New approaches for enhancing durability of transmission line tower foundations

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Abstract

The problem of early deterioration of some of the reinforced and pre stressed concrete structures has come to the forefront in recent years. In most of the advanced countries nearly 40% of the construction industry's budget is spent on repair, restoration and strengthening of the damaged concrete structures. All this has tarnished the image of concrete as a durable or maintenance free material. As India has a large coastal line and a number of cities and metropolis located in the vicinity of coastal belt, the civil structures including TLT (Transmission Line Tower) foundations in these areas are witnessing early deterioration. In this paper, new approaches for enhancing durability of new and old TLT foundations in different field environmental conditions have been presented based on a research taken up on the topic Durability of TLT foundations.

1. Introduction

TLT is considered to be the most stable and versatile semi-permanent structure. The oldest TLT still in service in India is more than 75 years old. But the recently constructed TLTs which are less than 10 to 20 years are experiencing deterioration on various accounts especially in the foundations.

If such deteriorations are not attended in time with due repair, such structures of paramount importance will fail, resulting in disruption of transferring large quantity of electric power from generating stations or sub stations to the load centers. TLTs are of a variety of configurations and designs, constructed to different specifications. Many of the transmission routes pass through the coastal areas are affected by chloride environments.

The TLTs erected in industrial areas are very much affected by industrial wastes and other chemical pollutants where sulphate/sulphide attacks are predominant. TLTs running through agricultural fields are affected by fertilizers like ammonia and other manures. Such environments cause adverse effect on durability of TLT foundations. There are incidences of corrosion of TLT foundations due to stray current mechanisms in pollute environments also. There are three main causes and mechanisms for corrosion of TLT foundations as below.

1. Corrosion of TLT due to stray current mechanisms
2. Corrosion at the stub angle /concrete interface at coping portion
3. Corrosion of embedded parts of TLT foundations

1.1. Corrosion of TLT due to stray current mechanisms

Also there is a possibility of leakage of current from power conductors through insulator string to the tower in variable magnitude depending on voltage intensity, insulator surface contamination and atmospheric moisture. In addition, due to induction in ground wires from the three phases, resultant induced current flow through the loop formed by ground wire, the two towers at each end of the span member. This stray current cause's corrosion at location where current leaves the structure and enters the ground through water electrolyte.

1.2. Corrosion at the stub angle /concrete interface at coping portion

Because of different conditions existing at the stub angle / concrete interface at coping portion, an electro chemical process sets up at the interfacial zone. As the stub angle interface is exposed to the atmosphere which

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has a higher concentration of oxygen with respect to the stub angle below the interface, there is a possibility of differential aeration – type of corrosion to occur like a ring of rust around the stub angle interface.

1.3 Corrosion of embedded parts of TLT foundations

Owing to highly alkaline nature (pH >12), concrete possesses corrosion protective features and normally provides a non-corrosive environment for embedded stub angle of TLT foundation. However, defects and cracks in the concrete can allow water and salts to penetrate into the concrete and leads to subsequent corrosion and weakening of the leg.

Submergence of stub steel above concrete chimney for some period during rainy season in water acting as salt dissolved electrolyte, the corrosion process is aggravated particularly in the presence of chlorides, sulphates and phosphates. The resultant produces of rust and complex compounds with chloride have a larger volume than the original material. This leads to the formation of local cracks and chip-off, which allows salt to penetrate further into the affected stub where the process of corrosion will be more and more accelerated. A mechanism of pitting or crevice corrosion will initially occur in the presence of aggressive ions such as chlorides. These ions are responsible in the formation of pits on the surface, which accelerates corrosion attack. An important consequence of pitting is that the localized attack may be very severe which may lead to structural catastrophe.

Because of the corrosion phenomenon, ferrous materials are oxidized to ferrous oxide and the volume of the ferrous material increases to a larger extent and sets in strain in the cover concrete leading to formation of cracks. The cracks open, draining the rain water into chimney concrete enhancing the corrosion process resulting finally in spalling of chimney concrete. The process continues further even to the extent of eating away of transmission tower leg starting from the coping level to the bottom level.

The difference in moisture level and salt content at the interfacial zone also aggravates the corrosion process. The symptom of this type corrosion in the interfacial zone is observed widely in all the towers. But the intensity is higher in the industrial areas located in coastal zones.

2. Research significance

The corrosion problems in TLT foundations located in coastal area of North Chennai has been referred to the Hydro Training Institute of TNEB (Tamil Nadu Electricity Board) Kuthiraikalmedu, Erode, Tamil Nadu, India. This was the reason behind the research and hence it was decided to diagnose the deterioration phenomena of TLT foundation after obtaining permission from authorities who looks after the operation and maintenance of TLT. It was also aimed to identify measures and means to improve the durability of TLT foundations after critically reviewing the literatures and based on rigorous experimental investigations conducted upon laboratory specimens and model tower foundations. The authors believe that this kind of an elaborate study dealing with the durability of TLT foundation is carried out for the first time in India and will be very useful to concrete technology.

3. Literature review

Kirkpatrick (1988) has presented actual case histories of sacrificial anode and cathodic protection installations on a variety of power system poles and tower foundations. Recommendations for design of foundation and cathodic protection system were made for future power line construction projects. Santhakumar and Murthy (1990) have dealt many topics related with transmission line structures and pointed out that the collapse of tower was often initiated by foundation failures. Further it has been stated that, the scope for research and development in this field is indeed vast.

David Hughes and Paul Davies (1996) have measured the corrosion currents of overhead line tower foundations in UK using the polarization resistance test and assessed the condition, where polarization resistance measurements and limited excavation indicate corrosion damage and use of sacrificial anode method has been recommended on the towers. Stanish et.al. (1997) have presented a review of various methods for determining chloride penetrability of concrete. ASTM C1202 test, a standard test to know the concrete's ability to resist chloride ion penetration (Rapid Chloride Penetrability Test) in terms of electrical indication have been explained. Gonzalez (1998) has studied the effect of chloride ions on the corrosion of reinforcements and indicated that the presence of chloride ions in concrete reduces the life of RC structures by less than 10 years.

Shah et.al. (2004) have presented a case study on renovation and modernization of TLTs in the Gujarat state, India. As a renovating measure, it was suggested that if the stub angle is found to be corroded less than 50% in thickness, the portion exposed after breaking the concrete is to be covered by an inside cleat and outside plates with a running weld. If the damage is more than 50% in thickness, the damaged portion is to be cut removed and a piece of similar stub angle is to be fitted in to the cut portion. In both the cases, newly welded assembly has been covered by a RCC cage and then encased in concrete.

Taklakar (2005) has briefly discussed various causes for failure of TLT foundations and mentioned that the TLT foundation may fail due to deficiency either in design or construction or deterioration due to the passage of time. Also it has been pointed out that the tower failure can be minimized if the erection practice is standardized.

Gupta et.al. (2005) have investigated and discussed about the corrosion of TLT foundation due to stray current mechanism and suggested application of a liquid component consisting alkali resistant polymer dispersion and a powder component consisting, blending of cement, silica fume, quartz sand and corrosion inhibitors on the stub angle against corrosion.

Marit Forsander (2006) has conducted test to measure soil conductivity, pH value and electrochemical potential to investigate corrosion phenomenon of TLTs in Sweden. The investigation concluded that, a large number of towers had lost their corrosion protection and remedial action was required.

Ha-Won Song and Velu Saraswathy (2007) have reviewed all the electrochemical and non-destructive techniques including Half-cell potential test from the point of view of corrosion assessment and their applications to bridges, buildings and other civil engineering structures.

Haji Sheik Mohammed and Samuel Knight (2008) have investigated the performance evaluation of protective coatings on steel reinforcements. Tests on chemical resistance, applied voltage, impressed voltage, open circuit potential, impact, and coating flexibility were conducted as per IS and ASTM Standards. It was concluded that the inhibited cement slurry coating, cement polymer composite coating and cement polymer anticorrosive coating possesses the necessary corrosion resistance properties as per IS standards.

Rokade et.al. (2008) have described certain case studies dealing with stub corrosion and deterioration of foundation concrete in TLT foundations. Factors affecting the durability of tower stubs and foundations have been discussed.

Garcia et.al. (2009) have performed tests on soil resistivity, corrosion potential, linear polarization resistance and electro chemical potential noise measurements in several transmission tower legs in Mexico as a part of an integrated maintenance program of transmission power line systems. Before measurements, visual inspection above ground level has been made in tower in order to assess the corrosion condition and to check out correlation among parameters. It has been suggested that more work is needed under laboratory conditions to corroborate field measurements

4. Visual inspection and experimental investigations

In order to identify the various factors leading to deteriorations of TLT foundations and evaluate the methodologies following studies have been carried out.

1. Visual Inspection and assessing corrosive condition of field towers.
2. Condition assessment of embedded portion of stubs
3. Laboratory investigations on specimens
4. Laboratory investigations on model TLT foundations
5. Investigations on effectiveness of coatings on galvanized stub angle

4.1. Visual inspection and assessing corrosive condition of field towers

Visual inspection to explore the causes for deterioration of TLT foundations was conducted besides conducting Half- Cell potential test at the coping portion of certain tower foundations to assess the intensity of corrosion at certain selected places in the state. Various causes for foundation failures found to be improper formation of pyramid / chimney, ingress of water / pollutants through the concrete and stub angle interface, corrosive environments, bush / fern growth in and around tower muffing area, unfavorable location of tower and insufficient curing, etc., The concrete above the ground level called coping concrete should have a muffing portion in slanting way. But in some cases it is observed that this is missing resulting in stagnation of water leading to pitting corrosion as in Fig.1. Ingress of saline water or other pollutants etc., leads to the formation of local cracks and chip off, which allows salt to penetrate further into the affected stub where the process of corrosion will be more and more accelerated as in Figs. 2 and 3 resulting in bulging and snapping of angles.

Fig.1.Formation of pitting corrosion at the angle concrete interface

Fig.2. Bulging of stub angle

Intensive of growth grass and bushes in the adjoining area also affects the coping concrete. Half-cell potential tests were conducted on legs of certain TLTs in Tamil Nadu state and there is an indication of more than 90% corrosion occurrence in coastal area, whereas in inland area it is less than 50%.

Fig.3. Snapping of stub angle

4.2. Condition assessment of TLT stubs:

As a part of the study, TLT stubs in two strategic locations had been removed by excavation after obtaining permission from the TNEB authorities for diagnosing purpose. The tower stubs as shown in Figs.4 and 5 were cut removed and transported to the lab at Hydro Training Institute, Kuthiraikalmedu, Tamilnadu, South India for testing purposes. The stub of these towers was erected nearly 30 years ago, and the super structures had been already dismantled for expansion purposes. To assess the condition of those stubs several tests/studies have been carried out as below.

1. Half-cell potential test
2. Rebound hammer test
3. Carbonation test
4. Chemical analysis of the soil around the stub and stub concrete using titration method
5. Measuring the crack depth and dimensions including loss of stub angle thickness

4.2.1. Half-cell potential test

The corrosion condition of the actual stubs dismantled from the field has been experimentally assessed by measuring the corrosion level using Half-cell potential test. Half-cell potential is used to measure the surface potential differences set up by the electrochemical process of corrosion. Anodic (corroding) and cathodic (passive) areas can be detected in the reinforcement just below the surface. The potential difference between the reinforcement and the Half-cell is measured using a high impedance voltmeter. The Half-cell consists of an

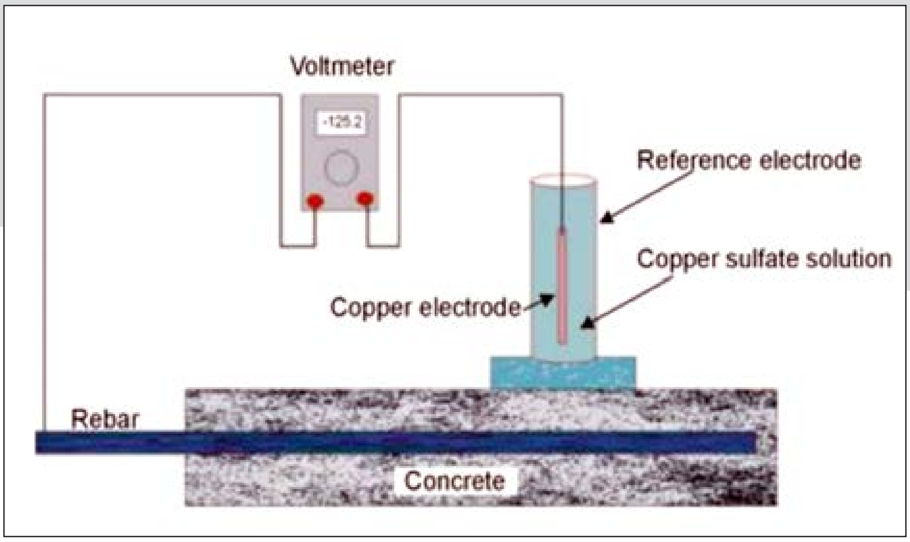

Fig. 3a.Half-cell measuring circuit

electrolyte (i.e. the saturated copper sulphate solution) and the conductor (i.e. the copper rod) which is made into a probe can be held against the concrete surface to

determine the probability of corrosion of the reinforcement in the location. The Half-cell measuring circuit is shown in Fig. 3a. The testing concrete surface has to be pre wetted before taking the Half-cell Potential reading. Direct electrical connection is made to the stub angle by means of compression type clamp. To ensure a low resistance connection, the stub angle is cleaned by emery sheet or by wire brush. The negative terminal of the voltmeter is connected to the stub angle. The positive terminal of the voltmeter is connected to the Half-cell and then it was placed on the prewetted concrete surface. The voltmeter is observed for potential reading that does not fluctuate. The stable reading is noted down and the test has been continued throughout the marked points on the stub. Large negative voltages (-350 mV) indicate that corrosion may be taking place. Voltage smaller than about -200 mV.

Half-cell potential test has been conducted on each side of the stub over the grid lines drawn on the inland stub as shown in fig.6. Though all the Half-cell potential values are negative, throughout the paper they have been shown as positive for drawing graphs.

Fig.4.Removal of inland stub

Fig.5. Removal of coastal stub

4.2.2. Rebound hammer test

Rebound hammer test is done to find out the compressive strength of concrete using rebound hammer as per IS: 13311 (Part 2)-1992. As per this test, when the plunger of the rebound hammer is pressed against the concrete surface, the spring –controlled mass rebounds and the extent of such a rebound depends upon the surface hardness of the concrete and is related to the compressive strength of concrete. A digital version of the rebound hammer was used for this test and the compressive strength values were directly taken from the display.

Fig.6. Close up view of Inland specimen

Fig.7. Close up view of inland stub specimen on removal of stub concrete

4.2.3. Carbonation test

In the Carbonation test, a solution of phenolphthalein in a diluted alcohol is sprayed on the freshly broken surface of concrete. If calcium hydroxide in the concrete is unaffected by carbon di oxide, the color turns out to be pink. If the concrete is carbonated, it will remain uncolored. The external surface of the stub specimen has been chipped from the loose debris and the carbonation test has been conducted throughout. The carbonation depth has been noted on the marked points. Whole of the stub was placed on rigid base and power hacksaw was used to partially remove the stub concrete to ensure that there will be no additional cracking of the chimney concrete. The crack depth, crack pattern and extent of deterioration of concrete was thus observed and noted. Also the thickness of the existing corroded stub angle has been measured and compared with the original thickness. The close up view of inland specimen at the broken stage during carbonations test is shown in Fig.7 and the Fig.8 shows the coastal specimen while the stub concrete was removed during the carbonation test.

4.2.4. Chemical analysis test and crack depth observation

In the chemical analysis program, the pH value, chloride and sulphate content of the soil around the stub and stub concrete were analyzed in a reputed testing lab by titration methods. The pH value, sulphate and chloride content of soil around the stub and stub concrete are shown in table.1.The crack depths and widths of the coastal and inland specimens are given in table 2. The size of the stub angle measured after removal of stub concrete is shown in table 3.

Fig.8. Close up view of coastal specimen on removal of stub concrete

Item / Parameter	Soil around the Inland stub	Concrete of the inland stub at coping area	Soil around the stub coastal stub	Concrete of the coastal stub at coping area
pH Value	8.40	8.90	7.80	7.40
Chloride	0.01%	0.03 %	0.12 %	0.19%
Sulphate	0.07%	0.23 %	0.18 %	0.26%

Table.1. pH value, sulphate and chloride content of stub specimens

Crack depth of the stubs		Crack width of the stubs	
Inland	Coastal	Inland	Coastal
300 mm	450 mm)	< 2mm	3-4 mm

Table.2. Crack dimension of stub specimens measured after removal of stub concrete

Item / Depth	Original size of the inland stub angle	Actual size of the inland stub angle	Original size of the coastal stub angle	Actual size of the coastal stub angle
0 m	65x65x6 mm	65x65x5 mm	150x150x12 m	130x130 x2 mm
0.25 m	65x65x6mm	65x65x6 mm	150x150x12 mm	130x130x6 mm
0.40m	65x65x6 mm	65x65x6 mm	150x150x12 mm	150x150x10 mm

Table.3. Size of stub angles measured after removal of the stub concrete

4.3. Laboratory investigations

4.3.1. Materials used:

Cement: Ordinary Portland cement (OPC), Cementious replacement of ordinary Portland cement: Fly ash (20 % by mass), ***Chemical admixtures:*** Silplas Super (2% by mass). It is a super plasticizer formulated to give very high early strength and tested for confirmation of BIS 9103: 1999 by Indian Institute of Technology, Chennai, ***Corrosion Inhibitor :*** (Calcium Nitrate) (2% by weight of Cement), Coatings: Flexi bond ACSR (ACSR refers to its trade name for the market purpose only) – Mix Ratio - (1(Water): 1(FACSR): 3(Cement)). It is blend of polymers and certain inorganic materials, which on mixing with cement – water system gives flexible properties at an appropriate ratio of Flexi bond ACSR (trade name of the product) polymer and cement. It sets and gives early strength to the system. ***Demech Chemical coating:*** It is a product of Demech chemical Products Pvt.Ltd. and specially developed as an anti-corrosive compound with 100 % solids with high performance, chemical acid, and alkali resistance. The product is completely free from volatile ingredients and is suitable for concrete etc. This specialty coating system when applied by brush or spray over the duly prepared metal/concrete surface provides along lasting anti corrosive layer thus protecting same from corrosion and chemical attacks. ***Demech deep pour grout:*** It is a three part product of demech chemicals pvt. Ltd. Mixing ratio is 16 parts of resin, 4 parts of hardener and 80 parts of aggregate by mass. (Aggregate is of flaky polymer material of size 2 to 6 mm). Its working time is 30 minutes. This has been applied in the interface of the concrete transmission tower stub angle. ***Nano Zycosil:*** It is a product of Zydex industries (USA based). It mimics the water repellency mechanism of lotus leaf. It penetrates deeply into the substrate and provides repellency into the cementious pores (5 to 200 nm), where other conventional coatings cannot penetrate. **Sacrificial anode:** Zinc sheet of 80 mm length, 35 mm width and 2 mm thick has been used as sacrificial anode in one of the leg of the model tower investigation.

Various Laboratory investigations carried out are as below.

1. Acceleration corrosion test (Impressed voltage test)
2. Chemical Resistance and applied voltage test
3. Rapid Chloride penetration test
4. Acid Resistance and water absorption test
5. Experimentations on Performance of protective measures on TLT model
6. Effectiveness of coatings on stub with galvanized stub angle
7. Rehabilitation of stub

4.3.2. Acceleration corrosion test (impressed voltage test)

In the accelerated corrosion test, the specimens were centrally placed in the container surrounded by stainless steel plate, which act as cathode and the container was filled with 3% NaCl electrolyte. The concrete cylindrical specimen of size 1500 mm x 300 mm were embedded with 50 mm x 50 mm x 6 mm angle as a stub. To assess the corrosion resistance efficacy of the different level of

Fig.9. Acceleration corrosion test set up

coating systems, it was decided to make specimens with different levels of protection for different tests and the legends of the specimens are as below.

4.3.2.1. Test specimens

Controlled specimen
CS 1 = Black steel angle + Plain Concrete (Concrete without any cementious replacement or chemical admixtures)

Single level protection
CS 2 = Black steel angle + SP Concrete (Conventional concrete with chemical admixtures (Silpas super 2% by mass)
CS 8 = Black steel angle + Recron Mixed Concrete
CS 9 = Black steel angle + Corrosion Inhibitor mixed Concrete

Two level protections
CS 3 = FACSR Coated angle + SP Concrete
CS 4 = FACSR Coated angle + Conventional Concrete (M 20 concrete with cementious replacement of ordinary Portland cement by fly ash 20% by mass)
CS 5 = Black steel angle + Conventional Concrete. + Externally Coated by FACSR
CS 6 = Epoxy Coated angle + Conventional Concrete

Three level protections
CS 7 = FACSR Coated angle + SP Concrete + Ext. Coated by FACSR) CS 10= Demech Coated angle + Conventional Concrete + Externally coated by Demech
CS11= Cement slurry coated angle+ SP Concrete + Externally coated by Nano Zycosil

In the experimentations, a constant potential of 12 V was applied to this system using a DC power supply regulator. The variation in the development of current was monitored at regular intervals using a high impedance multimeter, as per ASTM C876-90 and the acceleration corrosion test set up is shown in fig.9. The Half-cell Potential values were measured on those specimens at specific intervals of time. As the average chloride content in the sea water in the sea is about 3%, the same percentage was used in the lab test for relating to the field conditions. The variation of current with respect to acceleration time is monitored because of the impressed voltage in the accelerated corrosion test.

4.3.3. Chemical resistance and applied voltage test

Chemical resistance test and applied voltage test were conducted as per Indian standards: 13620:1993 to evaluate the resistance of different coatings upon the black steel angles of length 250mm. In the chemical resistance test, the coated angles were partially immersed in different mediums such as distilled water, three mole calcium chloride, three mole sodium hydroxide and saturated calcium hydroxide solution for 45 days. Performance points towards observations like blistering, softening, and bond loss characteristics like holidays in the immersed portion have been observed and efficacy assessed. In the applied voltage test, in each test set up, two number black steel coated angles of height 250 mm each have been suspended vertically in a nonconductive plastic container filled with 7% NaCl and a potential of 2 V was impressed for a period of 60 minutes using a DC supply unit. Observations for dissolution of coatings, corrosion products in the anode and evolution of hydrogen gas in the cathode have been monitored at specific intervals of time for assessing the efficacy of the coatings on the angle.

4.3.4. Rapid chloride penetration test

The rapid chloride ion penetration test (RCPT) was performed as per ASTM C 1202. The test method consists of monitoring the amount electric current passed through 51 mm thick slices of 102 mm nominal diameter of cylindrical specimen for duration of six hours. M20 grade of concrete has been used for casting the specimens. The protection against the chloride ion penetration has been done by adding admixtures in the concrete and applying coating on the concrete surface. The legends of RCPT specimens along with chloride ions penetrability found in the experiments are shown in Table 4.

Fig.10.Model tower combined with foundation concrete- stub system

Sl.no.	Specimens	Charge passed in coulombs	Chloride ion penetrability
1	RCPT1- Controlled specimen	4225.5	High
2	RCPT2- Plain concrete with cementious replacement of Ordinary Portland cement by fly ash 20 % by mass	2225.59	Moderate
3	RCPT 3 – SP concrete	2192.00	Moderate
4	RCPT 4- Corrosion inhibitor mixed concrete	4548.6	High
5	RCPT 5- Recron 3s fibre mixed concrete	5860.8	High
6	RCPT 6 – SP concrete Coated with coatings of FACSR	1743.3	Low
7	RCPT7-SP Concrete Coated with Coatings of Demech chemical	1515.6	Low
8	RCPT8- SP concrete coated with Nano Zycosil	688.56	Very Low

Table 4.Legends of RCPT specimens and their chloride ion penetrability

The total charge passed during the period was calculated in columbs as per the procedure described in the ASTM standards and the chloride ion penetrability of various specimens and the comparison of charges passed in coulombs for various specimens are shown in Table 4.

4.3.5. Acid resistance and water absorption test

Acid resistance and water absorption tests were conducted as per Indian Standards 456:2000. In acid resistance test SP concrete cube specimens of size 150x150x150 mm were cast and different coatings like cement slurry, FACSR, Demech chemical and Nano Zycosil penetrant. In each category three specimens were cast and immersed in water with 3% diluted hydro sulphuric acid solution and 3% sodium chloride solution. Weight differences after 45 days of immersion were noted and percentage loss of weight calculated for comparing the efficacy of coatings over sulphate and chloride attack together. In the water absorption test three cubes in each category of coatings were immersed in water with 10% NaCl for 24 hours. The specimens were taken out and allowed to dry. Alternate wetting and drying process for 10 days have been done and the weight gain at the end of 10 days were noted and percentage increase in weight of specimens were compared to know the efficacy of coatings.

4.3.6. Experimentations on performance of protective measures on TLT model

A model tower was fabricated for testing combined foundation concrete- stub system. The concrete mix was M20 as in the field was followed for the model tower foundations. The tower angle was black steel angle. In this model tower, the best protective coatings found through laboratory test results, were applied over the leg members. Besides the above, sacrificial anode was introduced separately in one of the leg member. In order to evaluate the performance of O-ring against corrosion in the stub angle concrete interface, Demech deep pour grout was poured in the interface of stub angle and concrete to form O-ring. The whole tower was lifted up after the foundation was cast and curing was over and the tower was placed upon four separate plastic containers so that each leg was positioned in a plastic container. The acceleration corrosion test was conducted similar to laboratory specimens. In the first test up, the tower foundations have been referred as controlled specimen MTF1 (Model tower foundation 1), Corrosion inhibitor added specimen MTF2, Flexi bond ACSR coated stub angle and concrete surface with SP concrete MTF3, and Demech Coated stub angle Nano penetrant, FACSR and Demech coated stub angle and concrete surface with SP concrete MTF4 have been tested. In the second test set up MTF1 and MTF2 was repeated in two of the legs along with one cement slurry coated stub angle and Nano Zycosil coated concrete surface over the SP concrete tower foundation, MTF5 and the sacrificial anode wrapped stub angle above the SP concrete tower foundation concrete, MTF6.The Half-cell potential readings taken at specific intervals of time and observations made on the O-ring formed using Demech deep pour grout are shown in Table.5.The close up view of the model tower with combined foundation concrete- stub system for acceleration corrosion test is shown in Fig. 10.

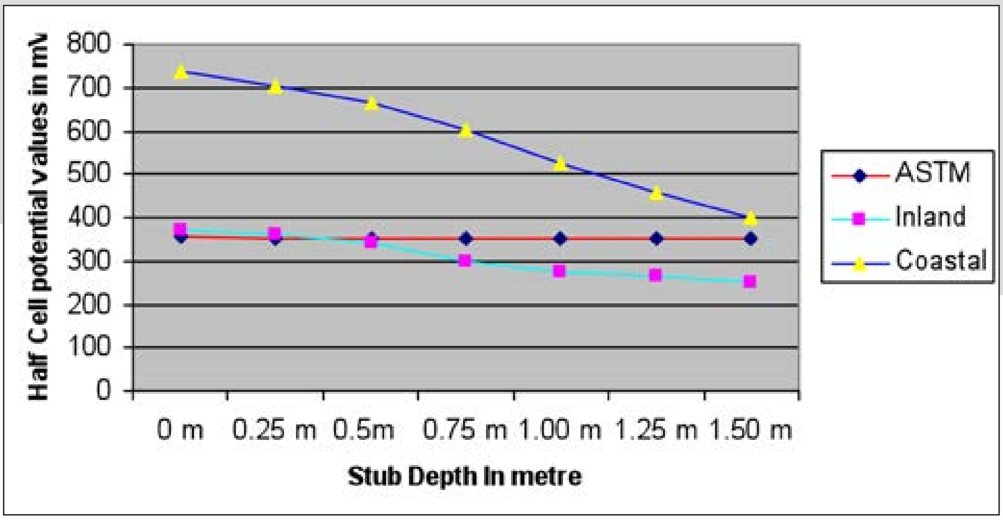

Fig. 11 Comparison of inland and coastal stub with respect to Half-cell potential values

Time in Hrs.	Half - cell potentiometer readings in mv					
	MTF1 (Control-led)	MTF 2 (Corrosion Inhibitor)	MTF3 (FACSR 3 level)	MTF4 (Demech 3 level)	MTF5 (Nano Zycosil)	MTF6 (Sacri-ficial anode)
0	-98	-21	-15	0	0	0
50	-156	-69	-28	0	0	0
100	-233	-96	-45	0	0	0
150	-259	-109	-57	0	0	0
200	-301	-126	-78	0	0	0
250	-372	-159	-86	-10	0	-35
300	-397	-168	-98	-48	0	-78
350	-423	-182	-123	-77	0	-87
400	-465	-198	-156	-116	0	-95
500	-563	-332	-167	-145	0	-112

Table.5. Half-cell potential readings of model tower with various protections

4.3.7. Effectiveness of coatings on stub with galvanized stub angle

For evaluating the durability performance of galvanized stub angle in the TLT foundations, four numbers of galvanized stubs combined foundation concrete- stub system have been set on the open ground. After 28 days of curing, outer coating with FACSR has been applied on one stub concrete and Demech chemical coating on the other stub concrete and cement slurry coating on the third one. The remaining one was left uncoated to observe the effect of coatings on stub concrete in the field. The corrosion is induced in all the stub concrete by alternate wetting and drying by salt water with 3.5% NaCl for 90 days. The Half-cell potential tests have been conducted to ensure the corrosion formation at an interval of 10 days. It is observed that the galvanized stub angle shows a superior performance.

4.3.8. Rehabilitation of stub

To evaluate the best coating systems combined with provision of O-ring for rehabilitation purposes, it was planned to rehabilitate the tested coastal stub. For this purpose the coastal stub whose stub concrete was partially removed was over a rigid concrete base. The concrete cavity formed because of removal of concrete from the stub during carbonation and other tests has been made up with SP concrete. The finished concrete surface has been coated with cement slurry coatings for 40 cm length, FACSR for 40 cm length, Demech Chemical for 40 cm length and Nano Zycosil Coatings for 40 cm length. All the rust particles of the stub angle has been removed by wire brush and rust removal solution. Demech coatings has been applied on the stub angle including O-ring at the crevice of stub angle and concrete. Thus rehabilitated stub has been subjected to accelerated corrosion by alternate wetting and drying method. Half-cell potential readings at every 10 days for a period 90 days were taken. Half-cell potential values at the end of 90 days were only zero for Nano Zycosil coated zone indicating no symptom of corrosion. The O-ring also was intact without any corrosion spots.

5. Results and discussions

5.1. Condition assessment of TLT stubs

The Half - Cell Potential readings taken on the stub specimen excavated from the inland area reveals that only in the top 0.5 m and little above the readings are above -350 which indicates 95 % corrosion. The readings were in more positive trend beyond 0.5 m towards the depth. Whereas the Half-cell readings taken on the stub specimen excavated from the Coastal area shows that only in the top 1.5 m and little above the readings are between -800 and -400 which indicates 95 % corrosion. The readings were in more positive trend towards the depth. Fig.11 shows the comparison of inland and coastal stub with respect to Half-Cell potential values.

The embedded portion of the stubs in the inland area are almost unaffected by corrosion and the Half-cell potential readings confirm this. The stubs tested in the coastal areas shows all the readings above ASTM values indicating an

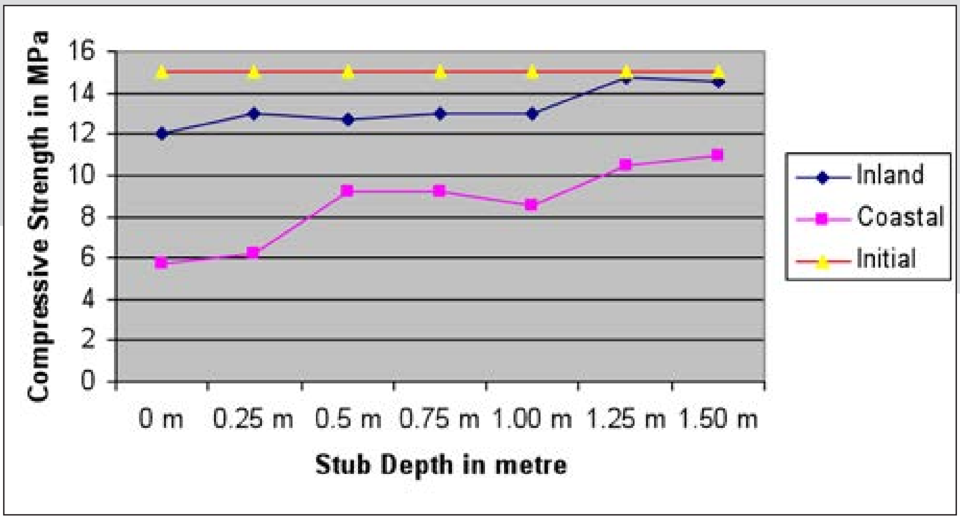

Fig. 12.Comparison of inland and coastal stub with respect to compressive strength

alarming corrosion level in the embedded portion also.

The rebound hammer test conducted on the stub from coastal areas indicates concrete strength below M10 in majority of embedded portion of the stubs because of carbonation, chloride and other chemicals in such a coastal cum industrial environment. The rebound hammer test conducted on the stub from inland area indicates the concrete strength above M 10. The variation in compressive strength of the stub specimens along the depth of the stub is shown in Fig.12.

From the results of carbonation test, it is observed that the top portion of the stub concrete (350 mm from ground level) has been affected by carbonation. In the Inland specimens, the full carbonation in the coping portion is due to failure of bond and poor quality. Fig.13 shows the variation of carbonation depth with respect to depth of the stub.

Chemical analysis of stub concrete and the soil around the stubs show the presence of chlorides and sulphates. The pH values of both the inland and coastal stubs are less than 9 indicating the loss of alkalinity of concrete. Because of this, the effect of passive layer around the stub angle has been lost leading to severe corrosion of stub angle at the coping portion.

Dimensions of crack in the coastal stubs are more than that of inland stubs. The thickness reduction of the stub angle of the coastal TLTs indicates the higher corrosion rate when compared to the inland TLT stub.

5.2. Investigations on lab specimens

From the results of accelerated corrosion test, it has been observed that the application of protective coatings on stub concrete specimens (2 level or 3 level) helps to reduce the rate of corrosion i.e prolonging the initiation period of corrosion process.

It was noted that, the FACSR specimens (3 and 2 level protections (CS5 and CS7), Demech coated specimens (3 level protection (CS 10)) performs well when compared to other specimens in accelerated corrosion tests. This is due to higher resistance of these coatings materials against chloride ingress. The longer initiation period of FACSR coating and Demech coating is due to the Barrier nature of the coatings. Nano penetrant applied specimen (CS11) shows a superior performance over FACSR and Demech coated specimens. The comparison of these best 3 level protections is shown in Fig 14. Fig.15. shows the variation of current density value with respect to acceleration time for the best three level protections.

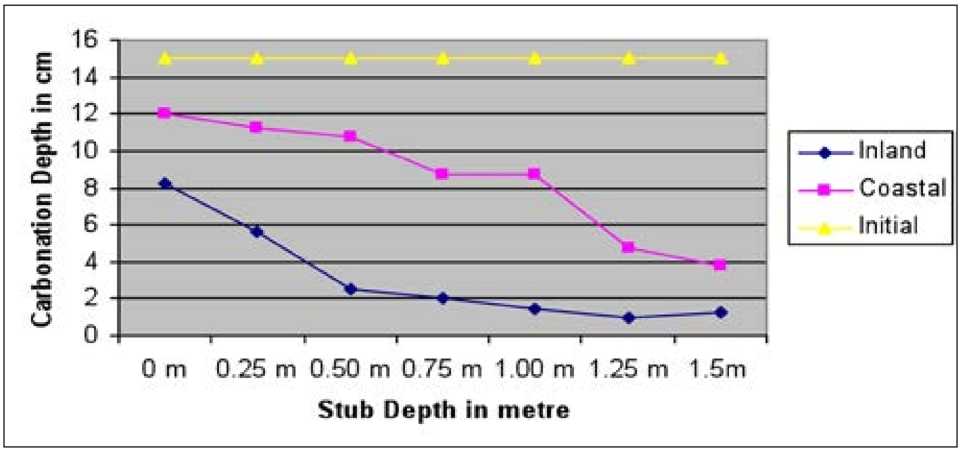

Fig.13 Comparison of inland and coastal stub with respect to carbonation depth.

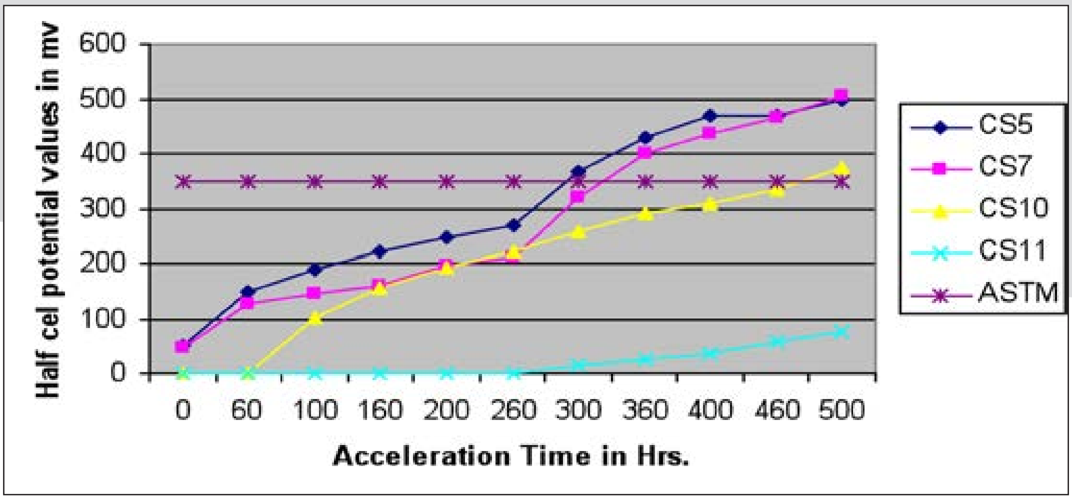

Fig. 14 Comparison of best 3 level protection specimen in accelerated corrosion test

It can be seen that for all coated angle specimens, the time required for cracking is higher compared to uncoated specimen. For FACSR coating and Demech coating, the behavior of current density exhibited that there is an initiation period followed by propagation period. This observation is due to a higher resistance of these coating materials against chloride ingress. The longer initiation period of Demech, FACSR and Nano Zycosil coating is due to the barrier nature of the coating.

As for applied voltage test results is concerned, there is no corrosion products of iron in anode and no hydrogen gas evaluation in cathode during the test period for Demech coated specimen and FACSR Coated specimen. Dissolution of Cement Coating, no Corrosion Products of Iron in anode and no hydrogen gas evaluation in cathode during the test period has been observed for Cement Slurry coated specimen, Light Rust Spots in anode and hydrogen gas evaluation in cathode during the test period for Epoxy Coated specimen have been observed, whereas innumerable rust spots in anode and vigorous evaluation of hydrogen gas in cathode during the test period for plain angle specimen.

The chemical resistance test conducted shows that Demech chemical and FACSR coated specimens performs well in all the test mediums except a light salt bridge formation in 3M CaCl2 solution. In epoxy coated specimen, loss of bond in all mediums and formation of white patch over the coating was occurred. High rust spot and floating of rust particles over the solution was occurred in Plain angle specimen.

The rapid chloride penetration test reveals that the specimens with Recron fibre (RCPT5), specimens with corrosion inhibitor (RCPT 4), specimens without fly ash (RCPT1) shows penetration of more chloride, Whereas the specimens made of SP Concrete (RCPT3), specimens with FACSR (RCPT 6) with Demech chemical coatings (RCPT 7) shows moderate and low level of chloride penetrability.

Nano Penetrant coating (RCPT 8) show an excellent performance with very low chloride ion penetrability. The chloride ion penetrability of various specimens and the comparison of charges passed in columbs for various specimens are shown in Fig. 16

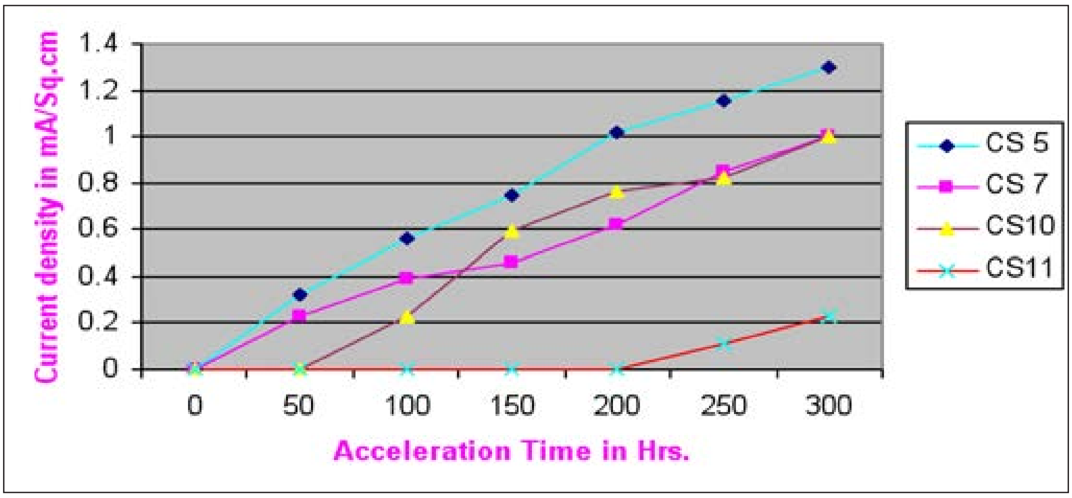

Fig. 15 Comparison of best three level protection specimens with respect to current density values

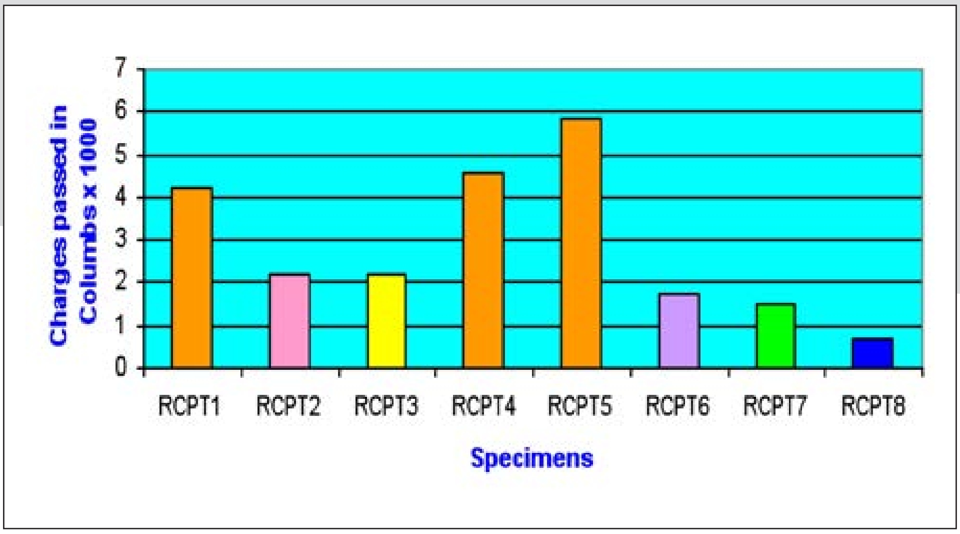

Fig 16. Comparison of chloride ion penetrability of different specimens

Weight loss of Nano penetrant coated specimens was only 0.11%, whereas uncoated SP concrete specimens were about 0.45 %. Other specimens were between these values indicating the superior performance of SP concrete coated with Nano Zycosil in resisting sulphate environments. Similar performance pattern was noticed in the water absorption test where weight gain 0.13% only observed for Nano penetrant coated specimens when compared to uncoated SP concrete specimens whose weight gain is 0.92%.

5.3. Investigations on effectiveness of coatings on tlt foundation model

Nano penetrant, FACSR and Demech coated specimen and sacrificial anode specimens perform very well in both accelerated corrosion test and impressed voltage test. Deep grouting out of Demech chemical for forming O-ring in the stub angle and concrete interface shows no symptom of rust staining till 400 hrs of accelerated corrosion. At 500 hrs few rust spots has been noticed. The effect of O-ring against crevice corrosion is very good for nano penetrant coated specimen. The observations made upon the O-rings are presented in Table 6. The close up view of O-ring formed in controlled specimen (MTF1), Nano Zycosil coated (MTF5) and Sacrificial anode fixed (MTF6) are shown in fig.17

Sl. No	Time in hrs.	Observation for crevice corrosion at the Stub angle / Concrete Interface					
		MTF 1	MTF 2	MTF 3	MTF 4	MTF5	MTF6
1	0	No rust	No rust	No rust	No rust	No rust	No rust
2	100	No rust	No rust	No rust	No rust	No rust	No rust
3	200	No rust	No rust	No rust	No rust	No rust	No rust
4	300	Few rust	Few rust	No rust	No rust	No rust	No rust
5	400	Rust staining	Rust staining	No rust	No rust	No rust	No rust
6	500	Rust staining	Rust staining	Few rust	Few rust	No rust	No rust

Table 6. Observations for crevice corrosion

5.4.Effectiveness of coatings on stub with galvanized stub angle

From the Half-Cell readings taken from stub model set on ground it is observed that the galvanized stub angle shows a superior performance when compared to the mild steel stub angle.

5.5. Rehabilitation of stub

It was observed that when compared with cement fly ash slurry coating, coatings by FACSR, Demech, Nano

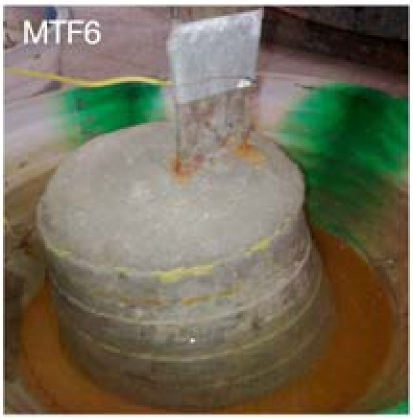

Fig.17. Deep pour grout o-rings after 500 hrs. of accelerated corrosion

penetrant are functioning far better while applying them over the rehabilitated concrete surface. Provision of O-ring in the stub angle and concrete crevice by Demech deep pour grout eliminates development of crevice corrosion. Hence cementious replacement of ordinary replacement by 20% of fly ash and coatings like FACSR or Demech chemical or Nano Zycosil preferably on the concrete surface besides inclusion of O-ring by the polymer material like Demech deep pour grout are utmost essential for making the transmission foundation a durable one.

6. Methodologies for enhancing durability of new TLT foundations

Based on critically comparing with the literature reviewed, visual inspection of field towers and on conducting condition assessment tests upon embedded portion of stubs and series of rigorous laboratory investigations following points are suggested as methodologies for enhancing durability of new TLT foundations in different areas.

6.1.Inland plain areas

- The concrete used in chimney as well as in coping and muffing of TLT foundations should be minimum of M 20 as per IS - 456 2000. **In the wet areas single level protection may be made as below:**
- FACSR coating on the stub angle or on the concrete surface for 600 mm below and 600 mm above the ground level.
- **In dry areas single level protection** like FACSR coating either on stub angle or concrete surface in the coping /muffing area and 300mm above and below the ground level. In both the wet and dry cases, provision of O-ring out of Demech deep pour grout at the concrete stub angle interface to be introduced. In order to form the O-ring 25.4 mm groove to be made around the stub angle as it was proved in the model study.

6.2. Agricultural or hilly areas

- The concrete used in chimney as well as in coping and muffing of TLT foundations should be minimum of M 20 as per IS - 456 2000. The **two level protections** can be made as below:
- FACSR coating on the stub angle, 600 mm below and 600 mm above the ground level.
- Nano Zycosil water repellant coating on the concrete surface of the coping and muffing area and 900 mm below the ground level.
- O-ring to be provided in the stub angle concrete interface by pouring the Demech deep pour grout.

6.3. Coastal or industrial areas

- The concrete used in chimney as well as in coping and muffing of TLT foundations should be as per IS:456 2000 depending upon the exposure conditions. **Three level protections** may be made as below:
- FACSR coating on the stub angle to the full length of the stub and 900 mm above the ground level.
- Cementious replacement of ordinary replacement by 20% of fly ash in the concrete and addition of 2% Silpas super (Super plasticizer) in the concrete.
- FACSR coating or Nano water repellant coating on the concrete surface of coping and muffing area and 900 mm below ground level.
- O-ring to be provided in the stub angle concrete interface by pouring the Demech deep grout chemical.

6.4. Coastal cum industrial areas

- The concrete used in chimney as well as in coping and muffing of TLT foundations should be as per IS :456 2000 depending upon the exposure conditions.
- Based on durability point of view, in the coastal lines and industrial pollution areas, High performance concrete should be used. (High performance concrete is not costlier than ordinary concrete, but by means of replacing certain quantities of cement with fly ash, silica fume good performance can be obtained.)
- Sulphate resisting cement may be used for foundations in industrial cum coastal areas. Three level protections may be made as below:

- Demech coating on the stub angle to the full length of the stub and 1500 mm above the ground level.
- Cementious replacement of ordinary Portland cement replacement by 20% of fly ash in the concrete and addition of 2 % Silpas super (Super plasticizer). Nano Zycosil water repellant coating on the whole concrete surface area of the foundation including pedestal sides and bottom, stub coping and muffing.
- O-ring out of Demech deep grout should be provided in the interface.

Besides the above, RCC cage is recommended in vulnerable area incorporating coatings on reinforcements and admixtures in concrete as followed in the case studies reviewed in the literature.

7. Methodologies for enhancing durability of in-service TLT foundations

7.1. General

Based on critically reviewing the literature and field visits in conjunction with the diagnosis of stub specimens besides laboratory investigations, the following suggestions are recommended for the proper operation and maintenance of existing transmission line tower foundation for preventive maintenance besides methodologies for attending mild, moderate, severe and very severe damages.

- A good vigil on the tower footing for the stub and the soil surroundings the footing every month.
- Special care of the footing in the monsoon to prevent water logging and damage
- Tower footing area has to be kept neat by proper bush clearance.
- Residual life assessment of transmission line Towers may be estimated and suitable preventive measures can be adopted to prevent the failure of TLT foundations.

7.2. Mild damages

If the existing coping /muffing concrete of the legs appears to be slanting, if there are only hair line cracks, and if the reduction in thickness of the stub angle is negligible. i.e. less than 10 %, the damage may be considered to be mild and has to be strengthened as below in the following sequence.

- All the rust and flakes from the corroded stub angle at the inter face should be removed using emery wire brush.
- A small groove in the interface of the stub angle/ coping, for a depth of 25.4 mm to be formed without making new cracks or aggravating the cracks and it has to be cleaned thoroughly.
- FACSR coating (Flexi bond ACSR : water: Cement at the ratio of 1:1:3) to be applied on the stub angle from the lower most point of the groove up to the depth of 600 mm above ground level.
- O-ring has to be formed out of Demech deep pour grout to be poured in the groove and allowed to set.
- The concrete surface to be cleaned thoroughly, Nano Zycosil penetrant at the ratio 1:10 (1 Part of Zycosil and 10 parts of water) to be applied on the concrete horizontal ands slanting surface by wet and wet method and at the ratio of 1: 20 (1 part of Zycosil and 20 parts of water) in the vertical surface up to a depth of 600 mm below ground level.

7.3. Moderate damages

If the cracks in the coping area are wider and if the crevice corrosion at the interface seems to be developing, and if the reduction in thickness of the stub angle is less than 20 %, and more than 10 %, the damage may be considered to be moderate and stub has to be strengthened as below.

- The loosened carbonated concrete in the coping area should be completely removed so that the resulting surface would be conducive to achieve high bond strength with over lay concrete.
- A simple carbonation test using spraying of phenolphthalein may be done for knowing the depth of carbonation and all the carbonated concrete

should be scrapped, and the concrete surface should be cleaned by water jet.

- All the rust and flakes from the corroded stub angle should be removed using wire brush.
- FACSR coating (Flexi bond ACSR : water: Cement at the ratio of 1:1:3) to be applied on the stub angle from the lower most point of the groove up to the depth of 600 mm above ground level.
- Application of overlay concrete out of M20 grade with cementious replacement of Ordinary Portland cement by 20 % of fly Ash and Silpas super chemical admixture and smooth slanting surface should be formed to drain out the water.
- A groove to be formed in the stub angle /concrete interface and allowed to cure and after setting, Demech deep pour grout to be poured in the groove to form a O-ring and allowed to set.
- After the curing of over lay concrete and the setting of O-ring, the concrete surface to be coated with Zycosil Nano penetrant at the ratio 1:10 (1 Part of Zycosil and 10 parts of water) to be applied on the concrete horizontal and slanting surface by wet and wet method and at the ratio of 1: 20 (1 part of Zycosil and 20 parts of water) in the vertical surface up to a depth of 600 mm below ground level.

7.4. Severe damages

If the cracks are extensive in the coping or if the concrete in the stub are deteriorated to a larger extent and if the reduction in the thickness of the stub angle is more than 30 % and less than 50 %, the damages may be considered as severe.

- All the concrete from the bottom of the corroded portion up to the muffing point should be removed and the surface of the left out stub concrete should be cleaned thoroughly by water jet.
- All the rust and flakes from the corroded stub angle should be removed using wire brush.
- Inner cleats and outer cover plates equal to the thickness of the stub angle for 600mm length in the corroded length have to be welded by fusion welding as reviewed in the literature.
- FACSR coating (Flexi bond ACSR : water: Cement at the ratio of 1:1:3) to be applied on the stub angle from the lower most point of the groove up to the depth of 900 mm above ground level.
- Concrete out of M20 grade with cementious replacement of ordinary Portland cement by 20% of fly ash and Silpas super chemical admixture should be used for forming the new stub from the bottom point of the corroded portion and smooth slanting surface should be formed to drain out the water in the muffing area.
- Groove to be formed in the stub angle /concrete interface and allowed to cure and after setting, Demech deep pour grout to be poured in the groove to form a O-ring and allowed to set.
- After the curing of concrete and the setting of O-ring, the concrete surface to be coated with Nano Zycosil penetrant at the ratio 1;10 (1 Part of Nano Zycosil and 10 parts of water) to be applied on the concrete horizontal and slanting surface by wet and wet method and at the ratio of 1: 20 (1 part of Zycosil and 20 parts of water) in the vertical surface up to a depth of 600mm below ground level.

7.5. Very severe damages

If the cracks are extensive in the coping or if the concrete in the stub are deteriorated to a larger extent and if the reduction in the thickness of the stub angle is more than 50 % the damages may be considered as very severe.

- All the concrete in the corroded portion should be completely removed so that the resulting surface would be conducive to achieve high bond strength with over lay concrete.
- The corroded angle has to be cut removed by the gas welding after guying the tower.
- The rust and flakes in the remaining portion of the stub angle should be removed using wire brush.
- New stub angle to be welded and splice jointing be made in the corroded portion by fusion welding
- FACSR coating (Flexi bond ACSR : water: Cement at the ratio of 1:1:3) to be applied on the stub angle from

the lower most point of the groove up to the depth of 900 mm above ground level.

- Concrete out of M20 grade with cementious replacement of ordinary Portland cement by 20 % by fly Ash and Silpas super chemical admixture should be used for forming the new stub from the bottom point of the corroded portion and smooth slanting surface should be formed to drain out the water in the muffing area.

- Groove to be formed in the stub angle /concrete interface and allowed to cure and after setting, Demech deep pour grout to be poured in the groove to form a O-ring and allowed to set, if the location is dry one. If the tower leg has to stand in a water stagnated area or coastal area, the O-ring should be formed out of Demech deep grout.

- After the curing of concrete and the setting of Demech grout , the concrete surface to be coated with Nano Zycosil penetrant at the ratio 1;10 (1 Part of Zycosil and 10 parts of water) to be applied on the concrete horizontal and slanting surface by wet and wet method and at the ratio of 1: 20 (1 part of Zycosil and 20 parts of water) in the vertical surface up to a depth of 900 mm below ground level.

8. Conclusions

Visual inspection of TLT foundations in various locations and condition monitoring of tower foundations using half-cell potential test has been conducted and various factors causing deterioration of TLT foundation concrete has been identified and deliberated. Condition monitoring undertaken in certain locations in the state of Tamil Nadu using half-cell potential test has been presented.

TLT stubs of two discarded TLT had been excavated from two strategic locations of Tamil Nadu and ASTM approved diagnostic tests like, Half -Cell potential test, rebound hammer test, carbonation test, and chemical analysis of stub have been conducted. Thickness of stub angle and dimensions of cracks in the stubs were measured. Based on the diagnosis, the phenomenon of corrosion of embedded stub angle and deterioration of TLT foundation concrete has been critically analyzed.

The effect of protective coatings on stub angle, addition of admixtures in stub concrete, corrosion inhibitors and barrier coatings on stub concrete against corrosion under accelerated environmental conditions have been investigated in the laboratory and the effect of individual and combined effect of coatings have been evaluated using half-cell potential test. The performance of protective coatings and addition of admixtures against durability of TLT foundations have been discussed. An experimental evaluation of chloride ion penetration of the specimens with different mineral, chemical admixtures and coatings has been studied using rapid chloride penetration test, besides other durability tests. Protective measures like O-ring provision, using various protective coatings and Nano coatings to combat the crevice corrosion, have been studied in the model foundation and a methodology for inclusion of O-ring provision has been suggested for field applications.

The effect of laboratory proven admixtures in concrete and protective coatings on stub angle and stub concrete surface of a model TLT foundation have been verified against corrosion by accelerating corrosion by impressed voltage method and suggested for field applications. Thus disturbed TLT stub has been renovated using admixtures in concrete and protective coatings identified based on laboratory study.

The performance of the renovated stubs has been studied using half-cell potential test under alternate wetting and drying. Based on the research, strengthening methodologies to enhance the durability of new and existing TLT foundations have been outlined.

9. Acknowledgement

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