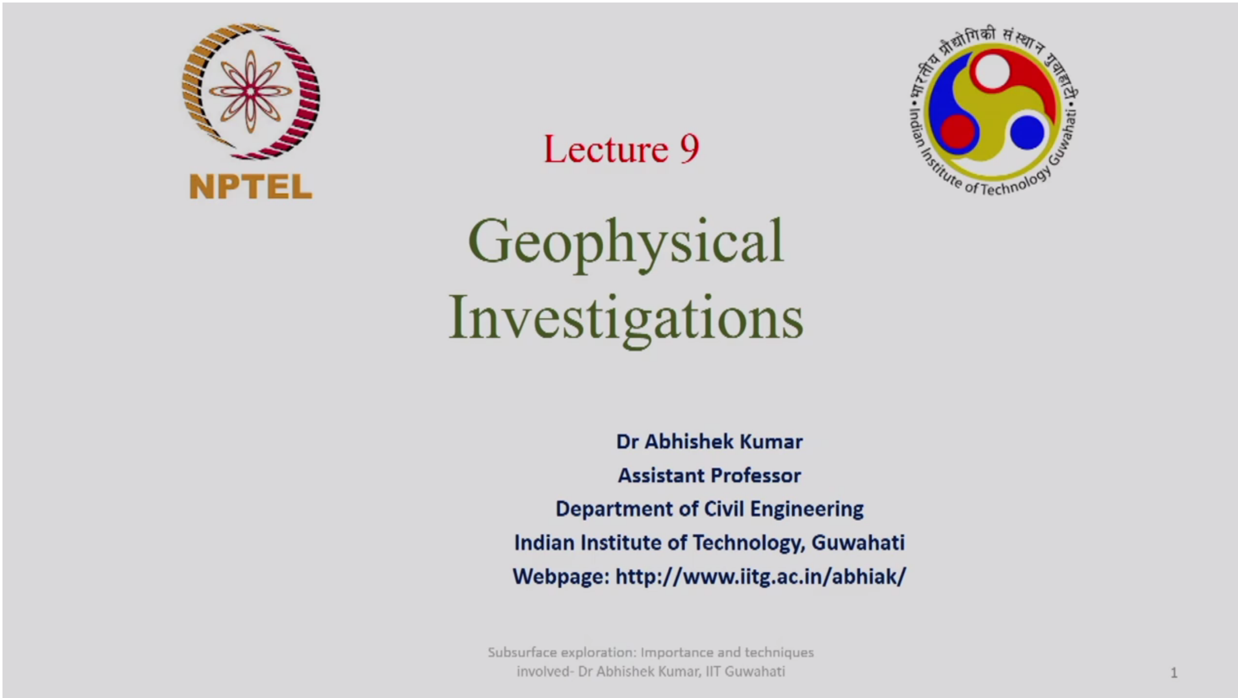
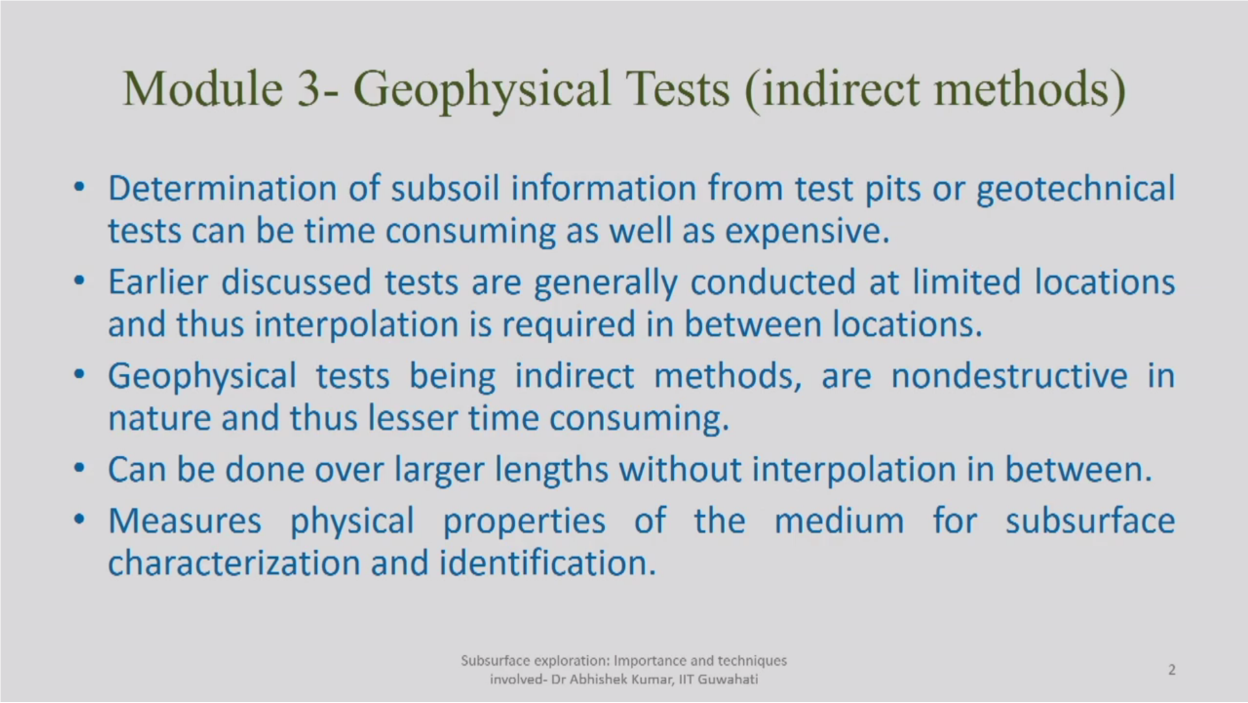


Dr. Abhishek Kumar: Welcome all to lecture 9 of subsurface Exploration: Importance and Techniques Involved. So far, we have discussed about different classification of investigations, then we started with direct method, slight test period, trial, trenches, then we went to semi-direct method that is mostly geotechnical investigation, different kind of geotechnical investigation we had discussed earlier like standard penetration test, cone penetration test, dilatometer test, pressure meter test and so on, 00:58 test; what are the advantages/disadvantages of each of those tests. And then we have also solved typical numerical problems like how to interpret field records in order to identify the soil type in order to determine different properties of the medium.

So as we know like most of the geotechnical tests are point based methods like whatever soil type you are determining it will be at that particular location and at that particular depth. However, whenever we are interested to find out subsurface properties of a particular set, we are interested to find out what is the little variation. At times, we are interested to go for deeper location probably where geotechnical investigations are not feasible. So considering the requirement for interpolation, considering the limitation with respect to a depth exploration at times. Moreover, in addition to that, like whenever we are going for any kind of geotechnical testing, it requires a lot of time, expertise, as well as -- because it requires a lot of time and specific equipments, most of the time geotechnical tests are expensive and time consuming.

So because of these three major limitations or issues, and in addition you can explore particularly when large area is there where the required number of tests are significantly larger, you have to invest more number of times and a huge amount of finance also, particularly when you are going to geotechnical investigation. So another option which comes to mind, which is not new, but even the techniques which are people following nowadays, even for smaller areas for regional study, even for a local study, site specific studies, so more and more methods have been evolved. In last one decade, even though because of use of geophysical investigation particularly for oil exploration, mineral exploration and even for geological explorations, it has been in use for quite some time maybe for three, four decades now, but more and more use of geophysical investigation has become more permanent nowadays, because such investigations can be done even at local scale and because of improvement in the interpretation, because of the significant reduction in the initial investment regarding the setup purchase it has -- I mean now the geophysical investigations are -- people can afford, that’s what I want to say here.

So from today’s lecture onward, we will be discussing about what are geophysical investigations and we will be discussing, just like geotechnical investigations, some of the geophysical investigation methods, what are the methods, how you interpret the typical field records in order to quantify the subsoil properties.



So as the name suggests geophysical investigation, we are interested to find out -- we are interested the soil type, we are interested to quantify subsoil properties, physical properties of the medium based on some ways of using geophysics. So it comes under module 3 as first lecture or overall it is lecture 9. So it consists of determination of subsoil information, which is a broad objective of this course. From test pits as well as geotechnical investigation, it is time consuming as well as expensive as I highlighted earlier.

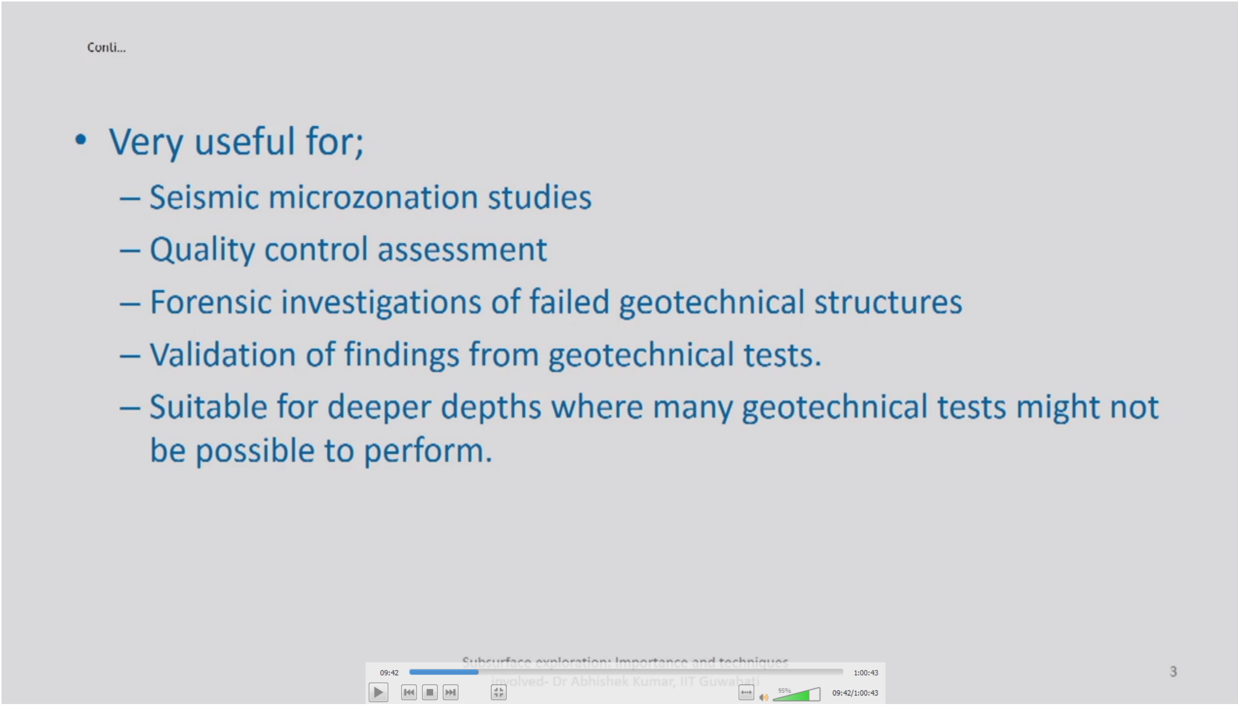
Moreover, earlier discussed tests are generally conducted at limited location. So whatever you site of interest depending upon the guidelines provided for different kind of structure for different kind of field investigation, even for different kind of seismic zones and areas, geotechnical investigation can be, I mean the entire area can be divided number of grids, and for each grid you have to conduct at least or more than one tests. At times, you have to validate the findings from geotechnical tests by one more test. So that we have discussed, but what about if the properties varying in between the grids, like you did the test at two locations and assuming like either it is same, if it not changing between the two test locations or whatever changes happening, it is happening linearly.

So in those cases where interpolation is required and considering the finance involved, you have to go for limited number of geotechnical tests, so more your field investigation and interpretation part depend upon interpolation between the field tests. So in those cases, geophysical investigation, because there you can actually explore a larger area, you can even go for continuous recording, you can even go for 2-dmentionsal methods, also where you can have complete information about how lithology is changing in terms of depth, in terms of physical properties along the survey line. So that is another important aspect when we go for geophysical investigation, like those are less time consuming in comparison to geotechnical tests and interpolation is also significant easier or most of the time you can rather than going for interpolation between two location which are wide apart, you can go for more number of tests, because these are relatively quicker methods.

So geophysical test being indirect method, because you are actually not getting any kind of soil sample from the depth or you are not taking about the sample or any kind of sensor, you’re not going to lower there. So mostly, these are called as indicted method, because you are putting the sensor at the surface, any kind of disturbance, which the sensor is detecting, even that kind of disturbance is also located at the surface. So these are call that’s why nondestructive tests, and thus lesser time consuming, because you need not drill a bore hole, you need not drill a trench, so you can simply put some sensor at the surface, and by means some typical measurements at the site of interest, you will be able to understand what kind of soil properties are there at the surface, what kind of soil properties are there below the depth at different, different layers, and depending upon what kind of depth you are interested to find out, you are interested to explore, you can go for different kind of sources, you can go for different choices of receivers as well. So these are overall less time consuming.

It can be done over larger areas, because these tests even can be conducted over larger area, because your sensors will be spread over larger area. You can go for tests even in 2-dimension. So you can actually got for these kind of tests over larger lands without interpolation, because that will be consist of almost continuous recording. So there will not be any much requirement for interpolation in between. What it does, depending upon the physical properties of the medium like depending upon which kind of test you are using, the geophysical test, each geophysical test will be able to determine some variation in the physical properties of the medium, either using those physical variation direction or by using some correlation, empirical correlation, you will be able to determine what kind of soil deposits are there, what are the strength characteristic of the soil deposit, which will be thereafter you can use it for subsurface exploration for interpretation, for foundation design, even for dewatering purpose also, and so and so forth you can use it, depending upon what is the choice of geophysical method you are using.

So it measures the physical properties of medium, so that you can go for subsurface characterization even you can go for identification, like at times it’s not only used for identifying different layers, it can also be used for identification of buried objects, it can also detect some unconformity, it can also detect some like in archeological survey also geophysical tests are very permanently used, so that you can actually able to find out without going for any destructive tests, because those are very important site, you cannot blindly keep on destructing the existing structure, so that you can explore a deeper depth, so you can go for nondestructive test and find out what are the buried objects, hidden objects, which are to be excavated out, and it can be brought to the public -- I mean it should be exposed to the public.



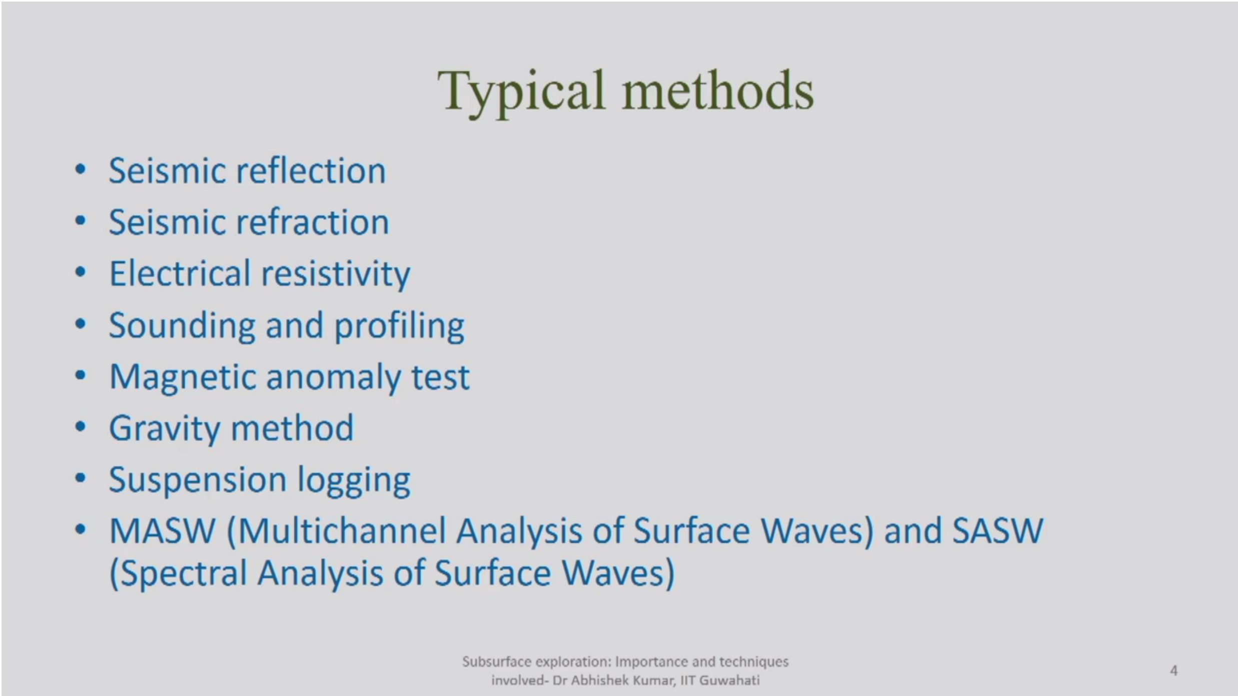
So I told you geophysical tests are very useful whenever exploration is required, whenever interpolation is required, whenever deeper depths are required for exploration, very useful nowadays, geophysical test particularly for microzonation studies, like microzonation -- as we know most of the time whenever we are interested to find out what is the inertial force because of seismic activity in a particular region, nowadays people are going for more and more regional studies or site specific study or even building specific studies in order to find out what is the seismic activity, what is the potential seismic hazard, what is the potential level of ground motion, which is expected at my site of interest. Further those ground motions will be altered because of the presence of local soil. So in order to take into account the variation in local soil property at your site of interest over which a building is located, geophysical tests are more and more -- nowadays people are practicing, so that you can quantify the subsoil properties. Once you know the subsoil properties, you will be able to identify how these subsoil properties are dominating in controlling the seismic vibrations into a building.

Then second thing quality control, like your designer suggested some minimum density of the medium at the site of the interest, even whenever you're going to subgrade laying or you're going for any kind of filled up area. So once the site is filled up, you can actually got for some kind of quality check, you can do some test and based on that test, it will be able to determine what is the strength properties for the densities of the medium, so that you can match those densities which you are getting from geophysical tests with the density provided by the designer. In order to ensure like your quality, the guidelines which are given for filling up the area for preparing the subgrid are those properly matched. So it is like quality control.

Third one is forensic investigation of failed structures. So whenever there is some kind of failure at the structure, particularly like abutments of bridges, flyovers, retaining structure, you can actually got for forensic investigation in order to find out, because those structures are already failed, at times it is not advisable to go for detailed geotechnical investigation, because again that can trigger more distress to the existing structure, though it has already failed. You can go for geophysical method, so without creating much of disturbance to the surrounding area of any disturbed, or failed geotechnical structure, you can go for -- you can explore the subsoil properties and find out whether there was some problem during laying of subgrade, whether there was some problem during filling for preparation of abutment, approach roach, or any preparation for zone of influence for any bridge periods and so on and so forth. So there are a number of varieties of which in which forensic investigation for failed geotechnical structure can be done very easily, considering the nondestructive nature of geophysical test.

The next one is validation of the findings. At times, whatever geotechnical investigation you are doing, you can also validate, so that if a particular geotechnical investigation has limitation with respect to the depth, you can go for geophysical investigation for deeper depth, so that way you will be able to develop some correlation between some measure of geophysical test and some measure of geotechnical test, and that’s how you will be able to determine the outcomes from geophysical tests at deeper depths in order to find out the equivalent properties in terms of geotechnical testing. So this is like validation as well as interpretation.

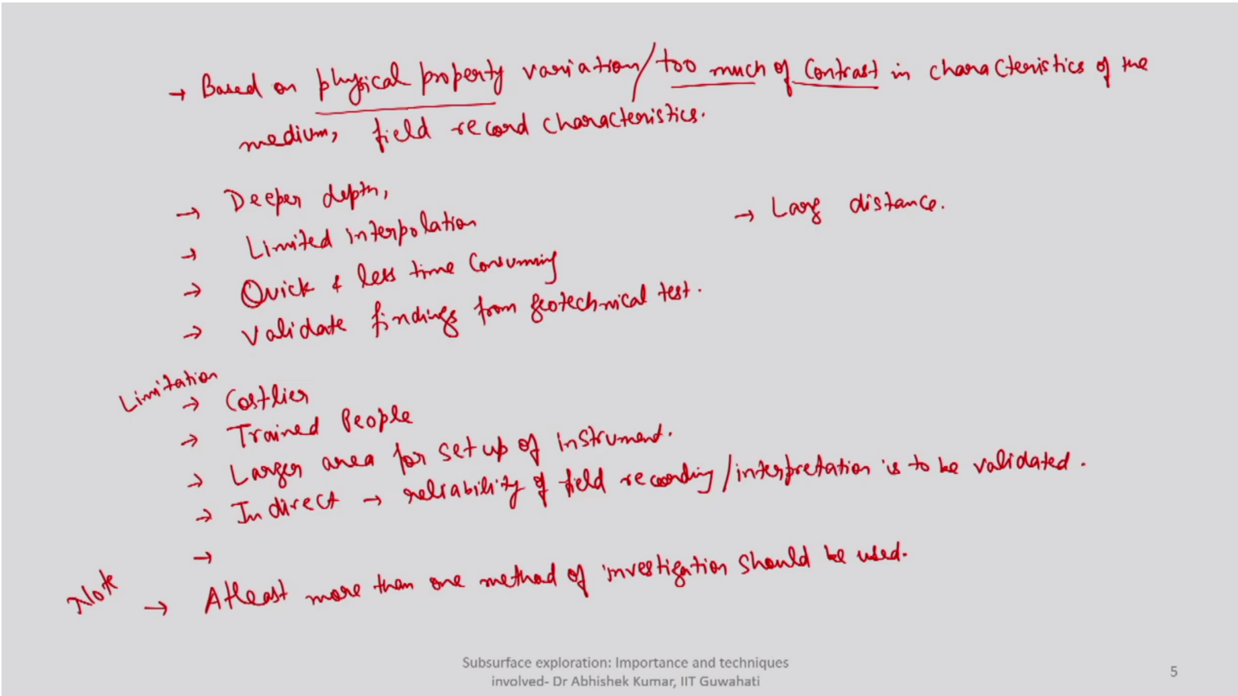
Then it is suitable for deeper depths where many geotechnical tests might not be possible to perform. So as we know like SVG test, CPG test, dilatometer test, each of tests has some in terms of the depth of exploration. So if your depth of influence is more than that particular depth of exploration, there must be some other ways with which you will be able to determine what kind of subsoil properties are there, what are the physical properties of the medium, what are the soil types. So in those cases also particularly for deeper depths, geophysical investigations are very important.



The common methods as I mentioned here like in earlier times people were going for more and more for gravity survey, magnetic anomaly method, then seismic reflection method for mineral exploration, for studying the geomorphology of the area, even for studying the geology or topography of the area, people were going, and even for oil exploration also. So people were going more and more for these methods, but over the period of time more and more advancement in the technology and more and more sophisticated and user-friendly equipments are nowadays available.

So you can see here, I've given here the list of different geophysical method which are more permanently, people are using nowadays, starting with seismic reflection survey, then seismic refraction survey, electrical resistivity survey, sounding and profiling survey, magnetic anomaly method or magnetic anomaly test, gravity method, suspension logging method, and then we'll also give some brief idea about what is Multichannel Analysis of Surface Waves, that is MASW, and Spectral Analysis of Surface Waves, that is SASW. Those two tests are more and more prominently people are using now for forensic investigation, even for quality control, even for microzonation studies.

So we will be discussing overall like these are the list of prominent tests which comes under geophysical testing methods. As far as the syllabus of this course is concerned, we will be discussing about seismic reflection test, seismic refraction test, electrical resistivity methods, magnetic anomaly, gravity method, suspension logging, and as I mentioned here, when we'll be discussing about other methods, I'll give also some glimpse about what is MASW and what is SASW.

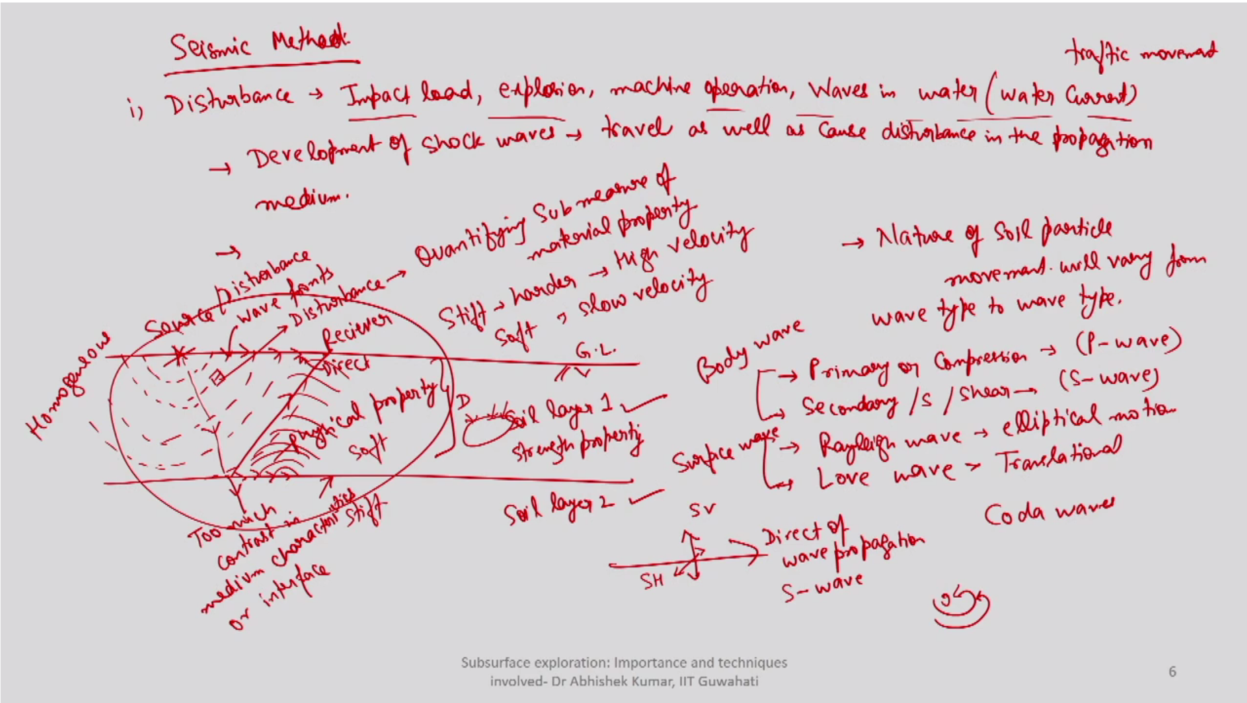


Now coming about to as I mentioned here, like geo physical tests has certain advantages, certain limitations. So I am going to list out here, what are the advantages. So what it does actually, it tries to find out based on physical medium, based on physical property variation or you can say, when there is too much of contrast in characteristics of the medium, what it does, there will be too much of variation in conductivity of the medium, whether it is related to reflection, refraction, whether it is related to magnetic properties of the medium, whether it is related to electrical properties of the medium. So it keeps on interpreting the physical property of the medium, rather changing its field record characteristics.

Suppose you're going for because of too much contrast, you have to be very careful with too much contrast. So like you're going for any kind of field test, you know like at the site of interest, there are very different layers, one maybe very soft layer, one maybe very stiff layer. So when a particular like you go for seismic method when any kind of waves will be there, when it will lease the interface, when the wave will face too much of contrast, that will show too much of change in the properties of the medium. So because of this too much contrast maybe in terms of velocity, you will also interpret okay there is change in the medium characteristics also. So geophysical test targets for identification in the physical properties, variation, because of change in field record characteristics.

So advantages include, you can go for deeper depth, almost limiter interpolation, because you can go for limited interpolation, then you can go for these tests are quick and less time consuming. Then you can go for less time consuming, limited interpolation and then can validate findings from geotechnical test. Disadvantages, I can say here limitation, requires -- most of the time these tests are significantly costlier, require trained people, because interpolation is required, at times require larger area for investigation for setup of instrument. Keep in mind these are indirect methods, so indirect, so always reliability, reliability of field recording and interpretation is to be validated. You have to get more and more confidence, whatever interpretation you are doing, it is correct.

Then another advantage here, you can do those tests here over larger distances. So that’s why very much similar to your geotechnical investigation. You can say here, one note you can put, suggested like at least more than one method of investigation should be used. In geophysical method, you can go for at least more than one method. Either you can go for additional geophysical method or you can go for geotechnical method. So that findings whatever you are getting, it will be validated. I mentioned here different methods also like seismic reflection survey, seismic refraction survey, electrical resistivity, magnetic anomaly methods, gravity test, suspension logging, then multichannel analysis of surface waves, spectral analysis of surface waves, so on and so forth.



Now we will be discussing here onwards what are the seismic methods, because as I mentioned here, the first two methods are called as seismic reflection survey or seismic refraction survey. So what do you mean by seismic methods, why it is called seismic methods. We know like because of any kind of disturbance, which maybe because of impact load, maybe because of explosion, maybe because of machine operation, maybe because of waves in water, that is water currents, there will be some kind of disturbance or some kind of shock. These will result in development of some kind of shock or shockwaves, which will travel as well as cause disturbance in the propagation medium. So depending upon which medium it is passing through, it will cause some kind of disturbance. What kind of disturbance it is going to cause, that depends upon what kind of wave you are targeting for.

So precisely you can tell like whenever there will be some kind of shockwaves, whenever there will be some kind of disturbance, because of ever mentioned reasons, there will be different kind of -- the disturbance at the surface will cause some of kind waves generated at the source, like if I am showing here, like this is your sources, this can be anything like exploration, explosion, it can be impact load, it can be a machine operation, it can be even passage of traffic also can come here, like traffic movement. Each of these can cause some kind of source. So I am referring source to any kind disturbance. As a result of which what will happen? Wave will be generated. I am showing here some kind of wave fronts. So wave front means whatever matter is available at this particular location, it will be undergoing some kind of disturbance, and depending upon how much the resistance against this disturbance, the material offers that will help in understanding, quantifying sub-measure of material property.

What I meant to say, if the wave is passing too quickly, we can say the material is stiff or it can be hard, because the resistance offered to the material is significant high. If the material is passing very high velocity, you can call it as stiff material, hard material. Same way, if it is very slow, slow velocity, you can call it as soft material or softer material. So what is happening as a result of this source, any kind of disturbance, actually wave fronts are creating now. Now you can see here, this is at the ground level.

Okay suppose this is soil level one. I do not know whether this soil layer is sand, clay or it is soft medium, or it is harder medium, because most of the geophysical methods give you quantitative assessment, and this is your soil layer two. Now when you went for trenching, when you went for test pits, when we went for geotechnical test, we were interested to find out what kind of soil layers are there. What is the measurement of strength properties. Even here also, our target will be to determine what is the thickness and what is the -- you can call it some ways of measurement of the physical property of this particular layer.

Now what will happen as a result of this wave front. I am showing you some partial this thing here. So once the wave front reaches this -- at the interface, why am I calling this is an interface because this medium suppose this is very stiff soft medium, this is stiff medium, because of the sudden change or too much contrast in medium characteristics, what will happen, the incident wave, either some wave -- first of all, some wave will travel along the surface. This will be called as direct some wave, you can see it based on the wave front, will reach at the interface and will reflect back. Some wave might travel to the deeper medium, so you can call it as either absorb or you can call it as -- yeah, travel downwards. Some wave will along the interface which keeps on creating more and more wave fronts, because once it traveling here, again it will be considered additional source, which will again transfer -- so I am putting here another receiver, which is actually going to detect what kind of disturbance you are getting from here.

So depending upon at which particular depth this too much contrast or the interface is there, or too much contrast in the medium or you can call or interface. So whenever the interface comes what will happen, the wave which is -- you can call it a shockwave which was generated because of any kind of disturbance causes the source. Once the wave reaches the interface, it will experience some kind of too much contrast in the medium characteristics as a result of it some energy the wave was carrying, it will be absorbed in the material, that is traveling downward. Some will travel, some will reflect back and start traveling towards the surface, which will be getting detected by the receiver.

So depending upon, you see here, because of the wave front, it is causing some kind of disturbance in the material. So depending upon what kind of disturbance, the nature of the disturbance causing the material or the kind of movement this material that is soil particle in this particular case, so nature of soil particle movement, that will help you in understanding what is the characteristic of this medium. So generally based on there can be different kind of waves, which can possibly be generated from the source and depending upon the nature of each kind of waves, it will be causing different kind of soil movement. So I am telling here, nature of the soil particle movement will change, will vary from wave type to wave type.

So when discuss about seismology, when people started interpreting about different layers of the earth, it is understood like precisely the kinds of waves which are generating because of any kind of shock can be classified as, I am calling here shock like the shock which can actually cause some kind of disturbance to the material. So we can precisely classify it as P wave or primary wave or compressional wave, which are causing compression and rarefaction to the material. You can call it as P wave.

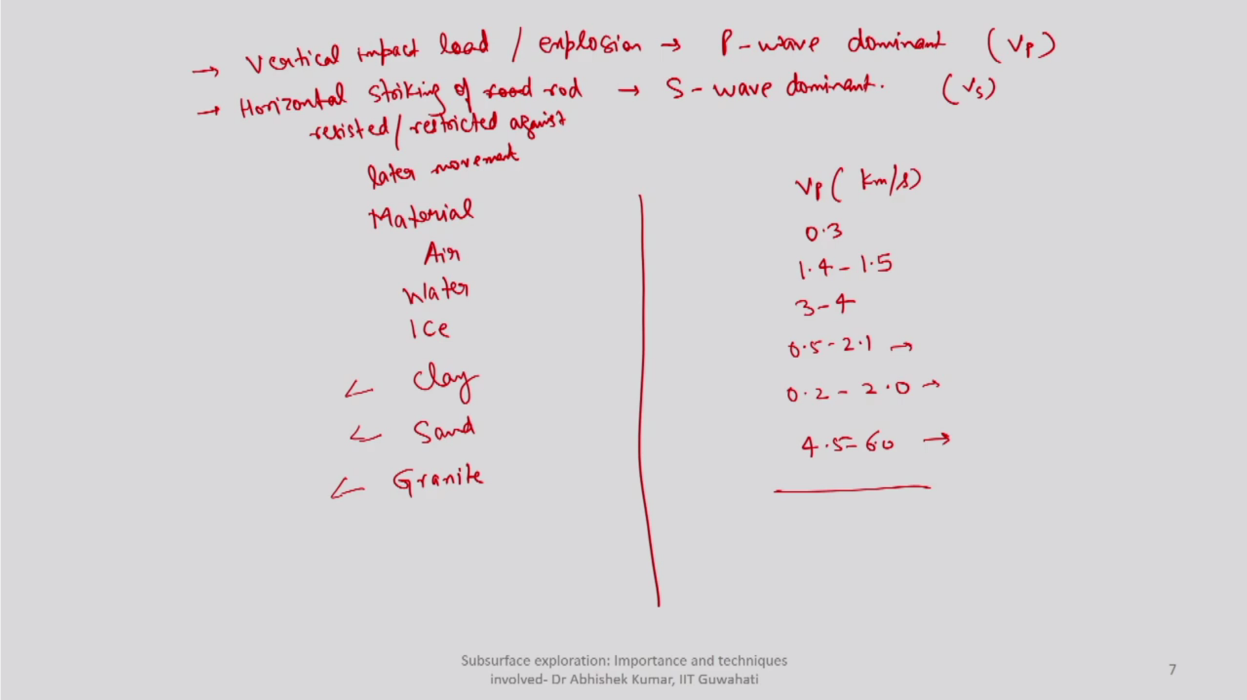
Then secondary wave or S wave or shear. So first one was causing compression and rarefaction, this is causing some kind of shear, you can call it a shear wave. So you see here, when a primary wave is passing through the medium, it is causing some kind of compression, expansion compression, rarefaction, like compress and then it will bring it to its original position. So with respect to second position, it will be expansion, but finally it will commit to its original position. Then second one is shear wave. So whenever the wave is passing like this is the direction of wave propagation. So what it does, once it is shear wave, it will be causing shear in mutually perpendicular direction.

So particle motion will be either perpendicular to the wave or other one will be perpendicular to this board. So depending upon what is the -- and which plain the shear stresses are getting dull or in which plain the particle is undergoing some kind of shearing, it is called SV or called as SH wave, but both of them are causing -- I mean it is happening because of passage of shear wave. So in order to -- I mean when shear wave is passing, the material is offering resistance in terms of shear strength of the material. And the third one is Rayleigh wave, which is precisely caused when this body waves interact with the surficial layer of the Earth. So these are called Rayleigh waves or it cause elliptical motion in the soil particle. So whenever particularly the Rayleigh wave is passing, the particle motion will be like this. So there will be some kind of elliptical motion.

The last one is called as Love wave. Here the particle motion will be translational, like side wave motion will be there. These again are classified as surface wave, because more prominent and near the surface of the ground. So these are precisely four kinds of waves. Whenever we go for seismic methods, there are precisely four prominent kinds of waves. Again, you can have other waves, which are mostly generated because of reflection happening from heterogeneities present in the medium, like there can be any local pockets which is available in the medium. So whenever that local pocket is there, again that will be considered as additional source of disturbance of additional source from which the waves are reflected or some energies is getting contained. So this will be again recorded at the receiver at later stage. Those are again called as -- I mean those waves are called to give you an example, those are called coda waves, which are generating because of the heterogeneity present in the medium.

Whenever we go for the interpolation, we generally consider any soil layer, this is homogenous. So whatever material property you are getting, it is like applicable throughout the material unless there’s too much contrast or there’s too much change in the medium characteristics. Otherwise, up till that depth, till which there is not too much contrast in the material, the entire material will be characterized as one kind of medium. So this is like -- so you will be able to -- when ever we are interested to go for seismic methods, we are interested to find out based on this, we are actually inducing some kind of vibration and depending upon what kind of disturbance it is creating, we will be interested to record those disturbance and depending upon the characteristics or time of arrival of those disturbances at your receiver end, you will be able to interpret the physical property of the medium.

Now one question which comes to mind is how you quantify which kind of wave you are actually determining like you have put the receiver, but receiver whether it is recording P wave, whether it is recording S wave, whether it is recording other waves. So that depends upon what kind of disturbance you are actually creating at the source.



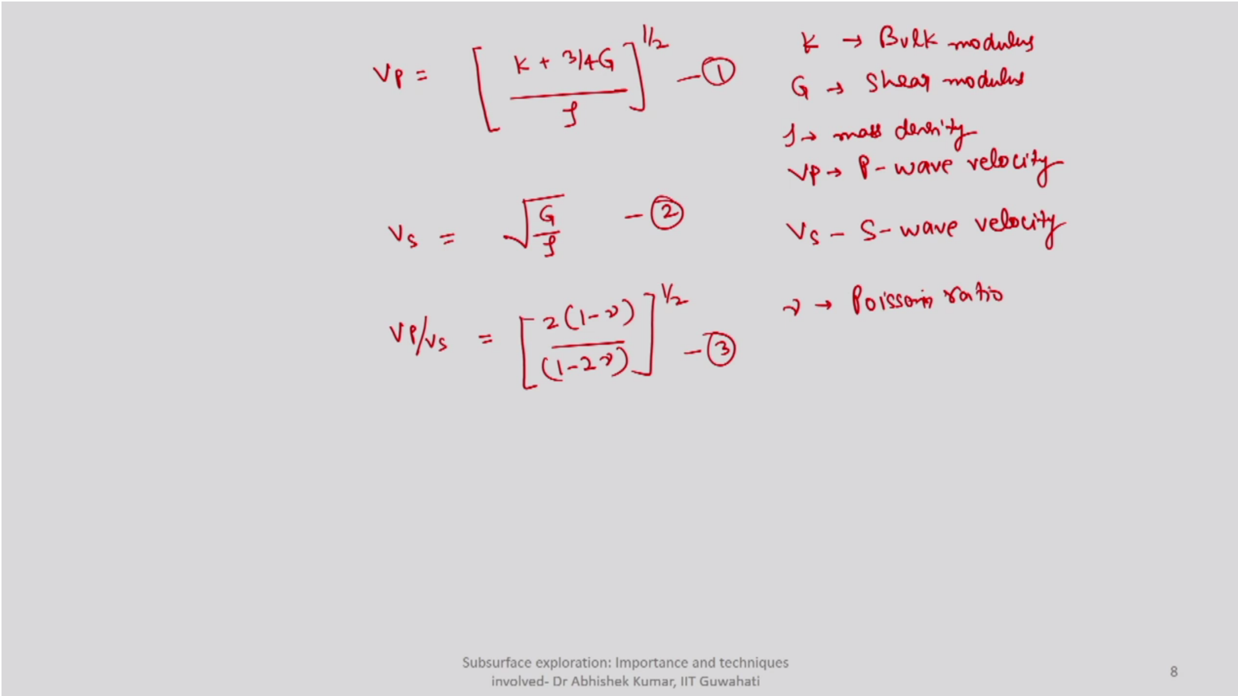
So whenever you are going for vertical impact load or explosion, mostly your shock will be dominated by P wave dominant. So if you put a receiver and this is a shock or this is your source, mostly it will be containing your -- maximum content or maximum energy will be transferred through P wave. Similarly, if you are taking some horizontal striking, of a rod, mostly it will be contained by S wave dominant. So if this kind of disturbance is there where you are actually -- some rod is there, which you are striking horizontally against any later movement, resisted/restricted against later movement. Otherwise fi later movement is there, then it will not cause much -- I mean most of the energy will be confined to the surface itself, and it will not cause any kind of disturbance or any kind of shockwaves or shear waves at deeper level.

So this is like when we are interested to find out, when we are interested to determine P wave velocity, we can go for vertical impact of explosion, when we are interested to find out S wave velocity, you can go for -- accordingly like depending upon what kind of source is there, you can decide which kind of wave your receiver is detecting here.

Now as I've been mentioning here, because this is method of exploration. So depending upon your velocity of the medium, we call it as VP that is primary wave velocity. This is called VS, so depending upon what kind of material is there, I am going to give you here some chart, and then the value of VP in kilometer per second. Let's see what is the overall velocity of primary wave of propagation through different material.

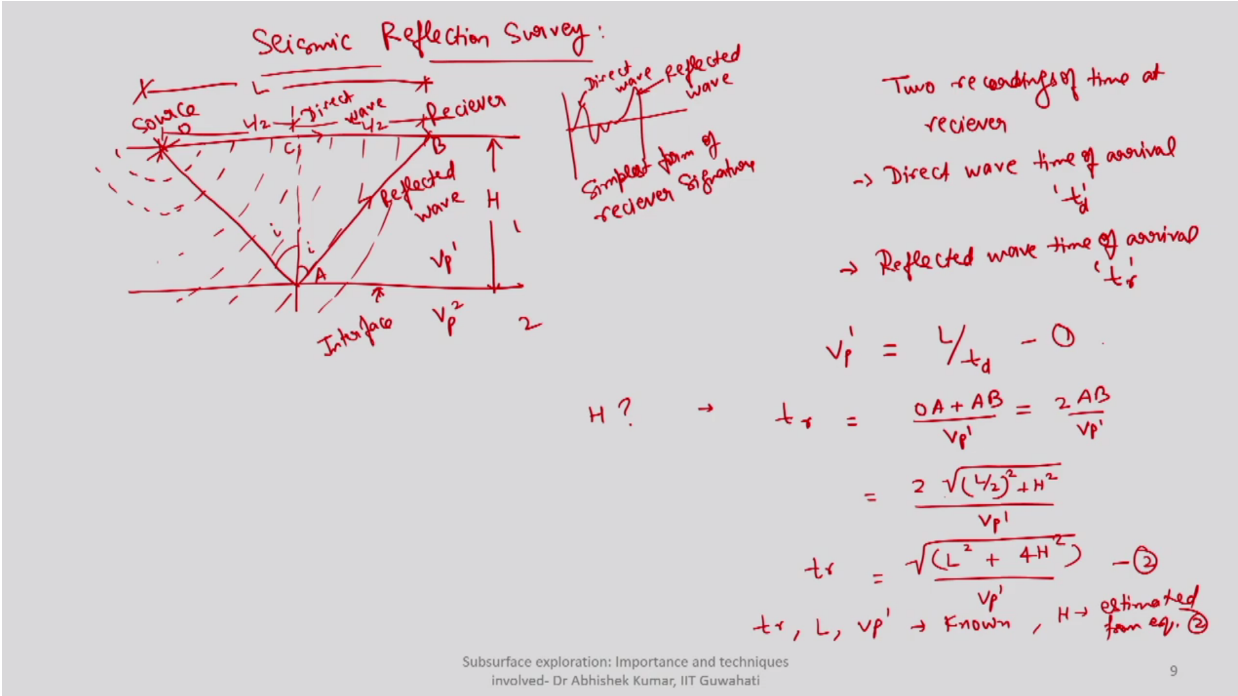
So to give you an example, if air is a medium, the primary travel travels at a rate of 0.3 kilometer per second, which is almost close to the velocity of the sound. When we go for water, the primary wave velocity increases from 1.4 to 1.5. Similarly, ice is like for different medium, what is the primary wave velocity, which if some seismic recording station is there, you will be able to detect the primary wave, because of any seismic activity happening in the other parts. Then clay, you can have primary wave velocity from 0.5 to 2.1. Then sand, you can have primary wave velocity from 0.2 to 2.0. Then granite, you can primary wave velocity as high as 4.5 to 6.0. If you remember, granite we had also discussed like this is very intact rock. So it is offering more and more resistance to any kind of primary wave passage or any kind of movement which the primary wave offers in terms of compression or rarefaction. That's why the primary wave velocity is like this.

So based on seismic method, if you are able to quantify your primary wave velocity is in this range or this range or this range, that is giving you an indication that a medium through which this primary wave is propagating and getting detected by the receiver, this medium is either granite, sand, clay and so on and so forth. So that's how you go for interpretation of subsurface medium. You try to measure some wave, the physical properties of the medium, and then depending upon what is the range of physical properties of different medium directly particularly when you're going for seismic methods or indirectly when you're going for other geophysical methods, you will be able to identify what kind of medium is there, what are the physical properties of the medium, and at times what is the depth of the medium.



So this is again as I mentioned here like each of these properties are related to physical properties of the medium. So let's see how these like VP that is primary wave velocity , it can be related to the elastic constant like [K + ¾G/ρ]$^{1/2}$ where K is bulk modulars of the medium, this G is shear modulars of the medium ρ is mass density of the medium. So based on this you can understand whenever your primary wave velocities give you indication of some other physical properties, elastic constant of the medium, and VP is P wave velocity. Same way you can quantify, because shear wave is causing disturbance in terms of shear, like shear failure, so it is directly related to your shear velocity. One, two so VS is your S wave velocity.

So in the previous table I had given you the range of primary velocity for different medium. Same way you can determine the shear velocity of the medium. Third is VP/VS itself can be correlated to [2 (1-ν)/(1-2ν)]$^{1/2}$, so that's how VP and VS ratio of a medium is related to the -- is almost constant where this is called is Poisson's ratio. So this way you'll be able to determine -- once you know one value, you will be able to determine based on the recording time of the kind of wave, the wave which is being dominated by the source depending on what is your choice of the source, you'll be able to determine VS value, VP value, once you know both the values, you can determine Poisson's ratio or vice versa. So just by measuring this time of travel or time of arrival of different kind of wave between the source and registry, but you will be able to quantify what kind of medium is available.



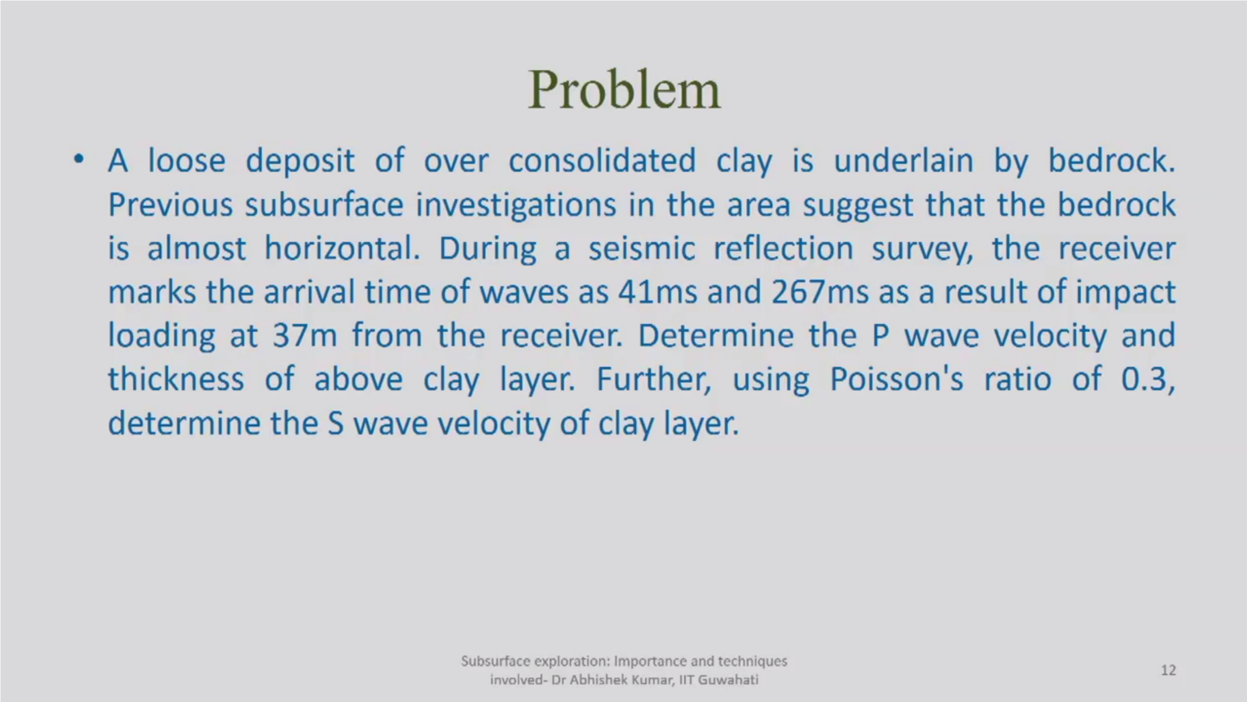
Now let’s see about seismic. So in order to go further into detail, we will be discussing about what is seismic reflection survey, seismic reflection we will be discussing in next class. Now as I mentioned earlier also, we are interested to find out what is the thickness of the medium. We are interested to find out what is the P wave velocity of the medium, and because for any disturbance or any reflection to take place at the interface, I am considering this interface’s indication of too much contrast in the medium characteristics. I am writing here interface. Otherwise, interface is not there or if the medium contrast is not significant, what will happen this bound the ratio downward unless there will be bound for too much contrast in the medium.

Now I am keeping a source here. This can be explosion, it can be vertical impact; I am keeping a receiver here, very much similar to the previous slide. So because of this there will be wave fronts, okay. So like this, wave front, it reached here. Again, some portion of energy will be reflected back. I kept here, I mean keep in mind like the angle of incidence here will be equal to the angle of reflected wave. Because it is reflection so, the angle of inclination will remain the same. So this is known as reflected wave. So in addition to this, there will be some kind of wave which is traveling along the surface, which is called as direct wave. So at the receiver if you see the receiver, you can see two kind of disturbance. First time will be the arrival time of direct wave and then it might minimize, and then again you will have second wave, which will be like arrival time of reflected wave.

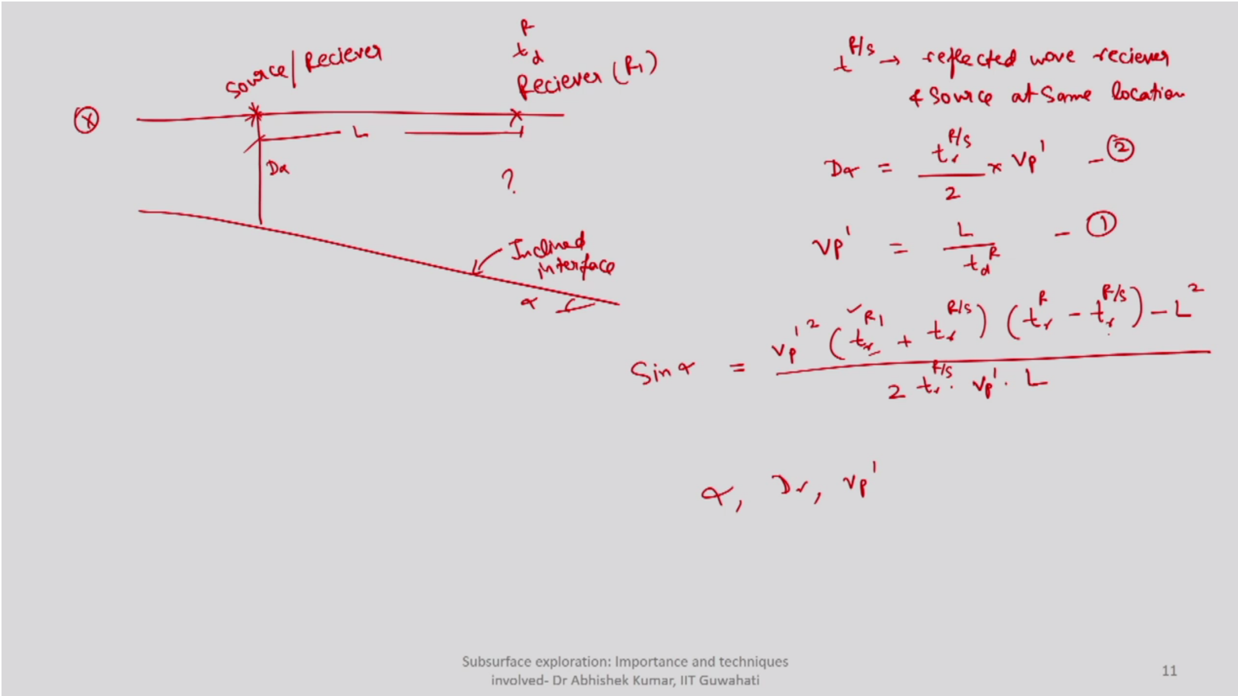
Now I am giving you signature of receiver signal. This is very simplest form. As more and more actual field condition keep on adding here, this will become more and more complicated. So I can say simplest form of receiver signature. Now I am trying here -- so I will be interested to go for two recordings of time at receiver. One is time of arrival of direct wave. So when your receiver detects direct wave, direct wave time of arrival. That will be called as 't_d'. Second one is time of arrival of reflected wave that is 't_r'. Now you see here, for a known distance between the source and receiver that is L, what will be the VP value. That is VP^1 for layer number one. VP^1 can directly be called as L/t_d, like for known distance between a source and receiver if you know what is the time of first disturbance to be detected the receiver. You will be able to determine what is the value of VP^1.

Now you see the second one, you are interested to find out thickness of the medium. So that time of arrival of reflected wave is a function of, so you say it is OAB that is called as OA + AB that is the length divided by VP^1. VP^1 is the propagation part velocity, so this P wave velocity along the propagation path of reflected wave between the source and receiver. Now this can be called as -- so OA and AB are equal. You can call it as $2AB/VP^1$. Now because this incidence angle is equal so this length will be L/2 and this another one will be another L/2. So you can call it as 2 times -- see this one you're interested to find -- suppose OA, you are interested to find out that is AB equals to -- so this will $(L/2)^2$ considering this as OAC as right angle triangle or ACB as right angle triangle. So $(L/2)^2 + H^2$ that will be the length of AB divided by VP^1. Take this 2 inside the square root, so that will be $L^2 + 4H^2$ square root divided by VP^1, so t_r. So for known values of tr, L, VP^1 known -- so this is equation number one, this is equation number two -- your value of H can be determined from equation, estimated from equation two.

So by means of one source, one receiver, based on detection of time of arrival of direct wave, time of arrival of reflected wave, that is t_r and t_d, you are actually able to determine what is the P wave propagation velocity. Based on your P wave propagation velocity, you can quantify whether you medium is sand, silt. Of course, you can better classify in terms of stiff medium, soft medium, hard medium, and then you can also determine what is the thickness of the medium. So this is the overall thickness of the medium. This is called the seismic refraction method.



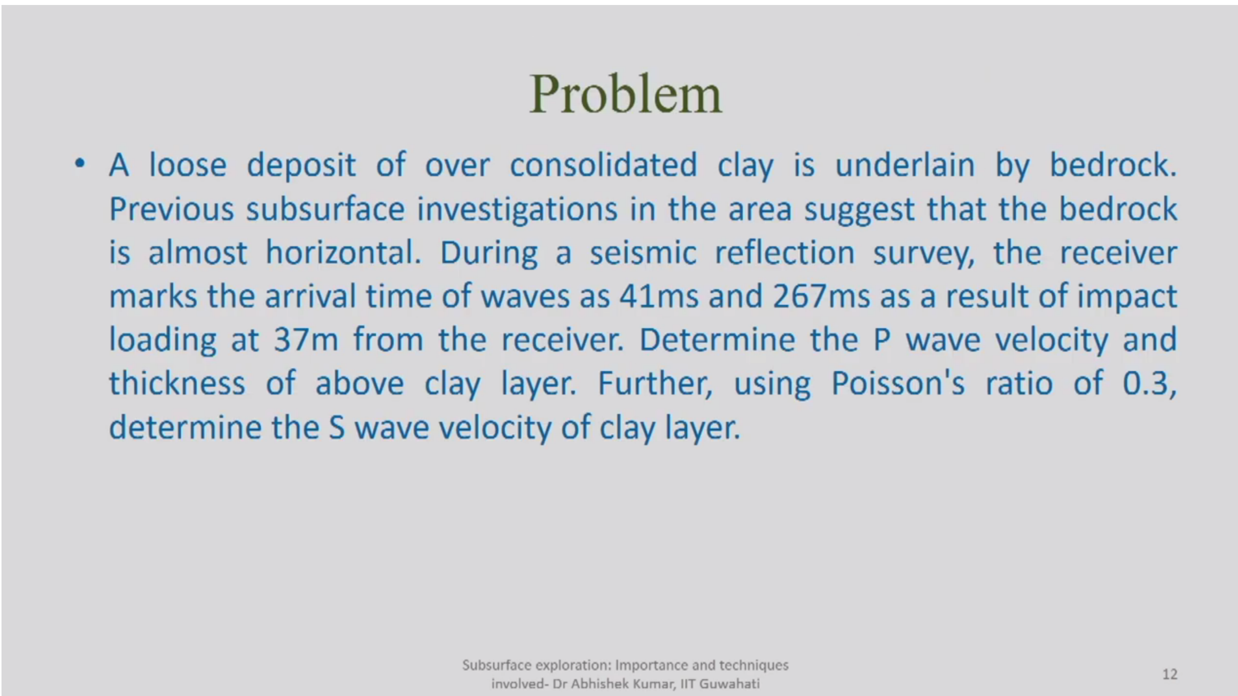
So let's solve numerical example here in order to understand better like what is the way you can actually quantify this medium characteristic. So the numerical is like a loose deposit of overconsolidated clay is underlain by bedrock. Okay, just before solving this numerical, I would like to highlight, like the numerical problem which I showed earlier it was related to this, the derivation which I showed you here it was considering relatively leveled ground.



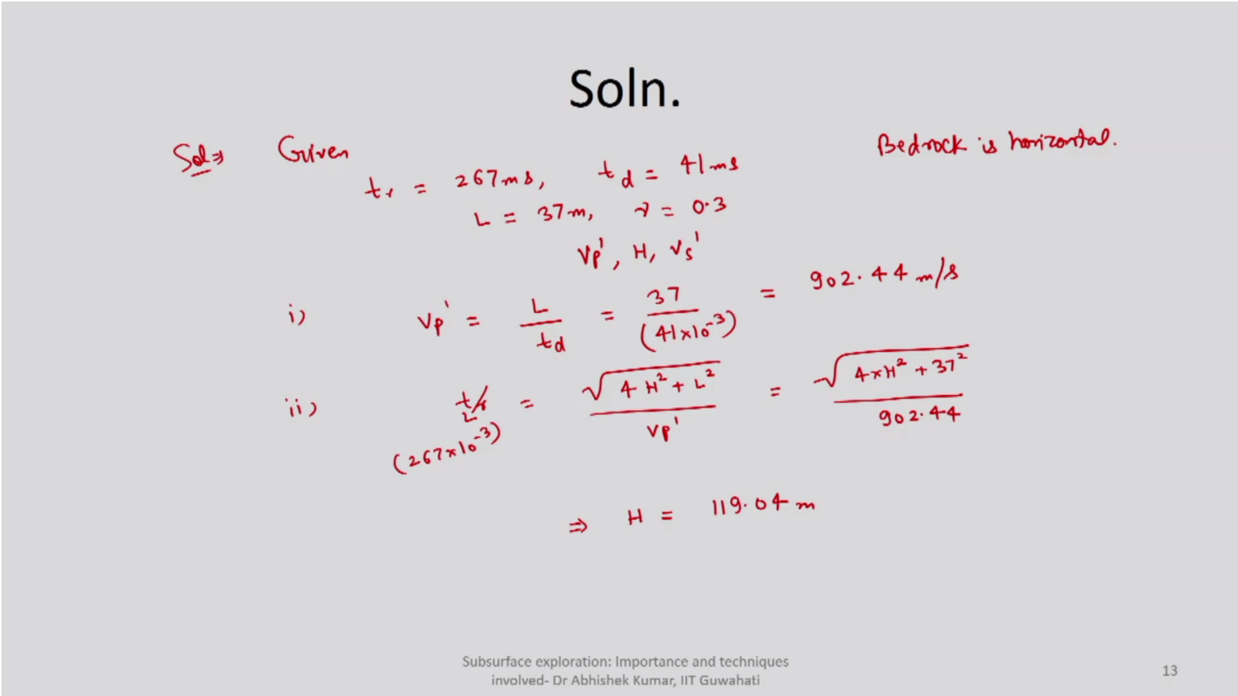
Same way if you go for inclined surface, so where this is the source and this is your inclined interface considering at an angle α. So this problem, here also you're interested to find out what is the thickness, what is the soil type here. What is the thickness? So thickness maybe I can tell you here Dα. What is the inclination here? This can be solved by keeping the source and receiver. So two receivers actually you can keep, one on one side, other receiver you can keep either here or you can keep here itself. Again, you will be having two measurements here. so this is -- Dα is the depth of investigation at 51:05 both the receiver and the source.

So suppose $t^{R/S}$ is the time of arrival of reflected wave when receiver and source at same location. If you know this, you will be able to determine what will be the value of Dα that is equals to $t^{R/S}/2$ VP^1. VP^1 you can determine -- if you know the value of this, that will be equals to L. So VP1 again based on detection of direct wave arrival that will be called as t direct at receiver. So that will be called t_d^R. So you using first one -- I am calling this one as first one, because based on this we will be determining first the VP1 value, put that VP value there and you will be able to determine what is the Dα.

Now sinα you will determine, so that will give you what is the angle inclination. You can determine based on the formula which is as V_P1^2 t that is time of arrival of reflected wave, that is t_r -- yeah, time of arrival of reflected wave at receiver, plus time of arrival of reflected wave -- direct wave at the source when both are kept at the source and receiver, then $(t_r^R - t_r^S) - L^2$ over 2 $t^{R/S}$. V_P^1. L. So t_r, this is called as the time of arrival of reflected wave, then you kept the receiver at the source itself. This is the time of arrival at the receiver. Okay, I can call it as receiver 1, R1. So time of arrival of reflected wave at receiver1, time of arrival of again reflected wave when source and receiver are kept at some location. L is the distance between the source and the receiver1. $t^{R/S}$ is the time of arrival between the source and the first receiver -- source and receiver both are kept at the same location. So that's how you can determine the value of α. Once the value of α, value of Dα, once value of VP^1 all are known, that will help you understanding who variation of interface layer is taking place and what is the physical property of the medium.

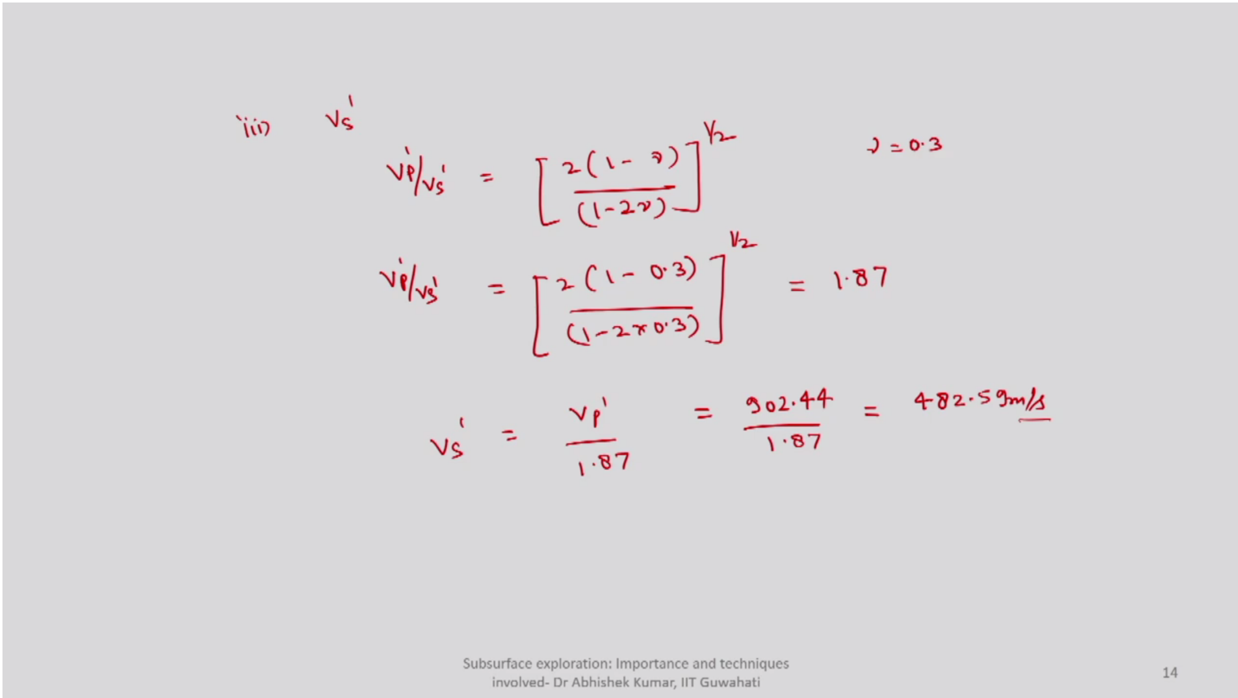


Okay. So this is a numerical problem. A loose deposit of over consolidated clay is underlain by a bedrock. Previous subsurface investigation in the area suggest that the bedrock is almost horizontal. So almost horizontal means you have to take up the first example where the bedrock was almost horizontal and you determine the thickness as well as primary velocity of the medium. During a seismic reflection survey, the receiver marks the arrival of waves as 41 milliseconds and 267 milliseconds. So based on that difference between the two values you can understand the first arrival will be direct wave, second arrival will be for time of arrival of reflected wave as a result of impact loading, which is kept at 37 meter from the receiver. Determine P wave velocity, thickness of soil layer and also using the Poisson's ration 0.3, determine the value of S wave velocity.



So this is the problem. So how we will solve this problem? First of all, write what are the things given here. So we have time of arrival of reflected wave that is 267 milliseconds, time of arrival of direct wave which is given as 41 milliseconds. Remember, be careful with the units and then distance between the source and receiver which is given as 37 meters and Poisson's ratio which is given as 0.3. We are interested to find out VP, H and VS. you can call it as one also because one layer is there. So going with the derivation which we did for seismic reflection survey first part when the bedrock is horizontal. So first one will VP^1 that will be equal to L/t_d that is 37/41, 41 is given in milliseconds, so you can covert it to seconds. That's how you will get to know what the value of VP that is 902.44 meter per second.

Now second one you are interested to find out, the thickness. So you can directly determine the thickness that is H. You can determine as tr equals to square root 4 . H^2 + L^2/VP^1 that is root $4*H^2$, you have to determine, plus 37^2 over VP^1 is 902.44, so you solve it and this tr value is given as ($267*10^{-3}$). So if you solve this equation, you will get to know the value of H = 109.04 meter.



The third part is determination of VS value. So we know like VP/VS is given as $[2 (1 - \nu)/(1- 2\nu)]^{1/2}$, nu is given as 0.3, so you will be determine the value of $[2 (1 - 0.3)/(1 - 2*0.3)]^{1/2}$ that will come as 1.87 that is VP/VS. So VS you can call it everywhere 1 also, VS^1 will be called as $VP^1/1.87$ that is 902.44/1.87 that comes out to be 482.59 meter per second. Be careful with the units, otherwise you will end up in -- though you will report your value in meter per second, but your time of arrival is given is milliseconds, because this is considering the layer thickness of just 119 meters, and considering the VP velocity of 300 millimeter per second of that order, so it will take more time for -- I mean it will take relatively lesser time rather it should be quantified in terms of seconds.

So with this timing, I hope this example in today's class had given you sufficient idea like what is the source, what is the receiver and depending upon the choice of the source what kind of wave be dominating and what will be the -- how the energy contained or generated at the source will be contained to the receivers depending upon the choice of the source, and once you know the choice of the source depending upon the time of arrival detected at the receiver, you will be determining -- corresponding either P wave velocity, S wave velocity and so on and so forth.

So that's how you can determine and then based on the numerical solve you can understand how you determine, how you interpret the properties of the medium. So you can determine the VP value, VS value, Poisson's ratio once it is known to you or you're able to detect VP and VS both, you can determine the Poisson's ratio itself. And then once you know the medium density also, which probably you can determine from geotechnical test, you can also determine the value of shear modulars, bulk modulars and other things.

So thank you all.

[Music]