Underground Space Technology
Prof. Priti Maheshwari
Department of Civil Engineering
Indian Institute of Technology – Roorkee

Lecture – 57
Rock Stress Determination Hydraulic Fracturing Technique

Hello everyone, in the previous class, we discussed the flat jack test method for the determination of in-situ state of stress on the surface of the rock. So, today we will take another method which hydraulic fracturing method for the determination of rock stress.

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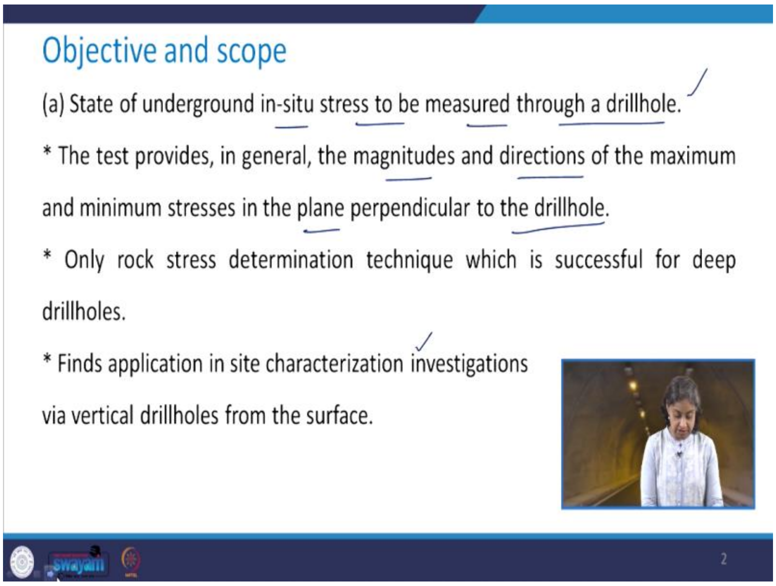

The objective and scope of the test includes the state of underground in-situ stress to be measured through a drillhole in this case. If you recall, in case of the flat jack test, we install the flat jack at the surface of the rock mass in a slot, and the state of stress was determined at the surface, but here it can be deep below the rock surface as well. So, this is measured through a drillhole.

This test provides in general the magnitudes and directions of the maximum and minimum stresses in the plane which are perpendicular to the drillhole. The only rock stress determination technique which is successful for deep drillhole. So, that is why hydraulic fracturing test is quite common in spite of having its own limitations, but then it is quite common as far as the determination of in-situ stresses are concerned. This finds application in site characterization investigations via vertical drill holes from the surface.

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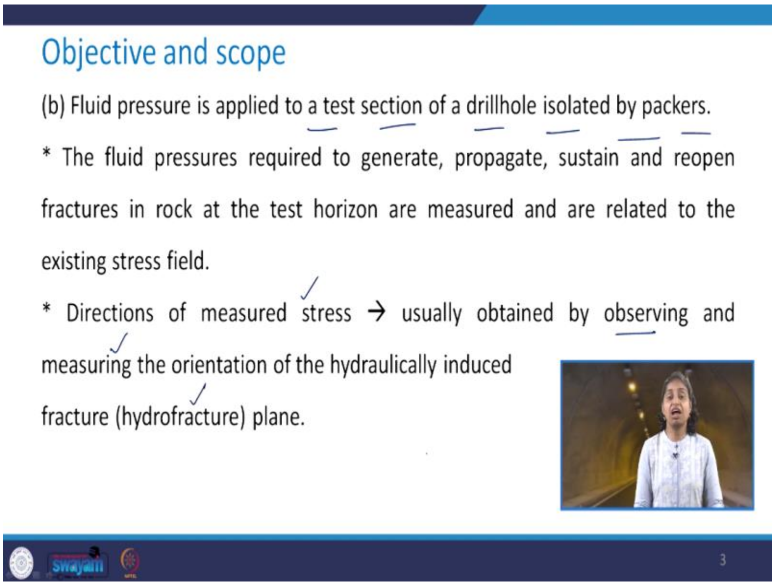

Second objective and scope includes the fluid pressure which is applied to a test section of a drill hole and isolated by the packers. So, the fluid pressures which are required to generate, propagate, sustain and also reopen the fractures in the rock at the test horizon. These all are measured and are related to the existing stress field. Along with this, the directions of the measured stress is usually obtained by observing and measuring the orientation of the hydraulically induced fracture, which we call as the hydrofracture plane.

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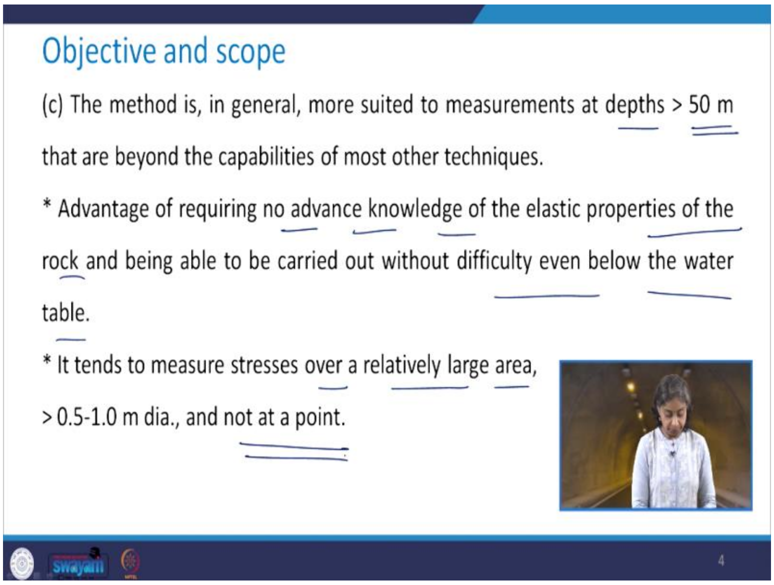

Then this method is in general more suited to the measurement at depth which are more than 50 meter. See these are beyond the capabilities of most of the other techniques which are available for the determination of in-situ stresses. So, the advantage of requiring no advance knowledge of the elastic properties of the rock and being able to be carried out without any difficulty even below the water table is the added feature as far as this test is concerned.

It tends to measures stresses over a relatively large area which can be more than 0.5 to 1 meter diameter and not at a point.

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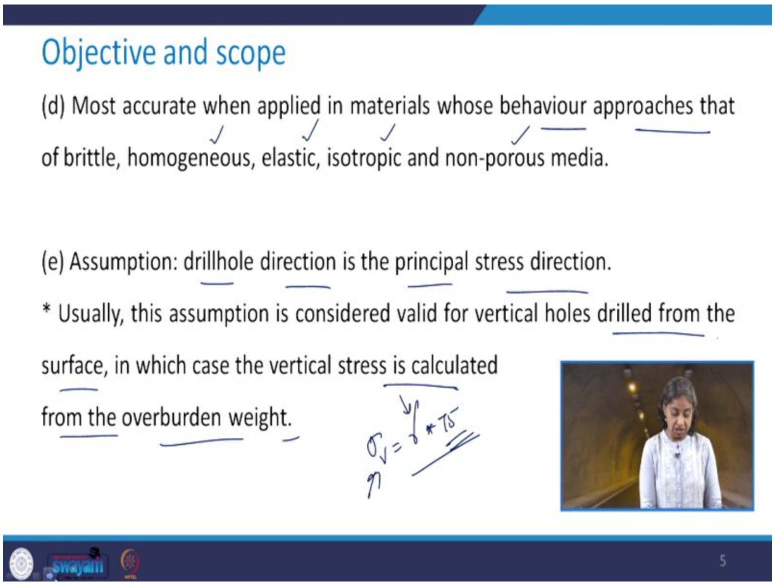

This test is most accurate when it is applied in materials whose behaviour approaches that of brittle, homogenous, elastic, isotropic, and non-porous media. The assumption which is involved with this test is that the drill hole direction is the principal stress direction which is usually considered to be valid in case of the vertical holes which are drilled from the surface and in which case the vertical stress is calculated from the overburden weight.

So, let us say if the drill or if the test is conducted at a depth of let us say 75 meters below the ground surface in a vertical borehole, then maybe the vertical stress will be equal to γ of the rock multiplied by the value of this overburden which is 75. So, based upon the unit of the γ σ_v will have the unit.

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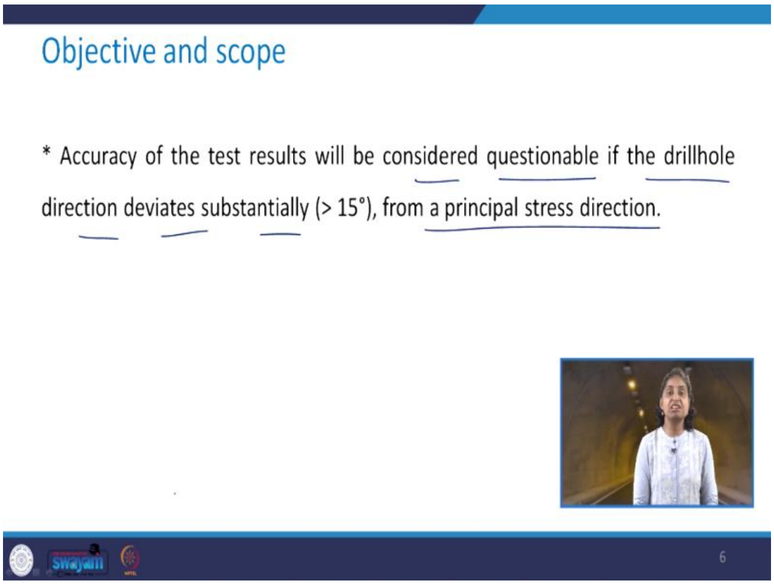

The accuracy of the test results will be considered questionable if the drillhole direction deviates substantially which is more than 15 degree from the principal stress directions.

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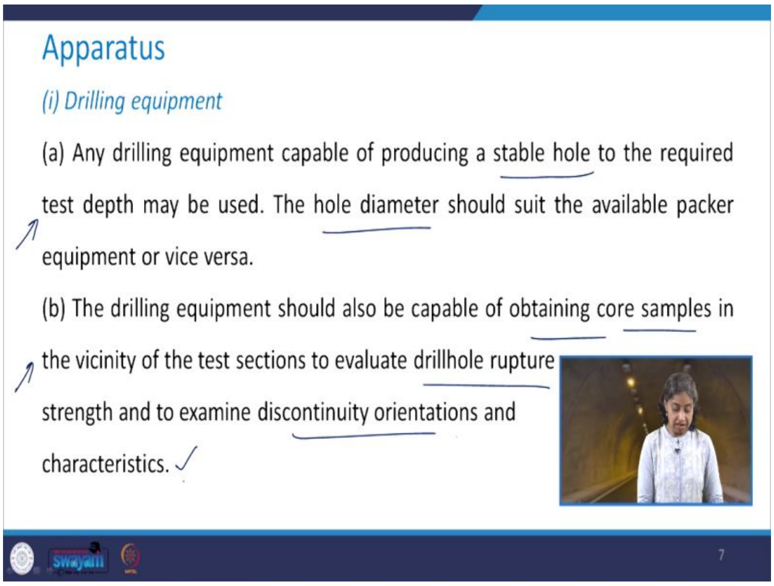

Coming to the apparatus of the hydraulic fracturing test. The first is the drilling equipment's. So, various points are here with respect to drilling equipment. So, any drilling equipment capable of producing a stable hole to the required test depth may be used. The hole diameter should be such that it suits the available packer equipment or vice versa. Then the second point that the drilling equipment should also be capable of obtaining the core samples in the vicinity of the test sections to evaluate the drillhole rupture strength and to examine discontinuity, orientations and characteristics.

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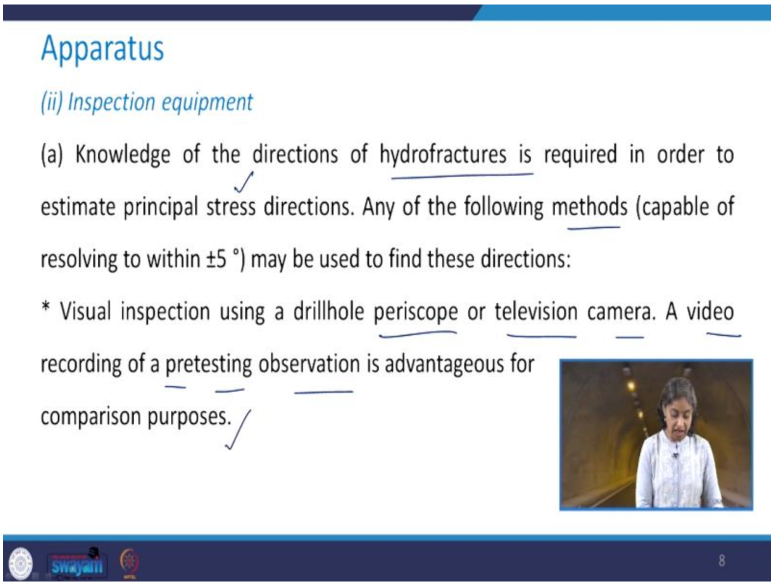

Coming to the second category, that is the inspection equipment. The knowledge of the direction of hydro fractures is required to estimate the principal stress direction and for this any of the following methods may be used to find the direction of the principal stresses. Of course, these methods are capable of resolving to within plus minus 5 degree. The first one is by visual inspection using the drill hole periscope or television cameras.

So, what exactly is done is the camera is lowered into the drill hole and then it is connected to wire which is connected to the system and the system catches the signal and then the analysis is done. Along with this, video recording of a pretesting observation is advantageous for the comparison purpose.

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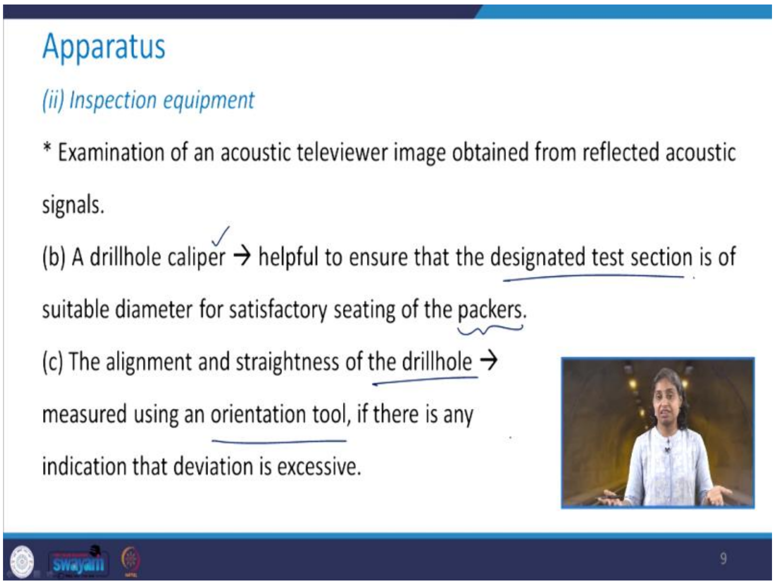

Then the second method for this is a drillhole caliper. This is helpful to ensure that the designated test location is of the suitable diameter for the satisfactory seating of the packers. So, when we discuss about the different other components of the apparatus there, you will realize that what all are these packers. Then the alignment and straightness of the drill hole it should be measured using an orientation tool if there is any indication that the deviation is more than the permissible one or if it is in excess.

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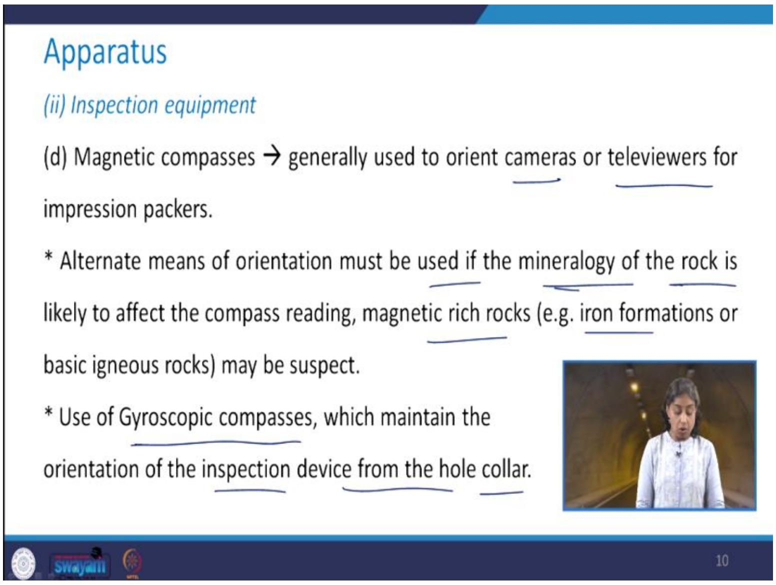

Then the next inspection equipment includes the magnetic compasses. These are generally used to orient the cameras or televiewers for impression packers. These are the alternate means of orientation must be used if the mineralogy of the rock is likely to affect the compass reading.

For example, if magnetic rich rocks are suspected then the presence of such rocks may influence the compass reading.

So, we need to have the alternate means of the orientation. So, such magnetic rich rocks may include say the iron formations or basic igneous rocks. So, the use of gyroscopic compasses which maintain the orientation of the inspection device from the hole collar.

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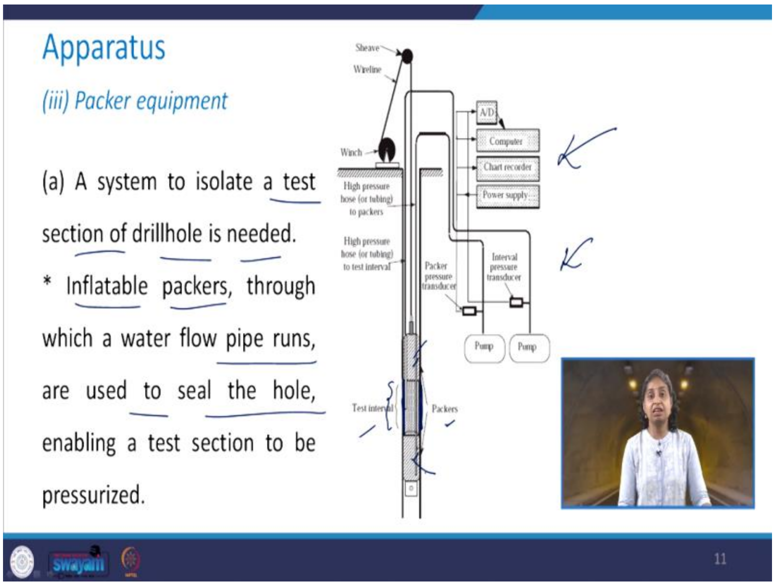

Coming to the next category of the equipment, which is the packer one extremely important as far as the hydraulic fracturing test is concerned. So, this is a system to isolate a test section of drill hole and it is essential. So, it has the inflatable packers through which water flow pipes runs, and these are used to seal the hole enabling a test section to be pressurized. So, you see that what happens is here in this figure, it is clear that we have this as the test interval, and on top and the bottom, you have the packers.

So, what happens is when the pressure is applied, there is going to be all around pressure in the drillhole and what will happen because of that. There is going to be the rupture of the borehole here in the test interval, and that rupture area may propagate in the vicinity of the rock mass or in the vicinity of this walls of the drillhole in the rock mass. So, this is how a typical test setup for the hydraulic fracturing test looks like.

Now, as far as this packer are concerned. Here you are seeing the two packers, but then single packers is also employed.

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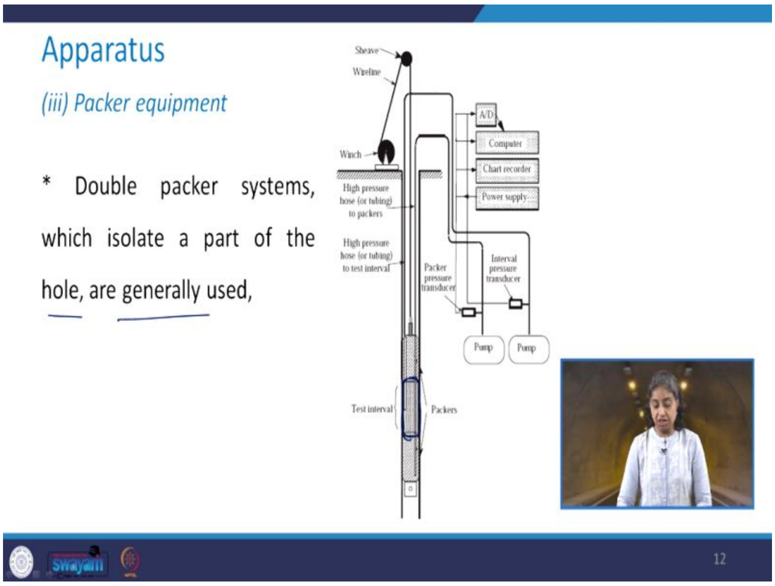

So, this is what is the double packer system, which isolate the part of the hole it is generally used. So, you see that this much part of the hole is being isolated from rest of the drill hole with the help of these double packer systems.

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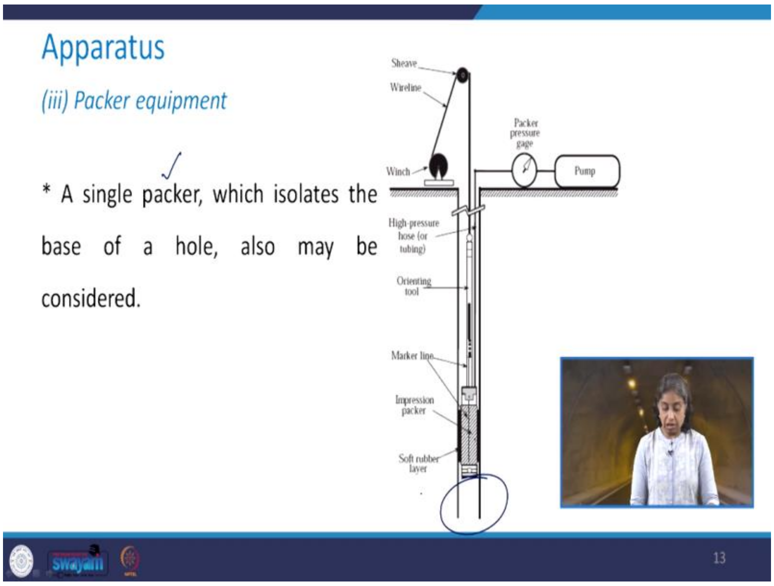

But then one can have single packer which isolates the base of the hole and this also can be considered. So, you see that here this is only one packer, so this is isolating the base of the hole here.

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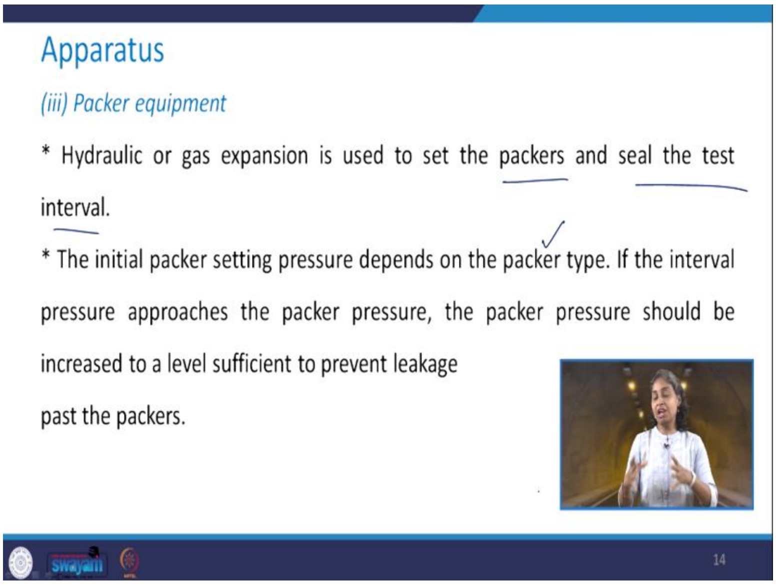

Hydraulic or gas expansion is used to set the packers and seal the test interval. The initial packer setting pressure it depends upon the type of the packer. If the interval pressure it approaches the packer pressure, the packer pressure should be increased to a level which is sufficient to prevent the leakage past the packers because what will happen because if the packers allow this leakage of the pressure to happen.

Then the test section will experience the lesser amount of pressure and then our test will not be successful.

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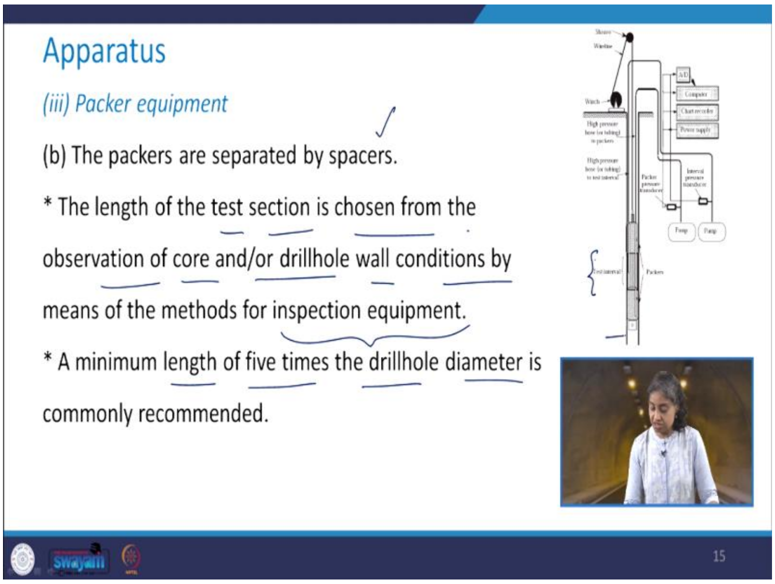

So, these packers are separated by spacers. The length of the test section is chosen from the observation of core or the drill hole wall conditions by means of the methods for inspection equipment. So, the minimum length of 5 times the drill hole diameter is commonly recommended that means the length of this it should be 5 times the drill hole diameter which is this, this is the diameter of the drillhole.

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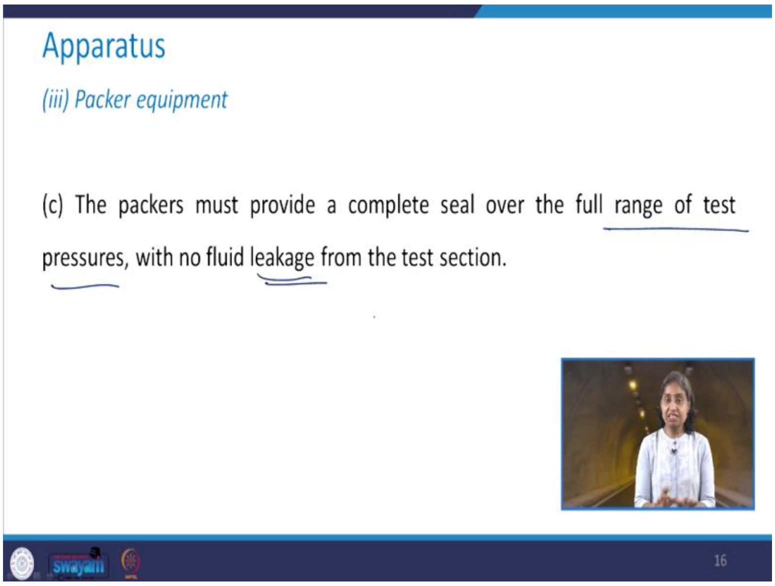

The packers must provide a complete seal over the full range of test pressure with no fluid leakage from the test section because the moment this leakage takes place, the test will not be successful.

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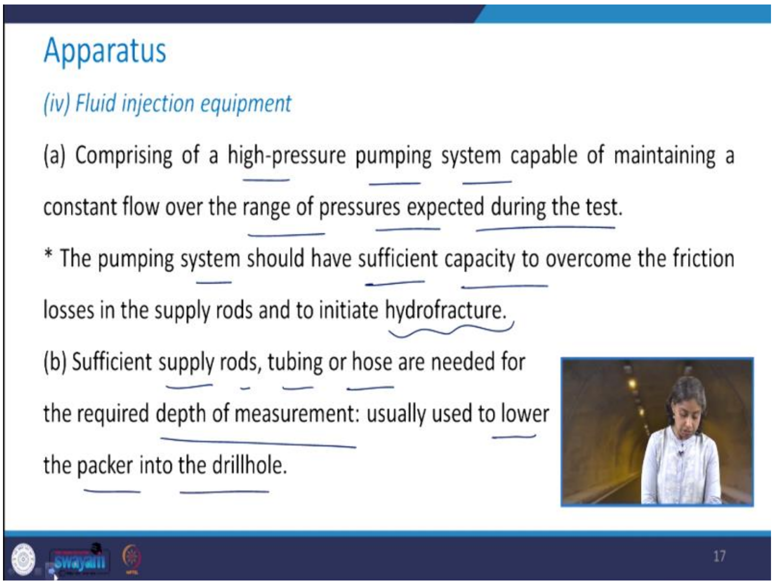

Coming to the next category of the equipment that is fluid injection equipment. So, these comprises of high-pressure pumping system which is capable of maintaining a constant flow over a range of pressures which are expected during the test. The pumping system should have sufficient capacity to overcome the friction losses in the supply rods and to initiate the hydro fracture.

See what exactly is happening. You apply the pressure and then there is going to be the initiation of the fracture because of that pressure. So, that we are calling as hydro fracture. Sufficient supply rods, tubing or hose; they are needed for the required depth of measurement which is usually used to lower the packer into the drill holes.

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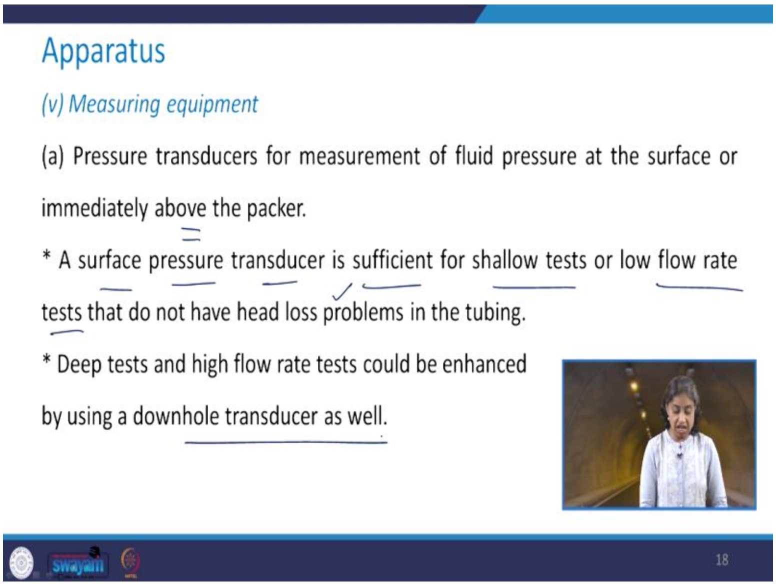

We need the measuring equipment; the first one is the pressure transducers for measurement of fluid pressure at the surface or immediately above the packer when you have the single packer system. So, a surface pressure transducer is sufficient for shallow tests or low flow rate tests which do not have the head loss problems in the tubing. Deep tests and high flow rate tests could be enhanced by using a downhole transducer as well.

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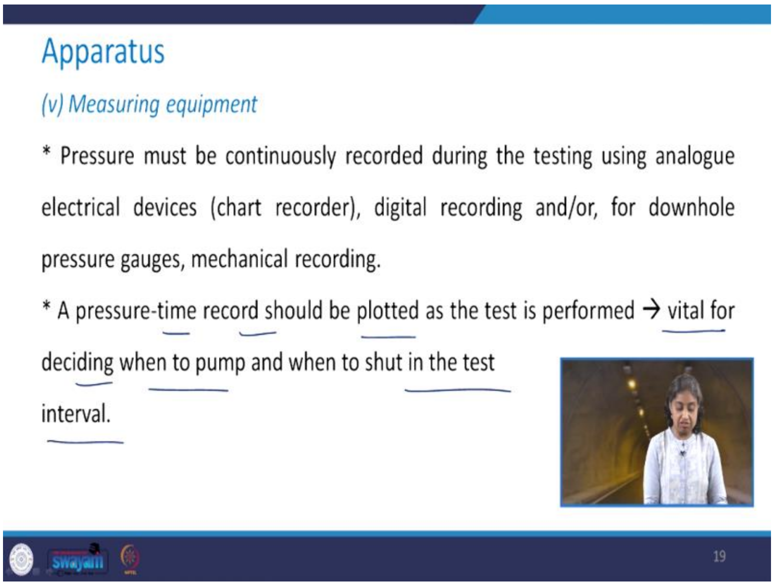

The pressure must be continuously recorded during the testing using analogue electrical devices or chart recorder, digital recording or all the downhole pressure gauges or mechanical recording. So, some of these terms we will learn when we discuss about the instrumentation and monitoring. A pressure time record should be plotted as the test is performed with respect to the time.

Pressure is recorded that means ultimately at the end you will get a plot between pressure and the time and then you have to interpret that pressure versus time record to obtain the in-situ state of stress. This is vital for deciding when to pump and when to shut in the test interval.

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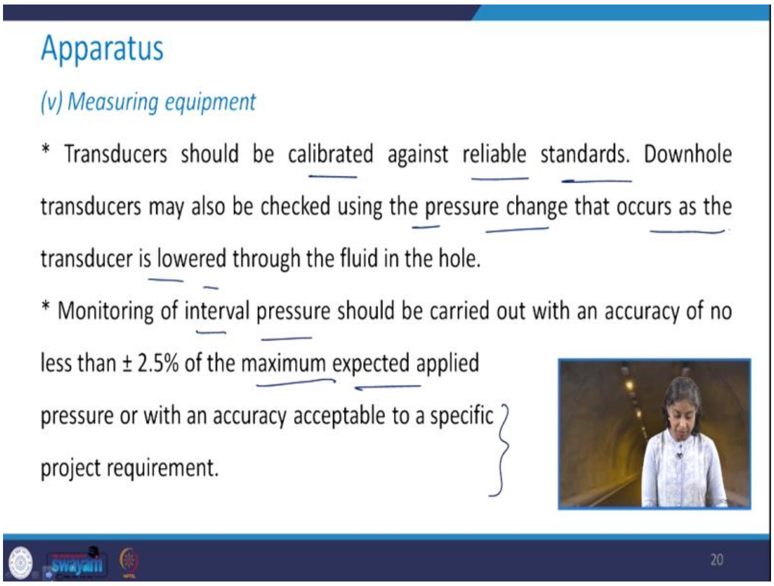

Transducers should be calibrated against reliable standards, which is the standard procedure for all such measuring equipment. The downhole transducers may also be checked using the pressure change which occurs as the transducer is lowered through the fluid in the hole. So, the monitoring of the interval pressure it should be carried out with an accuracy of no less than plus minus 2.5% of the maximum expected applied pressure or with an accuracy which is acceptable to specific project requirement.

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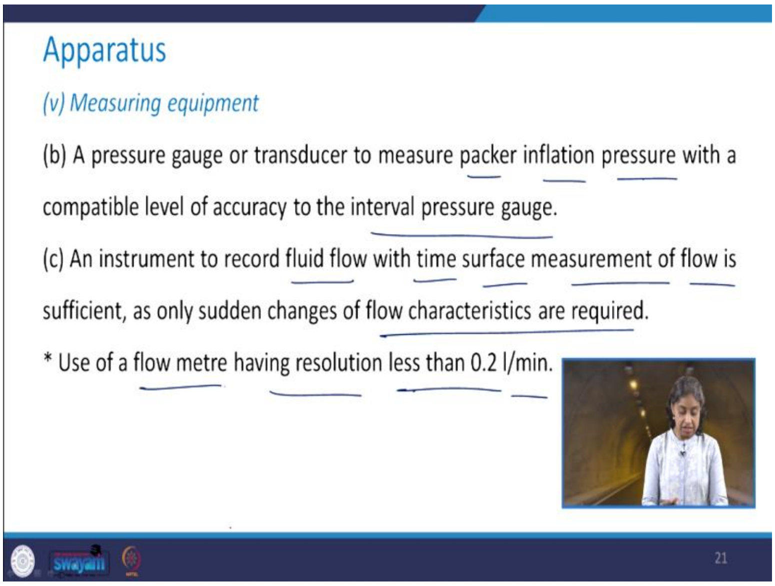

Then you need to have a pressure gauge or the transducer to measure the packer inflation pressure with a compatible level of accuracy to the interval pressure gauge and instrument is needed to record the fluid flow with time surface measurement of flow and that will be sufficient because only sudden changes of flow characteristics are required. So, use of a flow meter having resolution less than 0.2 liter per minute is recommended.

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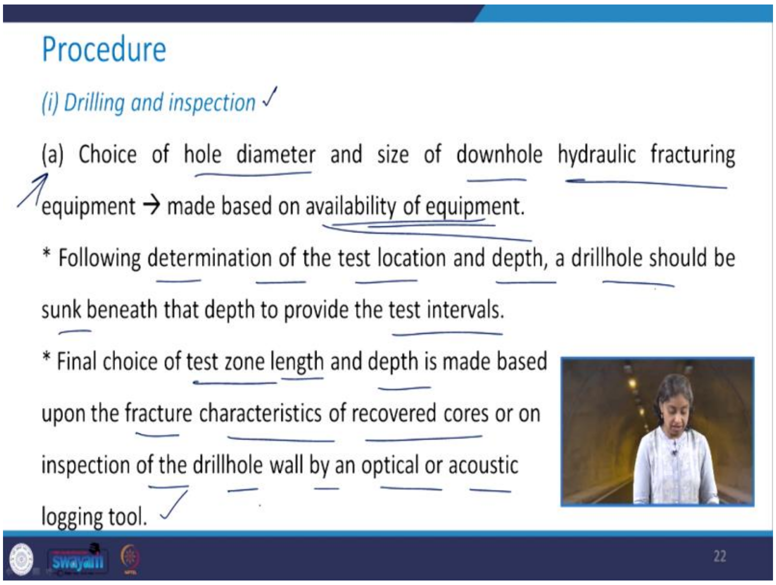

Coming to the procedure of the test. So, here we are going to discuss the step-wise activities which are to be carried out during the conduct of this test. The first one is the drilling and the inspection. In this category we have the first step as the choice of the hole diameter and the size of downhole hydraulic fracturing equipment which is made based upon the availability of the equipment.

See here this test is conducted at a deeper level from the ground surface, and therefore many things will depend upon the availability of the appropriate equipment. Following the determination of the test location and the depth a drillhole should be advanced beneath the depth to provide the test interval. So, let us say that you want to conduct the test at 75 meter. So, it should not happen that you terminate the drill hole at 75 meter only.

It should go beyond 75 meter so that test intervals can be provided. The final choice of the test zone length and the depth is made based upon the fracture characteristics of the recovered cores and or on the inspection of the drillhole walls by an optical or acoustic logging tool. So, in this case, if let us say you could not recover the core or you could not get the idea about the fracture characteristics then maybe we lower camera inside the drillhole. And that keeps sending the signal at the top which is connected with the system.

So, using that and there are many tools which can analyze those signals that is sent by that particular camera to give us the idea about the fracture characteristics, and therefore it helps in deciding the test zone length and the depth.

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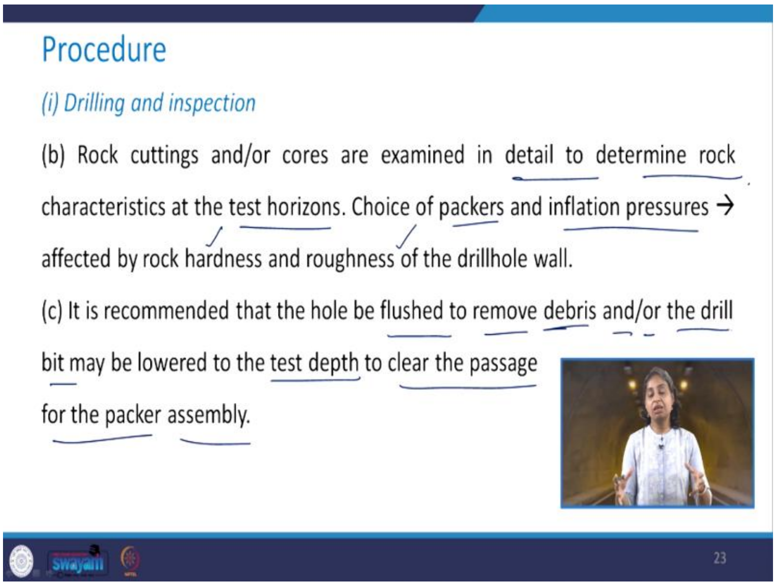

Then the rock cutting or cores or both these are examined in detail to determine the rock characteristics at the test horizons. The choice of the packers and inflation pressure these are affected by the rock hardness and roughness of the drillhole walls. It is recommended that the drill hole be flushed to remove debris and or the drill bit, which may be lowered to the test depth to clear the passage for the packer assembly.

See, sometimes this happens that you lower the camera or you lower this test assembly, and the borehole walls collapses. So, all these things we need to be extremely careful so that is why it is written that the hole should be flushed to remove the debris completely so that packer assembly can be lowered to the test depth.

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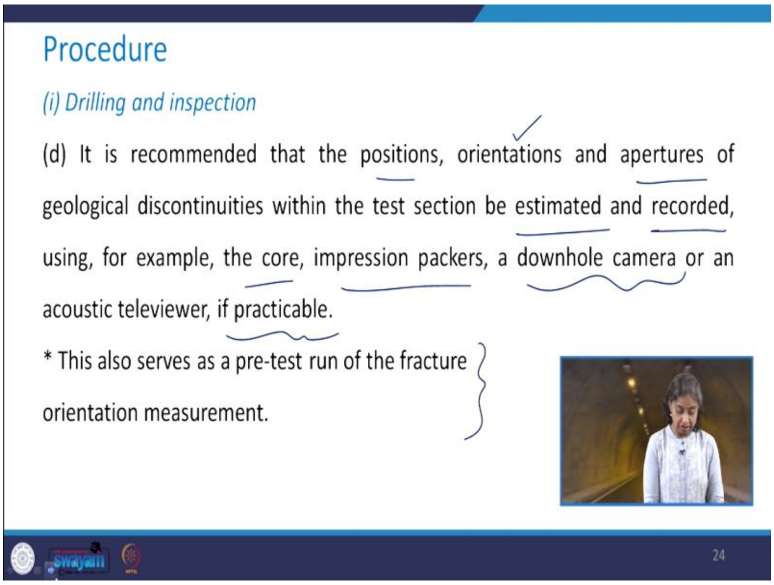

Then it is recommended that the positions, orientations and apertures of the geological discontinuities within the test section be estimated and recorded using, let us say, for example the core, impression packers or a downhole camera or an acoustic televiewer whatever is practicable. This also serves as a pre-test run of the fracture orientation measurement.

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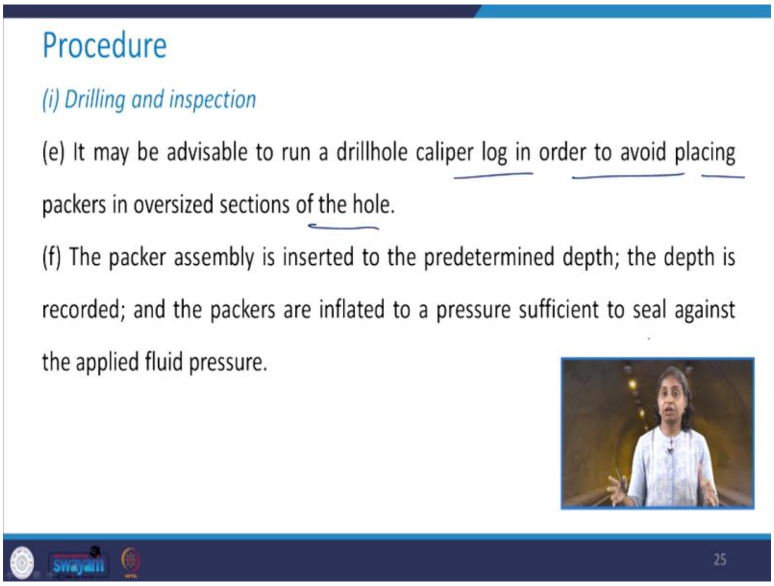

It may be advisable to run drillhole caliper log in order to avoid a placing packer in the oversized sections of the hole. The packer assembly is then inserted to the predetermined depth that depth is recorded, and the packers are inflated to a packer sufficient to seal against the applied fluid pressure.

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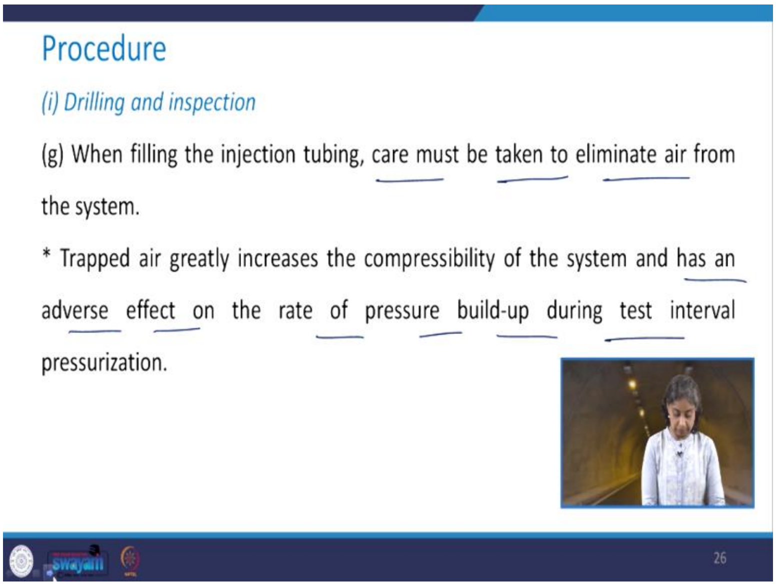

When filling of the injection tube is there then care must be taken to eliminate air from the system. Trapped air generally increases the compressibility of the system significantly, and it has an adverse effect on the rate of the pressure building up during the test interval pressurization.

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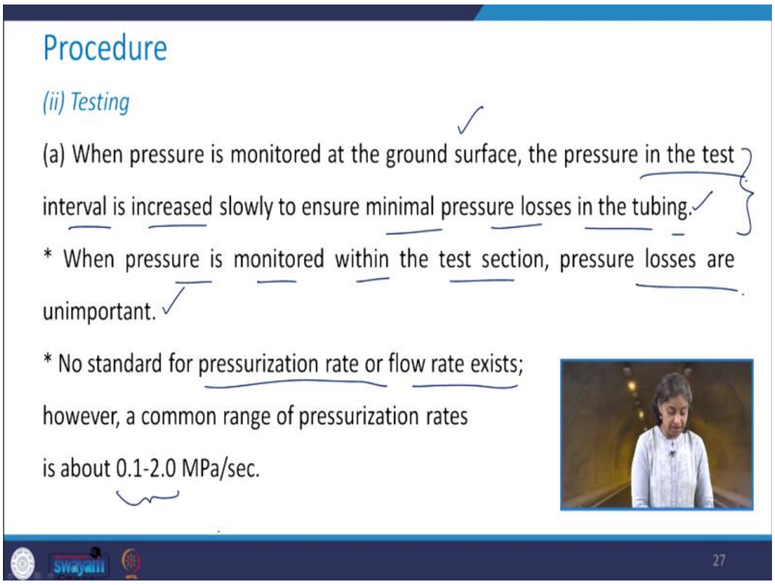

Coming to the testing part, once we decide the location of the test and prepare with the packer. When the pressure is monitored at the ground surface the pressure in the test interval is increased slowly to ensure minimum pressure losses in the tubing. So, if this is increased at a faster rate, there will be more losses in the tubing, and whatever pressure is desire to mobilize at the test location will not be done.

So, when the pressure is monitored within the test location, the pressure losses are unimportant, but then if it is monitored at the ground surface, we need to keep this in mind. No standard for pressurization rate or flow rate exists. However, the common range of this rate is about 0.1 to 2.0 MegaPascal per second.

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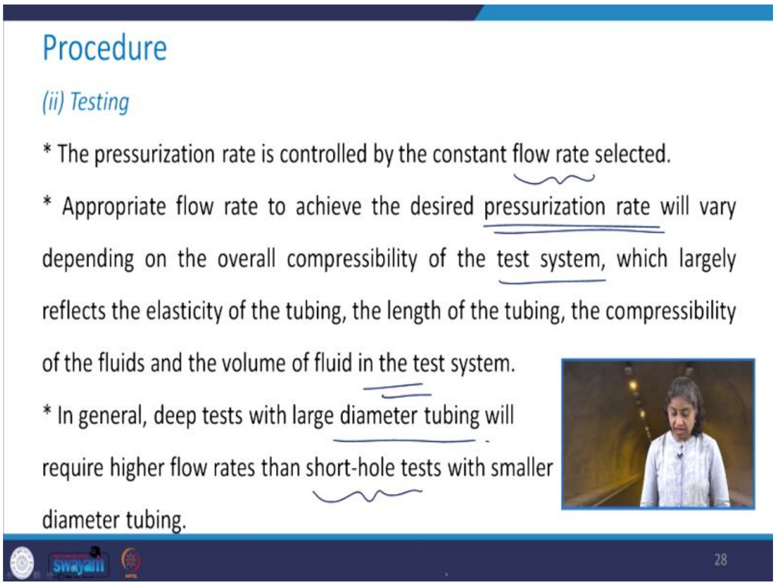

The pressurization rate is controlled by the constant flow rate which is selected. Appropriate flow rate to achieve the desired pressurization rate will vary, and it will depend on the overall compressibility of the test system, which largely reflects the elasticity of the tubing, the length of the tubing, the compressibility of the fluid, and the volume of the fluid in the test system. So, in general, deep test with the large diameter tubing will need higher flow rates as compared to the short-hole test with smaller-diameter tubing.

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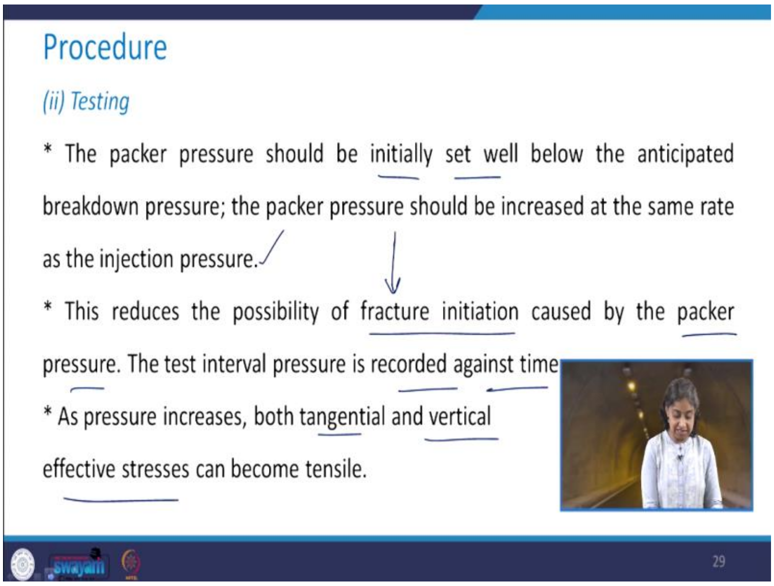

The packer pressure should be initially set well below the anticipated breakdown pressure. Packer pressure should then be increased at the same rate as the injection pressure. By doing so, we reduce the possibility of fracture initialization which is caused by the packer pressure.

See, we need to create the fracture by the injection pressure and not by the packer pressure. The test interval pressure is recorded against the time as this pressure increases both the tangential as well as the vertical effective stresses.

They can become tensile because you see it is a drillhole, and you have a tube which is packed from both the sides. So, the test section, when you apply the injection pressure it exerts the hydrostatic pressure to the walls of the drillhole, and therefore both the tangential and the vertical effective stresses can become tensile.

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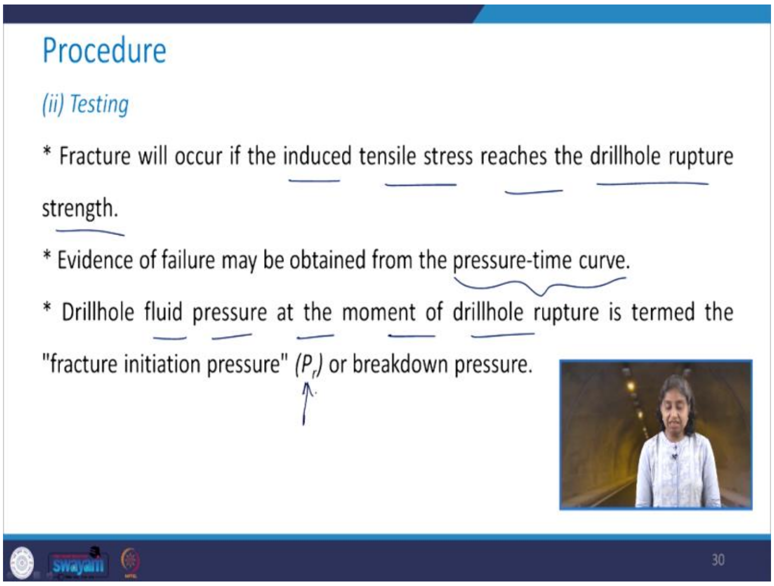

The fracture will occur if the induced tensile stress reaches the drillhole rupture strength. How to identify the failure? So, this will be done from the pressure-time curve. What we will do is we will take a typical result of the hydraulic fracturing test in terms of the pressure time curve, and with the help of that I will explain you that where this failure is observed. So, the drill hole fluid pressure at the moment of drillhole rupture is termed as fracture initiation pressure or breakdown pressure, this we are representing by P_r.

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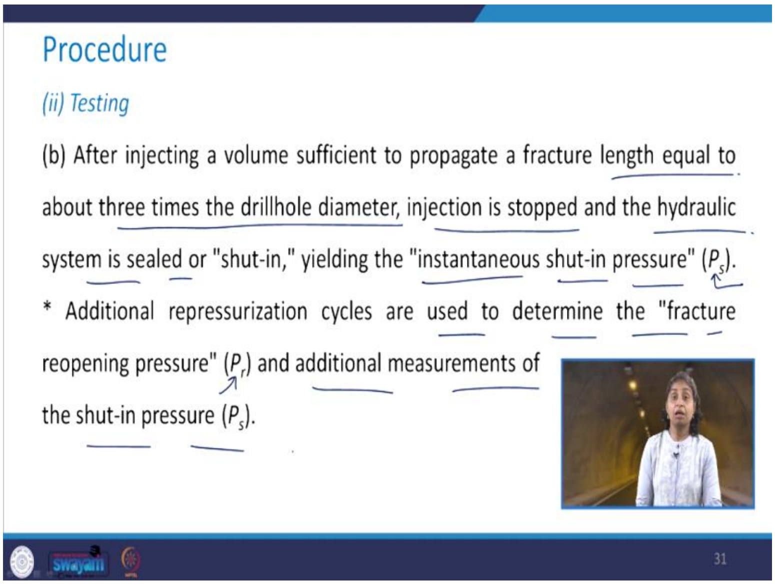

After injecting a volume which is sufficient to propagate length equal to about 3 times the drillhole diameter the injection is stopped, and the hydraulic system is sealed or shut in yielding the instantaneous shut-in pressure. So, this is another pressure different than the breakdown pressure and this we are representing by P_s. Then we have the re-pressure cycles. So, these are used to determine the fracture reopening pressure which is represented by P_r, and the additional measurements of the shut-in pressure P_s.

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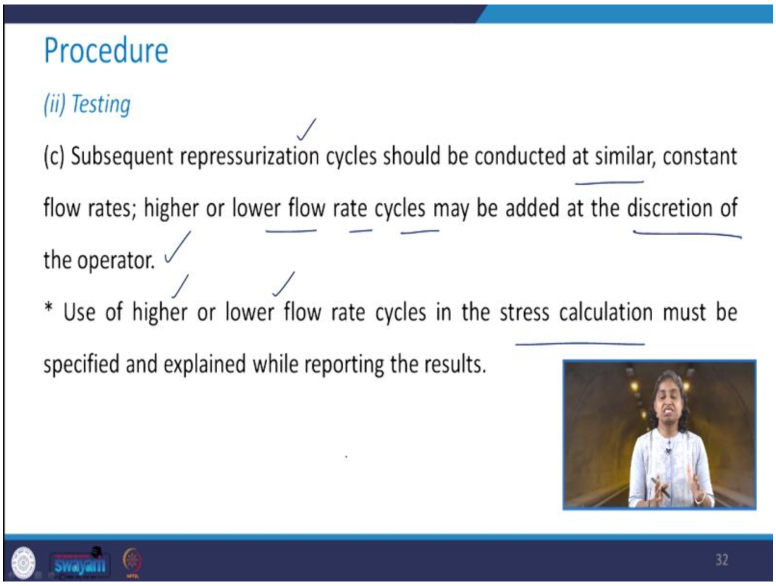

So, what will happen with this subsequent repressurization cycles so these should be conducted at similar constant flow rates higher or lower flow rate cycles may be added at the discretion of the operator. Use of higher or the lower flow rate cycles in the stress calculation these must be specified and explained while you report the test results.

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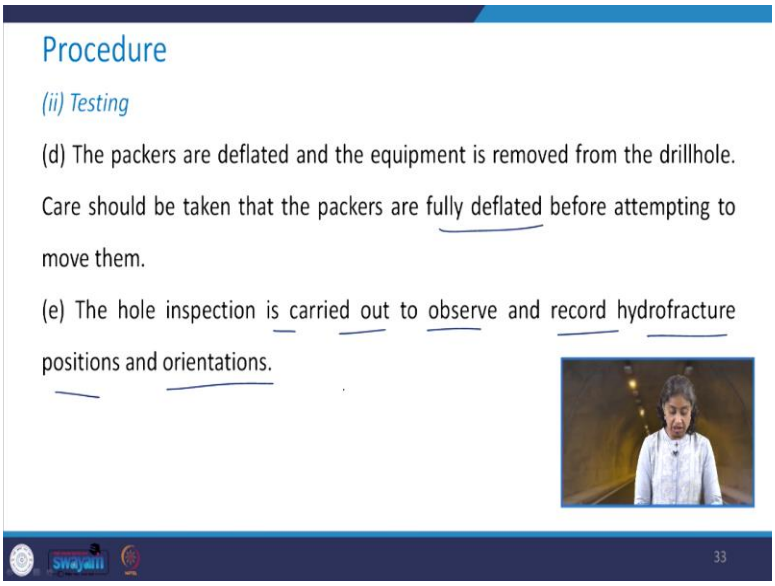

What happens then the packers are deflated once the fracturing has taken place then the packers are deflated, and the equipment is removed from the drillhole. The care should be taken so that the packers are fully deflated before attempting to move them because if they are not fully deflated, it will be very difficult to retrieve them or remove them. The hole inspection is carried out to observe and record the hydro fracture position and the orientation after the conduct of the test.

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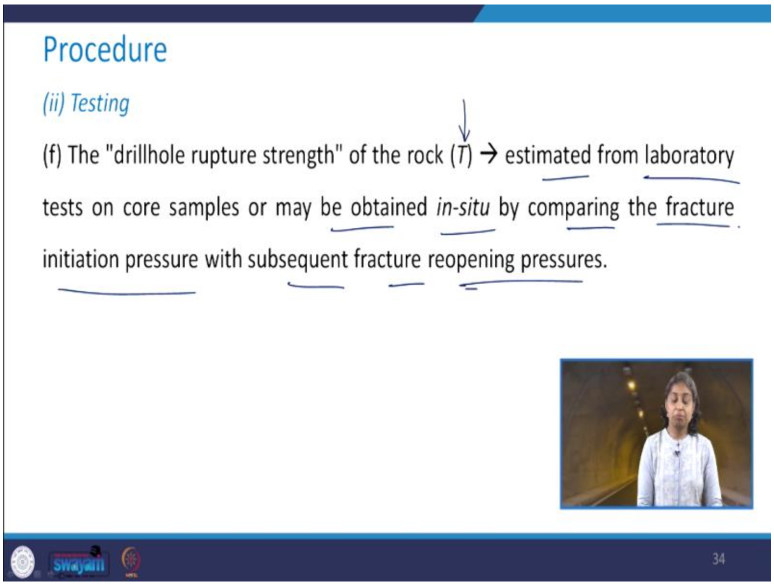

The drill hole rupture strength of the rock which is represented by capital T is estimated from the lab test on core samples or it may be obtained in-situ that is in field by comparing the fracture initiation pressure with the subsequent fracture reopening pressures.

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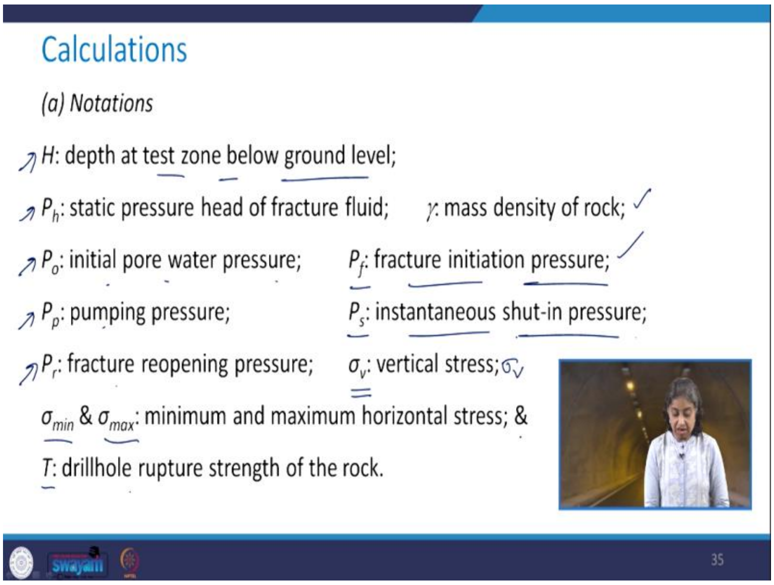

Now, we have some notations, and then I will show you with the help of a figure, that how a typical pressure time result or the plot looks like as the result of the hydraulic fracturing test. So, as far as calculations are concerned first, we take a note of various notations that are being used. So, H is the depth at the test zone below the ground level, P_h is the static pressure head of the fracture fluid, P_0 is the initial pore water pressure, P_p is the pumping pressure.

P_r is the fracture reopening pressure, then we have γ as the mass density of rock, P_f be the fracture initiation pressure. I just explained you the definition of these pressures. P_s be the instantaneous shut-in pressure and σ_v be the vertical stress, sigma minimum and sigma maximum they are minimum and maximum horizontal stresses. See vertical stress we are representing using σ_v and sigma minimum and sigma maximum; they both are horizontal stresses, and T be the drillhole rupture strength of the rock.

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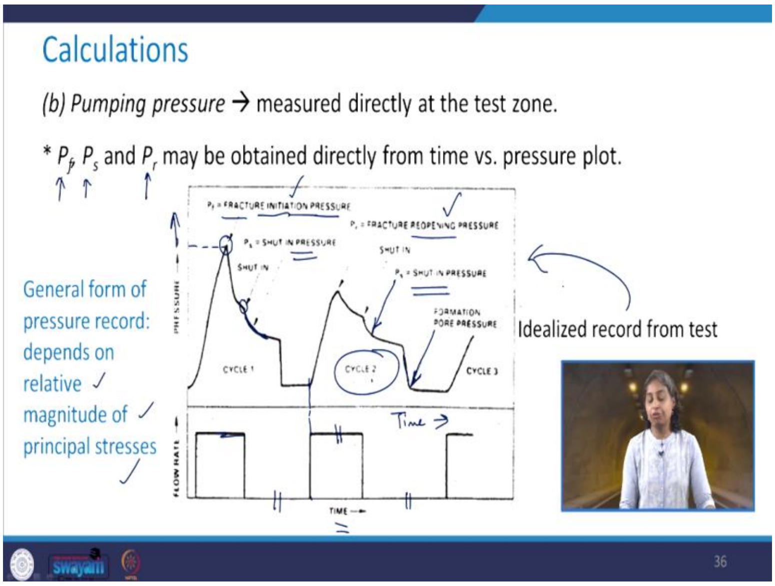

So, this is how the typical pressure record looks like, and it depends on the relative magnitude of the principal stresses. So, this is the idealized record from the test. See here this is what is the flow rate and the time. So, you see with time, here is the maximum flow rate, and then this is shut down period, then again, another cycle further shut down and then the cycle third is starting.

So, again here on this scale, we have time and this is what is the pressure, so you see first the pressure is applied, and then you have the first peak where the fracture initiation starts. So, the pressure which is called as the fracture initiation pressure, and then there is the reduction. So, here we have the shut-in, and the next one in this zone we will have the shut-in pressure which is P_s and then once we start loading it again, you see from here.

So, here we will get the next fracture reopening pressure for the cycle too. So, it will no more be called as fracture initiation pressure initiation because that is going is going to be always respective to the first cycle. In the second cycles all you have is the fracture reopening pressure, and of course, you will get the shut-in pressure which is this one in the cycle two, and then there is going to be the formation of the pore pressure at this location.

And then the cycle is continued. So, basically, we can determine P_f, P_s, and P_r directly from the time versus the pressure plot.

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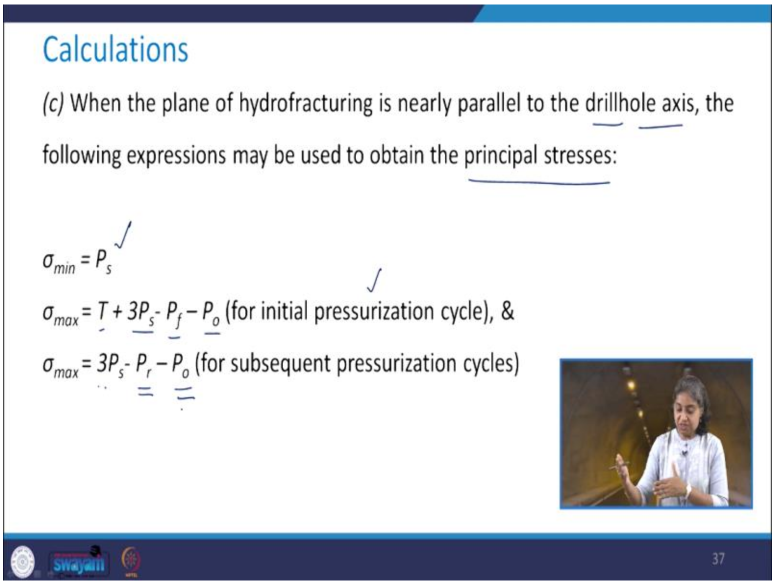

And when the plane of hydrofracturing is nearly parallel to the drillhole axis, the following expressions may be used to obtain the principal stresses:

$$\sigma_{min} = P_s$$

$$\sigma_{min} = T + 3P_s - P_f - P_o \ (for\ initial\ pressurization\ cycle)$$

$$\sigma_{min} = 3P_s - P_r - P_o \ (for\ subsequent\ pressurization\ cycles)$$

I mentioned to you that we have first the loading and then there is going to be the shut-in pressure, and then we have the next cycle. So, for the subsequent cycles, you have to apply this particular expression.

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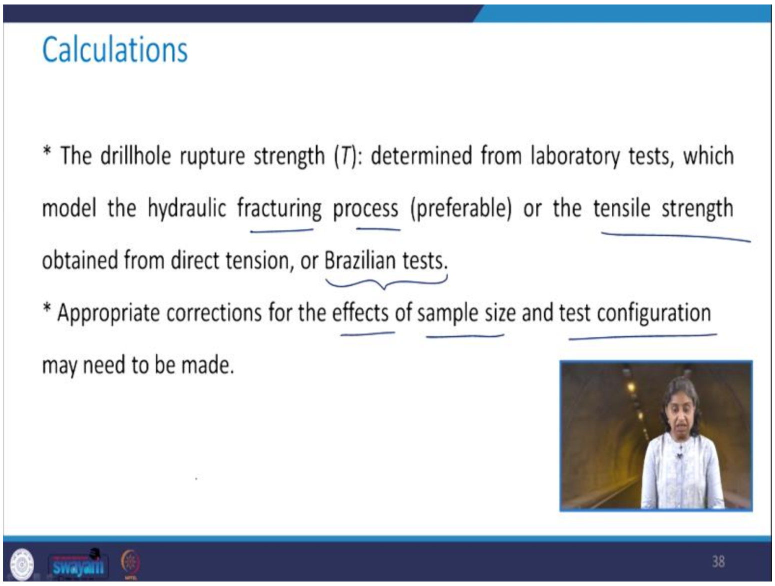

Coming to the drill hole ruptures strength T; this can be determined from the laboratory test, which model the hydraulic fracturing process preferably or the tensile strength test, which can be carried out in the direct mode or the indirect mode. You know that one of the indirect tensile strength test is the Brazilian test. The appropriate corrections for the effects of sample size and the test configuration may need to be made when the calculations are carried out.

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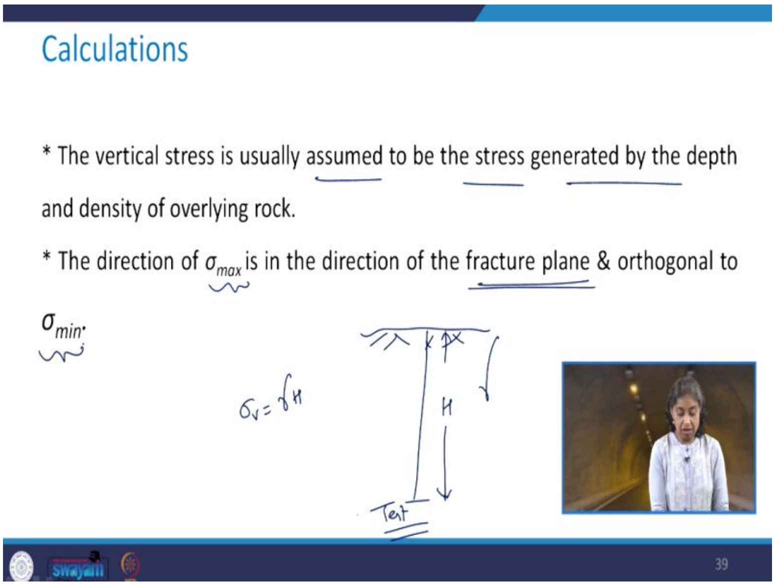

The vertical stress is usually assumed to be the stress which is generated by the depth and the density of the overlying rock. So, as I mentioned to you that let us say this is the rock surface and below that at say H, you are conducting the test. So, the test location is here. So, γ be the unit weight. So, you will have here the vertical stress σ_v as γ into H. The direction of for σ_{max} is in the direction of the fracture plane, and it is orthogonal to σ_{min}.

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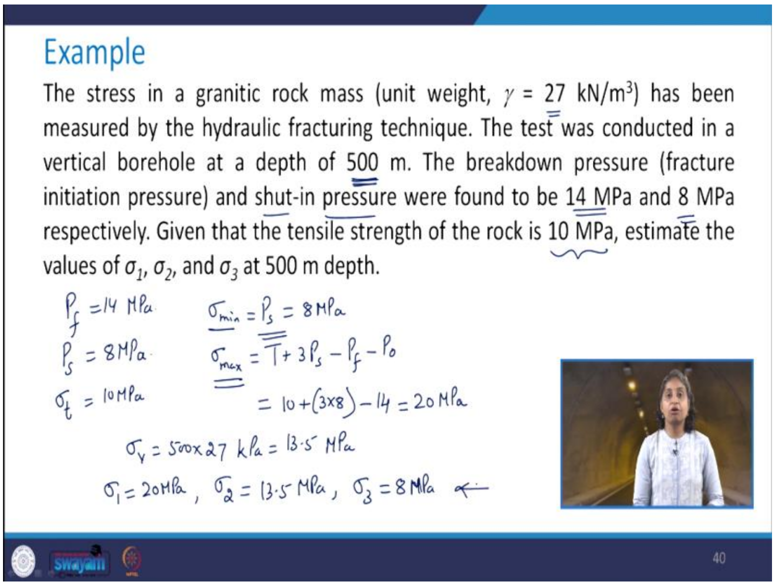

So, let us take an example and let us try to understand how we can find out the in-situ state of stress using the test data from the hydraulic fracturing technique. So, here is the statement of a problem where the unit weight of the rock mass is given as 27 kiloNewton per meter cube, and the test was conducted in a vertical borehole at the depth of 500 meters, and the breakdown pressure or the fracture initiation pressure was 14 MPa, and the shut-in pressure was 8 MPa.

The tensile strength of the rock is given to be 10 MPa, and we need to estimate the values of the principal stress's σ_1, σ_2, and σ_3 at the depth where we conducted the test, which is the 500 meter. So, we have this depth as the 500 meter then the breakdown pressure or the fracture initiation pressure is 14 MPa. So, basically this is P_f which is 14 MPa then we have the shut-in pressure as 8 MPa.

So, we have P_s equal to 8 MPa, and the tensile strength of the rock is 10 MPa, so sigma T is 10 MPa. So, basically as I explained you just now, this σ_{min} is going to be equal to P_s which is equal to 8 MPa, and in this case, your σ_{max} is going to be the first cycle. So, this is $T + 3P_s – P_f – P_0$. So, this is going to be 10 + 3 into 8 – 14, which is equal to 20 MPa.

Now, since γ is 27 kiloNewton per meter cube. So, what we will have is σ_v will be equal to 500 into 27 this is going to be kiloPascal. So, this we can write as 13.5 MegaPascal, and therefore what we will have is as the σ_1 = 20 MPa because it is the maximum one, then we have σ_2 equal to 13.5 MPa and of course because σ_{min} is equal to P s so this is going to become equal to σ_3 that is 8 MPa.

So, this is how we can analyze the data of the hydraulic fracturing test to obtain the in-situ state of stress in the rock mass.

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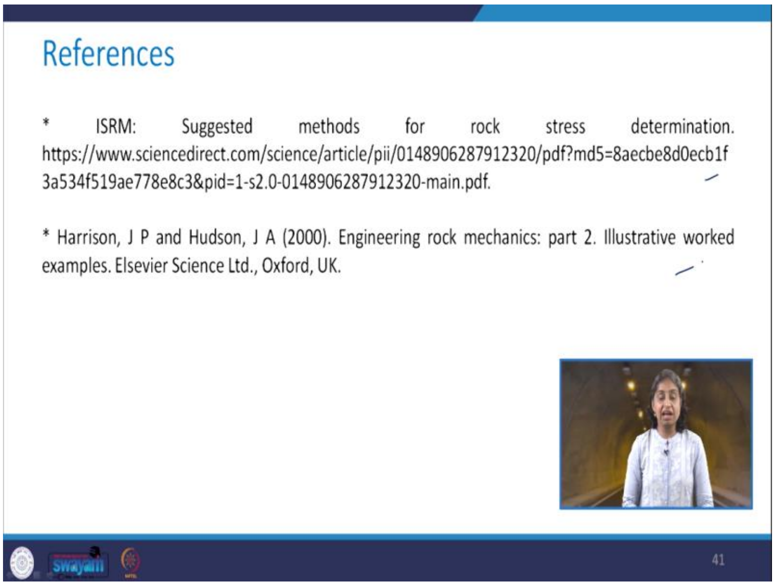

So, the references that we used here are listed here in this slide. So, we discussed about the hydraulic fracturing test to determine the in-situ state of stress in the rock mass. So, this finishes our discussion on the determination of the in-situ stresses in the rock mass. In the next class, we will discuss about the aspects related to instrumentation and monitoring of underground excavations. Thank you very much.