $\sigma'_{z0} \approx \sigma'_p$ . In this case, the effective vertical stress in the field was never higher than its current size. This condition is known as normal consolidated (NC).
- b)  $\sigma'_{z0} < \sigma'_p$ . In this case, means higher than the current size of the land in the past effective vertical stress. This condition is known as over-consolidated (OC) or pre-consolidated.
- c)  $\sigma'_{z0} > \sigma'_p$ . In this case, the soil is inadequate. This condition means that the soil is still in the consolidation process under the preload.

The pre-consolidation stress obtained from the consolidation experiment represented only the conditions when the sample was taken. If the sample is taken from another level, the pre-consolidation pressure is different [1]. For a soil to be excessively consolidated:

- a) Excessive erosion or excavation where the current soil surface level is much lower than in the past;
- b) Surcharge loading caused by the glacier that was previously present and melted;
- c) Surcharge loading caused by a structure such as a previously existing and removed storage tank;
- d) Increases in pore pressure, as in the rising water table;
- e) Drying due to evaporation, plant roots, and other processes leading to negative pore water pressures on the soil;
- f) Chemical changes such as the accumulation of binders  $\sigma$  on the soil;

g) It has to be subjected to processes such as aging effects [1, 23, 24]. Many methods have been developed to calculate the pre-consolidation pressure. We can list these methods as Casagrande, Schmertmann, Jambu, Butterfield, Tavenas, Van Zelst.

## 2.1 Casagrande method

The most commonly used method is the Casagrande method. The Casagrande method is a graphical method based on the pre-consolidation pressure value's determination using the void ratio-consolidation pressure ( $e - \log \sigma'$ ) graph drawn on the semi-logarithmic axis set [3]. As a result of the consolidation experiments, the gap ratio at the end of the loading stages is calculated, and the compression curve ( $e - \log \sigma$ ) is drawn (Figure 2). The point where the minimum radius of curvature is located on the curve is marked. This point is illustrated with the horizontal line parallel to the horizontal axis and the tangent line. The angle created by the horizontal and tangent is divided into two equal parts. The bisector line and the line extended from the high-pressure region where the pinch curve turns to the line coincide. The abscissa of the overlapping point gives the pre-consolidation pressure ( $\sigma'_p$ ) under which the soil was influenced in the past [1, 22, 25].

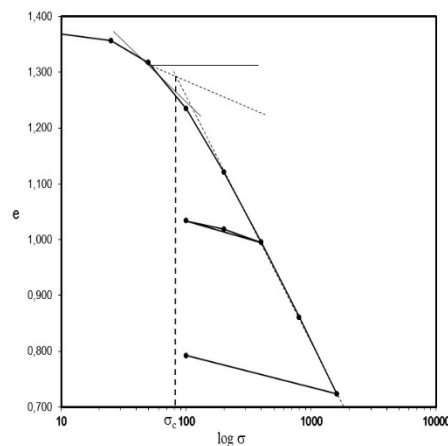


Fig. 2. Determination of pre-consolidation pressure with the Casagrande method

## 2.2 Schmertmann method

The Schmertman method reconstructs the land consolidation curve [26]. First, the estimated ( $\sigma'_{z0}$ ) is selected using the Casagrande process. In the sample depth, the effective vertical stress ( $z$ ) is calculated. A horizontal line is drawn at  $e = e_0$ , and then a vertical line is drawn from ( $z_0$ ). The estimated land compaction curve is obtained by drawing a line that extends the copper curve down to the level of  $e = 0.42e_0$ . The void ratio differences ( $\Delta e - \log \sigma_1$ ) between this curve and the laboratory curve are marked on the axis set, and a symmetrical curve is drawn (Figure 3). These processes are repeated until the process is symmetrically selected by selecting different pre-consolidation pressures [1].

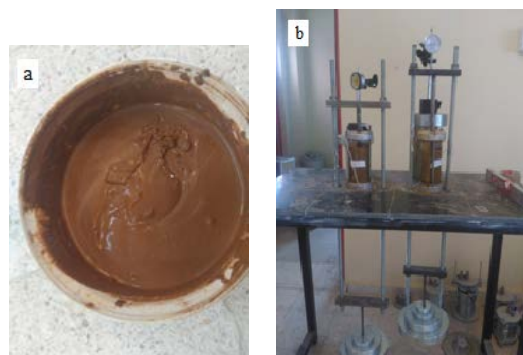


Fig. 3. a) Homogeneous mixed slurry mud b) 50kPa loading and consolidated mixture.

## 2.3 Janbu method

Janbu method has determined of  $\sigma'_c$  on plots of tangent constrained modulus values versus  $\sigma'_v$  [12, 27]. Using the Janbu method is easy [28]. In the curve of  $\Delta \sigma' / \Delta e$  and  $\sigma'$ , the point where the fracture appears directly gives

the front consolidation pressure. In the  $\Delta H/H$  and  $\sigma'$  curve, the point where the continuity is disturbed in the stress-deformation curve gives the pre-consolidation pressure [29].

#### 2.4 Butterfield method

The Butterfield method includes determining the soil volume change of the front consolidation pressure on the graph showing the variation with stress [30]. The point where the graph obtained by drawing the  $(\ln(1+e) - \log \sigma)$  graph instead of the  $(e - \log \sigma)$  graph is broken is defined as the pre-consolidation pressure [31].

#### 2.5 Tavenas method

The Tavenas method is based on determining the pre-consolidation pressure from the stress-strain energy relationship [32]. The deformation energy is equal to the area under the stress-deformation curve drawn from the oedometer experiment. The compression curve starts linearly and at a low slope, and the curve continues its linear and low slope movement as the stress applied to the soil increases. When the increased pressure reaches a certain value, the slope of this linear movement of the curve varies greatly and continues at the same high slope due to increased stress. The value of this point where the curve changes slope on the horizontal axis is taken as the front consolidation pressure [31].

#### 2.6 Van Zelst Yöntemi

The Van Zelst method is a simple method that can be applied to consolidation curves drawn by the data obtained by gradually increasing stress on the sample and removing this stress progressively. In this method, the graph of  $\Delta H / H - \log \sigma$  is used. A line (I) is drawn first, parallel to the discharge curve. A second parallel line (II) is then drawn from the loading parallel to this line. Finally, a tangent is drawn upwards from the linear bottom of the curve. Here, the trajectory of the point where this tangent cut line II on the apse is determined as the pre-consolidation pressure [31].

### 3. Materials and methods

In this research, the silt (ML) was crushed with a roller. The silt is shown in the plasticity chart, according to ASTM D2487 [33]. Three different mixtures were made using 100% Silt, 90% Silt +10% Sand, and 80% Silt +20% Sand. Liquid limit tests of these three mixtures were conducted and determined 45%, 43%, and 40%, respectively. For three different mixtures, silt and sand were taken and mixed homogeneously. Slurry sludge is formed by adding 1.5 times the water of the wL and left for one night (Figure 3a). Then, the slurry taken into the mold is mixed again, shaken by hand, and the air is removed. The sample is put into the mold in 3 layers with a spoon, and it is leveled with a spatula until water comes out from the surface. The sample and the porous stone on its top are kept under 5 mm of water to prevent air entry. Samples were loaded at 50kPa (Figure 3b). The deformation clock was placed in the experimental setup, and the values of the hours were recorded daily and recorded. The clocks were fixed, and samples were taken for the oedometer device [34]. The oedometer experiment for each mixture was performed. In the oedometer device, 50, 100, 200, 400, 800, 1600, 3200, 800, 100 kPa loads were made, and their deformations were recorded daily. The data were compared with the data recorded by finding the pre-consolidation pressure in 6 different methods.

### 4. Oedometer test and its results

The one-dimensional loading behavior of soils can be tested using an oedometer. The oedometer is found in the compression and speed of the soil (Figure 4). The prepared samples are placed on the steel consolidation ring and kept underwater until the experiment's end. Starting with standard loads, it is loaded with 24-hour intervals and 2-fold strain increments. This time, the jams indicated by the sample are monitored with a micrometer clock. After the readings are recorded, time (t)-compression ( $\delta$ ) readings are obtained for each strain interval. Thus, void ratio-consolidation pressure ( $e - \log \sigma'$ ) is drawn, and calculation is started for pre-consolidation pressure. Pre-consolidation pressure was calculated according to 6 different methods, and results are given in Table 1.

Sand content was effective in Casagrande, Van Zelst, and Janbu methods, but not in Butterfield, Tavenas, and Shmertman (Figure 5.). In the Casagrande method, the increase in the sand content caused the reduction of the pre-consolidation pressure. 10% increase in the sand caused 1% decrease in pre-consolidation pressure. In the Janbu method, the increase in the sand content caused the increase of the pre-consolidation pressure. 10% increase in the sand caused 1% increase in pre-consolidation pressure. In the Van Zelst method, the sand content increase caused the pre-consolidation pressure to give different values. Firstly, a 10% increase in the sand caused a 6% increase in pre-consolidation pressure, then a 10% increase in the sand caused a 12% decrease in pre-consolidation pressure.

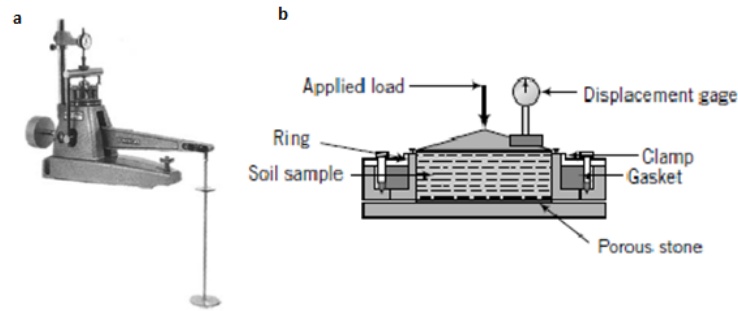


Fig. 4. a) Homogeneous mixed slurry mud b) 50kPa loading and consolidated mixture

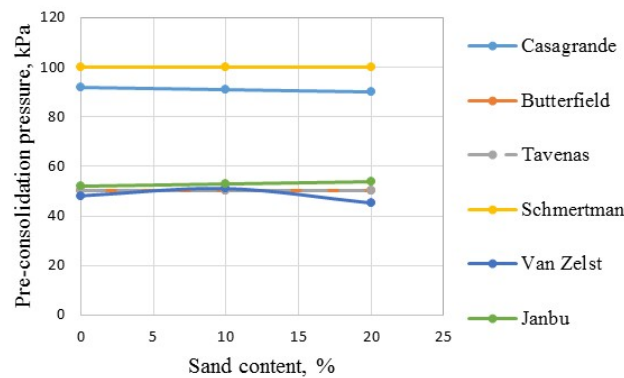


Fig. 5. Change pre-consolidation with sand content

Table 1. Pre-consolidation pressures of mixtures according to methods

Mixtures	Casagrande	Butterfield	Tavenas	Schmertman	Van Zelst	Janbu
100% Silt	92 kPa	50 kPa	50 kPa	100 kPa	48 kPa	52 kPa
90% Silt +10% Sand	91 kPa	50 kPa	50 kPa	100 kPa	51 kPa	53 kPa
80% Silt+20% Sand	90 kPa	50 kPa	50 kPa	100 kPa	45 kPa	54 kPa

Pre-consolidation pressure values calculated with the Casagrande method decreased with increasing sand percentage, according to Table 1. The pre-consolidation value of 100% Silt sample is 84% more than applied vertical stress. The pre-consolidation value of 90% Silt +10% Sand sample is 82% more than applied vertical stress, and the pre-consolidation value of 80% Silt+20% Sand sample is 80% more than applied vertical pressure. Pre-consolidation pressure values calculated by Butterfield, Tavena, and Schmertmann method gave the same result for three mixtures. The pre-consolidation pressure values for all mixtures are 50kPa by the Butterfield and the Tavenas method. The pre-consolidation pressure values for all mixtures are 100kPa by the Shmertmann method. The pre-consolidation pressures obtained by the Shmertmann method are 100% more than the applied vertical pressure. The pre-consolidation pressure values calculated with the Van Zelst method differed with the increase in the percentage of sand. The pre-consolidation value of 100% Silt sample is 4% less than applied vertical stress. The pre-consolidation value of 90% Silt +10% Sand sample is 2% more than applied vertical stress, and the pre-consolidation value of 80% Silt +20% Sand sample is 10% less than applied vertical pressure. Pre-consolidation pressure values calculated with the Janbu method increased with increasing sand percentage. The pre-consolidation value of 100% Silt sample is 4% more than applied vertical stress. The pre-consolidation value of 90% Silt +10% Sand sample is 6% more than applied vertical stress, and the pre-consolidation pressure value of 80% Silt +20% Sand sample is 6% more than applied vertical pressure. All mixtures were compressed under a load of 50kPa. The vertical stress values applied in the oedometer experiment were calculated correctly with Butterfield and Tavenas methods. This finding is also consistent with those of Tan and Karagöz [6]. Also, pre-consolidation values obtained by Vanzelst and Janbu methods were calculated close to the applied vertical pressure value. At the same time, the pre-consolidation values calculated by the Casagrande method gave almost twice the applied vertical loading pressure. The pre-consolidation values are twice applied vertical loading pressure by the Schmertman method.

## 5. Conclusion

In this study, mixes were prepared by adding different sand percentages to the silt, and then samples were mixed with the water content 1.5 times the liquid limit, and samples were prepared by the slurry sludge method. In the slurry sludge method, samples were exposed to 50kPa vertical stress. Afterward, samples were subjected to consolidation experiments with an oedometer, and time-compression data were obtained. Thus, the curves required for the pre-consolidation pressure to be calculated according to 6 different methods were drawn, and pre-consolidation values were obtained.

It was seen that sand content was effective in Casagrande, Van Zelst, and Janbu methods, but not in Butterfield, Tavenas, and Shmertman. In the Casagrande method, the increase in the sand content caused the reduction of the pre-consolidation pressure. In the Janbu method, the increase in the sand content caused the increase of the pre-consolidation pressure. In the Van Zelst method, the sand content increase caused the pre-consolidation pressure to give different values. Pre-consolidation pressure values were calculated with the Casagrande method more than applied vertical stress. Pre-consolidation pressure values calculated by Butterfield, Tavena, and Schmertmann method gave the same result for three mixtures. The pre-consolidation pressure values for all mixtures equals applied vertical stress by the Butterfield and the Tavenas method. The pre-consolidation pressure values for all mixtures twice by the Shmertman method. The pre-consolidation pressure values almost equal applied vertical stress by the Van Zelst method and Janbu methods.

Based on the results obtained from this study, it is recommended to calculate the pre-consolidation pressure by at least 2 or 3 different methods besides the most preferred Casagrande method in the application. Also, MORE tests are required on samples with varying properties in other soil classes to get conclusions about the applicability of different pre-consolidation pressure determination methods.

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