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A Review on Comparative Study of Bridge Failure due to Corrosion and Scouring

Mayank Kaushal¹, Gurinderjeet Singh²

Student, Department of Civil Engineering, Chandigarh Polytechnic College, Gharuan, Mohali, India¹

Student, Department of Civil Engineering, Chandigarh Polytechnic College, Gharuan, Mohali, India²

ABSTRACT: Bridges are one of the most important infrastructure systems that provide public and economic bases for humankind. When discussing about the problems facing India's infrastructure, bridge failures have been one of the leading problem. Failures of bridges are occurring, since the bridge started building thousands of years ago. A large part of the technical knowledge associated with bridge engineering today is based on the past failures of bridges. Infrastructure is the growth driver of the economy. India will invest Rs. 100 lakh crore (\$1.39 trillion) in the sector over the next five years, the finance minister Nirmala Sitharaman said, in a push to improve the country's economy. The budgetary allocation for the Ministry of Road Transport and Highways has been allocated Rs 1.7 lakh crore for Budget 2020-21. Experience can be an expensive teacher, and it is usually the best teacher. In reviewing the past bridge failures, it is natural, or manmade that with greatest loss of life and directly affects the individuals as well as country economy. From this point it is necessary to study the past failure to strengthen the future construction. This paper reviews the more common causes and mechanisms of some bridge failures around the world. These are Corrosion and Scouring. This study will be conducted to help analyse why bridges fail and minimize the failures.

KEYWORDS: Bridge maintenance, Inspection, Failure, Corrosion, Bridge scour, Climate change, Atmospheric pollution

I. INTRODUCTION

Bridges are one of the most important structures of transportation networks. The purpose of study is to make clear idea about past bridges failure and its summary to future awareness. The word "failure" as used herein includes corrosion and scouring beyond the design norms. Accept that failure is the part of our life. Our strategy is to learn from past failures, which usually the best teacher. In reviewing the past bridge failures, it directly affects the individuals as well as country economy. From this point it is necessary to study the past failure to strengthen the future construction.

There are many causes of bridge failures which occur, such are structural and design deficiencies, corrosion, bulking, construction and supervision mistakes, accidental overload and impact, scour, and lack of maintenance or inspection, etc. But in this we will only discuss bridge failure due to corrosion and scouring.

The maturity of the bridge system infers that future spending would be on maintenance rather than new installation capital expense. Reinforced concrete is used for majority of bridge structural elements as concrete has excellent compressive strength. However, concrete has an undesirably low tensile strength and elasticity. Steel are used to improve concrete's limited resistance to bending. But, deterioration of concrete structures due to harsh environmental conditions leads to performance degradation of RC structures, and premature deterioration of structures before completing expected service life is major concern for engineers and researchers. For steel bridges one of the most dominant forms of deterioration is corrosion.

The flow of water in rivers and streams excavates and moves material from bed and banks of streams and from around the bridge piers and abutments. Correspondingly, foundations of the structures are undermined by this erosive action of the flowing water, which is named as scour. Scour at bridge piers and abutments, has attracted the attention of engineers and researchers mainly because scouring can lead to serious failure and collapse of bridges. The importance of studying scouring is that it can induce complete or partial collapse of bridges and it can also induce the change of rivers' regime.

II. OBJECTIVES

Lessons have been learned from many failures and will yet continue to be learned. By giving an outline from the past failures of bridges and the cause of the failures, hoped that the same type of failures will not occur. It is, however, most of the failures are caused by same effect. The goal of this work is to learn from two most occurring failures i.e. Corrosion and Scouring. This study will be conducted to help analyse why bridges fail and minimize the failures. It is written in the hope that by contributing to the better understanding of cause of failures and knowledge of bridge failures and types of bridge failures in the past, the future failures of this type may be reduced greatly.

III. BRIDGE FAILURE DUE TO CORROSION

The use of steel for modern bridges has grown significantly over the last 25 years. Engineers and specifiers have recognised the benefits that steel offers as a construction material, which combined with imaginative designs has resulted in some striking bridges that have not escaped the public’s attention. The material used in bridges is vulnerable to environment degradation. In steel bridges, the primary metal used is iron and many problems can happen when this metal is in the environment. Corrosion and rusting are two major problems, known as “rust smacking,” which may weaken the bridges capacity whatever it feeds off of, appearing to bubble up the material. It’s true: Corrosion is one of the biggest controllable factors that can affect the structural integrity of bridges.

3.1 CORROSION:

Corrosion is the gradual chemical erosion of metal. Experts find that more than 95 percent of structural damage on bridges can be traced back to some form of corrosion. It’s a particularly big factor on the four out of 10 bridges in the United States that are more than 50 years old, because most have not been treated to prevent it. [1]

Bridges in two parts of the United States are more likely to experience significant corrosive damage:

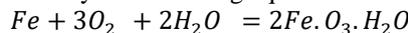
- (1) Northern states that frequently apply chloride-based snow and ice melting compounds to bridges.
- (2) Coastal areas, where bridges are impacted by salt water, high humidity, and extreme storms.

Bridges in dry locations, like deserts, are less likely to be damaged by corrosion.

3.2 CORROSION MECHANISM:

The corrosion of steel can be considered as an electrochemical process that occurs in stages. Initial attack occurs at anodic areas on the surface, where ferrous ions go into solution. Electrons are released from the anode and move through the metallic structure to the adjacent cathodic sites on the surface, where they combine with oxygen and water to form hydroxyl ions. These react with the ferrous ions from the anode to produce ferrous hydroxide, which itself is further oxidised in air to produce hydrated ferric oxide (i.e. red rust.) [2]

The sum of these reactions can be represented by the following equation:



(Steel) + (Oxygen) + (Water) = Hydrated ferric oxide (Rust)

The process requires the simultaneous presence of water and oxygen. In the absence of either, corrosion does not occur.

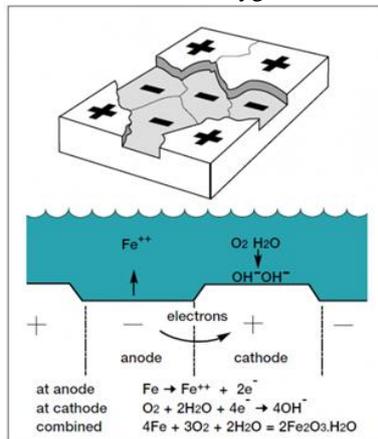


Fig. 3.2. Schematic representation of the corrosion mechanism for steel

3.3 HOW CORROSION WEAKENS BRIDGES:

Corrosion affects the structural integrity of bridges in a five critical ways:

3.3.1 Reduces the strength of individual structural elements:

Corrosion lowers the effective cross section of critical structural components, which makes them perform in unexpected and unintended ways when stressed. It lowers the axial and flexural strength, which can lead to the partial or complete failure of individual elements, potentially weakening the overall structure. This type of degradation occurs in both steel and reinforced concrete structures.

3.3.2 Lowered shear capacity:

As previously mentioned, corrosion can reduce the effective cross-sectional area of major bridge components, including beams and columns. This often reduces the shear capacity of individual sections and the ability to interact with sections connected to them. This leads to friction, vibration, and concussive action that the overall structure may not be able to sustain over time.

3.3.3 Increased fatigue

Corrosion can also impact the fatigue strength of steel components and connections. It is known to accelerate cracking and pitting, which is often concentrated in certain areas. This can cause metal elements to break and fail.

3.3.4 Decreased bond strength

The capacity of elements built from composite materials is dependent on how the concrete and rebar interact. Steel expands when it corrodes, which diminishes the bond with the concrete it reinforces and supports. This often weakens structural components, which can contribute to failure. It's often difficult to identify this type of damage. Use modern x-ray equipment to inspect bridge sections exposed to water and corrosive substances.

3.3.5 Diminished ductility

Corrosion lowers the ability of metal sections of bridges to bend and twist. Maintaining this integrity is critical, especially in areas that experience earthquakes, shifting traffic loads, or extreme weather, especially winds. Some of history's greatest bridge collapses were caused by structural elements that could not flex as engineered when exposed to these conditions. It forces loads to shift in ways the structure cannot support.

3.4 CASE STUDY :

3.4.1 Lowe's Motor Speedway

It was designed and built by Bruton Smith and partner and driver Curtis Turner in 1959. The complex features a 2.4 km quad oval track that hosts NASCAR racing. On May 20, 2000, When the NASCAR Winston stock car race ended, hundreds of pedestrians made their way back to the parking lot by crossing a pedestrian bridge that overlooked U.S. Route 29 in North Carolina. [3]

As they were making their way across. An 80-foot (24 m) section of concrete and steel walkway snapped in half, and pedestrians fell to the highway below. The bridge collapse injured 107 people and 13 were in critical condition.

After an inspection it was determined that all 11 steel cables that were holding the bridge together were corroded, and the bridge busted under the weight. The corrosion was caused by too much calcium chloride, an inorganic salt compound that's highly corrosive to steel, mixed into the grout that cemented the bridge's steel cables in place. The compound is acceptable in small amounts, but the construction company that built the bridge used about 40 times more calcium chloride than what was regulated. [4]

3.4.2 Silver Bridge

The U.S. Highway 35 Bridge, nicknamed the "Silver Bridge" since it was the country's first aluminium-painted one, was a major transportation route between West Virginia and Ohio. It was an eye bar-chain suspension bridge built in 1928 and named for the colour of its aluminium paint. It stretched 1,760 feet across the Ohio River, supported by 380-foot pillars that were driven into the bedrock below. [5]

For almost 40 years, the Silver Bridge served its function flawlessly. Then, on December 15 of 1967, disaster struck. At the height of the 5:00 traffic rush, there was a loud cracking noise (described later like a gunshot or sonic boom), and the bridge instantly folded in on itself. Within 20 second, the 1,460-foot main span of the bridge plunged into the 43-degree water, taking 32 cars with it. In the end, 46 people were killed, and several more were seriously injured.

Investigation of the wreckage pointed to the cause of the collapse being the failure of a single eye bar in a suspension chain, due to a small defect 0.1 inch (2.5 mm) deep. Analysis showed that the bridge was carrying much heavier loads than it had originally been designed for and was poorly maintained. A small crack was formed through fretting wear at the bearing, and grew through internal corrosion, a problem known as stress corrosion cracking. Constructed in the mid-1920s, the steel used for the bridge was not known for being susceptible to corrosion, so disaster was inevitable. In addition, the bridge was designed for Model-T Ford, which had an approximate weight three times less than cars in 1967.

3.4.3 Andheri Bridge

It is a Railway crossing two-way bridge formed by four longitudinal precast prestressed girders each with cast in situ RCC diaphragms and deck slab forming the composite girder system.

The 48 year old Gokhale, road over bridge that connect Andheri East to Andheri West collapsed onto the railway tracks on Tuesday morning at 7:30, resulting in one critical injured and four grievously injured and a day-long disruption of train services, was a disaster waiting to happen, according to the Western Railway's.

During the post-collapse inspection of Gokhale Bridge, railway authorities had stated that additional load created by cables and paver blocks are among the reasons behind the collapse, as BMC constructed the bridge but Western railways manage its maintenance.

The pedestrian pathway at Andheri train station, accident occurred due to heavy/deep corrosion and pitting of cantilever steel brackets supporting the pathway resulting in thinning down of section. Also, the extra weight of nearly 124 tones — comprising dry sand, paver blocks and cable wires — that led to the collapse provided by the BMC without prior permission from the Western Railway, not contemplated when the bridge was designed, also contributed to its weakening. [6]

This accident is classified as the failure of railway staff and others. Because the responsibility of the maintenance and repair work of this bridge was of the Western Railways. [7]

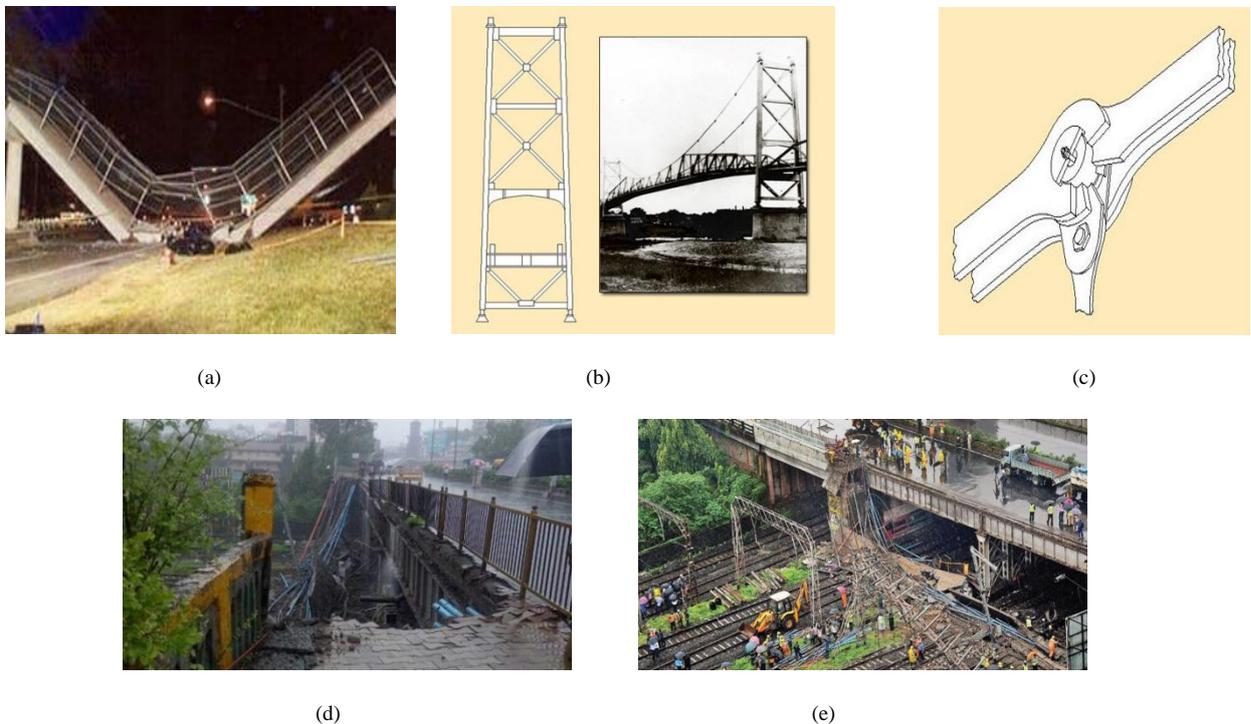


Fig. 3.4. Bridge failure due to corrosion (a) Charlotte Motor Speedway Concord, North Carolina, 13 mi (21 km) outside Charlotte (b) Tower of Silver Bridge (c) Section of an eye-bar joint in the Silver Bridge (d) and (e) Andheri bridge collapse, Mumbai (Image: Reuters)

IV. BRIDGE FAILURE DUE TO SCOURING

The most common cause of bridge failures is from floods scouring bed material surrounding bridge foundations. Bridge scour occurs when fast-moving water around a bridge removes sediment from around the bridge foundation, leaving behind scour holes. These holes, in turn, can seriously compromise the bridge's integrity. Highway bridge failures caused by scour and stream instability account for most of the bridge failures in the United States, resulting in substantial repair and replacement costs. In fact, the indirect costs associated with a bridge failure have been estimated to exceed the direct cost of bridge repair by a factor of five. A 2014 report in the Journal of Mechanics and Geotechnical Engineering says scour of bridge foundations is the number one cause of bridge collapse in the United States, and 600 bridges have failed due to scour problems in the past 30 years. [8]

4.1 SCOURING:

Scour is a phenomenon in which the level of the riverbed becomes lower under the effect of water erosion, leading to the exposure of bridge foundations. This happens either because of the increase of flow speed around the river piers or because of the long-time erosion of the riverbed. The scour phenomena depend on the flow rate, speed, type and condition of the riverbed, width and depth of the river [9]. With an increase in scour depth, the lateral resistance of the soil supporting the foundation is significantly reduced, thus increasing the lateral deflection of the foundation head. Furthermore, when the critical scour depth is reached, bending or local buckling of the foundation may occur under the combined effect of the dead load of bridge superstructures, the traffic load and/or lateral loads.

4.2 SCOURING MECHANISM:

At the obstruction in form of pier or abutment, the unidirectional flow changes into three dimensional as the water pileup in front face of the obstruction and the flow accelerates around the nose. This phenomenon results in formation of vortex at the base of the pier known as horseshoe vortex and the vortex form in the vertical direction downstream of the pier known as wake vortex as shown in figure 4.2 (a). [10]

The pileup of water due to obstruction because of decelerations of flow due to stagnation pressure of water causes a downward flow results in horseshoe vortex. The vertical component of the downward flow causes erosion around the base of the pier.

Due to rolling of unstable shear layers at the surface of the pier wake vortex are generated at the separation line and moves forward with flow downstream of the pier. It can be shown as in figure 4.2(b). [11]

In the practical case the river bed is generally composed of mixture of different sizes of material. Due to washing out of finer materials an armor layer is formed of coarser materials which protect the underlying finer particles from further scour. Due to presence of armor layer the clear water regime can be extended as the value of critical velocity increases. The armor layer is shown in figure 4.2 (c). [12]

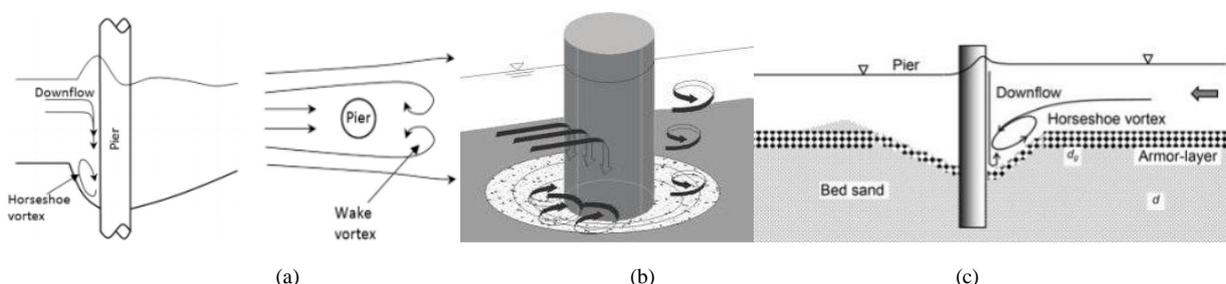


Fig. 4.2. Scouring mechanism (a) Presentation of vortex around a circular pier (b) System of vortex at a bridge pier (c) Scour in armored bed condition

4.3 FACTORS AFFECTING SCOUR:

The factors affecting the scour depend upon the type of scour. For contraction scour, the main affecting factor is magnitude of constriction by which the waterway became narrower and also the type of vegetation in the catchment area as the floating woody debris from the plantation also narrow the waterway by clogging. The main factors affecting in case of local scour are geometry of the bridge, the type, shape and size of the pier and the orientation of the pier in

the normal flow of water etc. The armor phenomenon also affects the local scour. In case of general scour, the main factors involved are natural and human activities factors. The natural factors involved are geomorphology of the catchment area, river bed characteristics and natural disasters such as earthquake induced riverbed uplift and human activities involves construction of hydraulic structures and riverbed mining etc.

The scour process is also crucially depends upon the properties of bed material. The mechanism of scour is quite different in the case of non-cohesive and cohesive sediment; as in non-cohesive sediment the properties of individual particle is the factor which decides the erosion threshold conditions whereas in case of cohesive sediment electrochemical bonding between individual particles is the deciding factor for erosion. The surface physicochemical forces in cohesive sediments are more important factors in comparison to weight of the particles that affect the possibility of erosion. These physiochemical forces vary with degree of saturation, drainage conditions, clay percentage etc. [13]. Also in the case of gravel as bed material the magnitude of scour depth is changed due to some other factors. The bed roughness is changed due to presence of gravel which results in different effects of gravel size and gradation on scour depth in comparison to sand as bed material. The change in bed roughness effect the vortex flow around the obstruction and also mobility of bed material is different in case of sand and gravel. Generally the scour depth in gravel bed is more than in sand as bed material [15].

4.4 CASE STUDY:

4.4.1 Jahu Bridge

The bridge was located at distance of 460 km from New Delhi and 30 km from District Hamirpur. On August 11, 2007 & August 12, 2007 due to heavy rain the concrete bridge got collapsed. Then with in two-year government constructed a new bridge over the site. But on August 14th, 2014 the steel bridge also got collapsed due to soil erosion from foundation. The site of bridge is at very critical point where two rivers i.e. Seerkhadd and Jabothikhadd meet each other. During summer these rivers have very low water level. The main source of water is only rain, which fed these rivers during Monsoon. The mean annual precipitation of Jahu (Himachal Pradesh, India) is 1411mm and the mean annual temperature is 21.9°C. The site includes clay and loose rocky strata with boulder deposits. [16]

This bridge collapsed mainly due to scouring of soil below the foundation. Scouring of foundation can occur all over the year, it reaches peak when flood comes in water body over which a bridge is spanning. Scour at bridges is a very complex process. The sum and interaction of all these river processes create a very complex phenomenon. The interactions of scour and channel instabilities are very difficult to predict.

4.4.2 Glanrhyd Bridge

The bridge is a single track with five spans comprising deck timbers resting on pairs of wrought iron box girders. These were supported from masonry bank seat abutments and by four intermediate masonry piers. On 19 October 1987 during an abnormally severe flood of the river Towy, the bridge collapsed at early morning about 07:15 when a passenger train ran on the bridge suddenly fell into the swollen river and immediately four passengers died. [17]

The collapse mainly caused by the scour at the downstream end of pier number 3 that undermined the foundations, allowing the pier to settle and eventually break its back. Many of the timber piles were missing and this had allowed the undermining to progress below the foundation slabs. A study of the river flow found that there was a re-circulating zone or eddy at the downstream end of pier 3 and up to 17000 tons of the sediment may have passed the bridge during the three hours of peak flows, indicating a major live bed scour with both erosion and deposition at the bridge. The depth of any anticipated scour at pier 3 could have been between 0.75 and 2.2m depth. It seems that local scour at the downstream end of pier 3 was the main cause of the collapse. The past arrangements whereby bridge superstructures were replaced without any check being made on the existing foundation construction to be unwise. The bridge severed from damage to the various parts of the steel superstructure of the bridge, the geometry of the collapsed structure, the secondary damage to the abutments. Bed was already being significantly eroded.

4.4.3 Cahdoora Bridge

This bridge connects the two important tehsils. The trade, communication and public transport fully depend on this bridge. It was constructed by R and B division Kashmir in the 2001 – 2002, the bridge is a balanced cantilever bridge with Total length of the bridge is 108.3mtr. It consists of 2 Dummy abutments and Solid wall type piers RCC with circular ends having open foundation. Two Balanced Cantilever bridges each supported on two piers formed by four longitudinal precast prestressed girders with 7.5mtr carriage way.

The source of the doodganga Nallah is pirPanchal catchment. Bed grade of the Nallah is 1 in 39. Longitudinal slope of the Nallah is 1 in 1659. Catchment area is 300 to 630sqkm. Most common cause of failure of

the bridges on river is scour. Scour is the result of the erosive action of the running water, excavating and carrying away material from stream beds and banks. Scour or soil erosion at a bridge is caused by the dynamic effects of the water in motion. The length of this bridge is 108.3metre long before flooding.[18] The main cause of the failure of this bridge is scour type failure. According to the reports, the discharge which was recorded earlier on 1973 was 5000 cusecs. But during the floods on 9 September 2014, it was 9504 cusecs. This high discharge is hardly a criterion for the failure of the Chadoora Bridge. The length of the bridge is 108.3mtrs, but during floods the linear waterway was recorded only 36.6mtrs which is negligible for such a major bridge. This waterway of the bridge was not enough to counteract the flood water. The flow of the water has been restricted to 36.6 meter with concentration of flow in only 27.8mtrs width while the bridge is about 108.3mtr in length with four piers in between and two side abutments. The waterway was grossly inadequate.



Fig. 4.4. Bridge failure due to scouring (a) Collapse of Jahu Bridge – (Jahu Bridge, Pankaj, 2018) (b) Glanhyd Bridge crossing Towy River in Wales in England, Llandeilo, Carmarthenshire (c) Chadoora Bridge

V. COMPARATIVE STUDY

As we had discussed bridge failure due to two major factors that are corrosion and scouring respectively. If we have to compare it, than we have to look back to the failures that took over in the past. In reinforced concrete bridges, corrosion and rust can cause problems because of the steel encased in the concrete. Bridges with other materials are also vulnerable to environment degradation, as shown in Figure-5(a), the number of timber bridges vulnerable to environment degradation is 18%. In this study, 17 out of 1,062 bridges collapsed because of environmental degradation. Whereas in this study, 200 bridges collapses happened because of scour. As seen in Figure 5(c) steel are more vulnerable to scour in comparison to other material. In Figure 5(d) the percentage of partial and total collapse is charted and it can be concluded that partial collapse and total collapse are equally distributed in bridge failure due to scour. [19]

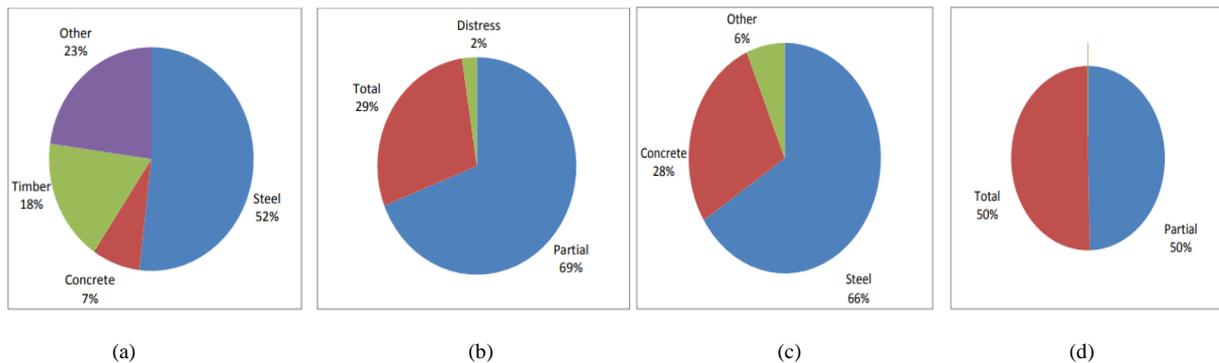


Fig. 5. Comparative study (a) Material type of the failed bridges due to environmental degradation, 71 failure (b) Type of failure due to environmental degradation, 71 failure (c) Material type of the failed bridges due to scour, 200 failures (d) Type of failure due to scour

VI. CONCLUSION

There are many causes of the failure of the bridges and all are dangerous. If the proper study is not conducted to analyze the past failures, future can't be saved. In future we again have to waste huge money to rehabilitate the bridge. So, by studying past failures, future planning can be done with some best techniques. As in this paper we discussed six bridge failures due to two major reasons i.e. corrosion and scouring. The first bridge, Lowe's Motor

Speedway was failed due to the use of 40 times more calcium chloride than what was regulated. Second bridge, The Silver Bridge was failed due to a small defect 0.1 inches (2.5mm) deep of a single eye bar in a suspension chain. Third one, The Andheri Bridge collapsed due to extra weight of nearly 124 tones -comprising dry sand, paver blocks and cable wires. Similarly the rest three bridges were collapsed due to heavy rain, scour at the downstream end of pier number 3 and the discharge of 9504 cusecs which should be passing through at least 91.5mtr width, only passed through 36.6m, thereby causing the scour failure of the bridge respectively.

So from above discussion we came to know that bridge does not collapse due to single reason, it includes number of aspects. Bridge failures have been classified into three categories: internal causes of failure, external causes of failure and cascading failure. The internal cause of failure is directed to the capacity of the bridge and consists of: faulty design, error in construction, low quality materials, and lack of maintenance. The external causes of failure are directed to the demand of the bridge and consist of scour, flood, earthquake, fire, collision, wind, overload, settlement, and environmental degradation of members. A cascading failure is a failure of bridge in which the failure of one element can trigger the failure of successive elements.

So the need of inspection is necessary for the bridges. Using advanced methods the bridges can be monitored anywhere. Periodical inspection and regular maintenance is necessary to keep the bridges functional. Otherwise disasters can come anytime as they are unpredictable and sometimes uncontrollable.

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