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Atterberg Limits Estimation of Pilani Soil Using Ultrasonics

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Abstract: Depending on water content, four physical states of soil consistency are used. The water contents at which soil undergoes physical state change are called Atterberg limits. Liquid as well as plastic limit are two commonly used Atterberg limits and are used extensively, either individually or together, with other soil properties to correlate with engineering behavior such as compressibility, compactibility, shrink-swell and shear strength. Conventional method of liquid limit determination requires test to be conducted at 5 (at least) different water contents for accurate estimation. Even liquid limit estimation using cone penetrometer requires experiment to be carried out at more than one water content. Same is applicable for plastic limit estimation. Sand content has effect on its liquid and plastic limit, as well as pulse velocity through it. Consequently, it should be possible to estimate liquid and plastic limit by knowing pulse velocity through it. Pulse velocity using through transmission technique (at constant water content and density); as well as their liquid and plastic limits using conventional techniques at varying sand content were determined and plotted for Pilani soil. This plot can be used as calibration curve for aforementioned estimation purposes and can be developed for other region soils as well.

Keywords: Atterberg limits, Calibration curve, Soil behavior, Through transmission technique, Ultrasonic pulse velocity.

1. Introduction

The Atterberg limits are basic measure of the critical water contents of a fine-grained soil, such as its shrinkage limit, plastic limit, and liquid limit. As a dry, clayey soil takes on increasing amounts of water, it undergoes dramatic and distinct changes in behavior and consistency. Depending on the water content of the soil, it may appear in four states: solid, semi-solid, plastic and liquid. In each state, the consistency and behavior of a soil is different. Consequently so are its engineering properties. Thus, the boundary between each state can be defined based on a change in the soil's behavior. The Atterberg limits can be used to distinguish between silt and clay. It can distinguish between different types of silts and clays. These limits were created by Albert Atterberg, a Swedish chemist. They were later refined by Arthur Casagrande. These distinctions in soil are used in assessing the soils that are to have structures built on it. Soils when wet retain water and expand in volume. The amount of expansion is related to the ability of the soil to take in water and its structural make-up. These tests are mainly used on clayey or silty soils since these are the soils that expand and shrink due to moisture content. Clays and silts react with water, thus size changes and they have varying shear strengths. Thus these tests are used widely in the preliminary stages of designing. It ensures that the soil will have correct amount of shear strength and not too much change in volume as it expands and shrinks with moisture content.

As a hard, rigid solid in dry state, the soil becomes a crumbly semisolid when a certain water content, termed the shrinkage limit, is reached. If it is an expansive soil, this soil will also begin to swell in volume as this water content is exceeded. Increasing the water content beyond the soil's plastic limit transforms it into a malleable, plastic mass, causing additional swelling. The soil will remain in plastic state until its liquid limit is exceeded with increase in water content. This causes it to transform into a viscous liquid that flows when jarred [1].

If silty clay content in sand changes, its liquid limit and plastic limit also changes. This change in liquid limit & plastic limit is due to change in soil micro-structure as well as due to change in inter-particle interaction between soil particles in the presence of pore water when silty clay content changes. These two limits are determined using standard experiments in the soil mechanics laboratory.

The original liquid limit test of Atterberg involved patting a mixture of soil and water in a round-bottomed porcelain bowl of 10–12 cm diameter. A groove was cut through the soil-water mixture with spatula, and the bowl was then struck many times against the palm of one hand. Casagrande subsequently standardized the apparatus and the procedures to make the measurement more repeatable. Soil is placed into the metal cup portion of the device and a groove is made down its center with a standardized tool of 13.5 millimetres width. The cup is repeatedly dropped 10 mm onto a hard rubber base at a rate of 120 blows per minute, during which the groove closes up gradually as a result of impact. The number of blows for the groove to close is recorded. The water content at which it takes 25 drops of the cup to cause the groove to close over a distance of 13.5 millimetres is defined as liquid limit. The test is normally run at several water contents, and the water content which requires 25 blows to close the groove is interpolated from the test results.

Another method for measuring the liquid limit is fall cone test, also called cone penetrometer test. It is based on the measurement of penetration into the soil of a standardized cone of specific mass. Although the Casagrande test is widely used across North America, the fall cone test is much more prevalent in Europe due to being less dependent on the operator in determining the Liquid Limit. In this method also, several water contents have to be tested.

The plastic limit is determined by rolling out a thread of fine portion of a soil on a flat, non-porous surface. If the soil is at water content where its behavior is plastic, this thread will retain its shape down to a very narrow diameter. The sample can then be remoulded and the test repeated. As the moisture content falls due to evaporation, the thread will begin to break apart at larger diameters [2]. The plastic limit is defined as the water content where the thread breaks apart at a diameter of 3.2 mm. A soil is considered non-plastic if a thread cannot be rolled out down to 3.2 mm at any water content.

It is clear from aforementioned discussion, that experiments involved in determining liquid & plastic limits are quite complicated and time consuming. There should be alternative technique of estimating it. In the present study, it has been achieved using ultrasonics.

Ultrasonic testing is a family of non-destructive testing techniques based on the propagation of ultrasonic waves in the object or material tested. In most common applications, very short ultrasonic pulse-waves with center frequencies ranging from 0.1-15 MHz, and occasionally up to 50 MHz, are transmitted into materials [3]. Ultrasonic testing is often performed on steel and other metals and alloys, though it can also be used on concrete, wood, soil and composites, albeit with less resolution. Obtained ultrasonic pulse velocity changes with change in material micro-structure, soil particle size composition for example.

When ultrasonic pulses travel through soil samples, the pulse velocity changes with changes in properties of the soil such as density, moisture content, void ratio, porosity, degree of saturation and particle size composition [4]. Hence variation in any one of these parameters can be correlated with the changes in the ultrasonic pulse velocity, provided other parameters remain unaltered. In the present study, variation in ultrasonic pulse velocity with soil particle size composition has been studied. Frequency of ultrasonic pulses used in the present study was 0.15 MHz. Study has been conducted at 10% water content and at constant density of soil compact at 1.45 gm/cm^3.

Ultrasonic pulse velocity testing is a long established non-destructive testing method. It involves determination of velocity of ultrasonic pulses through the sample. This can be achieved by measuring time taken by ultrasonic pulse to travel a measured distance in the soil sample. Transducers are placed in contact with the sample and low frequency transducers are used for this purpose. Measurement can be done using through transmission technique. In this method transmitting and receiving transducers are placed on the opposite faces of the soil sample. The axes of the transducers are aligned. The pulse velocity is determined by using the single equation:

Pulse velocity = path length/transit time (1)

This single equation can be applied to transmission of pulses through material of any shape or size. Only restriction being that the least lateral dimension (dimension measured perpendicular to the path of pulses) should not be less than the pulse amplitude. Plan area of soil samples used in present study in ultrasonic testing was 6 cm x 6 cm. Sample thickness was 1.7 cm.

The pulse velocity is not affected by the frequency of the pulse. As a result the wavelength of the pulse vibrations is inversely proportional to its frequency. Thus pulse velocity will generally depend only on the properties of materials. For assessing quality of materials from ultrasonic pulse velocity measurement, measurement should be of high accuracy. Path length and transit time should each be measured to an accuracy of about $\pm$ 1% [5]. Velocity of ultrasonic pulses in present study in which soil particle composition was changing was found to range from 340 m/s to 510.5 m/s.

Liquid limit, plastic limit as well as ultrasonic pulse velocity (at constant water content & bulk density) strongly depend on soil particle size composition. This fact has been used to develop calibration curves to estimate liquid as well as plastic limit by knowing ultrasonic pulse velocity through it for Pilani soil in the present study.

2. Experimental details and discussion

Experimental work required coarse-grained as well as fine-grained soil. Coarse-grained soil was collected from desert stretch located some distance from Institute campus. Soil from this location was predominantly coarse grained. Soil sample had an in-situ moisture content of 4 to 5%. Experimental work also required fine grained soil. This soil was available locally close to the Institute campus at a depth of 12 to 15 meters. It was collected in the month of April from a deep ditch excavated at that location and the in-situ water content of the soil was 6%. Both soils were oven dried for 24 hours before using it for experiments.

Coarse grained soil retained on 150 μ sieve has been classified as sandy. Similalrly fine grained soil retained on 75 μ sieve as well as on pan have been classified as silty clay. This classification is based on dispersion test.

Five different particle size composition of soil were used in the present study, S_{150} = 90% by weight, C_{75} = 5% by weight, C_p = 5% by weight; S_{150} = 70% by weight, C_{75} = 15% by weight, C_p = 15% by weight; S_{150} = 50% by weight, C_{75} = 25% by weight, C_p = 25% by weight; S_{150} = 30% by weight, C_{75} = 35% by weight, C_p = 35% by weight; S_{150} = 10% by weight, C_{75} = 45% by weight, C_p = 45% by weight. S_{150} refers to sand retained on 150μ sieve, C_{75} refers to silty clay retained on 75μ sieve and C_p refers to silty clay retained on pan.

Liquid and plastic limit of aforementioned five soil samples were determined as per specifications [6]. Ultrasonic pulse velocity of same these samples were determined by using ultrasonic materials tester (Model : Emefco type UCT3). This ultrasonic materials tester is a low ultrasonic frequency (150 kHz) tester for civil engineering applications. Coarse grained samples like soils can conveniently be tested with this ultrasonic materials tester. Transmission time of the ultrasonic wave was measured through a given soil sample of known thickness. Testing was done using through transmission technique.

Transmitting and receiving transducers having diameter of 36 mm each were placed on the opposite faces of the soil sample so that their axes remain collinear. Grease was used as coupling agent between transducer face and soil sample. Ultrasonic wave passes through the soil sample from transmitting to receiving transducer. Transmission time of ultrasonic pulse was measured using this ultrasonic materials tester and pulse velocity was determined from Equation (1). Results of the experiments are summarized in Table 1 and plotted in Figure 1.

Table 1: Liquid limit, plastic limit and ultrasonic pulse velocity variation with sand content

Sand content (%)	Liquid limit (%)	Plastic limit (%)	Ultrasonic pulse velocity (m/s)
10	29	19.4	459.4
30	28	18.2	510.5
50	24.4	14.1	448.5
70	23.7	13.8	376.1
90	24.5	14.3	340

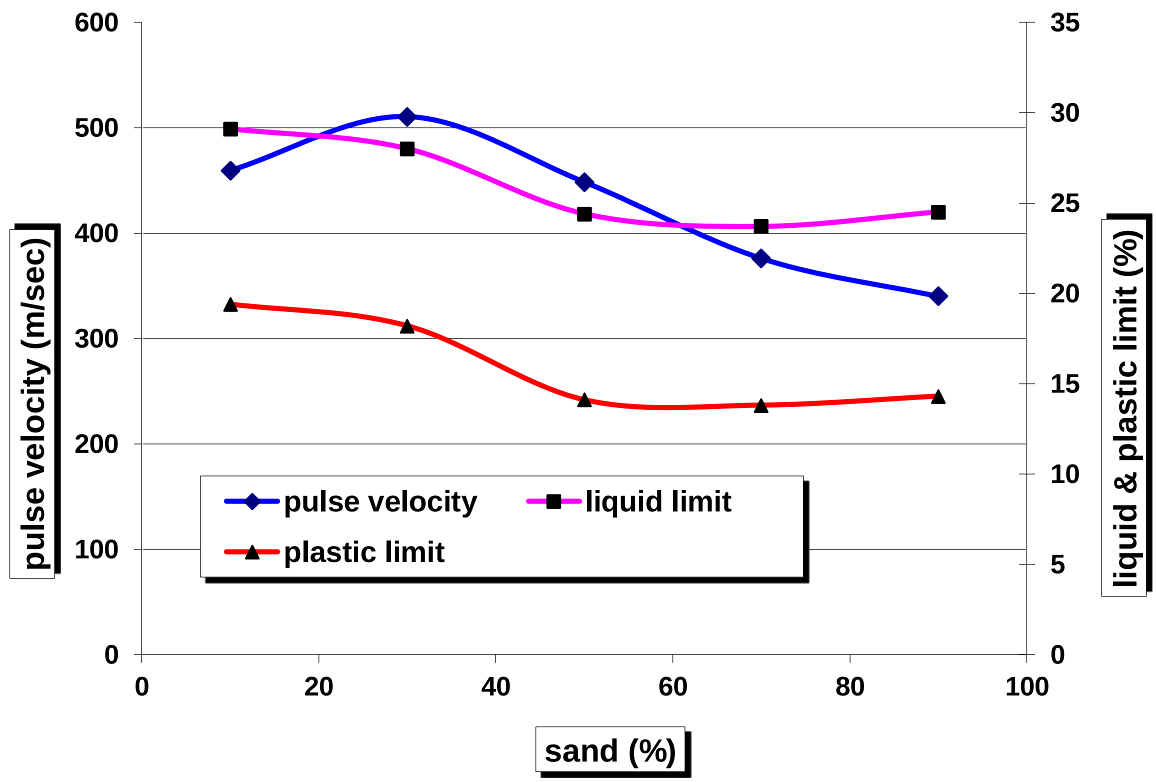

Figure 1: Liquid limit, plastic limit and ultrasonic pulse velocity variation with sand content

There is attraction as well as repulsion between soil particles in the presence of water [7]. From Figure 1 & Table 1 it is clear that as sand content increases from 10% to 70%, attraction effect decreases (in plastic as well as in semi-solid state) resulting in decrease in liquid as well as in plastic limit. For sand content increase from 70% to 90%, there is attraction effect increase (in plastic as well as in semi-solid state) resulting in increase in liquid as well as in plastic limit.

When an ultrasonic pulse propagates through soil, attenuation of the ultrasonic pulse takes place along the travel path. Scattering of ultrasonic pulse at the microscopic interface of soil particles is an important mechanism for attenuation of ultrasonic pulse. When particle size of soil increases, scattering of ultrasonic pulses also increases. Consequently an increase in soil particle size results in increased attenuation. An increase in attenuation of ultrasonic pulses through soil, in turn leads to higher transmission time of ultrasonic pulses through soil. Consequently ultrasonic pulse velocity decreases [8].

In the present study, sand content of soil was reduced from 90% to 30%, i.e. silty clay content of soil increased from 10% to 70%. This resulted in the decrease of ultrasonic attenuation leading to higher ultrasonic pulse velocity. The observed increase in ultrasonic pulse velocity was from 340 ms^{-1} to 510.5 ms^{-1} corresponding to the said decrease in sand content of soil from 90% to 30%.

If one goes for further reduction in sand content of soil from 30% to 10% i.e. increase in silty clay content from 70% to 90%, it leads to aggregation of silty clay soil particles in the presence of water resulting in floc formation. The flocculated silty clay soil particles behave like coarse grained particles. Consequently attenuation also increases under such conditions. This results in reduction of ultrasonic pulse velocity through soil. In the present study, ultrasonic pulse velocity through soil was found to decrease when sand content of soil was reduced from 30% to 10%.

3. Development of calibration curves

Figure 1 can be used as calibration curve. One can take soil sample from required location in Institute campus as well as from the vicinity, oven dry it, sieve it through 300 micron sieve (standard sieves used in soil sieving are 2.36 mm, 1.18 mm, 600 micron, 300 micron, 150 micron, 75 micron and pan in that sequence) and find out ultrasonic pulse velocity through it using the technique described in previous two sections. Estimated values of liquid and plastic limit then can be directly read from Figure 1 as long as pulse velocity is less than 459.4 m/sec for the obtained pulse velocity. For pulse velocity more than 459.4 m/sec, aforementioned soil passing through 300 micron sieve can be sieved through 150 micron sieve also to get exact silty clay content. Figure 1 then can be used to read estimated values of liquid & plastic limit for the obtained pulse velocity. It is clear from Table 1 as well as from Figure 1 that a wide range of particle size composition has been covered. Similar calibration curve can be developed for other reigon soil also.

4. Conclusions

Liquid as well as plastic limit are two commonly used Atterberg limits and are used extensively, either individually or together, with other soil properties to correlate with engineering behavior such as compressibility, compactibility, shrink-swell and shear strength. Experiments involved in determining liquid & plastic limits are quite complicated and time consuming. There should be alternative technique of estimating it.

Technique suggested in present study involves determination of ultrasonic pulse velocity through soil sample for the development and use of the calibration curve. Use of non-destructive testing (NDT) techniques is finding increasing applications for assessing the quality of materials including quality of soils. These testing techniques are very useful because they provide the desired information about the properties of the material. Ultrasonic testing is one such non-destructive testing (NDT) technique and is used for testing materials of civil engineering importance (e.g. concrete, wood, brick etc.). Measuring ultrasonic pulse velocity through soil samples requires only a simple set-up and is welcome alternative for assessing liquid and plastic limit of soils. Similar calibration curves can be developed for other reigon soil also, and hence developed calibration curves in present study involving the determination of ultrasonic pulse velocity through soil is of great significance.

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