Maintenance and Repair of Concrete Structures
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Lecture – 33
Cathodic Protection in Concrete Structures-Laboratory and Field Studies

Hi, welcome to this lecture on cathodic protection in concrete structures. Today we will be discussing about laboratory and field studies in which we were involved.

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So we will talk about first some of the experiences and overview of the present scenario of cathodic protection industry in India and also we will cover some aspects of worldwide scenario. Then we will talk about couple of 10-year long studies because most of the time we recommend to adopt cathodic protection people ask for long-term data. So I thought this is very important as a repair technologist you should know that these systems really work and we are trying to promote this.

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Now even though we covered cathodic protection in one of the earlier lecture, I thought of giving a little bit briefing on that before we get into the case studies and worldwide scenario. So, any cathodic protection system, and to be precise the sacrificial anode cathodic protection system (SACP) not the impressed current system (ICCP). So, in the SACP system, you have a sacrificial anode core metal like a disc, which you can see on the top left image, which is covered by an active cementitious matrix. I may also call this 'encapsulating mortar' in the coming part of the lecture. And then these are actually connected to a tie wire and the tie wire is used to connect the anode metal to the rebar. Now some of the pictures are also shown on the screen which indicates how it is actually practised at site.

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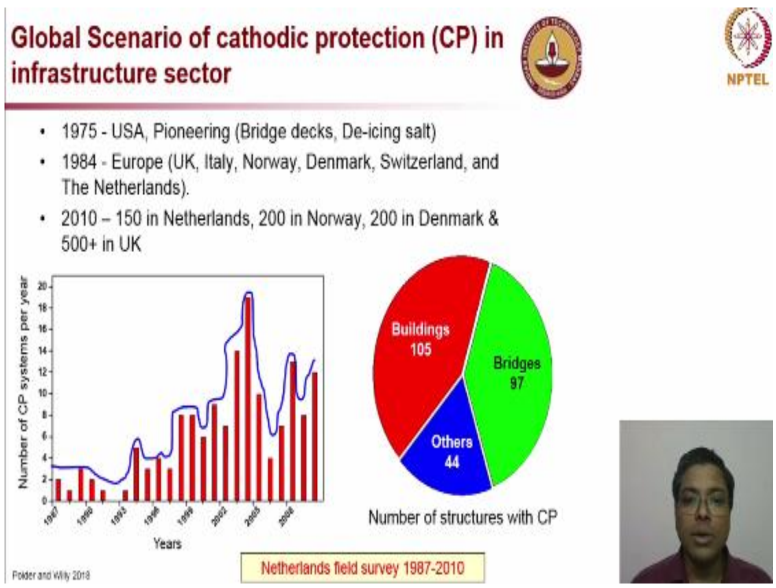

Now the global scenario of cathodic protection in infrastructure sector. If you look at the bar chart at the bottom, you will see that the data going all the way from 1987 until about 2010.

You can see that there is a significant increase in the number of CP systems installed, you can see some variations, but that may not be the reality, it might be just the lack of data available or data collected.

And, so, there is an increase in the use of cathodic protection systems both in US, Europe and also in Netherlands. The pie-chart on the right side is actually showing the distribution among different type of structures, which have cathodic protection system. So you can see that buildings and bridges are almost similar, but one should notice that, in the bridges, the impact of this cathodic protection on the long life, on the economy,etc., is much more in case of bridges as compared to buildings. So this data, both this bar-chart and the pie-chart are showing the data from one field survey conducted in Netherlands.

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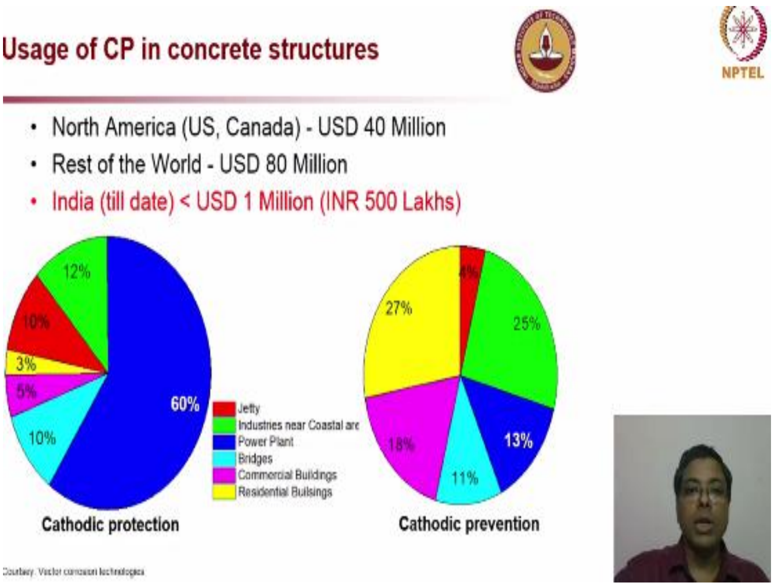

And then the usage of CP in concrete structures, if you look at North America, rest of the world, North America about 40 million US dollars, rest of the world is double that, which is about 80 million US dollars. Whereas in India, the number shows very clearly that there is a lot more room to improve or to penetrate into the market. Lot of structures we have serious corrosion and repair related issues.

I think it will be better if we adopt these technologies also, this cathodic protection also, to extend the life of the repair itself, because there is a fear in some sector of the industry that, if the cathodic protection systems are in place, then the other repair materials or repair systems will lose some of the market. I want to make it very clear that is not the intention. It is that, if we use cathodic protection along with the other repair systems, this cathodic protection will arrest the corrosion from happening and which will help the remaining systems like chemicals or coatings or fiber wrapping, etc., which we adopt, all those will be able to function to the full capacity or those systems will also tend to last longer.

So that is how we have to look at cathodic protection, not as a competitor for the other repairs, industries or products, but as a system which augments them, their performance, or a system which helps the other systems to perform well. How? Because cathodic protection stops further corrosion from happening, which then helps in enhancing the performance of the other systems. So the last slide of this, this lecture, I will explain one example where a fibre wrapping system without cathodic protection, how it failed, and if a cathodic protection was in place, how it would have helped.

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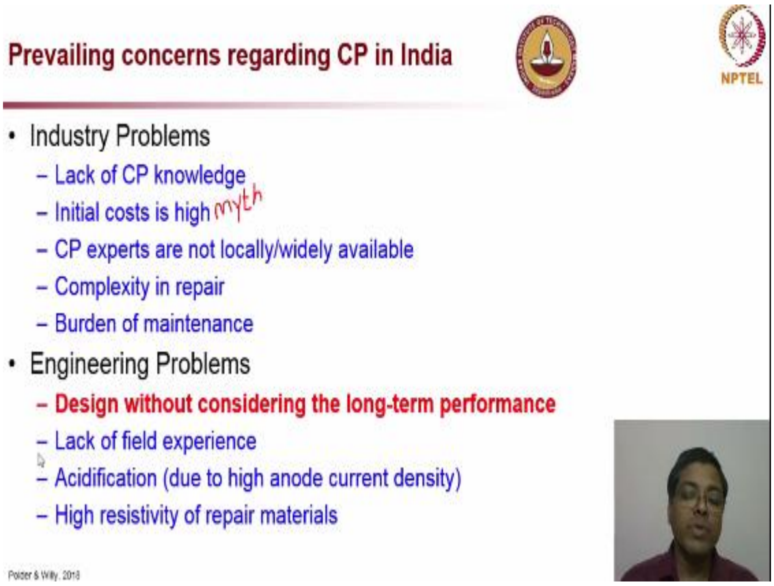

So let us see more on other prevailing concerns regarding cathodic protection in India. Mainly it is the lack of knowledge among many of the stakeholders, lack of knowledge about the CP and its usage in the concrete structure. People know very well that it is widely used in other metallic industry like any pipelines, etc., but in concrete structures there are still some hesitation in adopting this technology considering the poor practices at site, etc. But those are the things which we have to overcome to avoid the huge maintenance and repair cost, or rather, repeated maintenance and repair cost. So CP is very promising technology in my opinion.

Now initial cost is high, it is a myth, not necessarily high. I will show some data in this lecture showing that actually it does not really, increase the repair cost much, rather it will reduce the life-cycle repair cost. Now other problem is CP experts are not locally or widely available. And complexity in repair, then burden of maintenance, all these are general challenges.

Now what are the engineering problems? Now, one is design without considering the long-term performance. Many of the sites we have seen that neither the client nor the suppliers of cathodic protection or manufacturers, they are not having enough data to show that the systems will perform for long-term and neither are there any tests to ensure such long-term performance. It is very important, otherwise what might happen is, if we install systems which are not really of good quality and which cannot really last long, then after few years they will tend to fail, and then that will create a negative perception on the cathodic protection technology itself, which is the big danger.

So in fact at IIT Madras we have the developed a test method which we are calling as GAP test, which can be used to assess the long-term performance of cathodic protection system or galvanic anodes in about 3 to 4 months' time period, which is a very good indicator and which can be adopted before we install such systems. Especially to ensure that repair will actually last for long time.

Now, lack of field experience, then acidification due to high anode current density and high resistivity of the repair materials and sometimes we also put other chemicals around the steel reinforcement, like some kind of coatings, epoxy coatings, etc., which will have high resistance and that will adversely affect the performance of the cathodic protection system.

So those kind of engineering problems do exist. However there is enough technology or good products are also available in the market which can be used to ensure the longevity of the repair.

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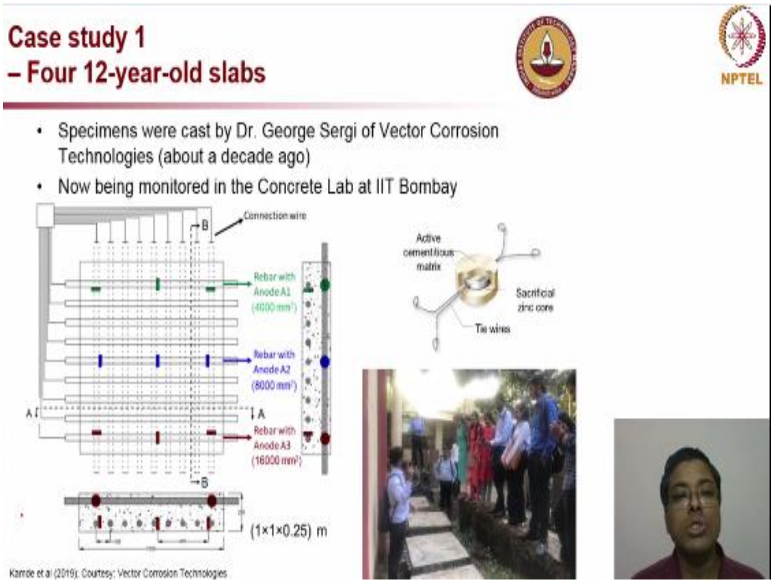

Now let us go through the first case study which is a lab study. We have some data on this. So these specimens were cast by Dr. George Sergi, who is a pioneering figure in cathodic protection technology, and he is from Vector Corrosion Technologies and he cast 4 slab specimens which you can see on the screen at the bottom right, and in Mumbai and these are about 12 years old right now.

And you can how the slab specimen looks like. It is about 1 m x 1 m slab and about 250 mm thick. 3 types of anodes are installed or embedded in these slabs. One with 4000 mm^2 (Anode A1) and another with 8000 mm^2 (Anode A2) and then 16,000 mm^2 (Anode A3); these are A1, A2, A3 type anodes as it is mentioned on the screen.

Now few years ago we got into this project, and then we started, continuing the monitoring of these specimens and these specimens are now stored in IIT Bombay laboratory, Dr. Prakash Nanthagopalan's lab and we take measurements regularly.

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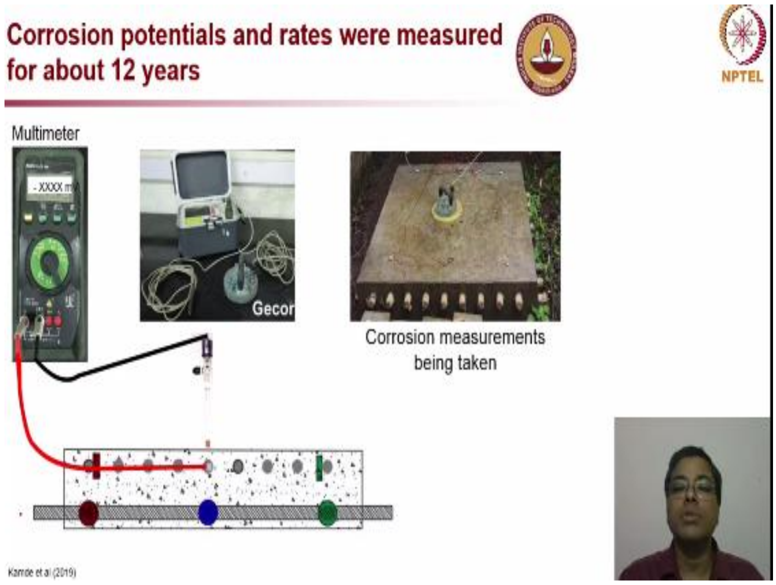

I will show you some of the data and then this is how we have taken the data. We take the potential using a simple multimeter and also corrosion rate using Gecor instrument which uses a guard-ring technology. So on the right side you can see an image which shows how the corrosion rate is being measured, you can see black wires, red wires, etc., going around the slab specimen. That is basically showing the connections to the embedded anodes and the reinforcement.

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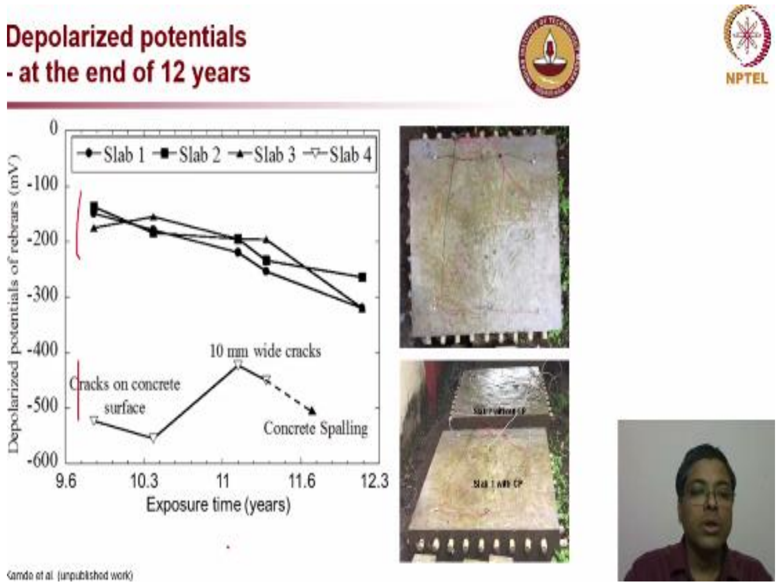

So what is depolarized potential? When we assess the sacrificial anode systems, one parameter which we measure is the depolarized potential. Basically what it is, is you disconnect the anode from the rebar, (during the exposure time it is connected and protecting the steel, but for the measurement purpose, we disconnect it temporarily) and after about one day (24 hours), we take the corrosion potential and corrosion current measurement, so that

that anode does not influence the measurement. We call that potential as depolarized potential, especially done about 24 hours after disconnecting the anode from the rebars.

So, in depolarized potential of rebars, you can see here, the top 3 curves (in graph in slide) are showing much more positive data or positive potential than this curve, which is slab 4, and slab 4 is the one without any cathodic protection system. Slabs 1, 2, and 3 have a cathodic protection system. So it is very clearly indicating that slab 4 is having much more negative potential and it is showing cracks on concrete and also started spalling after about 10 or 11 years, it started spalling. Now it is more of a spalled specimen. So you can very clearly see that the use of cathodic protection and it will really keep the potential at more positive range which indicates, more positive means less corrosion. So in these specimens it shows less corrosion as compared to the graph at the bottom.

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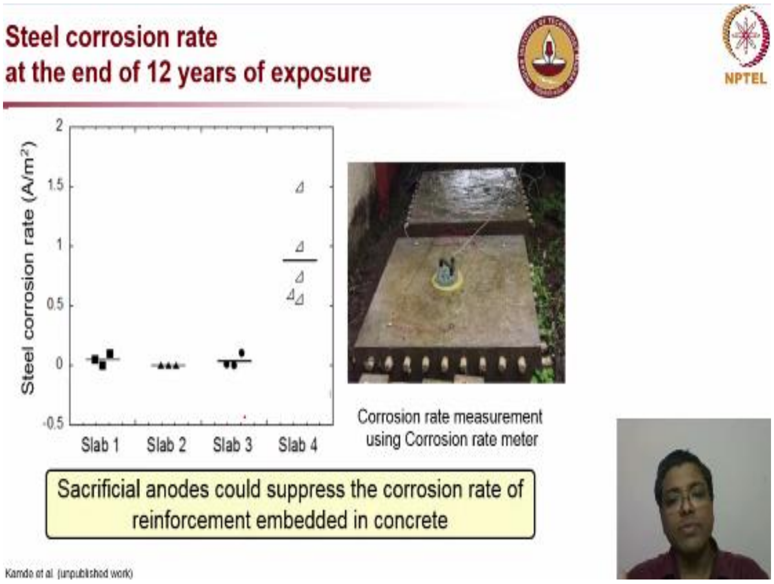

Now, let us see how the corrosion rates are, these are steel corrosion rate. So in cathodic protection when we talk about corrosion rate, it is mainly the steel corrosion rate, we also talk about corrosion current, which is mainly for the current drawn from the anode. So these 2 things are different and should be given adequate care which you are talking about, whether you are talking about the corrosion of the anode which is usually the zinc or the corrosion of the steel to be protected.

So here, steel corrosion rate, again on slab 4, you can see very high corrosion rate and the Slab 4 is the one without the cathodic protection and Slabs 1, 2, 3 have cathodic protection installed and this is at the end of the 12 years. 12 years of exposure is a significant long time and this graph itself is a proof that they really work in keeping the corrosion rate very low.

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Now here you have visual observation. On the left side is the representative image of Slabs 1, 2, and 3. You can see one of the slab images is shown with cathodic protection. No cracks at all, that means very low corrosion rate, very positive half-cell potential and at the same time no crack, which is demonstration, very clearly telling that it does not really corrode and it helps the steel from corroding.

Whereas on the right side you can see the slab without the cathodic protection, that is Slab 4, as mentioned in the previous slides, and heavy corrosion on that, along the reinforcement line. So you can see on the right side the zoomed-in image which shows very wide crack along the reinforcement, and also about to spall and delamination is also very clear as you see in the picture on the bottom side, the red curve on that, indicates basically the crack locations.

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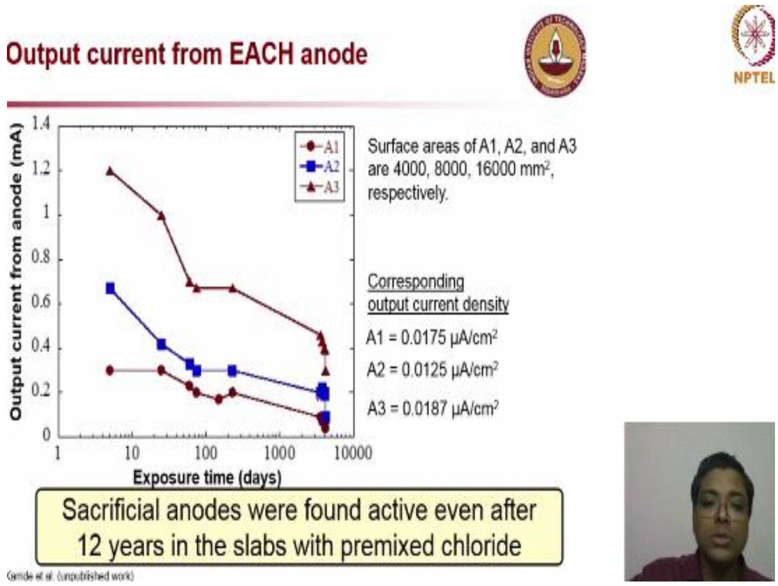

So there is also one more current which we talk about, that it is the corrosion current or the current given by the anodes. So A1, A2, A3 are the anodes, 3 anodes which were used and all the anodes are still being very active in providing the current demand. So here one thing you have to remember is that, someone might think that the curve is slopping down. So what is happening, why it is going down? So you have to think that in sacrificial anode galvanic protection systems, the anodes provide the current which is being demanded by the steel. So it is a dynamic system. So what we have to think is, as the time passes, the steel gets passivated and then the demand for current is also going to be less. When the demand is less, then anode will provide only that much current.

So point to be noted is whether the anode is providing current or not. So let us not look at the magnitude of that current, but whether it is above 0 or not, whether it is able to provide the current which is demanded by the steel or not. That is the idea here. And as you see on the screen, all the 3 anode systems are still able to provide the current as demanded by the already passivated steel. So it is still working even after 12 years.

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So then we also did some autopsy, we took one anode out of the slab and then just to see what is the condition of the anode. I want to show that, you can see some white patches here, which is basically the zinc corrosion products oozing out of the anode or through the encapsulating mortar and here you can see the point 1, 2, 3 which are the locations where further studies were done. I am not showing those results here, but just to show you how in-depth we have studied. You can see this point here (marked in slide) is the anode which is exposed, you can see that. So that is the exposed anode.

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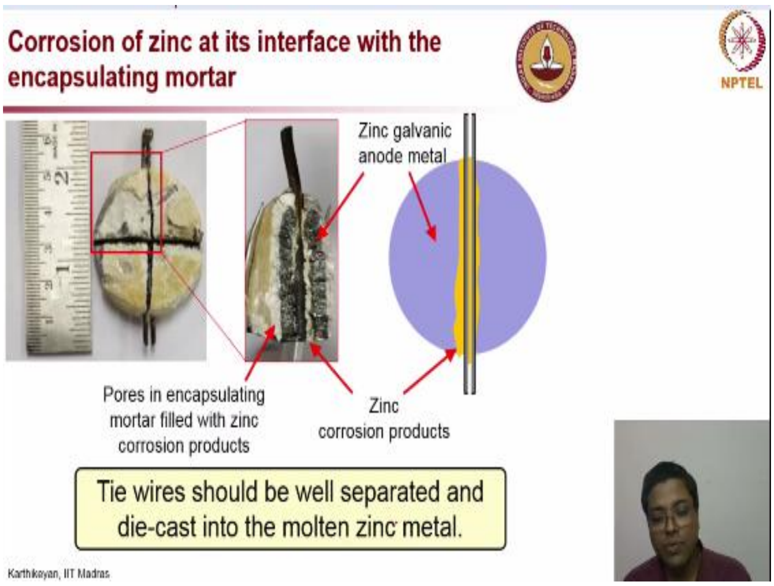

Now we took that anode out, and then broke or autopsied that further to see what is the condition of the tie wire. What we found is there was a lot of zinc corrosion product around the tie wires also, which can eventually disconnect or eventually affect the electrical connection between the tie wire and the zinc anode. Even now you can see some, but this anode is still functioning.

But you have to remember this is after 12 years, it is still functioning, but after some point of time, if you have an anode which will have these severe problems like corrosion around the tie wire, then it may not really function for very long period of time. So the idea here is the tie wire should be well separated. This is an old anode system. Now most of the anode which come into the market, they have die-cast tie wires or in other words the tie wires are cast in molten zinc metal.

So there is no possibility of moisture to get into the space around the tie wire and it is die-cast, and that really helps and one must make sure that whatever anode you are trying to get from the market, it must be die-cast, otherwise this will have this kind of problem, in relatively short period of time, so, depending on the condition. So, this is one thing to ensure that, there are multiple things associated with the quality of the anode.

One is the tie wire should be die-cast, you can ask for it when you order the anodes, the tie wire should be die-cast. And the other thing is the encapsulating mortar should be porous enough, so that the zinc corrosion products, which is white in color as you see on the picture, the encapsulating mortar should have enough void space to accommodate all the zinc corrosion products which are coming out. And at the same time, the mortar should be able to provide that high pH environment for the bare surface of the zinc, so that the zinc can continue to corrode. If the pH changes and decreases, then the zinc will stop, it will start passivating. In other words, zinc will stop corroding and once zinc stops corroding then the system won't work.

So it is not just zinc metal placed in a mortar, because why I am saying this is, there are many products out there in the market which are just having zinc metal with some kind of alkaline medium and a cementitious mortar around and that may not really work for long term. You have to really ensure that the mortar is porous enough to accommodate the zinc corrosion; and at the same time the mortar can provide sufficiently high pH (13 plus around), to enable the new surfaces of the zinc metal to corrode. So this performance is very, very important. Unless these are all ensured, the anode system will not work for very long period of time. So one must be very careful in checking how this is going to work. So now the question is can we really wait for very long time to really check all this? May not be possible because you do not have that much time.

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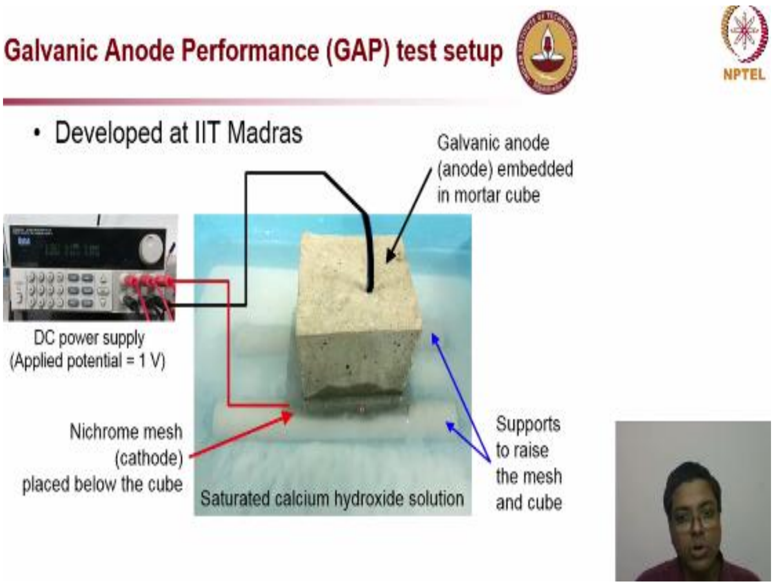

So there is a short term test method which we developed at IIT Madras. We are going to call it Galvanic Anode Performance test. You must have already seen a video on this in other lecture of the same course. Now we are calling it GAP test. So this test, as you see on the picture, it is a mortar cube or a specimen with an embedded anode, not necessarily cube depending on the shape of the anode, so that the cover is maintained at the same level.

And then you have a nickel-chromium mesh (Nichrome mesh) at the bottom here, which is the mesh that you see and square mesh which kind of touches the surface of the cube and then we apply current to it. I will show the electrical circuit in the next slide and then when you apply the current, what it is doing is, it is mimicking what happens in a real cathodic protection system. Here the nickel chromium mesh is kind of, it is representing the steel reinforcement in a real structure.

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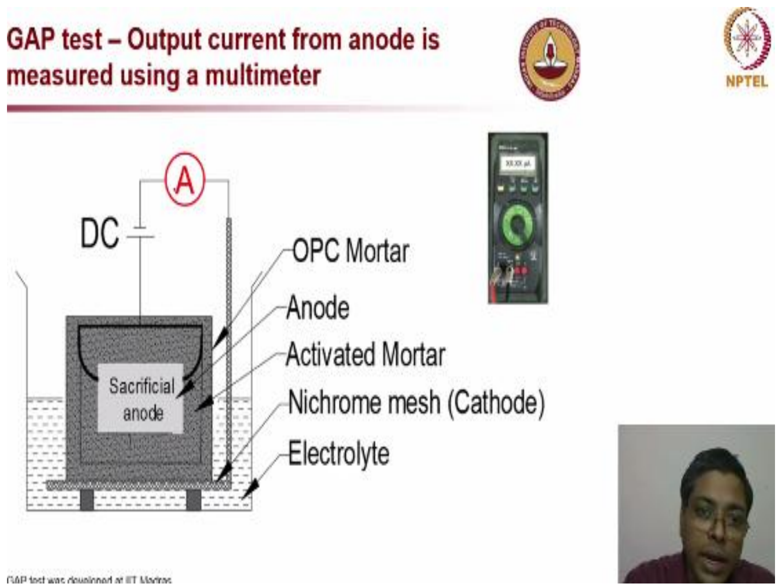

So this is how the specimen, the cross-section looks like. You have a sacrificial anode at the center, this is the sacrificial anode. And then you have inside this rectangle here, that is the encapsulating mortar (labeled as Activated mortar), and then you have another mortar here in the peripheral region (OPC mortar). Then, you apply the current and then measure the current using a simple multimeter.

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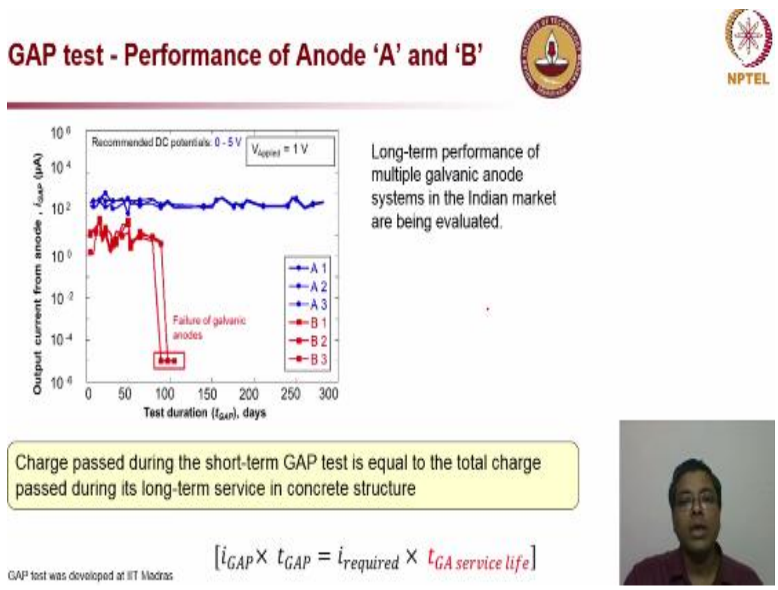

And then what you do is, you monitor this current driven from the anode. So after some time, you will notice that the anode is not able to provide any more current. The red curves on the screen indicate, after about 80-90 days, it just drops down. The current output from the anode is almost negligible, very low. So that indicates the failure of that anode.

Whereas the blue curve on the top, is able to provide the output current even for up to around 300 days, that is almost a year, at least 10 months. That means very clearly the blue anode in this system is much better than the red anode and the blue anode will be able to provide much more life for the repair than the red anode.

So this is a new test which we have developed. And it is a very promising test method to compare the long-term performance of the anode in short time. So we can say, if you want a life of about 20 years, how many months this should survive, something like that, we can look at, and that will clearly give an indicator whether a particular anode is good or bad.

And an anode can fail either by the corrosion of the tie wire or the disconnection between the tie wire and the zinc metal, because of the corrosion of the zinc around the tie wire, or corrosion of the tie wire itself, or the zinc is not getting enough high pH environment in the long run, as it corrodes it is not able to penetrate into the encapsulating mortar or the mortar is not able to provide sufficiently high pH, because of those reasons the zinc will get passivated and that means it will stop corroding and that means the anode does not work anymore.

So any of these things can happen and the red curve here shows an example of something like that which happened at about 3 months time period and then in 3-4 months of testing, you will know that whether this anode is functioning or not. Now you may say that 3 to 4 months of testing is too long, but in my opinion wherever you are applying this cathodic protection systems, it is very important, as you are doing something for very long period of service life.

It is really worth investing some time on doing this test for few months before you install something and then later on find that doesn't really work after 2 to 3 years. So it is very important to do this test or a similar test to assess the long-term performance of the anodes.

We are not installing these anodes for performing just 4, 5 years. We are expecting them to perform for 15, 20 years. So 3, 4 months of additional waiting is not really a big deal when you are trying to invest huge amount of money on service life which is expected to be 20 plus years.

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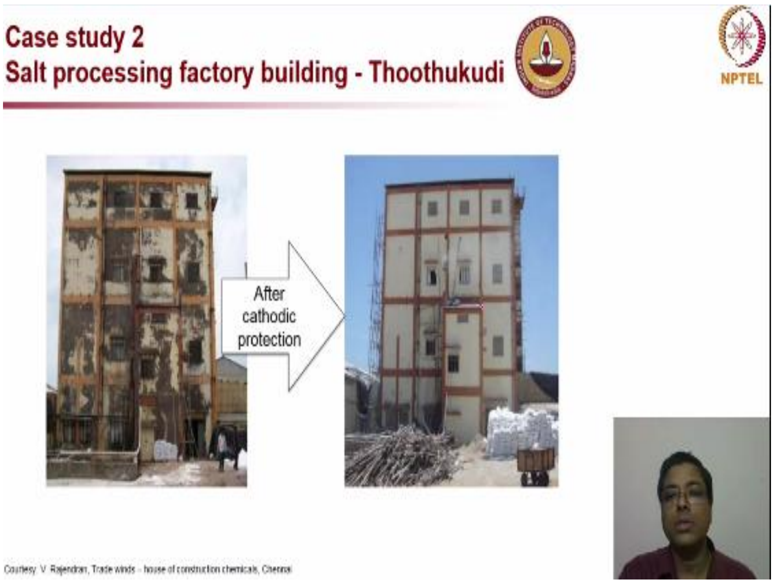

Another case study is a salt processing factory building in Thoothukudi or Tuticorin. You can see the picture on the left side, it is in a corroded conditions. This is before the repair, and after the repair the structure was strengthened.

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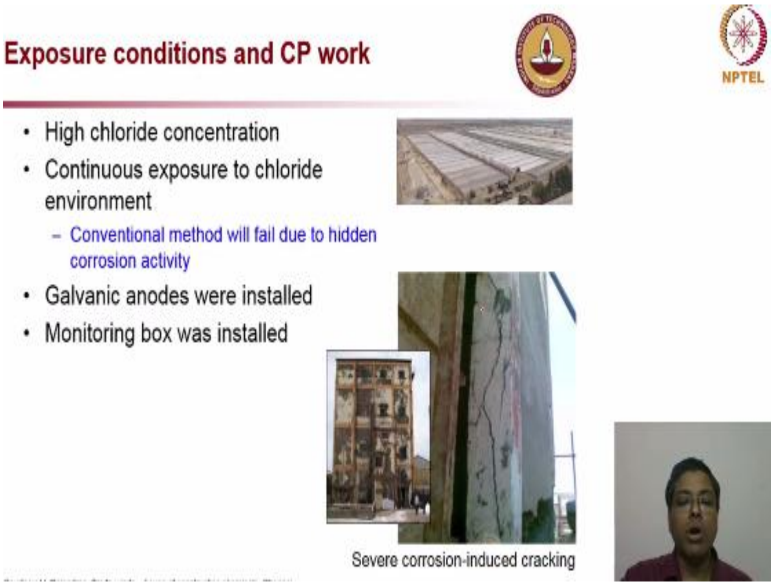

And you can see a lot of cracking on the vertical columns and then, what they did is, they stopped the corrosion at that moment by installing cathodic protection systems and additional reinforcement were also provided, but the fact that they have stopped the ongoing corrosion is the most important factor to be noticed here. Cathodic protection means you stop the corrosion. And then whatever the residual steel available, you see if it is sufficient. If not you add additional steel, but whatever be the case, there is no more corrosion going to happen to the steel. So that is the beauty of it.

So in this project, they found very high chloride concentration because it is a salt-processing factory and also a coastal region and then continuous exposure to chloride environment. Conventional methods were failing and will fail, due to hidden corrosion activity. So if you are just doing a patch work, it is not really going to last longer, because the corrosion will still continue to happen. So you have to arrest the corrosion from happening or stop the corrosion from happening and then best way to achieve that is to provide galvanic anodes and connect them to the steel and also some monitoring boxes were installed because this was done about 10 years ago and so people wanted to get data, how it works.

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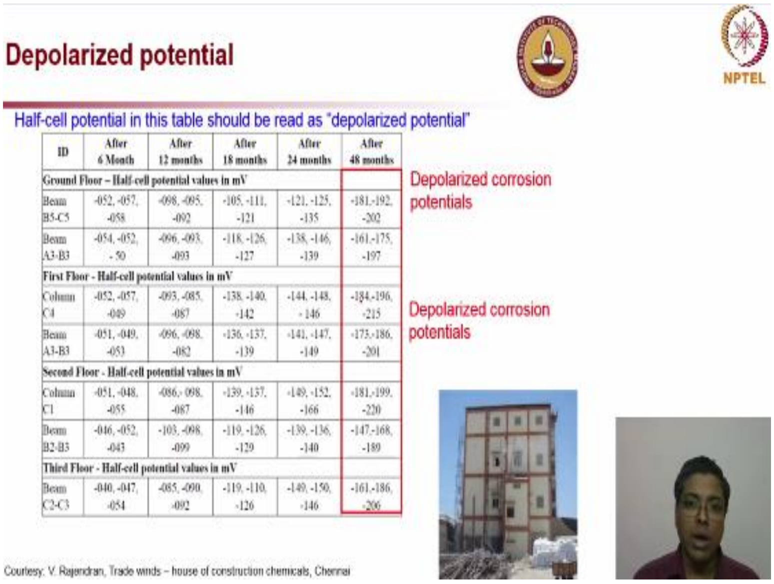

ID	After 6 Month	After 12 months	After 18 months	After 24 months	After 48 months
Ground Floor – Half-cell potential values in mV					
Beam B5-C5	-052, -057, -058	-098, -095, -092	-105, -111, -121	-121, -125, -135	-181,-192, -202
Beam A3-B3	-054, -052, - 50	-096, -093, -093	-118, -126, -127	-138, -146, -139	-161,-175, -197
First Floor - Half-cell potential values in mV					
Column C4	-052, -057, -049	-093, -085, -087	-138, -140, -142	-144, -148, - 146	-184,-196, -215
Beam A3-B3	-051, -049, -053	-096, -098, -082	-136, -137, -139	-141, -147, -149	-173,-186, -201
Second Floor - Half-cell potential values in mV					
Column C1	-051, -048, -055	-086,- 098, -087	-139, -137, -146	-149, -152, -166	-181,-199, -220
Beam B2-B3	-046, -052, -043	-103, -098, -099	-119, -126, -129	-139, -136, -140	-147,-168, -189
Third Floor - Half-cell potential values in mV					
Beam C2-C3	-040, -047, -054	-085, -090, -092	-119, -110, -126	-149, -150, -146	-161,-186, -206

So this is some of the data which we collected from Dr. Rajendran and you can see that the potentials are relatively in good range. And these are not the half-cell potential, very important, these are the depolarized potential, means the potential measured after the cathodic protection system was switched off and then waited for a day and then taken the measurement. So we call it depolarized potential.

Okay, you can see the data after 6 months, 12 months, 18, 24, 48. Even after 48 months, that is about 4 years, the data is still showing good protection. It is a much more positive than -350 critical range. So it is showing good protection.

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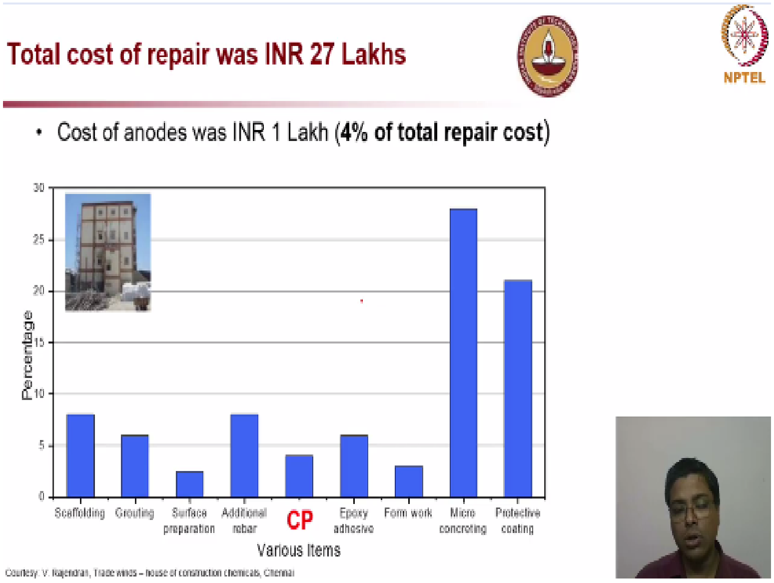

Now there is a myth that the cathodic protection system is going to cost more. But what in reality is, you can see on this chart for this particular project, we got the repair-cost data. For their entire repair work of this 4-storey building, you can see at the bottom, different type of project activities, scaffolding, grouting, surface preparation, additional reinforcement, CP (cathodic protection or anodes), epoxy adhesive, formwork, micro concreting and protective coating.

So these are all the different types of products and systems used for this repair work and you see that the cathodic protection cost only about 4% of the total repair cost, which is much less. So there is myth that cathodic protection means a lot of money, it is not really correct. And, in this project they have used micro concrete which accounted for almost 30% of the project cost and protective coating which is about 20%.

So 50% of the project cost is coming from micro concreting and protective coatings. So that is where you may have to work on, maybe you can even think of, do we really need to go for micro concrete, which is really expensive, because of the high cementitious content, etc., and other chemicals which are there in the micro concrete. So you can rethink whether, can we go for other types of concrete plus this other protection systems, so that we can reduce the overall repair cost also.

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Another case study is about, this is about 20-year old finger jetty structure at Chennai port and after about 8 years of construction, they found severe corrosion. So, in the red box here, is the type of structure that, those columns over there or piers over there are going to be discussed about.

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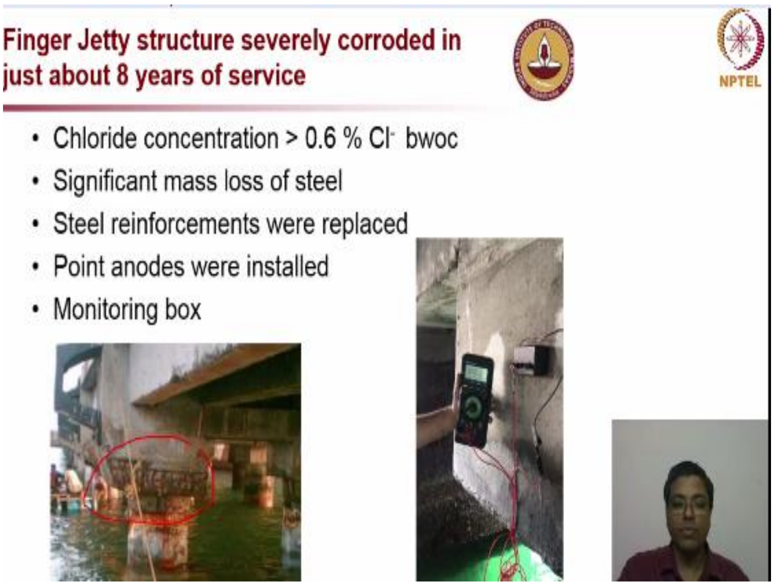

So this is the close-up view of those piers. On the left side you can see heavily corroded. This picture is taken about 8 years after the original construction. You can see very severe corrosion over here, the pier cap, you can see very severe corrosion and chloride concentration was found to be greater than 0.6 % of Cl^- by weight of cement. Significant mass loss, heavy corrosion and then what they did is they replaced, some of the reinforcement and point anodes were also installed all these sacrificial anodes and monitoring boxes. You can see the picture on the right side, which shows a monitoring box which is connected to the anode inside, that is a repaired pier cap. You can see that repair region and this picture on the right side was taken a just a few months ago.

It is still in very good condition; that is 12 years after the installation of the anodes. Picture on the left side was taken 8 years after the original construction and picture on the right side was taken 20 years after construction, which is 12 years of service of the anodes.

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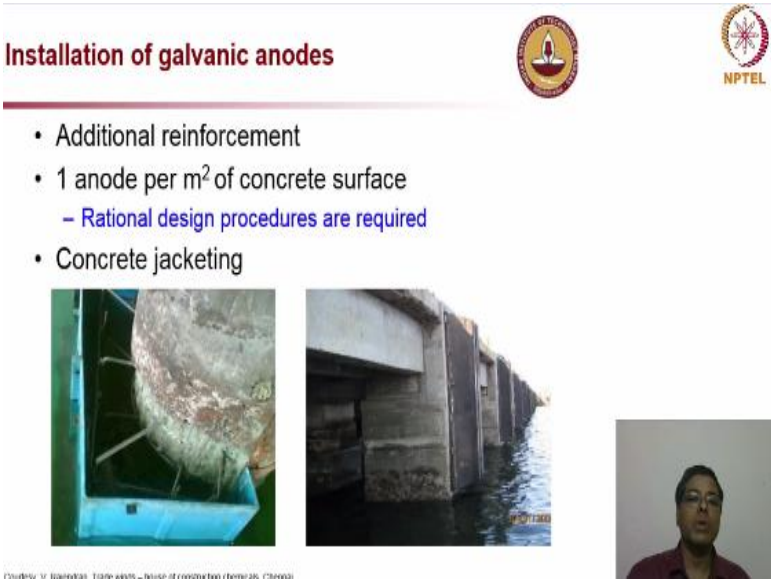

Now this is how the additional, the jacketing work was done. You can see the photograph on the left side, which shows the additional reinforcement which is anchored into the existing column and that square region was filled and their structure looks like one on the right side. So 1 anode per m^2 of the concrete surface was the typical application rate or, the spacing of the anode or something like that. Now that also indicates we need more rational design procedures rather than just going with a number like this.

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But still, this was a project done 12 years ago. So, at that time probably it was very difficult to even get the authorities to agree for this kind of work. So anyway, so let us have this data right now, and some pictures here show how the monitoring was done. So we recently visited the site and then took some measurements and also some photographs. So photographs very clearly indicate on the right side, you can see the photographs, which says no corrosion, no major cracking. I am not saying no corrosion, but no major cracking, even after 12 years of service. So that is very good and picture on the bottom right also it clearly shows no severe corrosion damage after 12 years of service.

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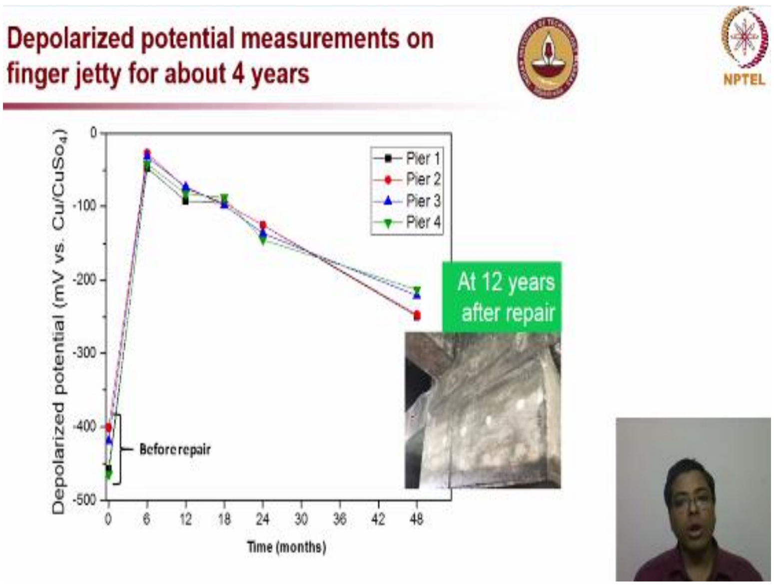

Now this is the data how it looked. Depolarized potential, you can see even though it is getting more and more negative, but, the plot is only for about 4 years and we could not collect the data after that, but what you have on the screen, that photograph is taken after 12 years of service and then it shows no corrosion-induced crack. That means it is really serving very well.

Imagine the picture which was after 8 years, so that is this (in previous slides). This picture on the left side, this was after 8 years of service without any sacrificial anodes and this picture (in current slide) is the one with sacrificial anode and after 12 years of service. So very drastic, you can very clearly see how the anodes are protecting the steel from corrosion, very promising.

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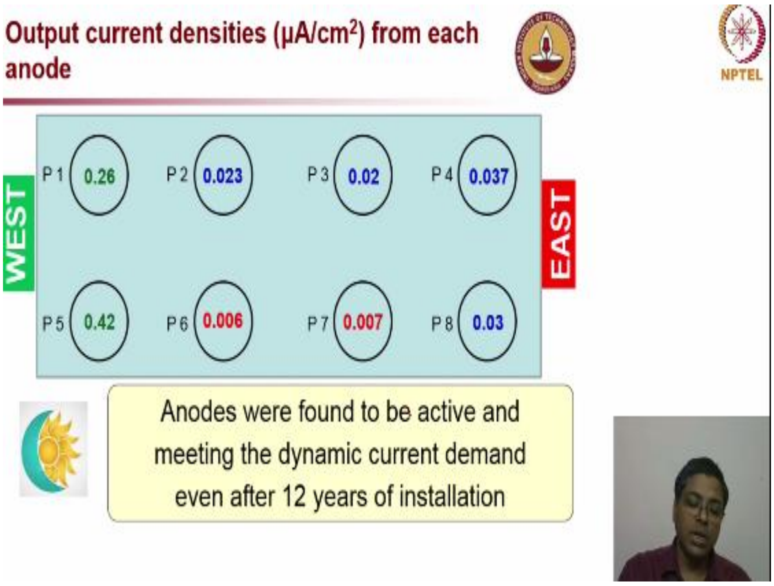

Now output current densities, this is some of the current densities which we got, from the site and you can see very, very low, and it is still able to provide current. That is the point, the anodes are still actively providing the current as it is required by the steel in the piers. So the point is, these are dynamic systems, so if the steel is demanding more current the anode will give more current, if steel is demanding less current, the anode will give less current.

So these also depend on the humidity conditions on the particular pillars, etc. So you can see, I put this West side, East side, etc., so depending on the day, what time of the day you are taking the measurement, and what is the humidity condition in the pillar, at that time or near the anode location, that will govern the demand, current demand and then if the anode is able to provide that is good.

So the message from this slide is that the anodes are able to deliver the current which is asked by the steel. You can see, even up to 0.42 $\mu A/cm^2$ in the P-5, (bottom-left), that is the highest current on the screen, and so the anode is able to deliver that much current even after 12 years of installation. So still the anodes are active. So the lesson learned is we can expect much more years of service with these anodes and the pier is going to be protected even for longer period of time.

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Okay, so picture on the left side, severe corrosion by 8 years in service without the anode. And picture on the right side shows minimal cracks - even after 12 years of CP installation. So the one on the left side is without any anodes, just 8 years, and the one on the right side is with anode, even after 12 years there is no significant corrosion. So people ask for data, so that is why we are providing this, there are sufficient data available proving that these systems really work. So let us practice this more and more and generate more and more data and then protect our structures also at the same time.

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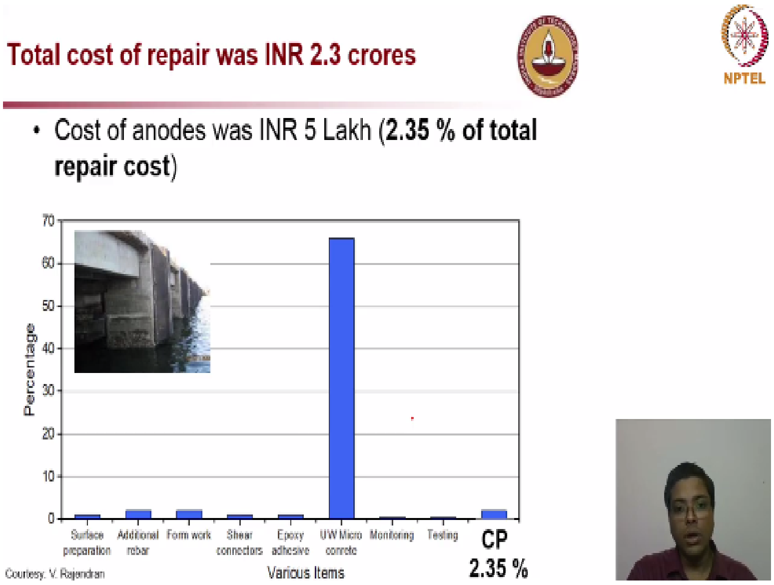

So cost factor, here again micro concrete is the largest cost and you have the anode cost just 2.35% of the project cost. So this anode cost is nothing, it is just that we need to have the will power and guts to actually start practising cathodic protection system. So it is not really affecting the capital investment of the repair, but definitely it is protecting the structure for much long period of time. That means the lifecycle cost is going to be much less, because we will not have to repair often.

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Another case study on a 5-year old building in one of the major cities in India and this building has about 500 units, apartment complex and severe corrosion is being observed, as I am talking it is happening. There are different columns, elevator shaft, basement, structural elements in the basement, living room, bed room, any point in the building you will see corrosion is happening and when we visited people were saying that, if you do not see corrosion on this location, you wait for 2 months you will see it there. So that much is the severity of this problem.

Why? Because, unfortunately the building was made with chloride-rich water or ground water which had sufficient chloride and the sand which was also available was rich in chloride. So these are the possible reasons because of which the chloride conditions were very severe in this building. So we tested the chloride concentration of the concrete and it was found very, very high.

And steel was also of poor quality, not like very good steel was used. And cathodic protection was the only viable option; about 3.5 lakh anodes are being installed. So imagine the amount of money which is being invested on to this through cathodic protection so that the building can be preserved or safe. So this is something very and someone would not invest this much money if there is no promises or if it is not guaranteed.

So definitely it is a promising technology we have to start using them wherever there are problems. So again let me also say this is not a replacement for other repair technologies. This is a technology which is helping the other repair technologies to serve better or augment.

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So these are some of the photographs showing columns and then other structures, and then on the bottom right you can see that is about a staircase where the anodes are installed. You can also see a control or monitoring box on the bottom right, you can see that. So these were the example anodes installed to check the performance of the anodes.

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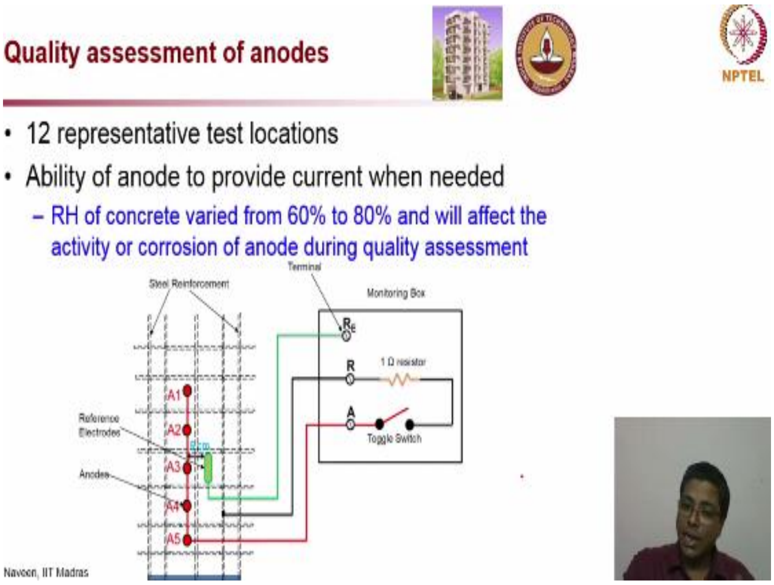

So one more important thing I want to tell is, when we check the performance, this is how the anode performance is checked. You can see 5 anodes were installed and reference electrodes, which is the green mark over there which is kept very close to and embedded into the concrete, which is very important, so that you get a uniform data.

And at the same time, the humidity of the test region should be maintained very high, because you are testing the anode, right? So if you keep the humidity in that region very dry, what will happen is, there is no demand for corrosion, so anode will not provide the current. So what you have to do is, this area where the test region, we call it test region, those regions should be kept relatively wet before we take the electrical measurements. And then, when we take the electrical measurements, we have to see whether the anodes are able to supply the necessary current or not. And this should be done after the installation, so that we can check whether the system is working or not. We are not checking whether the individual product or an anode is working or not. We are checking here whether the system is working or not; system when I mean, after the installation.

So for this, keeping very wet condition is important. The test region should be really wet. Let us say for example, you can spray the water or keep that region wet for almost one day, so that the resistivity of the concrete in that region becomes very low. When the resistivity is very low, then there is a possibility of the steel in that region to corrode. So when the steel tends to corrode, that means there is a high demand for the anodic current. And then, the anode will come into action, they will provide that current. Then if they are providing the current, we can say that the anodes are active and they are functioning at least at the time of testing. Again, it does not give any long-term performance indicator. This test provides only the on-site instantaneous performance. For the long-term performance, you have to go for GAP test, which I explained in few slides earlier and also in the other lecture.

Now if you do this on-site instantaneous performance test with dry concrete, then the steel does not tend to corrode. So there is no demand given to the anode, and so the anode will not provide the current. And then if your current is very low, you cannot say that anode is bad. So what you have to check is, you have to keep it wet and then try to corrode the system. And at that moment, the anode should come into the play, and they should prevent that corrosion by giving the current. One more time I will tell, this does not give the long-term performance indicator, this shows only that the anode, immediately after the installation you can do this test to check whether the workmanship was good or not. Connectivity between the bars, between the anode and the rebar, etc., were good or not, all that you can check with this. But for long-term performance you really still have to go for GAP test. When I say long-term, it means anything beyond 2 or 3 years of time, if you want to know whether the anodes are going to perform more than that time period, it is better to go for GAP test.

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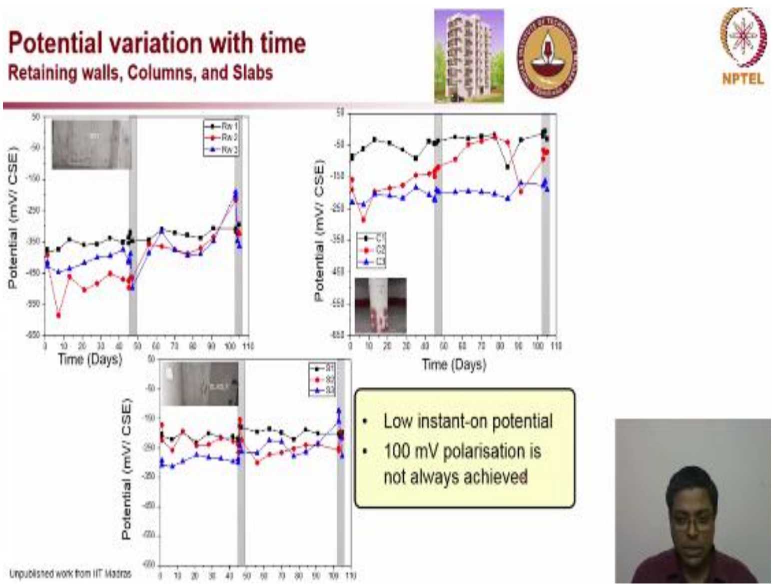

Now this is the potential, some data which we collected, and then here, why I put that is, instant-on potential is there, something which we call, means the moment the anode system is connected, you take a measurement. And then, generally there is a criterion that if there is a

100 millivolt (mV) shift in the potential, then the anode is good. This is a typical criterion which is practised in many places, but again this is not a necessary condition, in my opinion.

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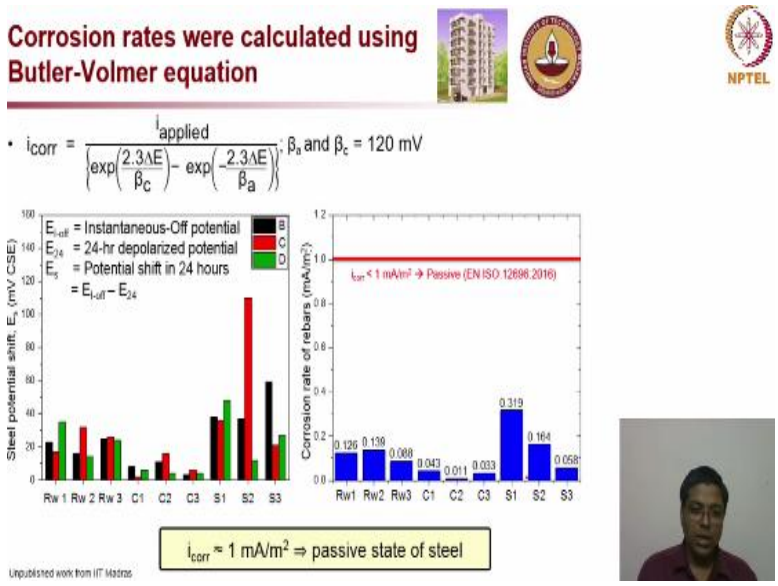

Because, here you can see, in these systems, there is a possibility that, even though the shift in the potential is less than 100 mV, as you see on the bar chart on the left side, the corrosion current for the same system is still very low. So at the end what we need is low corrosion of steel. So the blue graphs indicate that all these systems are actually providing good corrosion resistance or actually reducing the rate of corrosion of steel, even though the potential shift is not 100 mV.

So the message here is, this 100 mV criteria, if some anode systems which you get from the market, if they are not meeting the 100 mV criteria, it does not mean that they are bad. What you have to see is, whether those anodes are actually able to reduce the corrosion rate of the steel rebar. If the corrosion rate is less, then it is fine. So that is the message.

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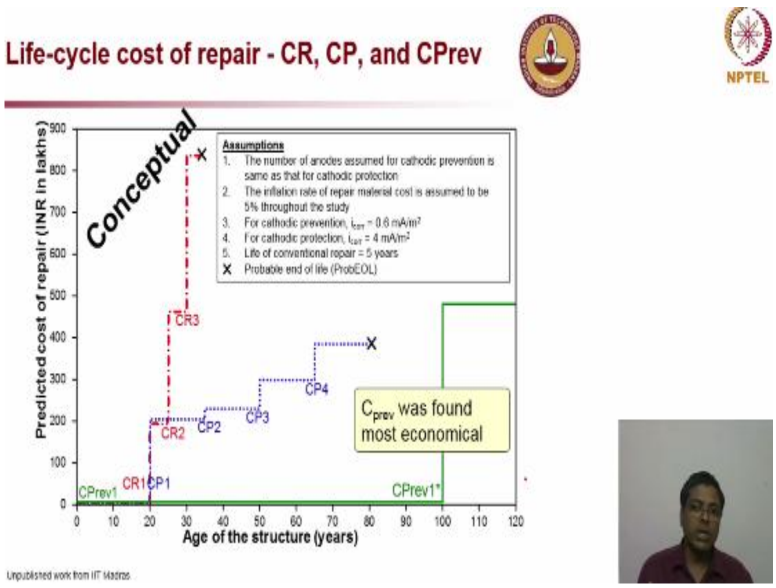

Now life-cycle cost, this is again a conceptual cash-flow diagram. You can see that on the horizontal axis, we have age of the structure, on the vertical axis we have predicted cost of repair. Now if we go with the red curve, that is conventional repair, that is patch work after the patch work after the patch work, without really having a system to protect the steel from corroding, that is cathodic protection, then your cost goes, significantly high. Very steep, and you can see very immediate step curves on CR1, CR2, CR3, like that. The cost is going to be significantly high, so the life-cycle cost of the structure is going to be very, very high.

Now if you go for cathodic protection, which is the instillation of anodes, after the corrosion is identified, that is when we call cathodic protection. Anodes are installed after the corrosion is identified, which is the blue curve on the screen, you can see CP1, CP2, CP3, CP4, these are the cathodic protection installation time. Let us say we are designing some installation for 20 years of life. So at CP1, you find that the structure is corroding and then you install a cathodic protection system. Then again after 15 years of life, if you find that system has exhausted completely, and then you go for CP2, that is the second installation of cathodic protection, like that you can go on. Still the overall cost is going to be much less, which is about 400 units on the graph, which is much less than the CR option, that is the conventional repair option. Cathodic protection is blue, conventional repair is red.

Now, a more beneficial system is cathodic prevention system, which is the green curve which you see. That is, you install the sacrificial anodes before even the corrosion, that means, during the construction itself, you install the galvanic anodes and we are going to call it cathodic prevention system – Cprev. That is the green curve on the screen. Very clearly you can see that it has much longer life. And, you can significantly increase the service life with minimal cost. So if you are targeting a 100-year service life, all the investment is just required in the very beginning. Again this is a conceptual graph, just to show the difference between the 3 options. So it is up to the designer or whoever is paying money to decide on which type of system is required for the desired service life.

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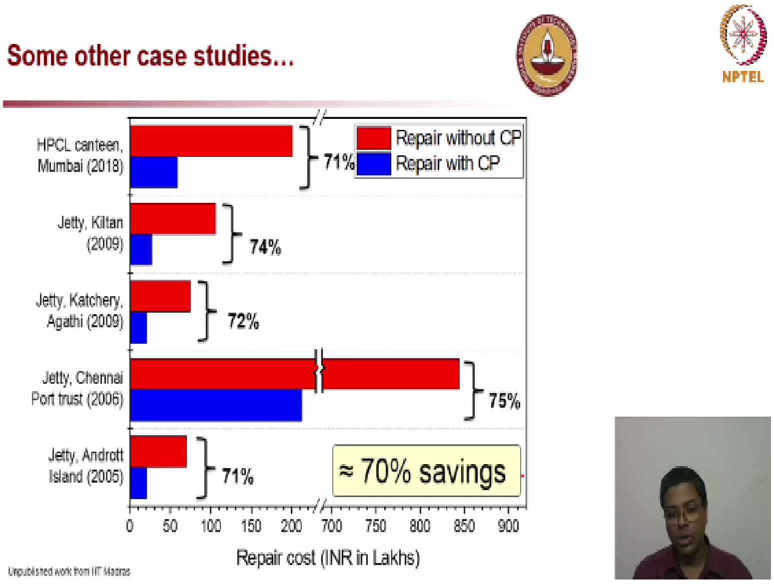

Now this is some more case studies, data from real experiences. Here I am showing a canteen building in Mumbai, multiple jetty structures; in all these structures, there is about 70% cost saving when you go for cathodic protection system. So that is very, very significant. And this is just one repair cost. So that will save significantly also on the life-cycle cost. So there is 70% saving. We really have to push this technology deep into our repair industry. It is very, very essential.

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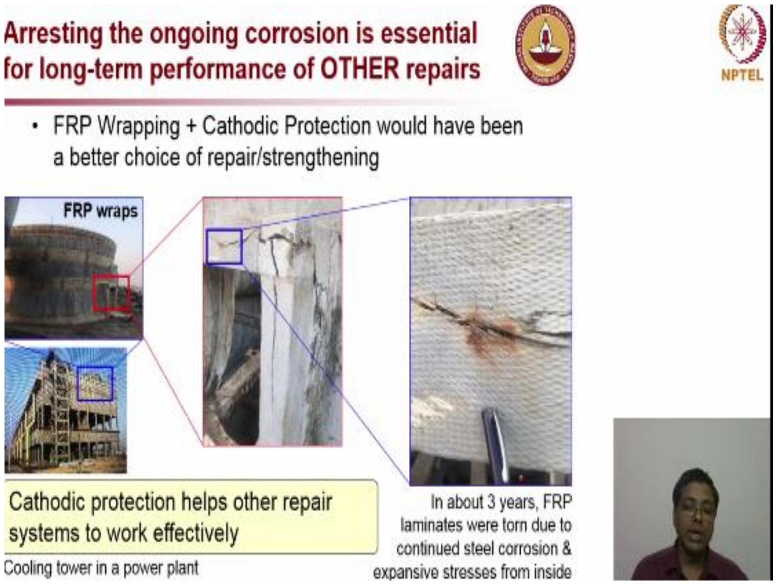

And one more thing I want to say, this is a demonstration of how an installation of cathodic protection could have saved this fibre wrapping. So this structure on the bottom-left image, it is not a clear image. But, you can see it is a cooling tower in a power plant and you have this funnels at the top; huge structure, very thin element, but very large in diameter. These are the cooling tower structures, in most power plants you will see this, and you can see a red square mark over there, which indicate the corroded region where the fiber wrapping was failed.

So you can also see on the top-left image, there is a wrapping; 3 rings, kind of, laminates you can see. They are installed, because this structure was experiencing lot of cracking due to corrosion because there is a lot of chloride-rich environment here, because this structure is right next to the sea shore. So it uses the sea water and then that water after the power generation, is cooled using this, so that is why we call it cooling tower. So this particular concrete structure is exposed to very rich chloride conditions and this structure corrodes very fast.

Then about 3 years ago, somebody recommended putting this fiber wrapping to contain that forces of corrosion, etc., but it did not work, because the stress is coming from the corrosion of the steel inside. So unless you stop that corrosion from happening, the stress is going to keep on increasing, and then keep on exerting that pressure on to the surrounding concrete. So just providing a belt (fibre wrap) around the structure is not going to help. You also have to stop the expansive stresses which are coming.

So you have to stop the corrosion from happening first, then provide the fiber wrapping, then it will help. So here is an example where you can very clearly see the brown rust oozing out of the fiber wrapping, and it has cracked the fiber wraps. So on the picture on the right side you can see, the brown color rust oozing out through that crack, it is a large crack, a few millimeters wide.

And the texture you see is the fiber wrap (fibre laminates). Only in 3 years this is happening. So they invested a lot of money or rather spent a lot of money because there is no return of investment here. So they spent a lot of money on wrapping this structure with fibers and then they found that they are not really helping because the corrosion was still happening.

So 2 things - One is, when you go for repair, you have to really think about durability aspects and the structural aspects. So in this case, the corrosion of the reinforcement inside should be stopped. That is the repair to ensure durability. And at the same time, for the structural strengthening the fibre wrapping is applied. So, these 2 systems should work together, if you are providing only one system it may not work very well.

So, stopping or arresting the corrosion is very important when we go for repair works. And that has to be done in an electrochemical manner. So that is cathodic protection, electrochemical chloride extraction or electrochemical re-alkalisation, these techniques are kind of becoming more and more important to ensure that this repair is going to be long lasting.

Otherwise, you will tend to go back again to the same point and keep repairing. And this particular structure on the picture is going to be demolished now, because of this poor repair practice. Poor repair practice means just providing fibre wrapping without any method to arrest the corrosion. So if this FRP wrapping was done along with the cathodic protection of the steel, then this structure would have lasted much longer. So that is the message. So let us plan both cathodic protection and other repair systems. So do not look at cathodic protection as a competitor for other repair systems, but as a system which helps the other systems to work effectively.

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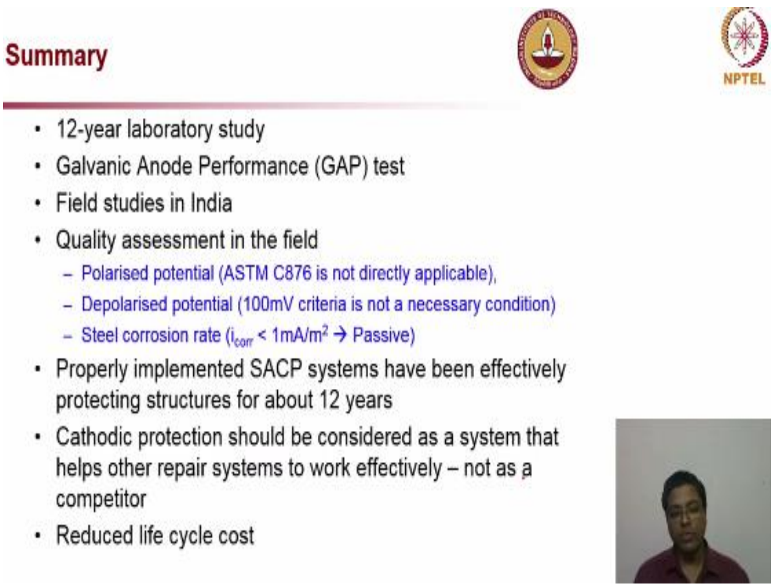

Just to summarize, we looked at different case studies, even 12-year old laboratory and field data were shown on photographs demonstrating that galvanic protection systems really work for even 12 plus years.

And then we have also demonstrated how the Galvanic Anode Performance - GAP test, can be used to assess the long-term performance of the anodes in very short term. And it is really worth doing that test, if you really are thinking about long-term performance, you need to do this test and it is highly recommended and then also shown some field studies in India. And quality assessment in the field - ASTM C876 is not directly applicable to these structures, but what we have to measure is depolarized potential and we also saw that 100 mV criteria is not a necessary condition. What we need to ensure is the corrosion rate of the steel, as long as it is less than 1 mA/m^2, then we can consider it as a passive condition.

And then properly implemented SACP systems have been effectively protecting structure for about 12 years. We have now sufficient field data to start distributing to everybody and then let us start using cathodic protection system as a system which augments the other systems to perform very well. So do not look at cathodic protection as a competitor to other repair practices, but as a system which helps the other systems to work effectively. And, very sure that this application of cathodic protection is going to significantly reduce the life-cycle cost by reducing the number of repairs. We also looked cost factors. So I think with that I will close, and these are the references which we used, to make this presentation and thank you.