Underground Space Technology

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Lecture – 59

Instrumentation and Monitoring of Tunnels - 02

Hello everyone, In the previous class, we started our discussion on instrumentation and monitoring of tunnels and, we discuss that what is the need of the instrumentation and then, we learnt about the various instruments which are used to monitor the deformation of the rock and, the extent of the loosened rock zone. So, today, we will focus on the instruments, which are used to monitor the load or the pressure in the support system. So, to start with the first one, that we have is the load cell on steel support.

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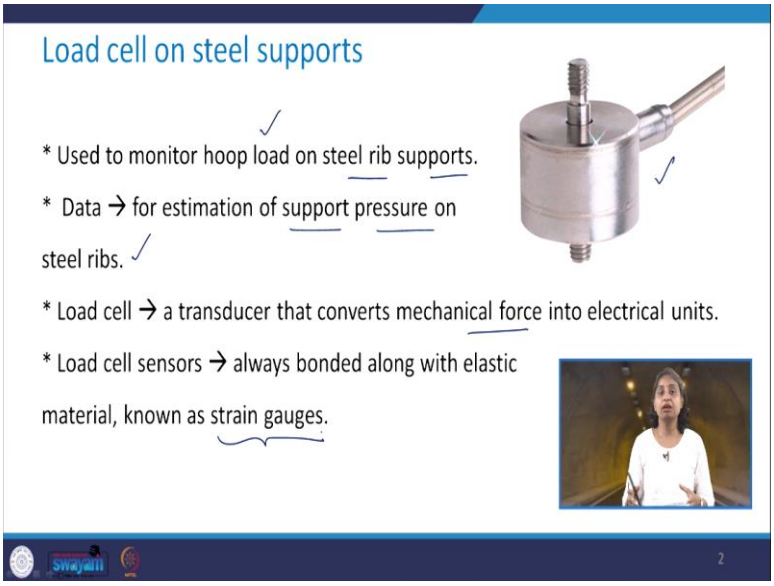

It looks like this, as shown in the figure. This is used to monitor hoop load on the steel rib supports. The data is used for the estimation of support pressure on the steel ribs. Basically, load cell is a transducer that converts the mechanical force into the electrical units. Loads cell sensors, they are always bonded along with the elastic material which is known as the strain gauges.

So, not only it is important for us to know about the load cell, but also about the strain gauges.

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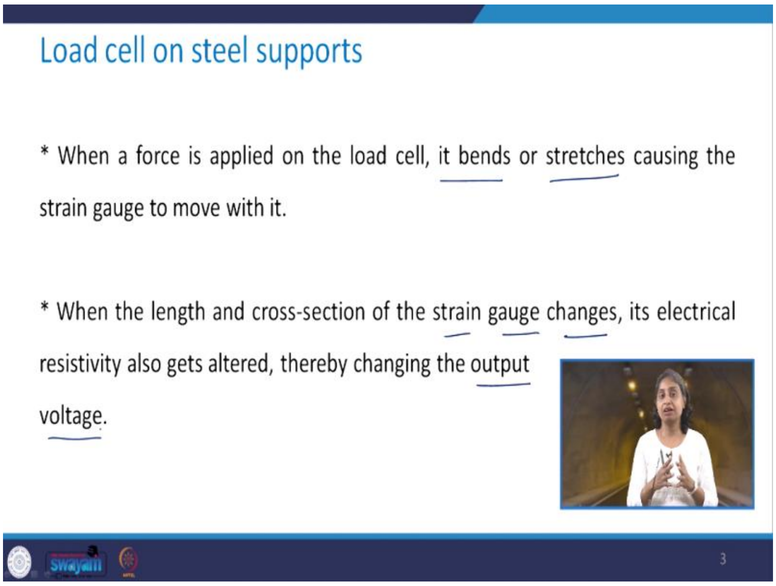

When a force is applied on the load cell it bends or stretches causing the movement of the strain gauge which is associated with it. When the length and the cross-section of the strain gauge changes, its electrical resistivity also gets altered thereby changing the output voltage. So, basically, philosophy is that, we are recording the change in the mechanical load in terms of the electrical output.

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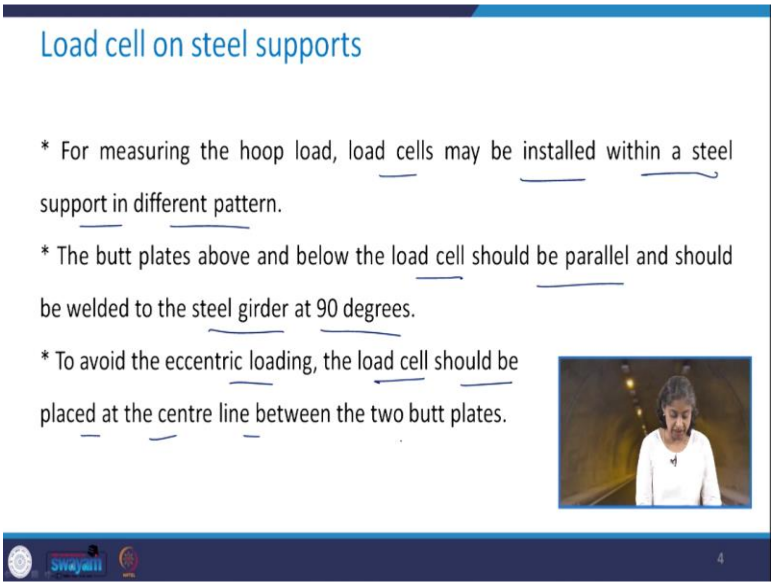

For measuring the hoop load, load cells may be installed within a steel support in different pattern. The butt plates below and above the load cells, they should be parallel and these should be welded to the steel girder at 90 degrees to avoid the eccentric loading. The load cell should be placed at the center line between the two butt plates.

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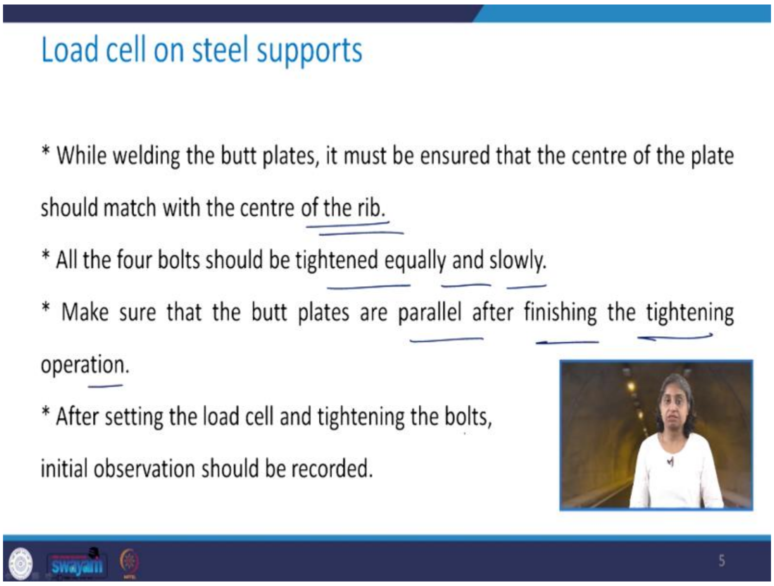

Now, when we weld the butt plates it should be ensured that the center of the plate matches with the center of the rib. So, all the four bolts should be tightened equally and slowly and we should make sure that butt plates are parallel after finishing the tightening operation. After setting up the load cell and tightening the bolts, we should start taking the observations.

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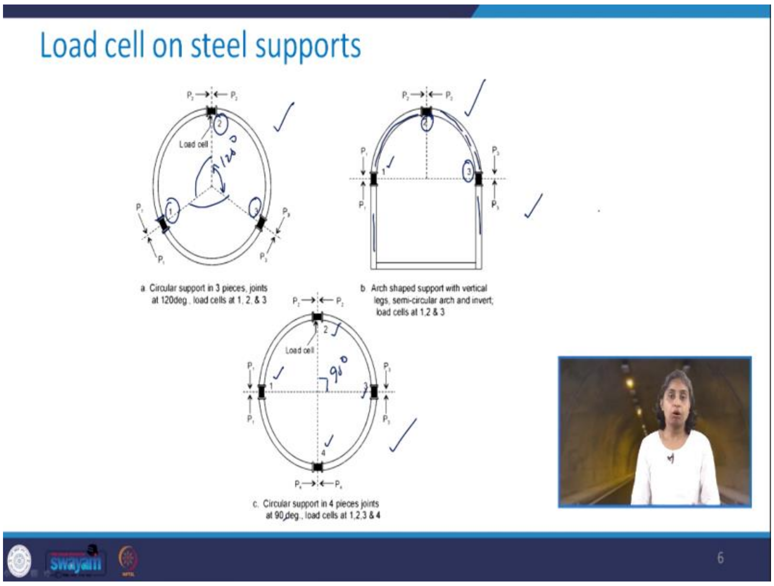

So, this is how the arrangement of the load cell on steel support looks like. Here, there are three conditions. The first one is where you have the circular support in three pieces joints at 120 degrees. So, you see that this is 120 degrees all these angles and load cells are provided at the points 1, 2, and 3. So, we need to be careful about provision of the load cell. Similarly, in the second one, it is the arch shaped support with vertical legs.

So, you see that this is the arch shape supports and, it has the vertical leg. So, we have the semi-circular arch and invert load cells at 1, 2, and 3 locations. In the third figure, you have circular support in four pieces which are at 90 degree. So, you see we have 1, 2, 3, and 4 load cells in this particular situation. So, this is how the load cells are installed on the steel supports.

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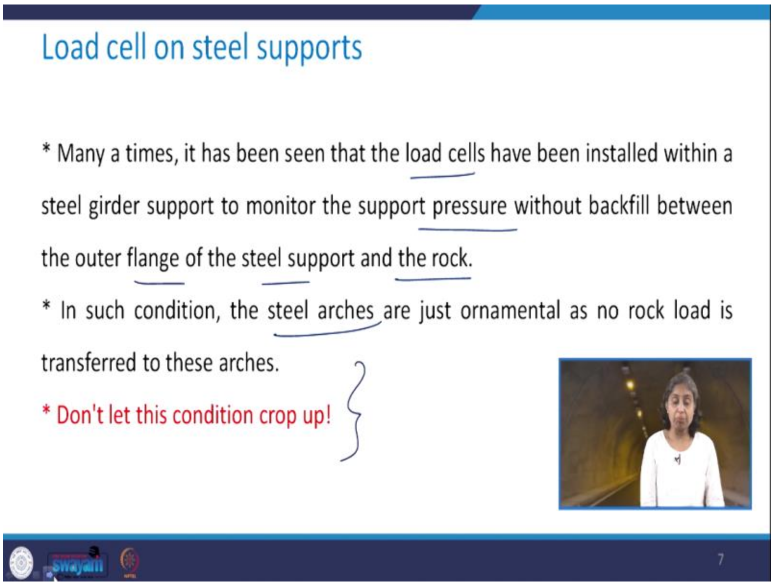

Now, many times it has been seen that the load cells were installed within a steel girder support to monitor the support pressure without backfilling between the outer flange of the steel support and the rock. See, we need to avoid this type of situation because in this condition, what will happen that the steel arches are going to be just ornamental, as there is a gap between the rock and the steel support.

So, the rock load will not be transferred to these arches. So, we need to be careful and do not let this condition happen there in the field backfilling should be done properly.

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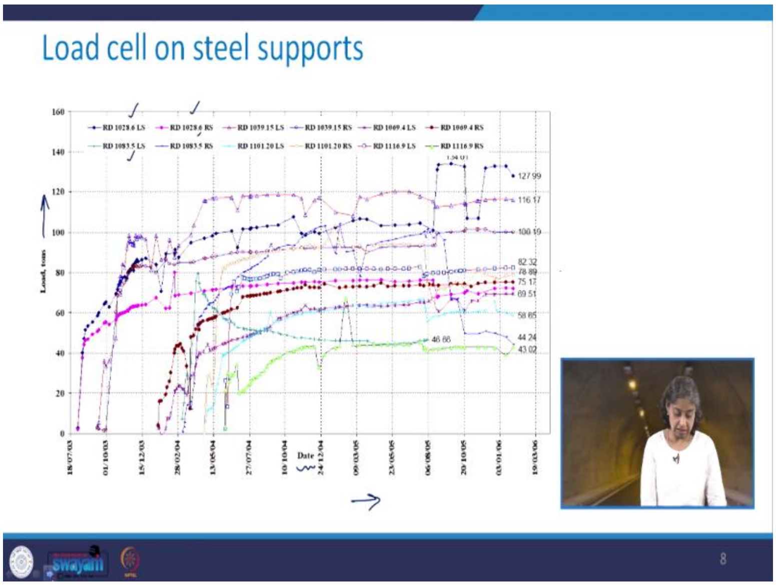

This is the typical load versus plot on these steel supports. So, you see that on the y-axis you have load in tonne, and on x-axis you have the dates. So, this is related to one of the project and these, that you see these are at different locations that the load cells were installed and, the recording has been taken.

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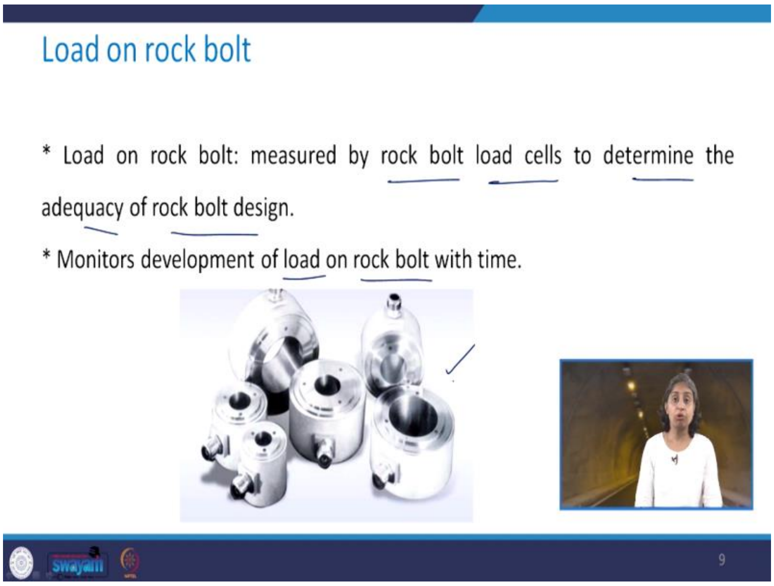

Coming to the next one, which is load on the rock bolt till now we saw load on the steel sets. This is related to rock bolt. So, these are measured by rock bolt load cells to determine the adequacy of the rock bolt design. These look little bit different, you see how these are different than the previous one that I showed you earlier. These monitor the development of load on the rock bolt with time.

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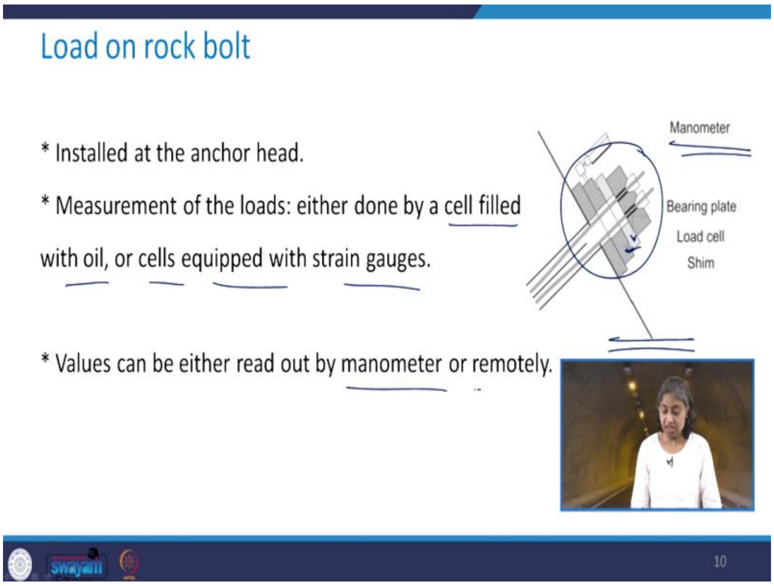

This is how the installation of a rock bolt load cell looks like. So, you can see that this is what is the load cell bearing plate is this one and the manometer is here. So, these are installed at the anchor head. So, this is what is the anchor head, head of the anchor and the load cells are installed in this location. The measurement of the loads they are either done by a cell which is filled with oil or cells equipped with strain gauges. These values can either be read out by the manometer or remotely.

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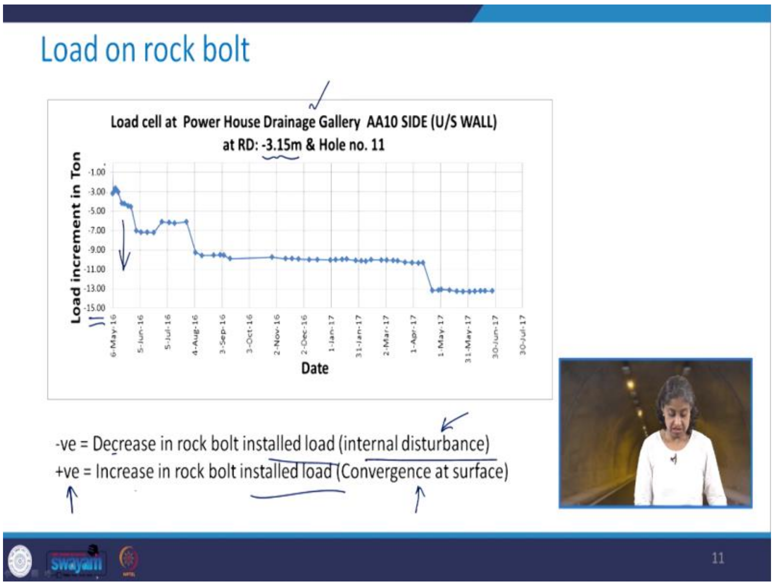

This is a typical plot between load increment in tonne and the date. So, this was related to one of the typical powerhouse drainage gallery and, the load cell was installed at the relative distance of – 3.15 meter at a particular hole. So, here the negative values, they show the reduction in the rock bolt installed load. This is representative of the internal disturbance and the positive ones are the increase in the rock bolt installed load that is convergence at the surface.

So, you can see that in this particular case it is all negative you see – 1, -3, and up to – 15. So, it is all representation of the internal disturbance.

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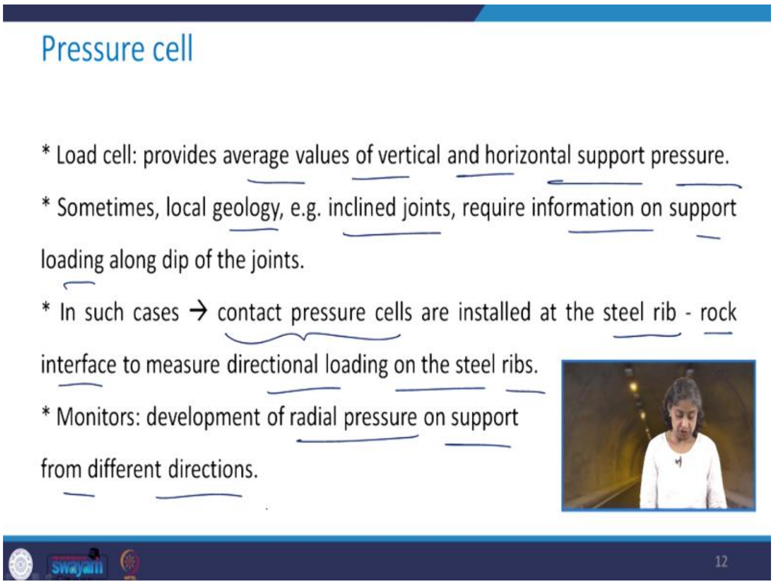

Coming to the next category of the instrument is the pressure cells. So, we had the load cell which provided us the average values of the vertical or horizontal support pressure. Now, sometimes as per the local geology which may be inclined joints. These require information on the support loading along the dip of the joint. So, in such cases, one needs to install the contact pressure cells at the steel rib rock interface to measure directional loading on the steel ribs.

So, basically, pressure cells monitor the development of radial pressure on support from different directions.

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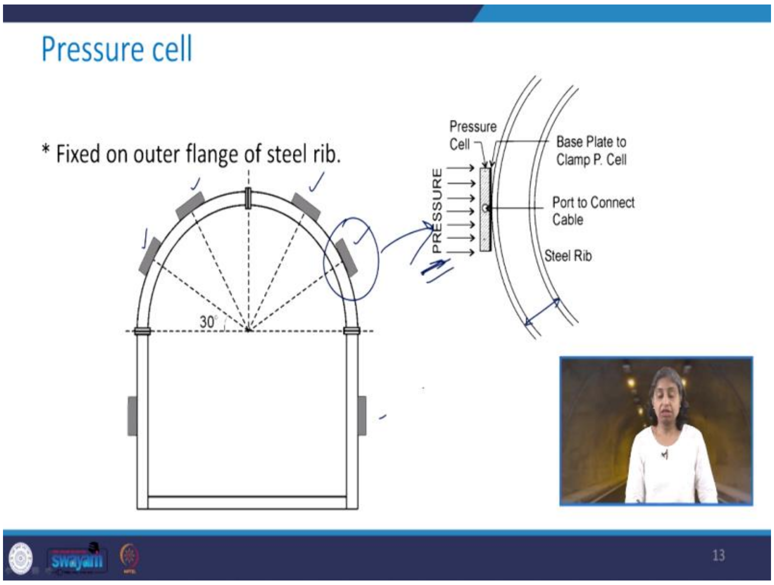

This is how the mounting of the pressure cell is done or the installation is done. See, these locations are of the pressure cells and, if you just take a enlarge version of this portion this looks like this. So, you have this as a steel rib. This portion is the steel rib it maybe I section or any other section. So, you have the pressure cell installed here and, then this is what is going to be the value of the pressure that is being exerted.

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So, we have typically this is how the pressure cells they look like. These are some of the pictures which are readily available on internet, just to give you the idea that how these look like.

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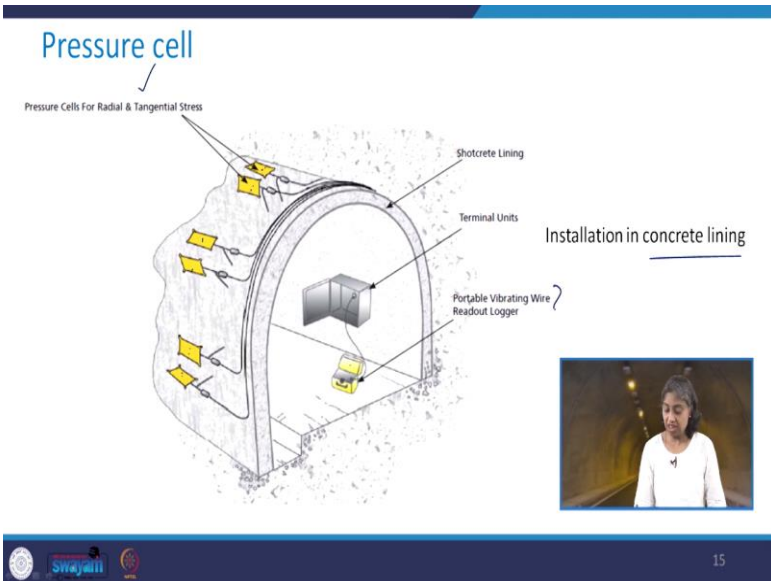

This is how the installation of pressure cells looks like in concrete lining. So, you see these yellow portions these yellow parts on the surface they are the pressure cells for the measurement of radial stresses. You see that these are all connected to the terminal units which in turn is connected with the portable vibrating wire readout logger.

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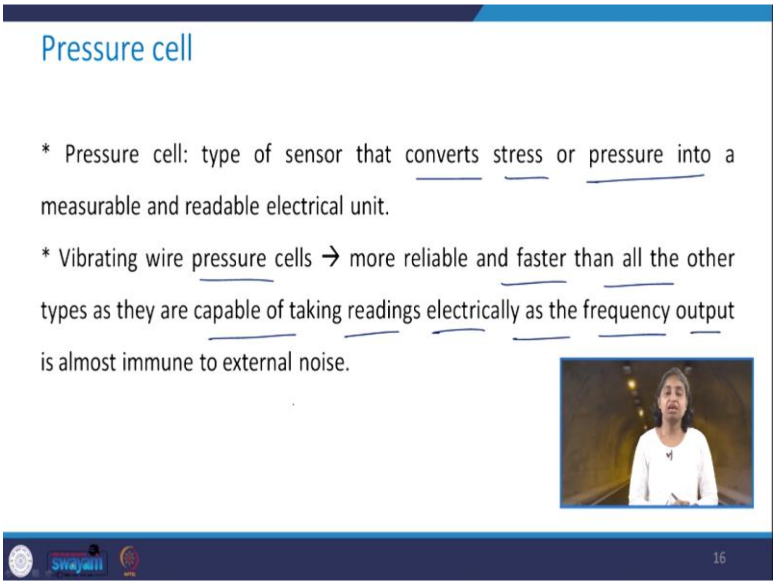

These pressure cells are the type of sensors that convert stress or pressure into the measurable and readable electrical unit. There are various types of pressure cells, but vibrating wire pressure cells are more reliable and faster than any other types because these vibrating wire pressure cells are capable of taking readings electrically as the frequency output is almost immune to the external noise. So, they have the added advantage over other types of pressure cells.

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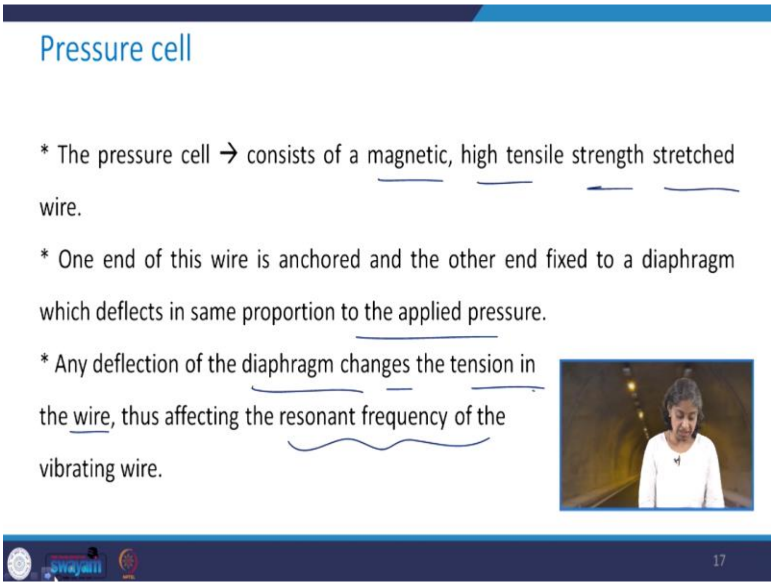

These pressure cells consist of a magnetic high tensile strength stretched wire. So, one end of this wire is anchored and the other end is fixed to a diaphragm which reflects in the same proportion to the applied pressure. Any deflection in the diaphragm changes the tension in the wire and hence affecting the resonant frequency of the vibrating wire.

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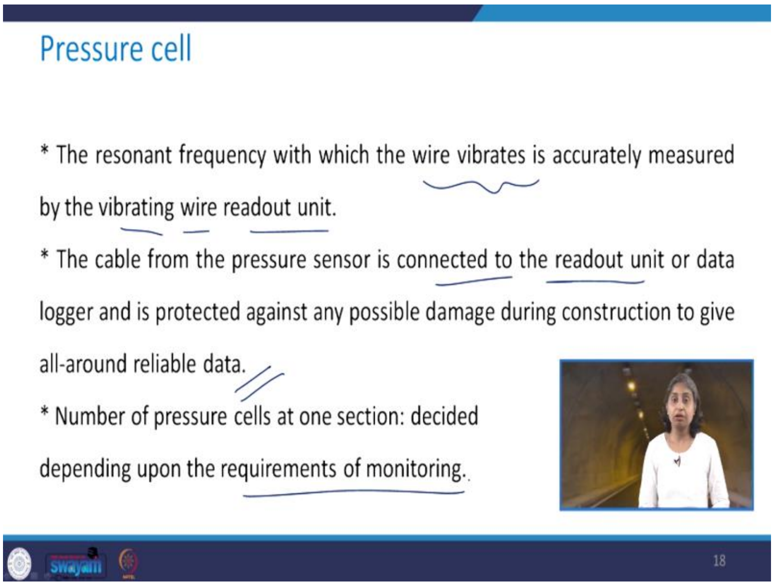

This resonant frequency with which the wire vibrates is accurately measured by the vibrating wire readout unit and the cable from the pressure sensor is connected to this readout unit or the data logger and is also protected against any possible damage during the construction to provide you all around reliable data with respect to time. How to decide the number of pressure cells at one location. This depends upon the requirement of monitoring.

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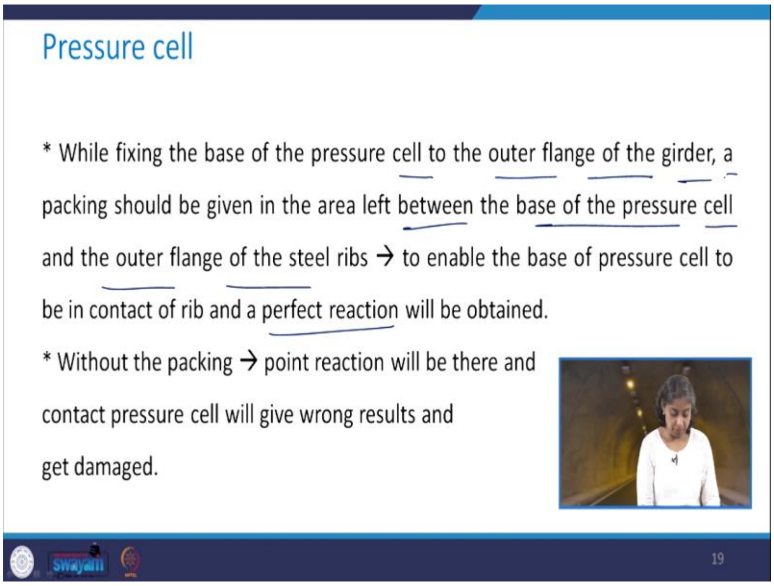

Now, while fixing the base of the pressure cell to the outer flange of the girder, how this is done we just saw it in a zoomed version of a figure. There should be a packing in the area which is left between the base of the pressure cell and outer flange of the steel ribs. What will happen when we do this there is going to be the proper contact of the rib and the pressure cell.

And, this will enable the perfect reaction without the packing there is going to be the point reaction and the contact pressure cell will not give us the correct result or it may also get damaged.

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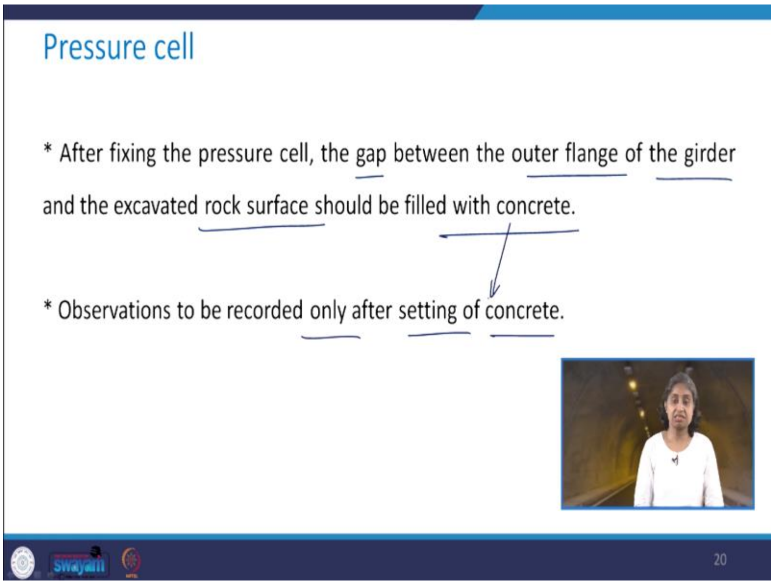

When we fix the pressure cell, we should keep that in mind that the gap between the outer flange of the girder and the excavated rock surface it should be filled with concrete because, if these are not in contact with each other the load from the rock surface will not be transferred to the girder and the readings that you will get from the pressure cells they will be erroneous. So, the observation should be recorded only after this concrete is set.

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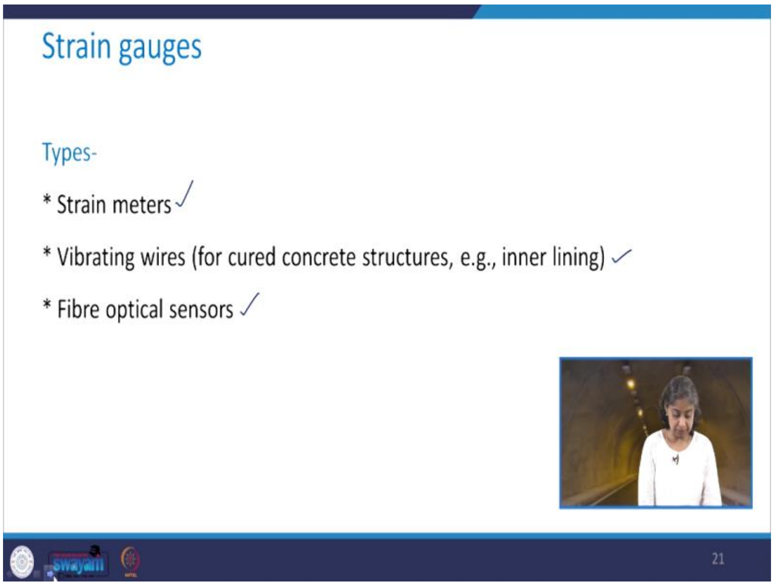

Coming to the next category, I mentioned to you that strain gauges are equally important. So, we have three types of strain gauges. One is the strain me,ters, second one is the vibrating wires these are suitable for cured concrete structures. For example, inner lining and then we have fibre optical sensors.

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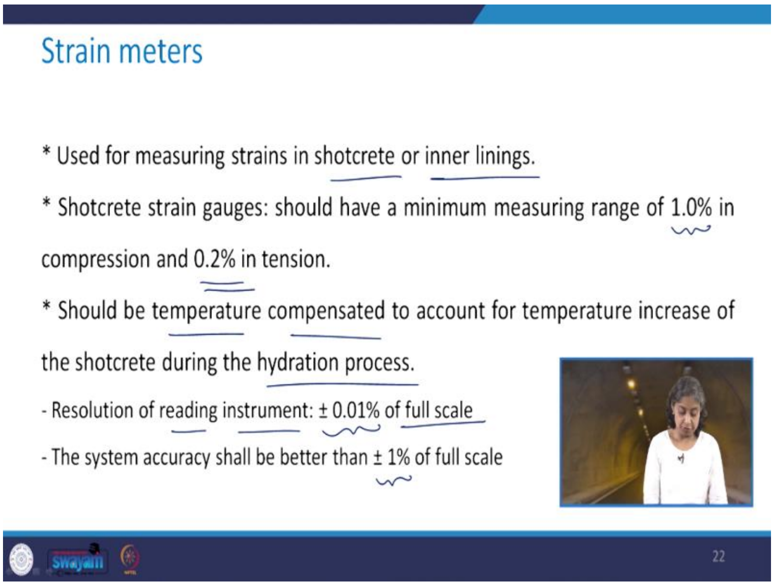

So, coming to the strain meters, these are used to measure the strains in shotcrete or inner lining. The shotcrete strain gauges should have a minimum measuring range of 1% in compression and 0.2% in tension. These should be temperature compensated to account for the temperature increase which will take place in the shotcrete during the hydration process. Further, the resolution of the reading instrument should be plus minus 0.01% of the full scale, and the system accuracy shall be better than plus minus 1% of full scale.

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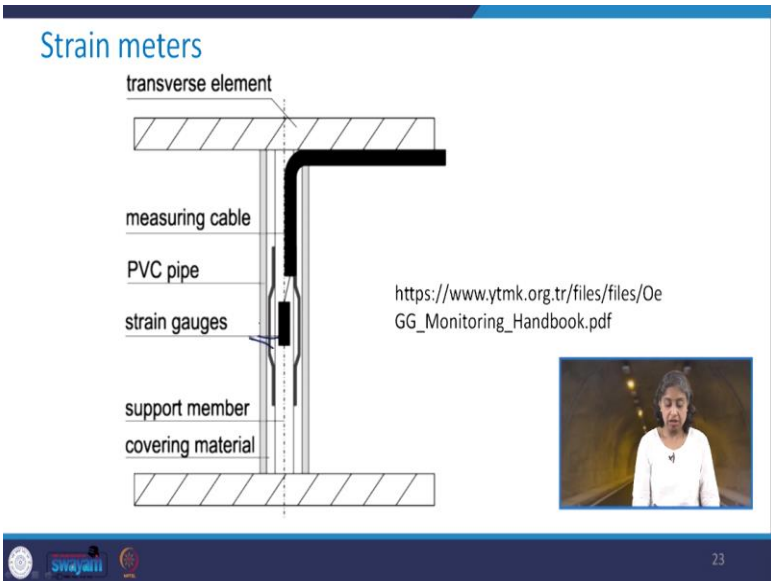

This is how strain meter here will look like. So, you have here these are the strain gauges which have been installed and you have the PVC pipe. This is what is the measuring cable.

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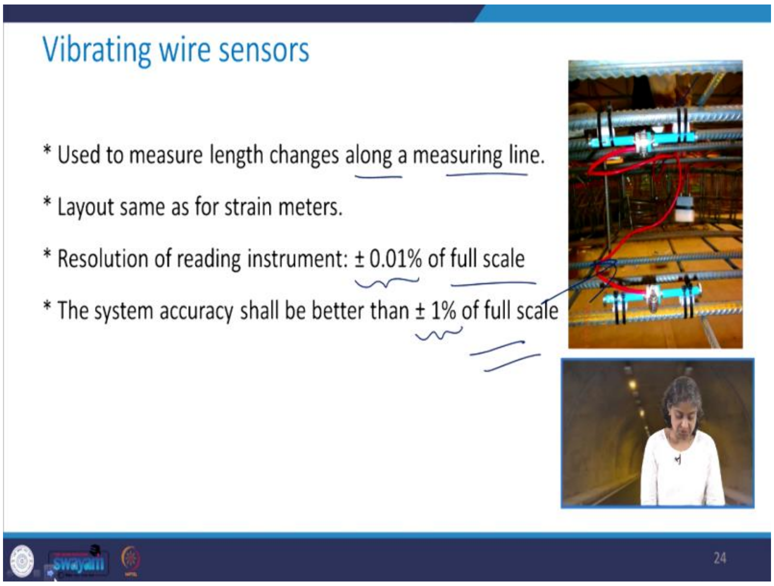

Coming to the next category which is the vibrating wire sensors as has been shown in this particular figure. So, these are used to measure the length changes along measuring line. Their layout is same as that for the strain meter and the resolution of the reading instrument should be 0.01% plus minus of full scale. The system accuracy shall be better than plus minus 1% of the full scale, as it was there in the strain meter case.

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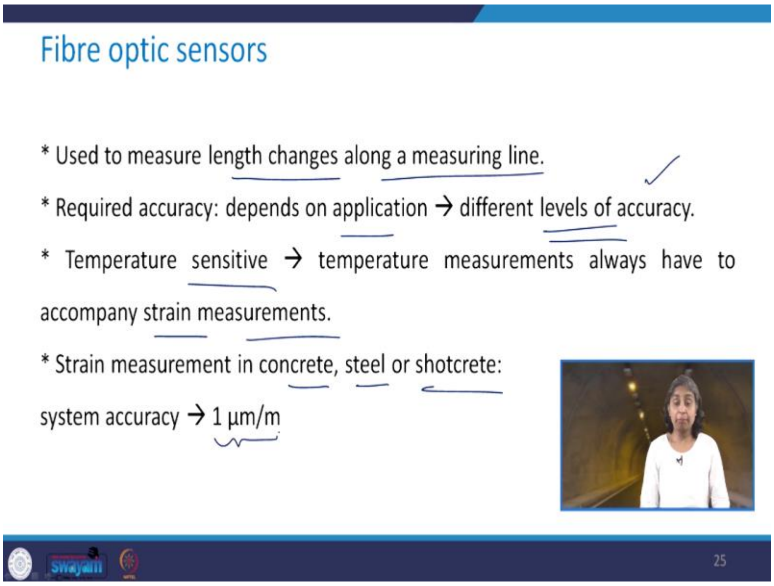

Then, we have the next categories of these strain gauges is optical fibre sensors. These are used to measure the length changes along a measured line. Required accuracy it depends upon the application and there are different levels of accuracy. So, accordingly, this will be decided. These are temperature sensitive. So, temperature measurements always have to accompany the strain measurements. Strain measurement in concrete steel or the shotcrete is done with the system accuracy of one micrometer per meter.

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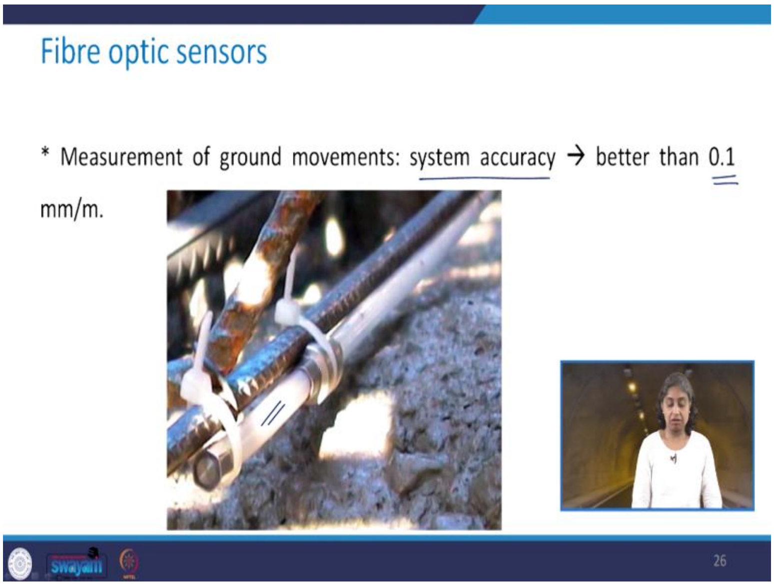

The measurement of the ground movement should be done with the system accuracy better than 0.1 millimeter per minute and, you can see here that this is the optical fibre and the sensors attached with the support system.

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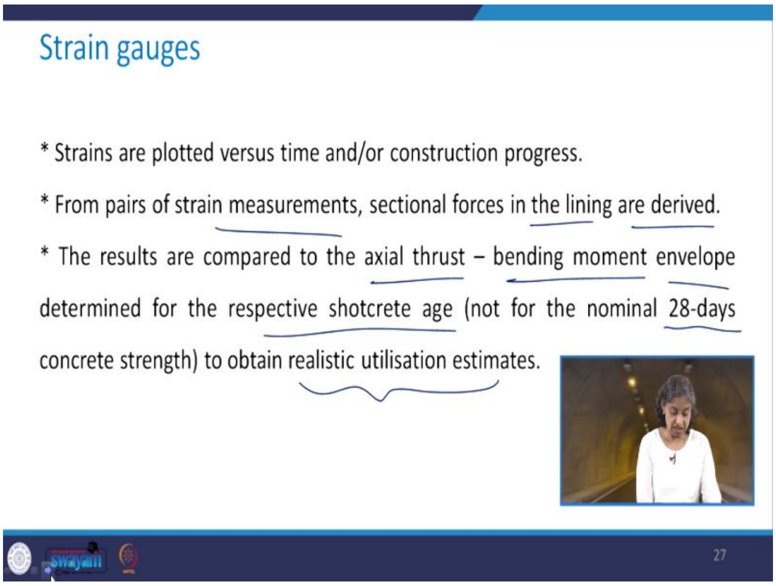

Strain gauges coming to the other aspects. In this case, the strains are plotted versus time and or construction progress. So, that means these strains are plotted with respect to time during the construction and even beyond that from pairs of these strain measurement. The sectional forces in the lining they are derived. So, always remember that these strain gauges should be used in pairs.

The results are compared to the axial thrust, bending movement envelope, which is determined for the respective shotcrete age and, which is not the nominal 28 days of concrete strength to obtain the realistic utilization estimates which you get from the strain gauges.

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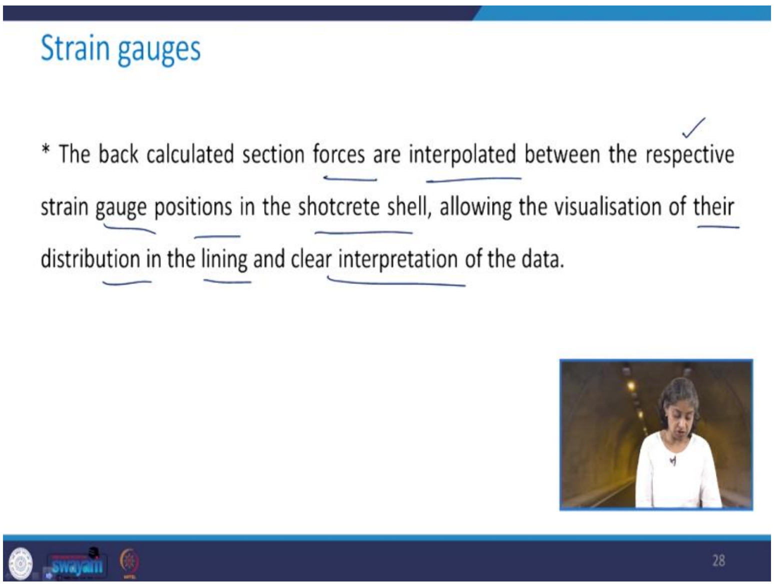

Then the back-calculated section forces are then interpolated between the respective strain gauge positions in the shotcrete shell. This allow the visualization of their distribution in the lining and the clear interpretation of the data that you obtain from the strain gauges.

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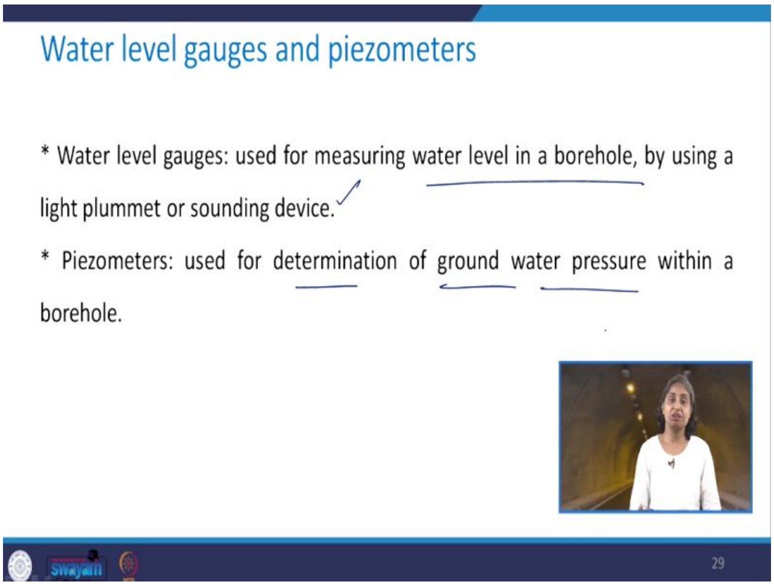

Now, wherever there is a presence of water it is important for us to use the water level gauges and the piezometers. So, this water level gauges, they are used for measuring the water level in a borehole by the use of sounding device. While the piezometers these are used for the determination of groundwater pressure within a borehole. So, you must have studied or heard of this piezometer, when you study the course on soil mechanics especially the chapter on permeability or seepage that how do you determine the pore water pressure? So, it is the same piezometer.

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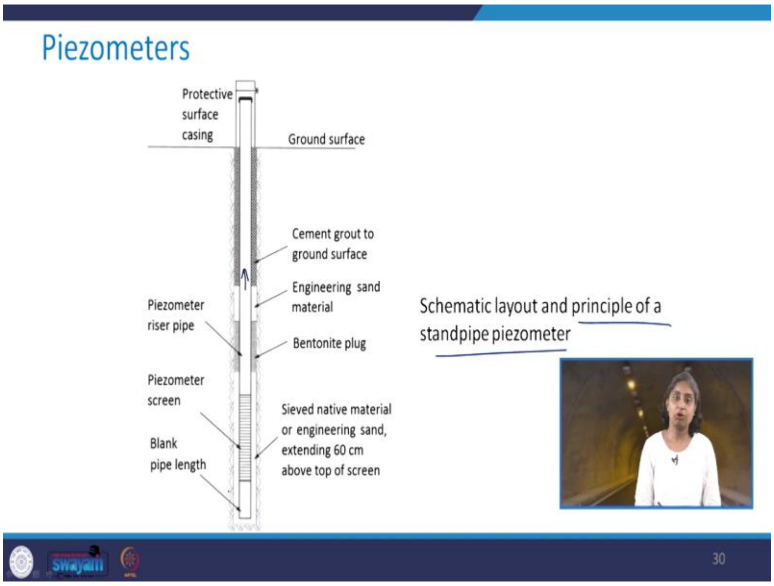

This is how, a typical schematic layout and principle of standpipe piezometer looks like. So, you insert the piezometer and with the pressure, the water rises into this particular pipe, and then from that height of the rise of the water you can determine the pore water pressure.

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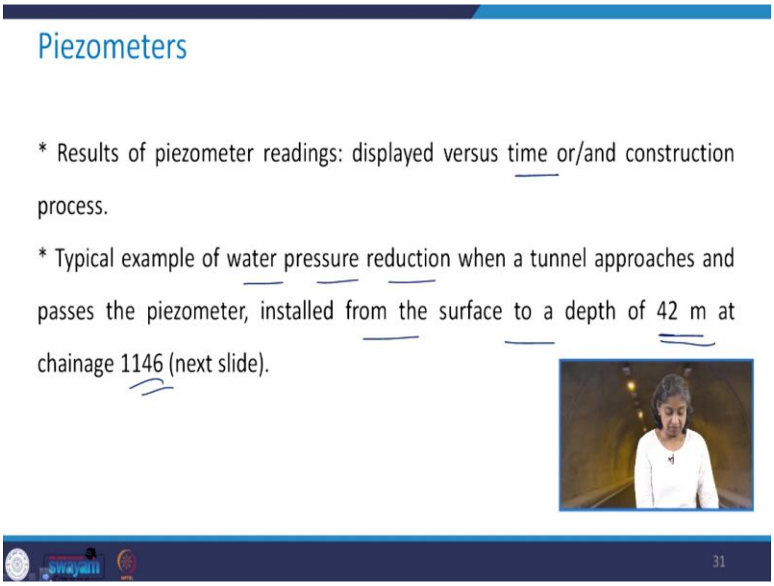

The results of the piezometer reading, these are displayed versus time during and after the construction. The typical example of the water pressure reduction, when a tunnel approaches and passes the piezometer installed from the surface to a depth of 42 meter at this chainage 1146 is just shown here.

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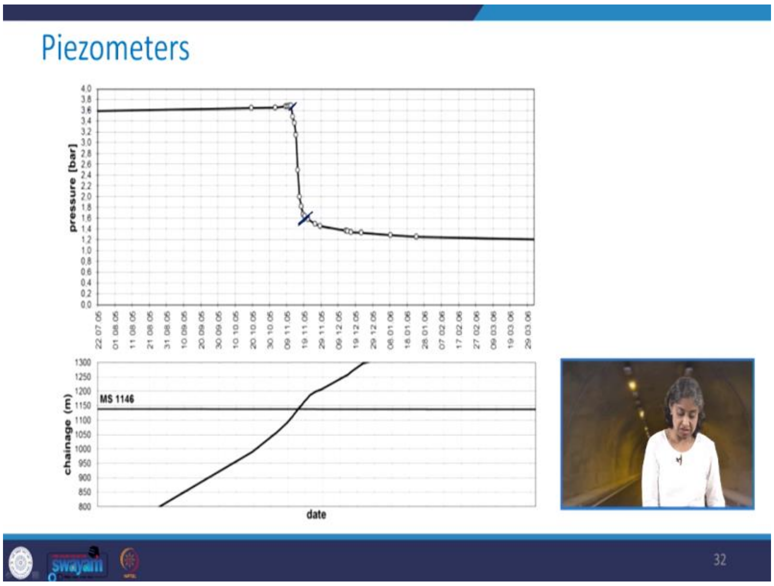

So, you can see that here there is a sudden drop of the pressure maybe to the tune of say from 3.6 bar to approximately maybe 1.6 bar. So, drastic change of 2 bar of the pressure is taking place.

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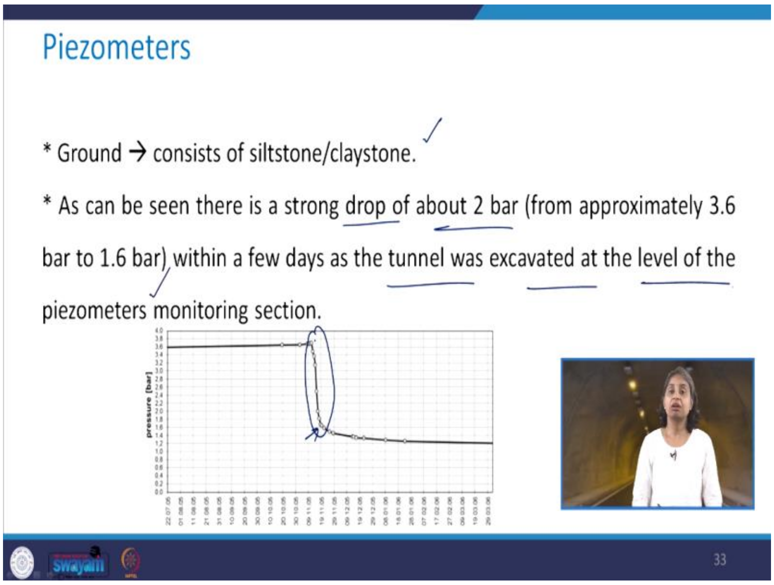

So, in this case, the ground was consisting of siltstone and the claystone, and as I mentioned to you that if you notice this particular zone, then there is a strong drop of about 2 bar which is approximately from 3.6 bar to 1.6 bar just within few days as the tunnel was excavated at the level of the piezometer monitoring section.

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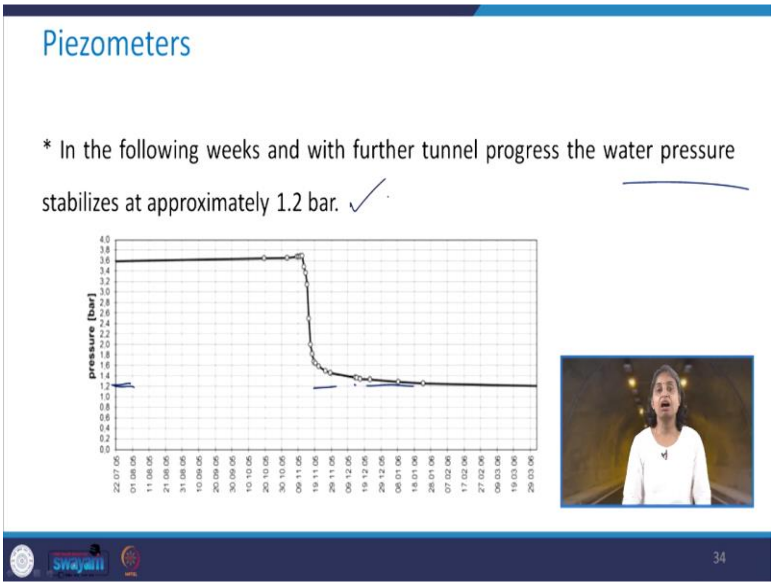

Then in the following weeks and with further tunnel progress the water pressure stabilizes at approximately you see here this is the one. So, this is approximately 1. 2 bar. So, this is how that we can get the idea from the piezometers.

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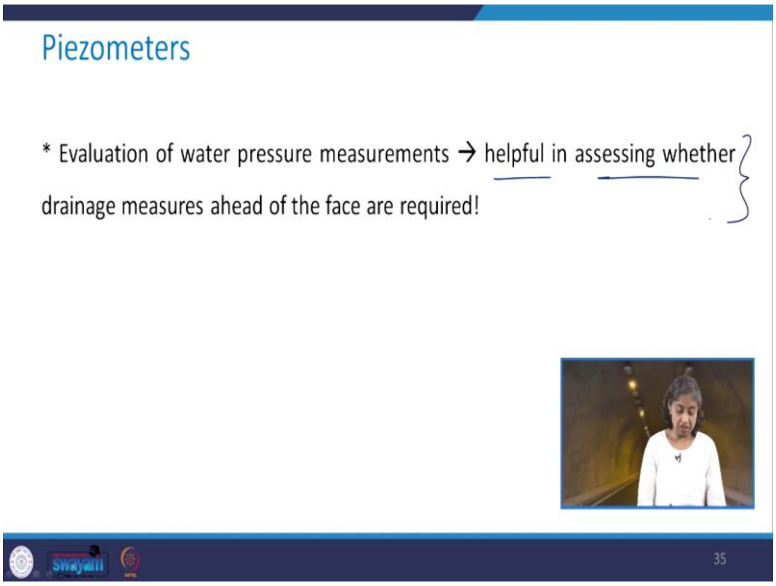

The evaluation of water pressure measurements these are helpful in assessing whether the drainage measures ahead of the face are required or not. So, therefore when we have the piezometer installed in the section this is how the information can be useful.

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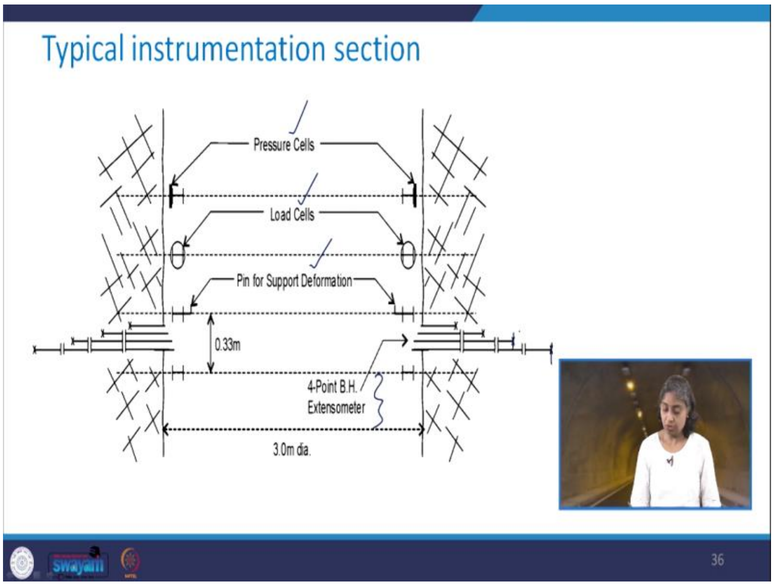

So, this was all about the various instruments used to measure the load or the pressure on the rock surface or in the support system. So, this is how the typical instrumentation section will look like and in this section, we have pressure cells, load cells and then pin for the support deformation along with the 4-point borehole extensometer. So, you see that the length of the borehole extensometer is known a prior.

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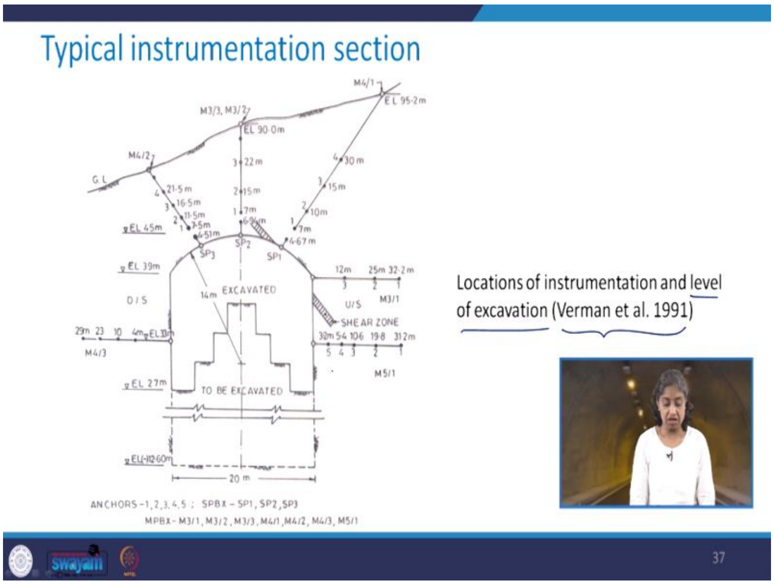

If we take the cross-section, this is how the instrumentation, location, and level of excavation typically may look like. So, this figure has been taken from reference which is given here. So, this is how here it was shear zone and all other properties, I mean I will give you the details of this reference towards the end of this class, and then maybe if you are interested you can take a look, but you see how extensive instrumentation has been done. All these are the location of the instrumentation.

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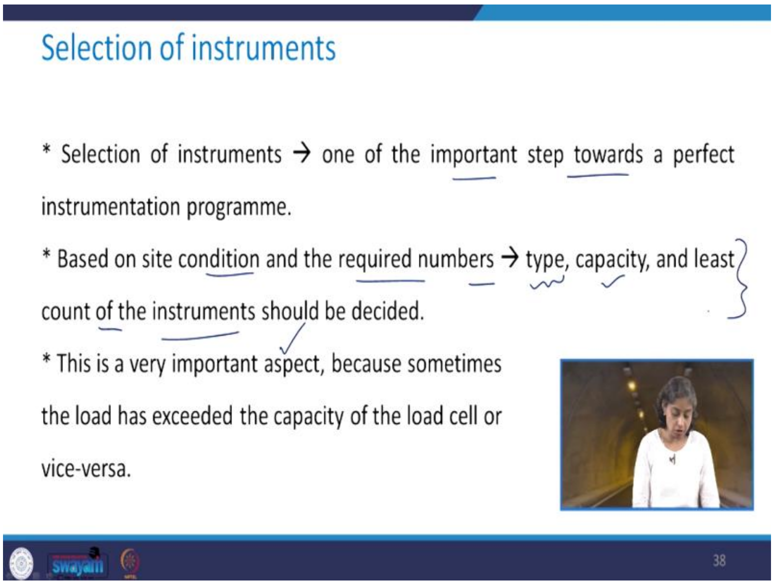

The question comes now is that, how should we select the instruments that which one should be used. So, this is one of the important step towards perfect instrumentation program. The selection of the instruments is done based on the site condition and the required numbers then type, capacity, least count of the instrument should be decided accordingly. This is a very important aspect because, sometimes the load if it exceeds the capacity of the load cell or if it is other way round, then it does not or then it defeats the purpose of the instrumentation.

So, we need to be extremely careful about deciding these parameters along with the selection of instruments.

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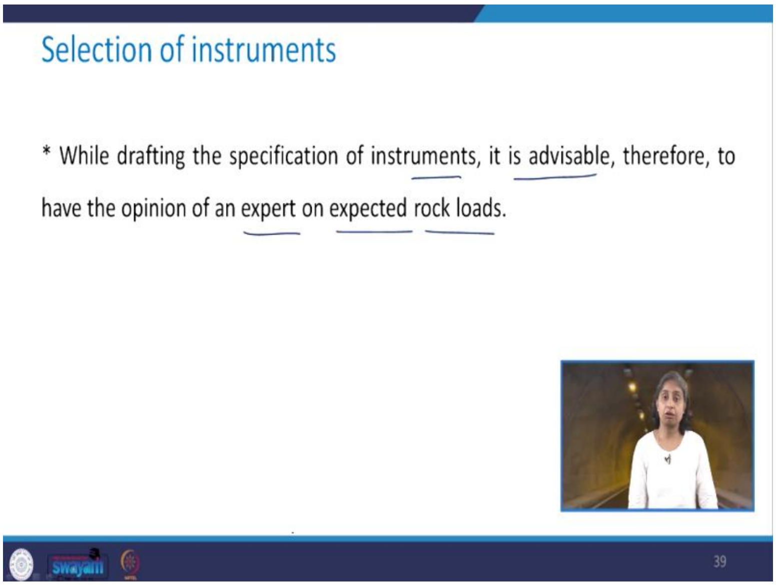

Now, while drafting the specification of instruments, it is advisable therefore to have the opinion of an expert on the expected rock loads.

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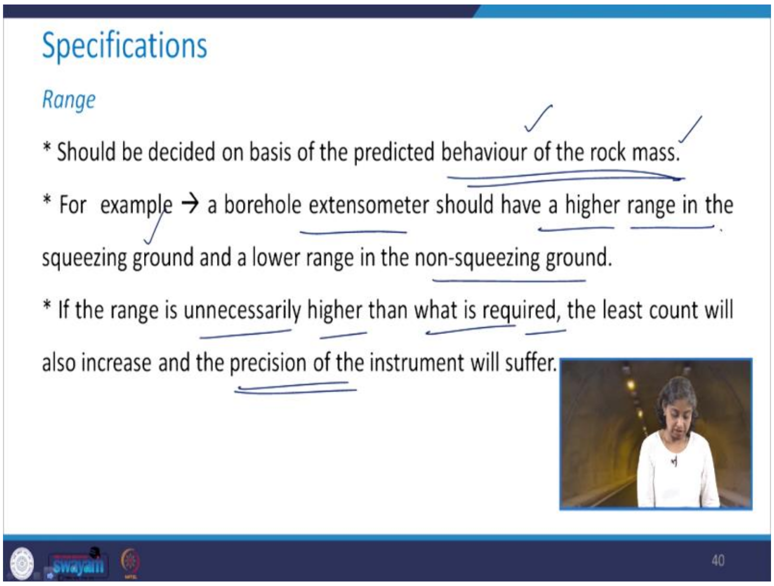

Coming to various specification of the different instrument. So, the first one is the range of the instrument which should be decided on the basis of predicted behaviour of the rock mass. Now, the question comes that how do we predict the behaviour of the rock mass? So, whatever we studied till now that knowledge will come handy to predict the behaviour of the rock mass.

For example, the classification of the rock mass and then what is going to be the support pressure, what is going to be the closure etcetera all those things will help here. For example, the borehole extensometer should have a higher range in the squeezing ground condition and the lower range in the non-squeezing ground condition, but then beforehand, we should know where is the squeezing ground condition at the site or if it is non-squeezing ground condition.

So, to decide this whatever that we learnt will be helpful. If the range is unnecessarily higher than what is needed the least count will also increase and the instrument will suffer as far as its precision is concerned.

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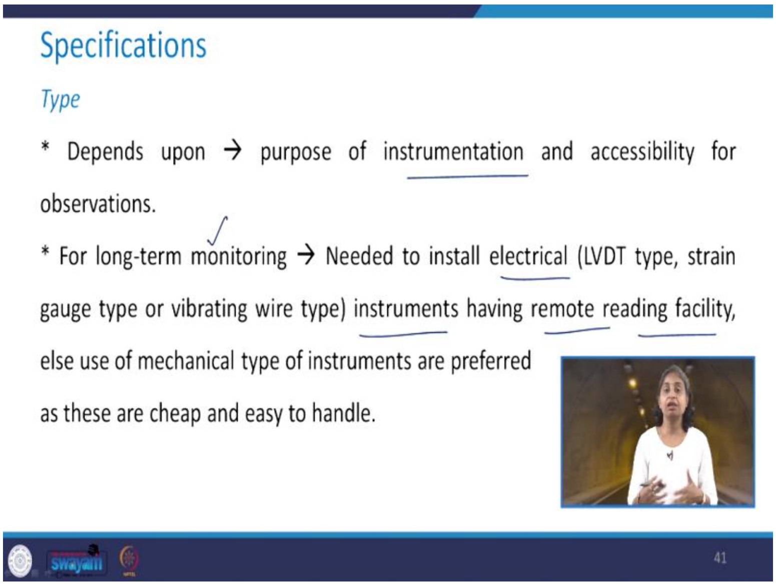

Type of the instrument that depends upon the purpose of the instrumentation and accessibility for observations. For long-term monitoring one should install the electrical instruments having remote reading facility. Otherwise, the use of the mechanical type of instruments they are recommended because, they are more economical and, easy to handle as compared to the electrical instruments.

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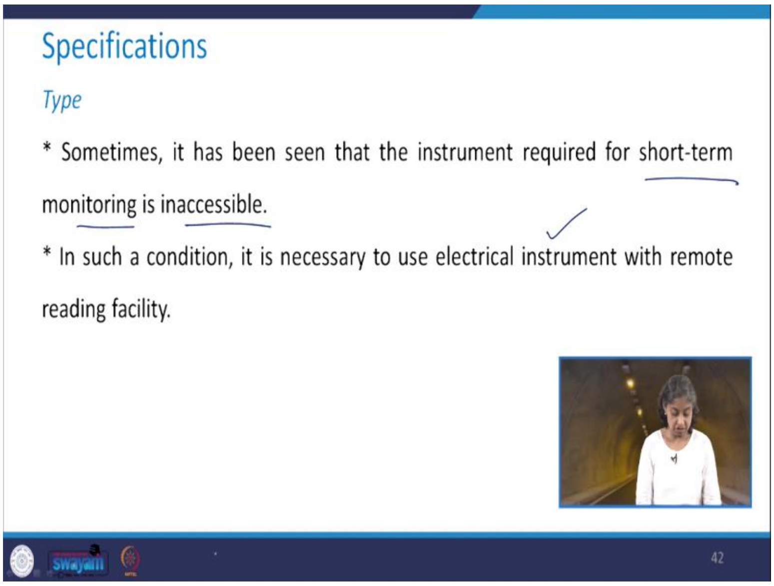

Sometimes it has been seen that the instrument required for the short-term monitoring in accessible and, in such a situation it becomes necessary for us to use the electrical instrument with the remote reading facility.

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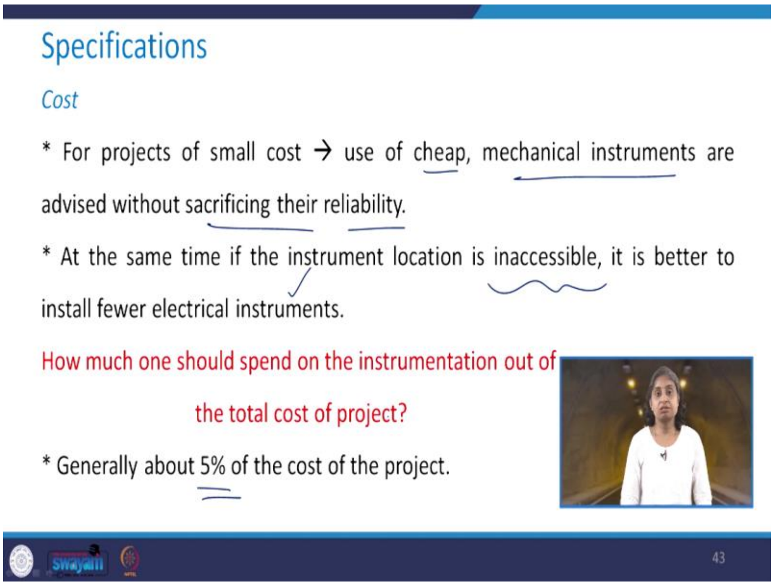

Cost is very, very important. So, when we have the projects of small cost one should use the cheap, mechanical instruments without sacrificing on their reliability. At the same time if the instrument location is inaccessible of course we do not have any choice, but to install few number of electrical instruments. So, the question comes that, how much one should spend on the instrumentation out of the total cost of the project.

So, the thumb rule is that about 5% of the cost of the project should be invested in the instrumentation and monitoring of the project which is usually compromised, so that should not be done because now you are aware that, why the instrumentation and monitoring of the underground excavations they are important.

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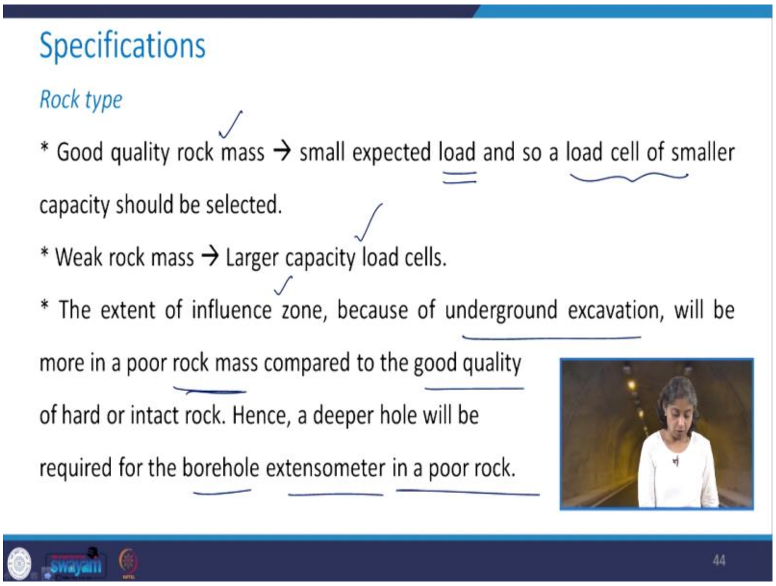

Coming to the rock type, so when we have the good quality rock mass we expect the smaller load and therefore the load cell of smaller capacity should be selected. However, in case of the weaker rock mass, one should go for the larger capacity load cells. The extent of the influence zone because of the underground excavation will be more in poor rock mass, as compared to the good quality rock mass which or maybe the intact rock.

And therefore, for the installation of the borehole extensometer in the poor rock, we would need a deeper hole because, if you recall what borehole extensometer does. It gives us the idea about the extent of the loosened rock mass. So, in case if there is the poor-quality rock mass there is going to be the larger extent of the influence zone or the loosened rock mass. So, the deeper hole will be needed for borehole extensometer in poor rock.

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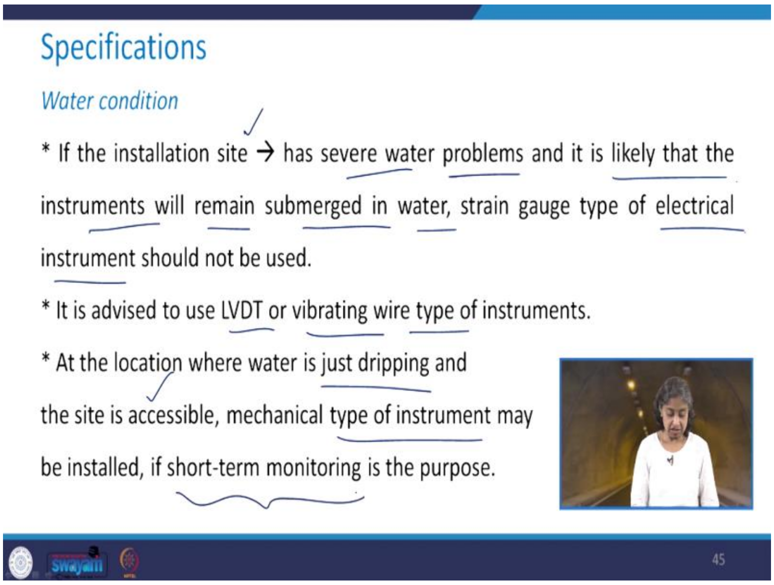

Coming to the water condition this is also one of the deciding factor about the specification of the instruments. So, if the installation site has severe water problems and it is likely that the instruments will remain submerged in water. Strain gauge type of the electrical instrument these should not be used. It is advised to use LVDT or vibrating wire type of instruments. At the location where water is just dripping and the site is accessible.

Mechanical type of the instrument maybe installed if you have the short-term monitoring to be done.

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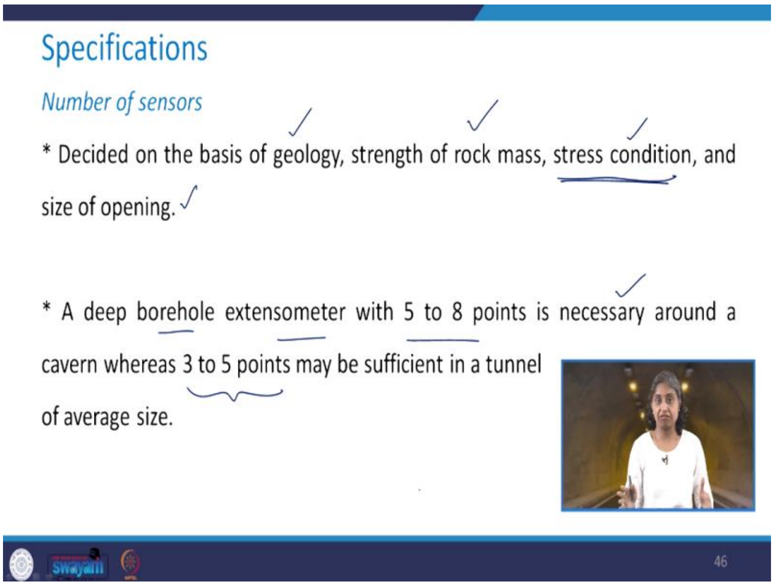

Coming to the number of sensors which should be installed. So, these should be decided on the basis of geology, strength of rock mass, stress condition, and the size of opening. When we say stress conditions, so, there we need to see whether it is a uniaxial, biaxial or true triaxial type of the state of stress in the field. A deep borehole extensometer with 5 to 8 point is necessary around a cavern, where 3 to 5 points may be sufficient in a tunnel of average size.

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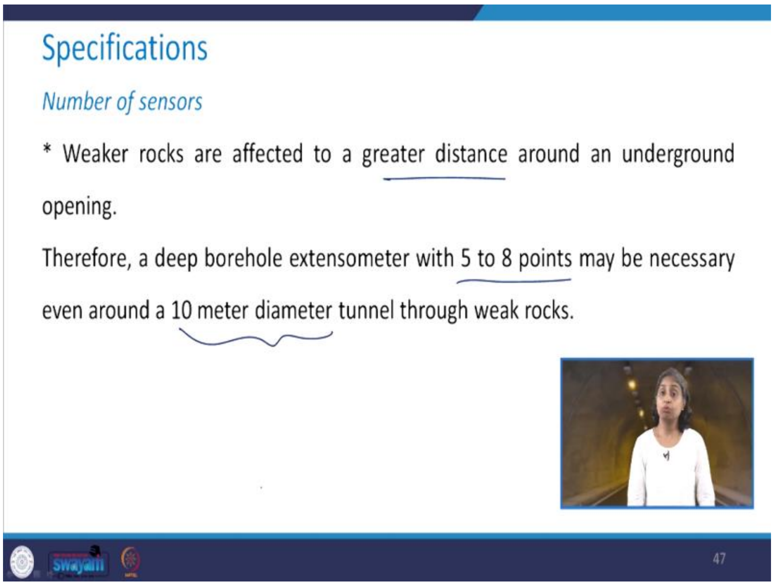

There is weaker rocks are affected to a greater distance around an underground opening and, hence the deep borehole extensometer with 5 to 8 points maybe necessary even for 10-meter diameter tunnel through weak rocks.

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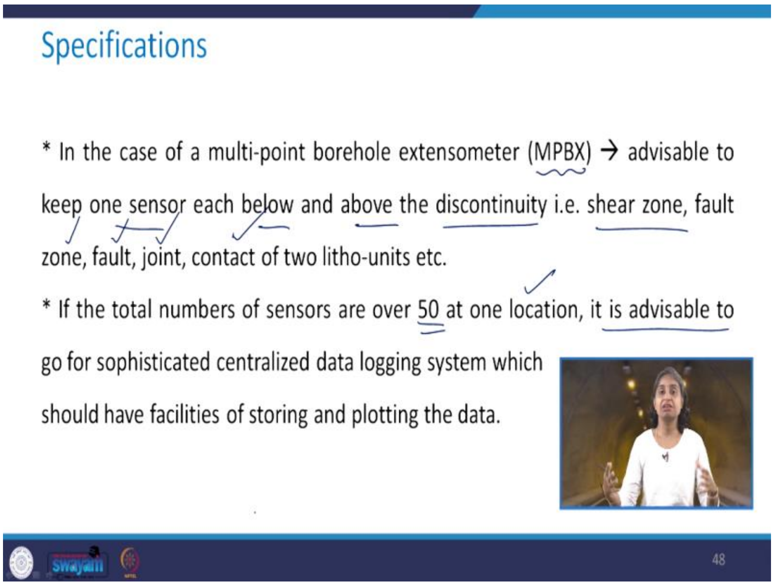

Now, in case of the multipoint borehole extensometer that is MPBX. It is advisable to keep one sensor each below and above the discontinuity which maybe the shear zone, fault zone, fault, joint, or the contact of two litho units. If the total number of sensors are more than 50 at any particular location. It is advisable to go for the sophisticated centralized data logging system, which should have the facility of storing and plotting the data. Otherwise, it will be difficult for you to handle such huge data.

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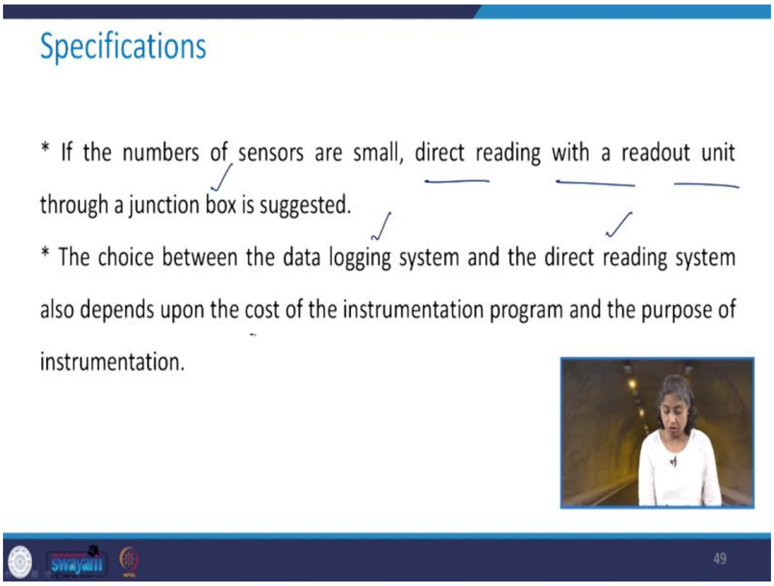

If the number of sensors are small, then maybe direct reading with a readout unit through a junction box will serve the purpose. The choice between the data logging system and the direct reading system also depends upon the cost of the instrumentation program and, of course the purpose of the instrumentation.

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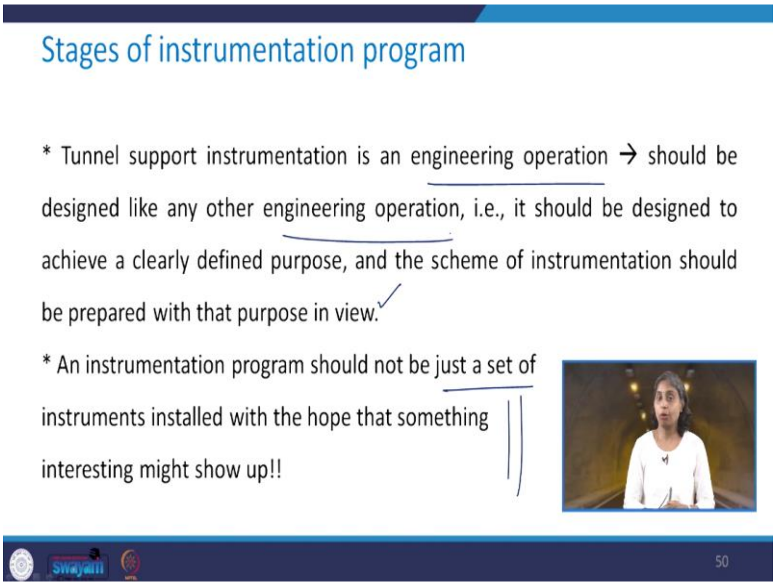

What all are the various stages of any instrumentation program? Basically, this tunnel support instrumentation is an engineering operation and it should be designed like any other engineering operation that is it should have the clearly defined objective, and then what should be the scheme of the instrumentation all these things should be prepared with that purpose in view.

An instrumentation program should not be just a set of instruments which are installed with the hope that something interesting might show up, but then it is much more than this particular thing. One needs to keep that in mind that, this is an engineering operation like any other engineering operation, where you need so many aspects to keep in mind.

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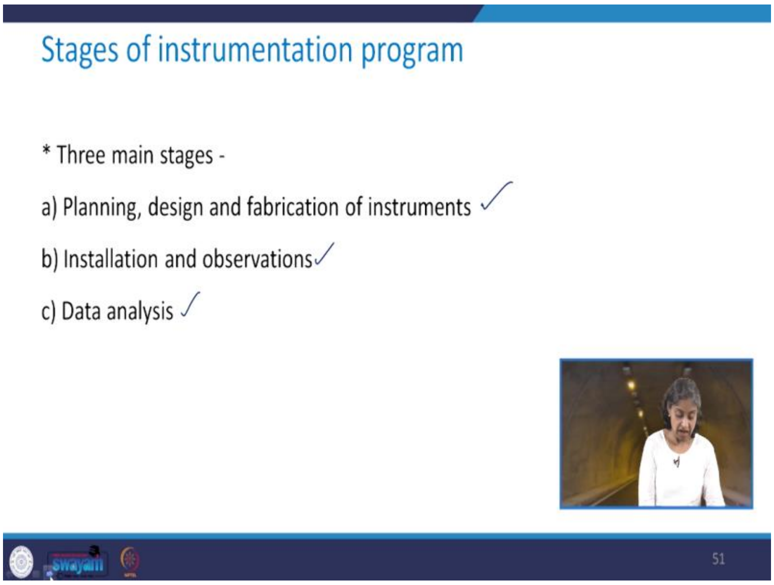

There are basically three main stages. One is the planning, design, and fabrication of instruments, then the installation and observation, and then whatever data that you obtain from these observations the analysis of that.

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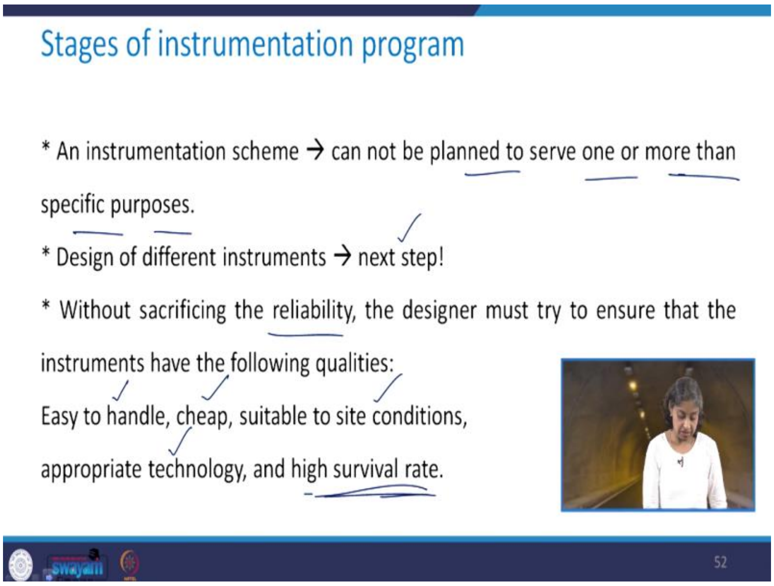

So, the instrumentation scheme, it cannot be planned to serve one or more than one specific purposes. The design of different instrumentation it comes as a next step. So, without sacrificing the reliability the designer must try to make sure that the instruments have the following qualities that is these should be easy to handle, economic, Should be suitable to the site conditions.

And they use appropriate technology and they have the high survival rate because this instrumentation will go on maybe for few years. So, this is very very important aspect, that is high survival rate.

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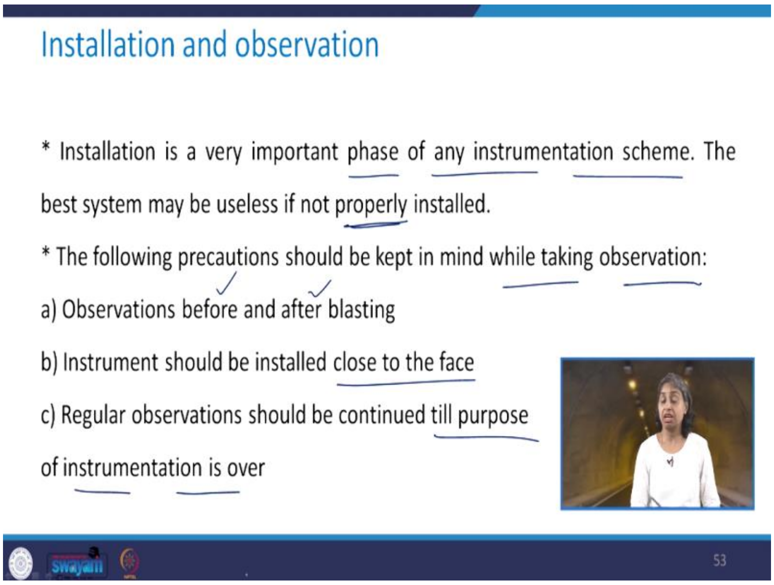

The installation of the instruments is a very important phase in any instrumentation scheme. The installation of the instruments is a very important phase in any instrumentation scheme. The best system maybe useless if you do not install it properly. So, the following precautions should be kept in mind while taking the observations. The observation should be taken before and after the blasting, instruments should be installed close to the face then regular observation should be continued till the purpose of the instrumentation is over even after the construction.

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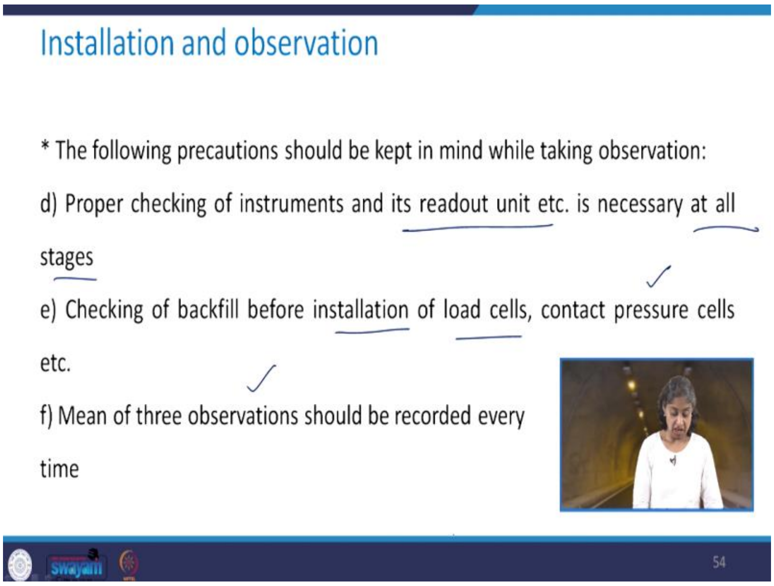

Then, the proper checking of instruments and its readout units etcetera is extremely important at all these stages. Checking of backfill before the installation of load cells and the contact pressure cells is important then you should always go with mean of three observation which are recorded every time. So, wherever you are going to take the observation, you take the three observation and record the mean of these three.

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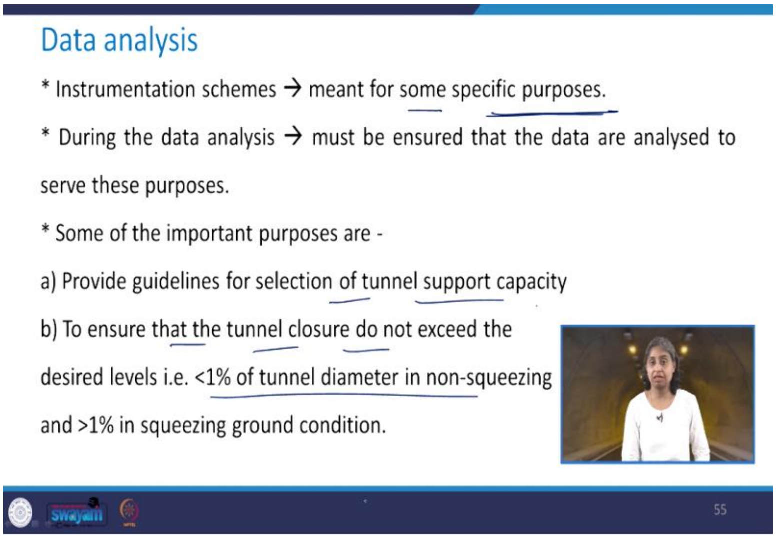

Coming to the data analysis, any instrumentation scheme is meant for some specific purpose. So, during the data analysis, we should keep that in mind that the analysis should serve all these purposes. Some of the important purposes can be, that to provide the guidelines for the selection of tunnel support capacity or to ensure the tunnel closure should not exceed the desired levels that is the tunnel closure should always be less than 1% of the tunnel diameter in non-squeezing and it can be more than 1% in the squeezing ground conditions.

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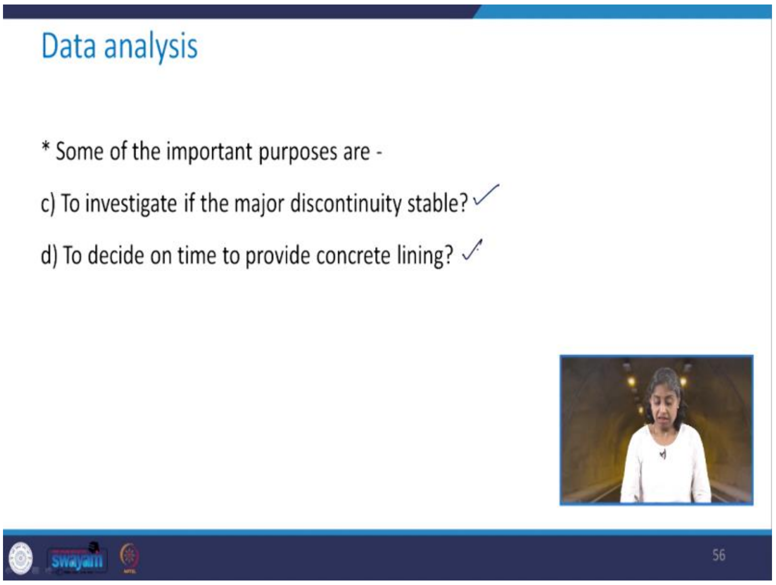

Then, other purpose is to investigate if the major discontinuity is stable or not and to decide on the time to provide the concrete lining.

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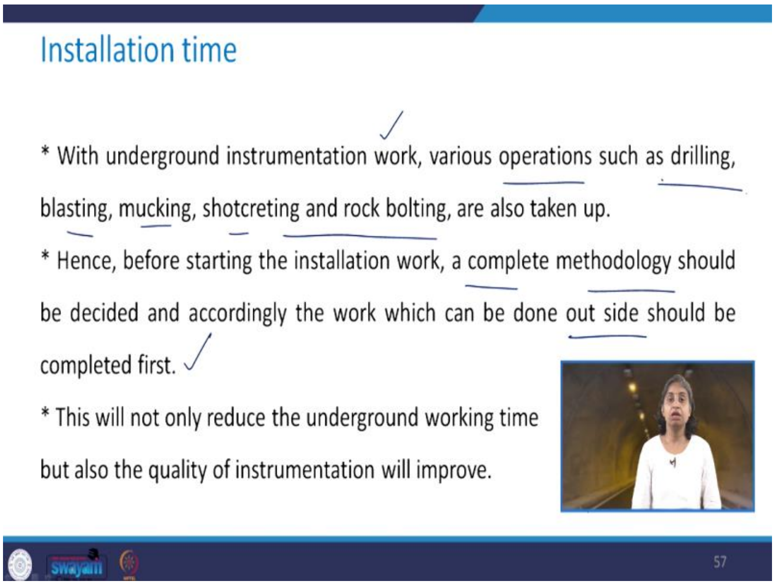

What about the installation time? So, we have discussed about the stand-up time and I mentioned to you that, the installation of the support system should not be too late or too early, but then here we are talking about the installation time of the instruments. So, with the underground instrumentation work various operations are there, such as the drilling, blasting then mucking operation then the installation of the support system.

Therefore, before starting the installation of the instrument a complete methodology should be decided, and accordingly, the work that can be done outside should be completed first.

This will not only reduce the underground working time, but it will also improve the quality of the instrumentation program.

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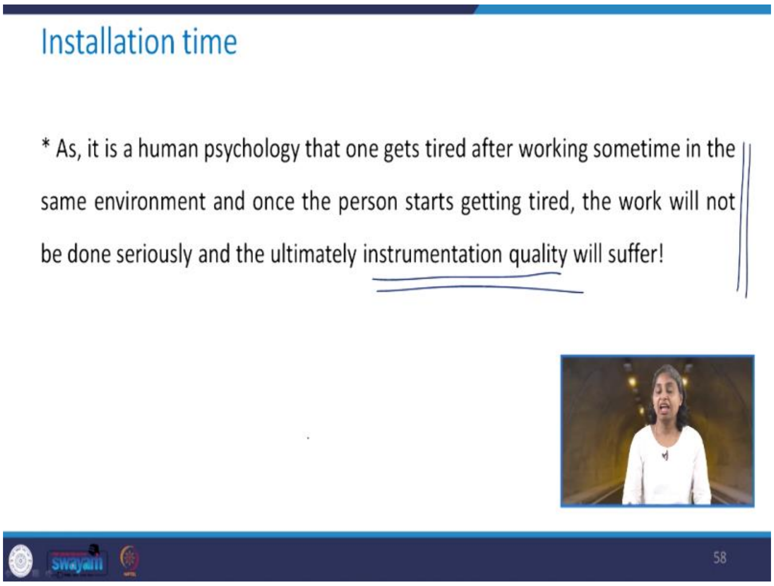

Since it is our psychology that, we get really tired after working for some time in the similar environment and one person starts getting tired then the work will not be done to that serious extent and the ultimate suffering will be to the quality of the instrumentation. So, therefore this should be kept in mind what I mean is the persons who are involved in the installation of the instrumentation.

We should be careful as far as their physical and mental conditions are concerned while working.

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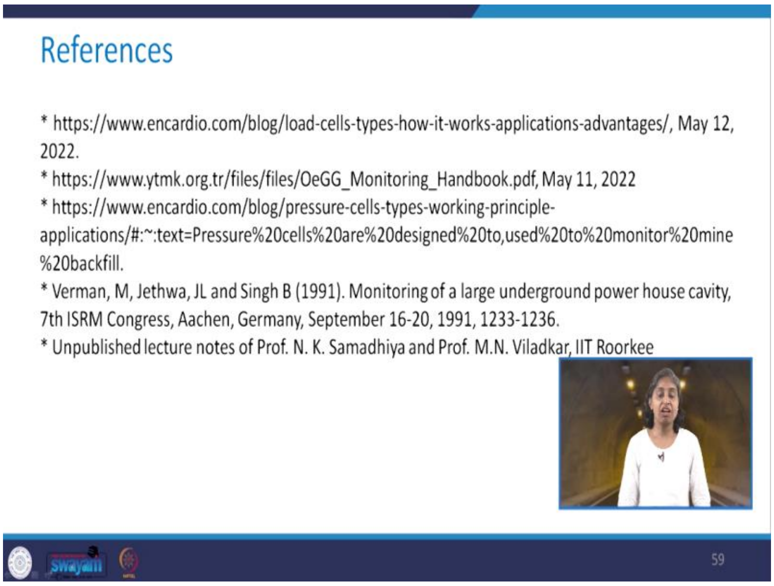

So, these are some of the references which have been followed for the preparation of this particular lecture. So, this finishes our discussion on instrumentation and monitoring of the tunnels. So, in this one, we discussed about, the various instruments to measure the deformation or movement of the rock mass and we also discussed about the instruments, which are used to measure the loads on the support system or pressure on the support system along with some discussion on strain gauges and piezometers.

So, in the next class, we will learn about some of the case studies, where the concepts that we have learnt till now were used and in some cases, the failure was there and, in few cases, because of this instrumentation and proper monitoring, we could say that particular underground excavation from failure. Thank you very much.