Soil Structure Interaction
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Lecture - 5
Settlement of Shallow Foundation

In the last class, I have discussed about the bearing capacity of soil and I solved a problem to show how to determine the ultimate bearing capacity of soil or foundation based on different available theories. Then, I started to describe the settlement, the other criterion of foundation design. Today, I will continue discussing the settlement of shallow foundation.

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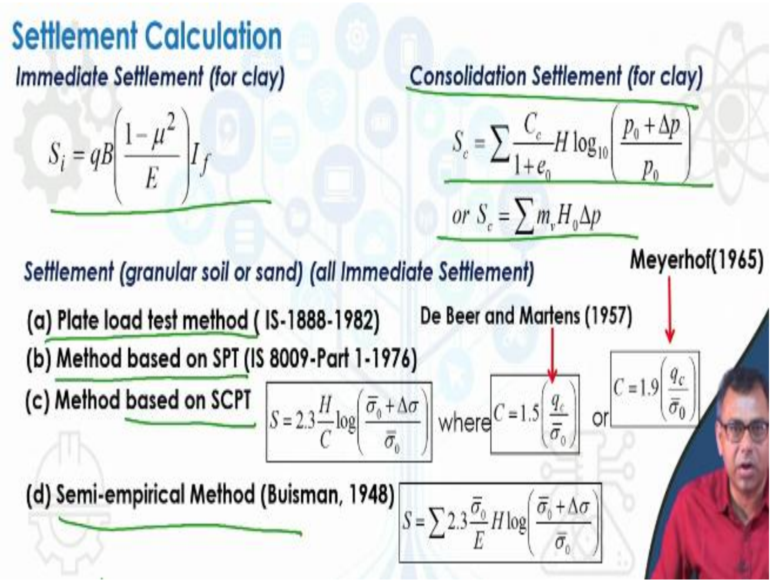

I have already discussed the settlement calculation. We are interested mainly in the settlement of clay or cohesive soil and that of granular or non-cohesive soil or sand. For a normally consolidated inorganic clay, most of the settlement will be immediate settlement and for a clayey soil, most of the settlement would be consolidation settlement. The immediate settlement we can determined by this expression:

$$S_i = qB\left(\frac{1-\mu^2}{E}\right)I_f$$

and the consolidation settlement can either be determined by this expression:

$$S_c = \sum \frac{C_c}{1+e_0} H log_{10}\left(\frac{p_0+\Delta p}{p_0}\right)$$

or by this expression:

$$S_c = \sum m_v H_0 \Delta p$$

depending upon the parameters that are available.

For the clayey soil, though the consolidation settlement contributes to the majority of total settlement, we still calculate the immediate settlement along with the consolidation settlement. But for the granular soil only immediate settlement will be considered as the total settlement which is usually determined by the settlement based on the field test. This can be done by plate load test, SPT (standard penetration test value), SCPT (static cone penetration test value) and also by some empirical expressions. I will discuss about the consolidation settlement, immediate settlement, then plate load test and the method based on SPT.

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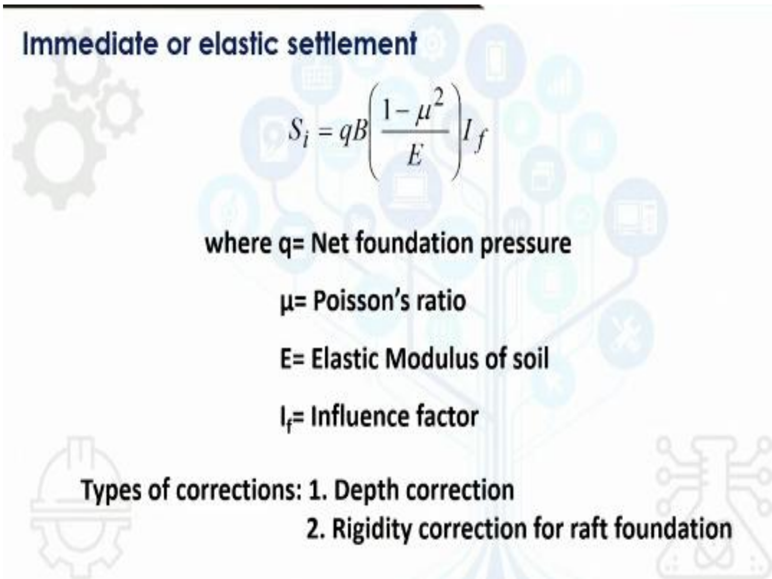

I have already discussed about the immediate settlement or the elastic settlement. This equation can be used: $S_i = qB\left(\frac{1-\mu^2}{E}\right)I_f$; where, q is the net foundation pressure, μ is the Poisson ratio, E is the elastic modulus of soil and I_f is the influence factor. To the value obtained from this equation, it may be required to apply two corrections: depth correction, and rigidity correction. Most of the times, depth correction is required because this expression is developed for a surface footing which is very rare practically.

Generally shallow foundations or isolated footings are considered to be flexible type of foundation and raft foundations as rigid type of foundations. So, for the raft foundation, the rigidity correction should be applied. This value is generally taken as 0.8.

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Shape	I_f for Flexible Foundation			I_f for Rigid Foundation
	Centre	Corner	Average	
Circle	1.0	0.64	0.85	0.86
Square	1.12	0.56	0.95	0.82
Rectangle				
L/B= 1.5	1.36	0.68	1.2	1.06
L/B= 2	1.52	0.76	1.3	1.2
L/B= 5	2.10	1.05	1.83	1.70
L/B= 10	2.52	1.26	2.25	2.10
L/B= 100	3.38	1.69	2.96	3.40

This is the table where the influence factor values can be obtained or read. To use the expression of immediate settlement, we will be needing the μ Poisson's ratio of the soil, E elastic modulus of the soil, and I_f influence factor. From the table, it can be noted that the influence factor depends upon the shape of the footing and L by B ratio where, L is the length of the foundation and B is the width of the foundation.

From the table, the I_f value for flexible footing, rigid footing at the center and corner of footing along with the average value can be read. When an I_f value is taken for a calculation, it is always recommended to take the value corresponding to the center because it is more compared to that of the corner. Besides, it is required to determine the maximum amount of settlement so that the settlement value can be adjusted to be within the permissible limit.

For a circular footing, the I_f value is 0.86 for rigid foundation and 1 for flexible foundation. Similarly for a square footing, it is 1.12 for the flexible at the center and 0.82 for the rigid foundation. So, it can be inferred that the rigid foundation I_f value is almost 0.8 times (80%) the I_f value of flexible foundation at the center.

So, for the design of a rigid foundation, firstly the I_f value at the center for a flexible foundation will be taken and multiplied with a rigidity factor of 0.8. The rigidity factor correction of 0.8 should be applied for consolidation settlement also.

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Types of soil	μ
1. Clay , saturated	0.4-0.5
2. Clay, unsaturated	0.1-0.3
3. Sandy clay	0.2-0.3
4. Silt	0.3-0.35
5. Sand(dense)	0.2-0.4
5.1 Coarse(e=0.4-0.7)	0.15
5.2 Fine grained	0.25
6. Rock	0.1-0.4

Ranjan and Rao, 1991

In the above table, the μ value or the Poisson's ratio for different types of soil was given. Clay soil which is saturated will usually have a μ value of 0.4 to 0.5. So, generally we take 0.5 as the μ value for calculation incase of a saturated clay.

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Elastic Modulus Calculation (E)

- Normally consolidate clay, E_u= (750 to 1200) c_u
- Heavily over consolidated clay, E_u= (1500 to 2000) c_u
- Normally consolidated sensitive clay, E_u= (200 to 600) c_u

The elastic modulus of soils depending upon the over consolidation ratio can be correlated to the undrained cohesion value (c_u) which is shown in the above table. If no other values are available/provided for E and if c_u value alone is given, then depending upon the type of soil, any value from the above range can be taken (preferably average of a range) to determine the E value. These values are like guidelines from where E value can be read depending upon c_u.

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Young's Modulus Calculation (E)

Type of soil	SPT (N) or CPT(q_c)
Sand (NC)	E= 500(N+15)
Sand (OC)	E= 250(N+15)
Sand(Saturated)	E= 250(N+15)
Gravely Sand	E= 1200(N+6)
Clayey sand	E= 320(N+15)
Silty sand	E= 300(N+6)
Soft clay	E= 5 to 8 q_c

Ranjan and Rao, 1991 * E is in kN/m^2.

Similarly, E value can also be calculated from the SPT or CPT data with the help of the above given correlations. N value is a result of SPT whereas q_c is a result of CPT. Remember that these are empirical expressions and so units are very important. Here the unit of E is kN/m^2.

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Elastic Modulus Calculation (E)

Soil type	E (kg/cm^2)
Clay	
1. Very soft	20-150
2. soft	50-250
3. medium	150-500
4. Hard	500-1000
5. Sandy	250-2500

Soil type	E (kg/cm^2)
Sand	
1. silty	70-210
2. loose	100-240
3.dense	480-800

Soil type	E (kg/cm^2)
Sand and gravel	
1. Loose	500-1450
2. Dense	1000-1900

This table gives the approximate range of E values depending upon the type of soil. Clay is divided into five categories (very soft, soft, medium, hard, sandy) for which the E value ranges from a minimum of 20 kg/cm^2 to a maximum of 2500 kg/cm^2. Similarly sand and gravel are also divided into groups and approximate range of values have been given.

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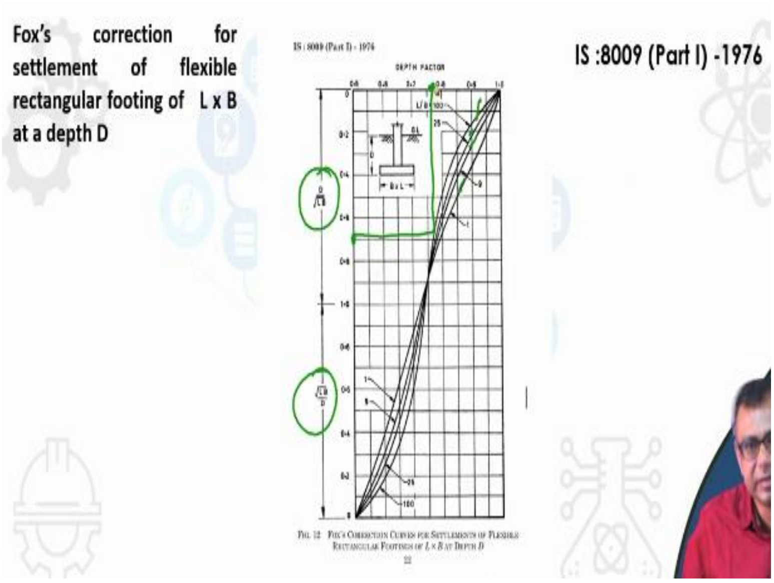

As discussed earlier, two corrections are to be applied for immediate settlement, depth correction and rigidity correction. The rigidity correction will be 0.8 as the influence factor values for rigid foundation are 80% that of for the flexible foundation. The above chart shows how to calculate the depth correction factor. This is Fox's correction chart for settlement that can be used for rectangular or square footing with different depths. The chart helps to read the depth correction factors on the X-axis. The values on Y-axis first increases from 0 to 1 and then decreases to 0 because the factor from 0 to 1 is $D/\sqrt{LB}$, and thereafter $\sqrt{LB}/D$. Basically, the upper half of the Y-axis has the $D/\sqrt{LB}$ values and the lower half, $\sqrt{LB}/D$. The lower half is usually applied for pile or deep foundation settlement calculation and upper half, for a shallow foundation settlement calculation. So, the same curve can be used for the shallow foundation settlement calculation and deep foundation settlement calculation.

So, from the D, L and B values, the depth correction factor can be read which should be multiplied with the calculated immediate settlement.

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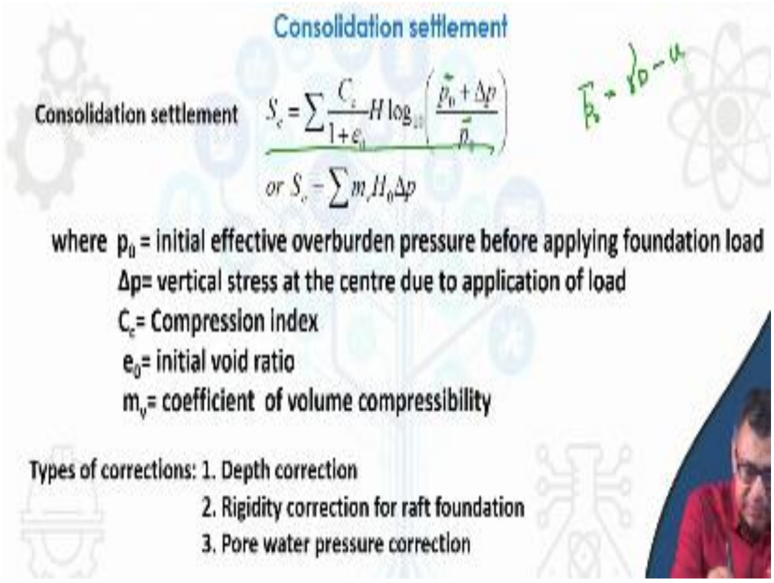

Another aspect of the total settlement of soils is the consolidation settlement. There are two different expressions to calculate the consolidation settlement and depending upon the available parameters, one of the two can be chosen:

$$S_c = \frac{C_c}{1+e_0} H \log_{10}\left(\frac{p_0 + \Delta p}{p_0}\right)$$

$$S_c = \sum m_v H_0 \Delta p$$

Where, H is the thickness of the different soil layer; H_0 is the thickness of different soil layers; Δp is stress increment due to the applied external load; $\bar{p}_0$ is the effective overburden pressure; Cc is compression index, e_0 is initial void ratio, and m_v is the coefficient of volume compressibility. As mentioned earlier, two corrections should be applied for immediate settlement, rigidity correction and depth correction.

For consolidation settlement, along with the depth correction and rigidity corrections, a third correction called pore water correction should also be applied. This is because according to Terzaghi, the soil undergoes one dimensional consolidation which is not true. In the field, consolidation usually occurs in all three dimensions (3-D consolidation). To cater for this difference between the theory and practical conditions, pore water correction need to be applied.

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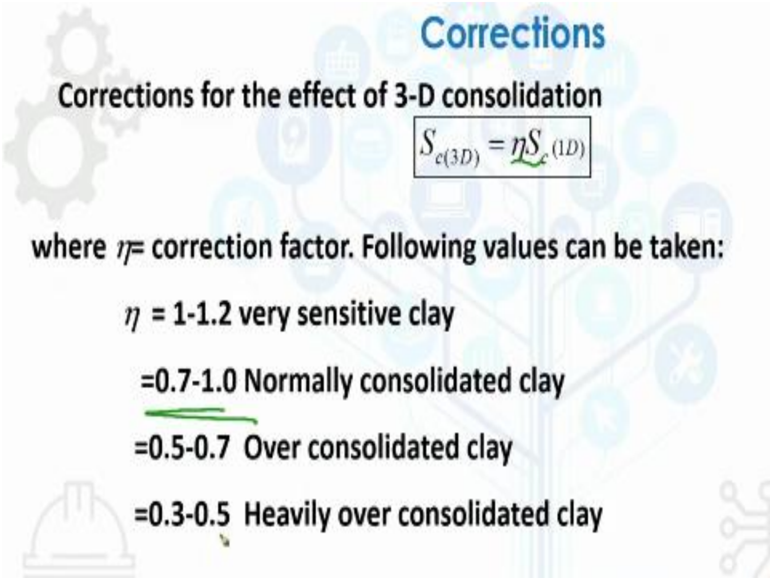

The values for the pore water correction factor depending upon the type of clay are given in this slide. It varies from 1 to 1.2 for sensitive clay; 0.7 to 1.0 for normally consolidated clay; 0.5 to 0.7 for over consolidated clay and 0.3 to 0.5 for heavily over consolidated clay. Note that only in case of a very sensitive clay, the correction factor is more than unity which is not true for all other cases.

The terminology used here like normally consolidated clay, over consolidated clay, heavily over consolidated clay can be found in any soil mechanics books which can be referred to because these terms will be discussed frequently in this course.

Till now, only the settlement calculation for clay soil has been discussed which consists of immediate settlement and consolidated settlement. Now, the immediate settlement of sandy soil will be explained because immediate settlement is the total settlement for sandy soil. So, first the plate load test will be detailed and then through an example problem, the concept of settlement from SPT will be looked into.

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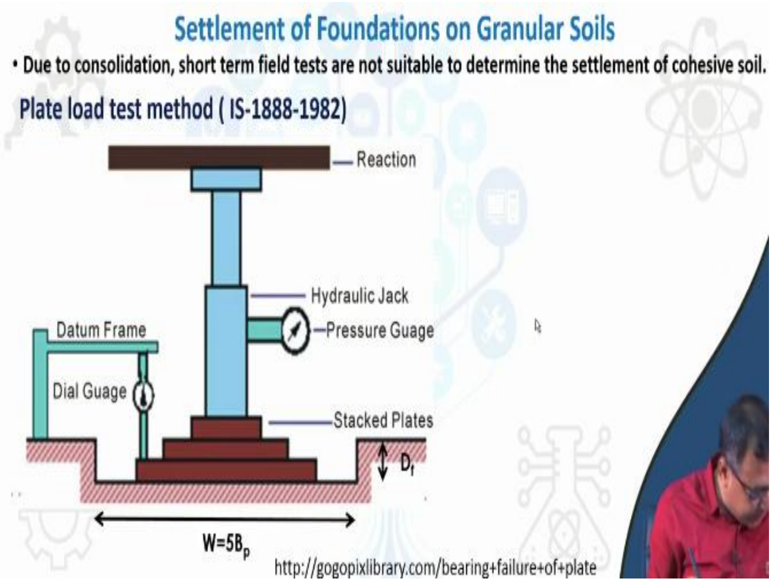

The next concept is about settlement of foundation in granular soils based on the plate load test. The plate load test is a short term test or for that matter, any field test is. So field tests are not recommended for cohesive soils because their behaviour is long term. As the permeability for clayey soils is very less, pore water pressure will dissipate after a long time and so the settlement occurs after a long time. So, for clay it is neither recommended nor suitable.

In a plate load test, the plate used for testing should ideally be equal to the depth of the foundation. If they both are not same, depth correction factor should be applied. The depth of plate (from ground level) will either be equal to the depth of foundation or lesser. It is usually not possible for the plate depth to be higher than that of foundation depth (from ground level). Sometimes, it is even difficult to reach the level of foundation which is when the test will be conducted above the foundation level. In that case, the depth correction factor should be applied to the settlement.

For the plate load test, first the soil should be excavated up to a desired depth. It is recommended that the width of this excavation should be five times the width of the plate. This is the minimum width of the excavated portion. The test setup consists basically of a test plate upon which plates with decreasing size should be stacked upon. The loading is applied with the help of a reaction frame and the corresponding plate settlement is calculated. The settlement is measured with the help of dial gauges and the load is measured with the help of a pressure gauge or proving ring. It is recommended to use at least two or three dial gauges. If three dial gauges are used, then the angle between the dial gauges will be 120^o. If only two dial gauges are being used, they should be at the two opposite corners of the plate. So quickly I will discuss the procedure of the plate load test.

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This is the typical photograph of a plate load test. The surcharge used is usually of sandbags or concrete blocks upon which the reaction frame acts upon to convert it into load on to plate.

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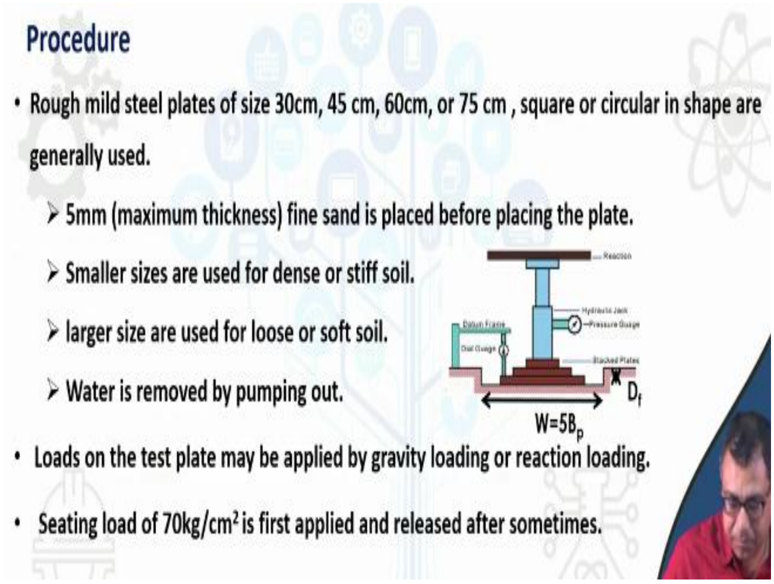

The test plate used is generally a rough mild steel plate of different sizes as 30 centimeter, 45 centimeter, 60 centimeter or 70 centimeter square or circular in shape. Remember that plate size less than 30 centimeter should not be used because the data will not be reliable. It is also observed that the behaviour of the plate does not change significantly if the plate size is more than 75. So the plate size can be restricted to 75 centimeter.

The data obtained from a 75 centimeter plate would be most reliable and also there would be no need to apply some corrections like shape factor. After excavating the soil, a 5 millimeter fine sand layer is laid on the ground and on that the test plate is placed. Then smaller size plates are stacked on it. The common practice is to use smaller test plates for dense or stiff soils and larger size test plates for loose or soft soils. If larger test plates are used in case of dense or stiff soils, the difference between the settlements corresponding to consecutive loads would be too small. On the other hand, if smaller test plates are used in soft or loose soils, the difference of settlements corresponding to consecutive loads would be too high.

The water is removed by pumping it out from the excavated portion and after that the load is applied by gravity loading or reaction loading. Before applying the actual loading on the plate, a seating load of 70 kg/cm^2 is first applied and released after some time. This load is applied to assure a perfect contact between the soil and the plate.

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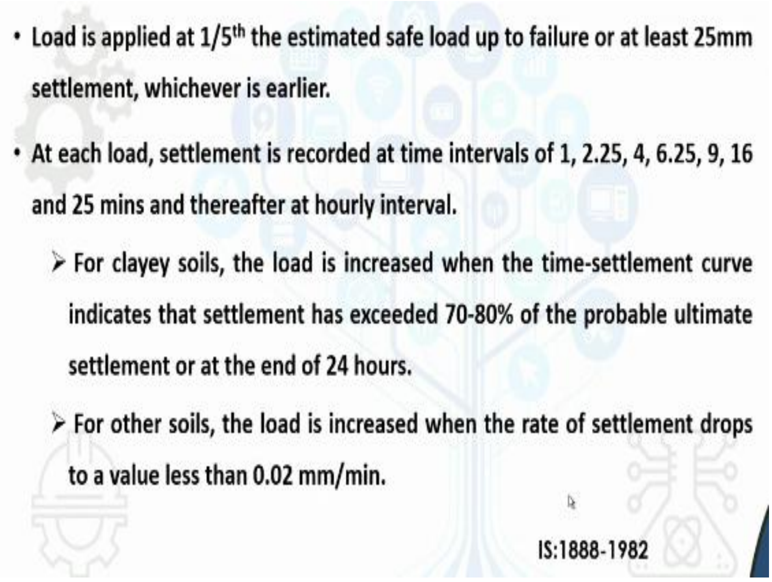

The safe load is estimated and one-fifth of it is applied first. The settlement is recorded at time intervals of 1, 2.25, 4, 6.25, 9, 16 and 25 minutes and for every hour after that. This process is repeated till the soil fails or 25 mm settlement occurs, whichever is earlier. Remember that each load increment would be equal to one-fifth of the safe load and after each load increment, settlement is recorded at the above mentioned time intervals. But, there is still a clarification needed about when to stop recording settlement after a load increment. For sandy soil, recording the settlement can be stopped (next load increment can be applied) when the rate of settlement value is 0.02 mm/min. This is an indication that equilibrium condition or stable condition is achieved. But for clayey soils, because of their long term settlement behaviour, readings should be taken up to 24 hours after each load increment or when the settlement is 70-80 % of the expected value.

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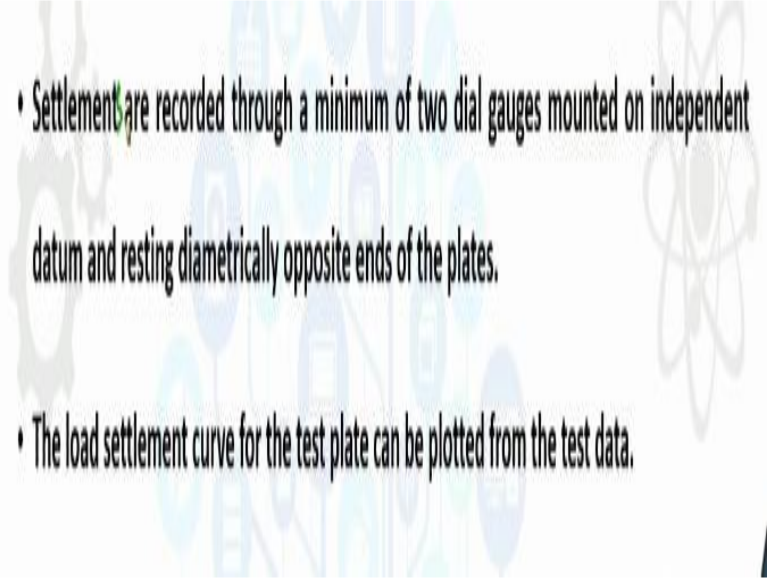

Settlements are recorded through a minimum of two dial gauges or three. From this data, ultimately a load versus settlement plot can be plotted.

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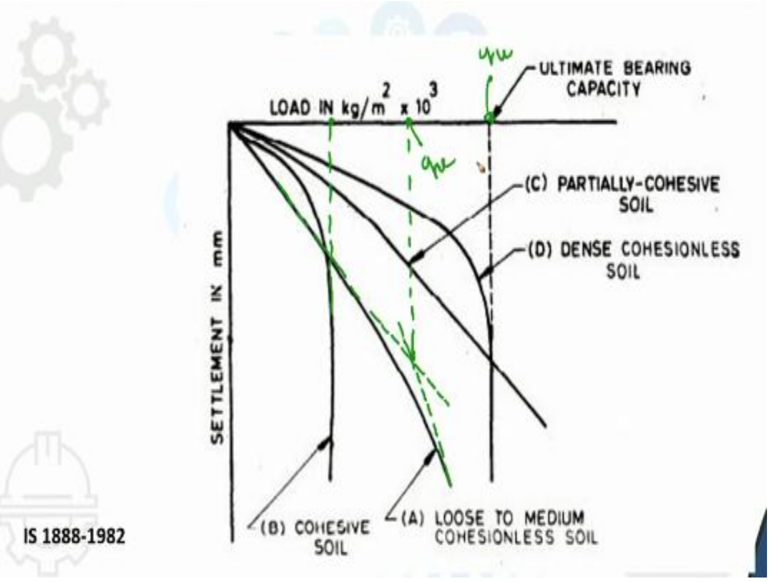

The recorded values of settlement are taken on the Y-axis where the load or stress is taken on the X-axis. It is from this plot, the failure load can be determined which will be diuscussed later on. Different types of soil give raise to different plots which are shown in the slide above, from which the failure load can be calculated. If a curve is almost parallel to the settlement axis (curves B and D), then the distance from the Y-axis (ordinate) will be the $q_{ultimate}$.

If a plot is in the shape of curve-A (ref. above slide), double tangent method should be used to find out the ultimate load. In this method, the initial portion of the curve is to be extended forward through a tangent and the final porion of the curve is to be extended backwards through another tangent. The stress corresponding to their intersection point will give the q_u, ultimate load. If there's a definite peak value like that of curve-C, the stress corresponding to the peak in the curve will be considered as the failure load. Sometimes, based on the settlement criterion the allowable load or stress will be decided.

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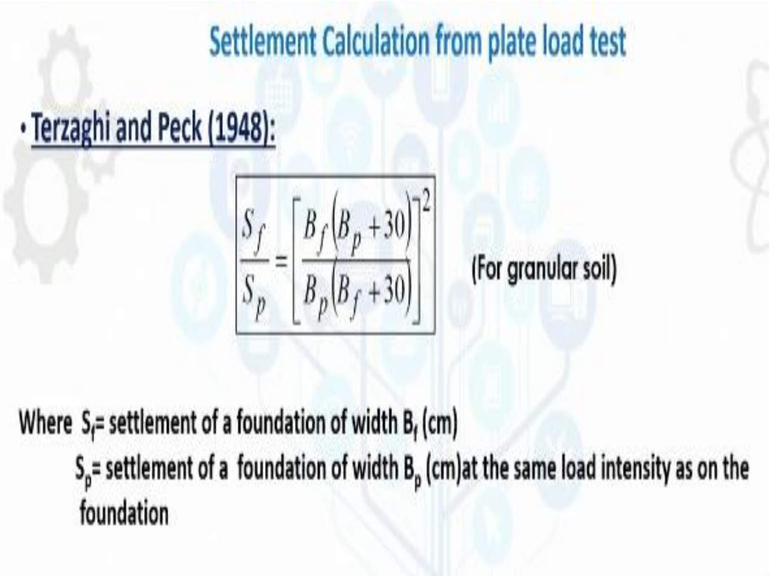

Once the load versus settlement curve is plotted, the above expression can be used to determine the settlement in granular soils. The above expression is an empirical expression where S_f is the settlement of foundation, S_p is the settlement of plate, B_f is the width of foundation and B_p is the width of plate. Remember that B_f and B_p should be in centimeter because it is an empirical expression.

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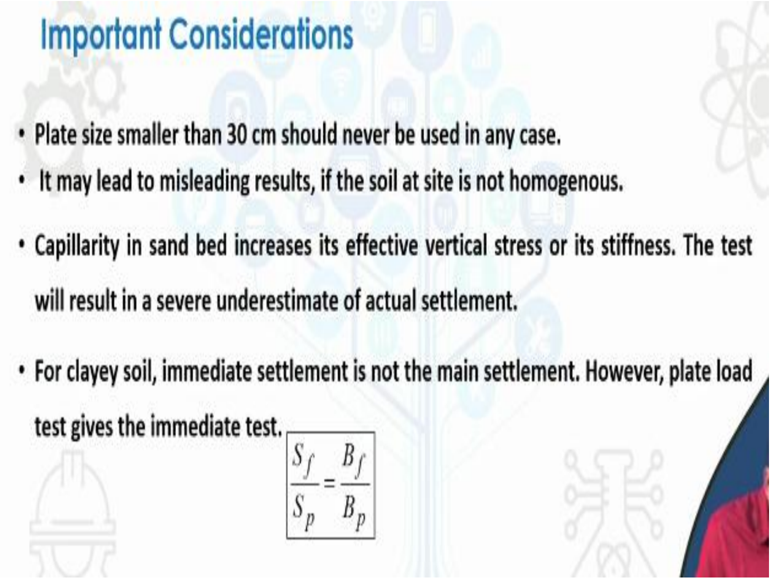

Some of the important considerations in the plate load test are that, the smallest plate size should be 30 centimeter. Sometimes capillary action in sand will increase the effective stress or stiffness which may result in underestimating the actual settlement. Though this type of test is more suitable for granular soil, it is used to determine the settlement in clayey soil also using the expression in the above slide. B_p and Bf being the settlement of plate and foundation respectively.

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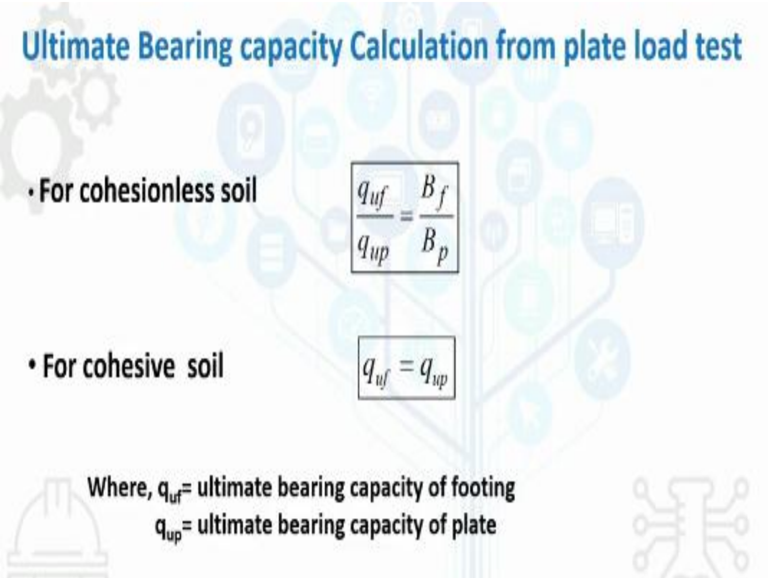

The ultimate bearing capacity for a foundation can also be determined from the plate load test once the ultimate bearing capacity for the plate is determined. The expressions for this in both cohesive and cohesionless soils are given in the above slide. For a cohesionless soil, the bearing capacity is a function of width, but for cohesive soil, it is not the case. In the expression for bearing capacity: $cN_c + \gamma D_f N_q + \gamma B N_\gamma$ here the middle term would be zero because the soil above the plate during the test would be removed making it independent of the foundation depth. Incase of a purely cohesive soil, the N_γ term would be zero resulting in a zero third term which is why for pure cohesive soil, the ultimate bearing capapcity is independent of both depth and width of foundation.

So for a pure clay, the bearing capacity from the plate load test can directly be used for any foundation, provided the soil is homogeneous. If the soil is layered, because of the lesser plate dimension, the influence zone may not intercept all the layers resulting in erroneous result.

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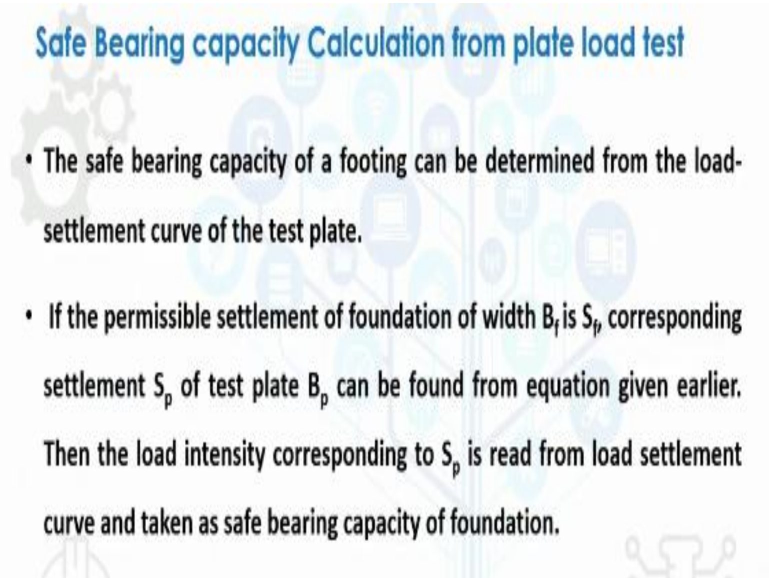

Till now, the determination of ultimate bearing capapcity and safe load carrying capacity in terms of bearing criterion has been detailed. Usually the term, safe bearing capacity refers to the settlement criterion. The lower value of the two criteria will give the allowable load carrying capacity. If there is a permissible settlement for foundation for a width B_f, it should be converted in terms of the permissible settlement of plate.

In the settlement expression (given) for granular soil, the S_f should be substituted with the permissible settlement value of the foundation to calculate the permissible settlement for the plate. Now, the stress corresponding to that permissible settlement will give the safe bearing capacity.

So, in the next class, I will discuss a few example problems and show how to calculate the settlement or how to design the foundation for granular soils as well as the cohesive soils. Thank you.