Underground Space Technology
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Lecture – 56
Rock Stress Determination Flat Jack Test

Hello everyone. In the previous class, we discussed about the support system, and to be specific we discussed grouting in rocks. So, today we will have the discussion on new topic, that is the determination of in situ state of stress in rock masses and rocks. So, in this connection, we will first take up the test which is called as flat jack test. So, first we will discuss few aspects related to in situ stresses.

And then, we will learn about this test, including the apparatus, how this is carried out, and then how the analysis of the test strata is done to obtain the in-situ state of stress. So, coming to the in-situ stress, we know that the underground rock masses these are subjected to the compressive stresses, which generally increase with depth.

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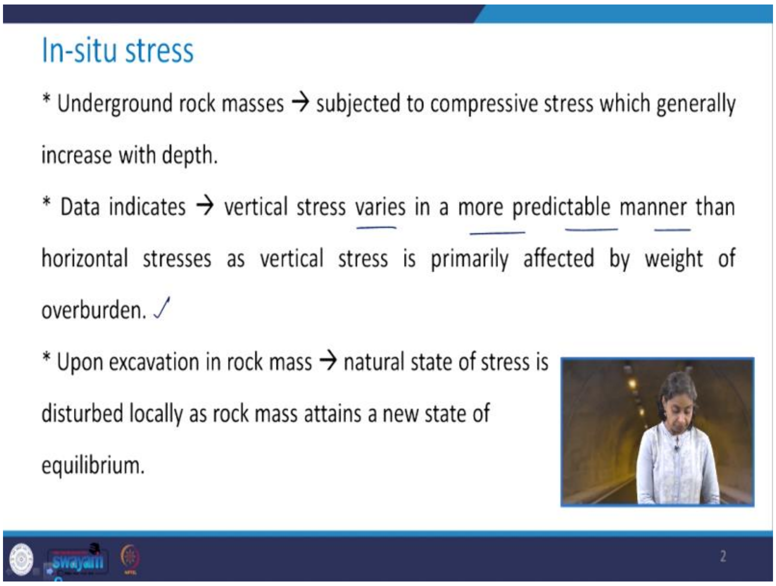

The data that we have over a period of many years it indicates that the vertical stress it varies in a more predicable manner as compared to the horizontal stresses. As the vertical stress is primarily affected by the weight of the overburden, while the horizontal stresses can be the function of various tectonic activities as well. So, upon the excavation in the rock mass, what happens is the natural state of stress gets disturbed locally because of the fact that rock mass attains a new state of equilibrium.

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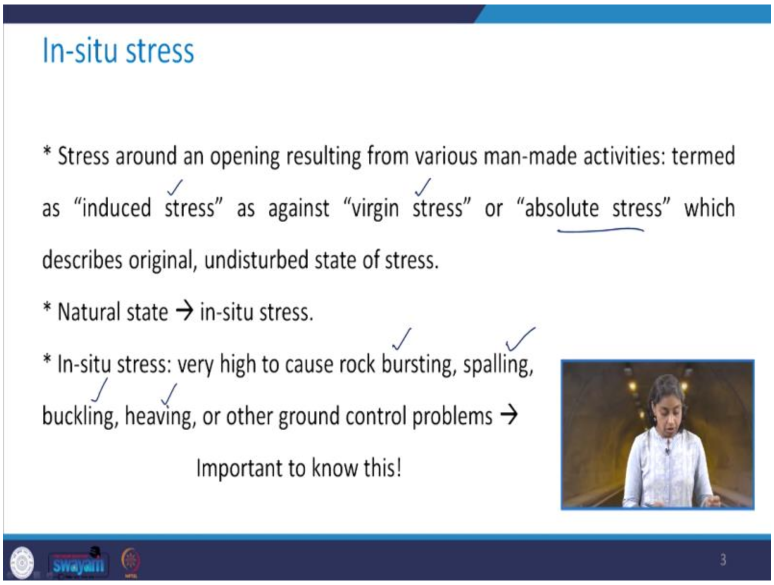

So, the stress around the opening resulting from various manmade activities is termed as induced stress as against the virgin stress or the absolute stress, which describes the original and undisturbed state of stress. The natural state of stress is what we call as in situ stress. So, these stresses can be very high to cause the rock bursting, spalling, buckling, heaving, or other ground control problems.

So, it is extremely important for us to know what exactly is the in-situ state of stress at any particular location in the rock mass.

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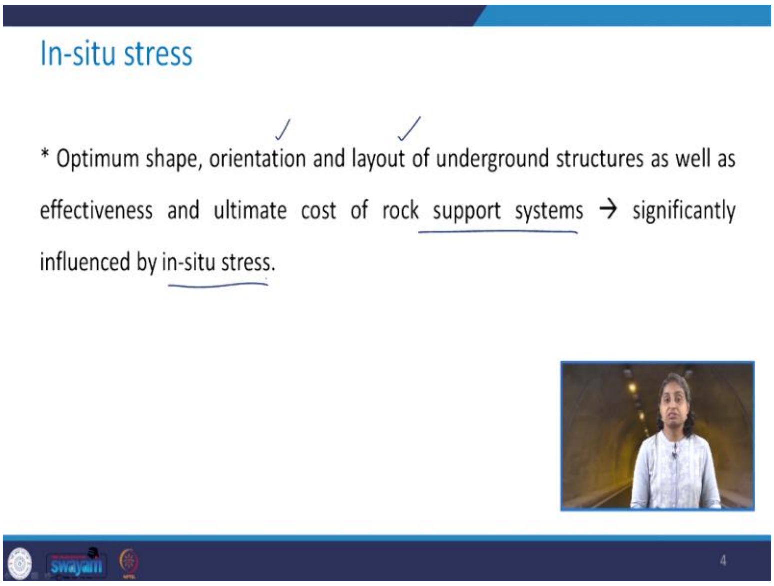

So, optimum shape, orientation, and layout of underground structures as well as the effectiveness and ultimate cost of rock support system. These are all significantly influenced by the magnitude of in situ stresses.

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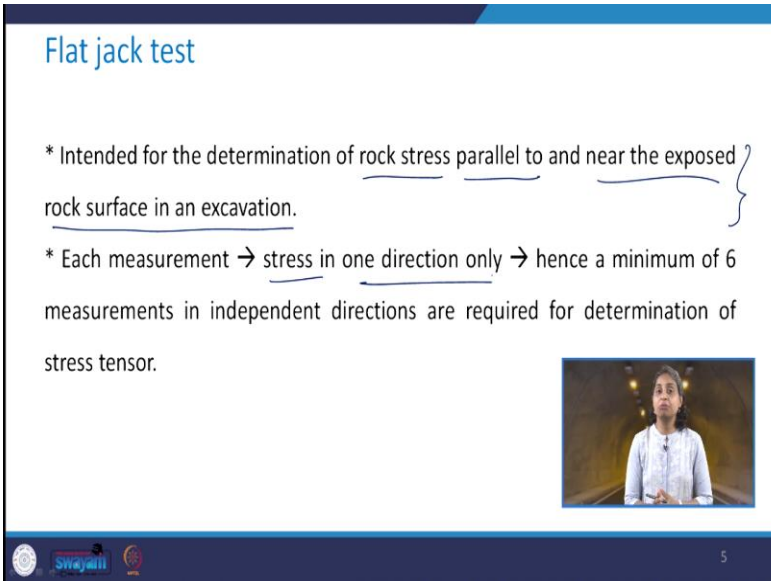

So, important for us to know the in-situ stresses. So, for that purpose, we have one test called flat jack test with us apart from the other test that is hydraulic fracturing test, that we will discuss later. So, this flat jack test is intended for the determination of rock stress parallel to and near the exposed rock surface in an excavation. Please keep that in mind that if we are conducting the flat jack test, this is what that we are going to get is the rock stress which is parallel to and near the exposed rock surface in an excavation.

Each measurement that is done during the flat jack testing gives us the stress in one direction only, and therefore to obtain the complete stress tensor, we need to have a minimum to 6 measurements in independent directions.

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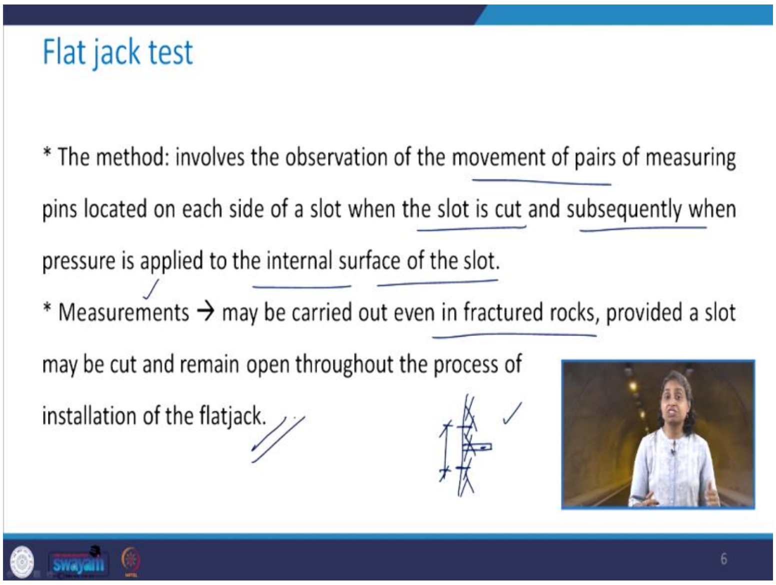

This method involves the observation of the movement of pairs of measuring pins which are located on each side of a slot when the slot is cut. So, basically let us say that this is what is the rock mass, and then we have the two pins say this one and this one, and there we need to cut a slot in between these pins like this to conduct the test and then what is done when this slot is cut what will happen.

There is going to be separation because of this slot and that will become the stress-free boundary, and there is going to be the redistribution of stresses. So, what we do is we put the flat jack in this slot, and then it is pushed so that this distance between the measuring pins is already known to us. So, the pressure that is required so that the distance between the pins they are maintained is what indirectly will give us the in-situ state of stress.

How we will see basically this is what is a philosophy of this particular test. So, when the slot is cut and then subsequently when the pressure is applied to the internal surface of the slot. How it is done, we will see. So, the measurements which are taken these can be carried out even in fractured rocks provided that in the fractured rock, it is possible to cut the slot and to have it open throughout the process of installation of the flat jack, which is done inside this particular cut.

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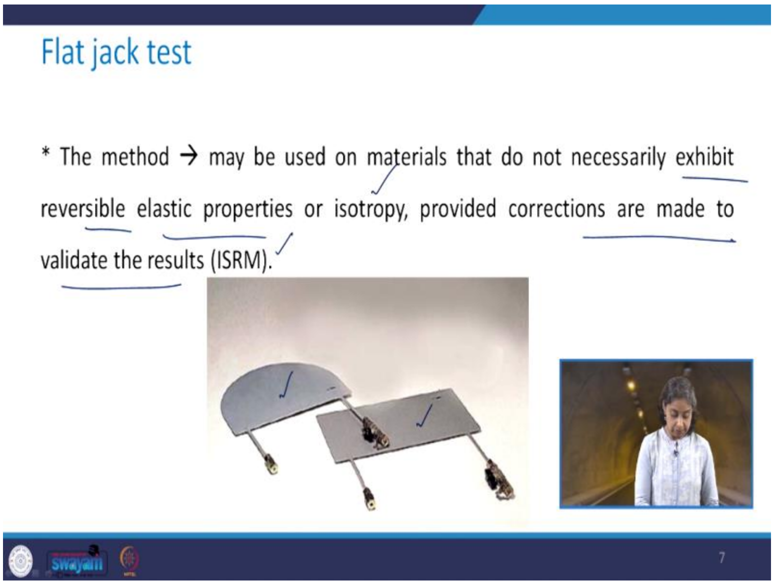

The method may be used on the materials that do not really exhibit reversible elastic properties or isotropy, provided the corrections which are made to validate the results this is as per ISRM. So, here is we are seeing the two flat jacks of two different shapes. So, you can see that why it is called as flat jack. So, it is kind of a flat plate here.

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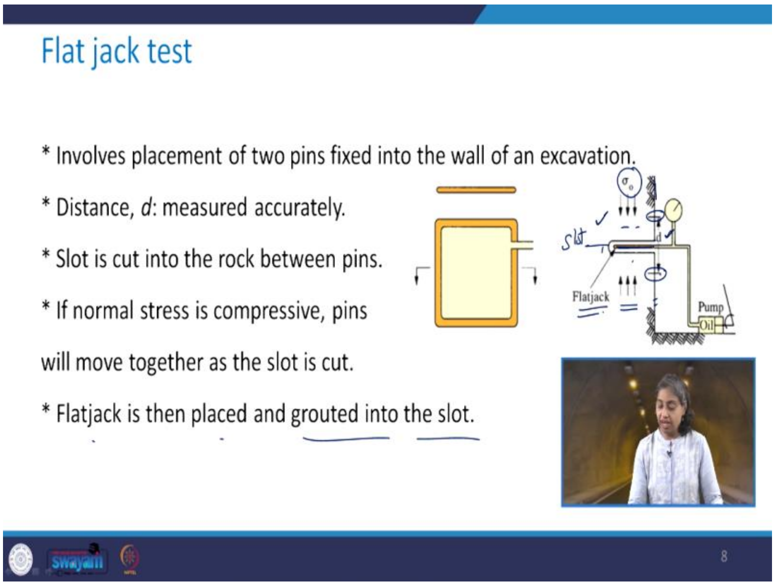

Flat jack test let us again understand the philosophy with the help of these figures. So, basically this test involves the placement of two pins which are fixed into the wall of an excavation. So, you see that if this is the wall of the excavation, two pins are fixed at a distance of d from each other. This distance d it can be measured accurately how the distances are measured etcetera that we will see little later when we discuss about the instrumentation and monitoring.

Then the slot is cut into the rock between the pins. So, you can see that this is what is the rock mass, and sigma0 is the in-situ state of stress vertical stress here. So, this is the slot which is cut between these pins. So, if the normal stress is compressive, which is shown in this particular figure, what will happen the moment you cut the slot the pins will start moving together.

They will try to close the slot because there is going to be the redistribution of stresses in the vicinity of this slot. So, what happens? Then we place the flat jack and grout it into the slot. So, you can see that this yellow portion this is what is the flat jack.

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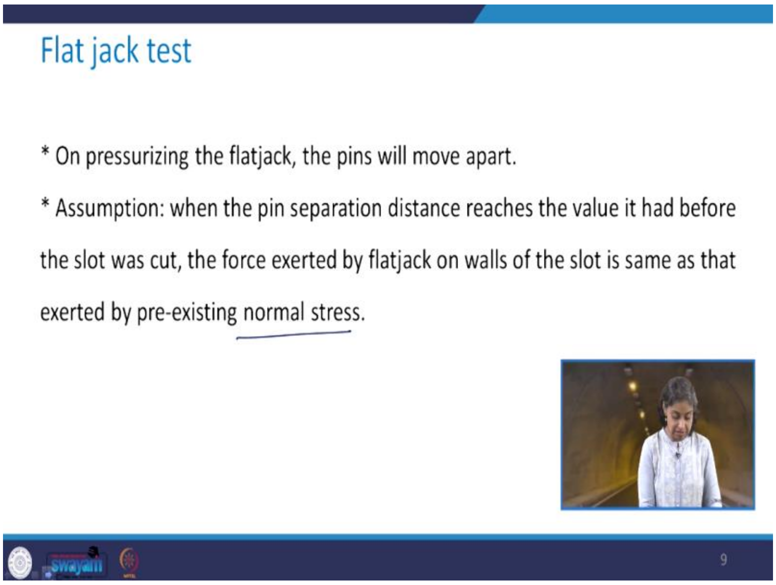

Now, on pressurizing the flat jack the pins will move apart, and we have an assumption here in this test that when the pin separation distance it reaches the value it had before the slot was cut. The force which is exerted by the flat jack on the walls of the slot is same as that was exerted by pre-existing normal stress. So, you see what happens we cut a slot we provide a flat jack test. So, when we cut the slot, this start coming together.

So, when we provide the flat jack then this exert the pressure on the inside walls of the slot such that the pressure which is exerted by the flat jack to have the same pin separation distance which was earlier before the slot was cut. When they achieve the same distance again so whatever is the force which is exerted by the flat jack on the walls of the slot, it is going to be the same as that exerted by pre-existing normal stress.

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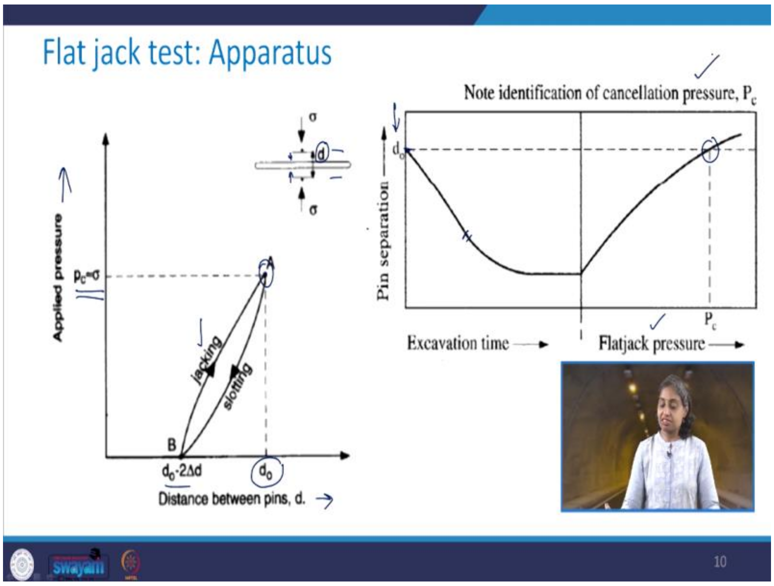

So, this is how the typical results of a flat jack test look like. So, we have the distance between the pins and the applied pressure. So, during the jacking and then the slotting; in the slotting what will happen? When you create the slot, the distance will be reduced. So, you see that if the distance between the two pins is d which is shown here. So, when the slotting is done, this will be reduced.

This pin and this one they will move towards each other, and when we start applying the pressure to the flat jack that means the process of jacking. So, we keep on increasing the pressure till the time that we receive, or we get the earlier distance between the pins, which is let us say d 0. So, this one is what is going to be equal to the in-situ state of stress which is given here as $p_c = \sigma$.

So, you see that the pin separation, in the beginning, it was d_0, and with the excavation it reduces and then you install the flat jack, and you start applying the flat jack pressure, and when you apply that pressure again, that pin separation starts increasing and then the moment it goes or it becomes equal to the earlier pin separation before the slot cutting that is what is going to be the identification for the cancellation pressure which we represent as p_c.

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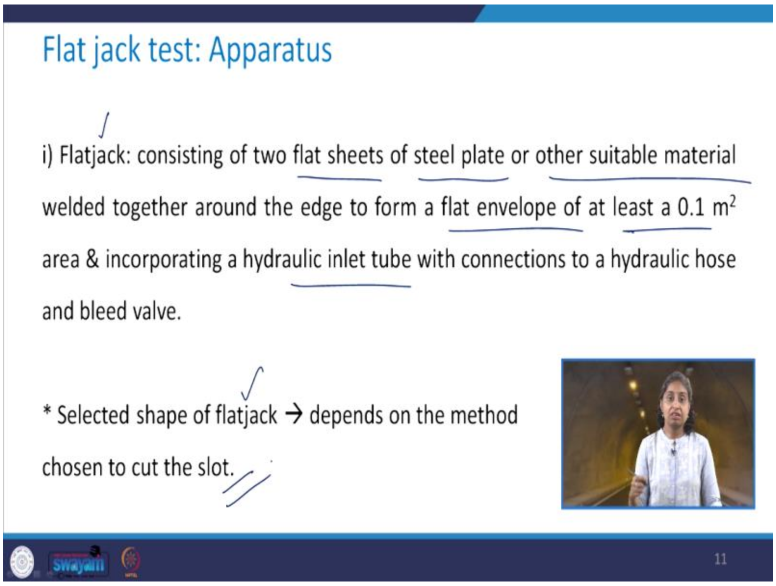

Coming to the apparatus, as far as flat jack test is concerned, it is comprising of many components. The first and the foremost, and most important one is the flat jack. It consists of two flat sheets of steel plate or any other suitable material which are welded together around the edge to form a flat envelope of at least 0.1-meter square area, and these also incorporate hydraulic inlet tube with connection to hydraulic hose and bleed valve because these jacks are supposed to exert the pressure on the inner wall of the slots.

So, that pressure is being mobilized with the help of hydraulic pump. So, accordingly such arrangements are to be needed. I showed you the picture of a typical flat jack just short while ago. So, selected shape of the flat jack depends upon the methods which is chosen to cut the slot. So, I showed you one was d shaped flat jack, another one was the rectangular shape of the flat jack.

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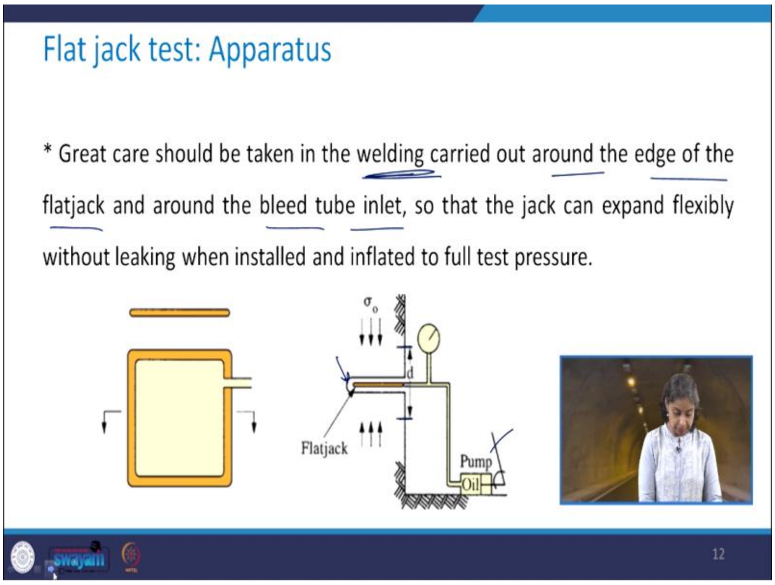

Here one needs to take lot of care in welding, which is carried out around the edge of the flat jack and around the bleed tube inlet so that the jack can expand flexibly without leaking when it is installed and inflated to full pressure test. So, you take a look here again. These are the two pins the slot is cut, flat jack is installed, and you can see that the pump is there with the help of which you mobilize the pressure.

The moment the pressure comes here, this inflates. So, we need to be careful about the welding, which is done around the edge of that flat jack and around the bleed tube inlet.

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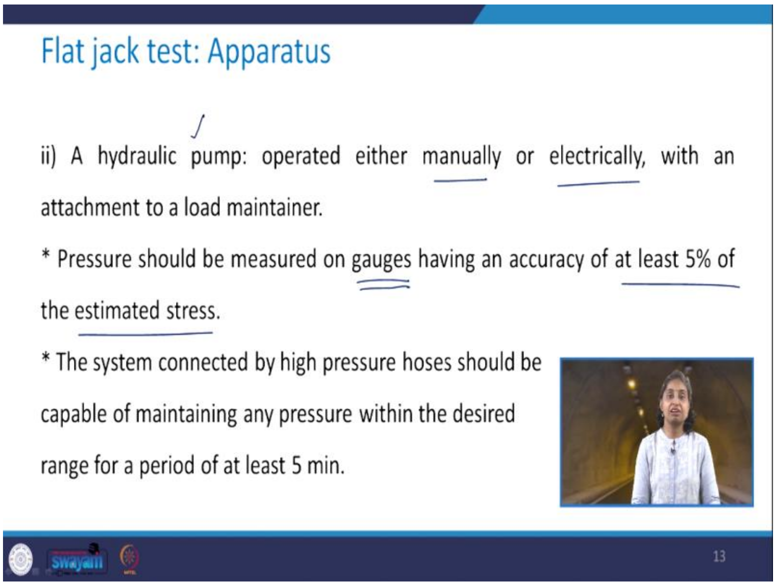

The second component of the apparatus is hydraulic pump. This is operated either manually or electrically with an attachment to the load maintainer or may be the proven ring. The pressure should be measured on gauges having an accuracy of at least a 5% of the estimated stress. The system connected by the high-pressure hoses should be capable of maintaining any pressure within the desired range for a period of at least 5 minutes.

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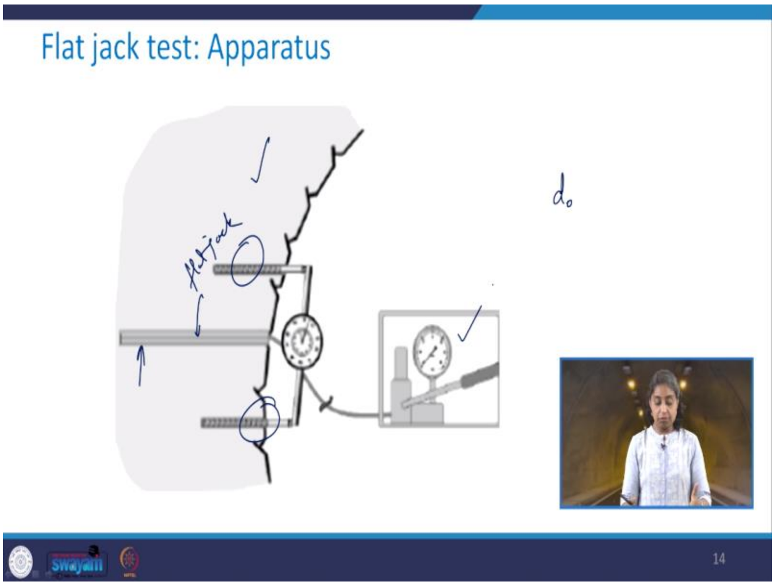

So, this is how the zoomed version of this setup looks like. So, this is the rock mass in which the slot has been cut, and these are the two pins which were marked or which were installed at a distance of, say d_0, and here you see that you have installed the flat jack this is the flat jack and is the connection to the hydraulic pump so that the pressure can be mobilized.

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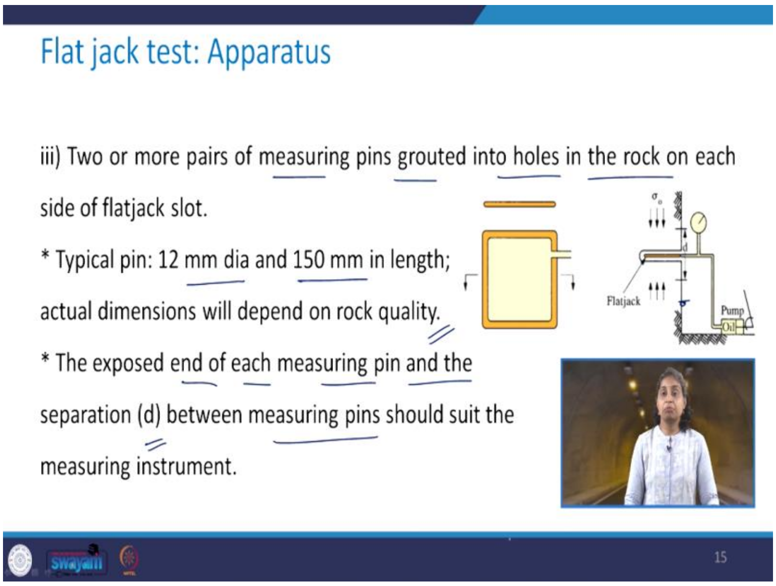

Then we have the third component is the two or more pair of measuring pins which are grouted into the hole in the rock on each side of flat jack slot. So, it is not that you will have two pins on one side of the flat jack no that is not correct. It should be on the either side of the flat jack slot. So, the typical pin is the 12-millimeter diameter and 150 millimeter in length. However, the actual dimensions will depend upon the quality of the rock.

The exposed end of each measuring pin and the separation d between the measuring pins should suit the measuring instrument.

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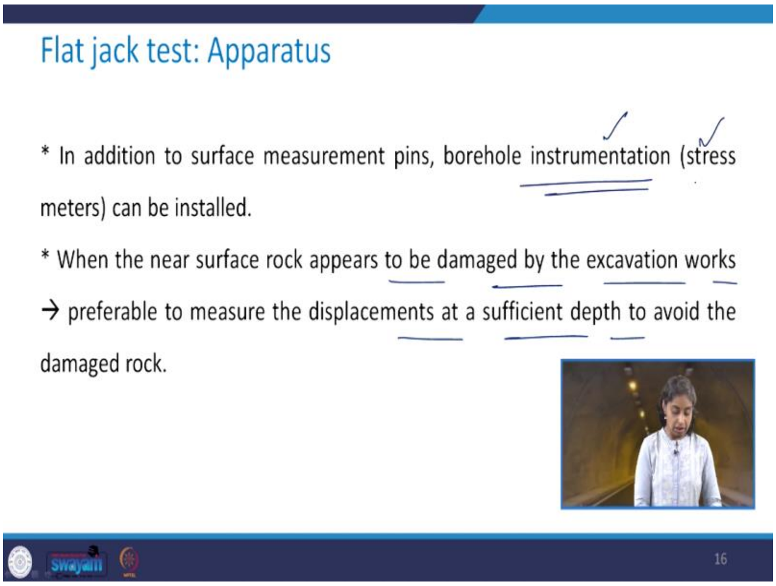

Now, in addition to the surface measurement pins, some borehole instrumentation can be installed to measure the stresses. So, these what all are these instrumentation that we will discuss as a part of the next chapter. So, when the near-surface rock appears to be damaged by the excavation works. It is preferable to measure the displacements at a sufficient depth to avoid the damaged rock.

So, as I mentioned that borehole instrumentation should be done, but then in case if near-surface rock seems to be damaged, then we can install the instrumentation at a sufficient depth.

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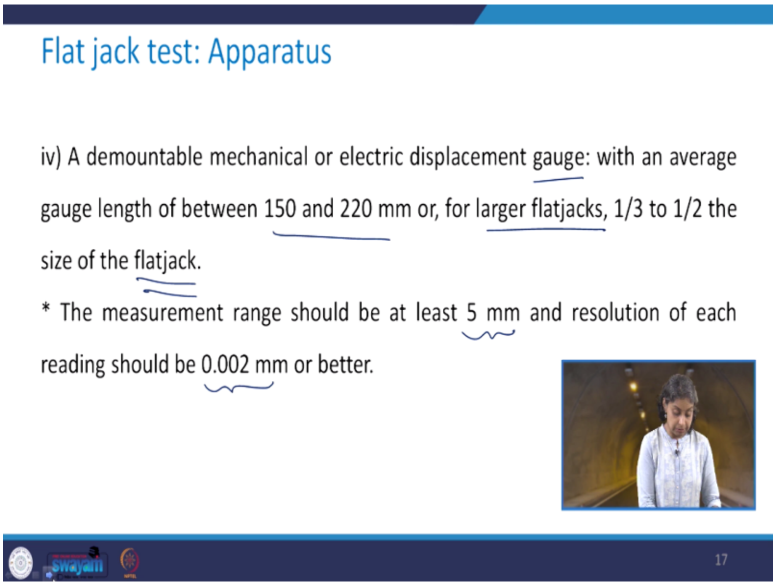

The fourth component is the demountable mechanical or electrical displacement gauge. It has average gauge length between 150 and 220 millimeter, or for larger flat jacks, it can be one-third to half of the size of the flat jack. The measurement range for these should be at least 5 millimeter, and the resolution of each reading should be 0.002 millimeter or even better than this.

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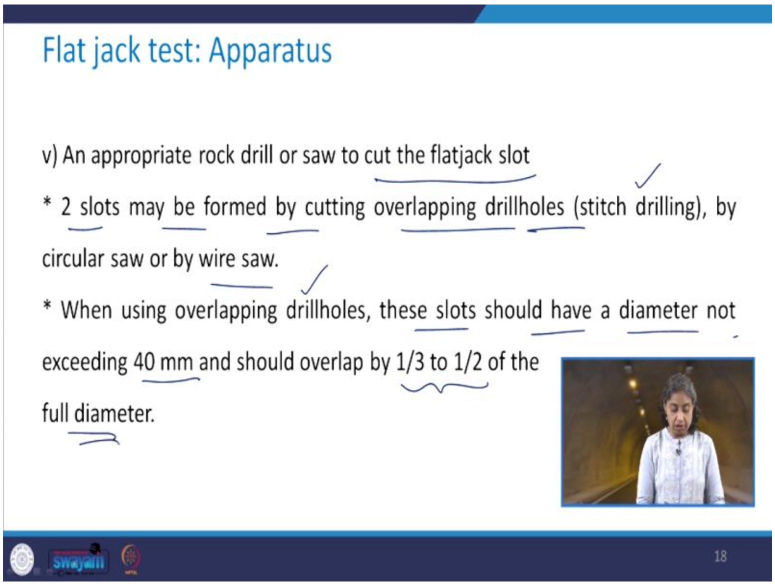

The next component, as far as the apparatus is concerned, is an appropriate rock drill or saw to cut the flat jack slot. It is extremely important activity during the conduct of flat jack test. So, basically here, two slots may be formed by cutting overlapping drill holes. This is also called as stitch drilling by the circular saw or the wire saw. So, when we use the overlapping drill holes, these slots should have a diameter not exceeding 40 millimeter and should overlap by 1 by 3 to half of the full diameter.

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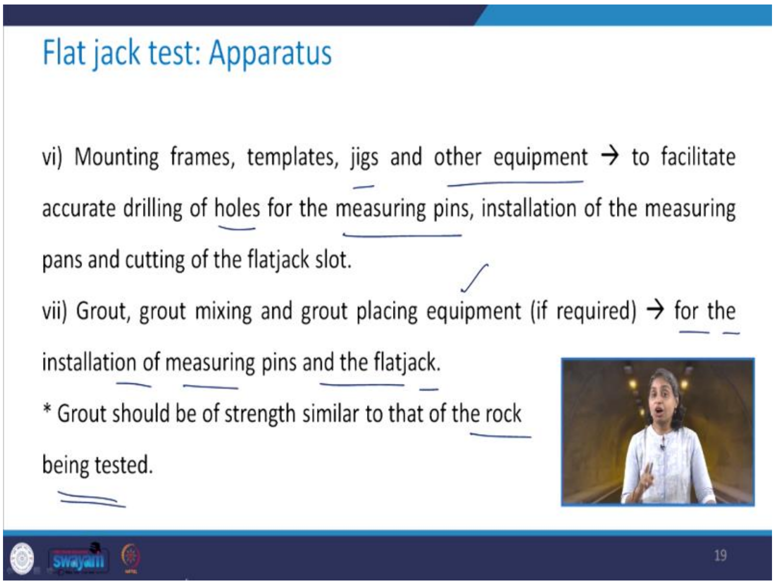

The next component is the mounting frames, templates, jigs, and the other equipment's. These are used to facilitate the accurate drilling of holes for the measuring pins then installation of the measuring pans and cutting of the flat jack slots then finally, we have the grout, grout mixing, and grout placing equipment if it is needed. This is for the installation of measuring pins and the flat jack.

So, this grout should be of the strength similar to that of the rock that is being tested. It should not be weaker than that rock, nor it should be stronger than that because in that case, when the flat jack exerts the pressure on to the inner walls of the slot, it may happen that grout may fail earlier. So, then you will not get the value of the proper in situ state of stress.

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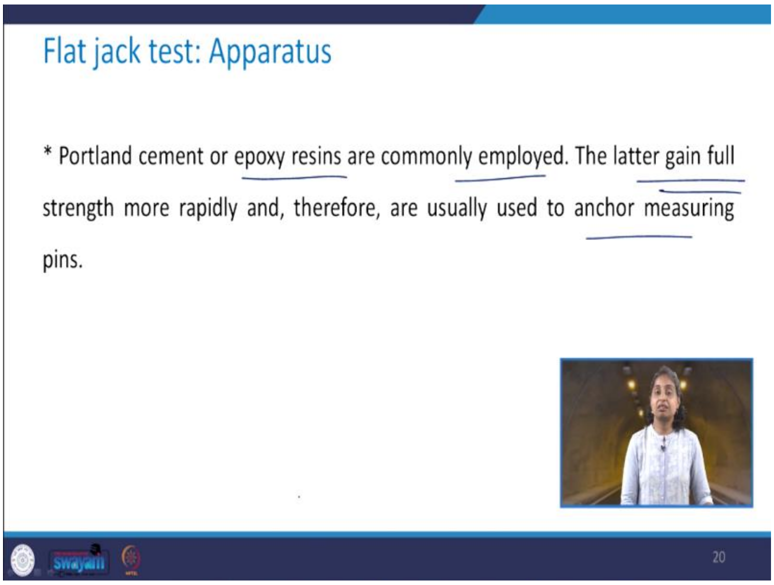

Then for this grouting purpose, Portland cement or epoxy resins are commonly employed. The epoxy resins gain full strength more rapidly, and hence these are usually used for anchoring the measuring pins. These we have discussed when we were discussing about the different types of rock bolts, and there we discussed in detail about the mechanically anchored rock bolt and resin anchored rock bolt. So, there I mentioned this particular property of the resin-anchored rock bolts to you.

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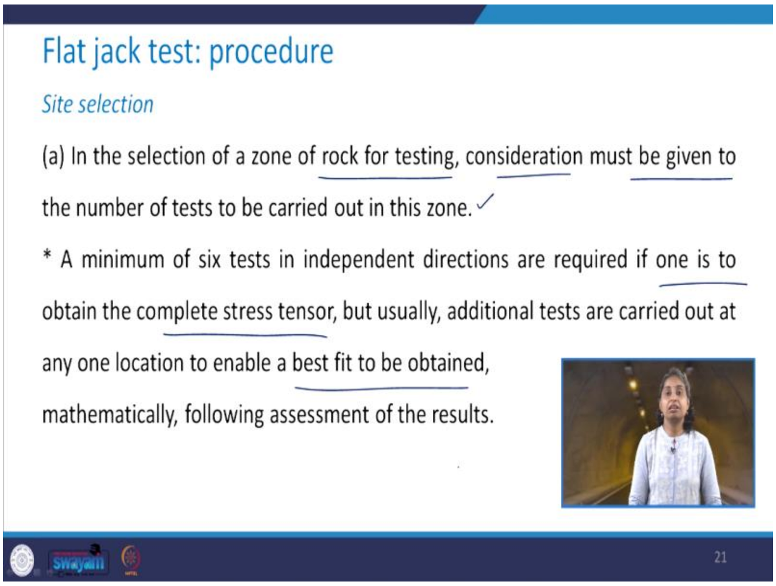

Now, coming to the procedure. So, first important thing is that what should be the site. It means that let us say the underground excavation is to be done maybe for few kilometers let us say some tunnel. So, at what location in those kilometer should we choose for conduct of the flat jack test. So, there are few aspects that one needs to keep in mind. So, first we discuss about some of those issues.

So, the first point that one need to keep in mind is that in the selection of zone for rock testing the consideration must be given to the number of test which are to be carried out in this zone. I told you that a minimum of 6 test are needed are independent directions if one wants to obtain the complete stress tensor, but usually, we carry out additional test also at any one location to enable best fit to be obtained mathematically following the assessment of the results.

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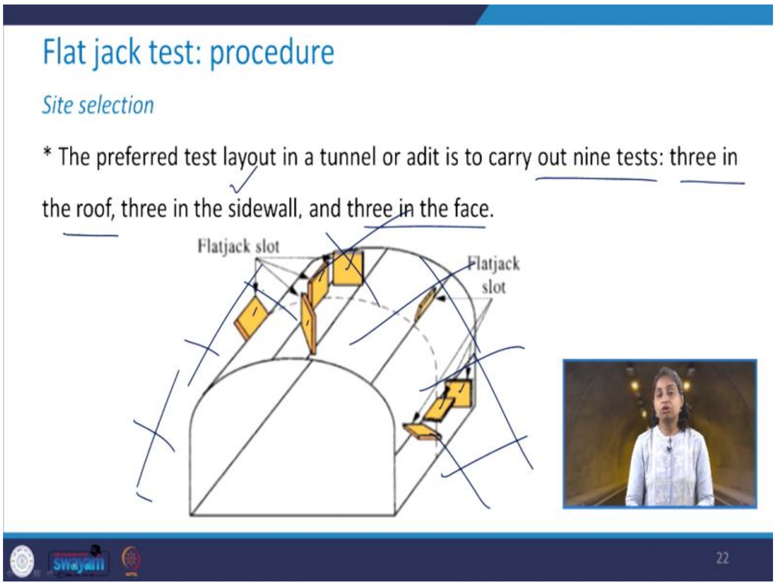

The preferred test layout in a tunnel or adit is to carry out 9 tests, out of which 3 are in the roof, 3 in the sidewall, and 3 in the face. So, typically here, this figure shows that the flat jack slots are made in the rock mass and how the flat jacks would be installed. So, you see, this is all rock mass outside the excavation. So, the flat jacks which you are seeing here not really flat jacks, but the slot for flat jack that you are seeing with the mustard colour here. So, this is how these are installed 3 in roof, 3 in sidewall, and 3 in the face.

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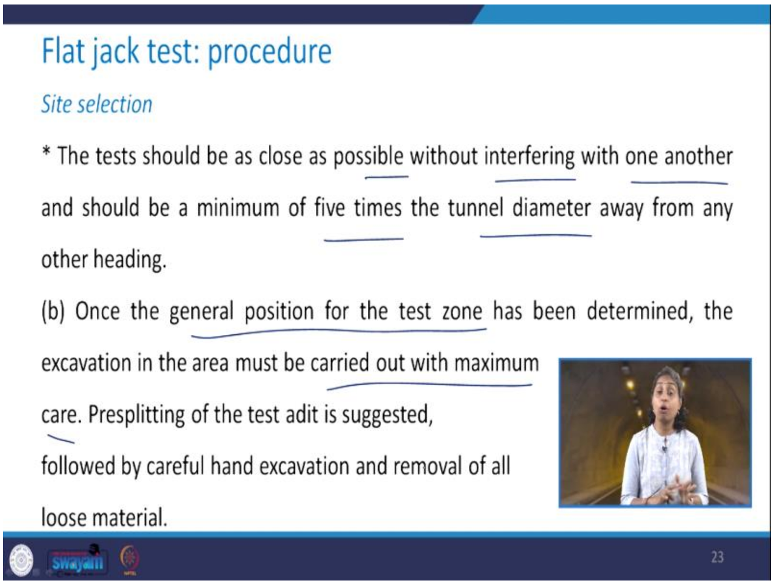

The test should be as close as possible without interfering with one another and should be a minimum of 5 times the tunnel diameter away from any other heading if there is. The second point which one needs to keep in mind as far as site selection is concerned is that once you determine the general position for the test zone, the excavation in the area must be carried out with maximum care.

Pre-splitting of the test adit is suggested, followed by the careful hand excavation and removal of all with the debris material which is there because of the excavation.

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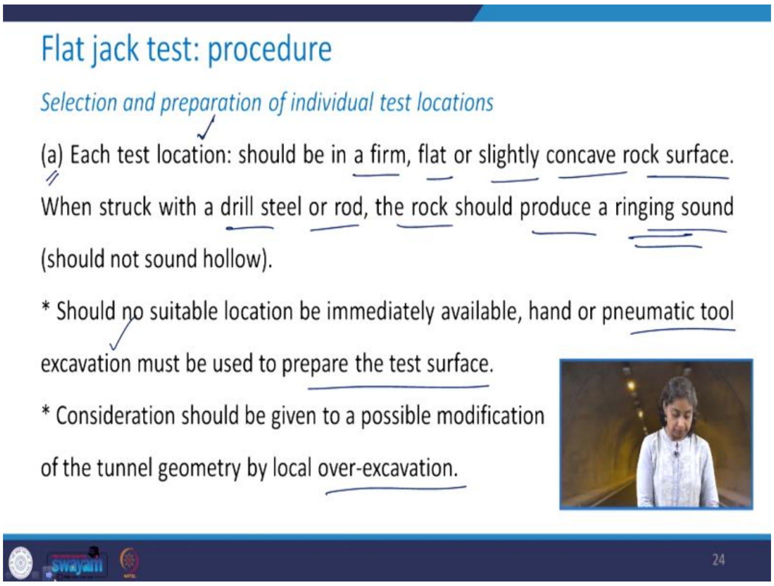

Then coming to the selection and preparation of individual test locations. So, what we did till now is that we select a zone of testing. Now, we select the individual test location. So, the first point which needs to be kept in mind is that each test location should be in a firm, flat, or slightly concave rock surface. When this is struck with a drill steel or rod the rock should produce a ringing sound, and it should not sound hollow.

So, we need to be careful wherever we are choosing this test location. The rock should be firm. It should produce a ringing sound. So, should no suitable location be immediately available in that case hand or pneumatic tool excavation must be used to prepare the test surface. Proper consideration should be given to a possible modification of the tunnel geometry by the local over-excavation.

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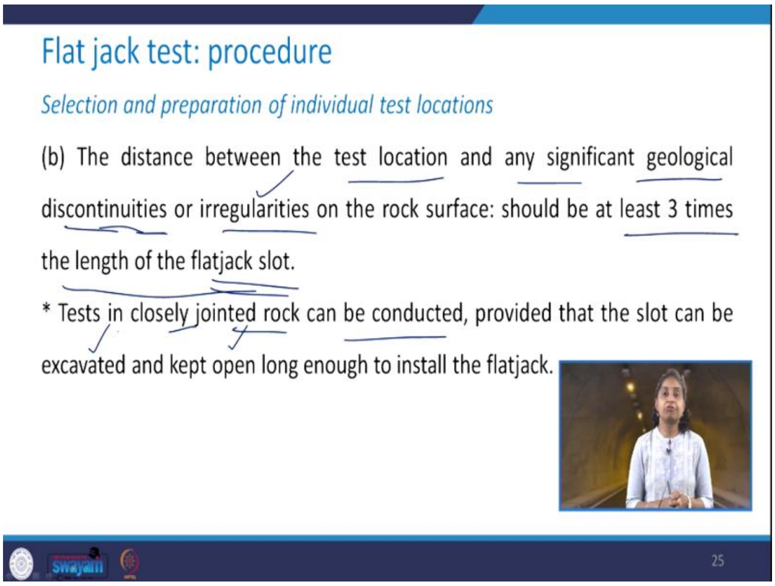

Next point that is to be kept in mind while selection and preparation of individual test locations is the distance between the test location and any significant geological discontinuities or irregularities on the rock surface. There can be the presence of, let us say, a fault zone or the shear zones so that we need to keep in mind. So, wherever we choose the location, that should be at least three times the length of the flat jack slot away from these discontinuities or the irregularities.

So, the test in closely jointed rock can be conducted provided that the slot can be excavated and kept open long enough to install the flat jack.

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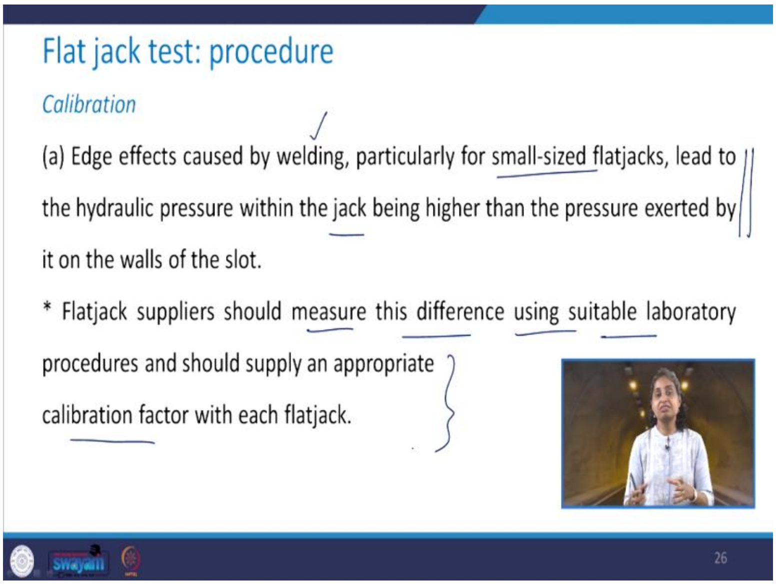

Coming to the calibration of the various components. So, here the edge effects which are caused by welding, particularly when you have the small-sized flat jacks, these lead to the hydraulic pressure within the jack being higher than what is being exerted by the flat jack on the walls of the slot. So, what will happen in this case is that the result that we are getting these are higher than what actually is being exerted in the field.

So, this is not going to be give me the correct picture of the in-situ state of stress. So, one needs to be careful about it, and usually flat jack supplier should measure this difference using the suitable lab procedure and should supply an appropriate calibration factor with each of the flat jack. You must have carried out hydrometer test in the soil mechanics, so there also you need to calibrate any hydrometer.

I mean this is used for the classification of the fine grain soil. So, any of such apparatus which needs this calibration to be done usually, this information is provided by the supplier.

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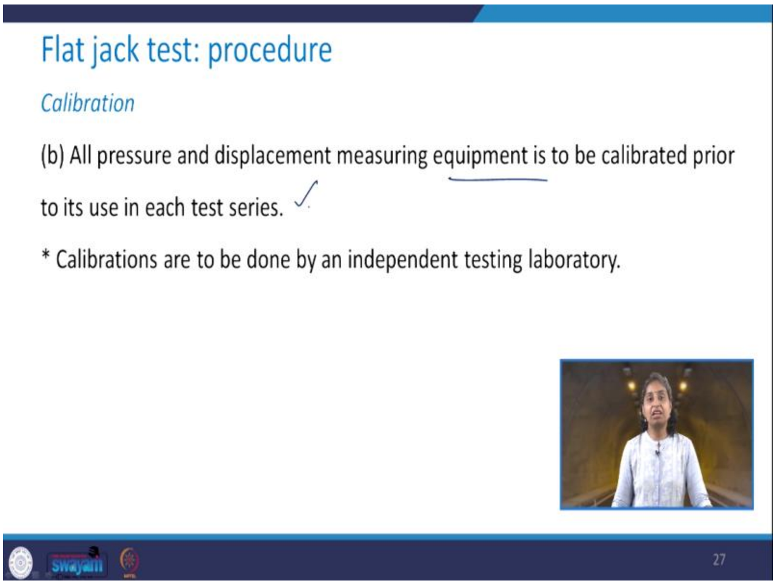

All the pressures and displacement measuring equipment these are to be calibrated prior to their use in each test series. The calibration should be done by an independent testing labs.

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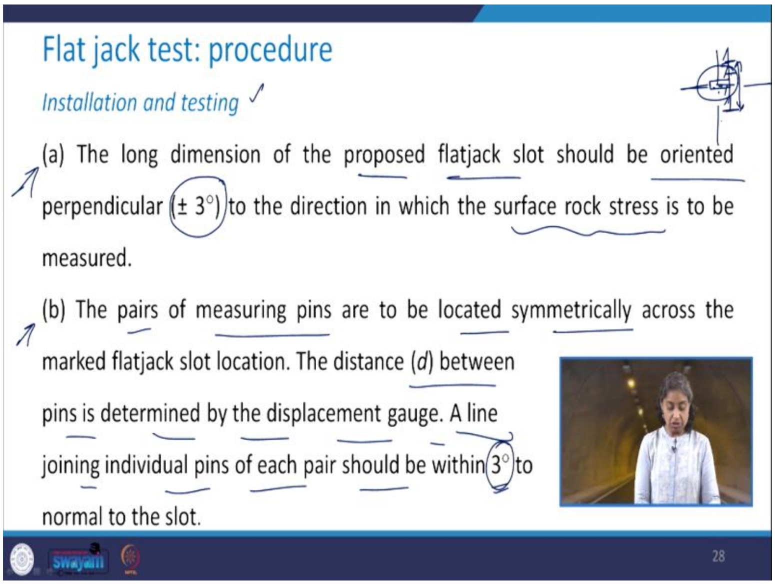

Coming to the installation and testing aspect for flat jack test. The first point that one needs to keep in mind is that the long dimension of the proposed flat jack slot should be oriented perpendicular to the direction in which the surface rock stress is to be determined. So, ideally it should be perpendicular, but then an error of plus minus of 3 degree can be allowed. Then the second point is that the pairs of measuring pins are to be located symmetrically across the marked flat jack slot location.

For example, this was the rock mass, and we had the flat jack slot like this, and we have two pins here. So, the assumption here is that these pins these should be placed symmetrically with reference to this particular slot not that on one side you have lesser distance between the slot and the pin and on other side you have no distance. So, this distance d between the pins is determined by the displacement gauge.

A line joining the individual pins of each pair should be within three degree to normal to the slot. This means if this is the slot so the normal to the slot is this. So, the distance which you measure it should be between plus minus 3 degree to the normal of the slot.

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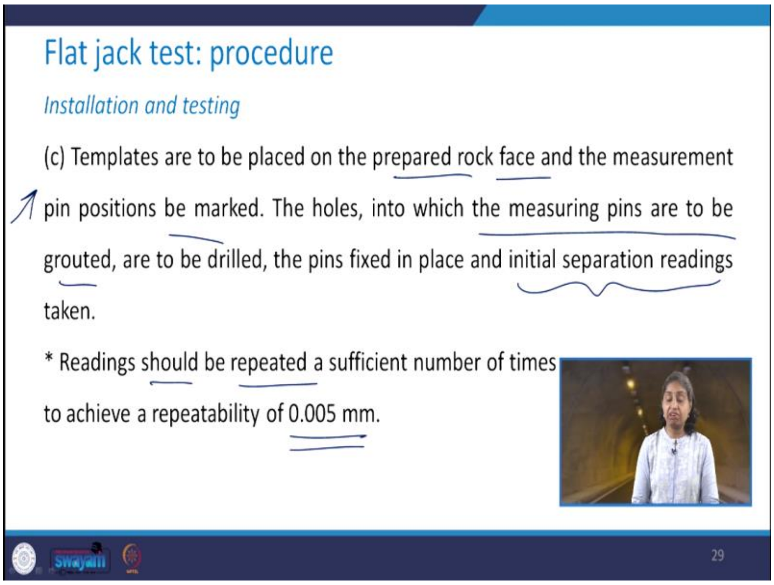

And the next step which one needs to keep in mind is that the templates are to be placed on the prepared rock face and the measurement pin positions be marked. The holes into which the measuring pins are to be grouted are to be drilled, the pins fixed in place, and initial separation readings are taken. See, this is how the procedure is first of all, we mark the location of the pin position.

Then we have the holes in which the measuring pins are to be grouted. So, we drilled those holes, then we fixed these pins into those holes, and then we take the initial separation reading between the two pins. Now, these readings should be repeated sufficient number of times to achieve a repeatability of 0.005 millimeter. This is a very, very important observation which is the initial separation reading. So, one needs to be careful here.

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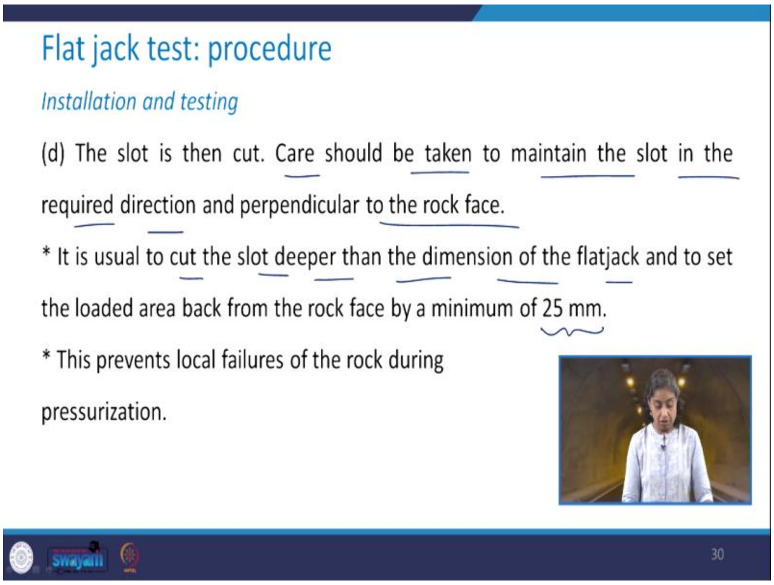

Then the next step after fixing this measuring pin is the cutting of the slot. So, one should be taking enough care to maintain the slot in required direction and perpendicular to the rock face this I have explained and discussed with you couple of times in this class only. So, it is usual to cut the slot deeper than the dimension of the flat jack (refer time: 31:34) and to set the loaded area back from the rock face by a minimum of maybe 25 millimeter.

Why we do this is that this prevents the local failures of the rock when the pressure is applied through the flat jack.

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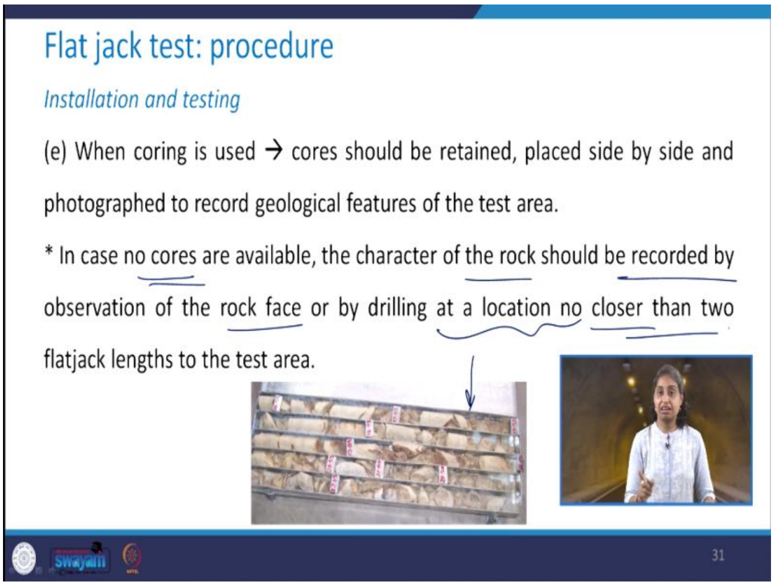

When the coring is used the cores should be retained, placed side by side, and photographed to record the geological feature of the test area. So, here I have put one of such data. So, this is how the course should be arranged and placed side by side. In cases where no cores are available, the character of the rock should be recorded by the observation of the rock face or by drilling at a location which is no closer than two flat jack lens in the test area.

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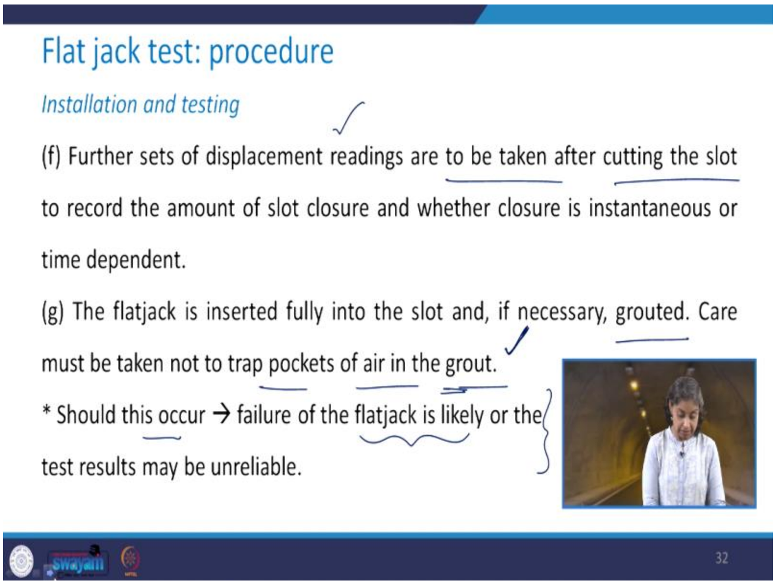

Then further sets of displacement readings are also to be taken after cutting the slot to record the amount of slot closure. When this closure is instantaneous, or it is time dependent that also should be recorded with the help of these set of displacement readings, then this flat jack is inserted fully into the slot, and if it is necessary, it should be grouted, and you should take proper care not to trap pockets of air in the grout in the process of this grouting.

Now, should this occur that is if there is the pockets of air in the grout then in that case failure of the flat jack is likely, or even if the flat jack is not failing, whatever test results that you are getting, these may not be reliable. So, you need to be careful about this aspect while going for the grouting of the flat jack.

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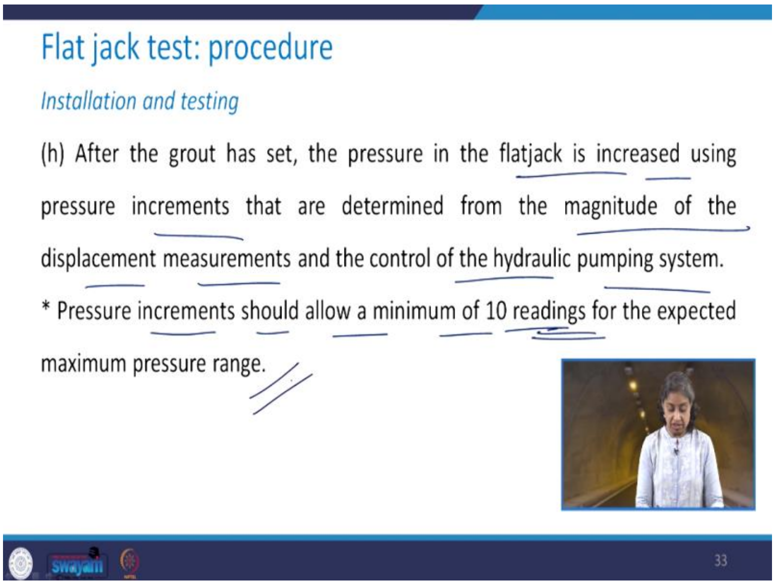

Then the next step is we let the grout set and once it is set, the pressure in the flat jack is increased using the pressure increments that are determined from the magnitude of the displacement measurement and of course, the control of the hydraulic pumping system. So, we apply the pressure, then we measure the displacement, and we see whether it has reached to the original initial separation reading or not. If it is not, then we further apply the pressure to the flat jacks.

These pressure increments should allow a minimum of 10 readings for the expected maximum pressure range.

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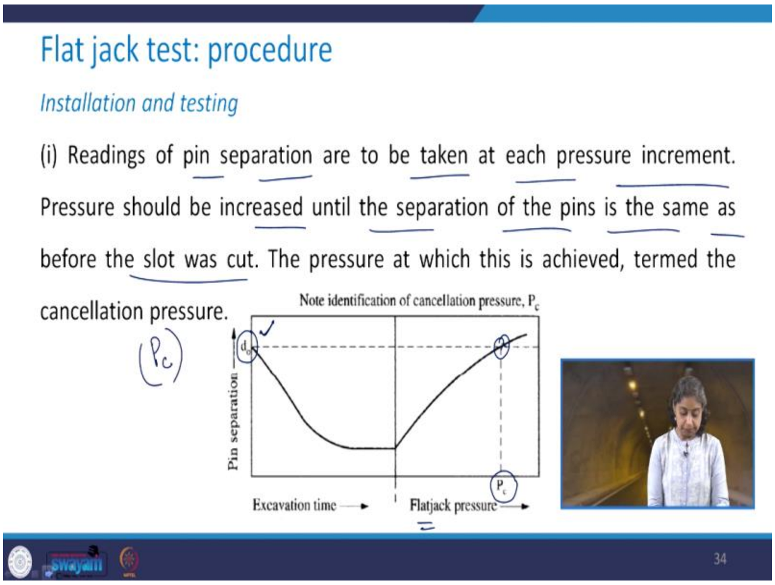

How to handle these readings? So, the readings of the pin separation these are to be taken at each pressure increment. This pressure should be increased until the separation of the pins is same as it was before the slot was cut. So, you see this I also explained earlier. So, in the beginning you had the separation as d 0. So, upon the excavation of the slot what will happen this separation will get reduced.

Now, you start applying the flat jack pressure. So, once you apply that the walls of the slot, inner wall of the slots they are subjected to pressure. So, they start moving apart again on the influence of the pressure that is exerted by the flat jack, and then continuously corresponding to each pressure increment, we are measuring the pin separation continuously. So, the moment this pin separation it reaches to the original value d_0.

So, we just take the value of that flat jack pressure, and then we record that this is called as cancellation pressure, and we are representing it as p_c.

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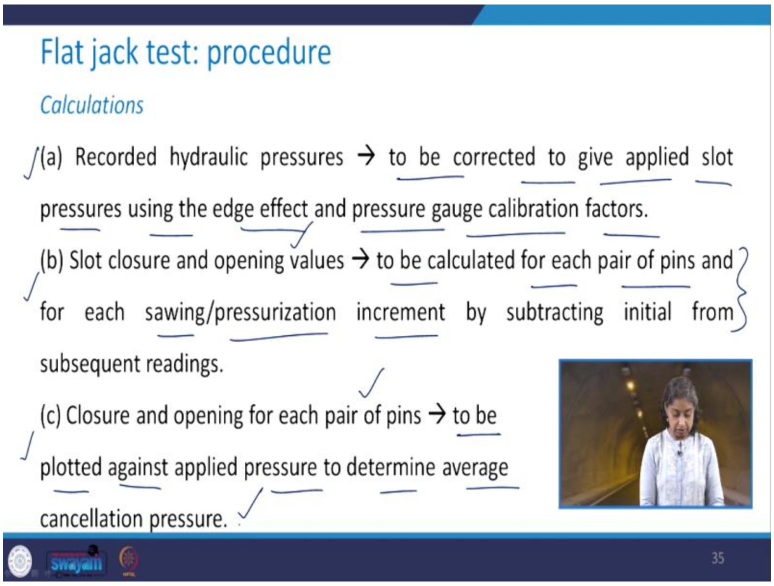

Now, coming to the calculations that means we have conducted the test we have recorded the data. Now how to go ahead as far as calculations are concerned and then how to interpret that what are the state of in situ stress. So, the first one is the recorded hydraulic pressures. These should be corrected to give applied slot pressure using the edge effect and pressure gauge calibration factor.

So, this I discussed with you when we were discussing about the calibration of the flat jacks, then the second one is the slot closure and the opening values. So, these should be calculated for each pair of pins and for each sawing or pressurization increment by subtracting the initial value from the subsequent reading. This is basically a usual procedure in various pressure versus deformation test, or the test where we get pressure versus deformation characteristics such as simple example is a plate load test. Then the third one is the closure and opening of each pair of pins.

These are to be plotted against applied pressure to determine average cancellation pressure.

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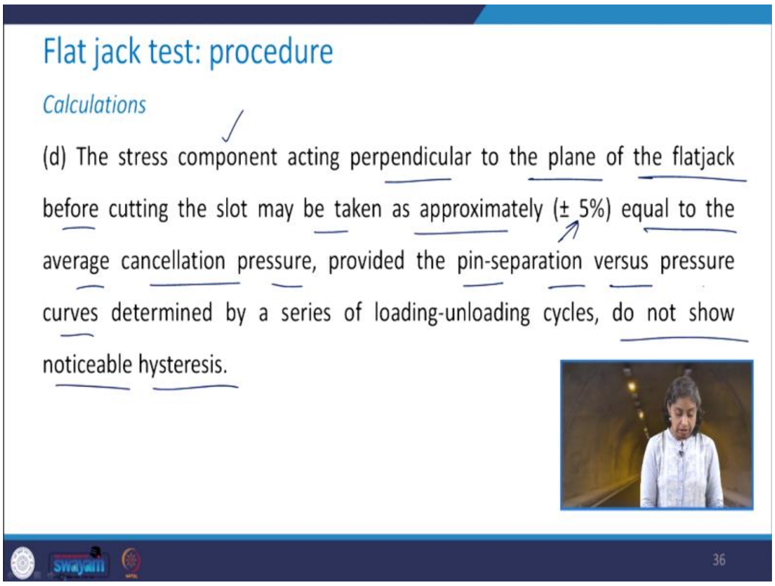

Then finally, we try to calculate the stress component, which are acting perpendicular to the plane of the flat jack, before cutting the slot. This may be taken as approximately equal to the average cancellation pressure of course some error will be involved to the tune of maybe plus minus 5%. Provided the pin separation versus the pressure curve determined by the series of loading and unloading cycles, these do not show noticeable hysteresis.

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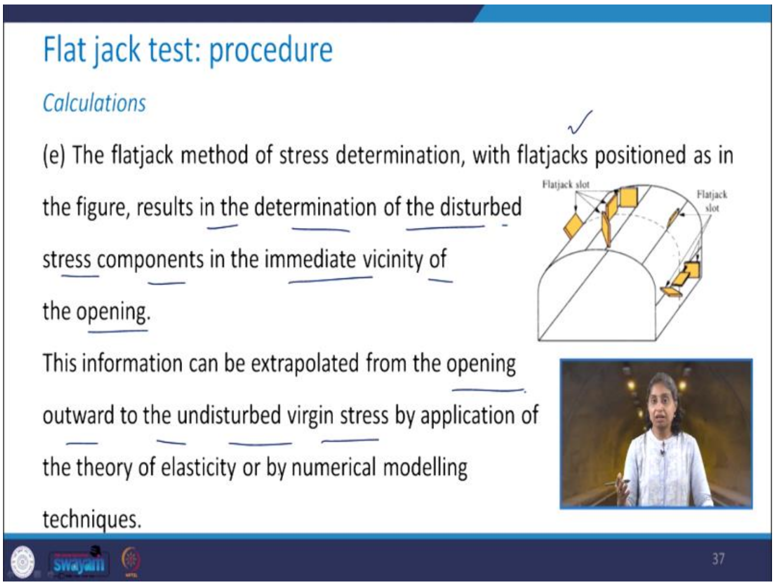

So, this is how we had the flat jack slot, we discussed this. So, in this method of stress determination with flat jack positioned as has been shown in this particular figure. The results in the determination of the determination of the disturbed stress components in the immediate vicinity of the opening. Now, this information can be extrapolated from the opening outward to the undisturbed virgin stress by application of the theory of elasticity or by numerical modeling techniques. So, how this is done, we will take up with the help of an example now only.

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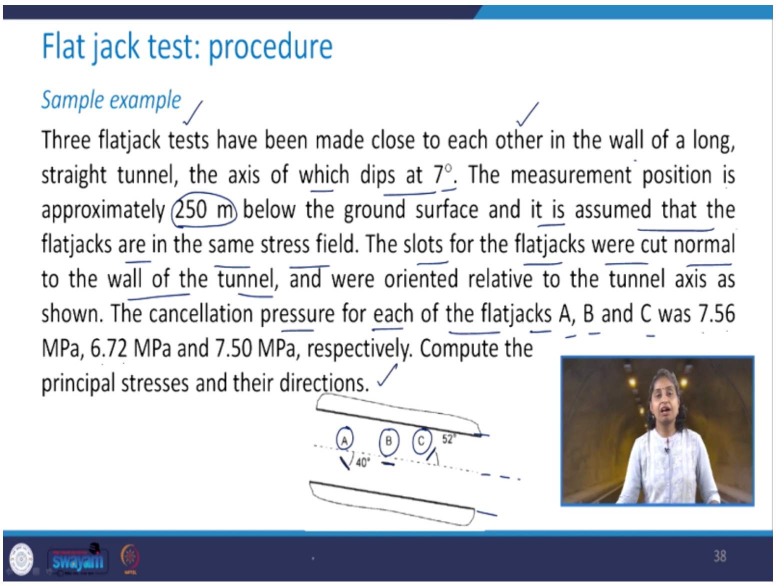

So, here is an example. So, please read the statement. We had three flat jack test here which have been made close to each other in the wall of a long straight tunnel. So, you see that it has been shown in the figure long straight tunnel, the axis of which dips at 7 degree.

So, you see, this is the axis of the tunnel, and it is dipping 7 degrees. The measurement position is approximately 250 meter below the ground surface that means the overburden is 250 meter and it is assumed that the flat jacks are in the same stress field. So, the slots for the flat jacks were cut normal to the wall of the tunnel and these were oriented relative to the tunnel axis as shown. So, you can see that how the slots were cut, so you see one is 52-degree, 40 degree, and other one is parallel to the tunnel axis, but then all were cut normal to the wall of the tunnel. The cancellation pressure for each of the flat jack A, B, C.

So, you see these are the three flat jacks A, B, and C that was 7.56, 6.72, and 7.5 MegaPascal respectively. So, all we need to do is to compute the principal stresses and their directions. So, let us take a look that how by using the theory of elasticity, we can perform this analysis.

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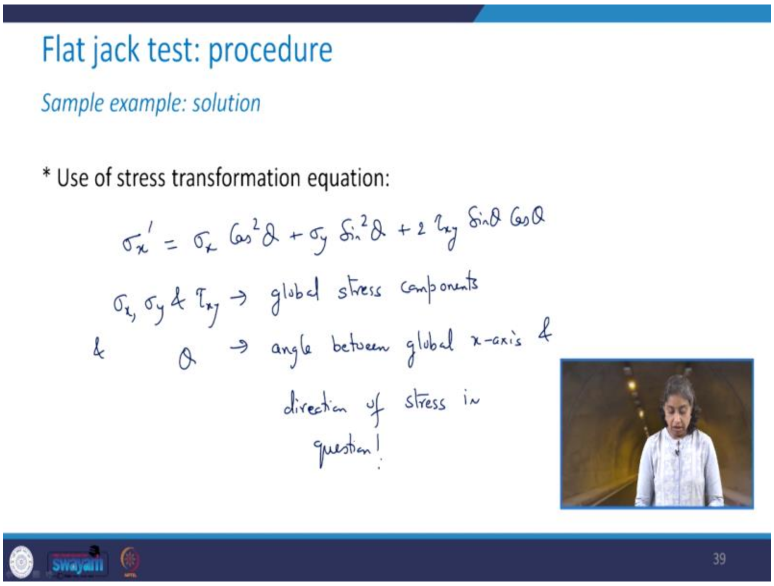

So, we use these stress transformation equations which are like this:

$$\sigma_x' = \sigma_x cos^2\theta + \sigma_y sin^2\theta + 2\tau_{xy} sin\theta cos\theta$$

Now, what are these σ_x, σ_y, and τ_{xy}. These are the global stress components, and theta is the angle between the global x-axis and the direction of the stress in question.

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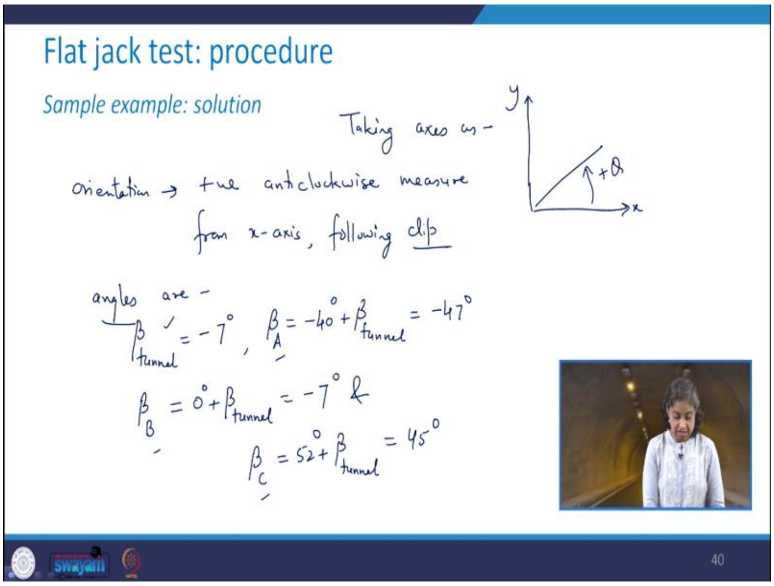

So, let us take the axis as in this figure. So, taking our axis as here, we will take this as maybe the x-axis and y-axis, and this direction we are taking this as plus theta, and the orientation as I showed this is in the anti-clockwise direction. So, orientation they are positive anti-clockwise measure from x-axis. So, if we do this, we will have the dip angles are going to be β for the tunnel is going to be – 7 degree.

And we will have here β_A which is equal to – 40 degree + β_{tunnel} that is going to be then – 47 degree, and we have β for flat jack positioned at point B that is going to be 0 degree + β for the tunnel that is going to be – 7 degree, and finally we have β_c that is going to be 52 degree + β_{tunnel} and that is going to be your 52 – 7; so that is going to be 45 degree.

So, this is how we can find out the dip angles for tunnel and the flat jack which are installed at locations A, B, and C which was shown in this particular figure. So, you see we are taking anti-clockwise from the x-direction we are taking anti-clockwise positive as theta. So, accordingly we are calculating the dip here at this particular step.

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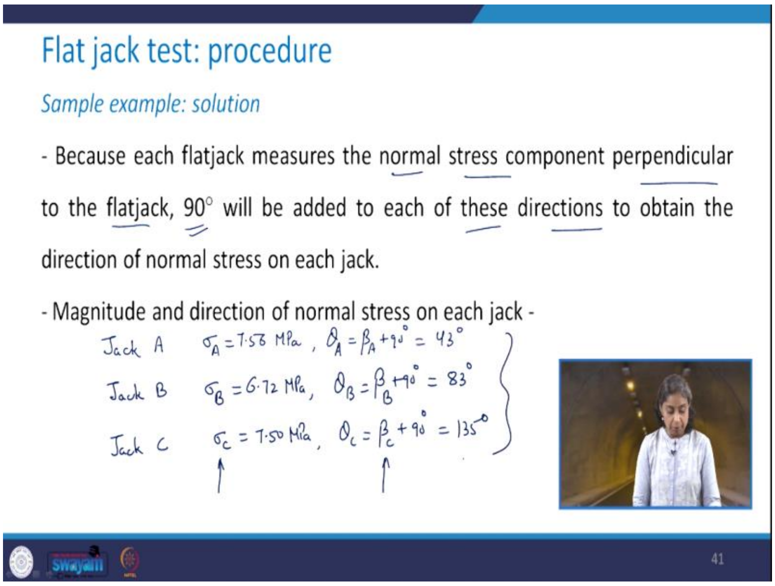

Now because each flat jack it measures the normal stress component perpendicular to the flat jack, we need to add 90 degree to each of these directions to obtain the normal or to obtain the direction of the normal stress on each jack and therefore the magnitude and the direction of the normal stress on each jack is going to be say first I write for jack A this is going to be σ_A which is 7.56 MPa with the theta A to be equal to β_A + 90 degree.

So, this is going to be 43 degree, and then we have jack B with the σ_B as 6.72 MegaPascal, and theta B will be equal to β_B + 90 degree, and that is going to be 83 degree, and finally for jack C σ_c = 7.5 MegaPascal and theta c will be β_c+ 90 degree, and this will come out to be 135 degree. So, this σ_A, σ_B, and σ_c; they were provided in the question itself or these are obtained from the results of the flat jack test.

And we already got β_A, β_B, and β_c in the previous slide. So, therefore we can obtain theta A, theta B, and theta C in this particular manner.

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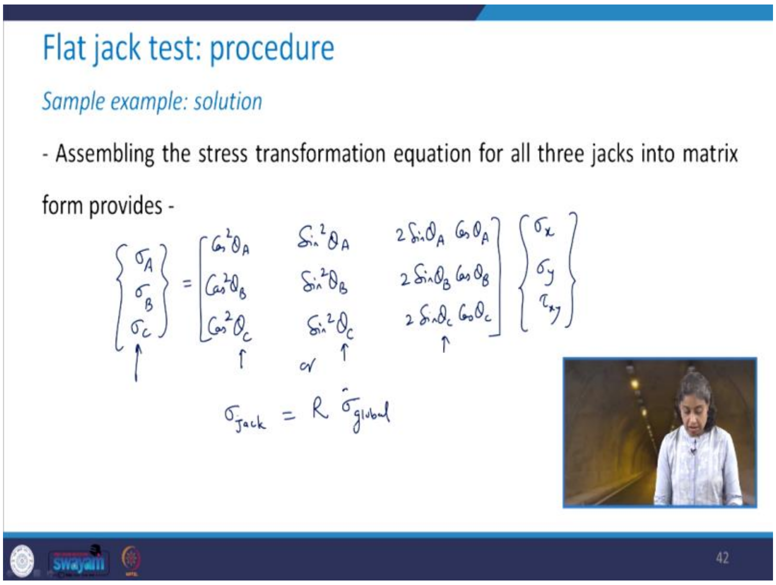

Now, if we just assemble the stress transformation equation for all the three jacks and if we write it into the matrix form this is what that we will get. So, here we will have the jack stress vector that is:

$$\begin{Bmatrix}\sigma_A\\ \sigma_B\\ \sigma_C\end{Bmatrix} = \begin{bmatrix}cos^2\theta_A & sin^2\theta_A & 2sin\theta_A cos\theta_A\\ cos^2\theta_B & sin^2\theta_B & 2sin\theta_B cos\theta_B\\ cos^2\theta_C & sin^2\theta_C & 2sin\theta_C cos\theta_C\end{bmatrix}\begin{Bmatrix}\sigma_x\\ \sigma_y\\ \tau_{xy}\end{Bmatrix}$$

So, this will complete this particular matrix, and then here we will have the global stress vector which is σ_x, σ_y and τ_{xy} or we can write it as sigma jack is equal to the matrix R and multiplied by sigma global. Now, if you just substitute the values of σ_A, σ_B, and σ_c that I told you just in the previous slide and also for theta A, theta B, and theta C in all these expressions.

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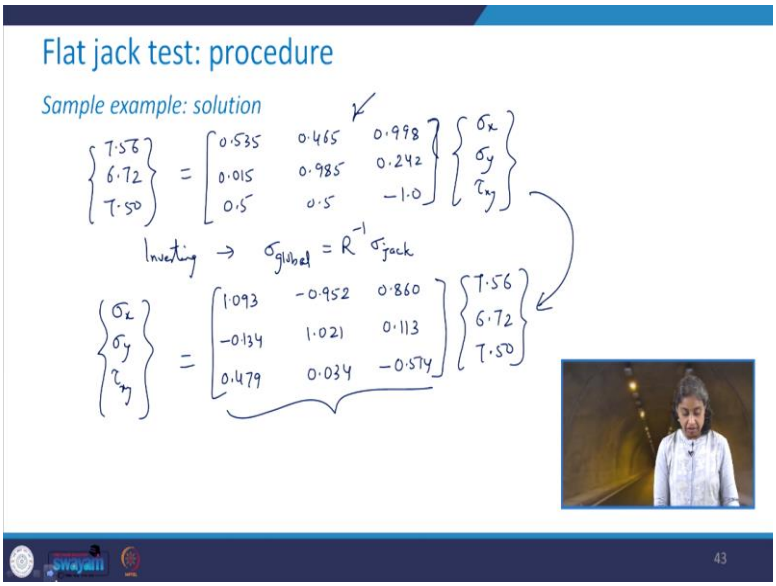

We will get the numerical values such as here, this is going to be 7.56, 6.72, and then 7.50. This is equal to 0.535, 0.465, 0.998, 0.015, 0.985, and 0.242 then 0.5, 0.5, and – 1.0 then, this multiplied by this sigma vector σ_x, σ_y and τ_{xy}. Now, if we invert this equation which is written in the matrix form what we get is σ_{global} as R inverse σ_{jack}. So, we need to find out the inverse of this matrix.

This is going to be σ_x, σ_y and then τ_{xy} that is equal to 1.093 – 0.952, 0.860 – 0.134, 1.021, and 0.113, 0.479, 0.034 – 0.514. This should be multiplied by the stress vector 7.56, 6.72, and then 7.50. So, this is how that we are going to obtain our inverse, and this equation can be written in this particular manner.

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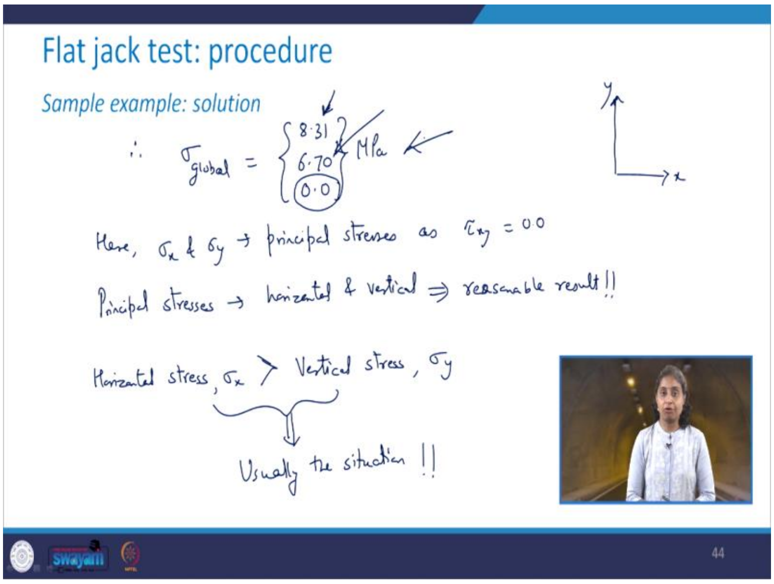

Now, we can find out by multiplying this matrix with the stress vector. So, we get sigma global as 8.31, 6.70, then 0.0 units are going to be MegaPascal. Now you see here this τ_{xy} coming out to be equal to 0. So, what does this mean that the stresses σ_x and σ_y; they are going to be the principal stresses.

So, here what we got is that σ_x and σ_y. They are going to be the principal stresses reason being that τ_{xy} working out to be equal to 0. So, these principal stresses these are horizontal and vertical. Why? Do you remember the axis that we took this was x-axis and this was y-axis and some of these is reasonable result, and here you see this is the σ_x 8.31, and the σ_y value is 6.70.

So, you see that the horizontal stress is coming out to be more than the vertical stress, that also is quite reasonable because similar situation is there in the field most of the time. So, in this case, what we have is the horizontal stress which is sigma x is coming out to be more than the vertical stress, which is σ_y which is usually the situation. So, this is how using various steps and analysing the data which we obtain from the flat jack test, we can determine the state of stress, which is global state of stress.

And therefore, this global state of stress gives us the in-situ state of stress in the rock mass. So, this is how we can use the data from the flat jack test.

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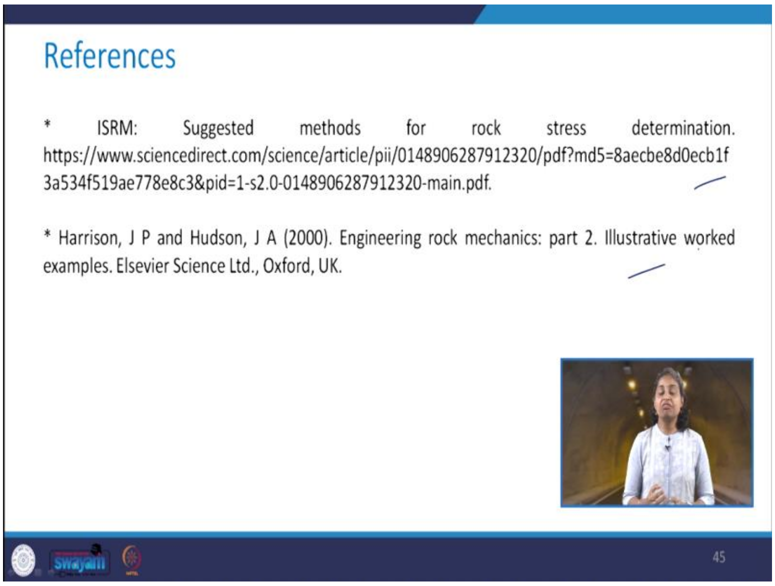

So, these are the references that I used to explain you this flat jack test. So, today we discussed about one test that is flat jack test for the determination of in-situ state of stress. There are other methods, such as hydraulic fracturing method. So, in the next class, we will discuss about this hydraulic fracturing test. Thank you very much.