Geoenvironmental Engineering (Environmental Geotechnology): Landfills, Slurry Ponds & Contaminated Sites

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Lecture - 21
Settlement of Landfills

So good day to all of you, and let us look at a new topic on landfills today that is Settlement of Landfills. I think I have mentioned in the past that landfills which are biodegradable waste undergo large settlements. And it is not unusual that over a very long period of time you may have settlements of the order of 25 to 30 percent of the height of the landfill; if it is made of municipal solid waste with high biodegradable content.

Let us see can we estimate this, can we predict this, how can we make use of it that is the topic of discussion today. Remember that if you have inorganic waste; waste which is not going to degrade and if it is well compacted the settlements are going to be much lower. And they will not be that much time dependent as a waste which biodegrades or decomposes with time. And therefore, shows much larger settlements.

So, what kind of settlements, what would be the components of the settlements? As we look at it we know how to compute settlement of soils. So, will the processes of settlement of waste be different from the processes of settlement of soil. One I already said that if there is biodegradation or decomposition that is one difference. Is there any other way in which waste will also differ from soil?

Student: Higher rate of creep.

So, higher rate of creep: creep means movement with no increase in effective stress or no increase in overburden stress, it is a time dependent phenomenon, it may result from so many things. So, quite clearly there will be higher rates of creep in municipal solid waste landfills. But there is another aspect which we need to understand that the matrix of the solid particles is very different in wastes. In soils what are the solid particles made of? In soils what are the solid grains made of?

Student: Silica.

Yes, basically silica and in waste it may have some silica in the form of soil, but they would be the solid matrix could be of each of the individual components. If you have a piece of wood it will be different, if you have piece of cardboard it will be different. So, the solid matrix will be different.

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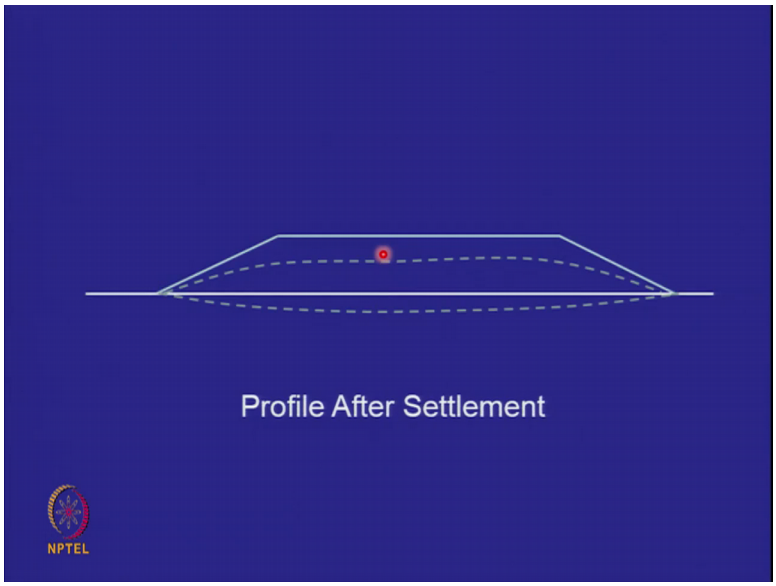

If I look at the settlement which takes place one is the settlement at the base. And this is the settlement of the foundation soil. So, this settlement we can compute.

What we are bothered about is; what is the profile of the landfill after the settlement has taken place. And this movement can be very large; this movement can be very large. So, it is this movement that we are going to focus on.

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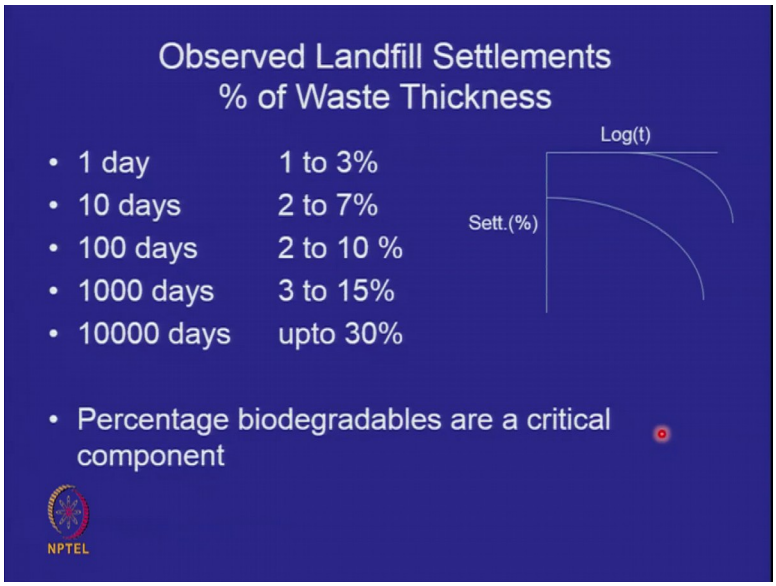

So, what kinds of observations are there in literature on settlements with time? If you plot settlement as a percentage of waste thickness with log time all the data falls between two boundaries. Firstly, the spread of the boundaries is very large. And secondly, it shows that even if you plot it with log time there seems to be increase on the log time basis as you go further ahead in time.

So, typically a waste may undergo 1 to 3 percent settlement within one day of its placement. 2 to 10 percent settlement within a 100 days. 3 to 15 percent settlement say within two and a half years, and as you said up to 30 percent settlement over 25 years or more. And the upper limits are all four when the percentage of biodegradable the high.

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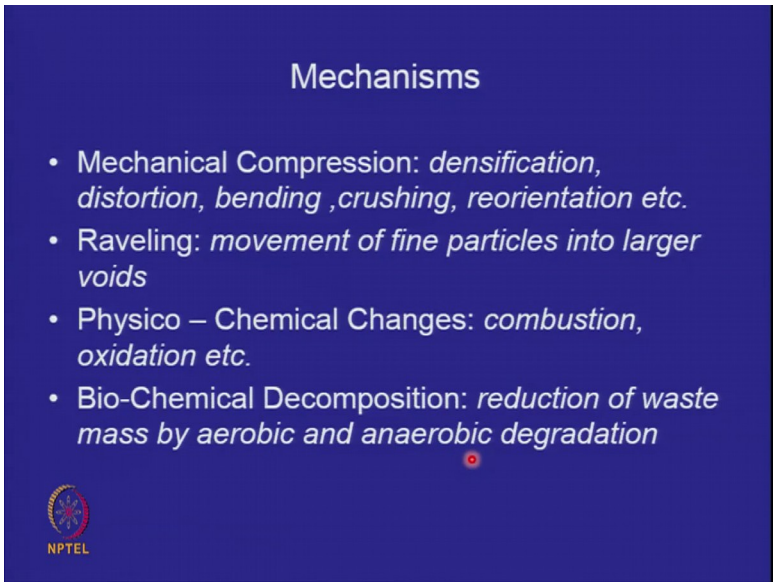

What are the mechanisms? We know that we have some mechanical processes, mechanical compression so densification; grains coming closer together on account of application of overburden stress. But, because the grains are not made of silica and they are not rigid you can have distortion of the drain. The grain itself supposed to begin with it is particle which has a particular diameter because of the stress the diameter may change its shape may change. It may undergo bending, you may have a linear element which undergoes bending. Many grains may crush, this is even at nominal stresses.

So, if there is crushing that is additional mechanical compression. And of course, there may be a reorientation. So, mechanical compression is not the same as in soils there are many many additional factors. So, mechanical compression will be higher. So, if you are going to compute the amount of settlement on account of mechanical compression it will be higher.

Another component which is new normally in soils unless you have placed a fine grained soil on top of a coarse grained soil and the fine grained soil can intrude into the wide space. Movement of fine particles in soil does not take place normally. However, here because of the heterogeneity of the mix your waste may have very large sized particles and it may have large size past particles as in construction and demolition waste, right. And you may have silt which has been cleaned up from the drains also coming, so that may be fine grain. So, with time what will happen is that the fine particles tend to move

down into the larger wide space. So, that is called raveling and that also adds to the settlement.

Even further you may have some chemical reactions taking place: a landfill fire. You have landfill fire of some material is burning, and it is going into the gaseous state, it leaves a little bit of residue, but settlements will occur on account of landfill fires. By further most important component is decomposition or degradation. And this is the one which causes the reduction of the waste mass by aerobic and anaerobic processes and which occurs over a long period of time.

So, all these put together give you the settlement in a landfill.

Another aspect which I just want to clarify is that.

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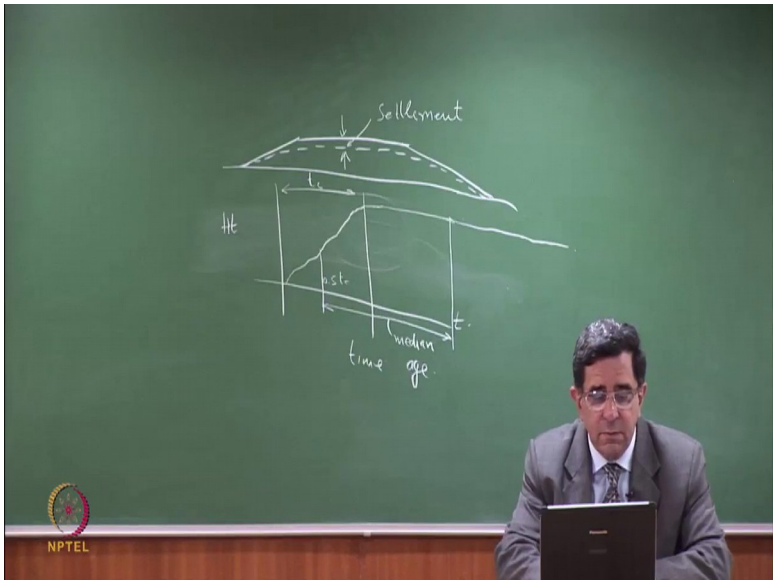

if I have a landfill, its settlement will be irregular because the lateral heterogeneity of the material. If everything was similar then it would settle in a similar manner and you would have perhaps settle profile like this. But, because this lateral heterogeneity; that means the waste right below my feet may have one set of properties and the waste here may have another set of properties. This may have a lot of construction and demolition debris, right. So, it is an organic. It is not going undergo biodegradation.

So, the truckloads which came when the waste was being placed here had a lot of C and D waste. Whereas, the waste which was put you placed here had a lot of food waste. So,

you have a lateral variability, that lateral variability in indicates that this profile is not like this, but it is more like that.

So, we are not trying to estimate this. We are trying to estimate this. I go back to the discussion of differential settlement in soils and total settlement in soils. Differential settlement occurs between two foundations: they may have equal stresses but they still may undergo differential settlement because, the size of the foundations may be different therefore the stress area may be different. Or they may like there may be lateral variability in the soil. So, the only way to tackle differential settlement was to limit the total settlement. That means if you know the total settlement, you know that the differential settlement will be lower than the total settlement. Therefore, if you limit total settlement you can limit differential settlement.

In our study today or discussions today we are looking at this settlement which is the total settlement which is going to take place. Now it is possible that in one region settlement may be much lower because of lateral variability and in another region it may be much higher. So, this issue above the depression which forms and covers is a totally different issue. The issue of depression which forms in covers is totally different issue, there you have to estimate the radius over which the depression will form and the amount by which it will form, which is much different from the total settlement which may occur.

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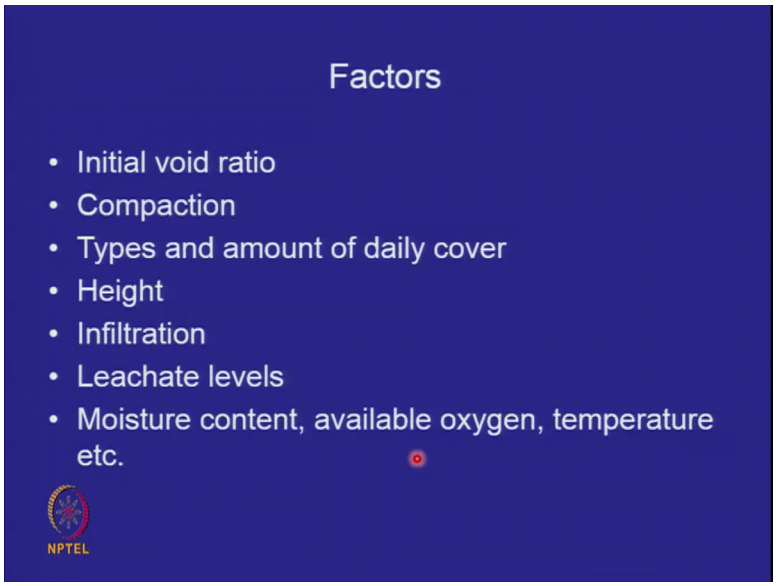

So, the factors which affect settlement and you will remember that for amount of settlement we had the effective stress, the initial void ratio, the ratio of the final stress to the effect initial stress. Here additional factors come into play. Yes, there is the initial void ratio e naught, but how much did you compact your waste that is a big factor. Because if your waste was placed loosely and at another side the same waste was placed by compacting with landfill compact which gave high stresses then it would make a difference.

Also the type and amount of daily cover: the rate of biodegradation is dependent on how much moisture gets into the waste, what is the available oxygen. So, wherever you are putting more daily cover there you are slowing down the processes of degradation. So, it would reduce the rate of settlement.

Height indicates the amount of stress: overburden stress that is coming onto the waste. Infiltration governs the rate of biodegradation; how much is the water which is infiltrating into the landfill. Leachate levels again how much of the waste is saturated because of accumulation of leachate at the bottom. Moisture content, available oxygen temperature etcetera.

So, there are a large number of factors which are affecting the rate of settlement in a landfill.

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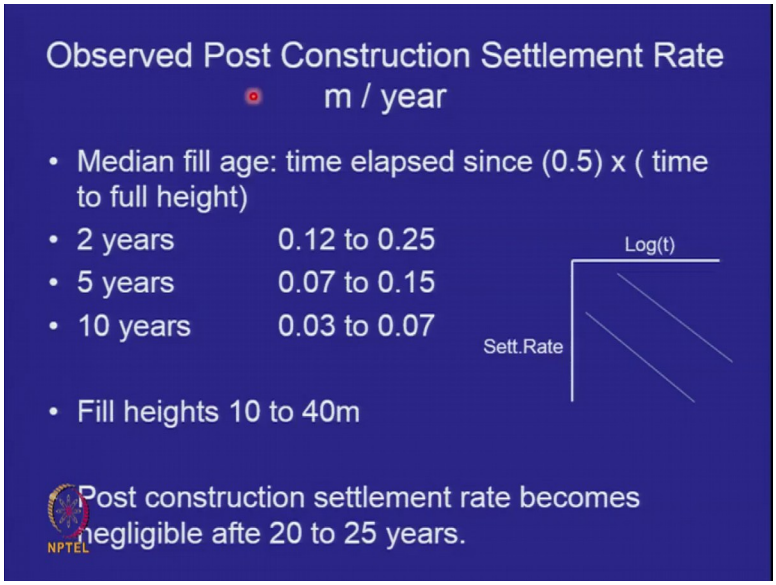

If you look at the post construction settlement rate, this is something which is observed maximum. You know you finish a landfill and you have got some settlement gauges on the surface of the landfill and you can keep on monitoring at what rate are they going down.

So, there is a lot of data on the rate at which landfills will settle and they use the concept of median fill age. So, let me say what is median fill age? If the landfill height increased like this; so this was the construction period and then no further construction. Then this is tc- time for construction. If at any point of time you want to find the settlement you take the reference point as 0.5 tc. So, with time this height is going to go down because the landfill is settling. So, there is data on this is what is called the median fill age. From 0.5 tc to anytime t which you are wanting to understand the what is the rate of settlement.

So, this time if you look at, then if it is 2 years then the rate of settlement of landfill per year is reported to be between 0.12 and 0.25. And you can see its decreasing the rate at which it is settling. So, if it is 5 years it is 0.07 to 0.15 meters per year. And if it is 10 years it reduces to 0.03 to 0.07 meters per year. This data is being all observed data and it is for landfill heights of 10 to 40 meters. And it seems to suggest as you can see the rate of settlement is going down that post construction settlement rate becomes negligible from 20 to 25 years

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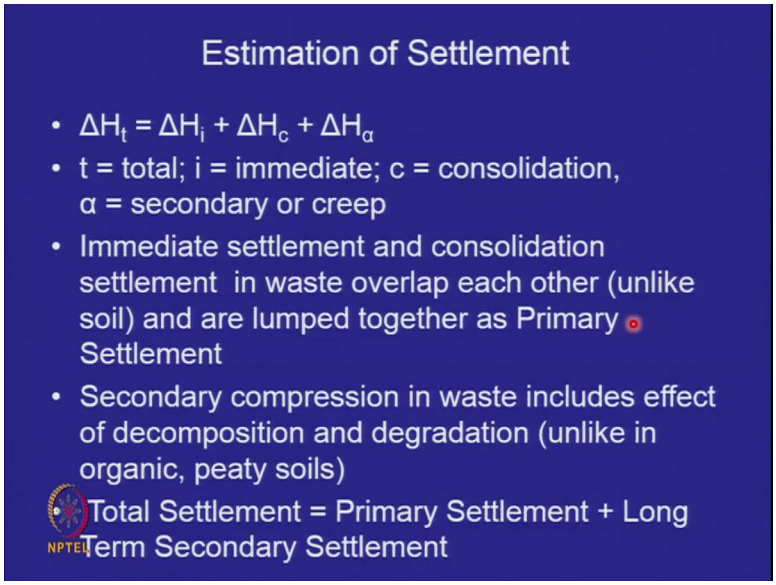

Let us look at how do we now estimate the settlement which will occur in a landfill. And let us go back to our soil mechanics principles. The total settlement is equal to a sum of the immediate settlement and the consolidation settlement and the secondary or creep settlement. Is it possible to distinguish between immediate and consolidation settlement in soils? Do you remember the square root of time method? You plot how the thickness of a sample and the immediate settlement would occur right in the beginning and then will have a consolidation settlement which is time dependent.

This is possible in clays, is it possible in sands. So, immediate settlement and consolidation settlement becomes lumped together in sands. Why? Because sands are free draining and water comes out instantaneously. So, immediate settlement and consolidation settlements happen together.

So, immediate settlement and consolidation settlement in waste also overlap each other, unlike fine grained soils. So, they are lumped together as primary settlement. And secondary compression in waste includes the effect of decomposition and degradation unlike in organic and peaty soils, where this may not be necessarily the predominant component; it will be there but it may not be the predominant component. So, the total settlement in waste is computed as primary settlement plus long term secondary settlement. And long term secondary settlement is primarily on account of decomposition and degradation.

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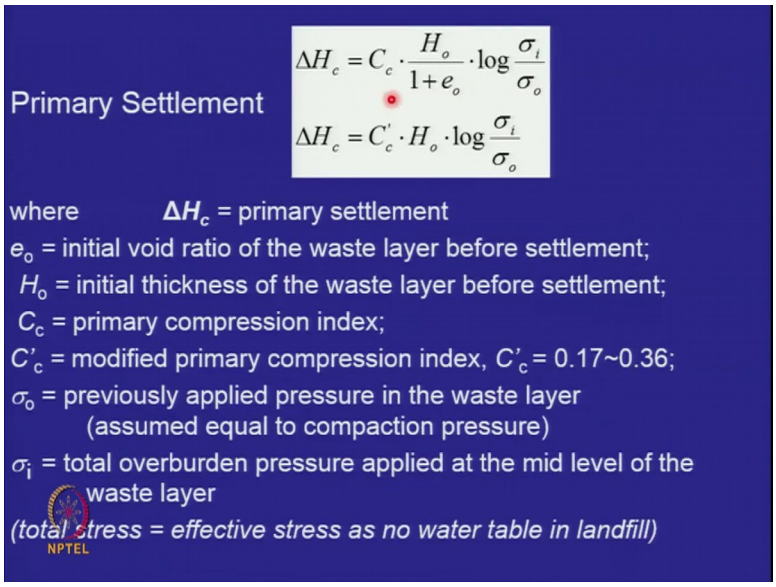

So, if we go back to the formulae that we are aware of then, primary settlement C c H naught over 1 plus e naught log sigma 1 sigma the i-th height over sigma naught. So, in our parlance it should be sigma dash and sigma dash, it should be the effective normal stress. In waste parlance normally there is no water table, when are you going to use effective stresses when there is going to be a water table. There may be a leach at head at the bottom 1 meter or 2 meter, but mostly an all above ground mounds or even below ground mounds where the water table is below the leach it tends to flow out. So, here the formula which is used very often is just used the total stresses.

The other important thing is that having worked with C c in soils first attempt was made to compute using this formula. But then as a computational device it was found that C c over 1 plus e naught if it is reflected as a parameter C c dash, that was much more easy to handle and established than C c over 1 plus e naught. And the problem was how to establish e naught most of the time.

See, please understand. To be able to compute C c I must know delta H which I can observe, I must know H naught which I know, but I must also know e naught. Now, e naught is simple to compute if I know the density of soil because I have one specific gravity, one type of grains and I can give me get the void ratio. Now let me take a a sample of municipal solid waste, it has got some soil in it, it has got some wood in it, it is got some paper in it, some cloth in it, some food in it; what gs are you going to use. You will fall back on your compositional analysis that this much percentage is this, well in that sample it may be very different. So, computing e naught for the waste is complicated. So, we can work with this modified formula for the primary settlement.

So, delta H c is the primary settlement, e naught is the initial void ratio, H naught is the initial thickness of the waste layer, C c is the primary compression index, and C c dash is what we are introducing here today is the modified primary compression index. And please note I have given some values here. Experience now shows that for municipal solid waste C c dash values typically lie in the range of 0.17 to 0.36. That is not a very wide range. In contrast C c range will be very high, I will show you.

So, sigma naught is the initial pressure which was applied which is equal to the compaction pressure. So, it is equal to the stress which has been implied by a roller or in municipal solid waste you may often be using a dozer, so it is the stress which is applied

by that. And sigma i it is the total overburden pressure applied in the middle level of the waste layer after the waste has built up. As you build up it is the final normal stress at the top, after placement of i-th layer.

Here total stress has been taken to effective stress as no water table is there in the landfill. This you must understand is the presumption in this analysis.

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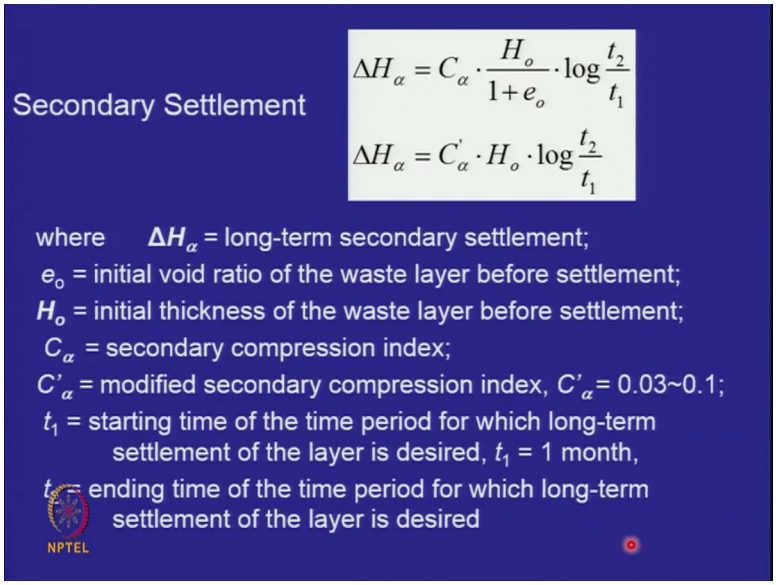

If I look at secondary settlement or the long term creep settlement the formula if you will recall changes to this. Whereas, where C alpha is the secondary compression index and now it becomes a function of t 2 by t 1; where t 1 is the starting time and t 2 is the ending time that we are targeting.

Again in this, the approach which is used for municipal solid waste is to substitutes C alpha over 1 plus e naught by C dash alpha. So, instead of using the secondary compression index you use a modified secondary compression index. And here also you will see that it varies about three fold 0.03 to 0.1.

So, we can use these formulae to estimate the primary settlement and the secondary settlement.

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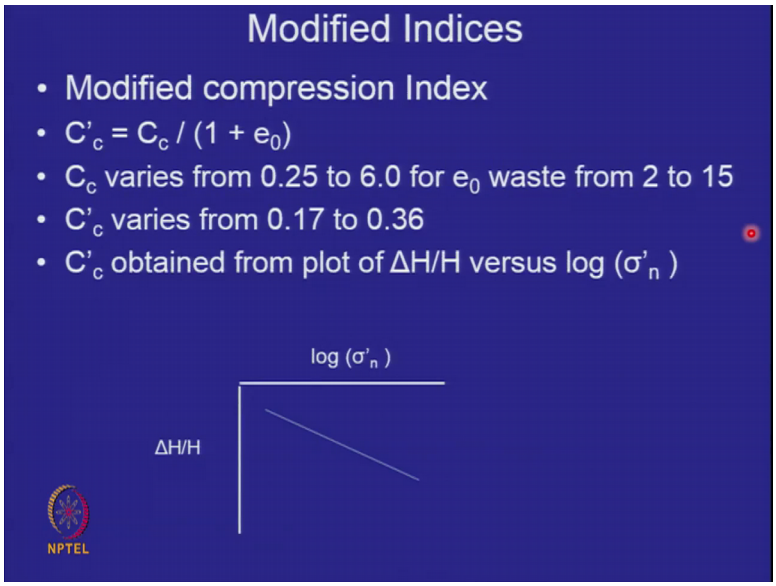

So, what are these modified indices? The modified indices are that C c dash is equal to C c over 1 plus e naught and C c dash is obtained from the plot of delta H by H. So, for landfills you know the delta H by H, and you can plot versus the log normal stress and you get a straight line relationship. And therefore, you get a value of C c dash. If you try and determine C c you can also determine C c, but typically C c varies from 0.25 to 6. For e naught of the waste from 2 to 15, please first remember what was are e naught in soils, what kind of e naught had a typically dealing with in soils.

Student: 0.5, 0.6.

0.5, 0.6, 0.8; 1 is rare very very soft and flocculated clay it may give you more than 1, but basically our void ratios which we have been dealing with have been less than 1. In this material which is such large heterogeneity and large such large void spaces your e naught can be very very high. So, using these two parameters in the formula requires you to have a very accurate estimate. And doing a consolidation test on waste is cumbersome because you require very large odometers or very large consolidation cells. Instead if you take the data which is available in literature and you look at this data, you plot of delta H by H versus log sigma dash n. Where, the time factor has not become very significant yet then you will get your C c varies from 0.1; C c dash varies from 0.17 to 0.36.

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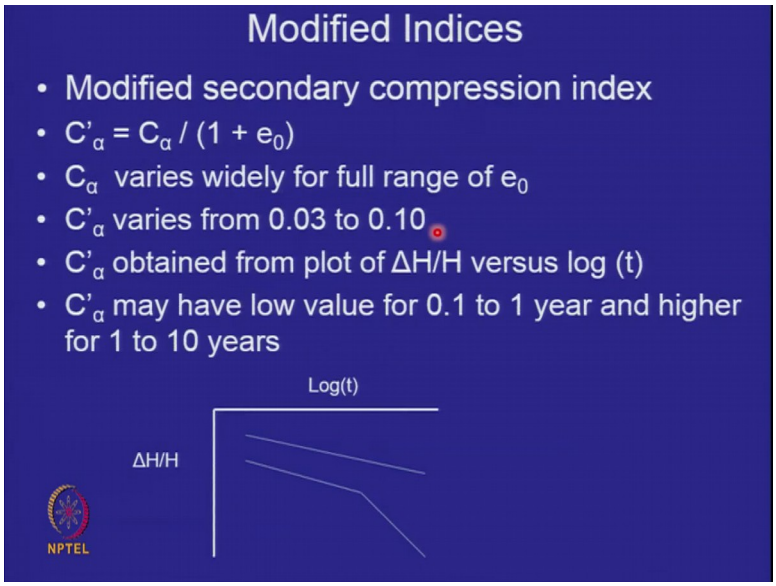

The other modified index is C alpha dash. Here also if you plot the delta H by H as a function of log time then you normally get a straight line relationship. And in such cases C alpha dash varies from 0.03 to 0.10.

However, in some literature you will find that they are talking of a bilinear relationship in the log scale: in which case you may have to use C alpha 1 here and C dash alpha 1 here and C dash alpha 2 here. The slope of this line will also be C dash alpha.

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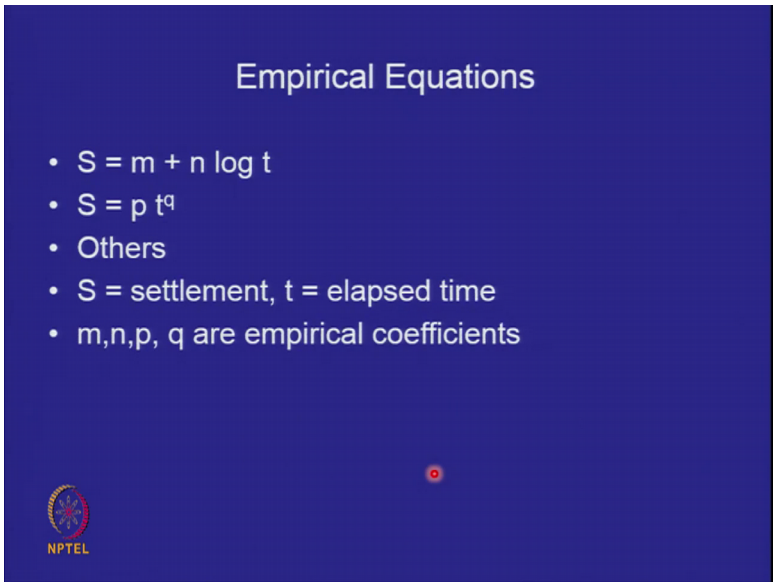

Some other empirical correlations have also been suggested, and these have been used. But there the settlement is directly correlated with time for a particular landfill. What they do is that observations of settlement with time are available from the previous years and you are trying to predict what it will lead to. So, you kind of do a regression analysis. So, there are some equations like S is equal to m plus n log t or S is equal to p t to the power of q web mp and m n p and q are empirical coefficients. But all that we are doing is relating S to t, so either a rule log relationship or S to t through a power law. So, such laws are useful for specific landfills, you cannot pick up this power law of a landfill in the US and apply it to the landfill in India, because that is not going to work.

So, I think the best way to demonstrate what we are talking about and how do use this formula is through an example. And I hope you have calculators here, because I am going to request you to do some calculations.

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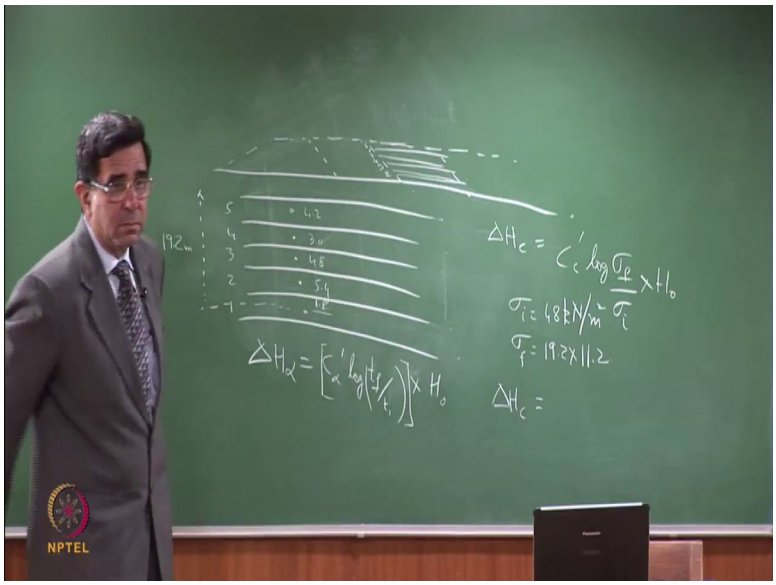

So, this is an example of a landfill which is operated in phases. And this example you know if I have. This landfill is going up to the top in 6 months, we talked about operating a landfill in 1 year phases and closing it. Doing a landfill in 2 years is not ok, because you have not covered it when the monsoons came. Doing the landfill in 6 months is ok? Yes, you can cover it every 6 months, and therefore you can be better prepared.

So what they are doing is, let us say I am looking now at this problem. The landfill is going up to its final height 1 2 3 4 5 it should be 6. So, 1 2 3 4 5 6; in 6 months it goes up

from the ground level to the top and then the next phase starts. And how much does the landfill rise in each month does not depend on our design, but depends on how much waste is coming in each month. So, sometimes the waste is more, sometimes the waste is less; I do not know whether there are festivals or whether there are other reasons for it. So, at this particular landfill we have been told that it is operated in 6 month phases and the waste which is coming in is of different thicknesses.

And what are we trying to estimate here we would like to know that as I went from here to the end of the 5th month then I have to place my final layer, right. Do I have additional space or not? Why? If the first five layers have settled then I will get additional space to put waste more than what I thought that I could place at that time. So, that is the exercise that we are going to perform; that in 6 months how much does settlement occurs so that in the 6 month I can put more waste.

So, let us see what the problem states.

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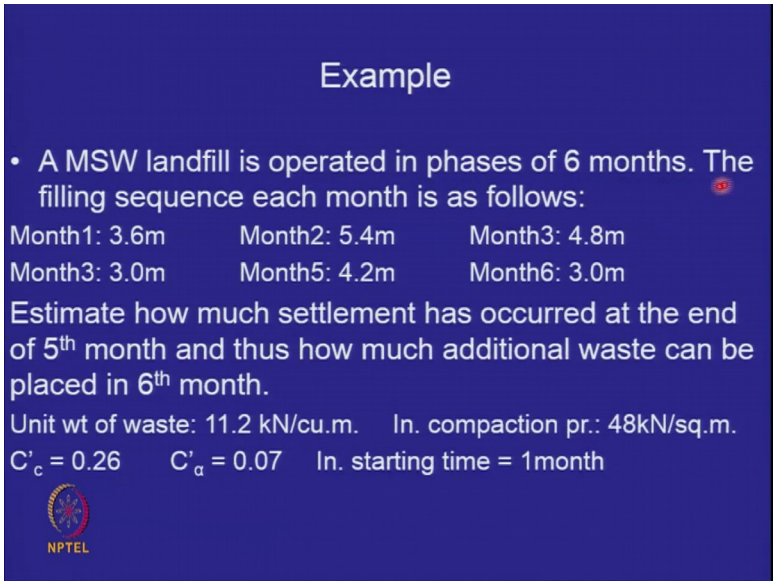

A municipal solid waste landfill is operated in phases of 6 months. The filling sequence is as follows. First month you put 3.6 meters, then 5.4 meters, then 4.8 meters, then 3 meters, then 4.2 meters, and then than 3 meters. Can you tell me what is the height of this landfill? Just total all these values.

Student: 24.

So 24 meter high landfill, in 6 months we are reaching 24 meters high. So, the question is estimate how much settlement has occurred at the end of the 5th month, and thus how much additional waste can be placed in the 6 month. I wanted to remember this that we have said that we can get 15 to 25 percent settlement, we can get up to 30 percent settlement, so this always very nice to think that maybe I can use this entire space. But on the other hand we are putting our final cover before the next phase starts, why because we want to keep the leachate generation to a minimum.

So, all additional space that we can utilize is the one which gets generated in 1 year because after that you have to cover it, once you have covered it then your the issue about having additional space you are not going to open up a cover after 5-10 years and then replace the cover on top of it. So, most of the space becomes available towards the end of the phase.

So, here you are given the unit weight, the initial compaction pressure was 48 kilo Newton's per square meters, C c dash has been given as 0.26, and C alpha dash has been given as 0.07, and always the initial starting time that you take is 1 month. What is t final over t initial, t initial always please take us 1 month. So, let us see what we can get from this example.

What kind of estimate would you think; let me ask you to quick questions. In 1 year what kind of settlement would take place? 2 percent, 5 percent where we said that maximum is 15 to 30 percent so obviously we are just talking 1 year, there we are talking over 25 years. So, we think that it may not be very significant. Also the next question is in 1 year which is more is the mechanical compression more or is the secondary time dependent compression more. So, let us see what emerges from this example.

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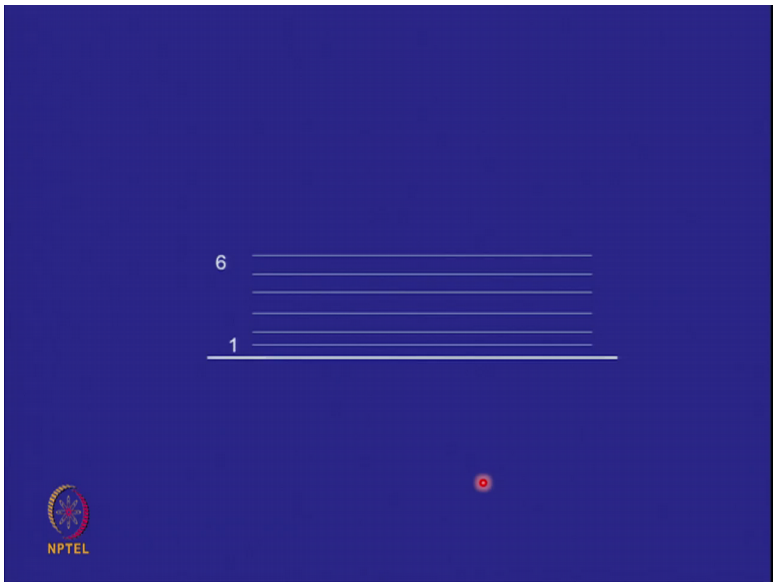

So, this is what we are saying we are just going to treat it as layers being placed one on top of the other and we are just going to look at the settlement of this large horizontal layers placed one on top of each other each of variable thickness. Here is the way you should go about it.

You have each layer, and do all work at the center of each layer and here we are only talking off till at the end of the 5th month, ok. So, let us first compute what is the total delta H c. These layers have different thicknesses, so for each you can find out the height of the soil above it and the stress above it. And what is given to you is sigma i is equal to. So, what is this table that has been given here?

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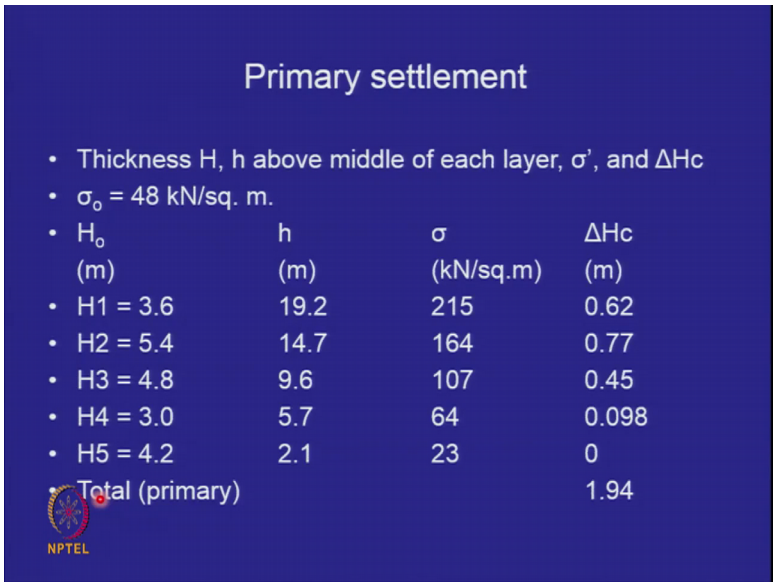

These are the thicknesses of the layers H 1 is the bottom most layer and it builds up like this. This is the H naught for each layer. So I want to know; what is the delta H for this first layer at the end of 5 months that is what I want to know. I want to know what is delta H for the second layer at the end of 5 months. So, tell me what will be the height of the waste for the first layer at the middle.

Student: (Refer Time: 34:43).

No, see this is layer 1 and this is building up with time. So, you have to take the middle of this layer, this layer is 3.6 so this is 1.8, then 5.4, 4.8, 3.0, 4.2. So, the height above this, this will tell me how much this will squeeze in 5 months on account of the change in the stress which is acting on top. So, what is this?

Student: 19.2.

19.2. So, the second column shows 19.2 and you have 11.2 as your unit weight. So, you know the stress, you know the initial stress, can you give me delta H c. In fact, it will work out that if this is 19.2; so sigma final or sigma at the top. So, anybody has delta H c for the first layer? You want to know what is the C c value?

Student: (Refer Time: 36:38).

Cc dash is 0.26 have I put the formula in error. This has to be multiplied by the, so you should to tell me now that this has been missed. Anyways, if you do if you complete this table you will get values like this. Your total settlement will be about 1.9 meters. This you can complete at home.

Let us look at the next computation. This is the primary mechanical settlement.

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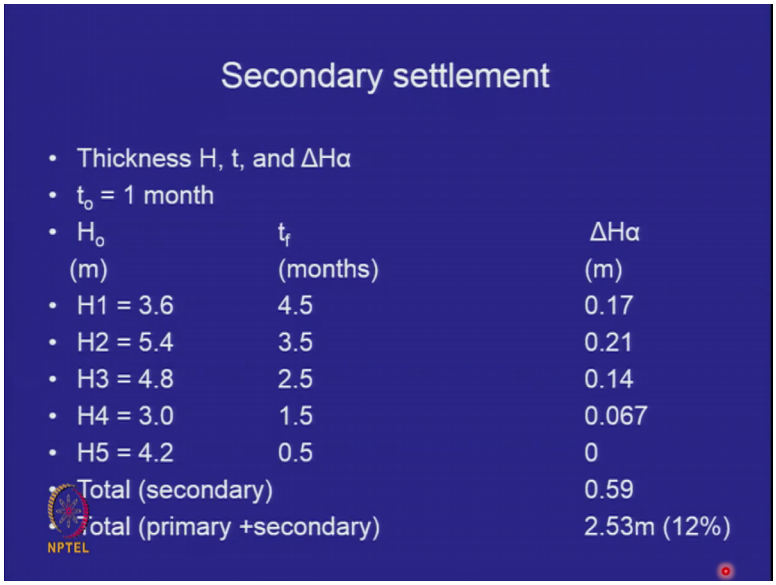

Now, I want to know the settlement on account of biodegradation and decomposition. This time I am interested in the time that has elapsed between the time that the waste was placed and, the time we are computing the settlement at the top. So, how much time would have elapsed for the first layer when the 5th layer is completed? At the center 4.5. So, if you were to do this you will get delta H alpha as 0.17 meter. Please confirm this for me.

So, if I complete all the computations this is what I will get. You can note down the higher layers have had less time, the lower most layer is at the maximum time, and these are the values. And the total secondary settlement is 0.59 meters and if I go back and the total primary is 1.9. The important thing to see is what is after 21 meters of waste has been placed; the 3 meters has still not been placed. We are getting an additional 2.53 meters of space to play waste within a period of 6 months. But that is substantive if you have a lot of biodegradable material limit.

So, we do not understand, we do not estimate this in the beginning but we can estimate it now as to how much additional waste can you put at the end. And in this case which was more, the mechanical compression or the degradation.

Student: Mechanical.

Mechanical was 1.94 and the degradation was 0.59. So, time has only passed as only 5 months, so obviously this has not taken over. But as more and more time will pass what will happen to the primary settlement.

Student: (Refer Time: 40:32).

Now after this the next phase will start. So, what will happen to the primary mechanical settlement as we build the other phases? 1.94 will it change? No, sigma will not change, other than the 6th layer coming on sigma will not change. So, the primary mechanical settlement has happened and it will not now increase with time, only the secondary settlement will keep on increasing with time. At some point of time the secondary settlement will overtake the primary settlement.

So, even primary mechanical settlement is very large in waste. And how much time does it take for the primary settlement to occur. The secondary settlement we are estimating over 5 months. Primary settlement occurs in how much time? Pardon, how much time does the primary settlement occur, the mechanical settlement occur. Suppose I had given you this problem in soil mechanics how would you found time for settlement? One is amount of settlement; the second is time for settlement. To find out time for settlement how would we have gone about it?

Student: Cv.

We would need cv coefficient of consolidation and on the basis of coefficient of consolidation we would find t 90 and you would say that 90 percent of the settlement will take in this much time. Here we are not talking of cv why? Because it is a free draining material, in free draining material time for 90 percent settlement is how much; instantaneous. So, please understand waste is being treated not likely or not like silty clay or clay silt where it takes time for pore water pressure to dissipate or water to come out, but it is being treated as behaving like a free draining material.

Let me take a quick analogy. As I said this waste is not saturated necessarily because there is no water table; if I have unsaturated clay which is the predominant settlement.

Student: (Refer Time: 43:16).

So, it is again the primary settlement is not on account of time dependent consolidation, but it is on account of immediate compression of the air voids. So, immediate plus the compression of the air plus the reorientation immediate gives you the settlement. So, please note that waste is not being treated similar to fine grained soil, but it has been treated like a coarse grained soil or a soil with a lot of air voids in it. And so all the primary settlement occurs instantaneously; with time it is not going to increase; it will only increase if the vertical stress increases over a period of time.

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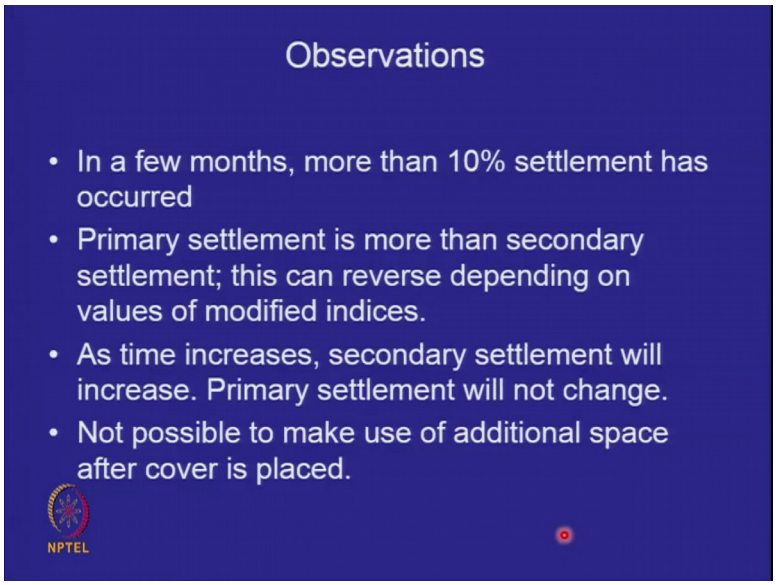

So observations: in a few months more than 10 percent settlement in terms of waist thickness has occurred. This is substantial. Primary settlement here is more than the secondary settlement. However, this could have reversed if the value of C c dash was lower and the value of C alpha dash was higher. So, if you had very high biodegradable you would have had a much higher C alpha dash. So, this could have reversed. As time increases secondary settlement will increase, primary settlement will not change. And it is not possible to make use of additional space after the cover is placed.

Now after 6 months or if it was a yearly phase I would have placed the cover, beyond that everything is moving by log time ok. So, the settlement that will occur from 0.1 year to 1 year will next occur in how much time: I am saying something. Suppose x centimeters occur from 0.1 year to 1 year then will the next x occur.

Student: 1 to 10.

1 to 10; so please do not think that with time the settlement is, it is going to go up with a logs only in log time. So, 10 percent has occurred now, the next log time will make it go up to the next level.

So, as time increasing secondary settlement will increase, it will not increase linearly with time it will increase linearly with log time. So, all the observations are for 0.1 year, 1 year, and 10 years. If you look at most of the landfills most of your observations are those cycle times. Primary settlement will not change and it is not possible to make use of additional space after the cover has been placed.

So, what we have introduced you to today a two new concepts. One is waste can be treated similar to soils. However, the concept of C c and C alpha is not so useful because the void ratio is a big issue. Concept of C c dash and C alpha dash has been proven useful because the readings of delta H by H versus normal stress and the reading of delta H versus H in terms of time are available. And we can do the correlations with log time and log sigma. And on the basis of those correlations we find that c c dash and C alpha dash are in narrow range. So, we can use these for the purpose of estimating.

Still we cannot estimate the depression. Whatever we estimated total settlement, if you go back to the concept of differential settlement if I just go back to soil mechanics principle.

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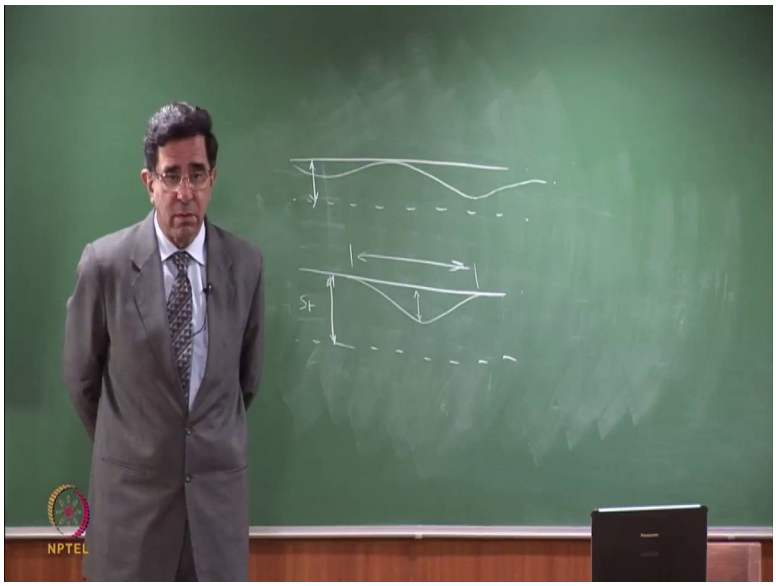

If this is total settlement then we say differential settlement will be a small percentage of the total settlement. Why? Because that is on account of lateral variability and total settlement you have taken out from a design parameter which has been taken out from all the engineering properties which you got of the ground. So, if you have done your settlement analysis properly and if you have chosen the value of C c properly or if you are using the modulus of elasticity properly you have got a correct value of the total settlement.

So, differential settlement may occur on account of the ground actually moving like this, right. But differential settlement will always be smaller than the total settlement. So, in foundation design restrict the total settlement and you will not have differential settlement and then you will not have cracks and therefore you will not be bothered.

In waste now we have estimated the total settlement. And this settlement is going to keep on changing with time because our decomposition processes around. When you design the cover for depressions or sudden subsidence you have to remember that your subsidence will be within this total settlement. However, you what is the problem? What is the width of the crater, what is the width of the depression? That is something which you are not able to predict, because that will depend on how the lateral variability is.

So, when you do cover designs for the purpose of design for a depression you have to identify this. So, do not use total settlement for the purpose of cover designs, because the

depression will be a small fraction of the total settlement. But we now have a handle on how to calculate STN, how to see the way it changes with time. And that is something very important.

Data is not adequate, data is still being generated, and things are improving with time. And maybe the state of the art will improve over the next 5 to 10 years, but this is what the state of the art is today as far as settlements of landfills are concerned.

So, I think will stop here.

Thank you all the best.