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A Study on Scour Failure at Bridge Foundation

Magdi M. E. Zumrawi[1], Hassan A. Abusim[2]

[1,2]*University of Khartoum, Faculty of Engineering,*
Department of Civil Engineering, Khartoum, Sudan
(E-mail: magdi.zumrawi@yahoo.com, E-mail:hassan.abosum@gmail.com)

Abstract: The success of a bridge relies on proper design and construction of its foundations. A Literature concerning water scouring at bridge foundation and some cases of bridge failure were intensively reviewed. Two global cases and a local case of foundation failure caused collapse of the bridge structure were selected for this study. The study was concentrated on Manshia Bridge in Khartoum. The investigation involved field survey and laboratory testing on this project to examine the existing foundation conditions. The eastern abutment investigated experienced sever failures in forms of excessive scouring and settlement in the embankment and the foundation piles surrounded by water. The causes of these failures were found mainly linked to the high scouring rate of water lead to washout the soil from the embankment of the abutment and the foundation piles. The foundation design mistakes, poor construction, inadequate abutment protection and lack of maintenance were detected as the main cause of the bridge failure. To protect abutment against scouring problem, it is recommended to use rock protection for the embankment and river bed around the abutment.

Keywords: *Abutment failure, Manshia Bridge, soil erosion, water scouring.*

1. INTRODUCTION

Bridge failures are fortunately rare, but every year reports contain details of some cases of bridge collapse that has occurred somewhere in the world. One specific type of failure that from time to time causes sudden catastrophic collapse of bridges is the undermining of foundations due to bed 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. Its importance is reflected in the large number of studies developed with the double purpose of understanding the phenomenon and quantifying the scour depth. There still exist important uncertainties, however, regarding the predictions supplied by available formulations.

In spite of important contributions of some researchers, the lack of knowledge seems more pronounced in the case of long abutments [1], [2]. For this reason, the purpose of the present study is to investigate the failure occurred in a recently constructed bridge in Khartoum. It can be stated that the influence of some factors on scour is not yet properly investigated [2]. 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.

This study mainly concerns about the foundation failure of bridges caused by water scouring. The following work was carried out.

- A brief over review of water scouring at bridge abutments; its types, mechanisms and causes.
- A review of some global events of bridge failure caused by water scouring of foundations in order to draw some important lessons.
- Detailed investigation of abutment failure of Manshia Bridge in Khartoum.
- Provide some practical solutions for scouring problem around bridge abutments.

2. LITREATURE REVIEW

2.1 Background

Scour is the result of the erosive action of flowing water, excavating and carrying away material from the bed and banks of streams. Different materials scour at different rates. Loose granular soils are rapidly eroded under water action while cohesive or cemented soils are more scour-resistant. However, ultimate scour in cohesive or cemented soils can be as deep as scour in sand bed steams. Scour will reach its maximum depth in sand and gravel bed materials in hours; cohesive bed materials in days; hard dense and cemented sandstone or shales in years; and granites in centuries. Massive rock formations with few discontinuities can be highly resistant to scour and erosion during the lifetime of a typical bridge [3].

Bridge scour is the removal of materials from around bridge abutments or piers. Scour, caused by swiftly moving water, can scoop out scour holes, compromising the integrity of a structure [4]. Scour may result from natural changes of flow in the channel, as part of longer-term morphological evolution, or as a result of human activity, such as the building of structures in the channel or dredging [5]. Scour can cause failure of the foundations of the abutments or piers of bridges.

There are three main scour types known as natural scour, contraction scour and local scour, which work additively to give total scour as shown in Fig. 1. Natural scour is the result of long term changes to the river or catchment. Degradation of the channel occurs as the river attempts to find a balance between sediment load and sediment transport capacity to reach an equilibrium condition called regime flow. Contraction scour occurs where the narrowing of a river channel due to the presence of bridge piers or abutments causes increased velocity and shear stress at the bed [6]. Obstructions to the flow in rivers can increase flow velocities and turbulence locally, which can cause the formation of vortices exerting forces on the river bed, leading to erosion. This causes the river bed to be lowered in the immediate locality of the obstruction [7].

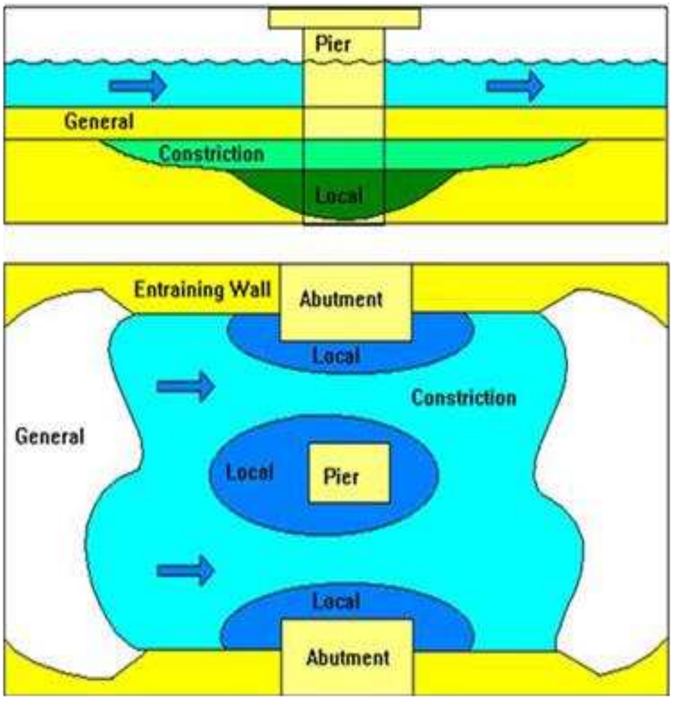

Fig 1: Components of total scour [6]

Scour can cause the undermining of bridge pier and abutment foundations, thereby causing failure of the structure through various mechanisms such as [7]:

- Pier and abutment settlement or tilting due to loss of support to foundation.
- Piers, abutments or footings damaged by collision, sediment abrasion or impact from boulders.
- Superstructure or deck sliding off supports due to hydraulic or debris loading or collision
- Scour hole or washout of embankment behind abutment.

2.2 Previous Researches

Bridge scour is one of the three main causes of bridge failure (the others being collision and overloading). Bridge failures due to scour at bridge foundations (i.e., bridge abutments and piers) have prompted a heightened interest. Researchers showed that the problem of scouring at bridge abutments is quite significant. Richardson and Abdel [8] quoted a study produced in 1973 for the U.S. Federal Highway Administration that concluded of 383 bridge failures, 25% involved pier damage and 72% involved abutment damage. According to Melville [9], of the 108 bridge failures surveyed in New Zealand during the period of 1960 – 1984, 29 were attributed to abutment scour. Melville also mentioned that 70% of the expenditure on bridge failures in New Zealand was due to abutment scour.

There have been several studies on pier scour. Some of these are Ettema [10], Johnson [11], Lagasse et al. [12], Mueller et al. [13], and Richardson et al. [14]-[16]. Also the Federal Highway Administration has developed several comprehensive technical manuals (HEC-18, HEC-20 and HEC-23) for dealing with the problem of bridge scour. In the United States, it has been estimated that 60% of all bridge failures result from scour and other hydraulic-related causes [17]. Water normally flows faster around piers and abutments making them susceptible to local scour. At bridge openings, contraction scour can occur when water accelerates as it flows through an opening that is narrower

Evidence that even prior to the bridge being constructed the rive

than the channel upstream from the bridge. Degradation scour occurs both upstream and downstream from a bridge over large areas. Over long periods of time, this can result in lowering of the stream bed [17].

It was found in previous work that bridge failure due to scour was most commonly associated with flood events broadly with return periods of 50 to 500 years. High intensity localized rainfall on small catchments appears to have caused a number of incidents in summer and early autumn [18], [19].

2.3 Historical Events

The paper presents historical events to illustrate the different ways in which scour has caused bridges to collapse or require protection. Two global cases of foundation failure that caused collapse of the bridge structure were intensively reviewed.

2.3.1 Glanrhyd Bridge in England

This is a railway bridge crossing Towy River in Wales in England. 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. The detailed investigation of the accident was reported by the railway inspectorate and briefly outlined below [19].

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 as shown in Fig. 2

The report showed that the pier was originally constructed by driving timber piles to form a cofferdam, making a base for the bridge foundations within the cofferdam of cemented river gravel and then placing stone foundation slabs. 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. Moreover, the remedial works previously carried out to defective bridge piers increased the likelihood of scour damage because the piers were widened and the shape of the cutwaters was changed. Nevertheless, there is the investigators concluded that prior to the collapse there were no visual indications that the bridge stability was in danger.

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. And piers, the positions in which bearing blocks were found after the collapse and the scour marks on the bridge bearing plates were all consistent with the sequence of collapse triggered by the initial collapse of the downstream end pier 3.

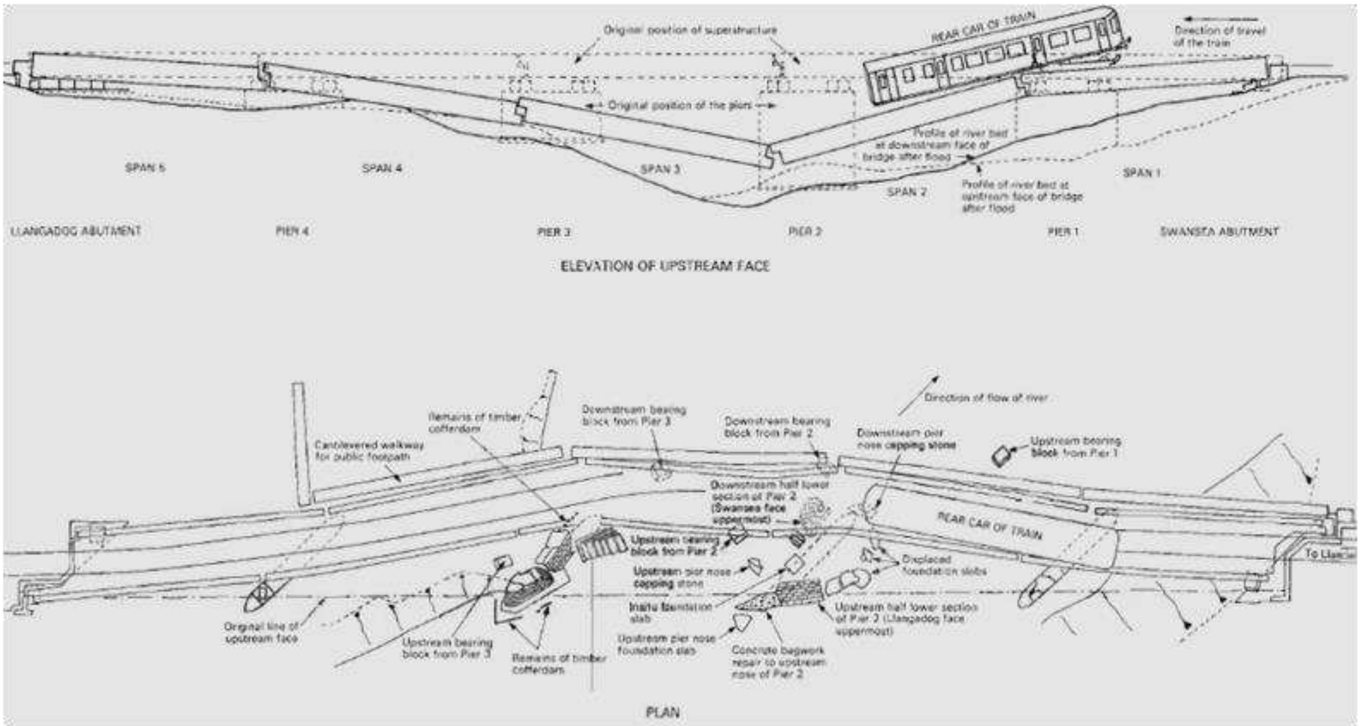

Fig 2: Sketch of Glanrhyd Bridge failure [19]

2.3.2 Malahide bridge in Ireland

On 21 August 2009, pier number 4 of Malahide viaduct collapsed into the estuary as shown in Fig. 3. This viaduct carries the main line between Dublin and Belfast. The investigation was carried out by the Railway Accident Investigation Unit (RAIU) [20]. The collapse was reported by the driver of a train that passed over the damaged viaduct but fortunately crossed immediately before complete collapse occurred.

Detailed investigations were able to prove that the masonry piers of the viaduct were built on top of a stone causeway that acted as a weir. This causeway was maintained in a fair condition for over 100 years by a regular regime of replenishment of the stones, although during that period the causeway elongated seaward due to migration of the stones. In 1967, a major grouting scheme was undertaken to fill voids in the weir. This scheme was reasonably successful but more stones were discharged to fill scour holes on a number of occasions up until 1996.

A hydraulic model of the bridge was built to investigate the failure mechanism. Contributory factors to the failure of the Malahide Viaduct resulted from:

i) The long term gradual elongation of the weir in the ebb tide direction (eastwards);

ii) The medium term degradation and partial removal of the 1.5m thick layer of grout that extends 1.5m in the flood tide direction (westwards) and 6.1m in the ebb tide direction (eastwards). The propagation of scour to the grouted rock armour weir continued in a westerly direction and was concentrated in between Piers 3 – 5.

iii) The losses were most severe in between Piers 4 and 5. The concentration of flow in this area resulted in a positive feedback mechanism that increased scour depth and allowed further propagation of the hydraulic jump in a headward direction (westwards);

iv) The short term propagation of the hydraulic jump, resulting in substantial removal of the grouted and non-grouted rock armour weir material in between Pier 4 and Pier 5 which resulted in the hydraulic jump migrating to a position westward of the bridge piers. The undermining continued in the manner until the invert between piers No 4 and No 5 collapsed, at which time the scour began to undermine pier 4 until it failed.

v) The grouted layer, which was about 1500 mm thick, acted as an invert but, as scour occurred at the seaward side of the causeway on the ebb tides, this became undermined. The undermining continued in the manner until the invert between piers No 4 and No 5 collapsed, at which time the scour began to undermine pier 4 until it failed.

3. Case Study

The main objective of this research is to carry out an extensive investigation to find out the structural and geotechnical weaknesses of the failed bridge. The study based on visual inspection, laboratory testing and review the documents of design, construction and maintenance of the bridge.

3.1 Project description

Khartoum is the capital and largest city of Sudan. The city is also the capital of the state of Khartoum. It is located at the confluence of the White Nile and the Blue Nile. Khartoum is linked by bridges to Khartoum North or Bahri and Omdurman to the west. Four bridges over the Blue Nile are connecting Khartoum to Khartoum North. Among them, Al Manshia Bridge is recently constructed bridge that links Khartoum with the industrial city Khartoum North as shown in Fig. 4.

Al Manshia Bridge has a total length of 340 m with six spans, four spans I girder the other two are Box girder, and a width of 20.5 m. The construction of the bridge was executed during 2003 - 2006 by Jilin Company, Chinese contractors and Mam Company, Sudanese Construction Company.

Fig 3: Malahide Viaduct Collapse [20]

Fig 4: Location of Manshia Bridge in Khartoum

3.2 Bridge failure

In the year 2015, the flood rate increased to a level more than the normal which lead the soil to wash out around the east abutment as shown in Fig 5. The embankment collapsed due to shear forces on the soil. The piles of the foundation appeared and the soil was washed out around them as shown in Fig. 6. By the end of the autumn season, the embankment around the abutment was completely exposed and the water flow around the piles. Excessive settlement developed in the abutment and the embankment soil escaped down the approach slab as shown in Fig. 7. This situation posed a serious danger to the vehicles and users life on the bridge.

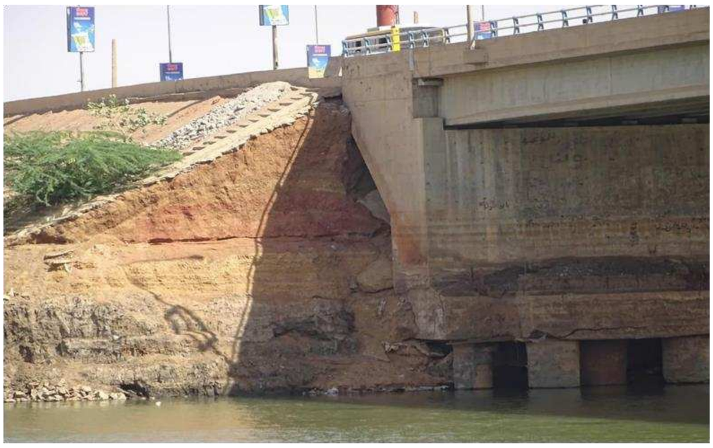

Fig 5: Excessive scouring occurred around the east abutment

Fig 6: The foundation piles surrounded by water

Fig 7: Embankment soil escaped away from the approach slab

In Oct. 2014, the ministry of infrastructures decided to maintain the fail abutment. The maintenance started by driven sheet piles inside and around the abutment to carry the approach slab and providing protection for the new embankment. Landfill works of the embankment took place under the approach slab which was protected by Granite stones and covered with a new asphalt layer on the roadway as shown in Fig. 8.

Fig 8: Sheet pile installed around the abutment

3.3 Current Situation

In this research, the bridge was visited to inspect the current situation of the bridge. It was observed as shown in Fig 9 serious failure and damage occurred in the protection made around the east abutment. As can be observed in Fig, complete collapse of the embankments and severe failure happened in the sheet piles surrounding the abutment.

Fig. 9. Serious failure and collapse of the protection around the abutment

A representative soil sample was taken from the embankment of the east abutment. The tests were performed to determine the physical properties of in accordance with B.S. [21].

4. Results and Discussion

The data obtained from the field survey and the laboratory tests conducted on soil samples obtained from the embankment materials of the east abutment were analyzed. The tests results are presented below in Table 1.

TABLE I: Tests results for the soil

Property	Value
Gravel, %	25
Sand, %	62
Clay/Silt, %	13
Liquid Limit, %	32
Plastic Limit, %	17
Plasticity Index, %	15
Max. Dry Density, KN/m3	18.7
Optimum Moisture Content, %	8.1
Soil Classification (USCS)	SC

Based on the field survey carried out for the current situation of the bridge abutment, the following are the possible causes of the failure:

- High Speed flow of Blue Nile river water.
- Since the loose soil scoured with high rate and from the result of the sample which had low plasticity.
- Neglect seasonal inspection and periodic maintenance.
- Taking decision of constructing structures around river without any study it's risk to the hydraulic structures.

The investigation shows that heavy floods in Blue Nile River caused scour which extended gradually over time below foundation level. The bridge did not collapse during the high flood period but on receding floods when a heavy tanker passed over the bridge abutment it’s approach slab settled and gone way.

5. Conclusions

This research work has been undertaken to evaluate the abutment failure of Manshia Bridge and provide maintenance advices. Some of the important conclusion and recommendations drawn from this study summarized below:

- Significant failure and damages were observed in the embankment of the east abutment as the result of water erosion and scouring.
- Investigations of historical cases of bridge failure have pointed out the main causes of abutment failures are design mistakes, poor construction, inadequate abutment protection and lack of timely maintenance.
- Linked to the poor condition of Manshia bridge abutment, the water scouring is the main factor of embankment failure. The lack of embankment protection is a reason that contributes to faster deterioration of the embankment.
- It is recommended that the urgent and necessary maintenance work to start in the summer season where the water level in river is low. Use rock protection for the embankment and river bed around the abutment.
- For sustainability of the bridge, regular maintenance is needed. Government authorities should consider providing a specific budget on annual basis for both maintenance and improvement works.

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