Foundation for Offshore Structures
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Module 1
Lecture 15
Pile Foundation 6

So we will continue with the API recommendations for lateral capacity and basically it is a combination of various recommendations.

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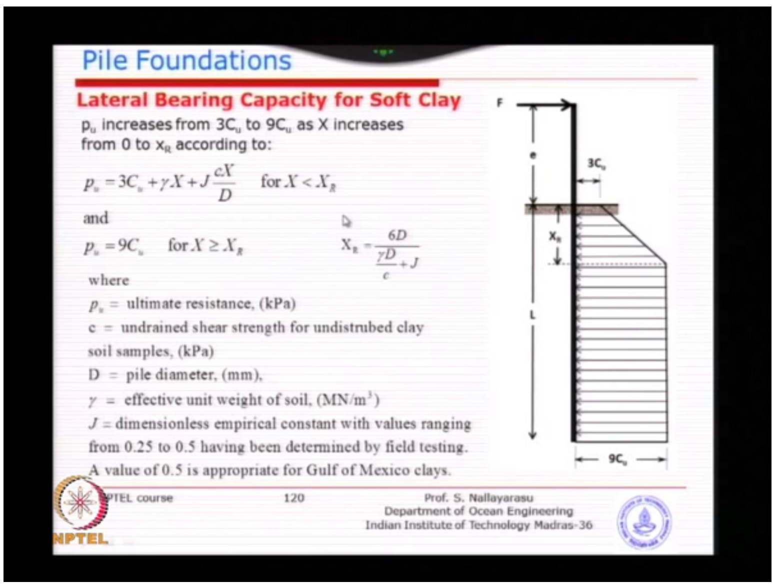

So you can see here for the soft clay basically the formula given by Brinch Hansen has been followed 3 C u at the top and linearly increasing up to 9 C u for depth which needs to be determined depending on the strength of the clay. So this limiting depth so called X limiting or X r is determined based on the diameter and empirical coefficient for a type of clay which is called j of course API does not give you the coefficient called J is a value very specific to gulf of Mexico but the studies shows that the values ranges from 0.25 to 0.5 or most of the type of clay and so you can select depending on the clay type if it is soft or hard or medium clay.

So the influence of J is actually minimum what influence is to a larger extent is the diameter of the pile. So the initial depth of certain say 3 diameter, 4 diameter which we were talking about I think one of the assumption earlier was 1 and a half diameter no strength was taken. Whereas in this case API do take some strength but the reduced value from 3 C u up to 9 C u for a depth X r typically it will be around 5 to 6 diameter, so that is the idea so you can easily understand that when you apply a horizontal load when the pile is trying to push the soft clay will start squeezing up and that is where the rim molding will happen once the soil like soft clay gets remolded it loses it strength, so that is why we have a reduced strength at the top.

And for offshore piles like what I was explaining the previous class is mostly long piles slender steel pipe piles and that is why you will see that the pressure distribution or reaction from the soil is almost going to be continuously uniform until that point where the pile gets full fixity after that the influence of the loading on pile at the soil is going to be minimum., so that is the concept adopted. So you could see here the lateral capacity is the summation of all these, for example this is the applied load for this pile to be in equilibrium without excessive you know displacement or rotation you could see that the load from the right side should matches with the load from the left side should matches with the reaction from the pile.

So you can just cumulatively add up and find out where the depth at which the equilibrium is going to be there. So the ultimate capacity is found as an integration from 3 C u from here plus gamma times X, X is the distance from the surface of the seabed. So as you go down it will be adding additional component which is basically nothing but your overburden component like what we have done earlier in the case of sand if you look at nq times p not, p not is your the overburden pressure to the depth at which.

So in this case you can see here 3 C u is a starting point suppose if you want to find out the capacity at the seabed you know just at the seabed area, so you can see X is 0 so ultimately will have a 3 C u as your starting value and as you go down the value keep increasing contributed by the type of clay which is basically this component contributed by the density of the soil due to overburden so the middle component is the overburden effect, the other one is the clay what type of clay it is contributing towards the lateral capacity.

So that is the value that you will find from P u, so that is the ultimate capacity after reaching the X r value it becomes constant you know, so after that it becomes almost uniform like this. And the units you have to little bit careful ultimate resistance is actually here if you multiply the total this whole term by diameter then it gives you the reaction in terms of kilo newton per meter that means per unit length or right now it is giving you a unit lateral capacity in terms of kilo newton per square meter just know it is a unit value.

Suppose if you want to find out the distribution along the length of the pile then you need to multiply by D that means P u times D will give you the resistance per unit length because later you will need to require to integrate for the total length you multiply by the length itself. So that is the idea for soft clay what happens to the hard clay we will see later quite a few works have done by Reese and other people on clay where the material is quite dense that means when you actually displays it does not come back it stay where it is, like if you take a very hard clay and cut into 2 half remove the first you will see that the vertical surface will stay where it is.

And if it is a soft clay it will try to remold and then come back and then stick to the pile. So that is where the demarcation between the soft and the hard clay or stiff clay is 96 kilo Pascal is the strength undrained shear strength and for hard clay API does not give you the recommendations but what it says you can actually go to the literature very few I would say for the hard clay you can refer to one of the paper by Reese and use that we will see that one in the later path. So you must remember all this formulas given here is specifically applicable to soft clay having C u values less than 96 kilo Pascal.

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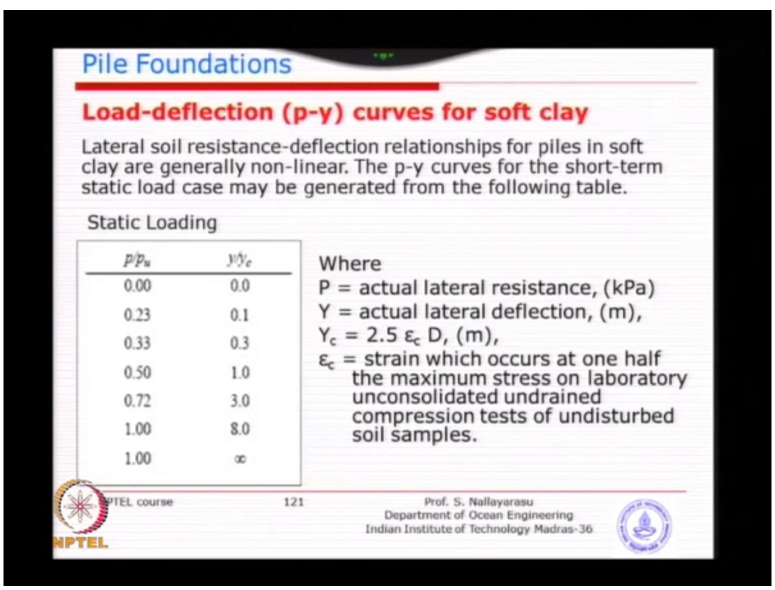

And when you want to look at the load displacement graph is very similar to what we were learning about t j or q z here also you will have the coordinates of the strength point as well as the displacement point but here in terms of ratios p is the actual lateral capacity p u is the ultimate capacity which you have calculated using this formula very similar to what we were having t z, t z t becomes t max at the maximum displacement and the corresponding y value is given in the horizontal axis.

So in this case P u is the ultimate capacity and Y c is the critical displacement after which you will have plastic deformation. So we need to find out what is that values so as long as you can find out P u value and Y c value you can just substitute back and you can get a real type graph of displacement versus strength. Now Y c is defined as 2 and a half times the diameter multiplied by the strain at 50 percent deviator stress when you are looking at the triaxial test I think we have learned drained and undrained eu and cd test.

So when you are doing that when the vertical stress is applied at 50 percent strain you plot the most circle so you find out what is the deviator stress the delta sigma. So that value is going to be the representative value of the soil failure against horizontal load. So that is the strain at which 1 half of the maximum stress in eu test so we can it will be normally given to you, if not then you need to know the range of values so that you can assume reasonably for a soft clay to medium and then hard clay we will see the strain values later.

So basically 2 and a half times the strain multiplied by the diameter will give you the sensitivity of the clay soil against horizontal loading which is denoted as a critical displacement and y is the actual displacement, p is the actual lateral resistance in terms of kilo newton per square meter.

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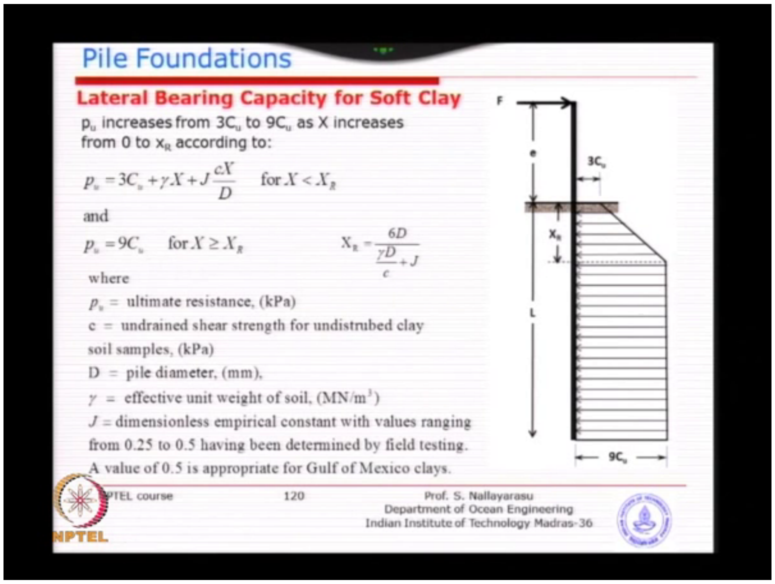

P u has been calculated using this formula suppose if I want to develop a P y graph at say some depth here we need to find out what is the value of P u first you have to find out what is the value of X r then substitute back and then here.

Once you find the X r you know which formula to use whether to use this one or this one because if it is below X r then it will be 9 times C u if it is above X r it will be the value interpolated between 3 C u to 9 C u. So once you get the P u value then is just P is equal to P u multiplied by all these coordinates points. So what happens is at 8 times the Y c it becomes maximum lateral resistance after which it will become plastic deformation this is for soft clay you must remember it will be a different shape when we go to hard clay.

And this is basically for static loading, now when you actually push the pile one time and leave it there say static state load then the soil keeps in contact but what happens when the pile is keep moving back and forth like what we have in our case of offshore structures you have the cyclic wave loading the pile goes forward and backward and the soil gets contact when it is compressed when it is going back it may or may not actually come back depending on the strength of the clay and the type of clay and of course there will be a gap created and then it comes back.

So during this process is skipping the soil in a dynamic condition gets disturbed and it loses its strength you can imagine when you keep on doing it several thousand cycles the top soil at the near the seabed gets loosened very easily and it might actually squeeze away or gets almost close to a liquid. So what happens is during the process of dynamic loading the P y or the load displacement relationship gets weakened, weakened very much higher at the surface level whereas when you go down below this seabed the disturbance is less I think that we can easily understand when you have a stick moving back and forth or a pile moving horizontally near surface soil will be disturbed more than the soil at the bottom, so that is 1.

Number 2, due to the movement comparing with static loading for sure there will be a degradation effect because the soil gets loosened means it is going to carry less load than the load at which it was carrying in the static condition so that is where we have to see. So that is the difference between load displacement graph for static loading versus dynamic loading when we look at tz we did not look at this because you know the horizontal displacements are not really going to affect too much of a vertical load displacement graph so that is why you will see most of the time tz and qz especially qz is too far for any influenced to be done by the pile movement due to dynamic loading.

So tz and qz we normally ignore the effect of cycling loading, whereas the P y because of the nature of loading as well as the disturbance created by the pile on the soil we have to see what difference it makes if it is a static loading or dynamic loading. So the graph what we saw just now is basically is for a static loading load is not dynamic.

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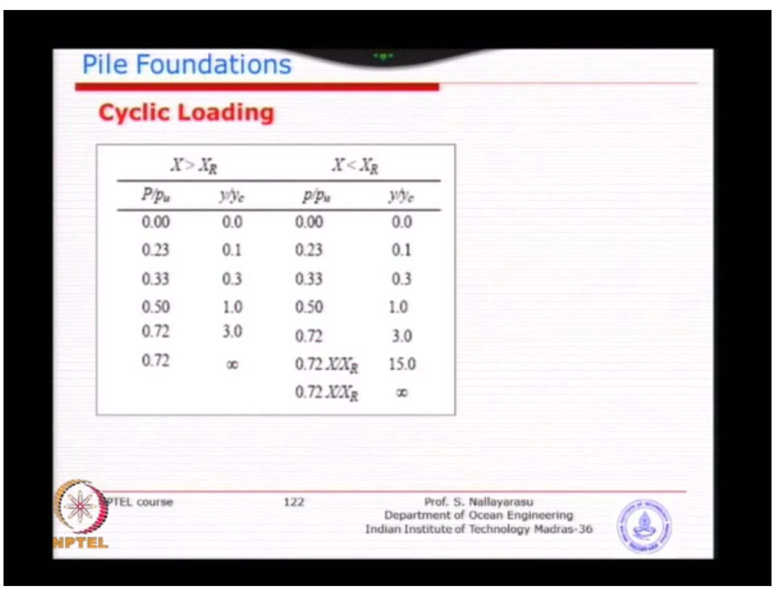

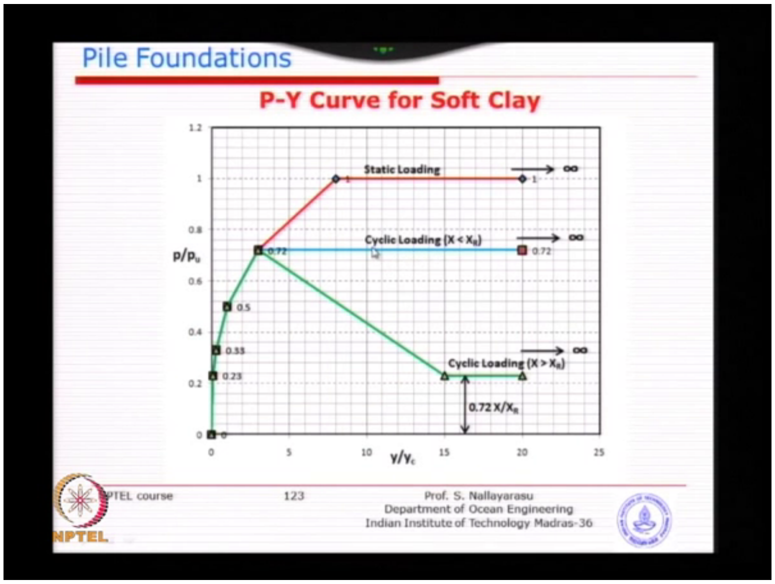

Now if you look at cyclic loading you got the point slightly different you will not be able to appreciate in terms of these numbers but if you over plot something like this I think this graph will give you an idea that what exactly is happening the one that we were looking at just now earlier on the first table is the green line followed by the red one.

So basically at maximum capacity is occurring at a 8 times Y c you know you can see here this is 5, 6, 7, 8 at 8 times Y c you get a maximum ultimate capacity of P u and after that it becomes plastic deformation but when you look at the other 2 graphs the green one and the blue one is basically the cyclic loading at two different places, one near the surface the other one is just below.

What we expect in fact this has to be X less than greater than X r this is X less than X r because near the surface you will get a higher degradation below or deeper depth the degradation effect will be slightly lesser, so that is the idea behind. So what happens is when you have a dynamic loading or almost you can see here from 1 it has come down to 72 percent as the maximum loading we maximum resistance beyond which the soil is unable to take because the effect of degradation has taken place.

So you can see the maximum P u you calculate from your ultimate formula multiplied by 0.72 will be the maximum but that too occurs at very much a lower displacement is not going to take higher displacement. So you can see here almost 1, 2, 3 instead of 8 so that is what you will see from this table it becomes 3 and here only 72 percent, so that means if it is a static loading and becomes dynamic loading you get a degradation of almost 28 percent.

So that is the difference and the difference between X greater than X r and X less than X r you can also see that it goes down you know for example if you keep moving the pile the soil near the surface gets loosened very much and when the displacement become larger it even loses strength even below the maximum value which was 72 percent of the P u goes down to almost half of it or even less than that 23 percent. So that is the idea that top few meters of soil the initial assumption by Brinch Hansen and others of 1 and a half diameter I do not want to take any strength at all.

So completely ignore, whereas here you could still consider but the effect is going to be quite less. So that initial works actually reflect the assumption that the first few meters will not be able to contribute any resistance towards the lateral capacity. So that is the idea behind the P y relationship for a clay which is soft in nature which will come in contact and basically as soon as the pile is moving away the soil will flow and get in touch, so that is the relationship.

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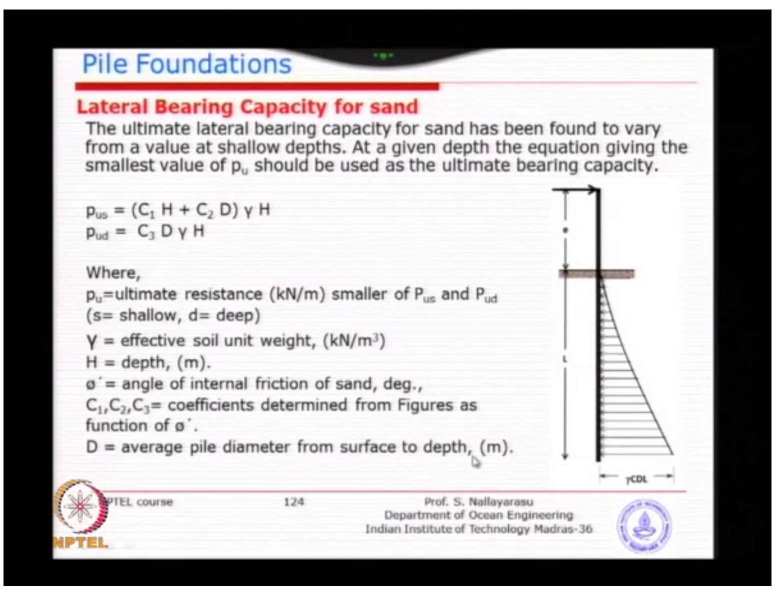

For a sandy material principle is almost similar only just the formula is little bit complicated, in fact the work done as early as 1970's quite a few empirical formulas where available but later part of you know 1980's people came with slightly modified formula which was adopted by API. So the ultimate resistance of the soil like granular materials you know against horizontal loading is determined as a highly empirical formula you can see here C 1 times h, h is the depth at which you are looking for, for example if it is say 5 meter below this h will become 5 meter C 2 times D, D is the diameter multiplied by density times h. So what is the value of C 1 and C 2 we needs to look at the either the original paper or API has actually summarized this numbers for different types of angle of internal friction you know because this is being a sandy material so you could take that values of C 1 and C 2 and C 3 times diameter times gamma h.

So we need to find out the values of ultimate strength from both this formulas one is for shallow depth another one is for deeper depth and whichever governs or whichever lower values you have to use it but generally here there is no demarcation what will be your so called shallow depth and deeper depth like unlike in clay you have a value of X r below X r you have a formula to be used in this case and above X r you have this.

Whereas in sandy material API recommends you find out the value of both whichever gives you the lower value use it for that particular location.

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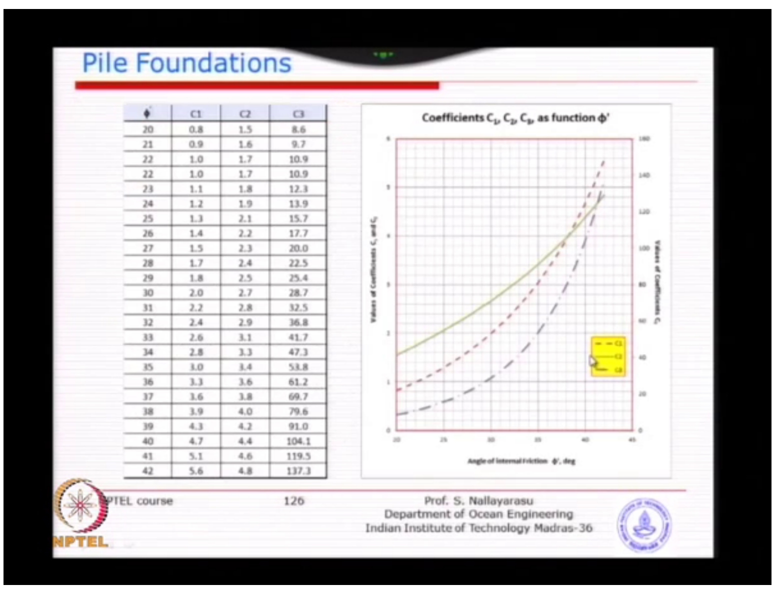

And we will just see the coefficients so this is a table given by API in fact not the table graph was given I have just digitized so that we could use it easily because you can see the angle of internal friction for every 1degree I have just plotted you are not going to get angle of internal friction in between two small values.

So basically you can use the C 1, C 2, C 3 values from here or from the graph which I have regenerated from API so you could use.

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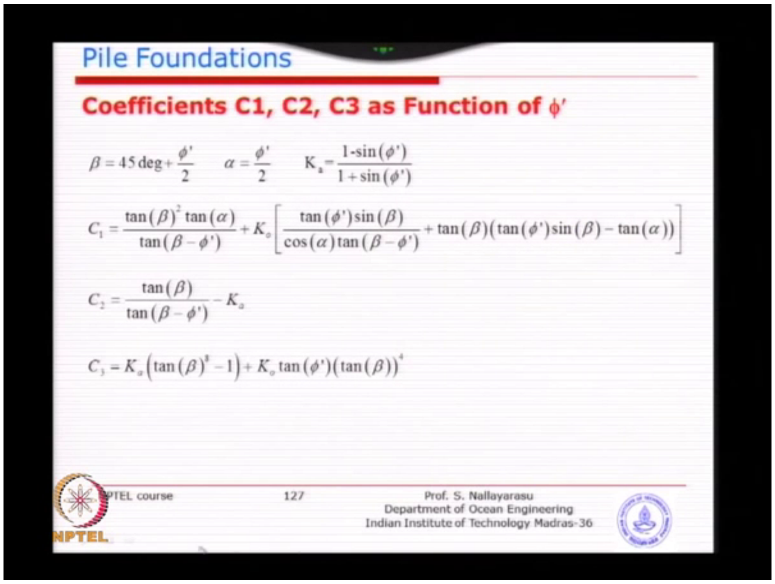

The original paper actually publishing this by Reese they have given the formula of C 1, C 2, C 3 which is quite complicated but all of them are expressed in term of angle of internal friction and there pressure coefficients either you can use this or the graph given by API or the table that is reproduced here.

So the C 1, C 2 values are part of if you go and substitute these values the formulas for the ultimate capacity becomes quite lengthy and complicated so that has is very similar to what we did for you know the bearing capacity of spread footing which nq and n gamma and nc with each term three terms appearing there is almost similar profile in fact I have shown you the profile bulb of the pile if for vertical loading.

Similar assumptions has been made by him and then he derived the whole pressure bulb and calculate the capacity and that is why you can see this original equations is coming from there because of its complexity API has just reproduced this in terms of a graph so horizontal axis is angle of internal friction and values of C 1 and C 2 to be read from the left side axis, C 3 has to be taken from the right side axis so you have to be little bit careful not reading all of them in one because the values are slightly smaller here and bigger here, so you have to be little bit careful here.

So for example if it is a 30 degrees to 2 and a half or 2.7 and 28.7 so you have to read the C 3 from in this and corresponding to the this blue color, something like that so or you can use this table (())(19:16) mostly I will be giving you the graph so that you can learn to pick up the values. So this ultimate strength is depending on the diameter density of the material and that depth at which you are going to. So basically this gamma h is nothing but is the effect of overburden you know as you go deeper and deeper the material density is better you will see that the soil will provide higher resistance against horizontal loading.

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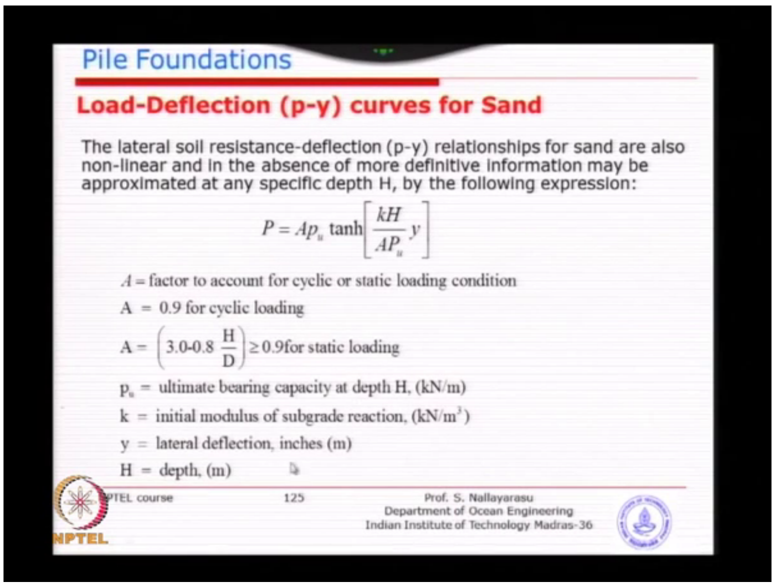

Now the relationship between load and the resistance also given in terms of a closed form equation like this slightly instead of you know coordinates of load point and coordinates of displacement point here you can see is given in terms of P u, P u is the value of ultimate resistance calculated from the least of these two values and the remaining parameters like the displacement this h is the depth at which you are looking for the load displacement relationship and then A is a coefficient which we will discuss just now basically the coefficient to adjust to static and dynamic loading.

So 0.9 for cyclic loading and for static loading it is calculated based on the depth to diameter ratio 3 minus 0.8 of course it has to be greater than 0.9 and if it is cyclic loading it is limited to 0.9 only. And k is the modulus of subgrade reaction which is what we were discussing in the previous class you know various values of modulus of subgrade reaction, of course you see here it is initial modulus of subgrade reaction the softer the soil gets disturb the modulus gets reduced.

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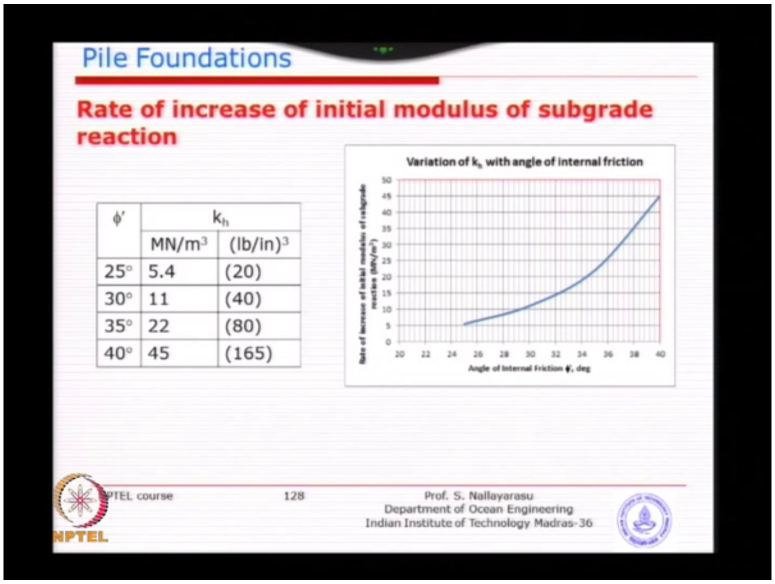

So this is what we have to read from the API in fact I hope I have given that graph here this is a reproduced graph from API for different values just the relevant values I wanted to highlight so that you will remember that numbers.

For a 25 degree angle of internal friction is only 5 mega newton per cubic meter note down the units and for 40 it becomes almost 8 times, so from a 25 degree lose to medium sand to a dense sand it becomes almost 9 times better so that means the strength increases tremendously as the angle of internal friction goes higher by 15 degree, so you did not remember the ranges of values if the values are not known you should be able to either pick from the graph or just use the relevant values of k of course I have also given the values in terms of lb per inch cube because the original graph is drawn in that just covert it to metric units.

So once you have the value of k and the depth at which you want to calculate the P y relationship and then the A values chosen depending on whether it is a static or dynamic loading and P u is the resistance that you have calculated from these two values and the least one is taken and then simply you have the relationship between p and y. So as you keep varying the y value you will get a continuous relationship between p and y. So that is the very easy one compared to the other types of p y curve for clay here you get a continuous form.

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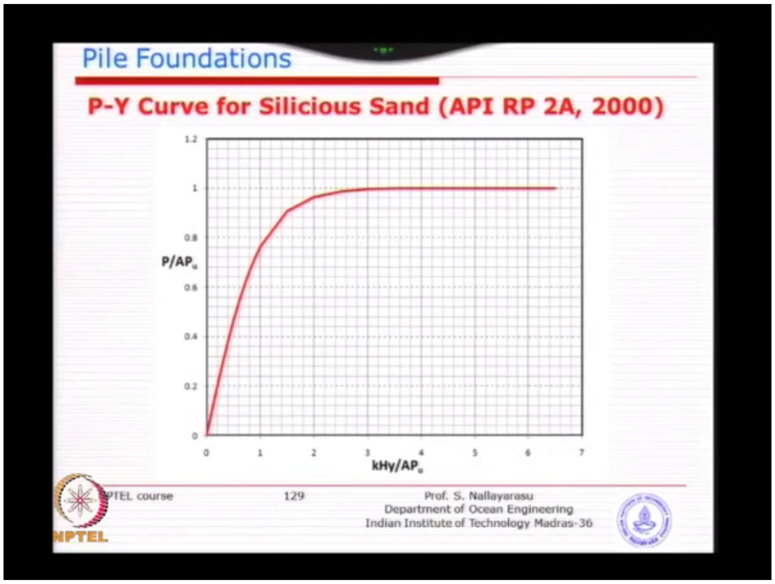

So if you plot it you will get something like this of course I have just normalized I just divide by P by AP u I brought to one side and the other side kHy divided by AP u of course if you substitute all the values P u A as well as H and k you will get the horizontal axis as y and you substitute hear you will get P so I just normalized so that I get a original relationship once you get that then you can. So you can see here how the representation of the relationship is almost very similar to a stress strain curve for a perfectly elastic and plastic type of material you now it goes except that in this portion you get a slightly nonlinear otherwise it goes straight and then just become almost plastic.

So it is the behavior that we could easily understand the sand material does not have any coefficient and just get displaced and it becomes plastic deformation once it is displaced so that is why you have to be little bit you know understand the idea of the difference between the clay and the sandy material.

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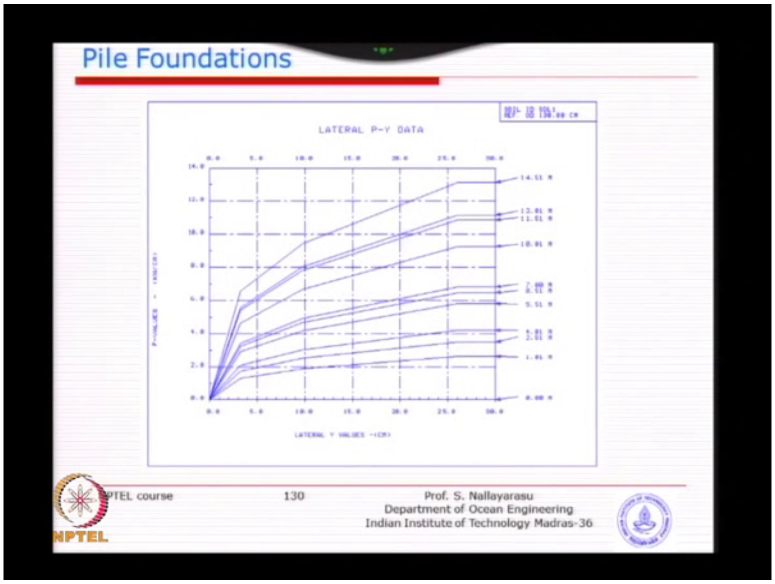

A typical P y graph which was generated by some software you can see here the comparison as you go deeper and deeper so at the near the surface the numbers that indicate at the right hand side is the depth at which this relationship is derived so that the deeper you go for sure you are going to get a better capacity because the soil disturbances itself is very less and the strength itself is higher.

So you can see for a similar displacement the if you go to the last one at 14.51 meter you can see the strength value is almost 10 kilo newton per centimeter. So you can see as you go down you will get a better idea so if you just plot the series of P y graph along the depth you will be able to understand the difference.

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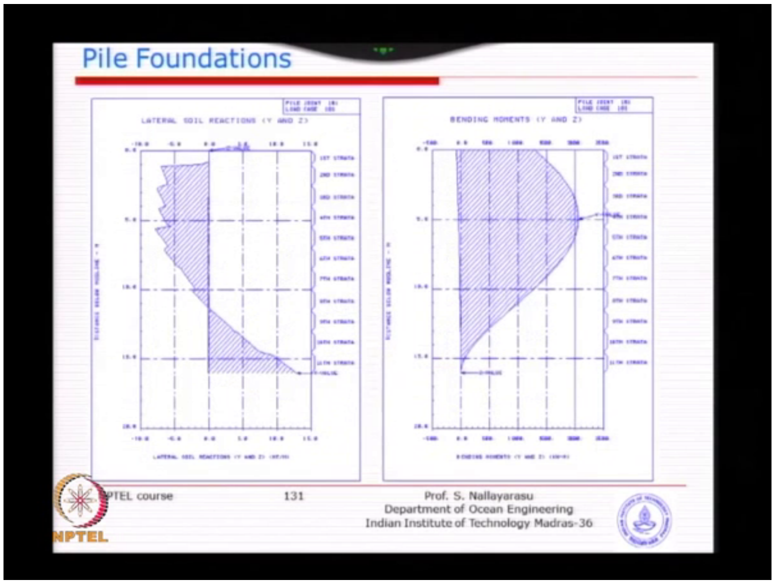

These are some of the plots which I think you really do not worry right now we will be looking at in our newer clay modeling course.

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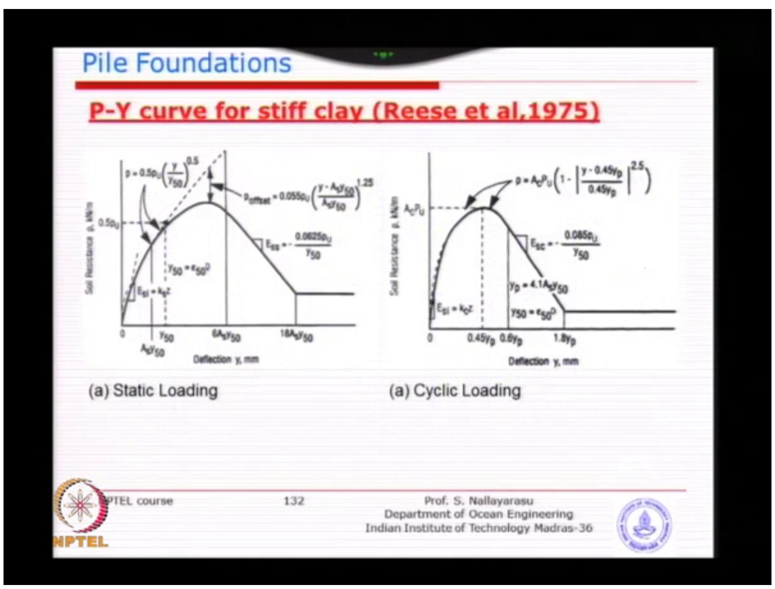

The next one we want to look at the stiff clay as the demarcation between this soft clay and stiff clay we need to understand the idea why we need to differentiate this strength values are higher means it is better that is what always we think because if the soil is very stiff but it is not always like this especially with respect to the cyclic loading when the pile is trying to push the soil forward and pile alone comes back because there is no contact or there is no (())(25:27) effect if the clay is very much harder.

So the pile will come back by creating a gap between the soil and the pile and that is the biggest worry for mostly offshore piles and that is what was investigated by Reese substantially he did require a bit of field work but the field work was not done offshore it was done onshore and later several others have actually given modification to his equations there were 2, 3 publications.

So we have to take the original equation proposed by Reese and modify to offshore conditions because all his prototype testing was done on a small pound of course he created artificially very similar to marine conditions but it is on a first water pound and did the testing of diameter less than 300 mm not 500 1 meter because it was to troublesome. So he did a very small diameter prototype testing just to look at how the behavior is.

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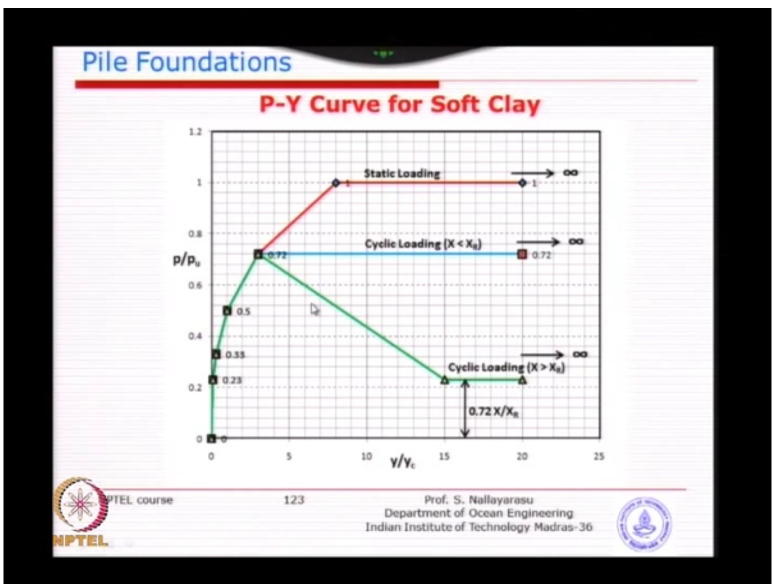

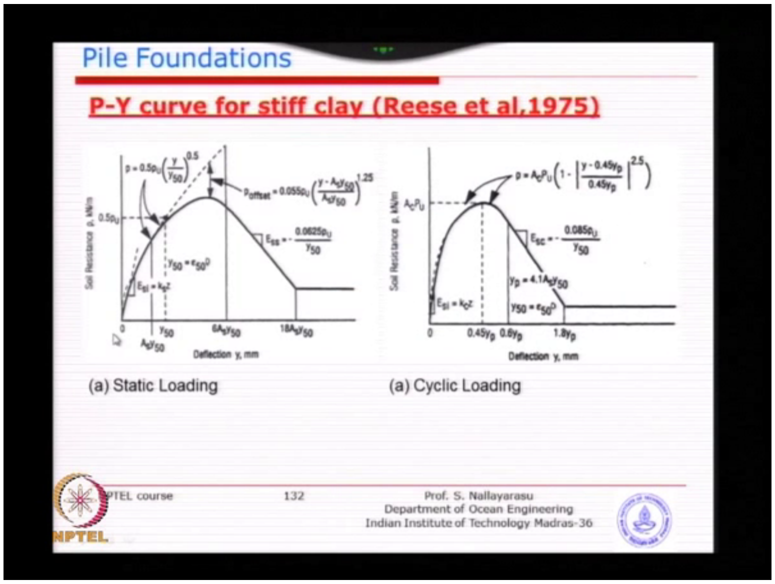

So ultimately he came up with basically the relationship between the resistance and the deflection almost very similar to what we saw earlier on for something like this green one you know so much downgraded even for static loading that is what he has come up.

So if you just compare them later we will compare something like this it goes by a linear or a straight line and then curvilinear and then goes down and then becomes plateau at this much displacement 18 times (())(27:05) times y 50. So in here this A s and there will be a coefficient called B s for cyclic loading which will be part of this Y p just to take into account the static and dynamic loading. So the shape is a little bit complex I would say and it is described by equation 1, equation 2, equation 3, equation 4.

So there are 4 segments in the graph instead of what we had simplified P y graph for a static loading compared to the stiff clay a soft clay was quite simple and this he proposed based on his research work each of this term we will just look at in a table.

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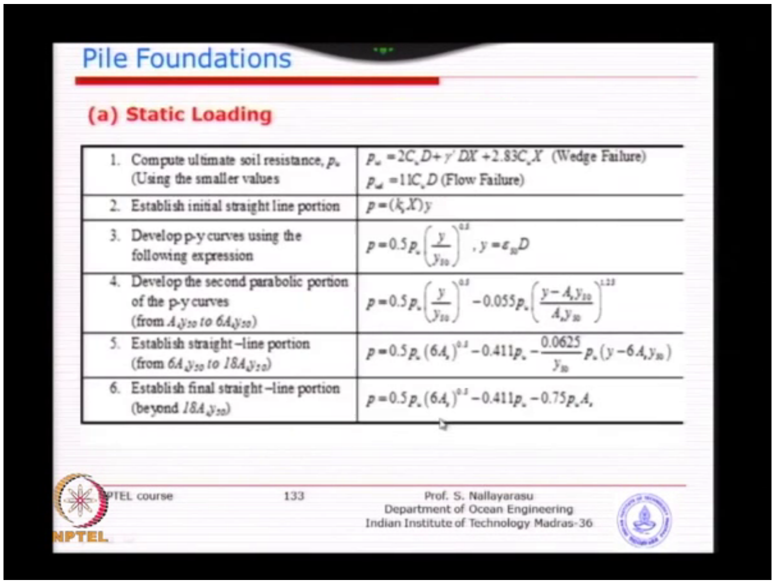

So we find out the first one if remember or recollect the soft clay we had 3 C u plus gamma h plus the term that is for sensitivity of the clay, similar equation you can see here the initial portion is almost similar except that he followed 9 C u has changed to 11 C u and you can see here every one of them is multiplied by diameter whereas when we look at the API equation the diameter was missing so you have to be reasonably clear the units here is kilo newton per meter per meter length of the pile whereas the API equations where kilo newton per meter square which is for a unit area.

So that is where otherwise you can remove the diameter because everywhere you can see the diameter will go away and if you do normalization here the diameter will come down so you can compare the equation it is almost same. And then the initial portion is a straight line in proposition with the depth at which you are trying to draw and the third segment, fourth segment, fifth segment all are polynomial relationship between the displacement and the resistance P u, P u was calculated according to whichever the depth that you are looking at.

So it is a very simple idea only thing is he divided into 3, 4 portions and compared if you look at his original paper he has modified this equation several times after plotting the results and then draw this type of graph because he has established several number of points and then finally he tried to fit the curve to this experimental results and after which I not many results where available at least for the last so many years, so we still use this whenever we encounter a hard clay for P y but fortunately one advantage is we may not encounter this situation very often because you know the top 30 meter of soil mostly will be soft clay you will encounter very rarely this type of material in isolated occasions.

So that is why many times in fact the focus of research and stiff clay was not so much because the use will be very limited that is why you will see very few papers are available.

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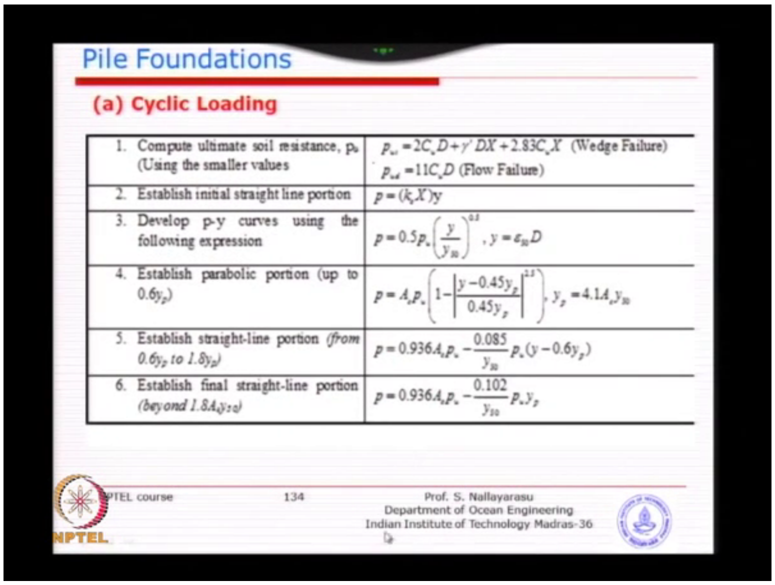

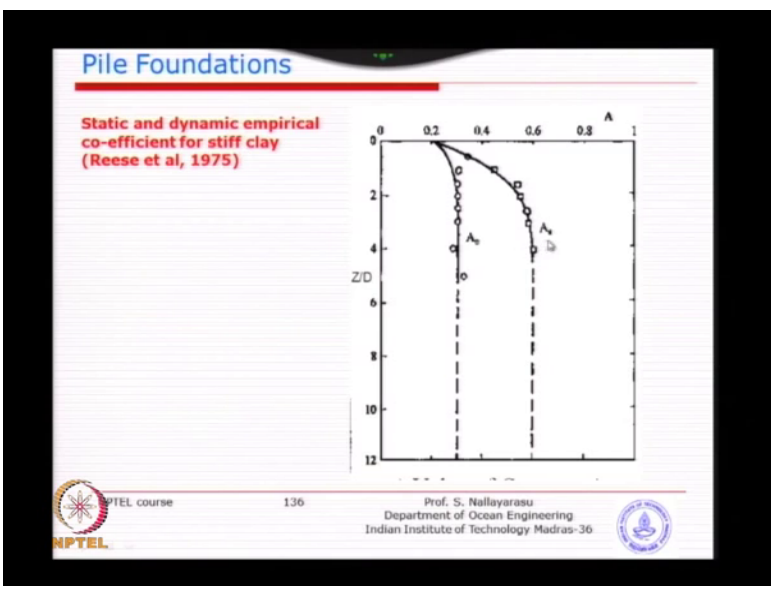

So you have to establish the graph based on this procedure, for cyclic loading is a similar only the difference is instead of A static you will replace the coefficient here you will see A static A s here you will see A c. So A s is for static loading A c is for cyclic loading the values of A s I just picked up from his original paper I am actually not reproducing it.

So you can see here A c and A s, A s is a static which is almost 0.6 throughout the depth z by d is the normalized depth with respect to the seabed as you go down after 3 diameter I would say the values of A s and A c has become constant value, that means 0.6 for A s, 0.3 for A c and so this is again reflex the idea of shallow depth is influenced by the moment of the pile and the soil gets remolded and as you go deeper and deeper these values become constant and those values can be easily substituted because you can see here the strength value increases with A.

So you can so the only difference between soft clay and hard clay is the shape of the P y relationship is almost curvilinear and the values definitely will be higher or lower it has to be lower because we know very well even though the strength of the material is good but because of its nature it is not going to get in touch with the soil or the pile that means it is not going to provide the required resistance one biggest problem is if the gap is created and the pile goes back and pile is trying to contact the pile will really move until the next time the soil gets in contact that means resistance is lower than the soft clay because soft clay will come back quickly and just prevent the pile from moment, so that is exactly the difference.

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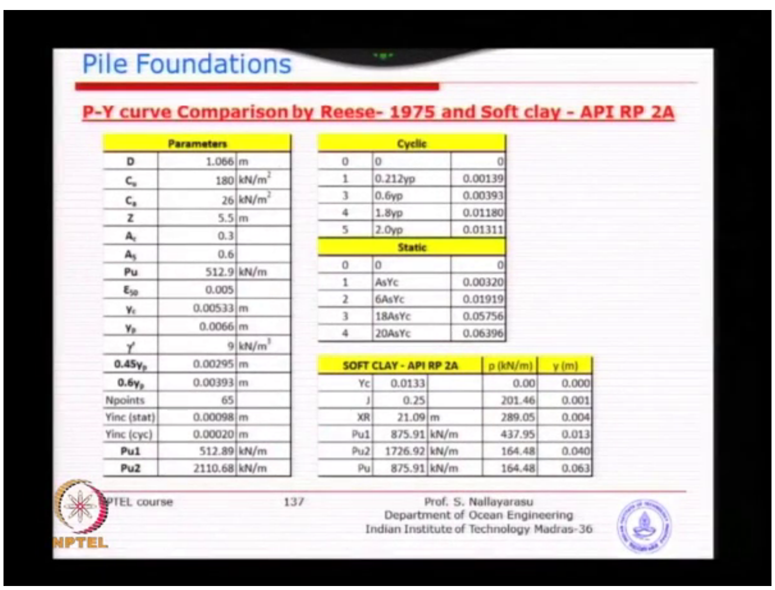

I try to plot you could see for a particular diameter and the soil resistance I just wanted to show you the just in a spread sheet you can put everyone of them all the equations learnt about soft clay hard clay soft clay at near surface and the hard clay at the near surface you can just see the comparison just show that you will understand what significance it makes.

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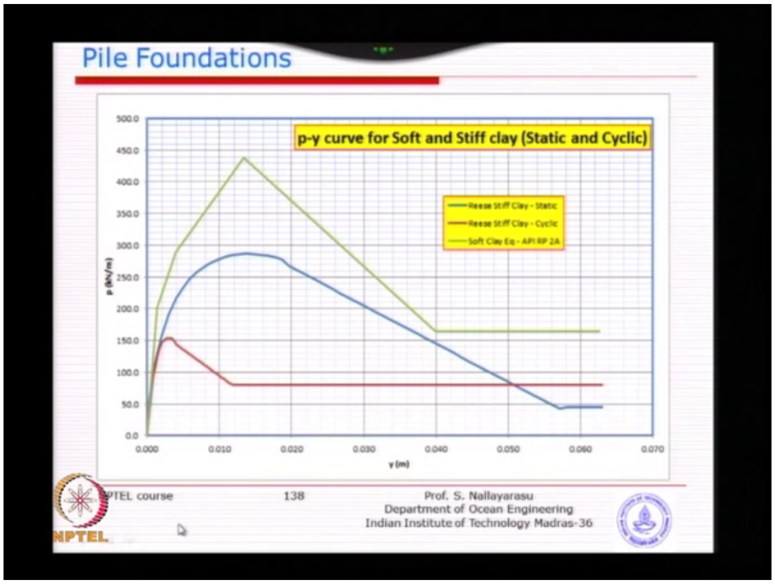

So you can see in this case the green one is basically the soft clay the equation given by API so you can see just built up and then comes down because its near surface and becomes plateau at 0.04 meters as the displacement.

Whereas the blue one is the stiff clay equation given by Reese so you can see still it is comparable to a soft clay not too bad because if you look at the ratio of the resistance is about 300 280 and this one is about 400 2400 and 30. So soft clay to stiff clay becomes almost 70, 80 percent or maybe 70 percent and then from that to a cyclic of stiff clay that is even worst is almost 150 so 1 third of it. So the understanding must be clear soft clay even if it is cyclic is reasonably better because the flow nature is there.

Whereas the hard clay because of the brittleness of the material you know it does not come back and you does not provide sufficient resistance against. So you can see here from a material of soft clay to this it degrades substantially lower so if you encounter at any site where this material the clay material is stronger you should not feel that it is going to provide you with the good lateral resistance it is going to actually degrade overtime and that is not very good. So that you could expect some problem in the examination time so we need to practice during the next tutorial time.

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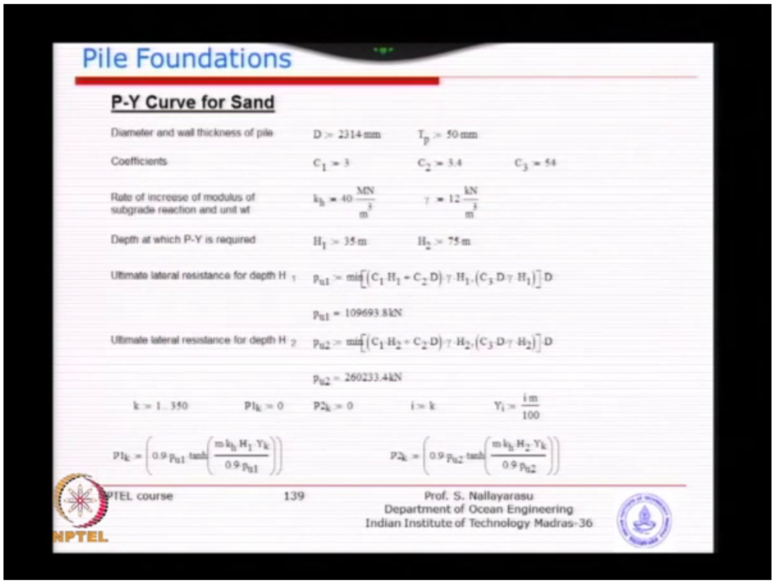

So I just given you two examples in this particular, one for sand so I can see here I have just used all those equations which we described earlier on the diameter is 2314 wall thickness C 1, C 2, C 3 coefficients are taken from those tables and kh value is given to you as 40 mega newton is a good one that means is a very good sand and then the depth two depth I have just wanted to show you an example how they differ and calculate the P u values and I have just put down the equation which we described earlier on for a cyclic loading case for two depths and this is how it will look if you generate yourself using computer softwares or by manual methods.

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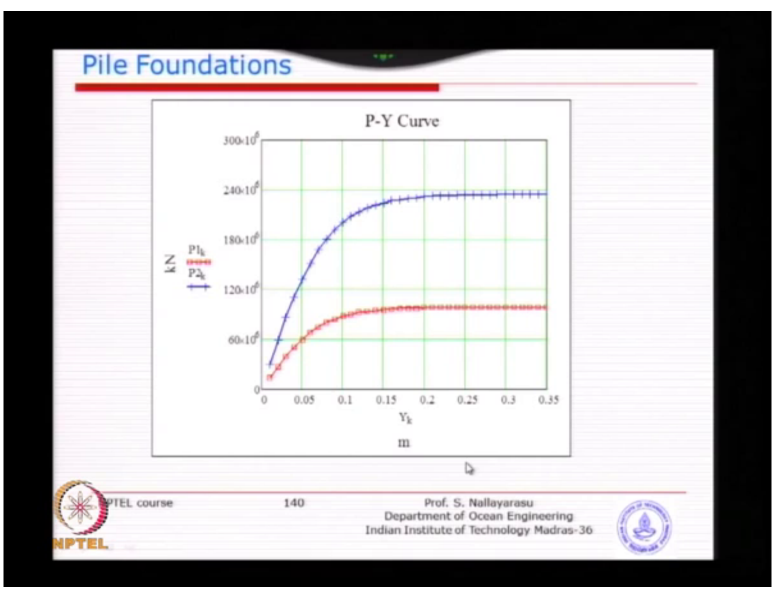

So you can see here is the displacement here and this is the kilo newton in terms of lateral resistance. So this is for us shallow depth this is for deeper depth basically P 1 and P 2 calculated at to different depths just so and that is what you need to try and do practice because ultimately when you want to do a computer simulation if in fact we should try and do that in our numerical modeling class that prepare few P y data from given soil material, for example if you are given earlier we were doing actual capacity for three layered soil or four layered soil.

Now if you want to program that in terms of computer software to simulate the horizontal load displacement behavior then you should know how to develop this. So you have been given sand particular angle of internal friction density is given so you should know how to generate this relationship and feed this relationship into the numerical model so that you can of course you can try and do manual calculation, for example you have a four layers and I give you a horizontal load you could still do a manual calculation if you have enough time because there is only a four segments.

So four springs you will calculate and each time you do an iteration until you get the load equilibrium but unfortunately it will even for four layers it will take several hours so that is why we use a computer.

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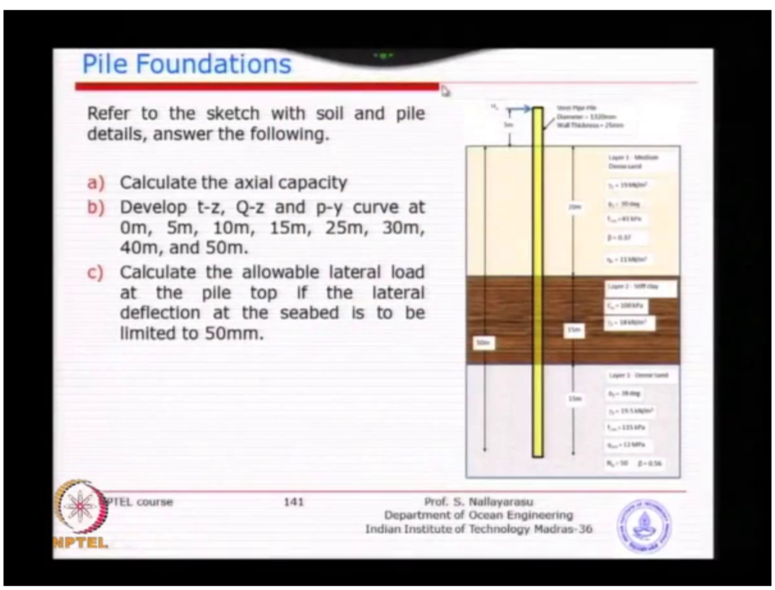

So this example is basically three layered soil we have sand dense sand and a stiff clay and again dese sand. Now you should now when you should also learn how to compute when you have a multilayered soil in all these equations what we saw just now either for clay or for sand it is for a single layer soil so we should know how to take into effect the weight of soil above.

For example when I want to compute at this point I want to do a P y relationship now you see here if you remember the equation given for clay we got P u is in relationship with 3 C u plus gamma h or gamma x plus another (())(37:45) that x is the depth gamma is the density. Now what will you do with this the sand layer above, what density you will use because only one term is there so we need to do a normalization or take into account the weight of the soil above and find out what will be the effect.

So we need to learn this multilayered soil will be a problem in fact API is not describing that clearly what needs to be done so from work done by Reese earlier we will use the normalization procedure. So in this particular example calculate the allowable lateral load at the pile top if the lateral deflection at the seabed is to be limited to 50 mm and that is the limiting condition given to you I have loading which I do not know how much will be applied but I know the limitation is this pile at the seabed should not deflect more than 50 millimeter which will be the most practical condition and calculate the load which will be suitable for such displacement and that is what in fact we will compute from even if you use a computer program ultimately we will be doing this we will be reducing the load if the displacement goes higher than 50 mm.