Underground Space Technology

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Lecture – 58

Instrumentation and Monitoring of Tunnels - 01

Hello everyone, In the previous class we discussed about the hydraulic fracturing test. This test is conducted to determine the state of in-situ stresses in the rock mass. So, today we will start a new topic which is related to instrumentation and monitoring of the tunnels. So, we will learn that what exactly is the need for the instrumentation of the underground excavations and then, we will learn about some of the instruments, which are used to measure the deformations in the rock mass.

So, first, we start our discussion with the question that what is the need for the instrumentation.

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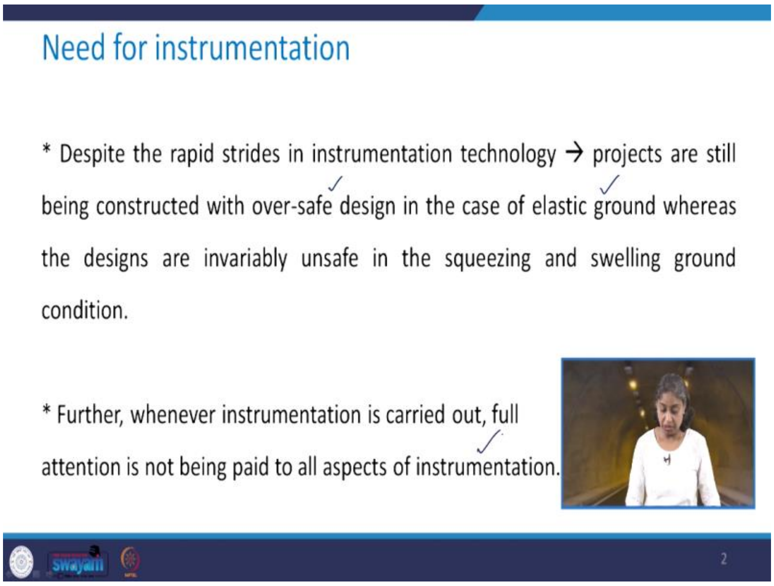

Now, despite of the lot of development in the area of instrumentation, still, many geotechnical projects are being constructed with over shape design, in case of the elastic ground, where the designs are invariably unsafe in the squeezing and swelling ground conditions. On the other hand, wherever the instrumentation is carried out proper attention is not being paid to various aspects of the instrumentation.

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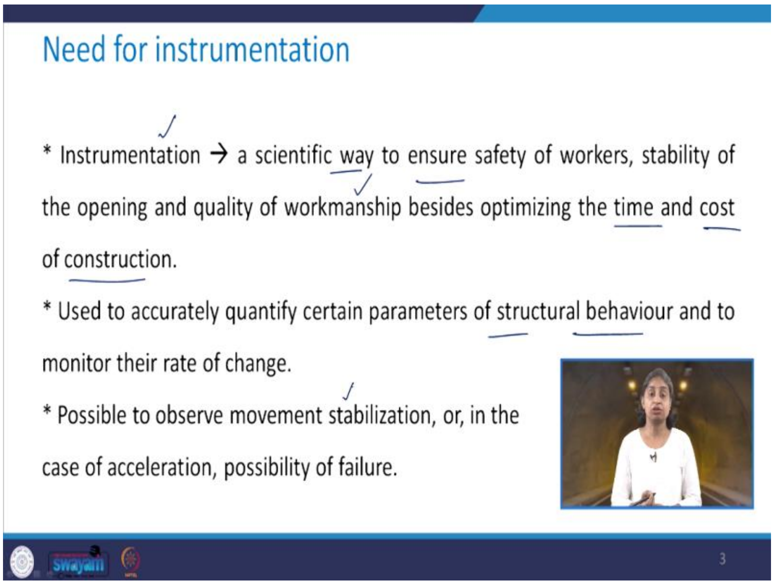

So, to keep this in mind, here, we are going to discuss some aspects related to the instrumentation that what exactly do we mean by the instrumentation, and then we will see that, what all instruments are available for the purpose of monitoring of the tunnels in rock mass. So, the instrumentation is a scientific way to ensure the safety of workers, stability of opening, and the quality of workmanship.

Besides it also helps in optimizing the time and the cost of construction. It is used to accurately quantify some of the parameters of structure behavior and to monitor their rate of change. So, some of such behaviour includes the deformation, the state of stress in the support system etcetera. It is possible to observe the movement stabilization or in case of the acceleration the possibility of the failure by means of instrumentation.

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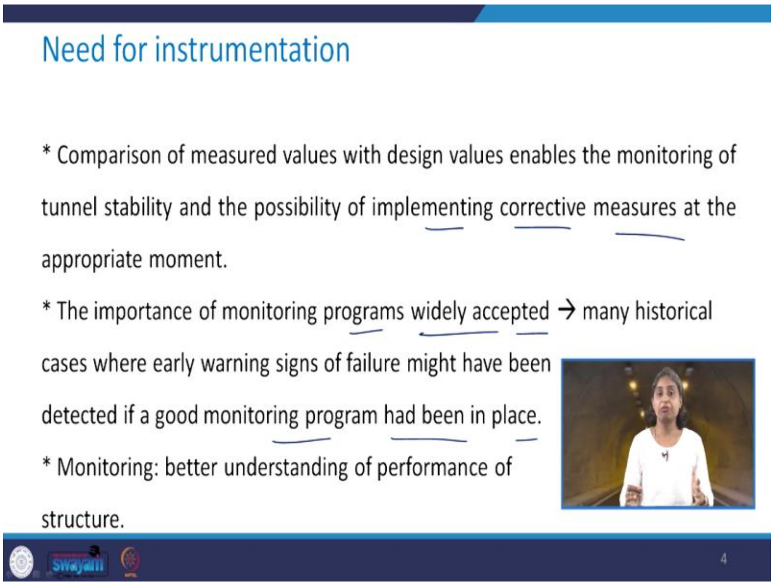

One can compare the measured value with the design values, this enables the monitoring of tunnel stability and the possibility of implementing the corrective measures at an appropriate moment. So, just before the failure or maybe, wherever you are getting the sign of let us say excessive deformation or the larger stress level. There you can, if you get the idea about the possibility of such things, then, you can take the appropriate measures at the appropriate times.

The importance of the monitoring programs is widely accepted. There are many historical cases, where early warning sign of failure might have been detected, if a good monitoring program had been in place. The monitoring provides us the better understanding of the performance of the structure.

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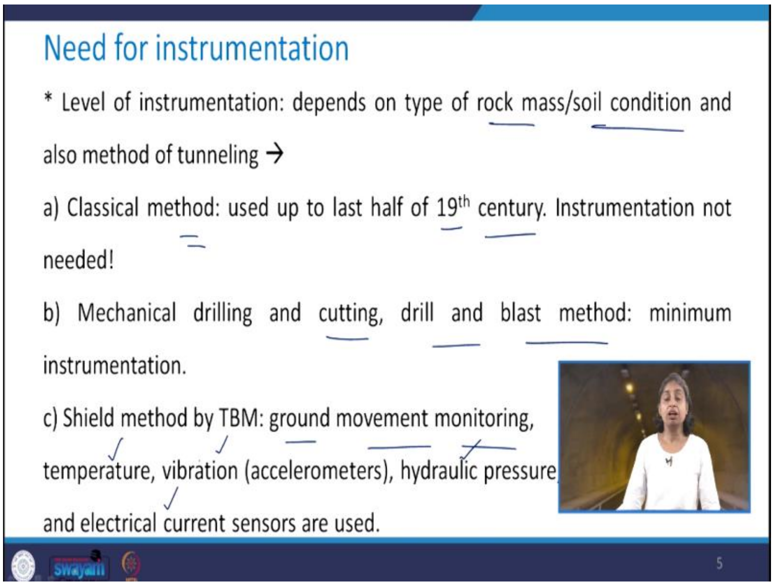

Coming to the level of instrumentation, this depends on the type of rock mass or soil conditions and also on the method of tunneling. So, if we have the classical method which was used up to last half of 19th century instrumentation was not needed. If we go for mechanical drilling and cutting or drill and blast method, minimum instrumentation is required, but when we go for the shield method by TBM which is tunnel boring machine.

In that case, ground movement monitoring, temperature, vibration, hydraulic pressure, and electric current sensors are used.

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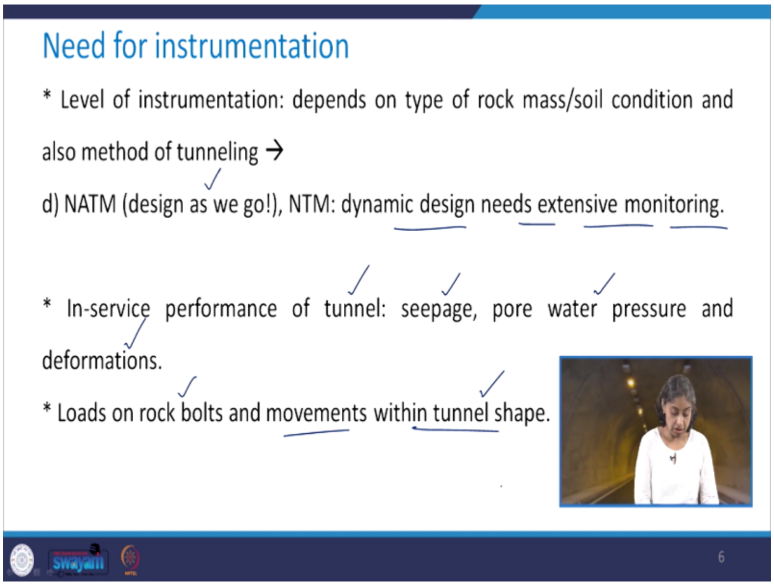

Another aspect is we have learnt about the NATM and NTM, which is the New Austrian Tunneling Methodology and Norwegian Tunneling Method. So, there also the instrumentation is needed because the philosophy of NATM is that, we design as we go and NTM is related to the dynamic design which needs the, extensive monitoring. Now, not only during the construction this instrumentation and monitoring is required.

But to know the in-service performance of underground excavation say, for example, tunnels such as seepage, pore water pressure, and deformation we should go for the instrumentation and continuous monitoring of the performance of the tunnel. Further, loads on the rock bolts, movements within the tunnel shape can also be observed using proper instrumentation.

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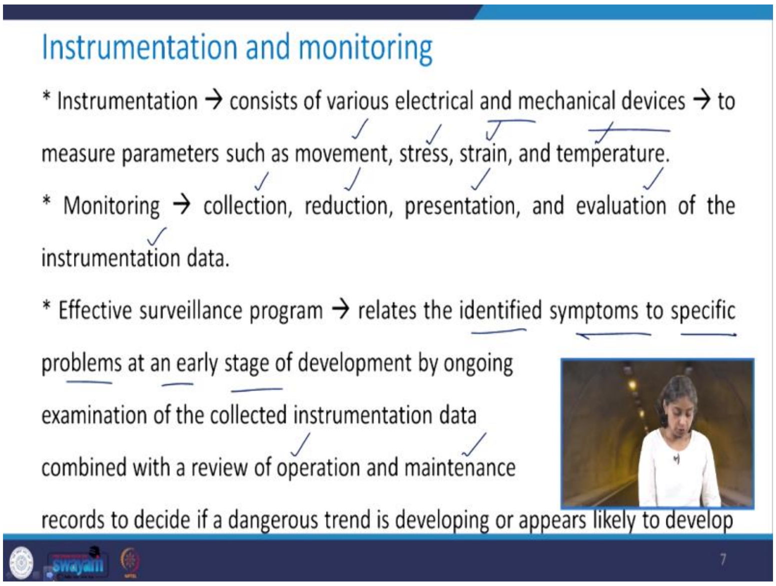

The instrumentation consists of various electrical and mechanical devices to measure the parameters such as movement, stress, strain, and the temperature. While monitoring is the action of collecting the data, reduction, presentation, and, evaluation of the instrumentation data. The effective surveillance program relates the identified symptoms to specific problems at an early age of development, by ongoing examination of the collected instrumentation data.

And, this is combined with the review of operation and maintenance records to decide if dangerous trend is developing or if it is likely to develop in near future. So, basically, if we have the proper instrumentation and monitoring, it acts as a warning signal to us if any untoward thing is probably to happen in future or during the monitoring.

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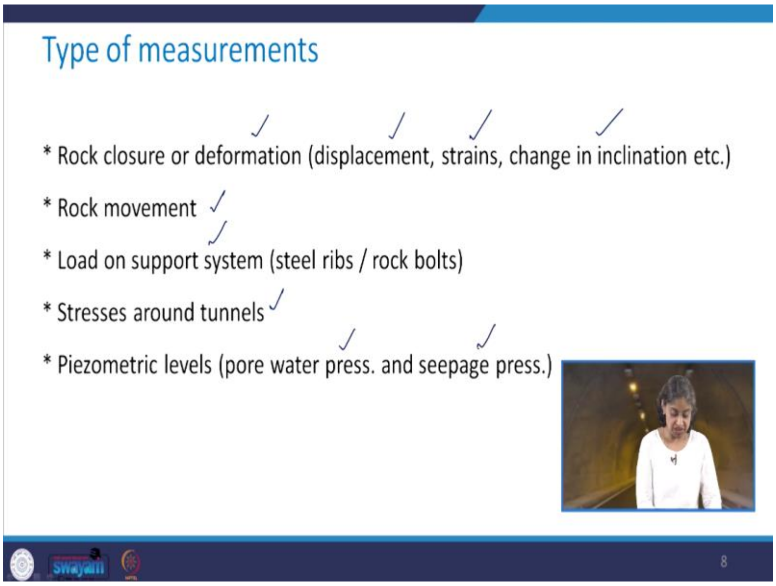

What all, are the type of measurements that can be done in the field? these include rock closure or deformation. Now, this include, displacements, measurement of strains then changes in the inclination. Further, the second one we can measure the rock movement. We can also measure the load on the support system whether it is steel ribs, or the rock bolts along with the stresses around the tunnels.

We can measure the piezometric levels, these give us the idea about the pore water pressure and the seepage pressure.

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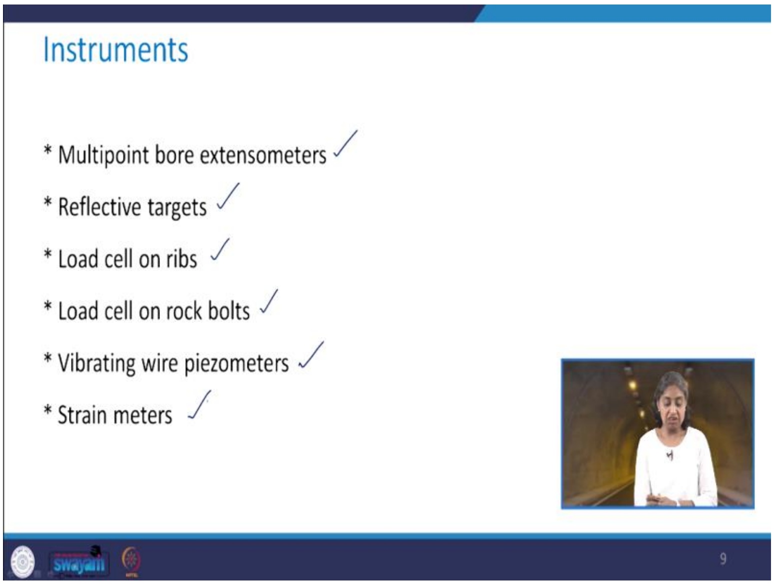

So, the various instruments used to monitor the performance of the underground excavation, they include, a multipoint borehole extensometer, then reflective targets, load cell on ribs, load cell on rock bolts, vibrating wire piezometer, and strain meters.

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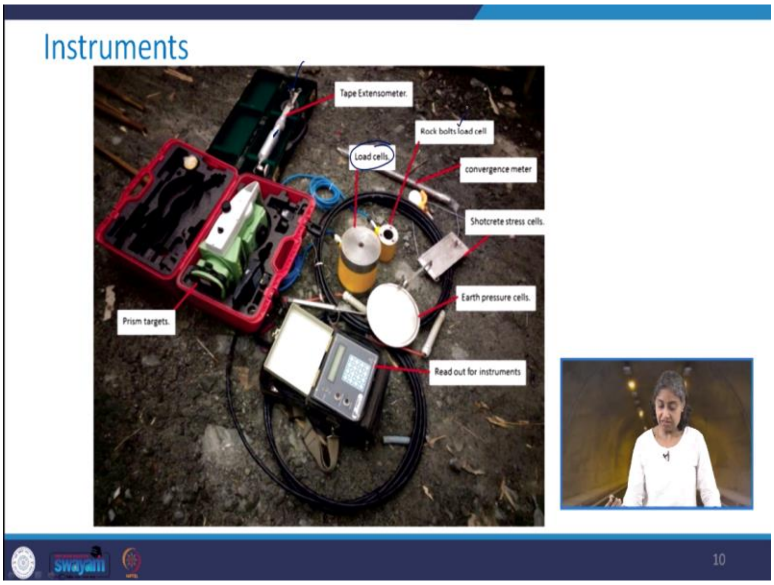

So, we will discuss some of these as has been shown here in this figure various instruments. So, this is the tape extensometer this one here is the load cell, rock bolt load cell then here is the targets and earth pressure cells, and so on.

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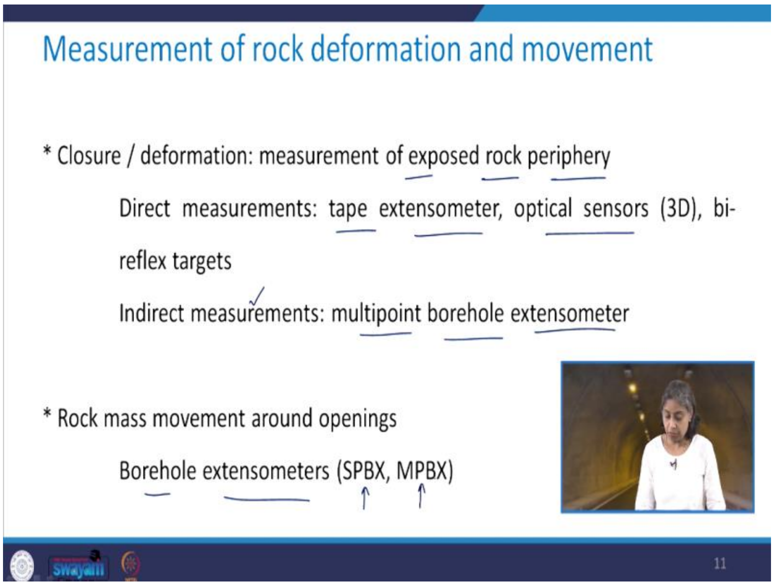

So, today we will focus mainly on the measurement of rock deformation and movement. The closure or deformation is basically the measurement of the exposed rock periphery. So, this can be done by either direct measurement or indirect measurements. As far as direct measurements are there, we use tape extensometer, optical sensors, or bi-reflex targets. For indirect measurements, we need to use multipoint borehole extensometers.

Rock mass movement around the openings is done using borehole extensometer and these are, two types, single point borehole extensometer which is represented as SPBX, and multipoint borehole extensometer which is MPBX

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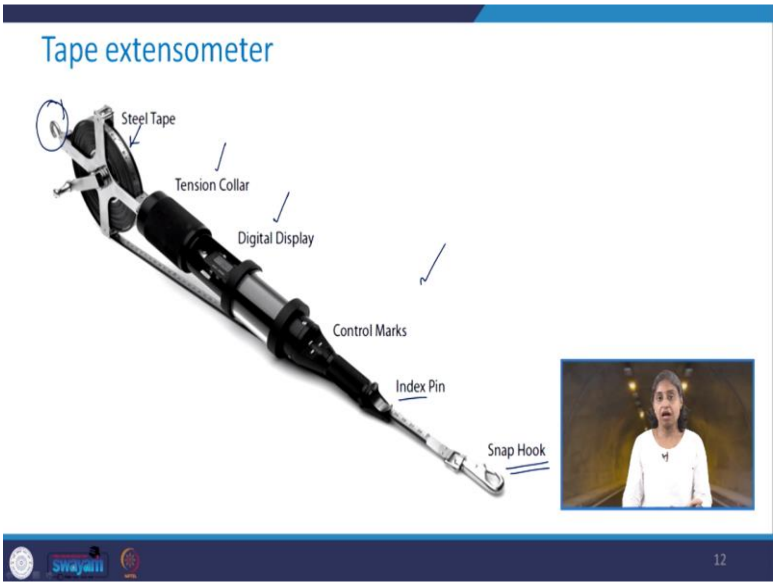

Coming to the first one, that is the tape extensometer. So, here is the picture, that explains you the various component of this tape extensometer. So, you can see that at one end, you have the snap hook followed by index pin and then, at another end, you have a steel tape and also a hook here. In between, you have the tension collar and digital display. Let us see one by one that how these components, what exactly their functions are, and how these are useful.

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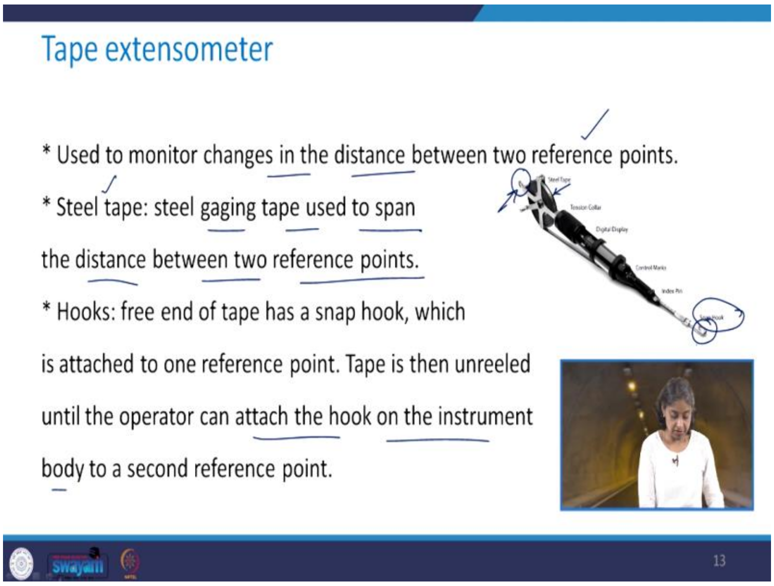

So, the tape extensometer used to monitor the changes in the distance between two reference points. There is a steel tape in this, it is, you can see here it is rolled here at this location which is the steel gaging tape and, used to span the distance between two reference points. They are hooks one at the free end of the tape, this has snap hook which is here. This is attached to one reference point.

And then, what is done is tape is unreeled until the operator can attach the hook on the instrument body, which you can see here to the second reference point. So, basically, you have the two reference point. You fixed this snap point to one reference point and then you unreel the tape and attach this hook to the other reference point.

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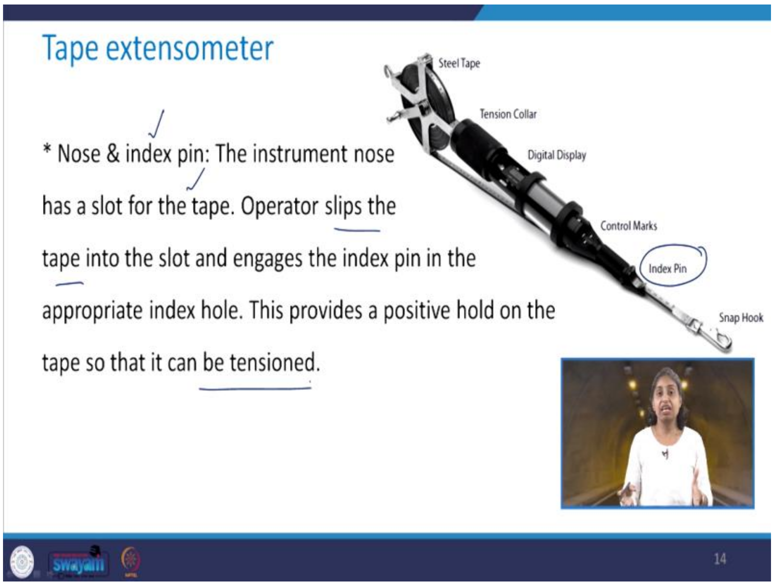

There is the nose and the index pin which is here. The instrument nose has a slot for the tape. The operator slips the tape into the slot and engages the index pin in the appropriate index hole. What this operation does it that there is a positive hold on to the tape so that it can be tensioned properly. You see that, if you have a tape and if it is now tensioned properly in between the two reference points.

Let us say, if it is not tensioned or if it is loose then the measured distance will be more than the accurate one and, if you look at let us say tensioned it more, then it may create some problem with the tape or the tape can break or the reading that you will get will not be proper. So, therefore proper tensioning of the tape is needed.

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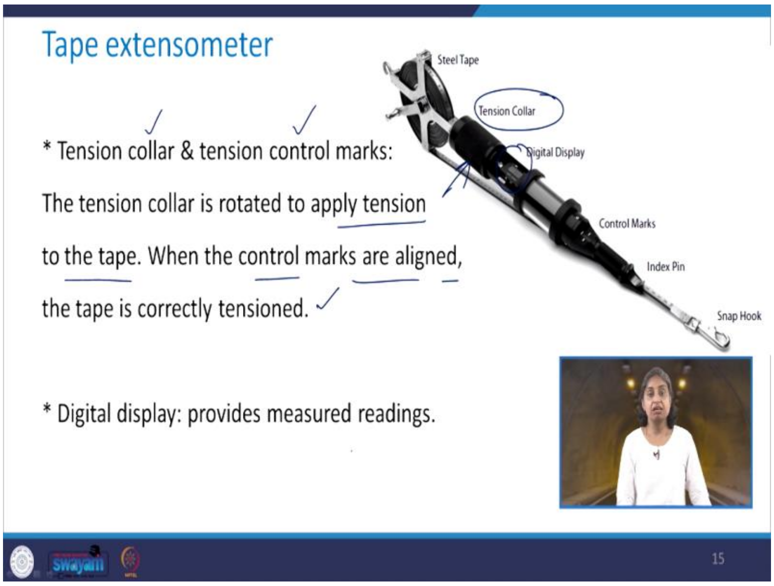

There are tension collar and tension control marks in this particular area. The tension collar is rotated to apply the tension to the tape. When the control marks are aligned the tape is correctly tensioned. So, as I mentioned that it should not be too tight or it should not be loose, it should be correctly tensioned. There is the digital display here in this area, which provides the measured reading values.

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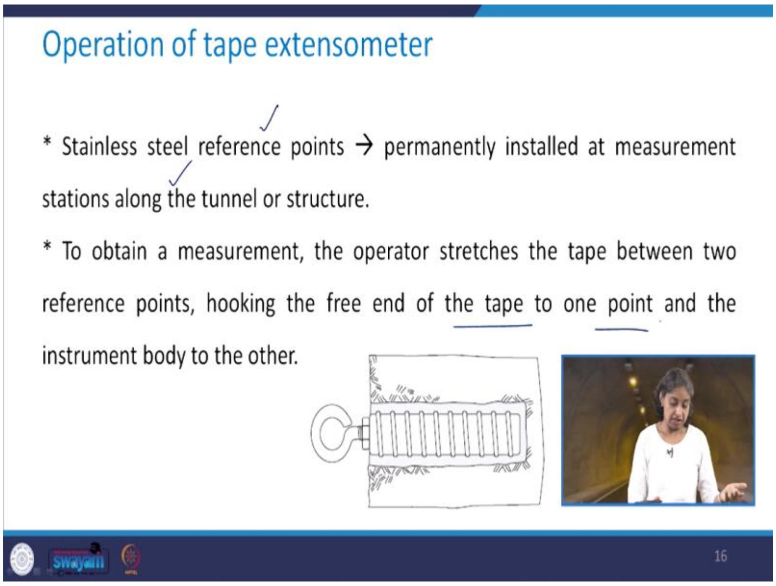

How the operation of tape extensometer takes place? We have these, stainless steel reference points, which are permanently installed at a measurement station along the tunnel or the structure. Now to obtain a measurement the operator stretches the tape between the two reference points hooking the free end of the tape to one point and the instrument body to the other as I just explained you.

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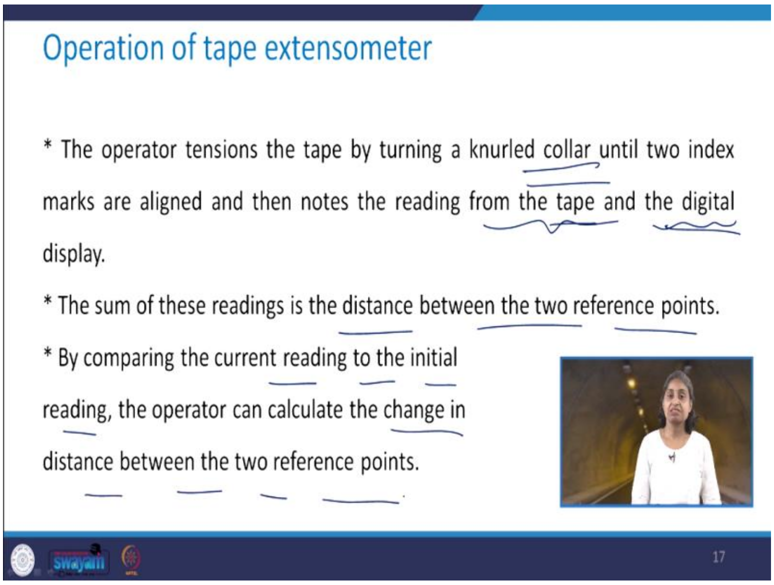

Then the tension is given to the tape by turning the tension collar until the two index marks are aligned and then, we note the reading from the tape as well as the digital display. So, some of these two readings will give you the distance between the two reference points. Now by incorporating the current reading to the initial reading, the operator can calculate the change in the distance between the two reference points.

We will take these things with the help of few figures and, we will try to understand it in a more clear manner.

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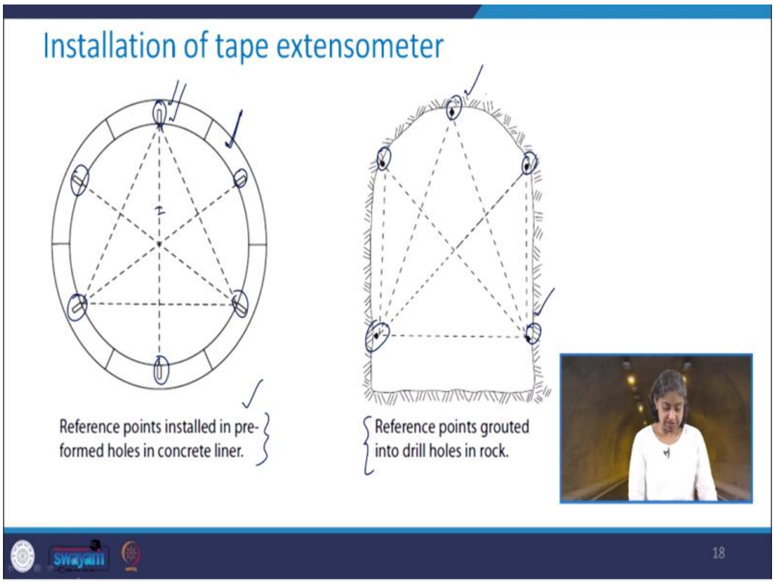

So, you see that here the reference points are installed in the preformed holes in concrete liners. So, these were the preformed holes. Now the tape one end is here, another end is here, and then it is tensioned and you can measure the distance. So, likewise, the similar operation can be done for all the opposite reference points or between the reference points that, we want to know the distance between.

So, let us say this you take some initial reading, and then maybe with time again you take the reading. So, whatever is the change in the reading that will give you the idea about the closure or the deformation of the rock mass. The second picture has the reference points which are grouted into the drill hole in rocks. So, you see that here the rock mass is there in this case it was the concrete liner.

But, in this cases, these reference points are there in the rock mass and then, you have to follow the same philosophy and, you can measure the distance between the reference points.

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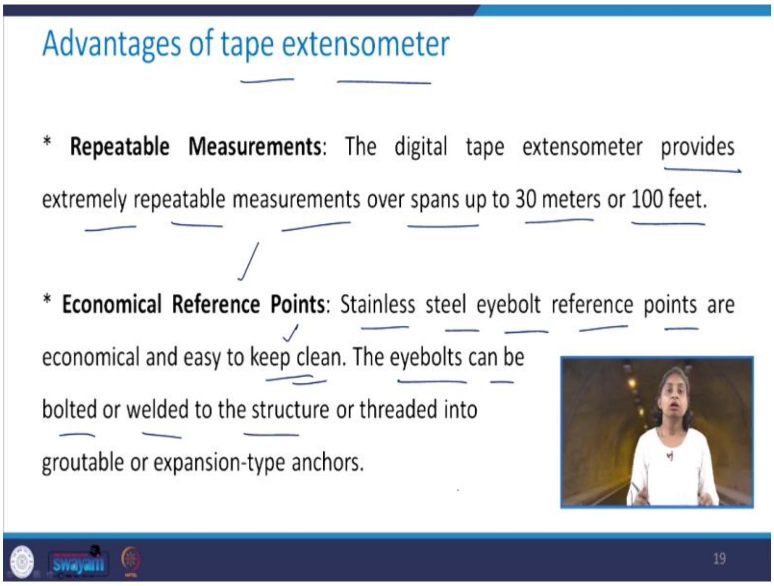

The advantages of the tap extensometer is that we can have repeated measurements. So, this provides extremely repeatable measurements over a spans up to 30 meters or 100 feet. While having the reference points it is always economical to make these reference points. So, stainless steel eyebolt reference points are economical and, they are easy to keep clean, why are we saying that easy to keep clean means that when the tunneling operation is happening then, lot of dust and water may be there.

So, it is important for us to have the clean reference points. So, it is easy with respect to tape extensometer. The eyebolts can be bolted or welded to the structure or these can be threaded into the groutable or expansion-type anchors.

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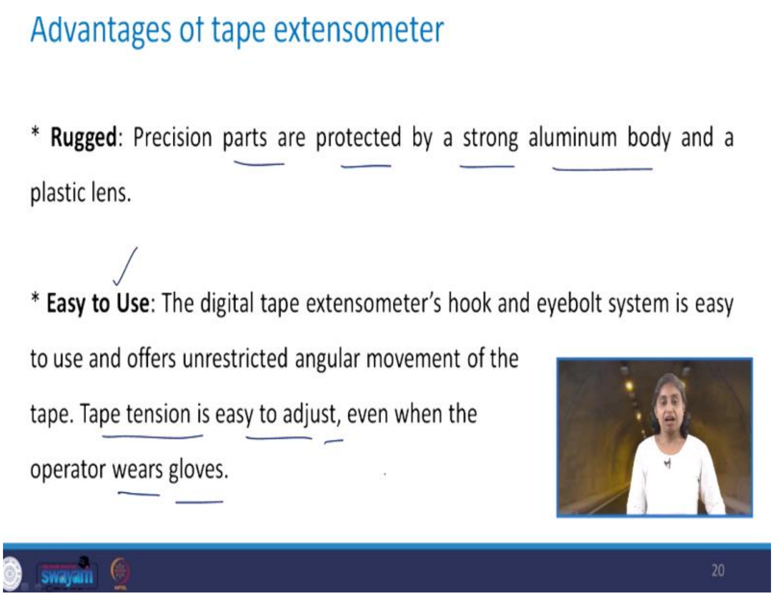

These are rugged, because the precision parts are protected by strong aluminum body and the plastic lens. It is very easy to use the tape extensometer because you know, you just have to hook the two ends to the two reference points and then provide a proper tension and then, just note down the readings. So, the tape tension is very easy to adjust even when the operator wears the gloves. So, therefore these are some of the advantages of the tape extensometer.

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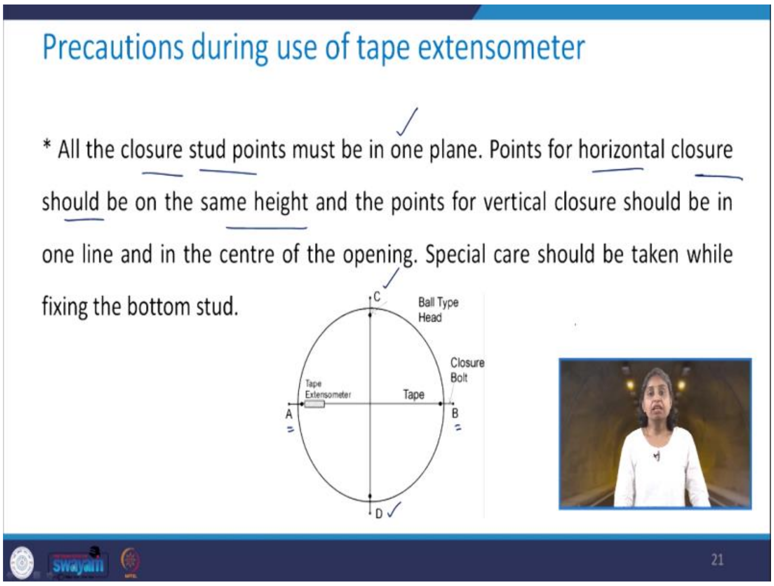

Coming to the precautions while using the tape extensometer, it is assumed that all the closure stud points, they are in one plane because otherwise whatever is the distance between the two reference point, that will not be the correct one. So, that is one of the precaution that, one needs to take that all these points, they should be in one plane. Points for the horizontal closure should be on the same height, which you can see here, that, let us say if you want to measure between the distance between the reference points A and B these should be at the same height.

As far as the vertical closure or vertical reference points are concerned, they should be in one line or and in the center of the opening like here you have for C and D. In case, if you have the bottom stud, you need to be careful while fixing this bottom stud.

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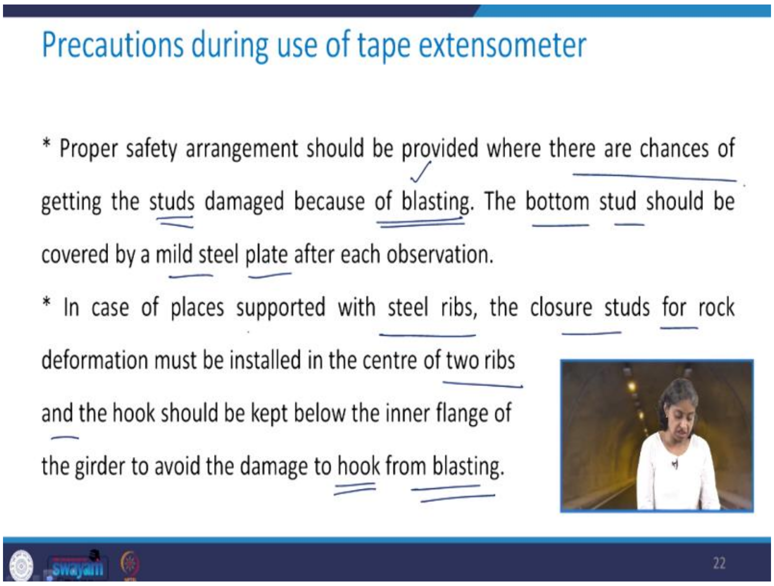

Proper safety arrangement should be provided, where there are chances of getting the studs damaged because of this blasting. So, basically, these studs are nothing, but the reference points only. So, please do not get confuse that, from where this new term is coming. So, this is the another word for the reference point only. So, the bottom stud should be covered by mild steel plate after each observation because of the factor that these maybe damaged due to blasting.

In case of places, which are supported with the steel ribs the closure studs for rock deformation must be installed in the center of two ribs and the hook should be kept below the inner flange of the girder to avoid the damage to the hook from blasting. So, some of these care, we should take while using the tape extensometer.

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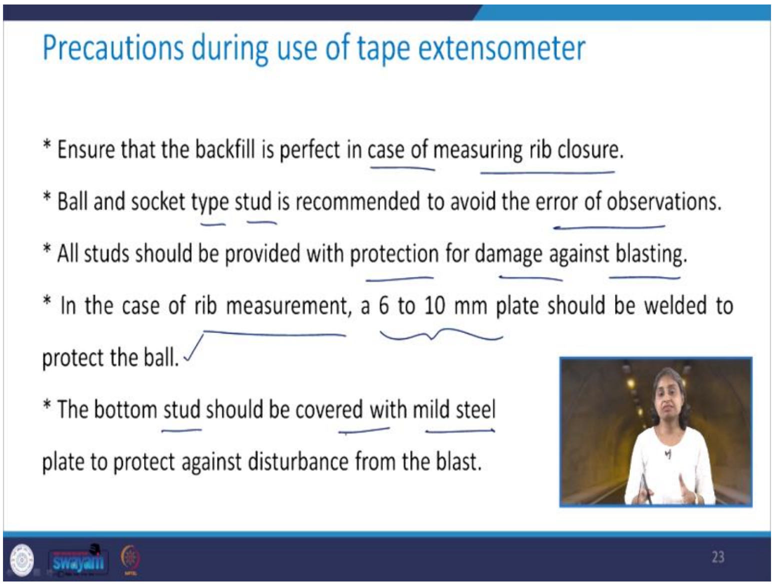

One needs to ensure that backfill is perfect in case we are measuring the rib closure. Then, ball and socket type of the reference point is recommended to avoid the error for the observation. So, all these studs should be provided with protection for damage against blasting because, if let us say these reference points they get damaged during blasting. Then, you will not be able to have the continuous measurement of the deformation or the movement of those two reference points.

Now, in case of the rib measurement, a 6 to 10-millimeter plate should be welded to protect the ball. As I mentioned that, the bottom stud should be covered with mild steel plate to protect it against any disturbance from the blasting.

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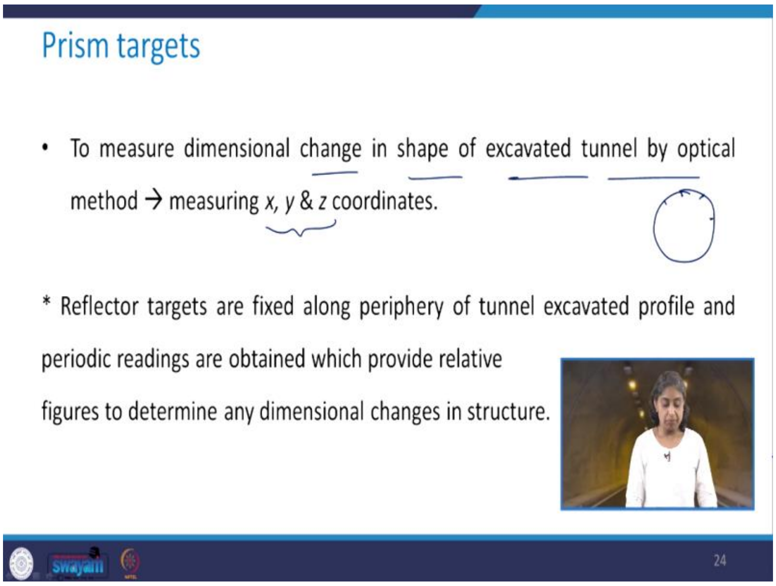

Then the second type of the measuring instrument is prism target see what happens in case of the tape extensometer. Let us say the excavation size is very large. Sometimes, it becomes very difficult for the operator to fix these hooks and, these it becomes bit time taking. So, then these days I mean as far as the small excavations are concerned, tape extensometers are used because they are easy to use.

They are used extensively. However, they have some problems associated with them. So, one will go with the other method of measuring the deformation between the two reference points or the deformation of the rock surface. So, this is one of that the prism targets. This measures the dimensional change in the shape of excavated tunnel, by the optical method and, it measures the x, y, and z coordinates.

What is done in this case is that reflector targets are fixed along the periphery of the tunnel excavated profile like this and, the periodic readings are obtained which provide relatively figure to find out if there is any dimensional change in the structure, but then these days prism targets they are also not being used.

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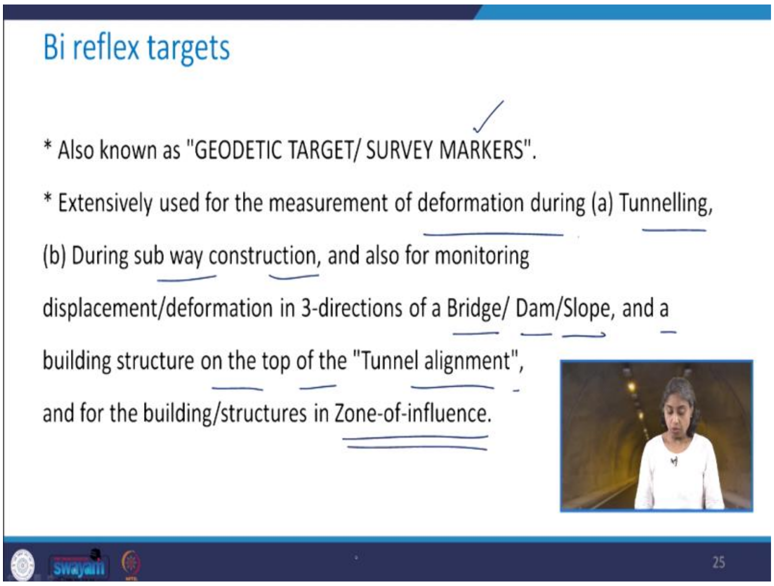

But bi-reflex targets are used these are also known as geodetic targets or survey markers. These are extensively used for the measurement of deformation during tunneling, during subway construction, and also for the monitoring of displacement or deformation in three directions of a bridge or dam or slope and the building structure on the top of the tunnel alignment or for buildings or structure in the zone of influence.

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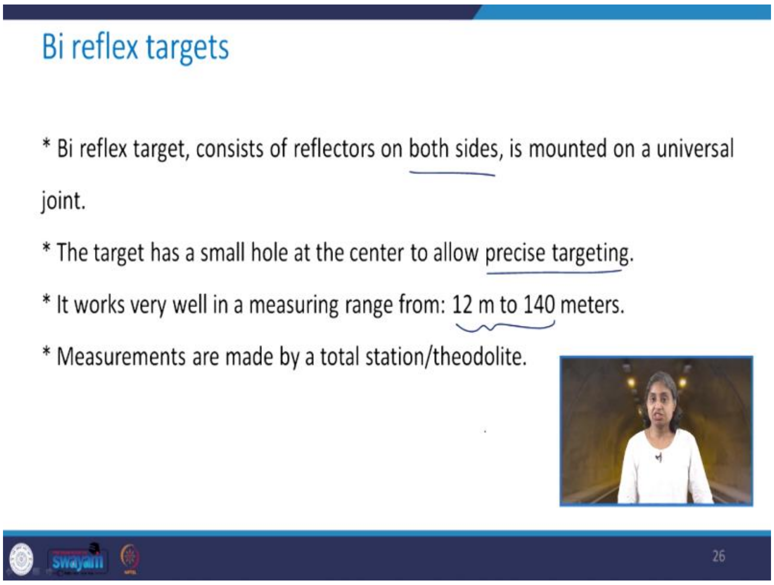

So, the bi-reflex target these consists of reflectors on both the sides, and they are mounted on a universal joint. The target has a small hole at the center to allow the precise targeting. This works very well in a measuring range from 12 meter to 140 meters. The measurements are made by a total station or theodolite.

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See this is how these look like bi-reflex targets. So, as I mentioned that here there is a hole

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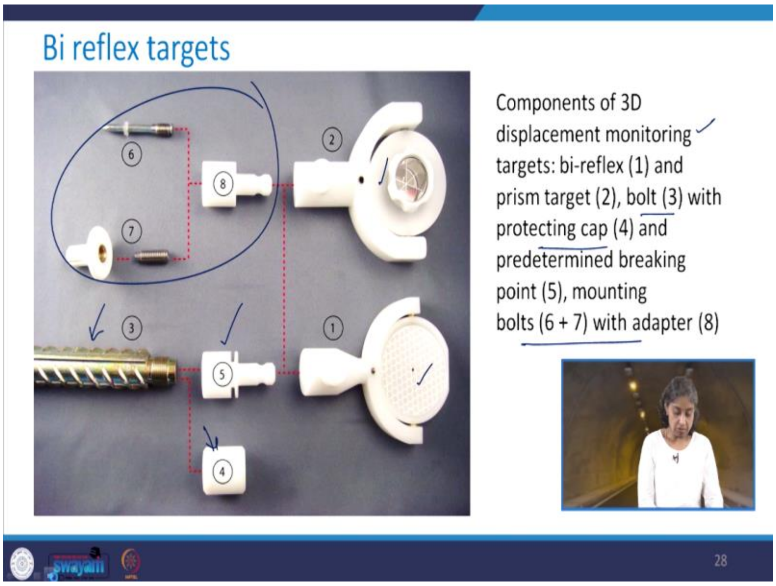

The various components of 3D displacement monitoring targets, they are shown here. This is the bi-reflex targets, this is prism target and then you have the bolt with protecting cap which is the, this one, third and the fourth one, and the predetermined breaking point which is this then mounting bolts with an adapter, it is this assembly.

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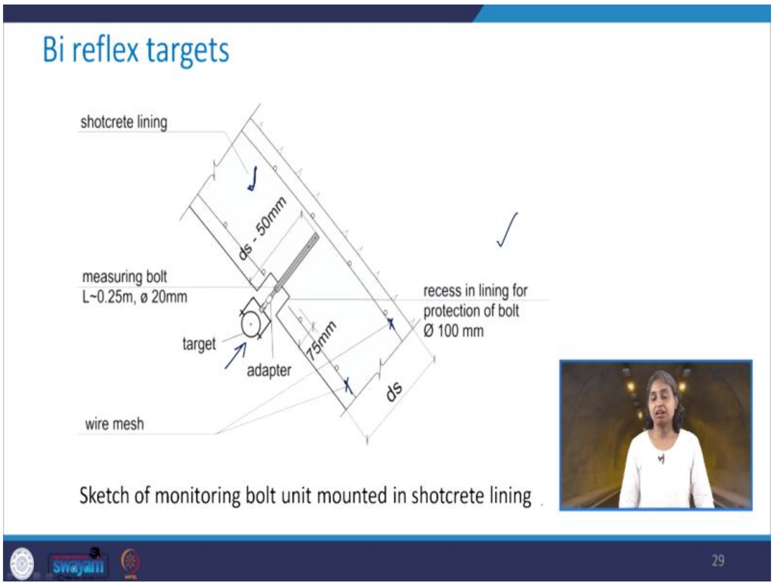

Now, how these are assembled and mounted in the shotcrete lining. This picture gives you the idea about it. So, you can see that how these have been installed in the shotcrete layer. So, basically, this is the shotcrete lining and, then you have the wire mesh here and in this one, you have the bolt that has been installed in the shotcrete lining and, this is how the bi-reflex target is protruding from the surface.

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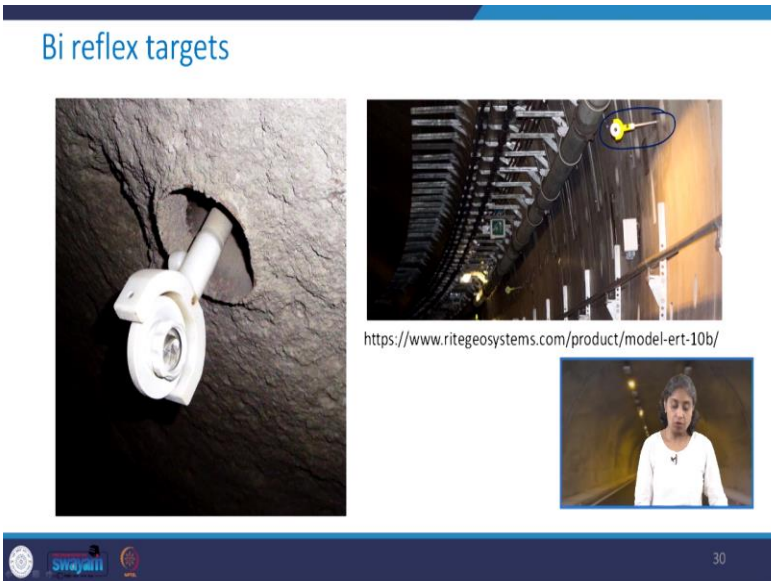

See, this is how it looks like as far as the installation in the field is concerned. So, you see here that, is the surface and this is how it will be installed and then, you have the total station you just have the initial reading, and then maybe through this again you keep on taking the reading through the theodolite or the total station.

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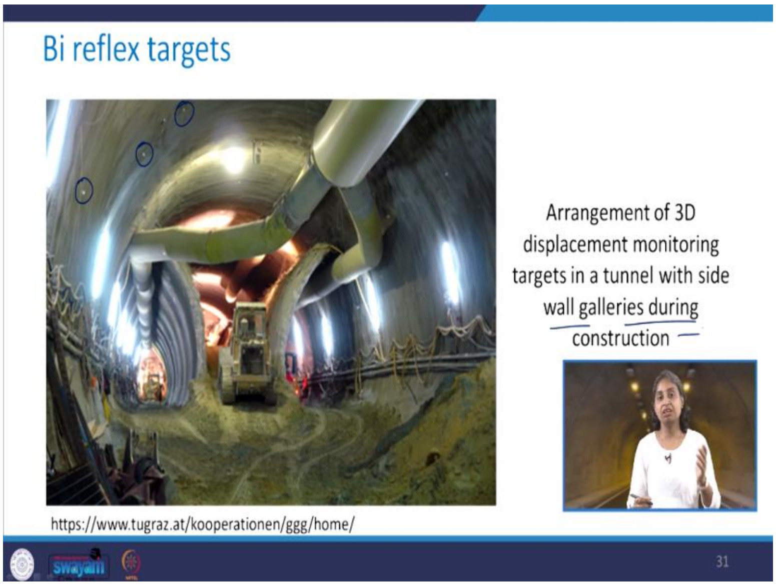

This is the arrangement of 3D displacement monitoring targets in a tunnel with sidewall galleries during the construction. So, you can see that some of these points which are although it is not very clearly visible, but then this is how the arrangement is made of the bi-reflex target.

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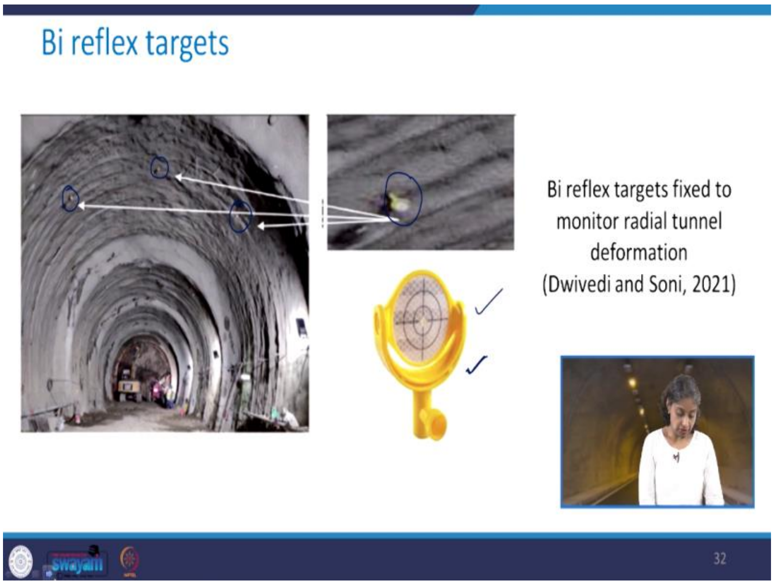

Another view here this is the bi-reflex target which when mounted looks like this. Although, it is not very clear, but it will give you the idea, and some of these points which are here you see these points where this has been installed for the observations.

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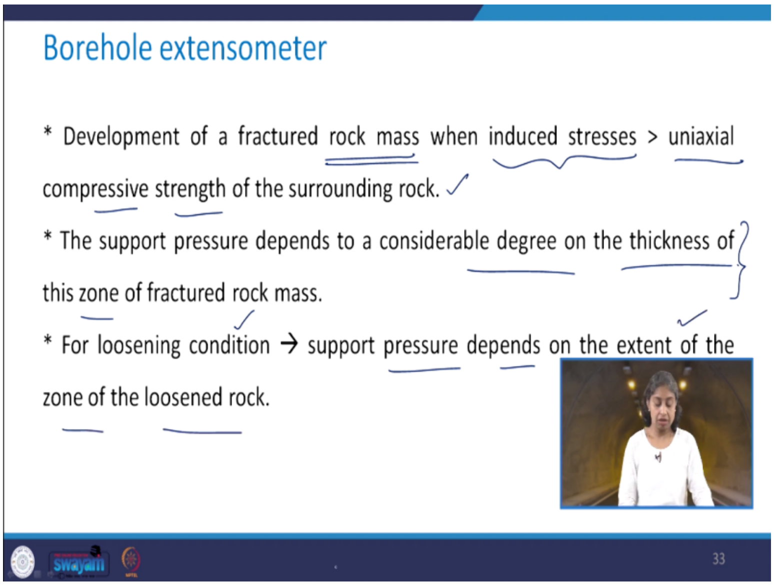

Coming to the next type of the instrument which is used for the measurement of deformation. This is called as borehole extensometer. So, in this case when the development of a fractured rock mass will take place when the induced stresses, they are more than the uniaxial compressive strength of the surrounding rock. The support pressure in this case depends to a considerable degree on the thickness of this zone of the fractured mass.

Now, all these things we already have discussed in the chapter on rock mass tunnel support interaction analysis. So, it should not be difficult for you to connect these things with the theory that we have learnt earlier. For loosening condition, the support pressure depend upon the extent of the zone of loosened rock.

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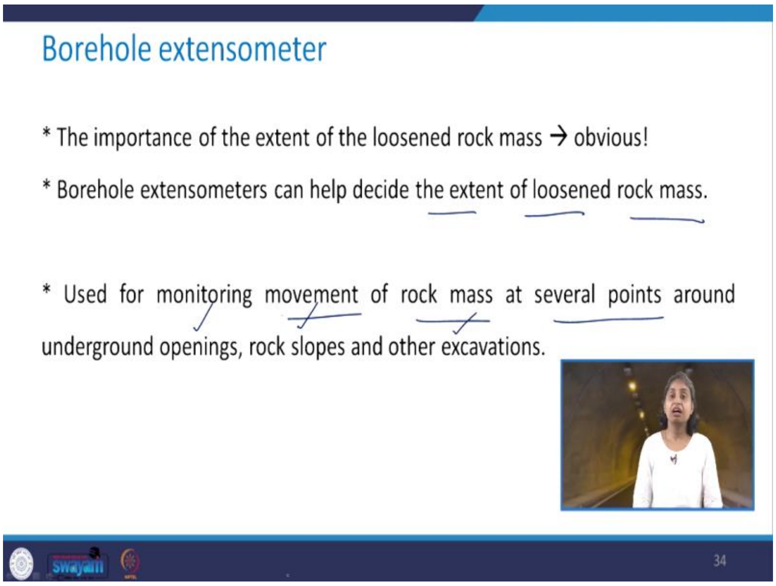

The importance of the extent of the loosened rock mass, therefore, is obvious. So, while using the instrumentation we should be in a position to know that upon the excavation in this type of rock mass, what will be the extent of the loosened rock mass? So, the borehole extensometer helps us in deciding this extent of the loosened rock mass. These are used to monitor the movement of the rock mass at several points around the underground openings, rock slopes, and, other type of excavations.

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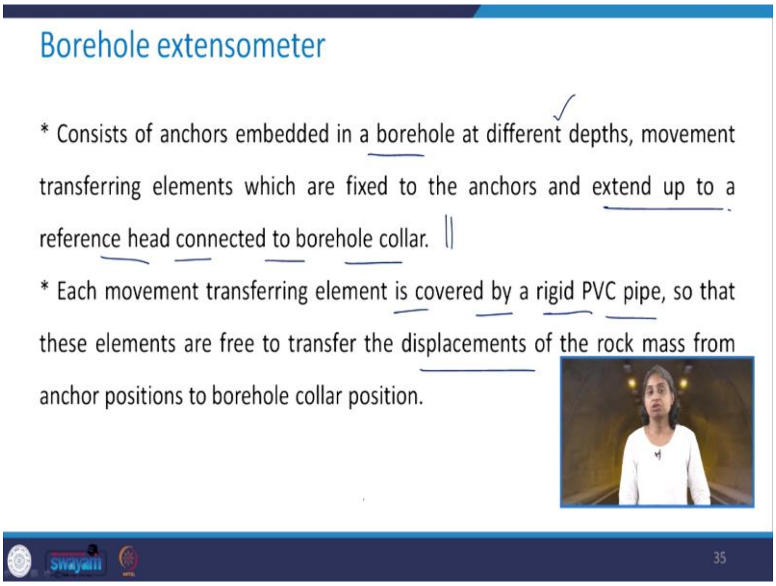

This borehole extensometer consists of anchors which are embedded in a borehole at different depth. The movement transferring elements which are fixed to the anchor and extend up to the reference head connected to the borehole collar. We will see these with the help of a figure in subsequent slides that what exactly is the working. Now, each movement transferring elements is covered by a rigid PVC pipe.

So, that these elements are free to transfer the displacements of the rock mass from the anchor position to the borehole collar position.

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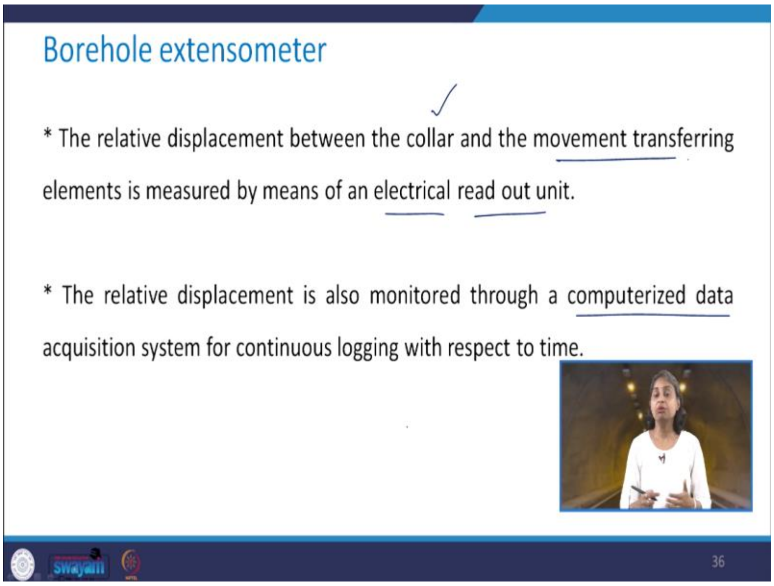

The relative displacement between the collar and the movement transferring elements is measured by an electrical readout unit. The relative displacement can also be monitored, through a computerized data acquisition system for continuous logging with respect to time.

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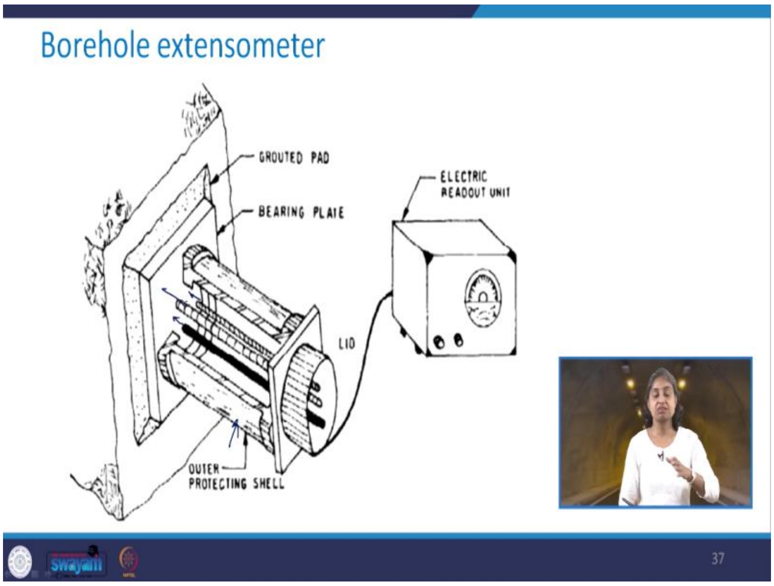

So, take a look this is a pictorial view. So, you can see here that, this is what is the outer protecting shell, this is the grouted pad and, you can see here that these are going inside the rock mass. So, beforehand we have the length of this borehole extensometer. So, when these are inserted into the hole then they are anchored in the rock mass.

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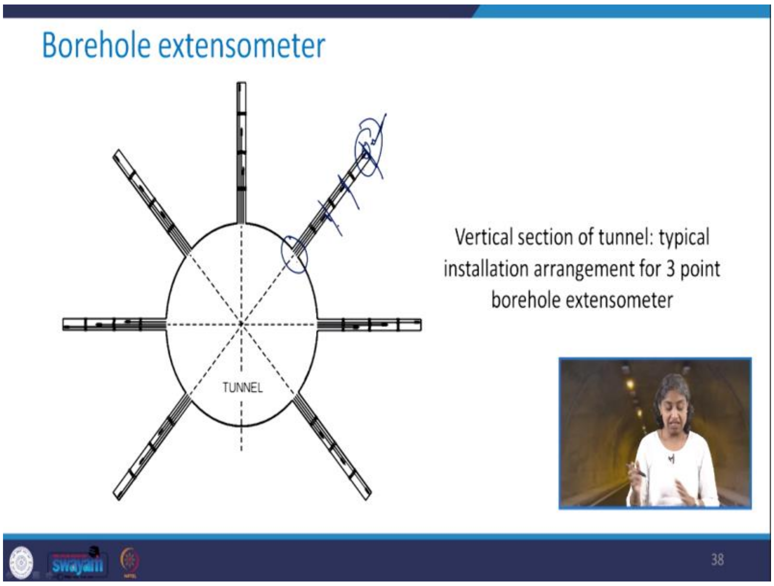

We have few other pictures like this one. You can see that this is the 3-point borehole extensometer, which has been installed typically in a tunnel of circular cross-sections. So, you see that the length. You take any of the location and, see what I mean by 3-point borehole extensometer? The length is up to here, then this is, and then this. So, this is what is the anchorage point and then the another one is here.

So, the relative movement between these is going to give us the deformation of these points up to which the borehole extensometer length is provided.

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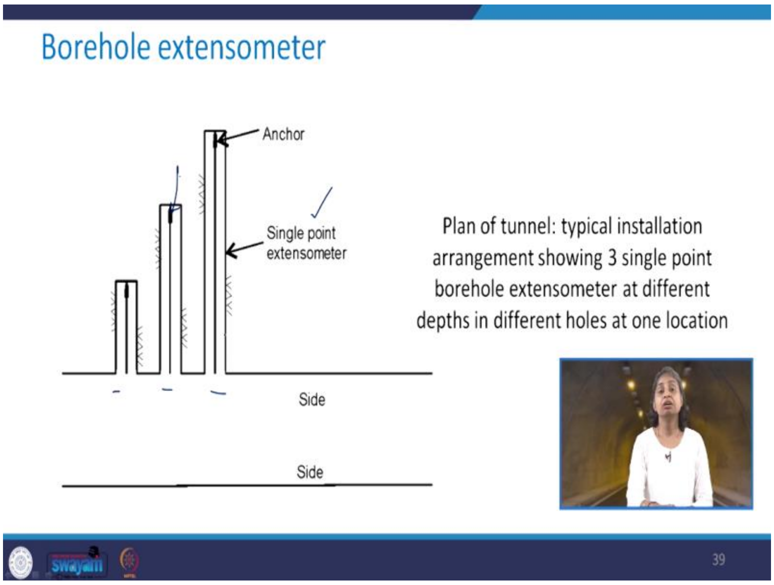

So, take a look here these are the single-point extensometer and, this is the plan of the tunnel. So, at this location 3 single-point extensometer, they are installed, and then you can see that this is how these extensometers, they are anchored into the drillhole, and having the measuring device, then you can determine the related displacement between the two points to give you the idea about the deformation or the extent of the loosened rock mass.

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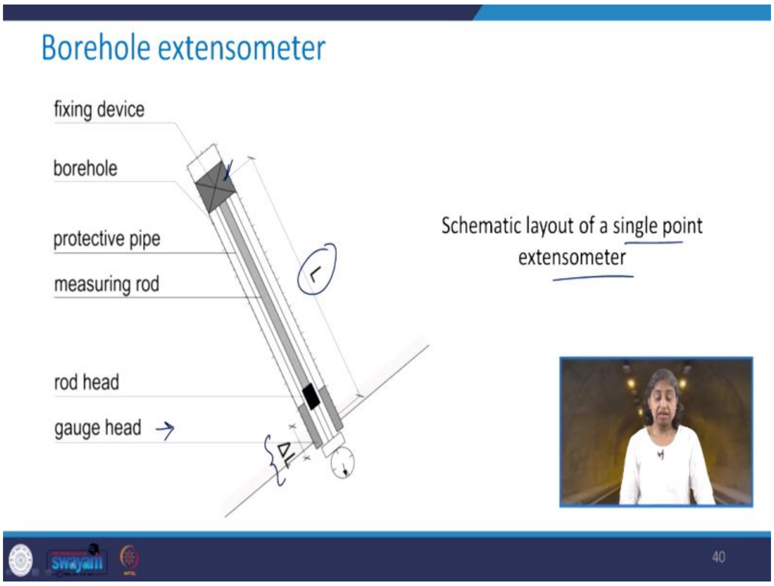

See, here this is the borehole that one needs to have for installation of the single-point extensometer. This is the fixing device, I mentioned to you that every borehole extensometer they will be having one known length, up to which that, these will be installed and then, you have a measuring rod. This is what is the rod head and then you have the gauge head. So, here you will be able to get this delta L.

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This is how it looks like, after you install it in fields. So, this is the 3-point extensometer that has been installed in at one particular location.

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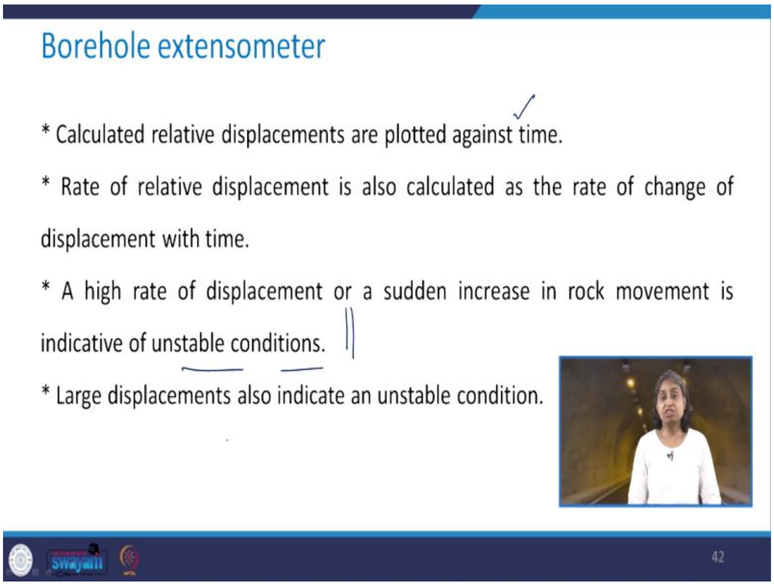

So, in this case the calculated relative displacements, they are plotted against the time. The rate of relative displacement is also calculated as the rate of change of displacement with time. Higher rate of displacement or sudden increase in the rock movement is the indicative of the unstable conditions. We will see with the help of few plots that, how we can get the idea about such situations. Larger displacements are also indicative of an unstable condition.

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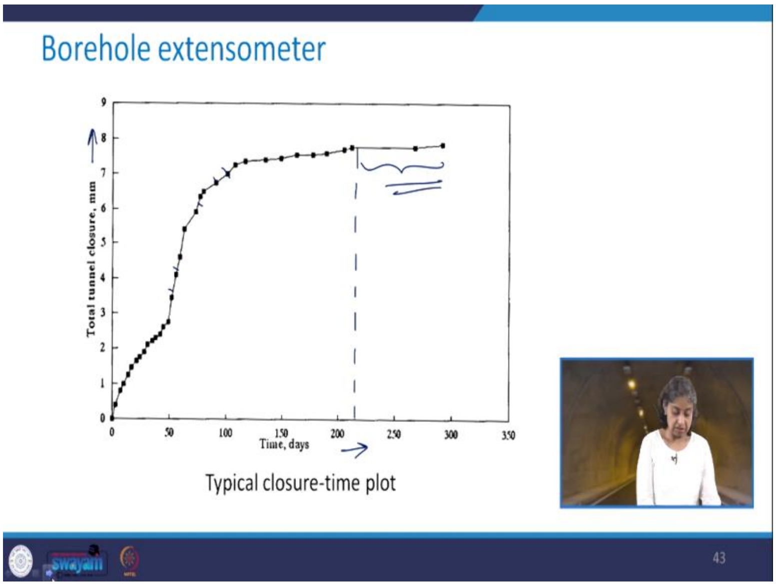

This is the typical closure time plot. So, you can see that, how after may be the time more than, let us say 210 or so days how this becomes just constant and, there is no more tunnel closure which is plotted on y-axis and the time is plotted on x-axis in days. So, in the beginning, you see how the total tunnel deformation was increasing, and then with time the rate of increase becomes less and here it becomes almost constant.

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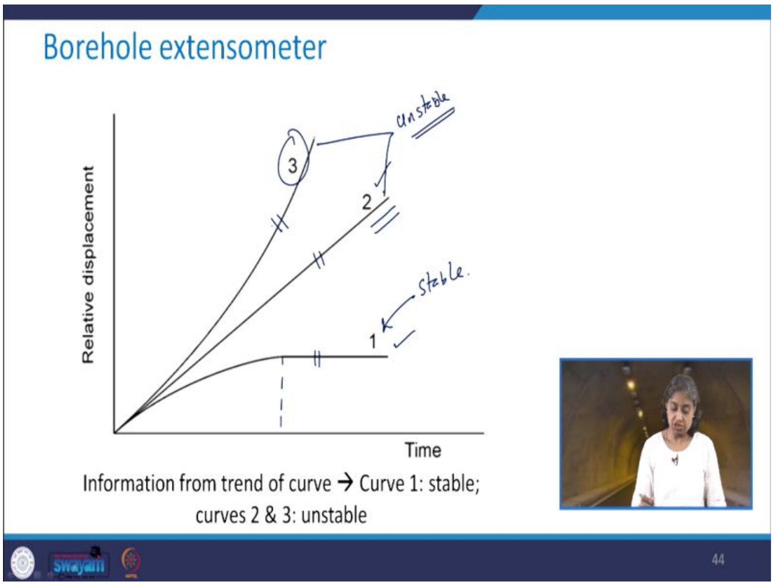

As I mentioned that the trend of the relative displacement versus time curve gives us the idea whether, the situation is stable or unstable. So, take a look at curve 1. Here you see that after some time, the relative displacement is almost the same. There is no change in that. So, this is giving me stable condition. However, for curves 2 and 3 in case of 2, it is still increasing. So, an unstable situation similar is the case here for curve 3. So, both of these situation, they are unstable situation.

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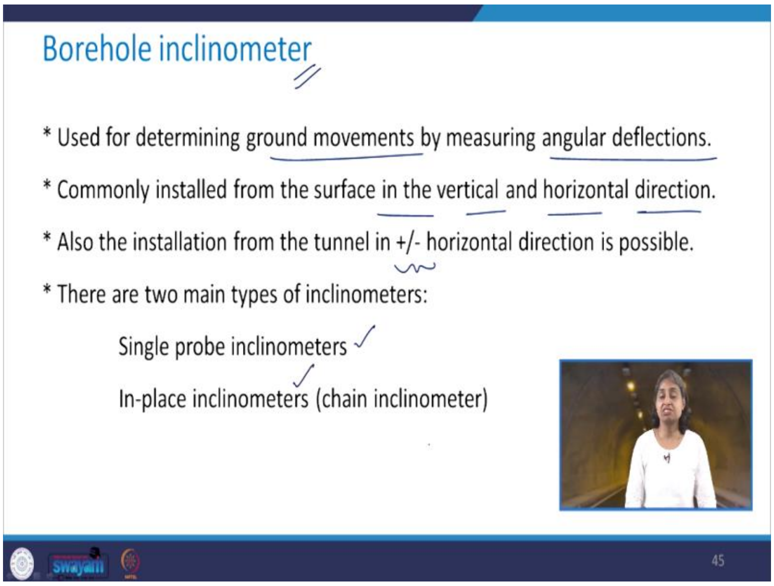

Till now we just saw that, how we can determine the deformation with respect to the rock surface or how we can find out the extent of the loosened rock mass using borehole extensometer. Now, in case, if we want to find out the angular deflections we have to use borehole inclinometer. So, this is used for the determination of ground movements by measuring the angular deflections.

These are commonly installed from the surface in the vertical and the horizontal direction also the installation from the tunnel in positive or negative horizontal direction is possible. They are basically two main types of inclinometer. One is the single probe inclinometer and, the second one is in place inclinometer which are also called as chain inclinometers.

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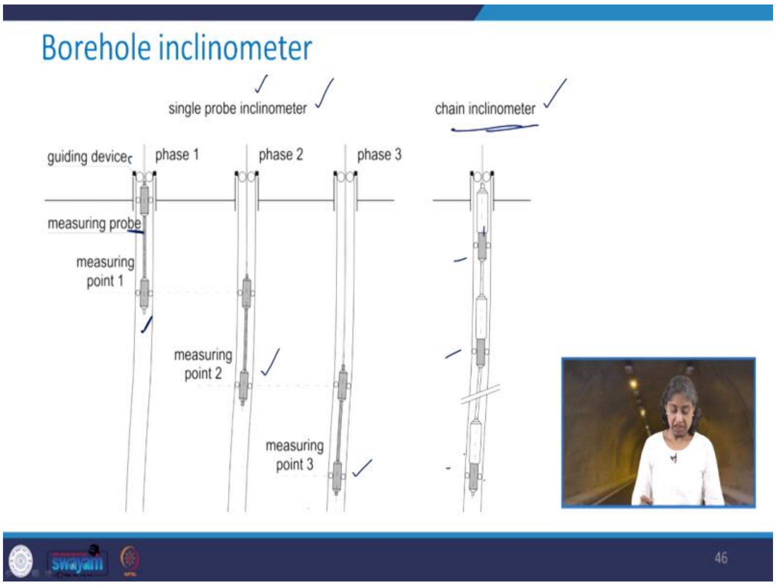

Here is the typical inclinometer working looks like with the help of these sketches. Let us understand, when we have the single probe inclinometer and, when we have the chain inclinometer. So, this figure is self-explanatory for you to know that, what is the difference between single probe inclinometer and the chain inclinometer. So, here we have these measuring points.

So, you see that, how we can get the information, when we have the borehole inclinometer. So, here we have this as a measuring probe here then we have a guiding device through this probe is lowered into the ground. So, here we have the measuring point 2 and, then we have measuring point 3. So, we have three phases. So, 3 points, we can find out that, what is the angular deflection.

In case of the chain inclinometer, you see it is not only 1, but it is the chain of the measuring points, which can be done simultaneously.

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This is the typical picture of the head of borehole inclinometer with the 3D displacement monitoring target.

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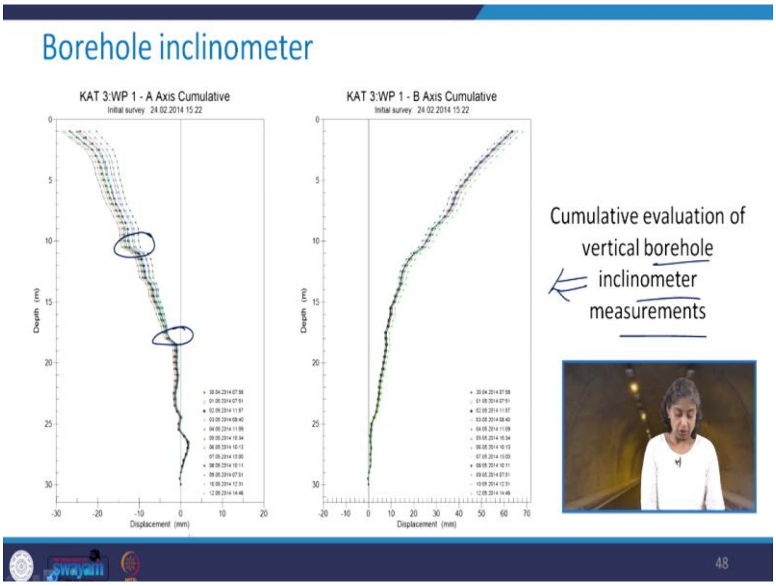

Now, the results of the borehole inclinometer typically looks like this which are the cumulative evaluation of vertical borehole inclinometer measurements. Now, take a look here the deviation about 11 meter and here at 18 meter. So, here you see there is a king in the profile of depth versus displacement plot.

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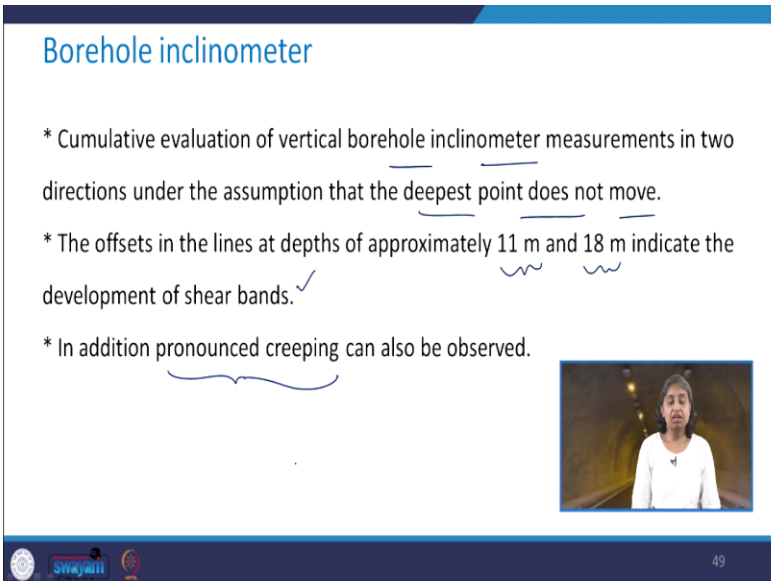

So, this is an indication of the development of shear banks. So, the cumulative evaluation of vertical borehole inclinometer measurements in two directions under the assumption that deepest point will not move. The offset in the line at depth approximately 11 meter and 18 meter take a look at these figure again. So, here you see the offset is there and, in this case also, this offset is there.

So, this indicates the development of the shear bands. In addition, we can also observe the pronounced creeping with the help of borehole inclinometer.

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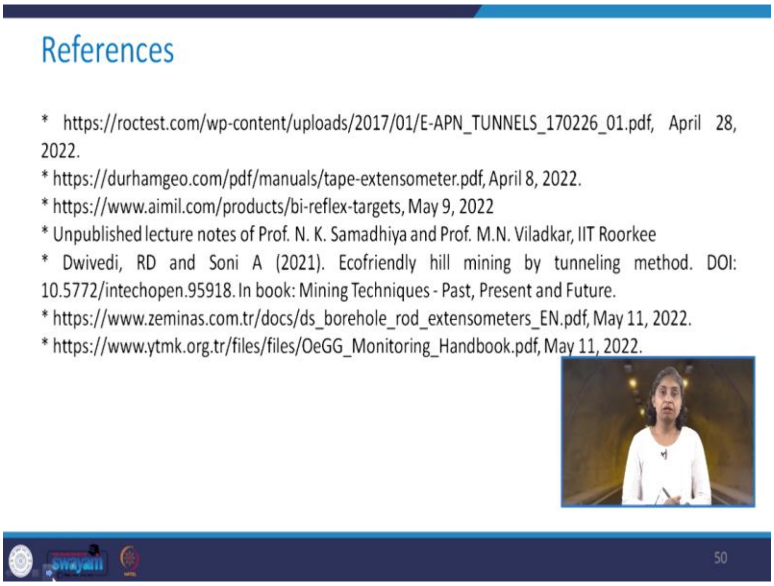

These are some of the references, which were used to prepare this particular lecture notes. So, this was all about the instrumentation or the type of instrument, that are being used to measure the deformation of the rock mass and, also the extent of the loosened rock mass. In the next class, we will learn about the instruments, which are used to determine the loads on the support system or pressure on the support system. Thank you very much.