Soil Mechanics
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Lecture – 27
Flow of water through soils-VIII

Welcome to lecture number eight of flow of water through soils. So in the previous lecture we have introduced the flow net concepts and we also seen the flow through unconfined seepage and confined seepage conditions. And we also considered the flow through anisotropic material. In this lecture we will try to understand the flow of water through earthen dams with rock filters or a rock toe at the toe of this slope and stability of some hydraulic structures agonize piping or heaving failure. So in the previous class we understood the flow nets construction in anisotropic material and we also solved some example problems by considering an anisotropic nature of the soil in horizontal and vertical directions. That means we considered the permeability is non equal in horizontal and vertical directions. And then we tried to get a transformed section by plotting to the scale which is with the variation of kx and ky. We also seen the seepage through embankment dams which is an example for an unconfined seepage.

So for calculating the flow through embankment dams or earthen dams, we said that the seepage is basically depending upon the construction of that phreatic line. So for that many solutions were put forward like we have seen the Dupuit's solution and Schaffernak's solution and we also seen the Casagrande's solution. So several solutions have been proposed for the determination of the quantity of seepage through a homogeneous earth dam. Dupuit's solution which was the first one and then Schaffernak's and then the consequent graphic construction and a Casagrande's solution were discussed by us.

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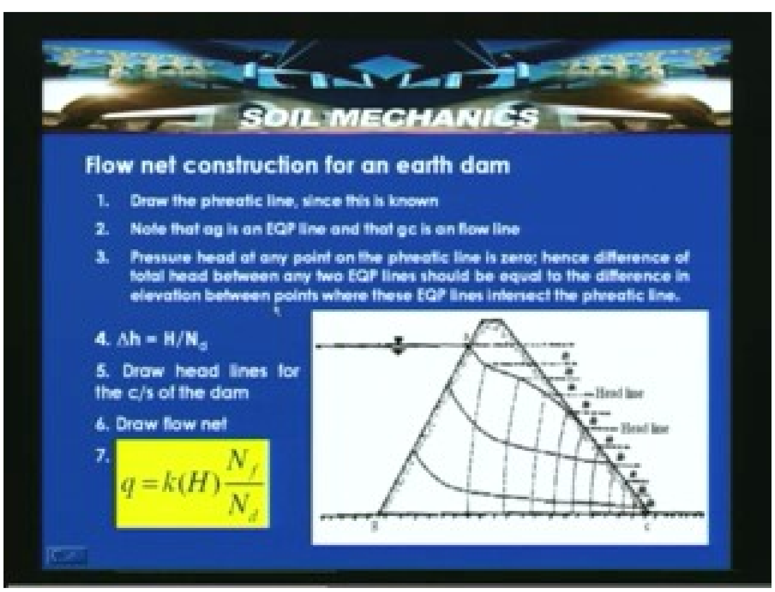

Then the flow net construction earthen dam, first we said that once the phreatic line has been constructed and approximated as per the methodologies suggested by Casagrande. Then if h is the head loss which is occurring suppose, if the h is the head which is driving the flow and this is the upstream side and this is the toe of the slope (Refer Slide Time: 03:08) and this is the downstream side. Then depending upon the number of equi-potential drops simply divide this into several delta h, if there are say n number of equi-potential drops and divide this total head by n.

So easy to construct flow net incase of a flow of water through an unconfined seepage conditions, the example is earthen dams. So in this case, draw the phreatic line since this is known to us by the constructions or methodologies which are discussed. And here we should note that ag is an equi-potential line. Suppose if there is a tail water level here then this happens to be again equipotential line. And pressure head at any point on the phreatic line is zero, hence the difference of the total head at any two equi-potential lines should be equal to the difference in elevation between points where these equipotential lines intersect the phreatic line.

So as the pressure head on this points is zero along the equipotential line, so the difference in the elevation between points where these equipotential lines intersect the phreatic line can be taken as potential drops. So delta h = H/ N_d where N_d is the number of potential drops. So draw the head lines for the cross section of the dam, these are the head lines what is called from the cross section of the dam and draw the flow net. Then the seepage is determined q = k (H) which is the head which is driving the flow N_f by N_d where N_f is the number of flow channels. So in this case if you approximate the two flow channels, 2.5 number of flow channels are there. Then this is the direction of the flow and then it can be numbered in this direction. So such a way that this equipotential drop number is N_d. So this is for a homogeneous earthen dam which is constructed and which we discussed about the method for determining the quantity of seepage passing through the earthen dam.

In another example like flow net construction for an earthen dam where you have got a head water level and tail water level. The situation is slightly different from the previous case, then how the phreatic line changes. For example here you have got a cross section of a dam which is shown here like this and which has got an upstream water level which is having a head of H 1 and downstream water level having a head of H_2. If you look into this upstream face which is an equipotential line with a head H 1 at all points. So AB is an equipotential line with total head H 1 at all points and AE is a flow line. If this boundary is assumed as an impervious boundary then AE transferred to be a flow line.

In this case DE happens to be equipotential line with head H_2. If H_2 is equal to zero, then this particular level will come down here but there is a downstream water level with head H_2. So in that case the DE which is the equipotential line with head H_2, so at all points here the total head is represented as H_2. Here in this case the pressure head is zero, so whatever the elevation which we are having with the relevant datum is referred as a total head.

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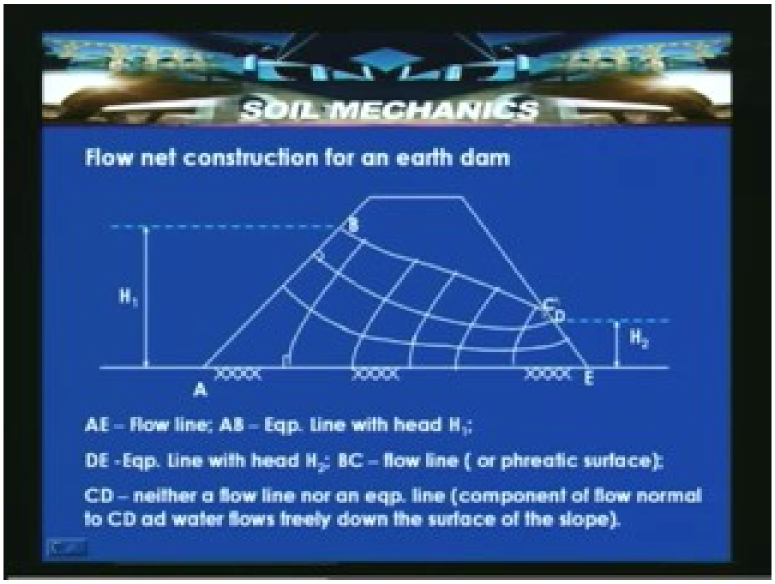

So this BC is an approximated phreatic line which is shown which is nothing but a flow line, the upper boundary of a flow line in this case of an earthen dam. If you come to this small stretch which is shown here the CD where you will see that this is neither flow line nor equipotential line. Because component of flow normal to the CD exists and water flows freely down the surface of the slope. So the component of flow down the slope is neither flow line nor an equipotential line because there is a component of flow which occurs down the slope and there is a flow also normal to the CD. It is eligible from both the point of view as an equipotential line as well as a flow line.

So this type of discrepancies do exist in the small locations there but many times what will happen is that it is required to keep the phreatic line within the dam either to provide some measures like chimney drains or rock toes. Let us look into this flow net construction for an earth dam with upstream water level and downstream water level. Let us consider on upstream side there is a head H_1 and on downstream side there is a head H_2. So in this case if you consider a homogeneous earth dam which is having a permeability of the material which is isotropic and having permeability k in both directions.

If A is the point here and then this is the crust of the slope and from here if this happens to be the cross section of a dam, then AB is nothing but an equipotential line with head H_1 and DE is an equipotentiual line with head H_2 and AE happens to be the flow line and BC which is nothing but the phreatic surface where here an approximated phreatic surface has been shown. If you note that if this being equipotential line, this flow lines have to be started orthogonal to this equipotential line. And the condition is they have to meet this equipotential line at right angles. So this indicates that this orthogonality has to be maintained and AE is nothing but a flow line and if that is treated as an impervious boundary then AE has be treated as a flow line. So as the flow cannot take place across this AE, because being an impervious boundary.

So then AE happens to be the flow line. So if you look here this is a first flow channel and second flow channel and then this qualifies as a third flow channels. If you approximate the number of flow channels works out to be around 2 or 2.8. If AB here, which is at all points on this particular line will be having a total head H_1 which is nothing but as a pressure head being zero, then whatever the elevation it has got from the reference datum that is actually referred as a total head. That H_1 will be the total head on the upstream side. So as the water flows with head H_1 to the downstream water level H_2, so the head loss which is occurring over a length which is nothing but total head loss is nothing but H_1- H_2.

So here if you look into this small zone where CD that happens to be a point where it qualifies both for an equipotential line as well as a flow line. Because there is a flow which is occurring perpendicular to that particular portion. If you look into the zone very close to that as a flow perpendicular to its particular zone which is very close to CD and there is also a chance that the flow can takes place downstream the slope. So in that case it is actually neither flow line nor equipotential line. So these types of discrepancies do exist in these small zones where this upstream water level and downstream water downstream particularly toe water level or a downstream water level exists.

This being a flow line you can see that this equipotential drops which are drawn perpendicular and again orthogonal to the flow line. So if this happens to be H_1- H_2 then divided by this number of equipotential drops we will get that delta H which is occurring that is a drop which is occurring between two consecutive equipotential lines. Like this one determines here and then again determines the number of flow channels, number of potential drops and then head which is causing the flow H_1- H_2. And by knowing the permeability one can calculate the seepage.

Let us consider many situations to keep the phreatic surface particularly within the upper boundary of the phreatic surface within the earth dam. Generally it is practice to provide some rock filters or rock toe or some measures like chimney drains have to be provided within the dam. So by providing that these phreatic surfaces are restrained within the dam itself. So that they are not subjected to a failure like against piping or so. This can be seen through an example if you consider a similar cross section of a dam and this being impervious boundary and if this happens to be the upstream water level H_1 and this is the soil with which the embankment has been constructed and this happens to be the downstream water level with H_2. Many cases when the flow line originates there is a chance that where a piping failure or erosion can occur which can create the danger for the stability of a structure.

So many cases or in many situations it is required to keep this upper phreatic surface that is this being phreatic surface (Refer Slide Time: 14:19). To keep this phreatic surface within the earth dam itself. So for that the measures which are generally adopted or some chimney drain which is provided or some rock toe or some rock filter at the toe of the dam. So in such situations how this particular measure can effect the flow net constructions and how the flow can be calculated?

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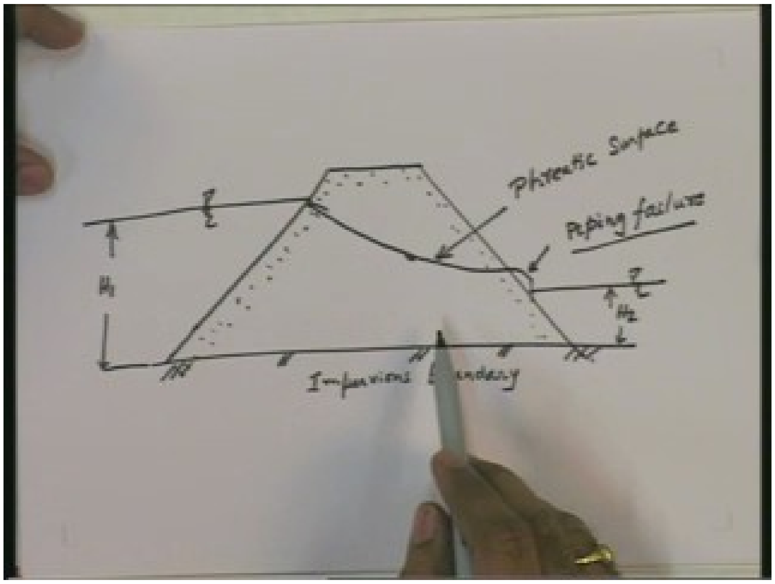

And in another case like how this filter can be designed, what are the drain size requirements, the criteria so that this filters will function. So let us look into this embankment with some permeable filters. So in this case and in this particular slide if you see there is an embankment with permeable filter which is resting here. There is a rock filter which is placed at the toe of the dam. So this particular line qualifies as an equipotential line with a zero head. If this happens to be datum then here the equipotential line with zero head. So this is the cross section of the dam which we constructed.

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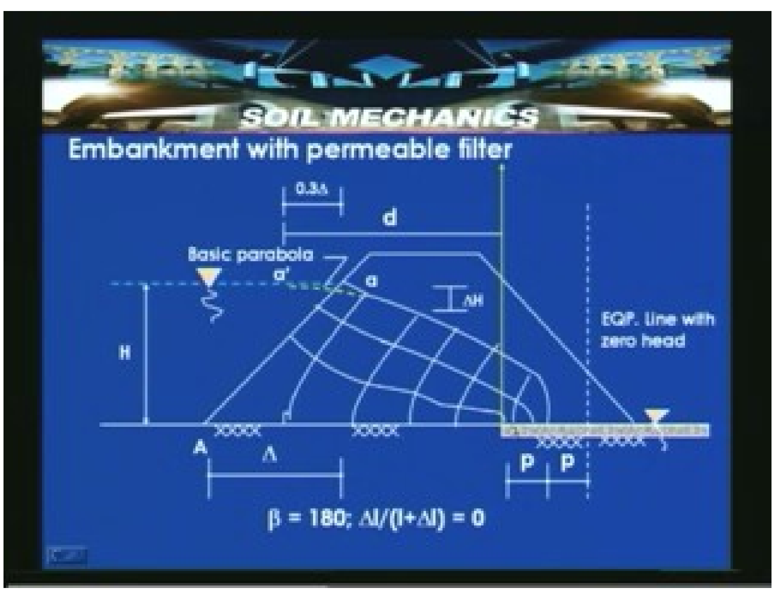

The difference from the previous slide and now is that there is a permeable filter exists at the toe of the dam. So H is the head which is on the upstream side, by using the Casagrande’s approximation this 0.3 times delta, where delta is the distance from this upstream point A to this point where this head meets that is the horizontal distance delta. This point is approximated as 0.3 delta from here. So this particular portion is called as a basic parabola. When this qualifies as an equipotential line this will be something like upper phreatic surface that is the phreatic line. So the phreatic line meets this equipotential line with the zero head orthogonally. If you look into this these are approximately shown as orthogonal that is around right angles. So if you see the second flow line this one meets this particular point orthogonally and again which is approximately shown here again meets orthogonally. If this happens to be the z and this happens to be x here then the directrix which is going to be there (Refer Slide Time: 16:59) and these determination of P and other from the basic properties of the parabola we have discussed in the previous class.

So this particular case with a rock toe filter happens to be beta is equal to 180, because previously when there is a downstream case where beta has got certain angle. Now in this case the toe filter is adjusting at the toe horizontally, in that case beta is equal to 180 degrees and then the delta L by L+ delta L that is at the downstream if you connect it to the previous lecture, the Casagrande’s solution the delta L by L+ delta L =0. So which is the case representing that particular properties and properties of the parabola. And now in this case if you look into it the H is being the head loss, so delta H which is any equipotential drop between two consecutive equipotential lines.

So in this case also again the procedure is simple, (Refer Slide Time: 18:09) because this qualifies as a flow line and immediately there is again a discrepancy there, where particularly its starts as an equipotential line. So here number of flow channels that is channel one, channel two and then channel three. So number of flow channels is 3. And then equipotential drops by estimating the number of flow channels and number of equipotential drives one can determine the quantity of seepage with rock toe filter. So the basic merit of this particular solution is that it keeps the phreatic surface within the dam. So it prevents endangering the performance of a structure from against piping or heaving failure at the downstream level.

Let us see how this filter can be designed then, before looking into different aspects. When a seepage water flows from a soil with relatively fine grains to coarser material. That means if water which is actually flowing from fine grain soil to the coarser material, there is a danger that the fine soil particles may wash away into the coarser particles. So when the fine soil materials wash away into the coarser particles then there is a situation that clogging can take place with that the hydraulic pressures build up takes place and again it endangers the performance of a structure. So such a situation can be prevented by use of a filter or a protective filter between the two soils. Previously the sand being permeable it is a practice to use sand as a filter material but nowadays with modern development advanced with geotechnical engineering there are some synthetic materials like geotextile have been erupted and evolved. They are being used widely for constructing this type of structures.

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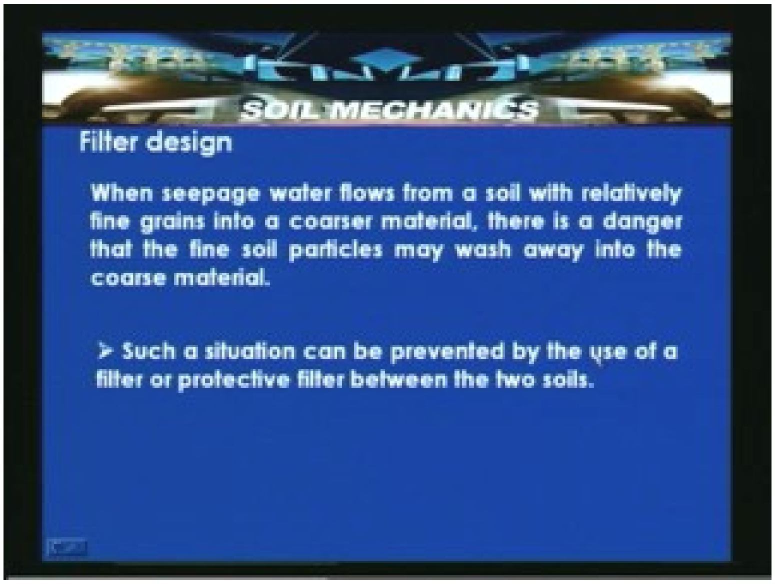

And these materials being synthetic in nature and they have got long life and enhanced performance compared to the conventional filters. So when the seepage water flows from a soil with relatively fine grains to a coarser material there is a danger that fine soil particles may wash away into the coarser material. And such situation can be prevented by the use of a filter. So the requirement or a situation that demands is basically to filter material, so that this particular phenomenon can be prevented. So if you look into this typical flow net for an earth dam with a rock toe, so without filter at the toe the seepage water would wash the fine soil grains into the toe and undermine the structure. Suppose if there is no filter then that seepage water would wash the fine soil grains into the toe and undermine the structure.

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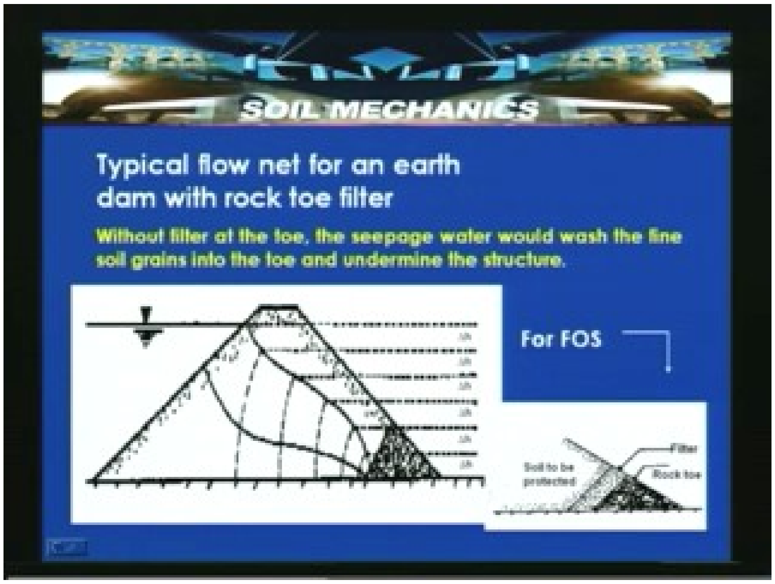

So here in this particular slide a rock toe is shown and this particular zone is constructed with highly permeable material. So it has got criteria to be selected, so that soil to be protected is not affected in undermining the performance of a structure. So here a cross section of an embankment dimension is shown. On the toe side you are seeing a rock toe with a filter. So the details which are shown here in this small window where soil to be protected that is the soil which is being used in the embankment or earth dam for construction. And the rock toe which is serving this purpose in preventing the undermining or a piping failure of the structure. So for better factor of safety these measures have to be adopted. So what are the criteria's for designing this filter?

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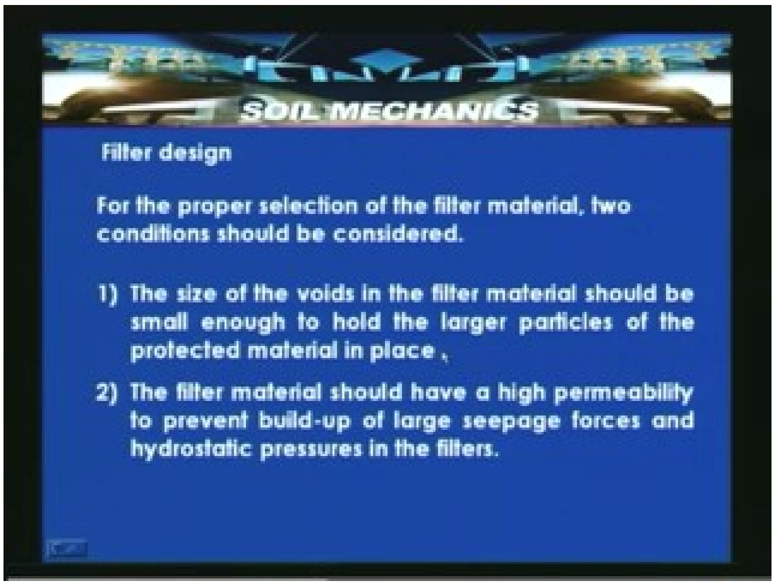

For the proper selection of the filter material there are two conditions to be fulfilled. The first criteria is the size of the voids in the filter material should be small enough to hold the larger particles of the protected material in place. So if this material gets washed out of the filter material then there is a endangering or the stability of this structure is in cohesion. So the size of the voids in the filter material should be small enough to hold the large particles of the protected materials in place. So that is the criteria number one.

The criteria number two is the filter material should have a high permeability to prevent build up of large seepage forces and hydrostatic pressures in the filters. So it should be freely drainable and basically the requirement is that to prevent the build up of the large seepage forces and hydrostatic pressures in these filters. So if this hydrostatic pressure can build up then there is a problem of endangering the structure. So the filter which has designed should be followed with this two criteria which are set forwarded and then the material has be selected and designed and then has to be implemented in the construction of earth dams or embankments. Let's say for this particular purpose if it is used and can be constructed with this type of filters with properly selected materials.

According to Bertram 1940 based on the experimental investigations, some criteria have been set forward for protective filters. And they are the ratio of D_{15} of filter to D_{85} of soil should be less than or equal to 4 to 5. This is to satisfy the criteria number one. That is ratio of D_{15} of filter soil to D_{85} of soil should be less than or equal to 4 to 5 and in order to fulfill the criteria two, that is another criteria which has been set forward is the ratio of this D_{15} of filter soil to D_{15} of soil should be greater than or equal to 4 to 5. So by fulfilling these two, if the material has been selected in such a way then that qualifies as an ideal filter material and then its serves the function like what has been deserved by satisfying this two criteria's which are discussed.

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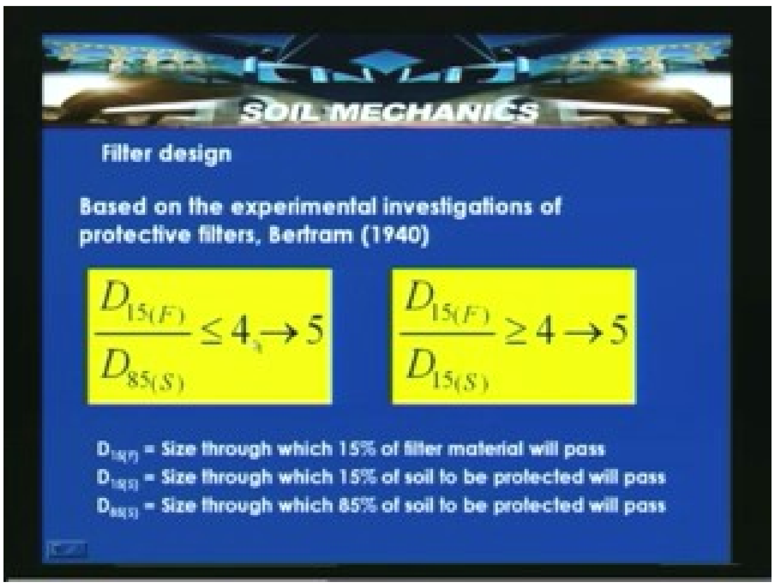

So $D_{15\,(F)}$ is nothing but the size through which the 15 % of filter material will pass. So here $D_{15(S)}$ means the size through which 15 % of this soil to be protected will pass and $D_{85(S)}$ is the size through which 85 % of soil to be protected will pass. So these are the definitions for the symbols which are used in these two sets of expressions, where the first one is for satisfying the criteria one that is D_{15} filter by D_{85} soil. Then S is nothing but the soil to be protected, F lesion is nothing but the filter material. So $D_{15\,(F)}$ to $D_{85(S)}$ should be less than or equal to 4 to 5. That is required to be the criteria number one. And for satisfying the criteria number two D_{15} filter to D_{15} soil should be greater than or equal to 4 to 5.

So this a typical cross section along with the flow net for an earth dam with chimney drain. So this particular construction, there is a toe filter at the bottom and then there is a drain which is placed. So with this what happens is that the phreatic surface will be restricted and restrained within the central part of the dam itself. And for the design there are methods which are to be arrived for arriving at the dimensions. And based on that once arriving then by using the methods which are discussed one can construct the phreatic surface and the flow net and then quantity of seepage can be calculated.

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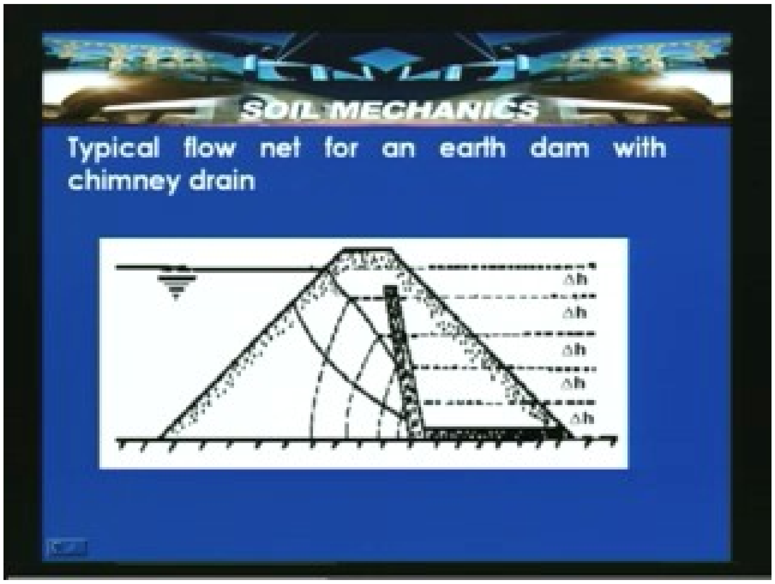

So here again that chimney drain is constructed with particular type of selected material and then we can have filter, so that it serves the function. So in this case there are one and two, so two flow channels which are there and this qualifies as a flow line and this particular boundary if it is treated as impervious and particularly this qualifies as the equipotential line with head zero (Refer Slide Time: 27:02). So here this particular portion again is qualified as equipotential line with head h, whatever it is here if small h is the head loss which is causing the flow and that is considered here as h. So based on that these are the equipotential drops which are going to occur and that is represented as delta h. In this case, for these lines 1, 2, 3, 4, 5 equipotential drops which have been considered, so N_d is equal to 5 and then N_f is approximated as a 2.5 or so. Then in that case we can approximate that N_f by N_d that particular ratio. Then by knowing the material k and by knowing the h which is there, we can again estimate the quantity of the seepage.

So having discussed now, then let us try to consider how to evaluate this factor of safety of this structures against piping or heaving failure. And while designing this particular phenomenon we said that when the flow takes place in the downward direction on the upstream sides say a row of sheet pile walls embedded in a soil. Then when the flow is taking place that is when the flow channel commences there is a downward flow but when it is erupting out that is when it is coming towards the downstream side there is a chance of an upward flow. So whenever we have an upward flow or a downward flow, incase of downward flow we knew that because of the energy which is transferred to the grains, then what happens is the effective stresses increases. Incase of an upward flow then we discussed that effective stresses decrease. So these decrease in effective stresses which are there on the downstream side of a structure can effect, particularly this performance of any hydraulic structure.

So let us consider a cross section of a sheet pile wall. Let us assume that this is $H_{1,}$ H_2 (Refer Slide Time: 29:55). So this particular depth which is referred as embankment depth of a sheet pile wall. So which is shown as a cross section and this is the impervious boundary. The impervious boundary is shown here, and then this particular line represents two dimensional view of sheet pile wall. In this case the first flow line creeps along the sheet pile wall, second flow line erupts out like this which are approximately drawn. So here being an equipotential line, orthogonality has been maintained. So this is the flow channel, if this being flow line, these are the equipotential lines which are drawn. So when the flow which is taking place like this, so here which is the downward flow taking place and here upward flow. So in this particular place, suppose if this happens to be the head which is occurring here, the head loss occurring between these two equipotential lines happens to be delta h and if this length happens to be say delta L. This length delta L can be obtained from the flow net construction and delta L is nothing but the length of the flow and delta h is nothing but the head drop which is occurring between this equipotential line and this equipotential line and here is the downward flow.

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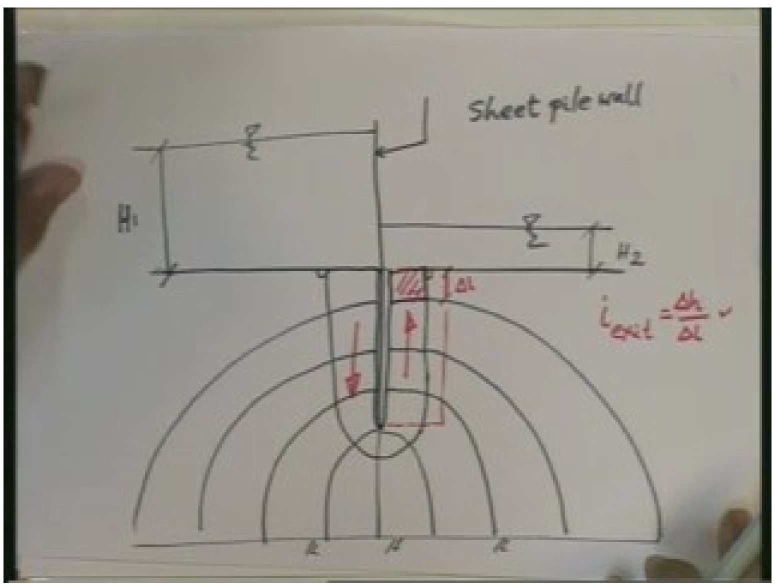

So as discussed here the effective stress increases here and the effective stress decreases here (Refer Slide Time: 32:42). So in the process this particular gradient which exits here is defined as i_{exist} that is exit hydraulic gradient. The exit hydraulic gradient which is nothing but delta h divided by delta L, this is one parameter. Then we also discussed that a critical hydraulic gradient which is again discussed while discussing the flow of water through soils. And we defined that when the head reaches the critical head by the length of the flow, that is actually treated as a critical hydraulic gradient and we have said that it can be related with gs -1 by one+ e divided by gamma dash by gamma w. So i_{exist} which is nothing but delta h by delta L and then critical gradient, by using these two we will try to get a factor of safety against this piping or heaving failure.

So here in this particular structure, this is being a typical flow channel is shown. There will be a number of flow lines. But this is the first flow line and second flow line typically shown here and exit gradient is defined here and this is the row of sheet pile walls. That means perpendicular to this figure, per meter width of the figure if you consider there will be a row of sheet pile walls which ensures the leak proof ness and then retains with head H_1 on the upstream side and H_2 on the downstream side. So then the flow takes place with head loss H_1- H_2 over a length here.

So the cross section if it is given and if it is homogeneous then this being a soil, this is how the procedure has to be done. But what we have been discussed is that two cases, there is a chance that this entire layer can get uplifted and that particular case will be discussed now. Then by using another method to evaluate the factor of safety against piping failure that is based on this exit gradient method. So these two methods we will discuss shortly.

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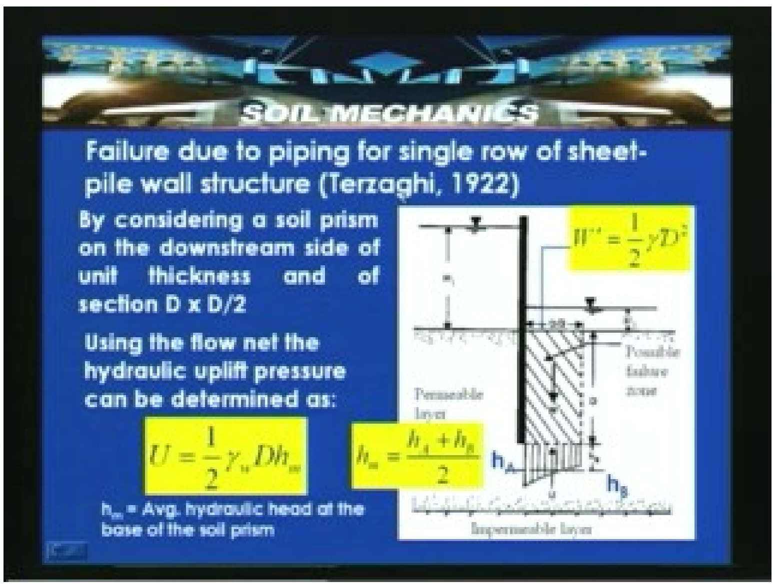

So let us try to look into the failure due to piping for single row of sheet pile wall structure. So this is after Terzaghi 1922. Consider a cross section of sheet pile wall and assume that on the downstream side, a wedge of soil or a prism of soil is subjected to some uplifts. Consider a cross section of a sheet pile wall which is embedded in a permeable layer and D is the embedded depth and this is an impermeable layer (Refer Slide Time: 35:20) and according to Terzaghi, this particular zone is referred as a possible failure zone. This particular zone which is of depth D and D by 2 that is embedded depth times that is 1 by 2 times the embedded depth, this particular zone is identified as a possible failure zone by the Terzaghi.

How to evaluate the failure due to piping for single row of sheet pile wall structure according to Terzaghi 1922? So by considering a soil prism on the downstream side, because that is what actually we have discussed that where the upward flow can take place with an uplift pressure at the base of the prism. So a thickness that is per unit thickness, if it is considered a section of D into D by two. That is the two dimensional plane area and per meter width is subjected to an uplift, which is existing at that particular portion. So using the flow net, the hydraulic uplift pressure can be determined. First let us look into this particular portion W, which is W dash is equal to half gamma dash D square. That is nothing but the self weight of this soil prism which is being subjected to an uplift. So here gamma dash is the submerged unit weight of soil and D which is nothing but the depth of the sheet pile wall which is embedded, so W dash is equal to half gamma dash D square. And the hydrostatic uplift pressure can be estimated by using U is equal to half gamma w Dh_m. Suppose if a points A and B are existing at the tip of the sheet pile walls say A and at a distance D by two from the sheet pile wall if it is say B. Then the total head which is available at A is h_A and the total head available at B is h_B.

So in that case the average head which is h_m or h average is calculated by computing the total head h_A and total head B. That is given by h_m is equal to h_A + h_B by 2. So with that now we can determine h_m, once the h_m is known at the base of the prism, what is the uplift pressure which is exerted by this pore water pressure, which is exiting at that point. Because as the flow taking place from upstream side the dissipation of pore water pressure takes place. But whatever is existing at point A and B, based on that we calculate the total heads and then that is used as calculating the hydrostatic uplift pressure. So remember here the average hydraulic head is determined by calculating the total heads at the respective equi potential lines or the lines approximated to lines which are passing to that particular zone. So here by doing that, this is the prism of soil that is the distribution which is there with h_A and h_B and which is approximated as u with an h_A or h_m which is given as h_A+h_B by 2, with that U can be determined as ½ times gamma w D into h_m.

So in this slide what we said is that, there is a self weight of the soil which exists is W dash is equal to half gamma dash D square and then on the same section at the base it is subjective to an uplift force u. So by considering the vertical equilibrium or a factor of safety which is nothing but the weight which is ratio double dash by U. If that has got adequate factor of safety then we can say that it is safe against piping failure. So we extend whatever we have discussed now. The factor of safety against heave can be determined. That is factor of safety is equal to ratio of W dash by U where W dash is nothing but half gamma dash D square, U is half gamma w Dh_m. So after simplification it turns out to be D gamma dash by h_m gamma w.

This is an expression for factor of safety against heave or piping failure which is nothing but D time's gamma dash divided by h_m gamma w, where h_m is the average head at distance between two points A and B at the downstream side of a sheet pile wall that is at the tip of the sheet pile wall, basically at the bottom portion of the sheet pile wall. So it can be simplified like factor of safety is equal to i_c by i_m and this i_c is a critical hydraulic gradient which is nothing but gamma dash by gamma w. So here this particular gamma dash by gamma w is written as i_c. So with that h_m by D which is defined as this hydraulic gradient, i_m = h_m by D.

So here with head h_m over the depth D which is the length of the flow. So that is the gradient over which the flow is taking place at the downstream side of the sheet pile wall. If this ratio, factor of safety is equal to i_c by i_m and if this ratio happens to be approximately 4 to 5, then we can say that there is an adequate factor of safety against piping or heaving failure. If this value comes out to be some 2 or so then we can think that the particular structure is unsafe against piping or heaving failure. To find h_m that is h suffix m, find the total head within the D/2 zone horizontally.

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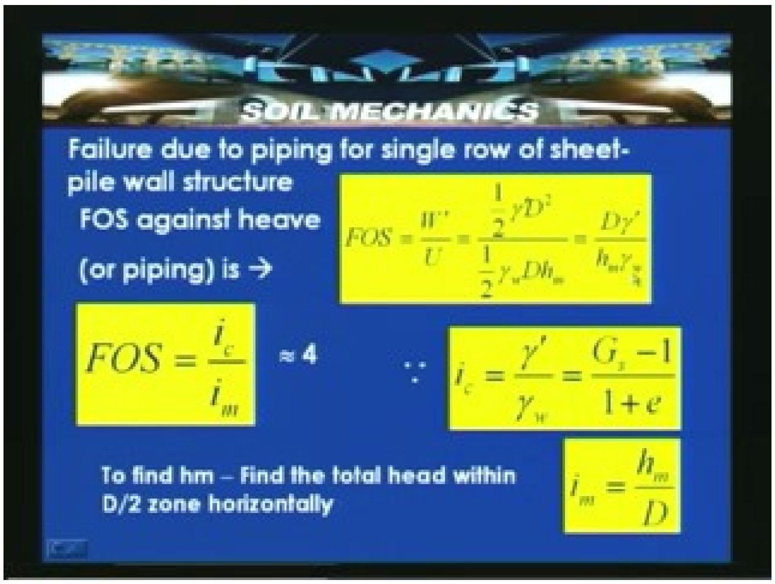

So here what we discussed in this slide is the factor of safety of structure against heave or against piping failure. So which is nothing but w dash by U and which is given by D gamma dash h_m by gamma w. The gamma dash by gamma w can be written as i_c. So the factor of safety expression against heave or failure is nothing but a ratio of critical hydraulic gradient to the mean hydraulic gradient $i_{m,}$ where i_m mean hydraulic gradient is nothing but i_m is equal to h_m by D where the D is the length of the flow which is nothing but embedded depth of the sheet pile wall in the permeable layer and h_m is the head which is adjusting at the base of the layer.

So what we discussed in the previous slide is for single row of sheet pile walls. Say for structures other than a single row of sheet pile walls, then Terzaghi 1943 recommended that D/2 × D dash ×1. So suppose this is a mesentery peer with downstream sheet pile wall. So this particular measure which is here is called the cut off sheet pile walls. These cut off sheet pile walls they do exist at the upstream side as well as downstream side. Particularly for downstream side they are very important because it increases the factor of safety against heaving or piping failure and without this the structure may be prone for heaving or piping failure. So to prevent any hazard from this piping or heaving failure, cut off sheet pile walls are provided.

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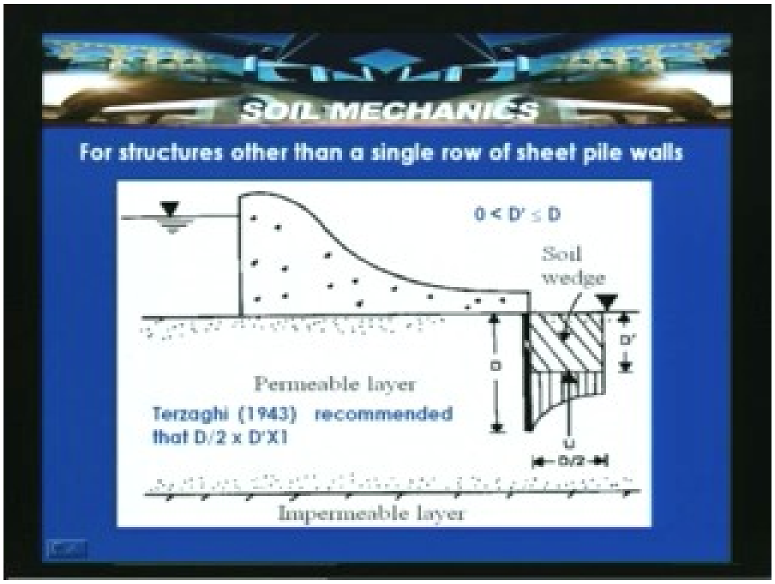

So in such situations for a mesentery peer which is here and a cut off sheet pile wall is here (Refer Slide Time: 42:52) and according to Terzaghi 1943, he recommended that if D dash is the zone which is the possible soil wedge or the possible failure zone and this is the zone where the uplift which is existing and by using the similar procedure, it is approximated that D/2 is this width and D dash. So D dash value which has been said zero to D. So recent work by Harr 1962 was mentioned that for a factor of safety of four and this D dash can be equal to up to D. With that, what has been mentioned is we are going to get factor of safety of four or so. For that we can calculate the factor of safety against structures.

So for the structures other than a single row of sheet pile walls and here we discussed the cut off sheet pile wall and then how to calculate the factor of safety against this type of structures. In this case they are different from single row of sheet pile walls. So here it is discussed in similar way but the only difference according to Terzaghi is that D dash which is approximated as between zero to D. But recent works of Harr indicates that the D dash can be approximated up to D, to get a factor of safety of 4 to 5 to evaluate the safety against hydraulic structures.

Then another method for calculating safety of the hydraulic structure against piping and we have defined this exist gradient. So based on that according to Harza 1935, he defines the factor of safety as i_c by i_{exist}. And we defined i_{exist} in this slide. The i_{exist} is defined by using delta h by delta L. Consider a single row of sheet pile wall, so this particular creeping of water along the sheet pile wall surface which is shown here and this is the first flow channel and second flow channel and third flow channel, it comes out. And typically one flow channel is shown here and delta L is the length over which this flow is occurring. So exist gradient is determined by using this particular definition i_{exist} = delta h by delta L. And this particular deduction can be obtained from the construction of the flow net.

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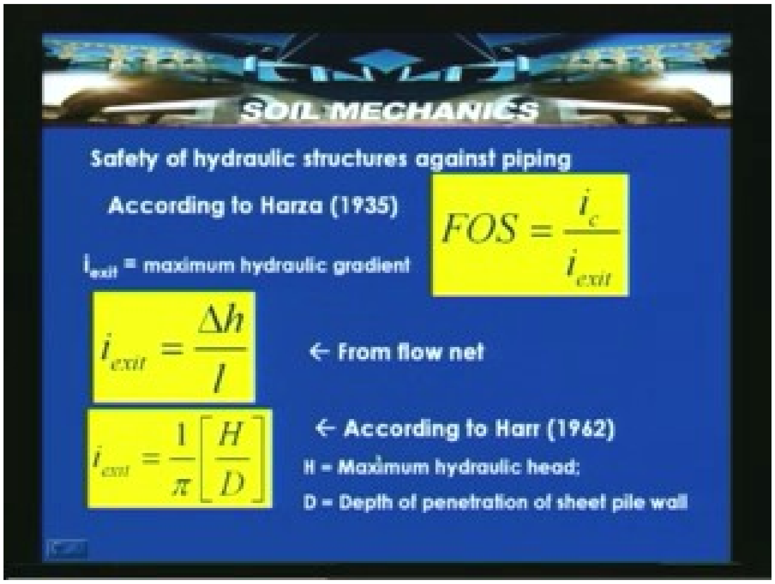

So having obtained i_{exist} then we can calculate whether this particular structure is safe against piping failure or not. There are two three methods to calculate this i_{exist} but one of the methods is to calculate by using the flow net. So i_{exist} is the maximum hydraulic gradient at the exit. So which is nothing but factor of safety is equal to i_c by i_{exist}, so from flow net construction if you do, it is delta h by L where L is that length of the flow. According to Harr 1962 i_{exist} is defined as 1 by pie times [H/D] where H is the maximum hydraulic head with which the head loss is occurring and D is the depth of the penetration of sheet pile wall.

So if the D is the depth of the penetration of sheet pile wall and say H is the head loss occurring between upstream side and downstream side. If there is an upstream head of H_1 and downstream head of H_2, the difference in levels H_1- H_2 = H and that is given by i_{exist} is equal to one by pie into [H/D]. So either by using this method or from the flow net construction we can obtain i_{exist} and calculate by knowing critical hydraulic gradient and one can estimate the factor of safety against piping or heaving failure. And again this has to be more than 4 to 5 to ensure a safe factor of safety of a particular hydraulic structure under consideration.

So let us consider like safety of the hydraulic structures against piping. For example if this particular structure is constructed and if there is no cut off sheet pile wall here and this particular zone may me prone for failure (Refer Slide Time: 47:09). So one of the remedial measures suggested is that to keep or some overburden or surcharge on the downstream side, so that this uplift trust can be minimized like which can be shown in a conventional way. Suppose if you have got a sheet pile wall which is there and say which is having inadequate embedded depth. This is the upstream water level and say this is downstream water level. So in order to enhance the factor of safety against piping failure, one of the remedial measures which has been suggested is to have a fill on the downstream side that is here (Refer Slide Time: 48:05).

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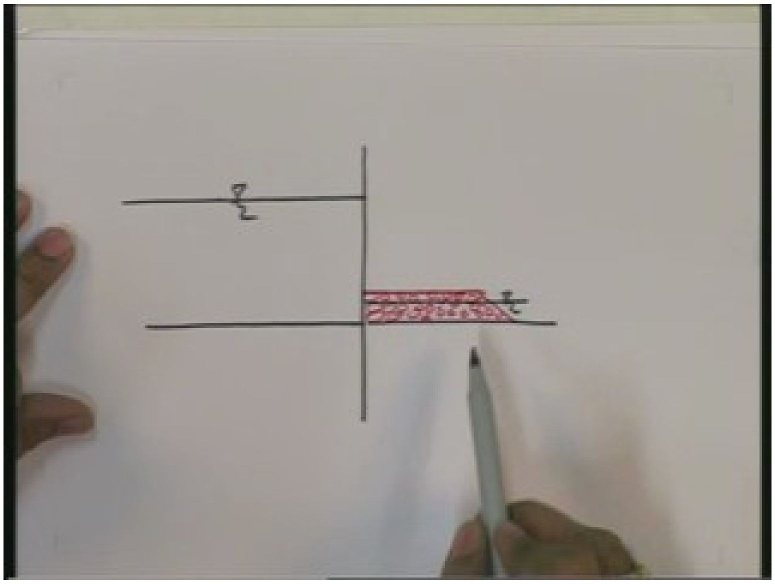

This type of construction allows one to enhance the factor of safety against piping failure. So here in this particular case the maximum hydraulic gradient exits here. Let us consider a problem where a stiff clay layer underlies a 12 m thick silty sand deposit. A sheet pile wall is driven into the sand of depth 7 m and a silty sands which is having 8 × 10 to the power of minus six meter per second that is the permeability and the stiff clay can be assumed to be impervious and e of the silty sand is 0.72 and specific gravity of the solids is 2.65. We need to draw the flow net construction and estimate the Q and what is the pore water pressure at the tip of the sheet pile wall and factor of safety against piping failure. So whatever we have discussed let us try to look into numerical terms.

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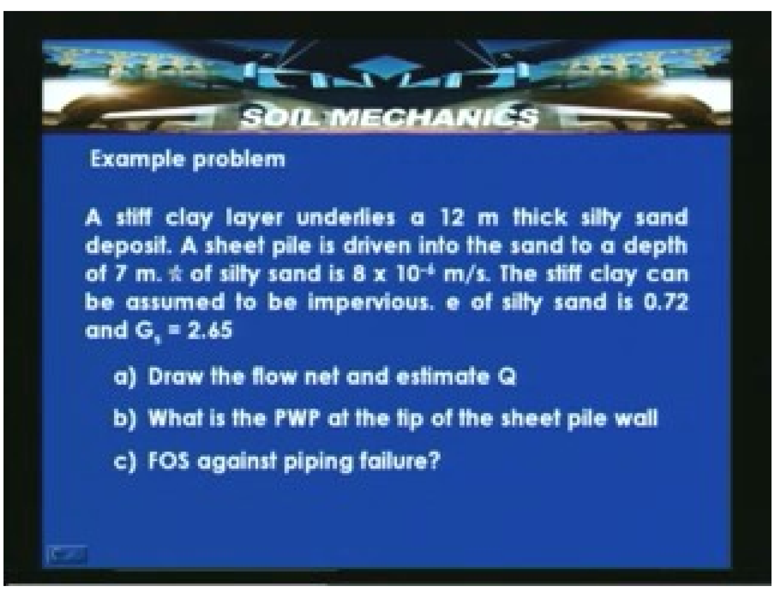

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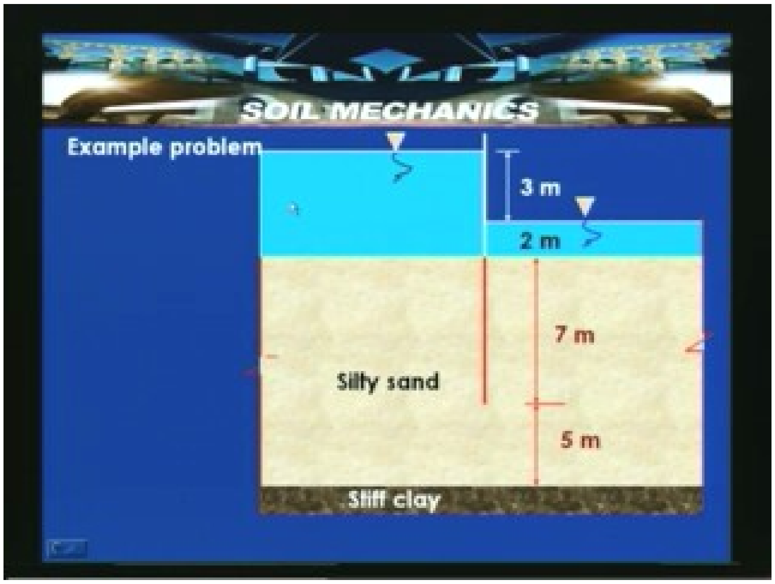

So this is the problem which is given, the silty sand which is having a void ratio and certain permeability. This is the upstream water level and downstream water level, the head loss is around 3 meters which is occurring between this upstream to downstream side. This is the stiff clay which is given as impervious boundary to us and this is an embedded row of sheet pile walls which separates this upstream water level and downstream water level. In such situations a skeleton flow net is shown here. So better flow net can be drawn by drawing to the scale but the skeleton flow net is shown here.

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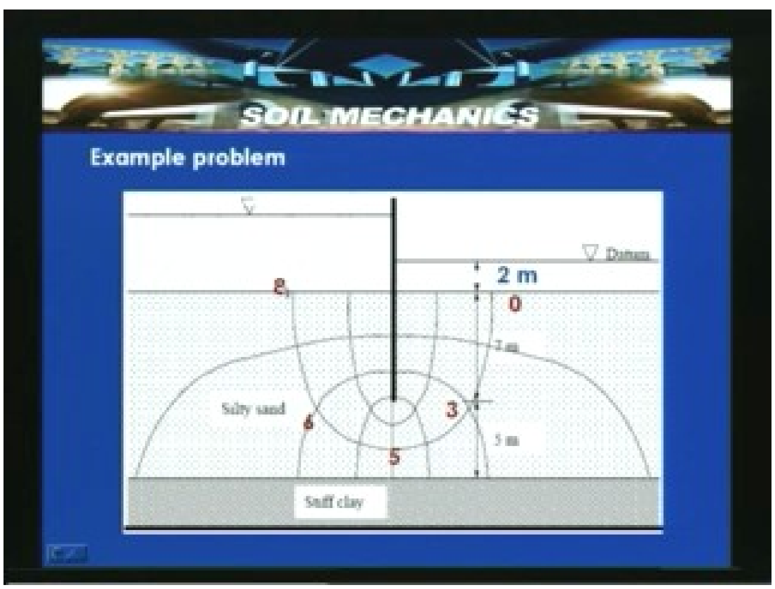

This is the first equipotential lines zero that is equipotential drops, second, third, four so on to eight equipotential drops which are shown. Schematically 1, 2, 3 and around 2.5 flow channels are shown here.

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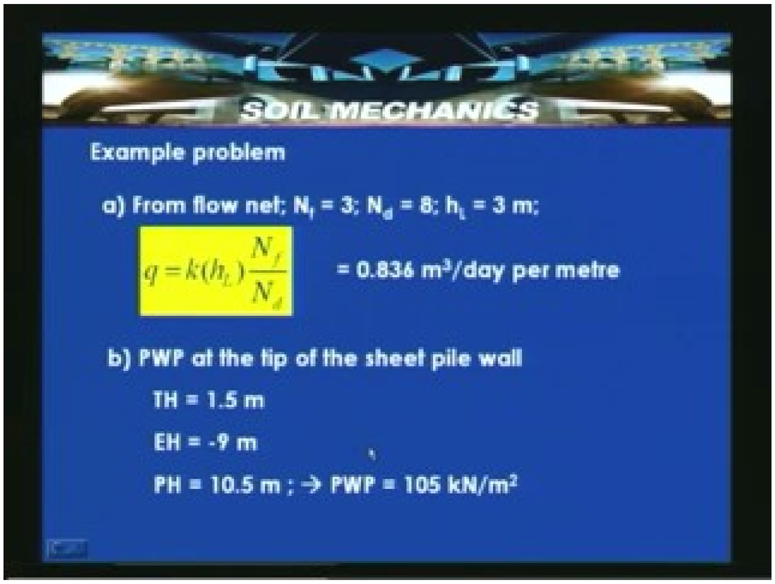

So by using the same methodology, we can calculate the number of flow channels, number of potential drops with that we can calculate the q. And pore water pressure at the tip of the sheet pile wall can be calculated by knowing the total head 1.5 meters and elevation head. By considering this as datum we can calculate this particular pressure here, elevation head is known with that we can calculate the pressure head. And the pressure head in this case that is at the tip of the sheet pile wall, the pore water pressure exits around 105 kilo Newton per meter square. And now having known estimate delta h. From here we can calculate the exit gradient and by knowing the stiff clay to solids and void ratio, we can calculate the critical hydraulic gradient.

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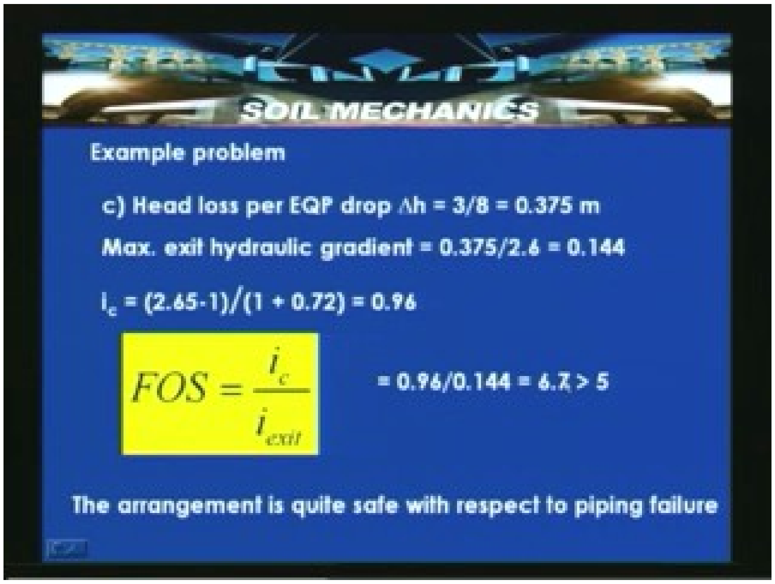

So by knowing the critical hydraulic gradient and particularly the exit gradient, we can calculate the factor of safety against piping or heaving failure. And here the critical hydraulic gradient happens to be 0.96 divided by 0.144 which is around 6.7. So this actually happens to be more than 5. So this indicates that the arrangement whatever is been shown with particular dimensions is quite safe with respect to piping failure.

So in this lecture we tried to discuss about the factor of safety, evolution against piping or heaving failure. And this completes the flow of water through soils. In total we have covered around a total of 8 lectures in this and we started with the definition of how the water can flow and how different materials show different permeabilities. We looked into this and we used this knowledge of flow of water through soils to evaluate the rate of seepage. This completes the flow of water through soils lectures.