Geoenvironmental Engineering (Environmental Geotechnology): Landfills, Slurry Ponds & Contaminated Sites
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Lecture - 18
Stability of Slopes - Part 1

Good day to all of you and welcome back to this class where we will focus today on stability of slopes or stability of landfills. Important thing to note is a lot of slope failures occur in landfills more than water current dams and embankments and one of the reasons is that we put some polymeric materials inside these landfills.

So, earlier it was not recognized the criticality of putting these polymeric materials inside the landfill cover and inside the landfill liner, but now it is by and large well recognized that we have to be very careful when we are designing these landfills where the tendency to slip along interfaces can result in instability.

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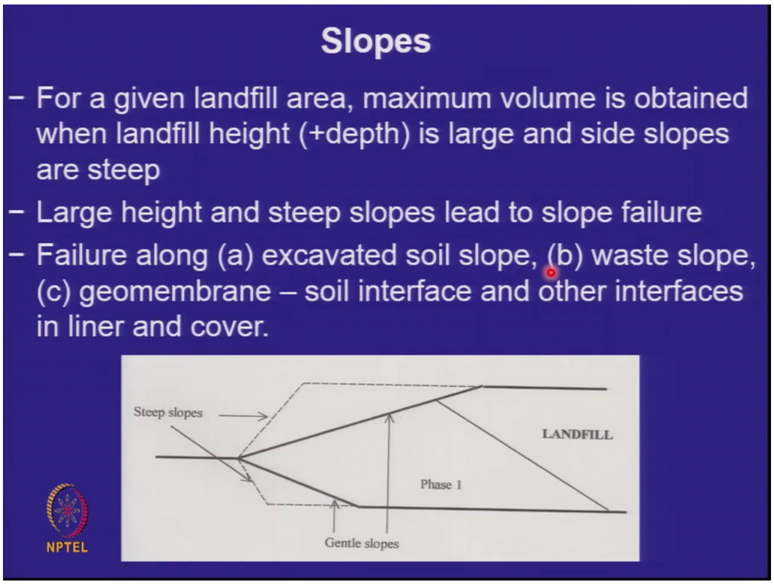

So, we are going to look at stability of slopes and remember the objective is that for a given landfill area we have very little control on the area we can ask for a certain amount of area for a 20 to 25 year design period whether we get that area or we get lower quantity of area it depends on the availability of land and also the shape of the area is not in our control. So, we will get land the way it exists and on that area we have to maximize the volume of waste that can be placed.

So, the attempt always is that can we increase the landfill height and the depth and can we make the side slopes steeper. So, as we already done this that typically what you govern the depth of a landfill. When there is high water table; that means, the water table is a few meters below the ground surface we cannot dig below.

Similarly, when there is rock a few metres below the ground surface we cannot dig below. So, we will not have much depth if there is water table at high level or if there is rock very close to the ground surface. If both of these are not present then there is a tendency to maximize depth, but I have already told you that to go to deep depths we need stability measures along the sides.

So, normally we would not go beyond 7 to 8 meters of excavation that is not to say that we cannot excavate to 20 meters, but then you have to put retaining structures you have to ensure that there is no instability while you are filling up the waste. So, normally the depths will be 7 to 8 meters. The height can be larger it is governed by aesthetics and typically it starts at about 15 to 20 meters, but as I have said earlier you can have larger heights about, even as high as 40 meters landfills have been constructed in valleys and inside slope configurations.

Large heights and steep slopes can lead to failure and again we are capturing this if I give a flat slope at the top and if I give a flat slope during the excavation then the amount of ways that I can keep is much lower than if I can give a steep slope both upwards and downwards directions. So, always there is an attempt to make this deeper and you see how steep we can go.

But what have what have we learned over the past tens of years when we have been constructing landfills failures can occur along the excavated soil slope. So, if this is the excavated soil slope it is possible that failure will occur if you do not make the cut at an inclination which is stable. Failure can occur along the waste slope now what is the waste slope as you fill the phase one for example and you are having to go to the top. So, that you can do a final closure before the monsoon comes this is your waste slope this is an intermediate cover and this is the waste slope. Now, this can also fail. So, you can have failure along the waste slope. And you can have failure along the geomembrane soil interfaces and other interfaces in the liner and the cover. So, if I look at this the many magnified view there will be several layers. So, to here and these interfaces can also cause slope instability.

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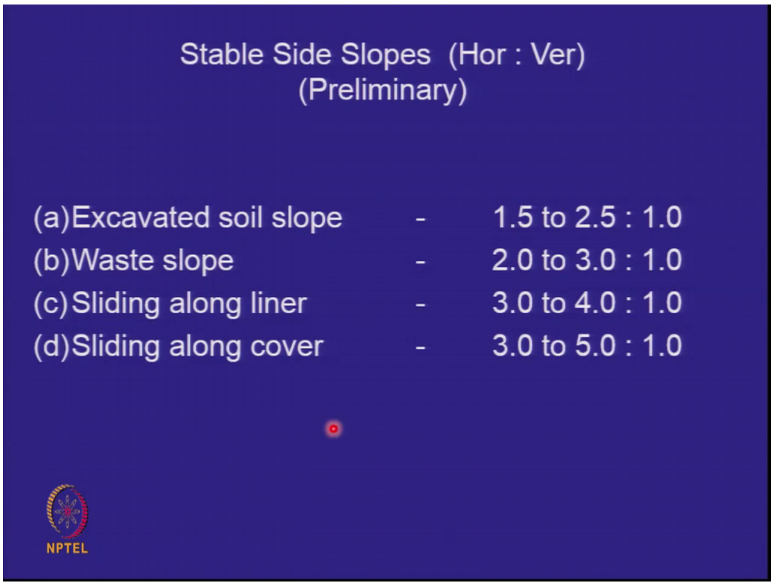

When you begin the design you have to start with some preliminary slopes and then you have to fine tune them you have to check their stability if they are unstable you make them flatter, if the factor of safety they are giving is very high then you make them steeper, but you have to have some preliminary values. So, these are typical preliminary values.

Excavated slope in soil 1.5 horizontal to 1 vertical or 2.5 horizontal to 1 vertical, when the soil strength is low you will have flatter slopes when the soil strength is high you will have steeper slopes. Typically you will not be excavating below the water table level because then dewatering is a problem and you normally your rules will not allow you to put a liner below the water table level.

So, those are the kind of slopes that you can cut in excavation. In the intermediate cover slope or the slope of the waste which goes to a pretty high value as you close the phase normally you use slopes of 2 horizontal, 1 vertical to 3 horizontal to 1 vertical.

But sliding along the liner and sliding along the cover the slopes are flatter. Typically for soil embankments you will be hand handling slopes of 1.5 to 2 is to 1. So, therefore, when you are making the liner of a landfill then you say that the slope is 3 is to 1 or 4 is to 1 immediately the construction contractor says sir in the soil we are always making slope of 2 is to 1. So, why are you making us make flatter slope that is because the contractor may not be used to putting polymer membranes or geotextiles in the excavator phase.

So, liner will have 3 to 4 is to 1 and cover will have 3 to 5 is to 1 covers are slightly more flatter than the liners and the reason is the excavated slope of the liner becomes buried with time as waste fills up. So, the slope is no longer a permanent slope whereas, the cover slopes are exposed for many more years and therefore, the stability of these slopes have to be assured for 50 to 100 years the stability of the liner slope has to be assured for the period which the excavation remains which may be 1, 2 or 3 years so obviously, you are having a flatter slope along the cover.

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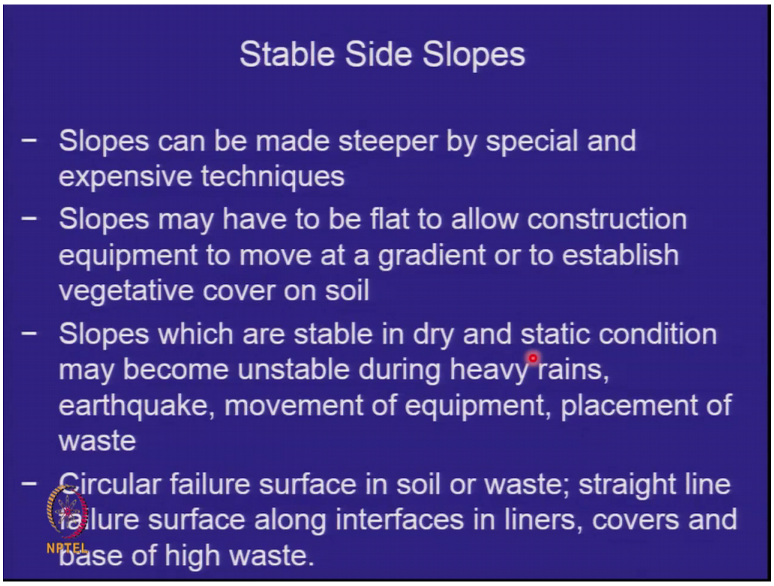

Now, can slopes be made steeper than this 3 to 4 is to 1 or 3 to 5 is to 1, the answer is yes we can always do engineering solutions slopes can be made steeper by special techniques, but an extra expenditure is involved. Also you have to remember why you can make the slope of a cover or liners steep you still have to compact the clay on the cover and compact the clay on the liner. So, you may have to allow construction equipment to move up the slope or down the slope. So, that is a limitation of the construction equipment at what gradient can it go up.

So, that may be a constraint for the slope; also when you make very steep slopes then establishing a good vegetative cover is difficult for example, you cannot grow grass on a vertical cut. So, just imagine that when the slopes are steeper it is more difficult to establish vegetation because during rains the erosion gullies form erosion takes place before the vegetation comes about.

Usually when you do the slope stability analysis you will find that the slopes are pretty stable in the dry and static condition, but they do become unstable during heavy rains earthquakes moving movement of equipment and placement of waste and these are the critical conditions which have to be analyzed. And more we are used to, you have done a course on slope stability or you are doing a course on slope stability.

Student: Doing.

You are doing very nice. So, are you doing finite slopes what kind of failure surfaces do you use in finite slopes.

Student: (Refer Time: 10:14).

What kind of method of stability analysis are you using?

Student: (Refer Time: 10:22).

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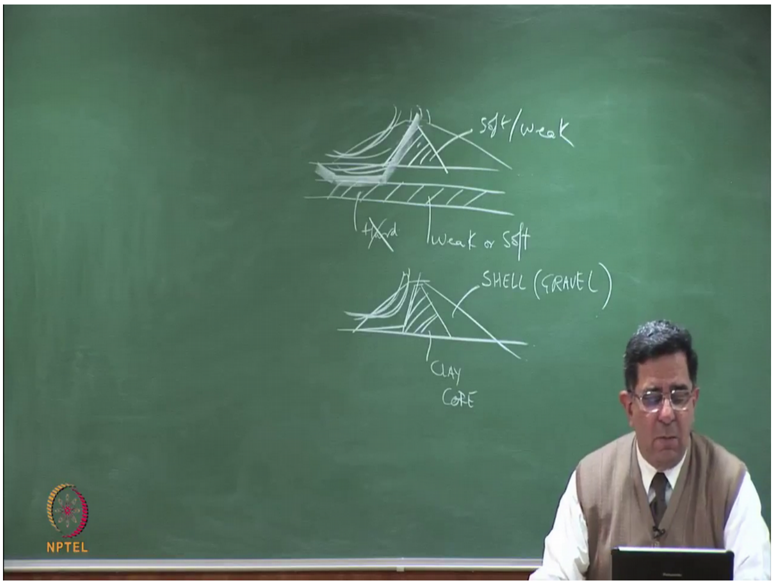

So, you basically tend to use circular slip surfaces in finite slopes. So, our experience as geotechnical engineers has been designing embankments and dams and normally we are looking at slope instability with circular failure surfaces. Can you tell me a situation where you use a straight line or a combination of straight lines for analyzing the stability of slopes?

Student: When there is hard strata and (Refer Time: 10:55).

If you have a hard strata here it is suggested that when I have a hard strata then I am only talking in an embankment. So, this is hard strata you think this will make me have a failure surface.

Student: (Refer Time: 11:12).

A combination of straight lines or.

Student: (Refer Time: 11:16).

So, somebody said hard surface now somebody said weak surface what kind of weak surface do you have. So, a failure surface will be; will have to go through a straight line, if there is a weak surface along a straight line if there is a hard surface the failure surface will tend to remain above it like if you have rock then the failure surface will remain above it.

So, if I have a weak surface weak or soft then this failure surface might be drawn towards it may not necessarily be the critical failure because you are doing a lot of circles as you said to find the critical factor of safety you will have so many circles which will be done.

So, which is the case in which you definitely get weak surfaces and you have to try for a straight line analysis as well in dams and embankments when do you have to check for straight lines. So, a failure surfaces in zone dams you have a clay core and you have a shell which is the weak of zone in zone dam is a shell is made of sand and gravel and the core is made of clay let us say gravel.

So, which is stronger clay or gravel, which is stronger?

Student: Gravel.

Gravel: so gravel is the stronger material clay is the softer or weaker material you can do your stability analysis like these. So, you will get a lot of failure surfaces circular, but you also should check that is it possible that the failure can take place like this because when the failure surface is in straight line then the failure will be through the clay which has got lower shear strength parameters this may be the critical surface this may not, but at least the failure surface tends to go through or the softer material.

Similarly, it was being suggested that I could have straight line here only if you are working with the zone dam let me explain to you suppose you have a zone dam here then you add a soft material here soft or weak and you had the soft material here, then you would like to check whether your failure could go through the weak material because this would be low strength parameters and this would be low strength parameters.

So, by a large as geotechnical engineers in homogeneous materials we tend to have circular failure surfaces. So, in the case of landfills these changes and we will see how it changes. So, what we say here is we normally adopt circular failure surfaces in soil or in the waste and we normally adopt straight line failure surface along interfaces in liners, covers and base of highways we will look at these separately. So, there are 2 types of failure surfaces that you are going to deal, with circular failure surfaces and straight line failure surfaces.

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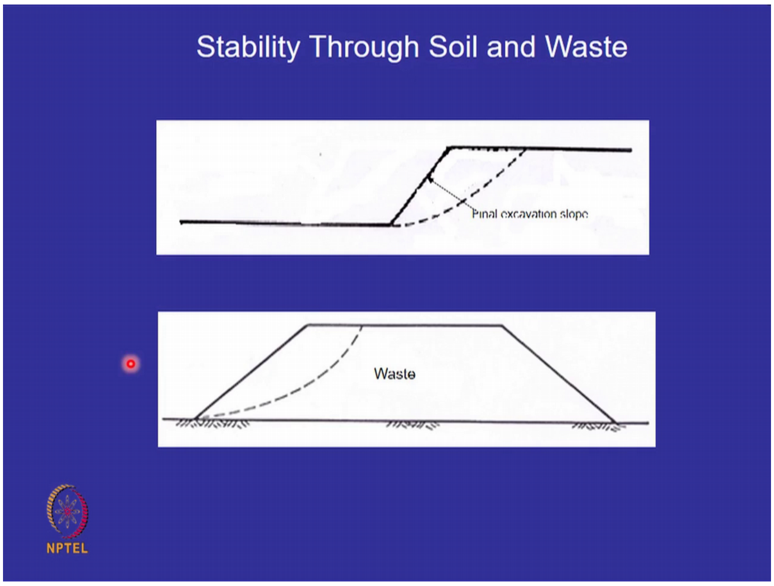

So, if you are looking at an excavation in soil you would be interested in what is the slope stability. So, it will be a circular failure surface will have to do. So, and if you are looking at a waste dump made of garbage or refuse then perhaps it is like an embankment. Does it look like soil embankment? Only we want to know the geotechnical properties of the shear strength properties of the waste, but there otherwise as far as the figure is concerned the section is concerned it very much looks like an embankment.

So, we want to know the strength characteristics of waste, but in either case you have the situation where a circular failure surface is adopted.

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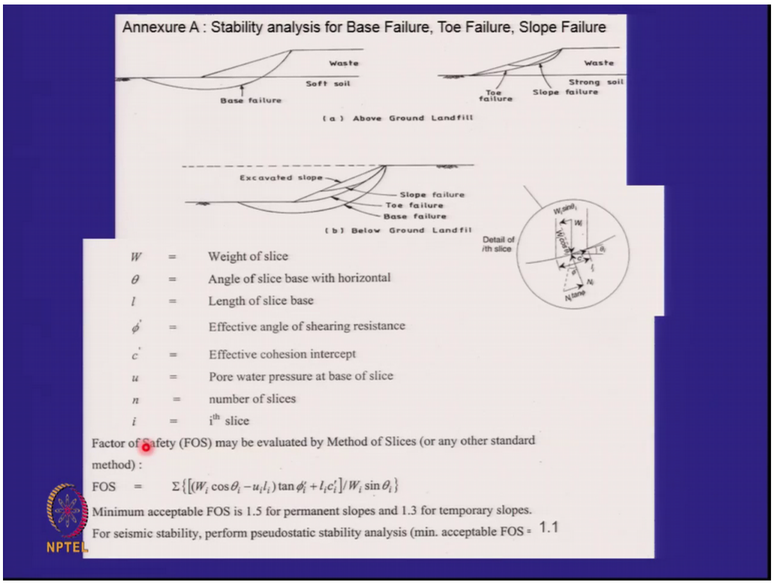

And then you have circular failure surface let me look at the cases which we will be analyzing, if I have waste over soft soil I can have a circular base failure, if I have waste over strong base I can have failure surface through the slope through the toe. So, I can have a base failure or toe failure or a slope failure right, and if I made an excavated slope I can have slope failure, toe failure and base failure and you have to use the method of slices there is no change in the way you do slope stability for either the waste mass or the soil mass, but you need the engineering properties.

So, do remember that the method of slices will be used in all these cases when I am using the slope failure surface and the Swedish method or any other method that you know we should simplify every transition simplified. So, you can use either of the any of these methods typically the minimum acceptable factor of safety adopted for these slopes is 1.5 for the permanent slopes and 1.3 for the temporary slopes.

In this diagram which waste is from which slope is temporary and which is permanent can you tell me? We have 1 2 3 diagrams, the excavated slope is definitely temporary why because this will fill up with waste right. So, in this case you would like to target a factor of safety or 1.3 this could be a temporary slope or a permanent slope, temporary slope is other phases have still to come forward ahead of this right. So, if other phases have to come this will get buried, so again you can target 1.3; however, if the waste filling is over this is the final phase and this is going to remain exposed for 50 to 100 years then this is a permanent slope. So, for this slope if it is the final slope you will adopt a factor of safety of 1.5.

There are other conditions for which you will perform stability analysis typically for example, for seasonal conditions for stability and the pseudo static method you may use a factor of safety of 1.1. What do you think are the shear strength parameters of waste and how would you determine the properties. We know how to determine shear strength parameters of clays silts and sands, how do you determine shear strength property of sand; if I am going to make an embankment of sand how do I determine the shear strength property of sand.

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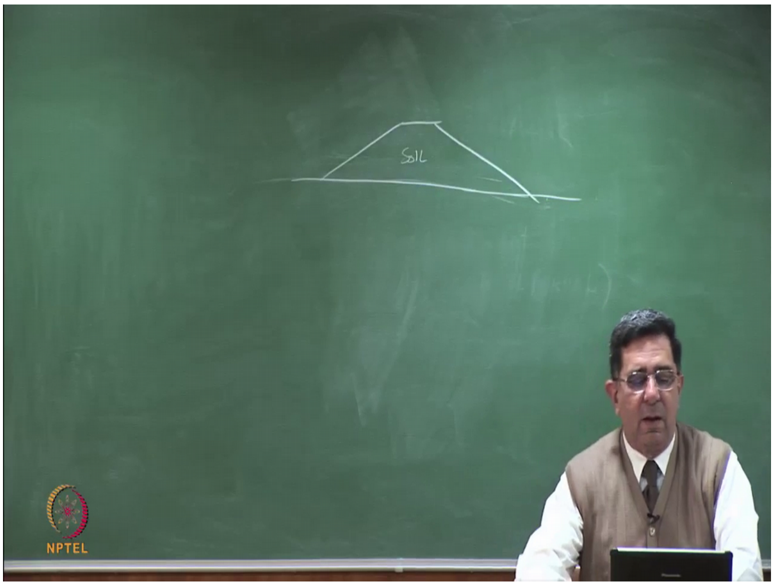

So, this is embankment of soil if it is coarse grained soil how do I determine its shear strength properties for designing this embankment?

Student: (Refer Time: 19:31).

Identify the borrow area pick up samples from the borrow area do the compaction test in the laboratory and do the strength test on as compacted sample right, that is how you will use this find out the c dash phi dash, what test will you do if it is sand or gravel direct shear test any other test?

Student: CD test.

CD tri axial test. So, you could do a CD tri axial test if it is gravel you will have to use a large shear large size tri axial you can put or you can use the direct shear test. In the direct shear test also the conventional 6 centimetres by 6 centimetres direct shear boxes cannot be used for gravel you need a bigger direct shear boxes. So, I can do the tests in the laboratory tri axial test give better and more accurate values than direct shear test.

If I have clay how will I do the test? Again I identify a borrow area or bringing the sample to the lab I do the shear strength tests on as compacted samples they can be as compacted or they can also be as compacted then saturated when I am simulating seepage if I am expecting any seepage. What test will you do on clay?

Student: (Refer Time: 20:55).

In the laboratory.

Student: (Refer Time: 21:00).

Normally the undrained condition will hold. So, you may either do total stress parameters which you can get from UC or UU tests or CU test or if you want to use the effective stress parameters then you have to do a CU bar test in the tri axial cell, but you will use undrained parameters; you will use drained parameters for?

Student: Coarse grained soil.

For coarse grained soils and undrained parameters for fine grained soils, they can be total stress parameters or they can be effective stress parameters.

What do you think of waste? Waste is definitely not a liquid right. So, it is going to behave more like soil it is a 3 phase media. So, it will have particles, it will have liquids and solid particles liquids and some air and trapped in it. So, what kind of test would you do if I said that please get me the shear strength properties of this waste its very heterogeneous. But let us first look at forget about heterogeneity I give you some waste, I ask you to find out its shear strength parameters what test would you do?

Student: (Refer Time: 22:26).

Pardon.

Student: Large box direct shear.

Large box direct shear is a good starting point because I do not know how the sample consistency will be is it going to be wet sample, is it going to be construction and demolition waste, but immediately it may not be possible to make a cylindrical sample. So, good idea let us do large direct shear test

Do you think this waste is going to behave like an undrained material or a drained material what is your intuitive gut feeling?

Student: Tendency.

So, tendency is that the there are no net negative charges and double layers and low permeability in waste. So, it is basically drained parameters. Again let us look at gut feeling what are the parameters that we are taking out if we are doing drained direct shear tests what size of the direct shear box would you like to adopt. Well it depend on the size of the largest particle, when we are doing the testing for dams for rock fill material you have when I use the word zone dam it could be shale could be made of rock fill what kind of large size boxes do we need.

Student: (Refer Time: 23:48).

Well, one foot by one foot may not depends on what is the size of your rock fill, but you could have 600 millimeters by 600 millimeters or even larger. So, here also if I am using waste which is heterogeneous the size of the direct shear box will depend on the size of the largest particle right.

But if there are only one or 2 large particles and others are relatively smaller then I can also remove those particles because my shear strength parameters are not going to be governed by 2 or 3 or 4 or 10 large particles they will be floating in a matrix of waste. It is like if you have ten particles of gravel in sand or 10 percent gravel in sand, will it make a lot of difference to the angle of shearing resistance of sand if the particles float amongst the sand particles they are not coming in touch with each other. So, only when the portion of gravel becomes significant 25 percent or more that you start to have an effect of the coarser material. So, sometimes you can even remove the coarser material. So, that you are able to do the test within the limit.

So, use large direct shear box do a slow test we get drained parameters if there are huge large sized chunks of construction debris remove them, what is large size anything which is beyond 300 mm a foot of size, so remove them and what is the parameter that you will determine.

Student: C phi (Refer Time: 25:29).

C phi, c dash phi dash there is no other parameter and if it is a drained test you are probably getting c dash phi dash. What value of c dash do you expect? What is your experience of c dash in clays tell me, if I am doing a drained test on clays typically the waste will not be dry when it comes to you remember it will be moister to be soggy. Because if it is coming from industrial process it has been through some moisture some liquid it is in the form of sludge or even if it is not in the form of sludge if in the form of a powder it has been transported from one side to another the liquid matrix.

So, typically waste will come to your soggy and if you force them to remove them water it will put it in the filter press they all squeeze out whatever comes out, but the waste itself will not be dry. So, you are getting c dash phi dash for waste which is has got high water content. So, what kind of c dash can you expect and why, what kind of c dash you get in soils, do you get c dash in sands?

Student: No.

Useless materials.

Student: C dash.

C dash is 0, do you get c dash in gravel.

Student: No.

No. So, only phi dash, do you get c dash in clays a trick question, this is a trick question. Do you get c dash in clays, do you get c in clays or do you get c dash.

Student: C dash.

Do you get c dash in clays? What is the c dash for normally consolidated clays? Effective cohesion intercept. So, the bulk of the data shows that c dash should normally consolidated clay is zero c can be there any value high value stiff clay from UC test from unit test, but remember c dash for saturated soils tends to be 0. So, quickly what is the c dash that we would get in waste.

If I get c dash 0 in clays I get c dash 0 in sands and gravel; obviously, c dash would be zero in (Refer Time: 27:46). So, what do you expect c dash to be in waste? Well I would expect it to be 0, but it is not sometimes it is 0 sometimes it is not.

So, what will cause c dash to occur?

Student: Apparent cohesion.

Pardon.

Student: Apparent cohesion.

Apparent cohesion is a good word it is the meaning that it is a mathematical representation.

Student: Fibrous material (Refer Time: 28:12).

So, if you have fibrous material they might give you some apparent cohesion the fibrous would be plastic sheets small polythene bags cloth. So, you do get values of cohesion intercept and so you get c dash phi dash. What phi dash would you expect for? So, c dash can be more than 0 for waste what kind of phi dash would you expect.

Student: (Refer Time: 28:47) geotextile (Refer Time: 28:48) quantify (Refer Time: 28:48).

For geo.

Student: Geotextile (Refer Time: :).

We are not doing geotextile sorry, we are just taking waste and we are trying to find out what phi dash.

Student: (Refer Time: 28:57).

No, no fibrous material geotextile means a roll the length is pretty long fibrous material means small fibers. So, they behave like random fibers they do not behave like a long fiber. So, my question is what kind of phi dash should you expect. So, either the fibrous materials may reflect itself as a c or it may reflect itself as a phi and increase in the phi.

Student: (Refer Time: 29:23).

So, what kind of values can you expect?

Student: More than 40.

More than 40; how low can the value of phi dash be for? What is the worst waste that you could be dealing with which would have very low phi dash?

Student: Pete.

Pardon, pete.

Student: (Refer Time: 29:43).

Organic Pete, Pete actually is not waste, but if it comes it I have low phi dash, but otherwise anything which is soggy and like a sludge and does not have many course strain particles then a powdery is will have low because water content is high. So, you would have low values. So, please do remember that the angle of repose tells you the phi dash of a material is that right.

Student: Yes sir.

But if you have very high content water content sludge it will become very low values. Same sludge when it is dried will have higher values. So, what I am going to do is give you the values which have come out from literature and do not ask me did they measure pore water pressure did they do, how was the drainage was there in because these were tests done by waste management people in large direct shear boxes they will not analyze like pore water pressure measurement b factors like we do in geotechnical engineering, but a lot of data is there and these are the values that you get.

So, first let us go through the through the densities.

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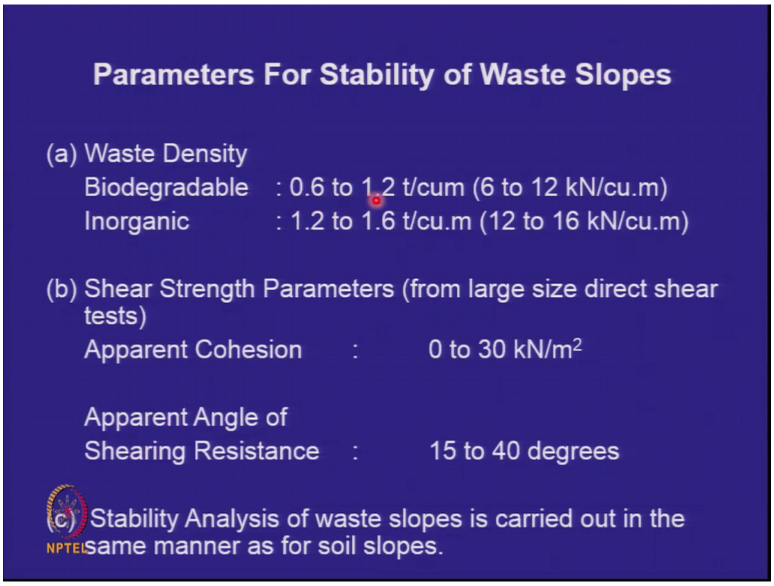

If you have biodegradable waste your density is what we call total unit weight will be low, but if you have inorganic waste it will be typically like soil. Apparent cohesion values 0 to 30 kilonewtons per meter square and apparent angle of shearing resistance 15 to 40 degrees.

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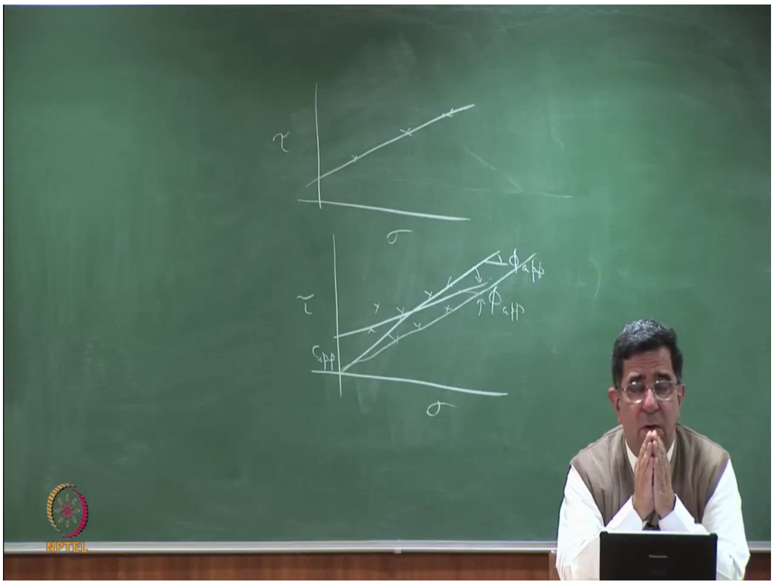

Just to understand that if I am giving you these ranges if my points from the direction test are like this then I get a very nice straight line right, but if my data is like this why because of heterogeneity I do many tests. So, you can have different interpretations of this data one interpretation could be.

So, basically the word apparent is being used to tell you that we are using this criteria to give it strength values the material is heterogeneous these are just mathematical parameters. And as I said you can have as low as 0 c dash and 15 degrees for a high water content fine grained material and you can have as high as 30 degrees sorry, 30 kilonewtons per meter square and phi dash as high as 40 degree it could be more. Do your design with lower bound values, why? Because when you are failure surfaces passing through a scatter of data on strength when material is uniform when you tend to take average values, but when material is heterogeneous you tend to take lower bound values.

So, if I have a scatter of data like this I am very clear that this is my lower bound shear strength values, and so somebody may say that you are very conservative, but you might you look at this value for your purpose of understanding. In any case what we are saying is stability analysis of waste is done the same way as stability analysis in soils and the parameters that you are measuring it is not written here whether they are total or effective because the drainage conditions are not very closely monitored, but by and large water is allowed to come in and what you are measuring are more towards the drained parameter than the undrained parameters, any questions.

So, you will use for example, in this stability analysis soil properties for the base and waste properties for the top in these waste properties for the slope failure and the toe failure.

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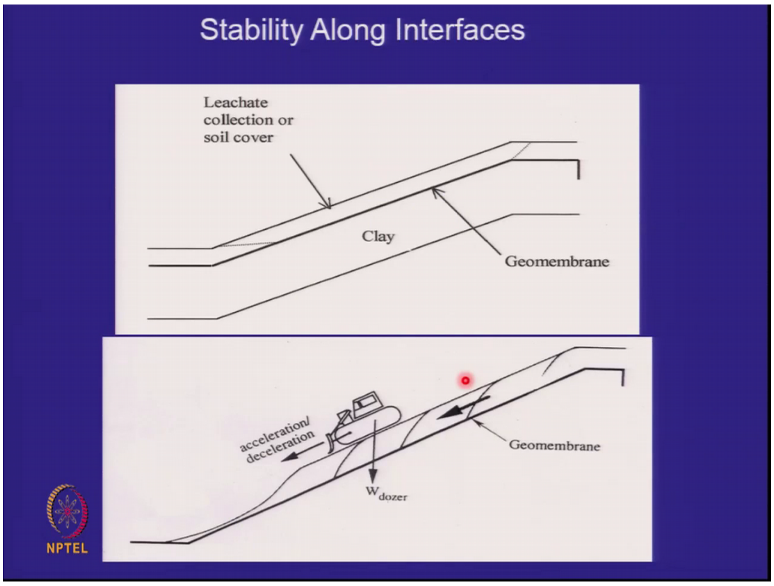

Now, let us come to the more critical issue of stability along interfaces. So, I said that failure surfaces tend to be in straight lines failure surfaces tend to be in straight lines when there is a soft interface. Now here geomembrane is not a soft or a weak interface the angle of shear between the geomembrane and the soil can be low.

Therefore, the failure surface may be like that and if you ignore the end effects it is like failure surface parallel to the outer slope which is the failure surface for an infinite slope. And not only this please do remember that there are some men and equipment which move on this right and when this men and equipment apply a brakes then there is a force which is acting parallel to the outer slope.

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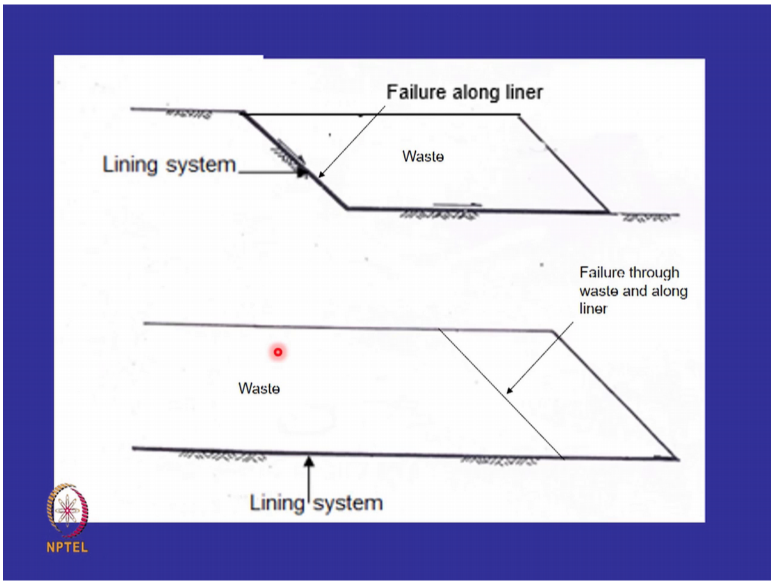

So, there is a weight of this and there are additional forces. If you have a garbage we would be doing stability analysis here, but now remember that there is a liner interface at the bottom is the liner interface a weak interface yes, we look at the angle of shearing resistance. So, maybe your failure will occur like this, this has to be analyzed or if this is far away suppose this is that far away then maybe the failure will occur like this.

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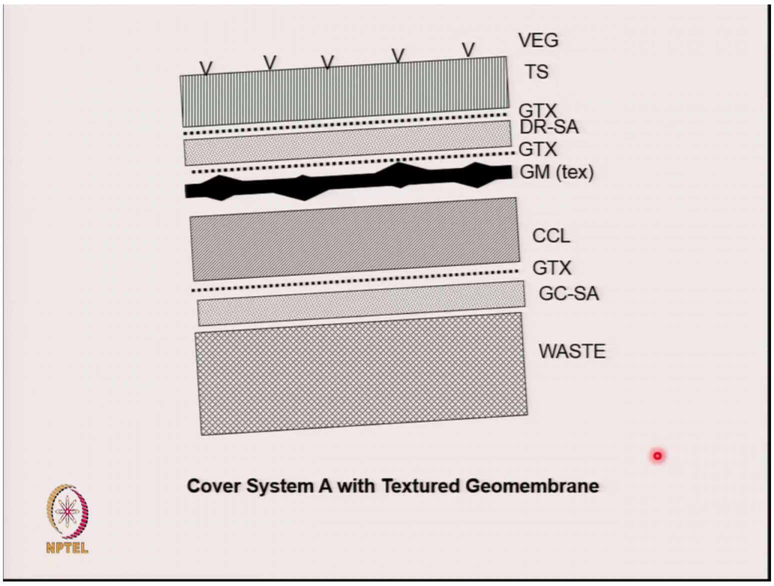

So, these are straight line failure surfaces and you will remember that when I had discussed the covers that there are several interfaces important for us is to identify the weakest interface. So, I have a topsoil to geotextile interface, a geotextile to sand interface or sand to geotextile interface, the geotextile to geomembrane interface, a geomembrane to compacted clay interface, a compacted clay to geotextile interface, geotextile to gravel sand lead interface and gravel sand interface the grass collection with waste, so many interfaces, so we always need to identify which is the weakest interface, and I will come back to this.

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Interface Friction / Adhesion Parameters

Geomembrane	Soil	Interface Friction Angle δ (deg)	Adhesion Cα(kN/m^2)
Smooth	Sand	17 to 20	0
Textured	Sand	25 to ϕ	0
Smooth	Clay (sat.)	8 to 12	Variable, ~10kN/m^2 or neglected
Textured	Clay (sat.)	14 to 16	0

Residual values

So, let us look at some angle let us I we talked about the fact that these interfaces are weak. So, before we say that these interfaces are weak let us look at the fact what kind of c dash and phi dash values do we have for soils.

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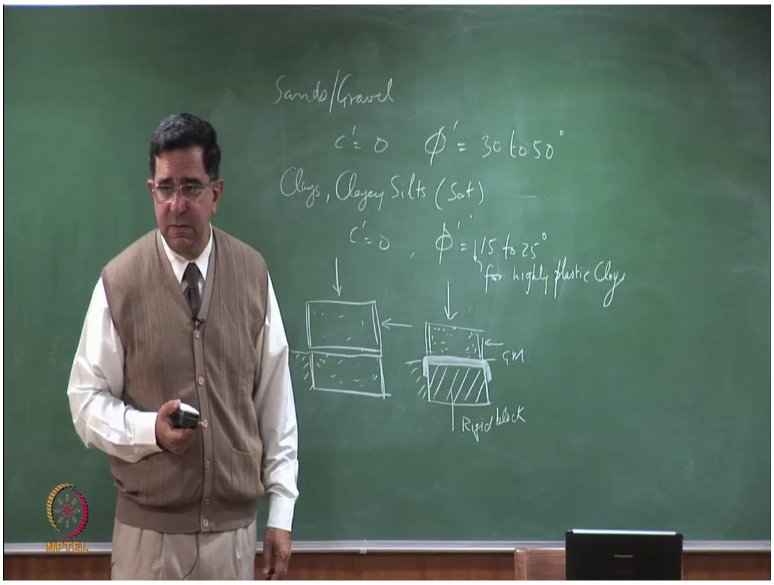

So, just for our understanding when we have been dealing with effective stress parameters typically for sands and gavels we are talking of c dash equal to 0 and phi dash from what would be the range, 30 to 50 degrees; is this a broad idea what we have been dealing with or then for clays clay slits we already said for saturated we are talking of c dash is 0. What about the phi dash, what kind of range of phi dash values do we come across in clays in saturated clays?

Student: 15 (Refer Time: 38:56).

15.

Student: (Refer Time: 39:01).

To?

Student: 25.

15 to 25 degrees not bad, can it be lower than 15 degrees what if I have bentonite clay and I saturated.

Student: (Refer Time: 39:18).

12 10. So, even lower for very highly plastic clays this can be lower. When you compare to ourselves with this the waste also had similar properties 15 to 40 degrees, 0 to 30 kpa.

So, waste is not that weak, but now when I look at interfaces when I look at interfaces I have to now like try and see how do the interfaces compare with these values very clearly and I told you this that if I have a clear core then my failure surface tends to go to the interface of the clay core to the sand, if I have a clay core clay is a weak material. So, when I am using materials of this type then my failure surfaces tend to pass along those softer materials. So, let us look at what values do we get.

Historically we started with smooth geomembranes, historically we started with smooth geomembranes. So, all our first set of 5 to 10 years before we realized how terrible it is and before we got the technology of making texturing we will start with the smooth geomembrane. So, let us look at what happens to if you have smooth geomembrane and the soil is sand. How will you find these values, how will you find interface friction values? By doing a?

Student: (Refer Time: 40:56).

Well, normally we do a direct shear test where the lower box the soil is on the top and the lower box has the geosynthetic element. A normal direct shear test would be let us say this is the walls of the box we will keep the bottom box fixed move the top box after applying a normal node right and that gives you the angle of shearing resistance along with interface, the direct shear test all of you have performed the direct shear test.

Now, if I take the lower box and instead of having soil in it I put a rigid piece and on top of it let me say I put the geomembrane then I put the top box on it and fill it up with sand, I apply the normal load and I move this. So, I can shear the sand over the geomembrane this geomembrane would have to be fixed clamped or fixed to this rigid block this will not move and the sand will impinge on it and I will move it and I can get the angle of shearing resistance by doing 3 tests.

So, this is a modified direct shear test it is also called the interface shear test which we do. So, with this I can find out the interface shear angle. So, this interface shear angle is used for the purpose of stability analysis. When I get data from such a test again I can do 3 normal stresses.

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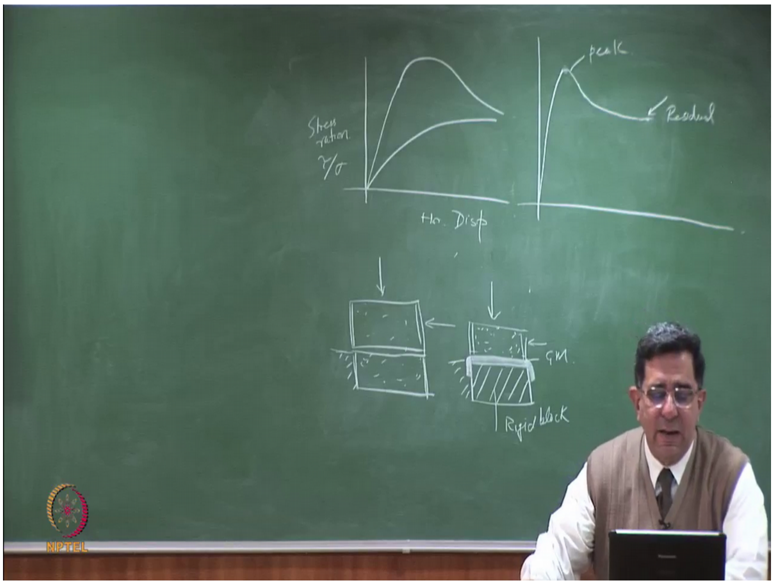

The important thing to see is what is the plot that we make from the in a direct shear test, stress versus strain.

Student: Stress versus (Refer Time: 43:31).

Or stress versus displacement or tau by sigma versus displacement because the area is changing. So, typically stress ratio if you want to call it a horizontal displacement.

So, for a soil which is a dense sand the result would be something like this right for a let me just make this a little better and for loose material or a soft material the stress strain behaviour would be like this right. What is the equivalent behaviour that we have in interface shear? So, this could be as much as 10 percent strain and interface shear phenomenon is a slippage phenomenon this is the bottom, this is a geomembrane a smooth geomembrane my soil is here I move it I will get a friction angle or an adhesion

So, will it require 10 percent strain to get a peak or a 5 percent strain, no the peak comes much earlier typically the peak would come and then it would slip. So, you will get a peak value and you will get a, may not fall that much I do not want it to you get a feeling that it falls to half the value, you will get a peak value and a residual value, and you have to use this 3 tests you will do at 3 different normal stresses and you will get a peak delta and a peak c.

If there is a huge debate about what should we use in design. In soils what do we use? The design, we use the peak values peak failure values. In geosynthetics on which soils are placed should we use the peak values or the residual values it all depends on how much pre shearing takes place you know when you are a roll is being rolled down a slope or you are placing it and then you are pulling it to remove the wrinkles, what is happening? Some pre shearing is taking place. So, there is one school of thought you see in soil if some if some pre shearing takes place in soil then you would have a residual value which you would use.

So, there is one school of thought that please use residual values for the purpose of design because these are all rolled out and they do get adjusted before you put it into the anchor trench we remove the it may not always be possible, but you will see sometimes 10 people will be pulling you want to lay it, hard you layered a polymeric membrane on the cricket field when the rain comes 10 people will stand in line and they all run with it on the field right. So, what are they doing? They are pre sharing between the under contact and the over contact

So, typically as a designer you can make a choice right as a designer you can make a choice. So, what do I get from the tests that we have done in the laboratory? We get, if I have a smooth geomembrane and if I have sand 17 to 20 degrees is the interface friction angle and if I have a texture geomembrane then it is almost like sand to sands failure phi dash. And just go back to your delta for skin friction between pile wall and soil something similar, but nothing is as smooth as a geomembrane, your concrete piles will not be as smooth, your wooden piles will not be as smooth, even your steel piles will have some rust you know some kind of a roughness to it if you put your handle. So, smooth is smooth as far as the polymeric material is concerned.

Therefore, remember you get low values. So, everybody has gone towards textured geomembranes, textured geomembrane is 25 to phi and like a typical designer even I when I have designed these some of these facilities in India on all the slopes whether in the liner or in the cover we have been using texture geomembranes.

But at the base do we need a textured geomembrane at the base. Not really because there is nothing going to slide on a base this is what we talked will be really did in an analysis recently. So, we have been using smooth geomembrane on the basis cost is not much is a

10-15 percent cost difference in the cost of textured geomembrane versus a smooth geomembrane.

First let us look at the smooth geomembrane to clay interface, this is the important interface for the composite barrier geomembrane in intimate contact with the clay underneath and see the value extremely low. You do get a cohesion intercept sometimes in your direct shear test and the cohesion sorry this should be called adhesion cohesion is soil to soil this adhesion intercept. So, the adhesion intercept in unsaturated soils is higher in saturated soil is lower, but if you look at it very microscopically if you have clay and the clay surface is totally saturated then adhesion is likely to be negligible.

So, sometimes in design we will neglect it or you have to be very sure that this will be always operated. If you do textured clay textured geomembrane to clay the 8 to 12 goes up 14 to 16, still nowhere near sand, still nowhere near sand.

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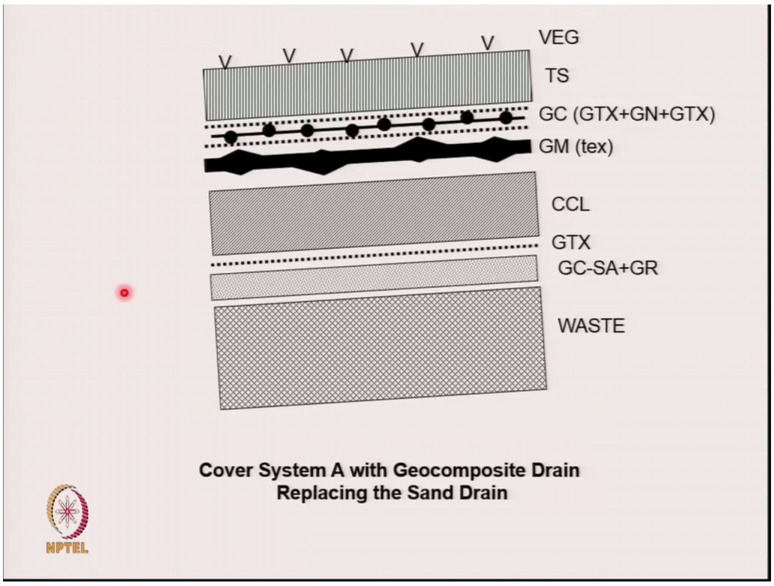

So, the realization is smooth is bad textured is better and it is not necessary that we will have only a geomembrane to clay this is the geocomposite liner. So, geomembrane here I have shown a textured geomembrane to clay just look at above let me go back one more. This is the traditional hazardous waste cover topsoil and protective layer drainage layer geotextile as a protector for the geomembrane geo compacted clay liner. So, this is a critical interface compacted clay to geomembrane delta is low if it was smooth it would be 8 to 12, but it is textured it is what did you say 14 to.

Student: 14 to 16.

14 to 16, but let us look at the top there is also the interface between the geotextile to geomembrane we want to know what is this because this could be the minimum value or this could be the minimum value I cannot presuppose which one to check unless I have the I have the values of delta. So, this is one.

Let us look at this here I have changed the sand into a geocomposite I have said I do not need the sand layer it is too thick, it is too heavy, creates too much problems I will do the roll. So, now, you have to look at the interface between the geomembrane and the compacted clay the geomembrane and the geocomposite, the geocomposite will have a geotextile at the bottom, but it may not have the same angle of interface shear we will have a look at and then there is also one between the topsoil and the geocomposite.

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Interface Friction / Adhesion Parameters

Geomembrane	Geosynthetic	Interface Friction δ (deg)	Adhesion $C\alpha$(kN/m^2)
Smooth	NW Geotextile Geonet Geocomposite	7 to 10 6 to 9 9 to 13	0 0 0
Textured	NW Geotextile Geonet Geocomposite	15 to 18 9 to 11 14 to 16	0 0 0
NW Geotextile	Sand Clay	30 to 33 18 to 20	0 0
Geonet	NW Geotextile	14 to 16	0

So, the second slide this one now shows if I have a smooth geomembrane and top of it if I put a nonwoven geotextile as a protector I am down to 7 to 10 degrees, if I put the sand directly I had said if I put the sand directly on a smooth geomembrane its 17 to 20, but now I introduce a geotextile and it goes 7 to 10 I do not like it therefore, I would like a textured geomembrane with the geotextile and it goes up from to about 15 to 18 degrees. So, the geotextile to the geomembrane interface can be also critical if you are using a smooth geomembrane. If I put a geocomposite on the smooth geomembrane I am getting 9 to 13 and if it is textured I am getting 14 to 16.

So, texture geomembrane is better for slope stability and there are other interface friction angles which I have given you here as well, but do remember that smooth will bring things to about 10 degrees textured will bring things to about 15 to 20 degrees and we have to be very careful, these are now when I say 10 degrees we have below the clay value you are not used to these values before and when I am saying 15 to 20 degrees we are in the clay range. So, the interfaces are not strong interfaces no matter what you do they become weak interfaces.

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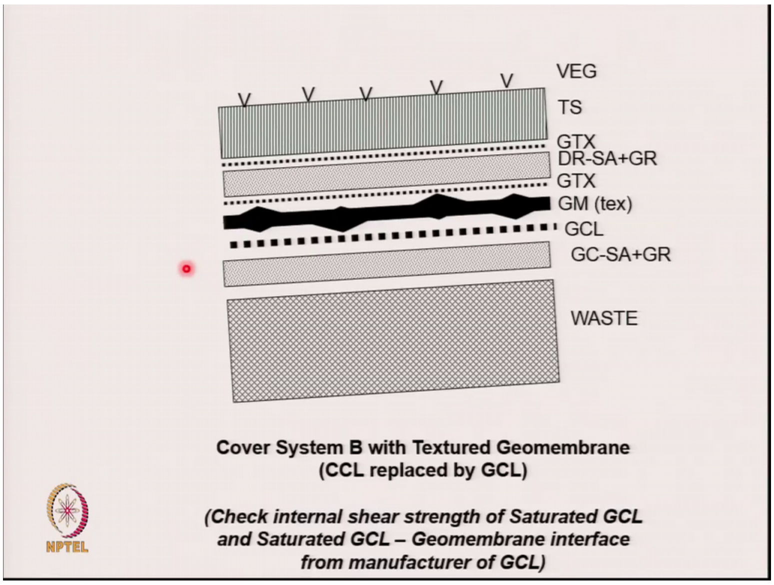

And something else in some of the covers or in some of the liner systems we replace the compacted clay with geosynthetic clay liner, you remember we talked about the geosynthetic clay liner in which bentonite is there between 2 geotextiles. Here there is another problem where we said that for clays the least phi dash comes when we have hydrated bentonite it can be extremely low.

So, now see the situation the GCL only works if it is hydrated. So, the bentonite should be saturated, some of the bentonite can actually extrude out of the geotextile why, because the geotextile at the top and the bottom is not a geomembrane it has a finite pore space. So, the water is given to the powder inside that on the top and the bottom is the geotextile the bentonite swells and it comes out of the pores where does the bentonite now touch when the bentonite comes out of the pores it sits on the underside of the geomembrane.

So, now you have a bentonite 2 geomembrane interface and that is going to be super critical. So, I have written here very clearly first check the internal shear strength of saturated GCL and also the interface angle of saturated geo GCL to geomembrane. When you use geo GCLs you normally have to drop your side slopes to 3 from 3 is to 1 to 4 is to 1 because strength really false and since GCLs are being produced change very rapidly I mean they are always under development.

You do not pick up this value from a textbook please get a value because a lot of research is being done to improve this with delta value, but the delta value goes down to 10 or 8 when you have hydrated bentonite inside the GCL and if it extrudes out then it is going to be like you are putting a bentonite coating on the bottom of the geomembrane and that can cause a problem. So, this is an important thing for you to remember.

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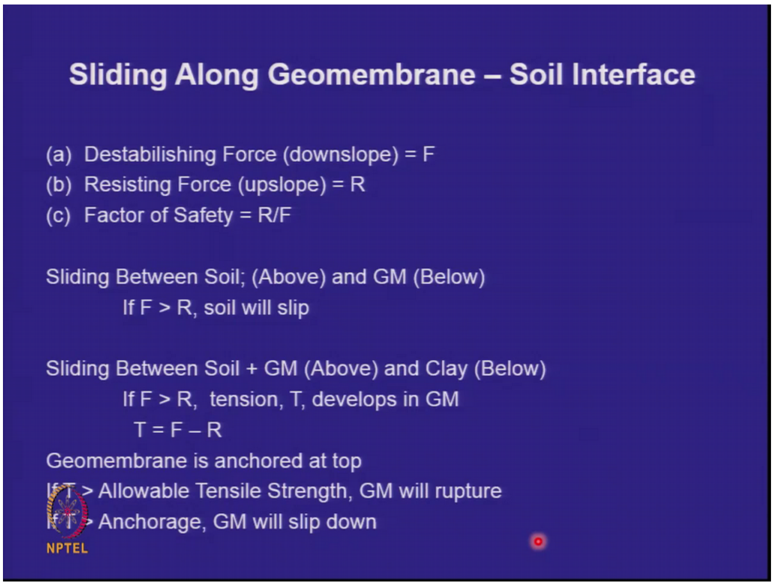

So, if you are looking at sliding along a geosynthetic or along the geomembrane it is simple to remember 2 things. Firstly, it is a straight line failure surface right. So, it is like an infinite slope failure surface parallel to the outer slope is very difficult very simple to analyze you have done it, W caused something.

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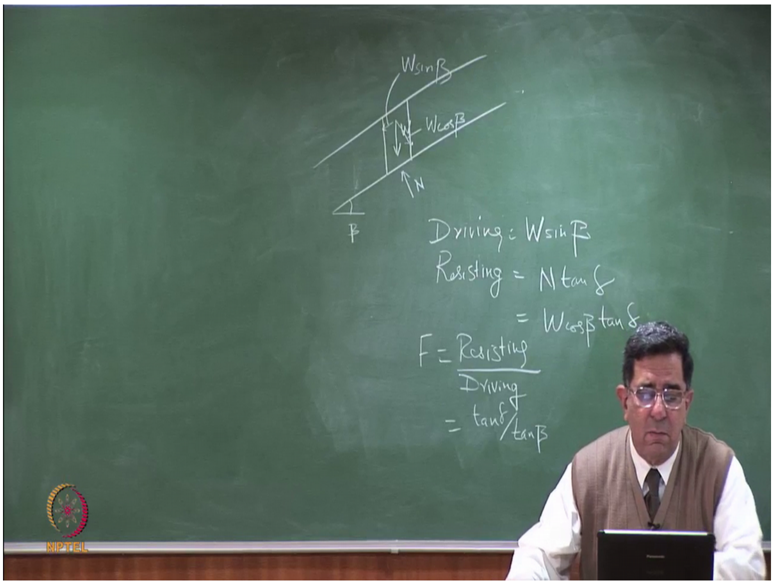

You all remember failure surface parallel to the outer slope here in this case geomembrane at the bottom and soil on the top or vice versa, but in any case you have a W suppose this angle is beta. So, what are the forces which are causing this to go down what is the driving force and what is the resisting force. So, what are the 2 components of W?

Student: (Refer Time: 57:47).

This is what W?

Student: Sin.

Sin beta and that is W cos beta. So, the instability is coming from the W and the beta, the more the inclination the more is w sin beta the thicker the soil at the top the more is the w sin beta, so more the weight that is why people try to make the layers thinner. Let us reduce W my driving force will go down let us reduce inclination my driving force will go down. So, driving force, what is the resisting force? So, this has an N and we have looked at it that at the interfaces c is almost negligible. So, what is the resisting force? N tan delta and what is N?

Student: (Refer Time: 58:41).

W cos beta, N is equal to W cos beta, the normal force is getting a reaction, so factor of safety is equal to.

Student: (Refer Time: 59:02) resisting by driving.

Resisting by driving and what does it becoming in this case.

Student: Delta (Refer Time: 59:17) tan delta.

Tan delta by.

Student: Tan beta.

Tan beta. So, in its very simple elemental form if the driving force is more than the resisting force then it is going to fail, if the driving force is less than the resisting force it is going to stay there.

If there is a difference between the two, maybe the geomembrane can take some tension so now, that is the new thing, you are wanting to slip down, but maybe the geomembrane can hold you back. So, that is where the t or the tensile strength of the geomembrane or the tensile strength of a geogrid comes into play, can we make use of the tensile strength or the tensile force for the purpose of analysis.

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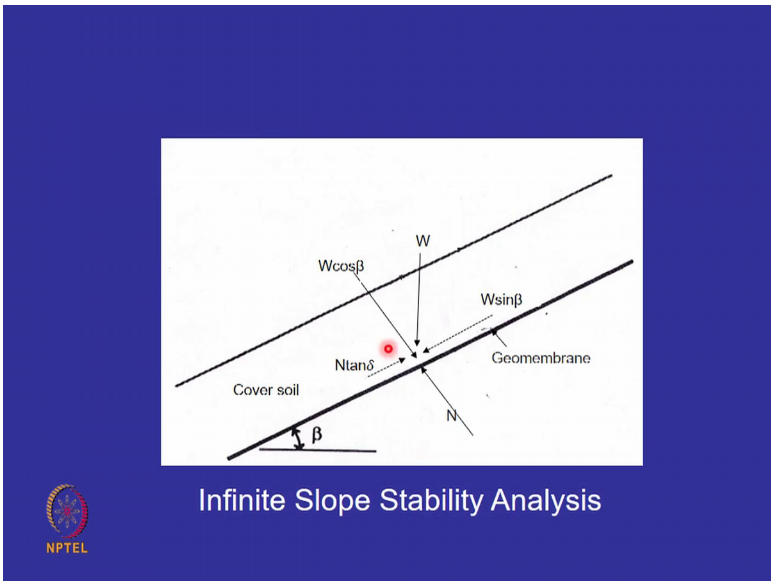

So, very quickly I will come back to this slide again what we have put on the board is what we have said here W, W sin beta, W cos beta N, this is the infinite slope stability analysis. The trigger is that most of these slopes are stable till the following happens.

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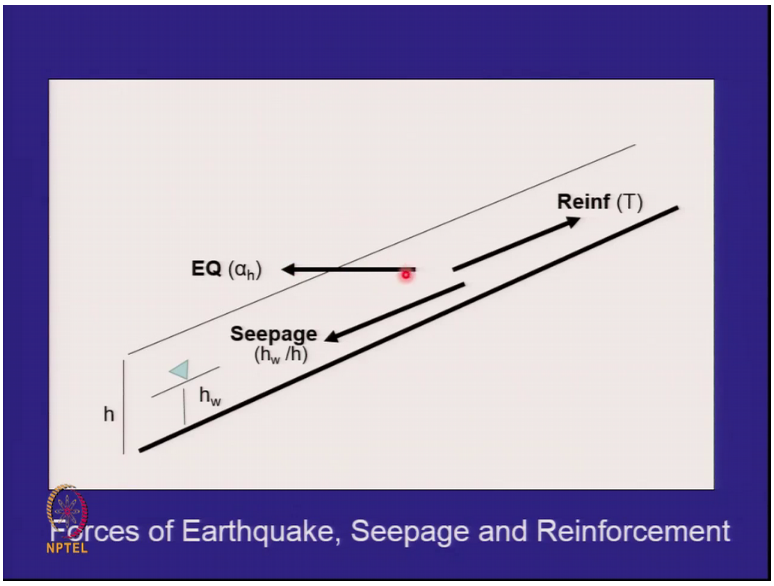

If an earthquake comes it gives you an additional alpha h right it can also give you an alpha v, but the main force which causes problem is alpha h it gives you a horizontal force. If rain comes what happens suppose this is a geomembrane if there was no geomembrane the rain water would go in and go into the waste, but we have put a barrier what starts to happen to the rainwater it stops here and starts to go downward and it generates a seepage force and that seepage force can act as a destabilizer. So, the earthquake can act as a destabilize, the seepage force can act as a destabilizer and that will depend on what is the amount of water that gets collected over the geomembrane and this hw by h is called the submergence ratio and if submergence ratio is 1 then you can have a very low factor of safety.

But luckily for us is there is some strength in the geomembrane or if you put a geogrid or if you put a geogrid then you can have a T which helps the resisting force n tan delta is resisting and now T will also resist. So, by putting a geogrid by putting a geogrid here please see this GG geomembrane sand geotextile are put a geogrid, a geogrid is a relatively stiff I showed you the for graph is a relatively stiff geosynthetic which is in the form of a mesh and it can give you a T. So, once you have a t that will add to your stability.

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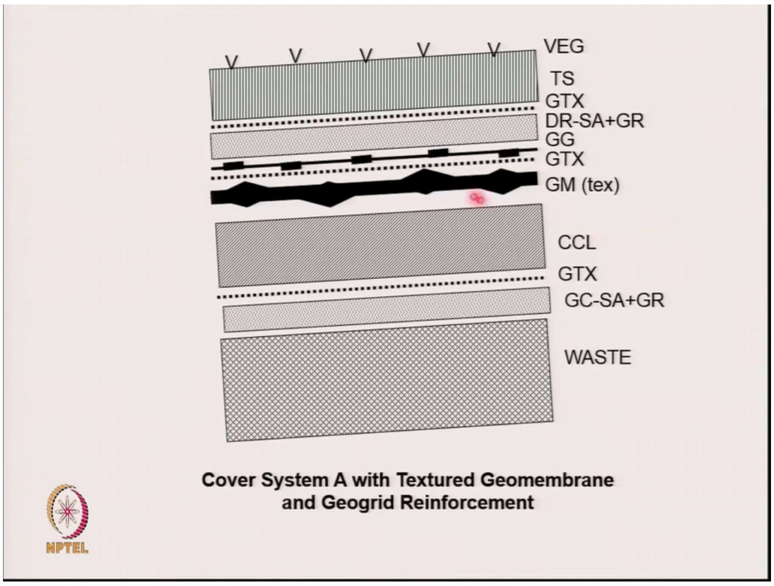

So, for these conditions we can analyze the factors of safety, for these conditions we can analyze the factors of safety and we can, we will look at them in detail in the next class, but definitely we can improve our stability by taking T.

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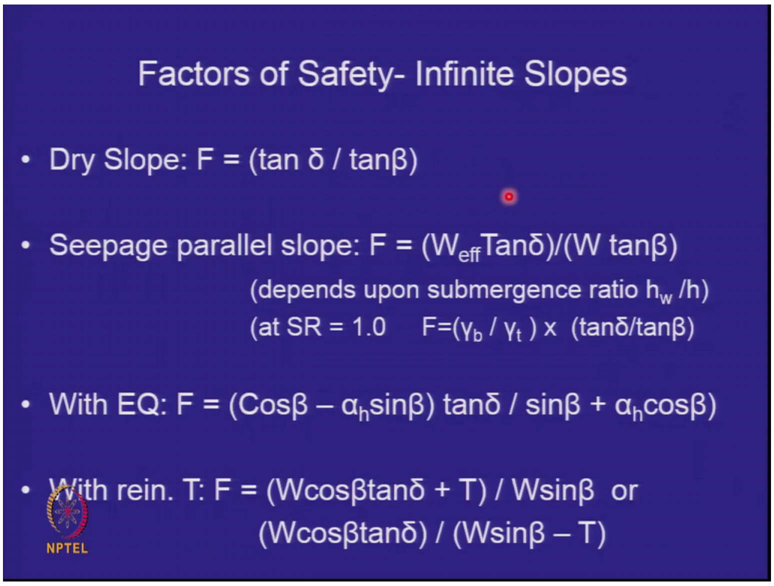

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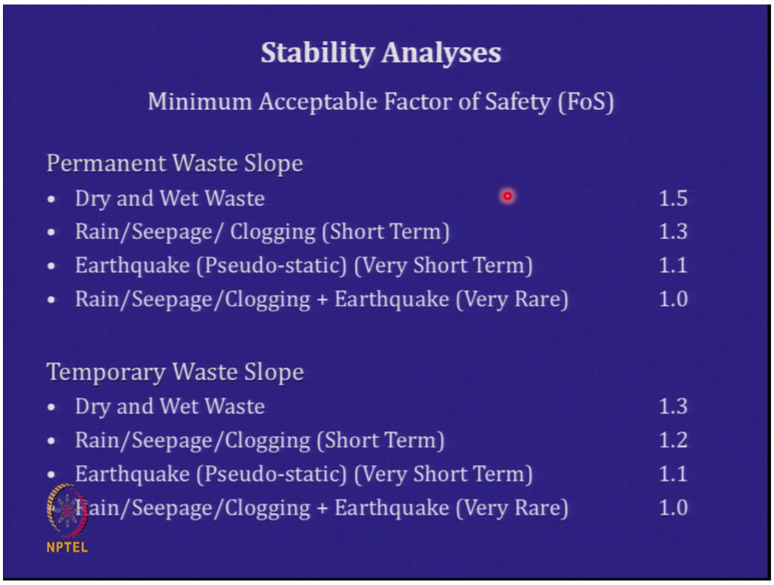

And finally, we will also have to address what factors of safety do we need for our slope, we will have to address what factors of safety. And I talked about permanent slope and temporary slope and I said if it is a permanent slope the long term factor of safety I want is 1.5 this is also true for dams right, but if it is a temporary slope I want a factor of safety of 1.3.

Within the permanent slope rain or seepage can occur temporarily, it will not occur all the time. So, maybe you will use a lower factor of safety as acceptable during rain and then if you have earthquake even lower factor of safety. So, what I am trying to show you here is that you have different factors of safety for different conditions those which are very short term condition earthquake will occur for how many hours, an earthquake will occur for how many hours?

Student: Seconds (Refer Time: 63:45).

A few seconds; therefore, we are saying an acceptable factor of safety are 1.1 and earthquake during heavy rainfall.

Student: (Refer Time: 63:54).

Unlikely, its only God is not happy with you then only the earthquake will come while the rain falls the peak rainfall is occurring, in which case you can even accept 1.0. But yes monsoons will be there for 3 months, so you can have high rainfalls from several months and that is the dry slope. And same similar values are slightly reduced for the first 2 conditions for the temporary of a temporary waste slope is the advancing waste slope that we have which eventually will no longer exist similarly it is the waste slope of the cut that we make in the soil between no longer exist.

So, we will stop here today what we have tried to do is we have introduced the concept of interfaces, we have introduced the fact that failure surface can occur along straight lines. These are critical elements in the liners and in the covers and more and more data shows that failures do occur.

In fact, they are so critical that bulk of the landfill failures the big one not the cover, you see what is the cover failure a cover failure the topsoil will slide down, but if the whole landfill slides that is a much bellow failure and do remember that you are putting the landfill on a geomembrane and designers like us have been originally saying base is flat. So, let us have a smooth geomembrane or maybe it is only tilting at to 3 degrees does not matter, but what you have seen over the here is that landfills can move along the basis specially if each at head collects inside the landfill due to accumulation of water. So, these are the cases how do polymeric materials which are embedded inside the landfill affect slope stability.

So, we will continue in the next class, we just open this critical aspect and we will have one discussion in one more lecture of this. Any questions you have welcome to ask, anything which. So, most of the analysis is like soils except for the interfaces which is like failure parallel to the outer slopes and in that now you will start to get two wedge also, we just, you just done an infinite slope analysis, but you can have a 2 wedge and 3 wedge method also.

Thank you, have a good day.