Maintenance and Repair of Concrete Structures
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Lecture – 32
Case Studies on Structural Repairs Right Methodologies and Systematic Approach

Good day to you. In today's lecture we will learn right methodologies and systematic approach for repairs, rehabilitation and strengthening of RCC structures. We will learn this with the help of various case studies of different types of structures.

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The course content comprises of:

- Basics of repairs and strengthening.
- Approach to systematic repair and strengthening methodology.
- Case studies for various types of structures and strengthening techniques.

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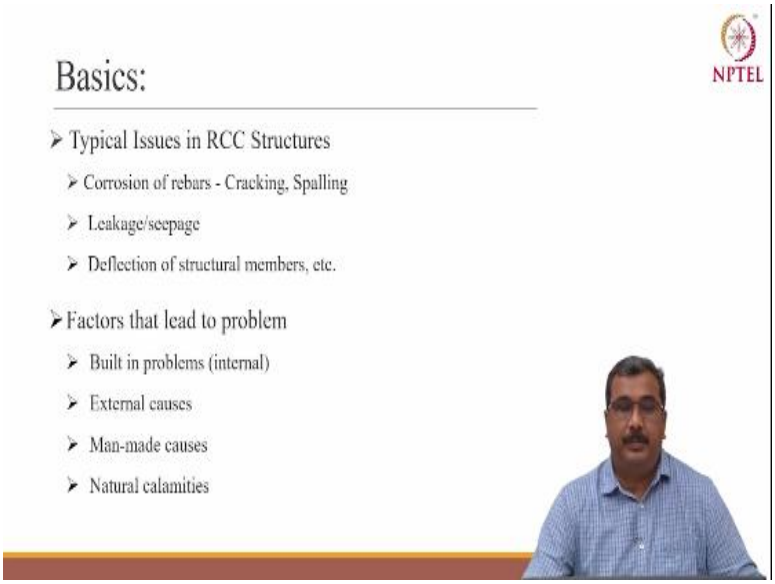

So coming to the basics of repairs and strengthening. In your previous lectures, you have learned in detail about basics of repairs and strengthening. I will just go through it briefly.

What are the typical issues in RCC structures? One of the main issues with RCC structure is corrosion of rebar. Any RCC structure cannot be constructed without reinforcement and reinforcement are prone to corrosion. Because of corrosion it induces cracks in RCC elements. If these cracks are not attended in time it leads to advance stage of corrosion defects, which we commonly term as spalling.

Another major issue is leakage or seepages. They are adding to the corrosion of rebar. Also they are making the structure not rehabilitable. If there is an ample amount of leakage, you cannot use the property beneath the slab or backside of the wall or if there is a server room or there is a control room in the industry, the leakage will create a problem, or if in a chemical plant, if there is a leakage it will create lot of issues, so this is one of the next major issue.

Another is deflection of structural members, or you can say failure of elements in form of shear, flexural, compression, deflections which may lead to various problems like crushing of concrete, hogging, sagging of the slab and all sorts. You would've learned this in detail in your earlier lectures.

What are the factors that lead to this problem? Broadly they have been classified into 4 different types.

1. Factors which are built-in problems - built-in problem means design fault, workmanship fault during construction, wrong selection of type of material, wrong specification of material or water proofing system failure, wrong specification of water proofing. If there is a problem with the water proofing, it will lead to leakages, further it might lead to cracks and this being a cyclic circle, it will lead to corrosion, again leakage, again more cracks, if the right material is not selected. What do you mean by right material? If you are not selecting sulfate-resistant cement for an underground structure in a coastal area then your elements that are below the ground are not resistant the sulfate attacks. You will have problem if you are not selecting a material considering durability and performance of the element. You may use slag cement in an adverse environmental condition, it is going to be helpful. Wrong selection for material of protective coating, wrong specification, and all these factors are built-in problem.
2. External causes - environmental effect, it can affect your structure, if it is in coastal environment. We had come across that within a span of 3 to 5 years of construction, because of environmental effect, there are major issues. Another external cause may be carbonation - in densely trafficable area, chloride attack, sulfate attack, chemical plant environment.
3. Man-made causes - Yes, we also do various problems to our structures. We do faulty design, we change the use of the structure, people make addition and alteration in the structure without considering overall capacity of the structure or what the problem could be. If in a commercial complex to have a large hall, people cut the column if it is coming in between their interior planning. There are examples wherein the building has collapsed because of that. Change in use. If building has been designed for residential purpose and because of some reason if there is a change in use to a commercial building or a hospital, then your loading changes and your building strength requirement changes and you need strengthening.
4. There can be natural calamities - earthquake, cyclone, floods. All these create a huge damage, huge impact on our structures. We need to carry out repairs and rehabilitation and strengthening for various structures because of any of these 4 problems.

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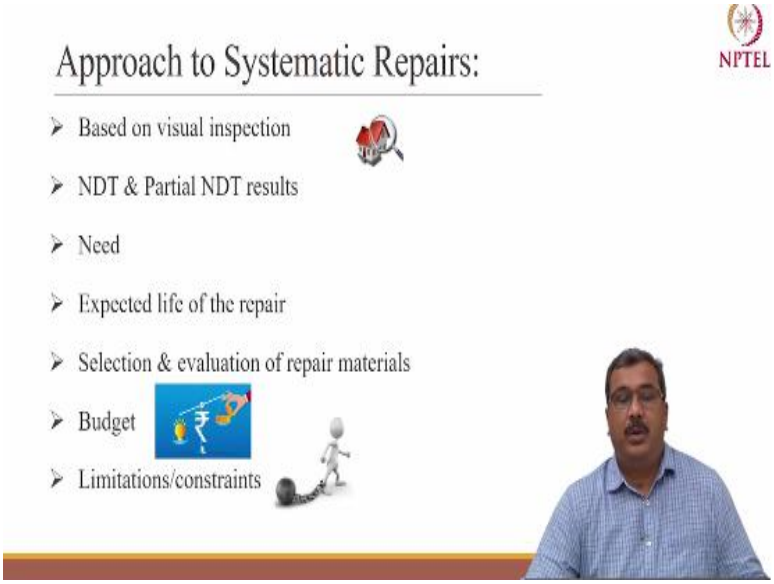

How to do a systematic approach for repairs and strengthening of such structures which need treatment? Very first thing comes is visual inspection. It has to be on the basis of visual inspection. We need to observe the structure properly, carefully see the pattern of the cracks, alignments, signs of leakages, colour of the concrete, corrosion marks, how particularly such defects are on one face, another face, bottom of the building, settlement of the building. Everything has to be noted and mapped on the drawing and interpretation has to be carried out to know the reason of the failure or to know the reason why you need repair or strengthening.

After you carry out visual inspection the second most important point is to carry out NDT and partial NDT results. I am sure you are well aware of various types of non-destructive and partially destructive tests. But it is very important to select the location of test and what type of test should be carried out. If based on your visual inspection, it is required to carry out corrosion survey because you found that visually, apparently, it is a problem because of corrosion of rebar, then you need to carry out chemical analysis of the concrete, half-cell potential, corrosion resistivity of the concrete, to find out how fast there is a movement of ions. If it is more resistant, then the corrosion rate will be slow. You can also measure the corrosion rate. But if you found that there is no corrosion and there is only a deflection or a crack, then you do not need corrosion survey. So selection of type of test is very important. Also location of test, you should get the test at good condition, bad condition and in-between. Try to get 3 type of locations so that you can compare the test results for that building, apart from comparing it to the latest codes.

Once you have done the visual inspection and carried out test, one should know why you need repairs and rehabilitation or strengthening of the structure, what is the requirement? You can ask to the owner or user.

Expected life of repair - This is very important to determine how much my repair or strengthening will last. You cannot afford to spend handsome amount of money on repair today which will last for 25 years or you can spend 25% or 40% of same amount and you may go for repair next time after 10 years or 15 years. Or sometimes it is so important that you need to select the repair methodology such a way that your repair and strengthening scheme should last the age of the structure. So that is one more important point.

Then selection and evaluation of repair material. What material should be used for proposed repair and strengthening? You should evaluate the material. Material means starting from rust removal material, corrosion protection for rebar, bonding agents, strengthening material, polymer modified mortar material, micro-concrete or it may be steel plate, steel, cathodic protection material, protective coating, water proofing. You cannot use epoxy grout for injection grouting for a leaking cracks, vis-à-vis, you cannot use a polyurethane grout for structural crack repairing. Similarly, you should not use polymer modified mortar for a large area and very high thickness. It is always good to go for micro-concrete.

So once you have selected the material, it comes to the budget also. Based on your approach from visual inspection to selection of material and the system, if the owner, user or client does not have money for life of 25 years, then you may need to rethink and to carry out entire exercise depending upon the budget.

Limitation and constraint to work - You need to design or approach to a system such a way, that the work can be carried out in spite of constraints or limitation. You cannot have a bridge or a traffic stop for very long period in a city where you do not have an easily available alternate route. Or you cannot carry out some repair of a building, may be university, during the exam time. So in vacation you have a limited time of 2 months or 1.5 months, so time is the constraint. Similarly, in industry, plant working condition, shutdown is the constraint, accessibility to the location is the constraint, working condition is the constraint, and so all constraint has to be taken care of. So based on type of causes, type of

problem, systematic approach evaluation, right repair methodology has to be derived. We will see practically how this systematic approach has been implemented at site.

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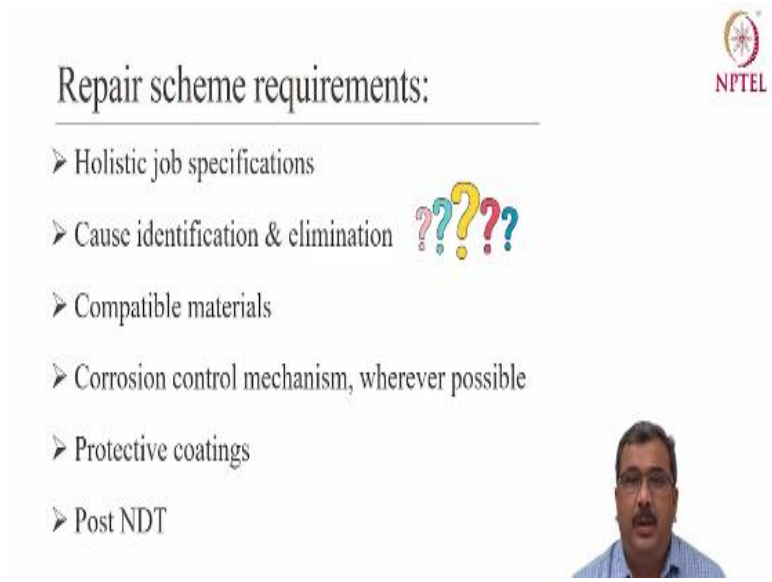

Also what is the repair scheme requirement? It should be a holistic job specifications, that is, you need to frame your specification in such a way that it complies with your all the system of repairs and strengthening. You can have a carbon fibre strengthening, but then you need a final finish with a protective coating or you may need further beam strengthening by using steel plate. You need to check whether these both will comply or not.

You must identify the cause. If you see a crack, you should not just repair it with injection grouting or making it V-groove and filling it with some epoxy putty or mortar. Find out why that crack has occurred and prepare a scheme which will eliminate the cause of the crack. So this is second important point.

Third is compatible material. The material which you are going to use for repair should be compatible with the parent material. If it is not compatible, it will be a big failure of specification stage.

Corrosion control mechanism wherever possible - if you have identified the cause and if it is corrosion, if you do proper preparation, do proper repair, but if you do not incorporate corrosion control measure, you will have similar problem in near future. So try to incorporate corrosion control. That is the best way of elimination of problem of corrosion. You can use

sacrificial anodes or you can use cathodic protection by means of ICCP and various other means.

Protective Coating - Type of coating, thickness of coating, application methodology, that all has to be derived based on the site condition. You cannot have a non-aliphatic epoxy coating on outside of the surface or you cannot have a simple anti-carbonation coating for a chemical resistance element. So a protective coating has to be selected properly.

Finally Post NDT. A systematic approach of repairs is complete with a Post NDT. It is like carrying out an X-ray after your fracture got healed which ensures that 'yes, my structure is good now', if you carry out NDT post repair.

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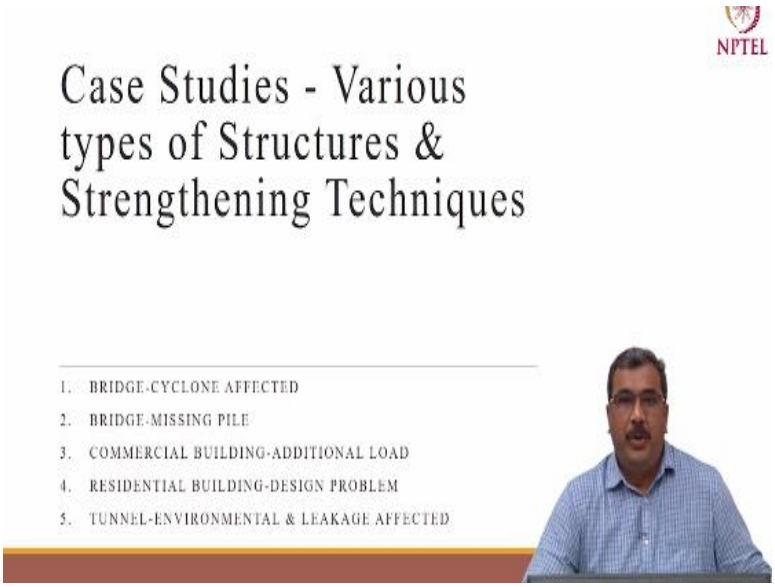

So with these based, we will go one by one, these 5 case studies - 2 for bridge, 1 for residential building, 1 for commercial building and 1 for industrial plant.

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Let us start with first case study - it is a bridge structure.

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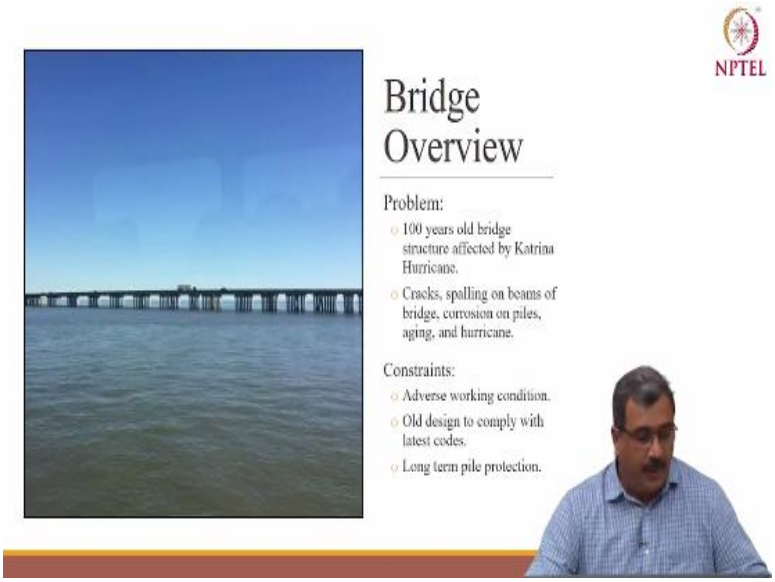

You can see this bridge; it is few kilometers long, it is located in Louisiana state of United States of America in New Orleans. This bridge is 103 years old and the problem occurred when there was a hurricane named Katrina a few years back. Because of aging, because of corrosion and hurricane when they checked the bridge, they found there were a lot of cracks, spalling in the beam of bridge, there were corrosion in the piles.

And they were not sure that it can withstand another hurricane, although it had, it has withstand the Katrina hurricane, but it was always a question. So a detailed study has been carried out in terms of visual inspection, various tests have been carried out and it was confirmed that there is an ongoing corrosion. So, electrochemical repair and strengthening

was the requirement. Being an important bridge over a very wide river, so budget was not the constraint.

But there were limitations, like adverse working condition. It is a 100-year old design, it is not complying to the latest code. You can always replace a partial deck of the bridge span by span. This is a common practice is USA and Canada, that is North America, but to replace the pile, it is not that easy. So they wanted to carry out pile protection, like protecting the pile against corrosion and strengthening for further 50 years or more than that.

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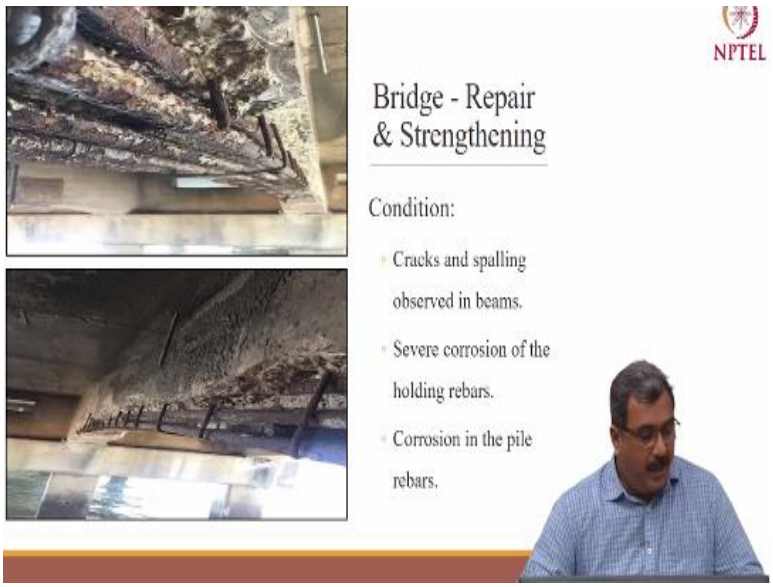

This was the condition of the beam. You can see cracks and spalling. The holding bars, these are the bars which are holding the main reinforcement. You cannot see the holding bars, they had fully corroded here. There was corrosion in the pile rebar.

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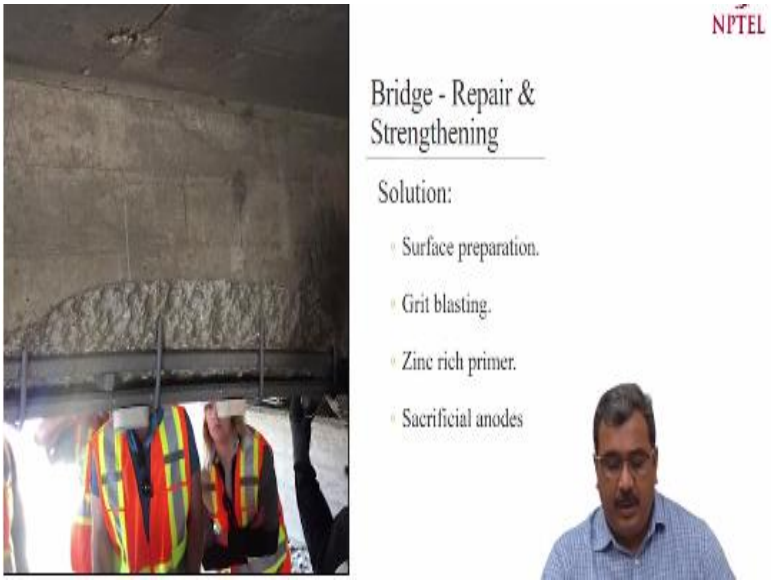

So a solution has been derived. All the beams need to be properly prepared by removing all the loose concrete or the concrete which is not in good condition. The good quality concrete although may be contaminated is not removed. All the steel reinforcement were grit blasted using copper slag. You see the quality of surface preparation. This is an old steel reinforcement just grit blasted, it looks like, say half type cleaning of the rebar. New rebar has been planted and sacrificial anodes, this white anode (refer to Figure in slide), are being tied to the rebar based on the design of steel density of the bridge considering the life of 25 years for the anodes. So, the damaged surface of concrete was prepared, steel was cleaned and protected, and an electrochemical protection using sacrificial anodes has been installed. Such a long bridge, so much spans, a very deep river, it is difficult to do shuttering.

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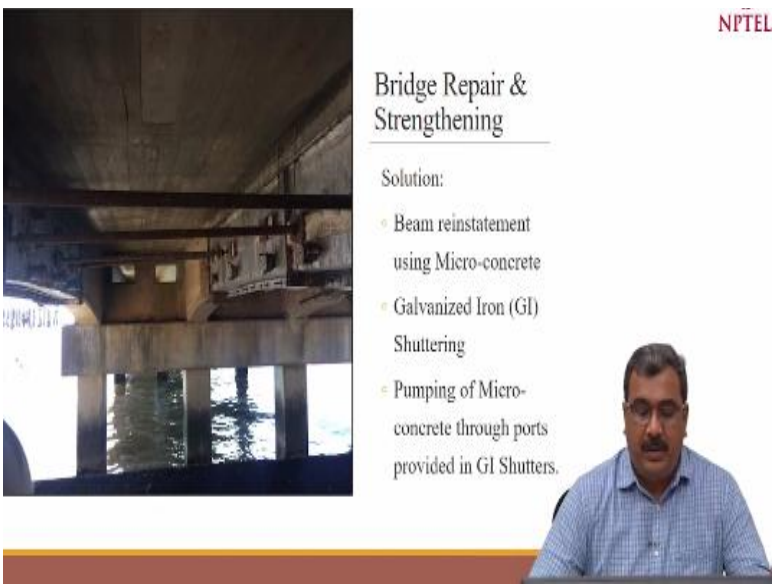

So a GI shutter has been decided to carry out reinstatement of damaged portion of the beam using micro-concrete. These GI shutters were held in place with horizontal supports, what you can see in the photograph. Holed U-shape shutter were anchor bolt and they had been supported horizontally. That way you do not need a bottom support in the water. There were ports at the bottom to pump the micro-concrete.

And this micro-concrete has been pumped by keeping the pump on the shore or on the boat. So once it is filled, shutters are removed. It is good that all spans were of same size. So these galvanized iron shutters can be used for multiple spans.

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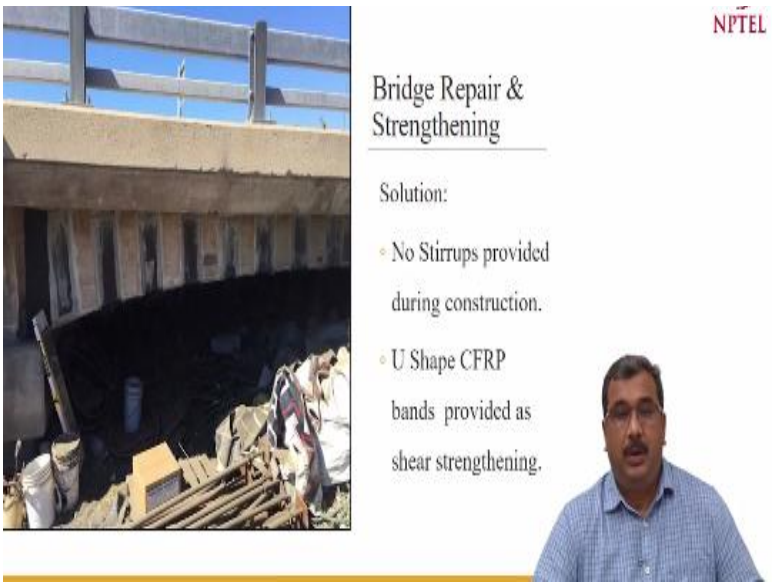

One interesting thing is that, no stirrups or shear reinforcement were found in the beams. Amazing that the beams without shear reinforcement, stirrups, are standing for 103 years, withstanding hurricane. But latest code does not permit this. So structural analysis has been carried out and shear reinforcement were provided using carbon fiber wrapping in U-shape as per equivalent amount of steel reinforcement required for shear. That amount of carbon has been installed in the form of wrap on 3 sides. Structural analysis has been carried out based on prevailing codes and design calculation for CFRP has been carried out based on ACI 440.2R 2017.

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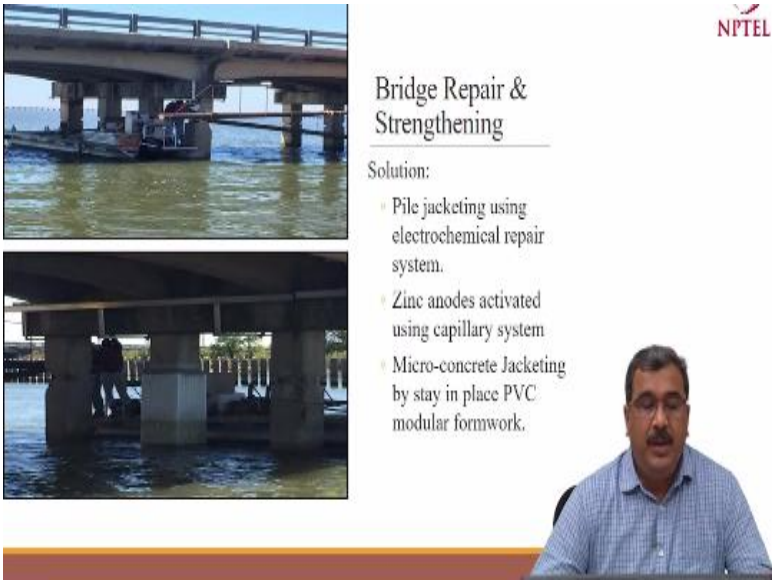

So you have repaired and strengthened your beam to match the need of enhanced life, longevity, easiness to construct, right material specification, now question comes for the piles. So a new system has been installed for the protection of piles from corrosion and strengthening. All the piles, there are more than 6,000 piles, has been protected in the tidal zone, which is most prone to corrosion, because this river meets sea very nearby.

A zinc plate wrapped in a cloth specially designed by competent authorities (competent company), were installed on all the sides of pile and a connection was established. You can see the column broken for establishing the connection, between the zinc and the rebar and the length of anodes were such that because of the cloth by capillary, by wick action this brackish water will keep zinc corroding, so that steel are protected from corrosion.

After temporarily tying the anodes to the pile, a special PVC modular formwork which comes in strips and it can take any size, any shape, has been erected and the annular space between the pier and the stay-in-place formwork is filled with micro-concrete, along with additional reinforcement provided as per the structural design.

So you have a strengthening requirement, you have a corrosion protection requirement, a long-term requirement, easy to work in adverse conditions. Everything has been sufficed by providing a PVC modular jacket with micro concrete with sacrificial zinc anodes activated by wick action for all the piles. This way it was ensured that the piles and the beams of the bridge last for more than 50 years.

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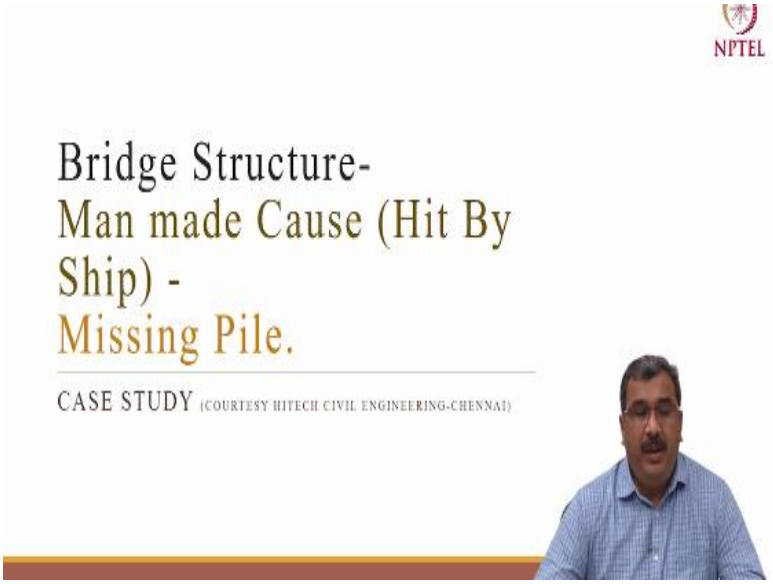

We will go to second case study. The problem was man-made. A very interesting case study.

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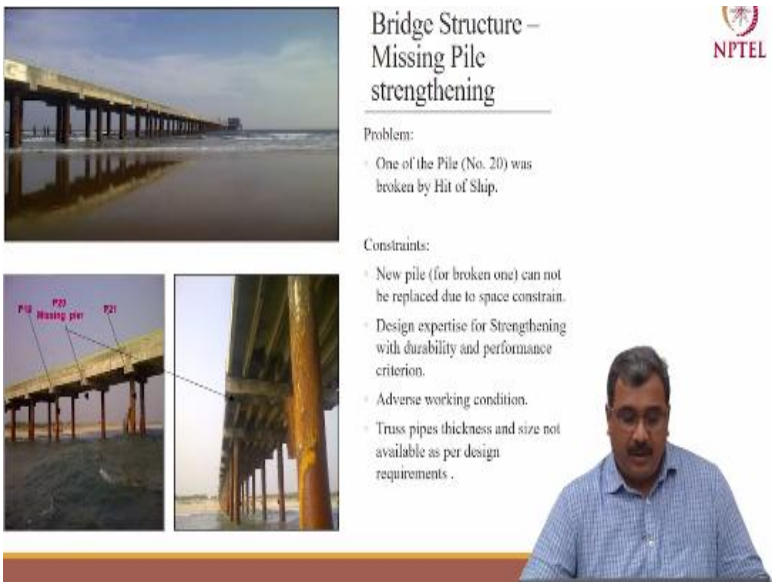

This case study is for a missing pile (missing pier) of a bridge. This bridge is connecting an intake of a power plant which is well inside the sea to the way-ahead power plant which supplies water. Now one of the piles, you can see the pile number 20, was broken or damaged as it was hit by a ship. So this span is not safe, this is pile P-19, this is P-21 and Pier-20 is missing.

Coming to the constraints, if there is no deck slab, you can have an adjoining pile, you can design it, but there was a pile broken portion inside, you cannot grow the pile, you cannot have an adjoining location pile. Practically how to construct that? That was a limitation. Here

a non-destructive test or visual inspection is not that important. Important is design for strengthening, how to provide support for the missing P-20 with durability and performance. Conditions are very adverse; you are in the middle of the sea and how to transfer the load to the newly planned truss.

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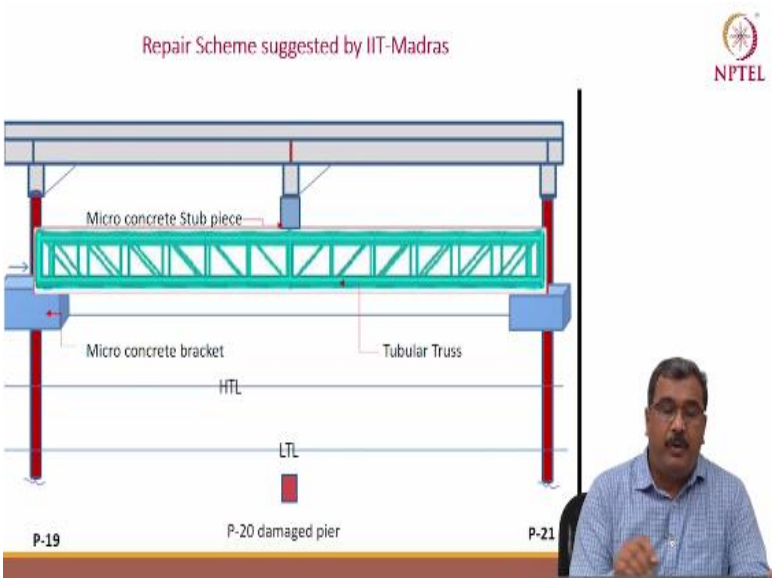

I will explain in detail. With the help of IIT Madras, a scheme has been derived, wherein a new truss has to be fabricated, a new bracket has to be constructed, the truss is to be placed on these 2 brackets. Another stub piece of micro-concrete to be installed with base plate and then this whole truss has to be loaded jacked such a way that the load being transferred to these 2 pile. Also analysis has been done that these 2 piles are capable of taking the 50% load from the missing pile.

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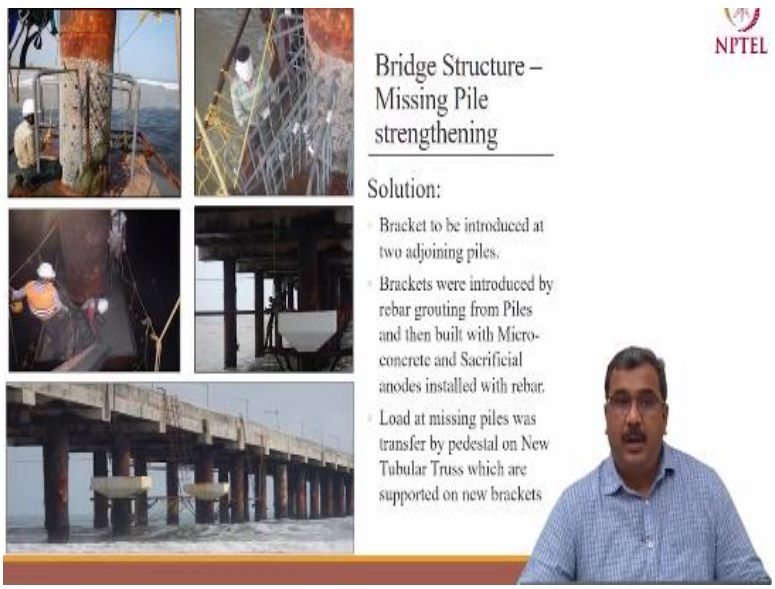

So these 2 brackets has to be constructed on P-19 and P-21 to support for this P-20. So proper access has been made, a hole has been drilled in the liners, 32 mm hole, depth as per requirement of calculation; rebar grouting of the main rebar has been done. Sacrificial anode, again, an electrochemical repair for protection of this reinforcement from corrosion is done because of environmental effect, location of the structure.

It will induce lot of corrosion. So the steel has been installed using rebar grouting, sacrificial anode has been installed, a zinc-rich coating has been done on the rebar, shuttering has been provided and micro-concrete has been poured in the shuttering to form a bracket. These brackets again have been coated with a high performance, anti-carbonation, anti-chloride-ion diffusion, acrylic aliphatic coating. This is how 2 new brackets have been made. On these 2 new brackets a truss will be placed.

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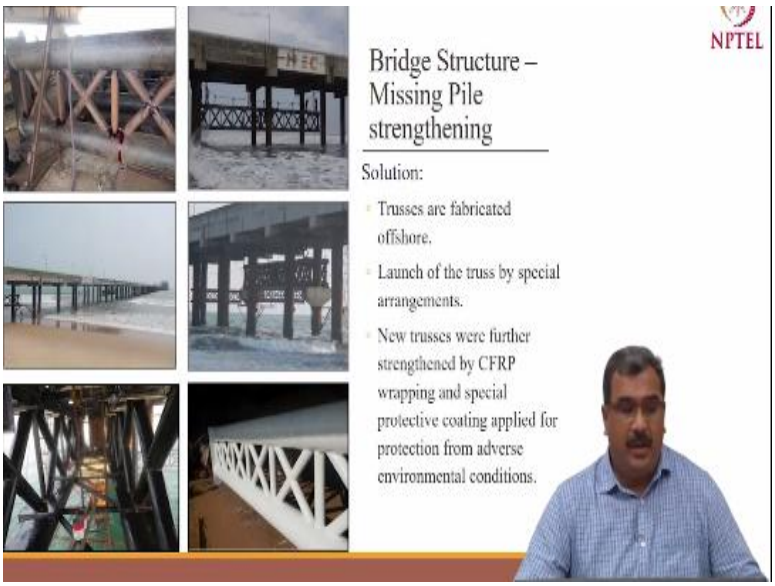

Now this truss has been fabricated offshore. The maximum available pipe thickness was 17.5 mm for a diameter of 350 mm of pipes. Although that was not sufficient, but initially a tubular truss has been fabricated, as you can see in the photograph. This truss has to be taken and placed on these 2 brackets. That was a big problem.

But thanks to the contracting team, they had carried this truss by launching and using winch, from the existing support of the bridge, by mean of a wire rope and the whole of this truss has been launched from shore, right up to the bracket and placed on 2 brackets. After placing, as I told you that the specification of available pipe was not sufficient, so entire truss has been strengthened further, by using carbon fiber strengthening.

A proper care has been taken that there is no direct contact between the carbon fiber and the MS pipe which might induce further dissimilar metal corrosion. So there is an adhesive or surface is prepared in such a way that there would not be any direct contact between the carbon wrap and metal. There will be insulating coating in the form of epoxy which will not allow electrons or ions to move, travel from carbon to iron, no direct contact.

After carrying out carbon fiber strengthening, a further protective coating has been applied on carbon fibre system. So your brackets are in position, truss has been put in position, protected properly, then jacked to take the load of the pile, so it is properly transferring load exactly on P-20 not on P-19 and 21 as if it was doing when there was no pile, and proper deflection, loading check has been carried out at location.

And most important while launching this girder, there was a cyclone. It is our luck that contracting team does not have any major loss in form of loss to truss or any other thing. So a design issue, material availability issue, adverse working conditions and new concept. This is how a missing pile has been replaced and been strengthened.

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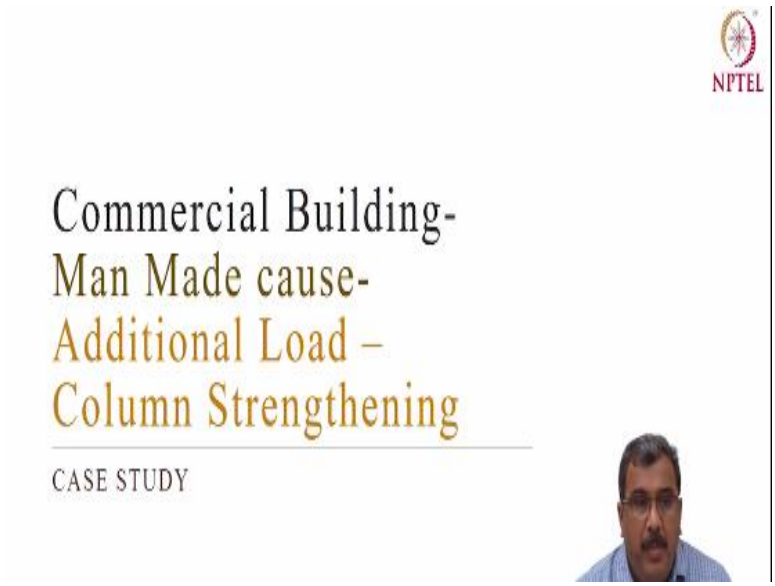

We will have another example of commercial building, man-made cause again, additional load.

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This is an ongoing building which is meant for commercial use, when they had constructed up to 7th floor and 8th floor was under construction, the 8th floor was sold to a company who is in business of IT sector. They were supposed to have a large server placed on 8th floor slab and this additional load, this live load, was not considered in the original design. So considering the new load, whole structural analysis has been carried out.

And it was found that 4th, 5th and 6th floor columns, few of the columns of these 3 floors were not adequate and they were found to be deficient for moments. Axially, for compression and for shear, they were safe. As I told, the 8th floor was not constructed. So based on new requirement, the slab and beam of that floor, design has been altered and there was no requirement of strengthening for that floor.

So only requirement was for few of the columns on 3 floors. But the constraint - lower 3 floors were already constructed. The floor above it were also constructed. And architect and interior design and use of the lower floors does not permit to have a jacketing or increase in size of the column. Also if you want to increase the size of only 3 intermediate floor, you need to carry out jacketing right up to the basement, which again a limitation, space-wise, hindrance-wise, cost-wise. So we had designed a CFRP system as an alternate without increasing the size of the columns.

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So CFRP laminates, plates of 100 mm wide and 1.4 millimeter thick were installed on the face of the column. The construction area of the laminate that is 100 * 1.4 * numbers of laminates, were derived on the basis of area of steel required for the deficient moment. Once the numbers have been derived, a proper care has been taken for junction development, that is to transfer the load from column capital to the column.

For the columns which were supposed to be strengthened, a proper surface preparation has been done to even out the face of the column. Also the edges were rounded, because there is a partial confinement also for enhanced moments, to take care of shear and compression and to avoid delamination of the laminates. So rounding is very important, the radius of rounding should be based on the design. If in your design you have taken 'R' as 25 mm, there should be minimum rounding of radius with 25 millimeter. If it is taken 50 mm, you should have a rounding of 50 millimeter. Surface should be even out; all the protruding thing should be grounded. Now to avoid delamination, fibre anchors made from carbon fibre were installed at the top and the bottom of the column. You can see a hole which has been drilled for 10 mm diameter and 100 mm depth.

Stem of the anchor been inserted inside and grouted using epoxy, and fan portion were inserted in slots. That is one anchor; there are 6 anchors. So there will be 6 plates, like this. Once the anchors are installed and cured, plates are installed on the surface prepared and the adhesive between the plate and the anchor will avoid delamination, debonding.

So you have surface prepared, you have anchor installed and laminate installed. Then you need junction development. So you need to prepare surface on the capital, up to the size of junction development and on the wall, and also preparation for the bands. I will explain further why and how the bands and junction development has been carried out.

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Whatever amount of carbon is provided on a one face of the column, by means of laminate, say 140 * 6, that much amount of carbon has to be provided for junction development in the form of L-shape. So 500 mm by thickness of 430 GSM CFRP will suffice one laminate. So this is 3 layers, this is 3 layers so you have a proper amount of carbon transferring load from slab to the laminates. Anchor has to be made installed here, anchor has to be installed here, here and here, to avoid debonding.

Further this type of CFRP wrap bands, all around the columns, has to be installed. This will help in enhancing the shear capacity, because of the enhanced moment carrying capacity due to laminates also and also it will not allow this laminates to bulge out, to debond. Also it will help in some increase of compressive strength by way of confinement. All these bands will be carrying an anchor at the lap. This is how the completed CFRP columns look like. It is having laminates, bands, anchors before the laminate, anchors on the band, L-junction developed equivalent to laminate carbon area and anchored properly. Finally, this will be covered with a plaster to have a fire rating of 2 hours as per requirement of client.

So your strengthening is safe. This whole CFRP strengthening was possible because this element column was complying with the requirement of ACI 440.2R. That column should be capable of DL + 0.75 LL without wrapping. So you cannot simply go for CFRP for all the members.

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We will have one more case study for punching shear failure.

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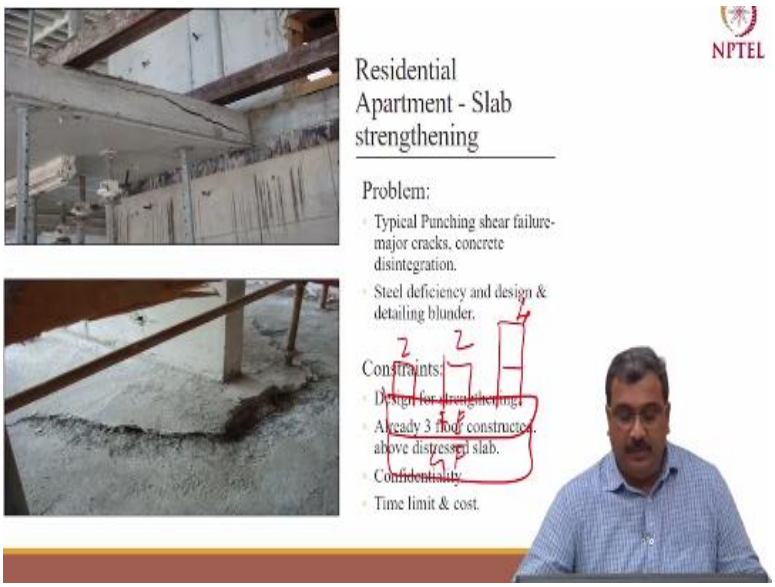

It is a residential apartment, wherein because of design failure, there was a typical punching shear failure cone. It failed in punching shear law, it has a ground floor and the first floor were continuous, there were 3 towers like, ground floor, 1st floor and 3 towers - 2 floors, 2 floors and 4 floors (drawn in slide). When they were constructing the fourth floor, there was a blast and these cracks were developed.

A proper analysis has been carried out, redesigned, and it was found that there was a steel deficiency and it was a detailing blunder. Constraint was you cannot demolish entire floors; you have to do it with confidentiality. Cost has to be considered because this is a real estate project, time limit and how install it - the deficiency, in terms of steel.

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So it was decided to incorporate the column capital, where there were not. The surface was roughened within 6 mm amplitude and a design shear anchors were installed. The 6 mm amplitude and the numbers of shear are such, that they will transfer the shear load to the main slab, it is based on design. It is not 3 numbers per square meter. We see friction coefficient and everything else has been considered.

And then what shear force it is going to transfer has been designed. The portion which was distressed, crushed has been removed after proper supports. The outer part was also roughened, new reinforcement has been tied, proper side shuttering has been done, closed from the bottom and the micro-concrete was pumped from the top and this is how the column capital looks after completion. So additional capital was incorporated.

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Now the second requirement was to suffice the positive and the negative moment reinforcement deficiency. So this type of 25 millimeter by 2.4 millimeter thick carbon laminates were used by nearly surface mounted system as per ACI 440, like, at the location you need to cut the slots and insert this in the slot with the use of adhesive. This is the completed one (photo). These holes are for pouring the micro-concrete beneath the slab.

But this is good for negative reinforcement part on the top of the slab. The area where the concrete was broken, there also at the top, steel has been inserted, how you have inserted the steel? From the bottom, in positive moment deficient area, a groove of 1.5 times the rebar diameter, a 12 mm rebar has been inserted into the slab from bottom. The hole slot has been made and the steel has been inserted by using a special adhesive.

The distance between each slot, the size of the slot has been designed as per ACI 440 NSM bar insertion parameters. Also this entire area has been coated with a special coating which is equivalent to 25 millimeter of cover. So you will get a proper cover for entire area also. So a punching shear failure slab, a design deficiency has been derived, a column capital has been incorporated. A negative moment reinforcement deficiency has been sufficed by slot and insert carbon fiber laminates. A positive deficiency of moment has been sufficed by insert of steel rebar from the bottom and derived.

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Now we will go for the last presentation, which is of an industrial plant for repair and strengthening of a tunnel.

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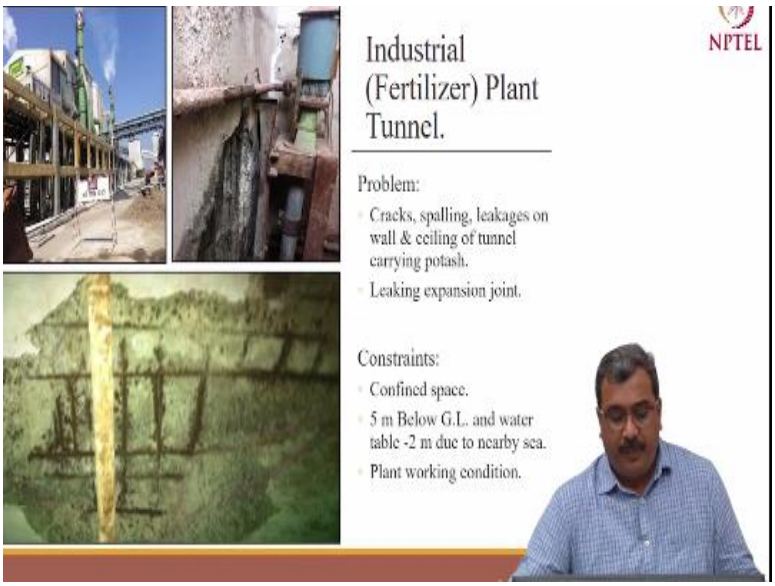

In one of the fertilizer plant which is located near the seashore, there is a tunnel which is carrying in potash from their bug storage to the further process. And the tunnel starts at ground level, below the ground level, 5 meter is the height of the tunnel. So at the starting it is –5 meter below the ground level and it slopes towards –11 meter. And the sea water, ground water level is –2 meter.

The tunnel wall thickness is 1 meter at the bottom and 600 mm at the top. There was lot of leakage, cracks and spalling which was found during routine inspections. They had carried out a large number of various types of repair, but the root cause was not determined

and not eliminated. So we carry out proper survey, we carry out NDT, the strength was okay, contamination in the concrete was there, leakage was found severe, expansion joints were failed, and the constraint was working condition, confined space, lot of smell because of potash. You cannot work, you cannot stay there for a long period. It is nearby sea, so during high tide there will be more leakage, continuous leakage and plant is in working condition. You cannot stop, conveyor belts are moving.

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A holistic approach has been decided. Whatever the original wall damage spalled has occurred, has been reinstated using polymer modified mortar, after proper treatment of reinforcement and surface preparation. Injection grouting has been carried out to stop the leakage from the wall and entire wall of the tunnel has been reinstated, strengthened by providing additional reinforcement with shear anchor and guniting, 60 mm thick guniting for M40 grade. After carrying out guniting, expansion joint has been re-profiled applied with hypalon strip.

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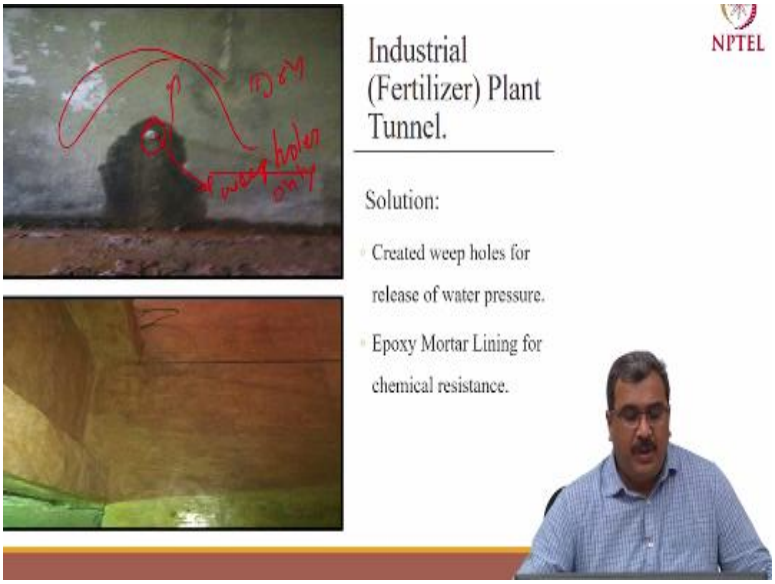

But to decrease the pressure of water, weep holes have been introduced. It has been drilled through the wall for 1.2 meter inside, and all the water pressure in high tides were been released on the wall. So the whole area becomes dry and water comes from weep holes only. And then, to protect it from chemical of potash, epoxy lining has been carried out.

You cannot see the photograph properly because the working condition is very, very severe. You cannot have a good photograph, but this whole entire is epoxy lining. So this way you can have a protection from chemical, you have a way to release the pressure of water and repair and strengthening has been done. Thank you.