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MECHANISMS OF COLLAPSE AND SCOURING OF BRIDGES AROUND THE WORLD: LITERATURE REVIEW AND FUTURE TRENDS

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Abstract- This paper presents a review of the main causes of bridges collapse and it focuses on scour phenomenon. The first part classified two types of factors starting with natural causes (flood, scour, and landslide) and human factors (overloading vehicles, lack of inspection and maintenance) with different examples that made the history of many countries. The second part is a detailed review of scour from the definition to the factors influencing this phenomenon through types and regimes of scour. The main purpose of this paper is to summarize the information needed to understand the impact of these factors on the stability of structures and to highlight the scouring phenomenon and make it comprehensive for researchers and engineers in order to find better solutions and reduce the number of collapsed bridges due to these phenomena.

Keywords: Bridge Failure, Collapse, Scour, Factors, Damages.

1. INTRODUCTION

Due to different reasons, many bridges collapse all over the world and causes human and materiel damages. In 1967, Ohio Bridge collapse when it was congested with rush-hour traffic, resulting the death of 46 people. Most recently, the I-35W Bridge across the Mississippi River collapsed, causing 13 deaths and 145 injuries [1]. In the United States, and during the period between 1989 and 2000, 503 of bridges collapse causing many materiel damages what drove researchers and engineers to study the causes of the collapse of these bridges [2]. After the tragic collapse of Tacoma Narrows Bridge that killed nearly forty people and wounded about ten, the causes of failure have drawn more attention from researchers and civil engineers. According to Wardhana and Hadipriono, [3] the most frequent reasons are scour, floods (almost 53% of all the failures), 20% of the total bridge failures are due to overload, earthquake and fire. Moreover, design and conception models can be a reason of collapse. These statistics are presented in the Figure 1.

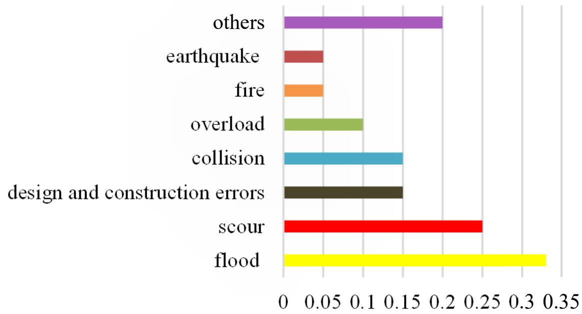


Figure 1. Causes of bridge collapse in the United States between 1989 and 2000

In the past two decades, engineers have developed many useful methods in order to study the stability of structures starting with a finite element method based on numerical modeling and also experimental studies. However, bridge collapse is a complex process generated by natural factors that makes forecasting difficult [2]. This paper presents a detailed overview of scour phenomenon that represent a main cause of bridges failure and finally a conclusion.

2. SCOUR MECHANISM IN BRIDGES

Scouring is a natural phenomenon that appears in rivers and caused by the flow of water. The erosive action of water causes the displacement of sediments and the creation of scouring pits [4]. The Federal highway Administration of the United State defines scouring as the downgrade of the level of a river bed by the erosive effect of the water, which will cause instability of the Structures. It is caused by any flow condition except that it can be very severe during a flood, which results in the appearance of a deep pit near the piles of the Structures.

2.1. Types of Scour Phenomenon

There are two main types of scouring: General Scour and localized scouring:

• General Scour: is independent of the existence of an obstacle in the watercourse and is caused by severe floods and human intervention through urbanization and deforestation as well as the extraction and modification of the watercourse ([4], [5]). In fact, during floods, a general scouring of the bed occurs over a sometimes-significant thickness called short-term scouring. The long-term scour develops over a longer period of years [6].

• Localized Scouring: is directly related to the existence of a bridge or other waterfront structures. It is divided into two types [5]

• Local Scour: This type of scouring is generally caused by obstacles (piles and abutments) in the watercourse, which generate eddies, velocities, accelerations and frictional stresses that are quite strong and which tear the material from the bottom and expose it. As demonstrated in the Figure 2, the shock between the water and the pile redirects the flow towards the bed ('down flow') and causes local erosion around the obstacle, which gives rise to horseshoe vortices ('horse shoe vortex'). On the sides of the pile, the tearing off of the materials creates wake vortices. These two vortices tear off the materials surrounding the side surface of the pile ([4], [7]).

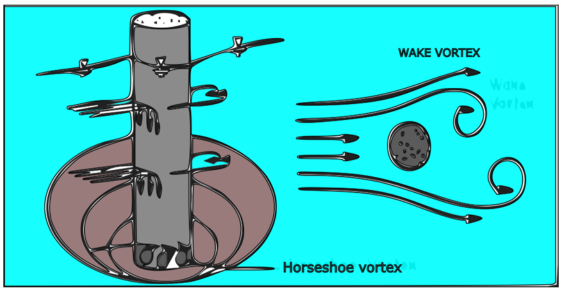


Figure 2. Local scour mechanism around bridge pier

• Contraction scour: This type of scour is mainly due to the constriction in the section of the wadi and therefore the narrowing of its width naturally or due to the presence of a structure [4]. This leads to an increase of the water speed and also the bed shear stress through the contraction causing a significant erosive force and thus a tearing off of the materials, which leads to a local lowering of the river bed. Near a bridge over a river, the 3 types of scours can occur simultaneously or not. the total scour is thus the sum of the effects of the 3 types as shown in Figure 3.

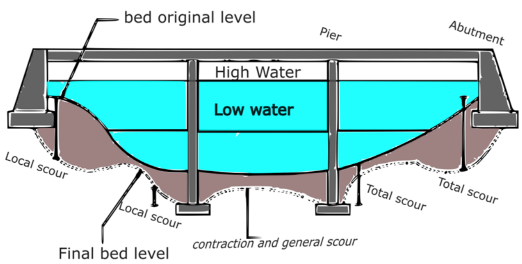


Figure 3. Types of scours caused by bridge piers [8]

Each abutment creates an obstacle to the flow. A vortex layer is formed and is responsible for the creation of an approximately conical scour pit located upstream in line with the vertical edge of abutment as shown in Figure 4.

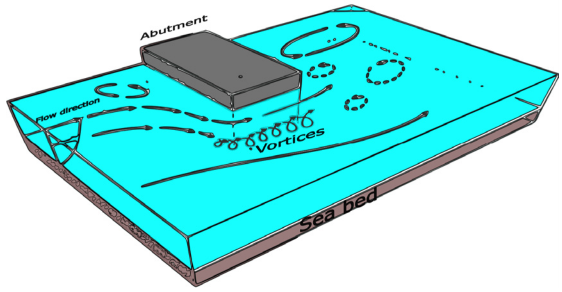


Figure 4. contraction of the fluid vein when passing abutments and soil scouring

2.2. Local Scouring Regimes

The scour regime is determined by comparing the average flow velocity V to the critical sediment transport speed V_c calculated according to the Equation (1) [9]:

$$V_c = 6.19 h_0^{1/6} d_{50}^{1/3} \tag{1}$$

where, ho: the water height, d_{50}: the average grain diameter.

Local scouring can occur as Clear-water scour or Live-bed scour: Indeed, first regime is produced when all sediments are at rest, i.e., they do not move upstream of the structure and when $V<V_c$. This type of scouring is favored by the presence of a flat bottom, vegetation and a coarse grain size. The second regime occurs when $V>V_c$ and thus the sediments of the bed bottom move from upstream to downstream. The entire bed is subject to erosion, which is reinforced near the obstacle ([4],[9]). Melville shares researcher's views on definition of clear-water scour and live-bed scour [10].

The clear-water scour initiates and increases continuously unlike the bed-live scour that's why the time to reach the maximum scouring depth is longer in the first regime than the second. As shown in Figure 5, initially, the depth of scouring is linear as a time function and when the water flow become incapable of removing the sediments from the scouring pit, the depth becomes invariant because this scouring regime is characterized by the non-displacement of sediments from upstream to downstream of the scour holes. The maximum of the scour depth is in this situation achieved. In live-bed scour, scour depth is sinusoidal and depends on the time. The equilibrium scour depth occurs when the number of materials removed from the scour hole is equal to the amount deposited [6].

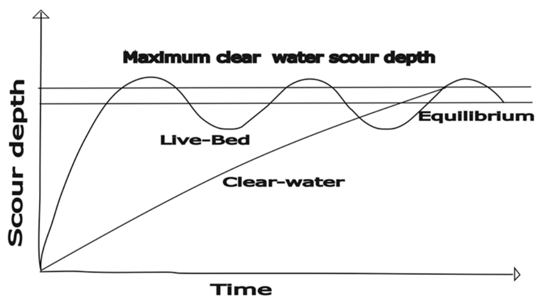


Figure 5. Development of scour depth with time - *ds* represents the maximum scour depth in equilibrium conditions

2.3. Factors Influencing Bridge Scour

The depth of scour in bridges is influenced by many factors such as: geomorphic factors, geotechnical factors and hydraulic factors. That means that the sediments size, flow intensity and dimensions of the pier control the scour depth [7].

2.3.1. Geotechnical Factors

2.3.1.1. Effect of the Soil Type

Extensive knowledge has been accumulated over the past decades on the scouring of foundations in sandy soils ([11],[12]). Indeed, non-cohesive soils such as sand and gravel are eroded particle by particle and therefore scouring occurs rapidly, allowing maximum depth to be reached after a few days or even hours [9]. Scouring is therefore, for this type of soil, a function of the average grain diameter d_{50}, the force of gravity g and grain dispersion σ_g [12]. Unlike non-cohesive soils, scour in cohesive soils is difficult to predict because the fine particles of silt and clay are bound by Van der Waals' electromagnetic and electrostatic forces [9] and the flow conditions depends on many factors such as the percentage of clay and stage of compaction or consolidation [13]. As a result, the scour rate is slow and can be spread over years. Their erosion is influenced by several factors: plasticity index, void percentage, temperature and shear resistance of the bed, etc.

2.3.1.2. Effect of Relative Grain Size

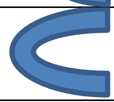
The influence of relative grain size b/d_{50} was studied by many researchers. In fact, (Raudkivi and Ettama, 1983) take the case of six pier sizes and d_{50} from 0.24mm to 7.8mm [14]. They confirm that the maximum value of scour depth is not influenced by particle size as long as b/d_{50}>20 to 25. With the decreasing of the value of b/d_{50}, the sediment becomes more coarser compared to the width of the groove excavated by down flow and stopped the erosion because the bed becomes porous and dissipates the energy of the down flow. According to (Melville and Chiew, 1999), the independence between scour depth and relative grain size is assured when b/d_{50} is larger than 50 [15]. (Sheppard et al., 2004) made experiments with larger values of b/d_{50} [16]. These experiments show that the scour depth decrease with the increase of b/d_{50} for b/d_{50}>25., (Lanca, et al., 2011) [17] confirm that the parameter b/d_{50} is inversely proportional to the scouring depth when 50< b/d_{50}<100. This conclusion corroborates what was found by the other researchers.

2.3.2. Structural Parameters

Extensive research has linked the geometry of bridge piers and abutments with scour depth. Indeed, the studies are made on a set of pile shapes. Many researchers have shown that the rectangular shape of the pile produces the maximum scour contrary to the lenticular shape [12]. In addition, piers are classified into blunt-nosed and sharp-nosed. The scour depth reaches its maximum when the pier is blunt-nosed because of the presence of horseshoe vortex system upstream (HSV) the pier.

In contrast to sharp-nosed form where the HSV doesn't appear and scour doesn't exist [18]. The scour depth depends also on the apex angle for the rounded sail pile and the pile with a pointed nose [19]. Indeed, as the apex angle increases, the scour depth also raises due to the augmentation of the effective frontal width of the pier. (Laurson and Toch, 1953) examined the effect of pile shape on scour depth in terms of shape factor [20] as shown in the Table 1. It is noticed that the rectangular shape gives the maximum scouring depth unlike the elliptic shape [20].

Table 1. Correction factor K_1 for pier nose shape (L/a: dimensions of the pier)

Shape of pier nose	L/a		K_1
Rectangular			1
Semicircular	1:1		0.9
Elliptic	2:1		0.8
	3:1		0.75

They also proposed a correction factors K_2 related to angle of attack for rectangular form of the pier as shown in the Figure 6.

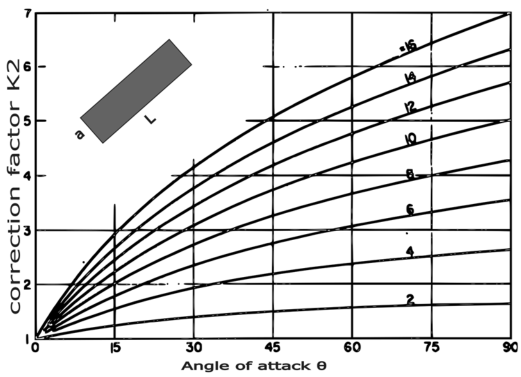


Figure 6. correction factor K_2 for apex angle θ

It should be noted that the stack geometry becomes negligible if the angle of apex θ is non-zero except for circular stacks. If θ increases, the face width of the pile increases and therefore scour depth increases as well [9].

2.3.3. Hydraulic Parameters

Raudkivi (1986) confirms that scour depth is controlled by many factors such as: the ratio of the water depth to the diameter of the pile [21] (h_0/b where, b is the diameter of the pier), relative diameter and flow intensity.

2.3.3.1. Effect of Flow Intensity

The flow velocity v is an essential parameter that influences the scouring depth. As we have already indicated, the comparison of and v_c allows to define the scouring regime [9] and the ratio v/v_c allows to control the depth which is maximum if $v=v_c$ i.e., in the vicinity of the transition between the two scouring regimes. For uniform materials, clear-water scour occurs when $v/v_c<1$, and the scour hole doesn’t receive sediments from upstream [9, 11, 22]. The scour depth is a linear function of flow intensity and it increases with it until it reaches a maximum value called threshold peak as shown in the Figure 8. Live-bed scour appears when

$$v/v_c>1 \tag{2}$$

For Non-uniform materials, v_c depends on the distribution of sediment’s size that represented by the median grain size d_{50} and the dispersion σ_g [23].

The conditions of scouring are characterized by the mean speed v_{ca} that represent the transition between clear-water scour and live-bed scour. If $v>0.8v_{ca}$, the clear-water scour exists, if not, the live-bed scour occurs. Initially, the scouring depth increases next to the threshold peak and then rise again to a second maximum named live-bed peak. This peak appears at about the transition flatbed stage of sediments transport on the bed [7], [24].

2.3.3.2. Flow Depth

As for the relative water height h_0/b (with h_0 the water height and b the diameter of the pile) it was also examined. For shallow flows, the maximum value of the scour depth is smaller than in deep water because water loses its eroding energy faster with the increase of scour hole ([24], [25]). Many researches confirm that the vortices are affected by the parameter h_0/b [8]. In fact, the more the depth decreases, the more the impact of the surface roller on the riverbed increases, damping the vortices in front of the pier and decreasing the depth of the scour hole.

A lot of threshold values are defined and beyond them the scour depth is independent of the flow depth. (Briaud et al., 2004) discovered that the scour depth is independent of water height as soon as the deep-water condition is satisfied (h_0/b >2) [25]. (Raudkivi, 1986) concluded that h_0/b >3 provide this independence [21]. (Raudkivi and Ettama, 1983) concluded after a serial of experiments that the reduction in the equilibrium scouring depth is because of the interference of the water surface roller trained around the pier with the horseshow vortex in scour hole. As long as they don’t interfere with each other, maximum local scour depth is independent of flow depth [14].

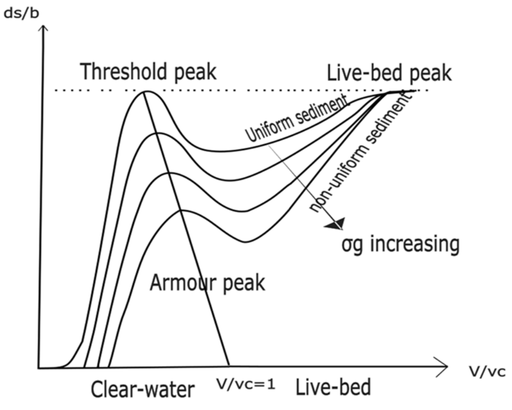


Figure 7. Variation in scour depth with the flow intensity
ds/b: relative scour depth - reprinted from [24]

2.3.3.3. Froude Number F_r

Froude number F_r is defined as an a dimensional number that characterizes the relative importance of the forces related to velocity and gravity in a fluid. An inquiry made by Jain and Fisher confirmed that for $F_r>F_{rc}$ (critical Froude number), scour depth varies according to the number of Froude since it is a linear function of approach speed. This means that scour depth is proportional to approach velocity for a given approach depth.

Table 2. Empirical equations for scour

Authors	Mathematical expression	Validity domain	Parameters
Shen, et al. [26]	$d_s = 1.35 \times b^{0.7} \times h_0^{0.3}$ (4)	Clear-Water	b: pier diameter h_0: water high
Sheppard, et al. [27]	$f_1 = \tanh((h_0/b)^{0.4})$ (5) $f_2 = (1 - 1.2 \times \ln(\frac{v}{v_c})^2)$ (6) $f_3 = \dfrac{\frac{b}{d_{50}}}{0.4(\frac{b}{d_{50}})^{1.2} + 10.6(\frac{b}{d_{50}})^{-0.13}}$ (7) $d_s = 2.5bf_1f_2f_3$ (8)	Clear-Water	v: flow velocity v_c: critical velocity
Froelih [28]	$d_s = 0.32bK_1F_r^{0.2} \times$ $\times(\frac{D_p}{b})^{0.62}(\frac{h}{b})^{0.46}(\frac{b}{d_{50}})^{0.08} + 1$ (9)	Live-Bed	K_1: factor for pier shape F_r: Froude number D_p: projected width of pier d_{50}: average grain diameter
Gao, et al. [29]	$f_1 = \tanh((h_0/b)^{0.4})$ (10)	Clear-water	k_ξ : factor for pier shape and flow attack angle on scour depth
	$d_s = 0.46b^{0.6}k_\xi d_{50}^{-0.068}h_0^{0.15}(\frac{v-v_c'}{v_c-v_c'})^n$ (11) $n = 0.645(\frac{d_{50}}{b})^{0.053}v_c$ (12) $v_c' = 0.645(\frac{d_{50}}{b})^{0.053}v_c$ (13)	Live-Bed	

2.4. Empirical Formulas for Scour Depth Estimation

Table 2 summarizes the most used equations. In Morocco, an investigation was launched by the public laboratory of tests and studies (LPEE) to inventory and synthesize the various methods used to estimate the scouring at the right of the structures of road crossings. in most cases, it is assumed that layers with poor mechanical properties are more likely to be eroded or to lose mechanical consistency under flood stress, so if the bedrock is shallow, the scour depth is given by the thickness of the overlying layers. In the contrary case, the scouring is calculated by using the most frequent formula in Morocco, named LPEE formula.

$$d_s = 0.217Q^{6/7}d_{50}^{-2/7} \tag{3}$$

where, Q is flood flow.

It is important to note that Moroccan engineers face several difficulties in using this formula since it depends on the flood flow which remains a difficult parameter to calculate accurately. In addition, there is no formula that has been calibrated or corroborated by experimental tests on a Moroccan wadi.

Several studies have been made to calculate local scour depth of bridge foundations taking into consideration different parameters. These models are based on experimental methods in laboratories and are affected by oversimplified setups (channel geometry, experimental errors, hydraulic conditions, sediment size…). which leads to results that are not accurate. In general, scour depth formulas depend on sediment size, hydraulic parameters (flow depth h_0, flow velocity V) and bridge geometry (shape of the pier, angle of attack) [30].

2.5. Scour Protection: Adaptation to the Moroccan Context

One of the most important problems to be solved in the establishment of a river structure is that of its protection against scour. The most common method of protecting river foundations in Morocco is the use of rip rap. The principle of riprap protection is very simple: scouring occurs because the grains of soil that make up the bed are small enough to be carried away by flood currents.

If a mat or mass of riprap is placed on the bed around a pile, each one heavy enough so that the most violent currents cannot move them, the materials of the bed removed from the action of the current will not be carried away and the bed will not be scoured in the protected zone. Experience proves that riprap, however heavy it may be, is always displaced since the level reached by the riprap against the shaft of a pile always drops with time and must be maintained by recharging it.

We must understand the mechanism of this displacement. It is not the riprap on the surface of the pile that is dragged away, if it has been chosen wisely heavy enough. The bed scours where the riprap stops and the riprap slides into the ditches thus dug. They move by what the foot of their slope is ruined. The solution "riprap" presents a great variety of types of profiles and structures; however, the dimensioning always passes by the definition (calculation) of the mass (or diameter) of the constituent materials (unitary block) and this, whatever the part of the work concerned.

3. CONCLUSION AND RECOMMENDATIONS

Due to many factors, several bridges collapsed, causing human and material damage. In this paper, a comprehensive review of these factors is presented and a detailed study on the scouring phenomenon is included. Consequently, these conclusions can be drawn:

1) Natural factors are unpredictable and can cause severe damages on civil engineering structures therefore it's necessary to create investigation companions in order to predict degradations that can appear on the structures and set up different remedial techniques.

2) The intervention of the human being is done at the level of the study of the structures, their execution and their exploitation; therefore, it is necessary to show an awareness of the dangers caused by their bad dimensioning or exploitation.

3) Scour phenomenon is among the most frequent reasons of bridge collapse in the USA (Figure 1) and is affected by many factors. Its complexity has made it a subject of study for many researchers. The down flow causes local erosion and creates the horseshoe vortices around the obstacle. On his side wake vortices are generated and tear off the materials which expose the pile.

4) Scouring occurs quickly in non-cohesive soils and the maximum scour depth is reached rapidly unlike cohesive soils whose grains are linked by electromagnetic and electrostatic bonds. The decrease of relative grain size lead to stop the process of the erosion and reach the maximum value of scouring depth.

5) The shape of the pile and the angle of attack influence the scour depth consequently many researchers made studies on different forms of piles and taking into consideration many values of the angle of approach.

6) Intensity of flow (v/v_c for uniform sediments and v/v_{ca} for non-uniform sediments) is a significant factor in the local scour. In clear water scour conditions, flow intensity is lower than 1 and the maximum scour depth is reached between clear-water scour and live-bed scour conditions where the scour bore receive sediments from upstream. The flow depth was also examined. In fact, the maximum scour depth decreases with the decreasing flow depth until a critical value.

Empirical equations were established to calculate the maximum of scouring depth taking into consideration various parameters, except that these equations are based on experimental studies made in laboratories and their expressions varies from one researcher to another which gives uncertain results and may underestimate or overestimate the scouring of the piers and therefore the poor dimensioning of the structure that can lead to serious problems with the time, hence the interest to compare the empirical results with a mechanical modeling by finite elements to choose a moderate maximum depth value.

NOMENCLATURES

Symbols / Parameters

b: pier diameter
h_0: water high
v: flow velocity
v_c: critical velocity
K_1: factor for pier shape
F_r: froude number
D_p: projected width of pier
d_{50}: average grain diameter
k_ξ : factor for pier shape and flow attack angle on scour depth
Q: flood flow
d_{50}: the average grain diameter

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