EXPERIMENTAL STUDY OF THE PHENOMENON OF LOCAL SCOUR AROUND BRIDGE PIERS

A Thesis
Submitted to
The Faculty of Graduate Studies
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In Partial Fulfillment
of the Requirements for the Degree
Master of Science in Civil Engineering

by
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ABSTRACT

The purpose of this study was to investigate the phenomenon of local scour around bridge piers and to develop functional relationships between the various parameters that influence the phenomenon. All the data used in the study were obtained from experiments conducted in a laboratory flume.

The study was limited to rectangular piers of length to width ratio of 5.3. All the piers essentially behaved as blunt-nosed and were in all tests aligned parallel to the flow. Subcritical, unidirectional and uniform flow conditions were maintained at Froude numbers ranging from 0.12 to 0.23. Only non-cohesive bed material (sand) was used and clear-water scour conditions were maintained by keeping the flow velocity below the threshold value for the initiation of sediment movement.

The results of this study indicated that a reduction of the bluntness of the pier nose reduces the scour potential when compared to a square-nosed pier which causes the deepest scour depths. The depth of flow was found to have negligible influence except for depths less than 2.6 pier widths. The depth of scour was found to vary linearly with the mean approach flow velocity.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF PLATES

NOMENCLATURE AND DIMENSIONS

Symbol	Dimensions	Definition
a_1, a_2, a_3	-	Coefficients in Scour-Depth Equation 5.9
a	L	b/2
b	L	Width of Pier (equivalent to diameter of pier in the case of a circular pier)
c	-	Pier Shape Factor
D	L	Characteristic Size of Sediment
DG	L	Equivalent to D_{50}
D_{15}	L	Sediment Size of Protective Layer of Rip-Rap at Which 15% by Weight is Finer (in Eq. 8.2)
D_{50}	L	Mean Grain Diameter of Sediment (sediment size at which 50% of material by weight is finer)
D_{50}	L	Sediment Size of Protective Layer of Rip-Rap at Which 50% by Weight is Finer (in Eq. 8.2)
d_0	L	Depth of Approach Flow
d_s	L	Depth of Scour
d_{se}	L	Equilibrium Depth of Scour
d_{sm}	L	Maximum Depth of Scour
d_{s3}	L	Depth of Scour After 3 Hours of Test Run
d_{s4}	L	Depth of Scour After 4 Hours of Test Run
d_{s5}	L	Depth of Scour After 5 Hours of Test Run

Symbol	Dimensions	Definition
d_{15}	L	Sediment Size of Protected Layer Under Rip-Rap at Which 15% by Weight is Finer (in Eq. 8.2)
d_{50}	L	Sediment Size of Protected Layer Under Rip-Rap at Which 50% by Weight is Finer (in Eq. 8.2)
d_{85}	L	Sediment Size of Protected Layer Under Rip-Rap at Which 85% by Weight is Finer (in Eq. 8.2)
Eu*	-	Scour Euler Number (= $U/\sqrt{2gd_s}$)
F	-	Equivalent to Fr
FRD	-	Equivalent to Fr
Fr	-	Froude Number of Approach Flow (= $U/\sqrt{gd_0}$)
Fr*	-	Pier Froude Number (= $U/\sqrt{gb}$)
G	-	$\dfrac{\left[(\frac{\rho_s}{\rho})-1\right] gD_{50}^3}{\nu^2}$
G_s	-	Specific Gravity of Sediment
g	$\frac{L}{T^2}$	Acceleration Due to Gravity
H	L	Equivalent to d_0
h_0	L	Equivalent to d_0
k	L	Equivalent Sand Roughness Size
k	-	A Constant in Equation 5.2
Le	L	Longitudinal Extent of Scour Hole
ℓ	L	Length of Pier

Symbol	Dimensions	Definition
N_s	-	Sediment Number $(= \frac{U}{\sqrt{(s-1)gD_{50}}})$
N_{sc}	-	Lowest Value of the Sediment Number for Which Scour Will Occur
Q_s	L^3	Solid Volume of Sediment Removed From Scour Hole
q_{s1}	$\frac{L^3}{T}$	Capacity of Flow to Transport Sediment Out of Scour Hole
q_{s2}	$\frac{L^3}{T}$	Rate of Sediment Supply to Scour Hole
Re*	-	Pier Reynolds Number $(= \frac{Ub}{\nu})$
RNP	-	Round-Nosed Pier
SG	-	Equivalent to S
SNP	-	Square-Nosed Pier
S_0	-	Slope of Channel Bed
s	-	Ratio of Solids Density to Fluid Density $(= G_s)$
TNP	-	Triangular-Nosed Pier
t	T	Time
U	$\frac{L}{T}$	Mean Velocity of Undisturbed Approach Flow
U_c	$\frac{L}{T}$	Threshold or Critical Velocity for Initiation of Movement of Undisturbed Bed Material
VMC	$\frac{L}{T}$	Mean Velocity of Approach Flow at the First Displacement of a Grain or Grains on Rip-Rap Around the Pier
Y	L	Equivalent to d_0

Symbol	Dimensions	Definition
y	L	Equivalent to d_s
z	L	Equivalent to b
α	-	Angle of Attack
β	-	Wedge Angle of a Sharp-Nosed Pier
γ	$\frac{F}{L^3}$	Specific Weight of Fluid
γ'_s	$\frac{F}{L^3}$	Submerged Specific Weight of Sediment Grains
μ	$\frac{FT}{L^2}$	Dynamic Viscosity of Fluid
ν	$\frac{L^2}{T}$	Kinematic Viscosity of Fluid
ρ	$\frac{FT^2}{L^4}$	Density of Fluid
ρ_s	$\frac{FT^2}{L^4}$	Density of Sediment
ϕ	-	Angle of Repose

CHAPTER I

INTRODUCTION

1.1 General Aspects of the Problem of Local Scour

Local scour is defined as the abrupt lowering of the streambed in the vicinity of a hydraulic structure. In the specific case of a bridge pier, the scour is due to the erosion of the bed material by the local flow structure induced by the pier. The flow structure itself consists of eddies which are generated by the significant changes in the direction of the flow caused by the pier.

Many of the bridge failures in the past were largely attributed to the undermining of the foundations of piers and/or abutments by scour holes created by the flowing water. Consequently, early bridge designers often over-designed their bridge foundations to circumvent this hydraulically related problem. Common methods of design often comprised erecting massive piers and abutments, aligned across long-crossings, usually with very short spans, and selecting bridge sites in relatively straight reaches with stable banks. However, a lot of these early methods of combating the scour problem met with only limited success. One major flaw was failure to recognise the fact that any obstruction placed in a stream modified the flow pattern in the vicinity of that obstruction, thereby causing severe scour to occur, and pier massiveness only contributed to an enhancement of the problem. Additional, but not as severe, scour occurred when the designers placed the piers at such a spacing as to cause extreme contractions to the flow sections, resulting in streambed scour due to higher induced velocities.

A pier will obviously have an increased factor of safety from scour if it is based on a firm bedrock. However, such a foundation, albeit desirable, is not often economically feasible, particularly in alluvial streams where access to a solid geological formation may require unjustifiably excessive excavations. It is clear, therefore, that in order to avoid over- or under-design of the foundations of piers in an erodible bed, it is necessary to know the maximum depth which will be reached by the scouring process. This, in turn, requires the understanding of the mechanism of local scour. Clearly, this understanding will not only facilitate the evaluation of potential scour depths, but will, in addition, lead to the development of methods to be adopted in the design of pier foundations to accommodate the scour, to reduce its magnitude, or to eliminate it completely; the choice as to what extent this is carried out will undoubtedly be dictated by economic analyses.

1.2 Purpose and Scope of Study

The phenomenon of local scour is among the many fields of sediment transport where the processes of water and sediment movement are very complicated. Given the overall complexity and multiplicity of the factors influencing local scour, it is not surprising that no entirely satisfactory theoretical solution of the scour problem has yet evolved. One obvious approach to the evolution of predictive principles is to conduct an experimental study. This has the advantage of exercising separate control over each of the individual factors affecting the phenomenon, once they have been recognised. The influence of each of the various factors is, therefore, sorted out from the total phenomenon.

Many studies of local scour have been conducted by various investigators previously. The results from these studies, however, have not always been in complete agreement. Experimental data have, in some cases, been regarded as inadequate and data from different sources have, many times, been in conflict. The present trend, however, appears to be in the direction of unanimity as regards the important parameters governing local scour.

The object of this research reflects a continuing effort in the attempts to provide more experimental data on local scour, with the hope that, coupled with certain theoretical approximations, functional relationships between the various parameters might be developed.

This study was limited to the following conditions:

(i) rectangular piers with length to width ratio of 5.33; for each pier both the nose and the tail were of the same shape; three shapes were investigated, namely round, square and triangular; the length and width dimensions were the same for all piers.

(ii) subcritical, unidirectional and uniform flow conditions.

(iii) non-cohesive granular bed material (sand).

(iv) clear-water scour which, herein, refers to the condition in which the bed material upstream of the pier is undisturbed and, therefore, the flow of sediment into the scour hole is zero; in other words, movement of sediment begins in the vicinity of the pier and proceeds downstream therefrom.

(v) zero angle of attack; each pier had its major axis aligned with the main direction of flow.

CHAPTER II

CATEGORIES OF SCOUR AT BRIDGE PIERS

2.1 Scour and Degradation of Channel Bed

General degradation of an alluvial channel bed is usually a combination of local scour and other forms of scour. The term "scour", by itself, is used to mean

> 'a lowering by erosion of the channel bed below an assumed natural level or other appropriate datum, tending to expose or undermine foundations that would otherwise remain buried' (Neill, 1973).[1]

There are several interrelated factors which may lead to the lowering of the channel bed at a bridge pier site leading, therefore, to the following categorization of scour:

(i) Degradation, Temporaty or Progressive is associated with a change of river regimes due to natural geological processes or induced by man's activities either upstream or downstream from the bridge site; thus, a river may change from a meandering to a braided one.

(ii) Natural Scour in alluvial channels is associated with variations in flow conditions and changes in sediment supply. This results in temporary or progressive shifting of the thalweg (the deepest flow depth in a river section), bed-form migration and channel shifting. Thus a small channel within the main channel that shifts its course closer to a pier will lower the bed elevation adjacent to the pier.

(iii) General Scour is associated with the constriction of the flow section. Bridge piers contract the width of the channel, hence reducing the net waterway area. This results in an increase in

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[1] All the technical literature is listed in the Bibliography at the end of the main text.

the flow velocity under the bridge and hence the scouring capability of the flow.

(iv) Local Scour around the piers is caused by local flow disturbances (vortices or eddies) induced by the piers themselves. These disturbances are a result of the abrupt change in the direction of flow caused by the piers.

The progressive or temporary degradation and the natural scour usually occur over relatively long reaches and over long time spans. The first three factors may cause the elevation of the entire bed to be lowered. Local scour, however, is confined only to the vicinity of a pier and may occur in conjunction with or in the absence of any one, two or all the other factors. General and local scour are illustrated in Fig. 2.1.[1]

Inasmuch as the four forms of scour described in the preceding paragraph are caused by entirely different phenomena, it is virtually impossible to single out the influence of each of the various factors from the total scour phenomenon. By the same token, it is prohibitive to find a single criterion to predict the magnitude of the scour due to their combined effect near each pier. However, by carefully studying each factor, estimates of their contributions to the total scour can be made. This study is restricted to the phenomenon of local scour only.

2.2 Local Scour Due to Bridge Piers

Local scour is, as defined in an earlier section, the abrupt decrease in bed elevation in the immediate vicinity of a pier due to erosion of bed material by the local flow structure induced by the pier. Local scour

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[1] All figures are to be found after the main text.

is the most important cause of a decrease in bed elevation and has been extensively studied both in the past and recently, and is still being investigated upon today. Besides its severity, another reason why it has received the most attention is that it is most conveniently studied with the aid of hydraulic models. The other forms of scour, on the other hand, are more complex in nature and difficult to model for the purposes of laboratory study; it is also apparent that their severity is not significant enough to warrant the often expensive model studies.

Three classes of local scour may be identified by considering the amount of sediment transported into and out of the scour hole:

(i) Stable Scour: The local disturbances caused by the pier result in a scour hole of a certain magnitude, after which there is no additional scour, a condition which is established when the sediment discharge into the hole is equal to the sediment discharge out of the hole. The condition of "no scour", whereby both sediment discharges are zero may also be classified as stable scour.

(ii) Clear-water Scour: The rate at which sediment is supplied to the scour hole by the approach flow is zero, but the capacity of the flow to transport sediment out of the hole is greater than zero. The flow then continues to erode the scoured zone, increasing the depth of scour with time until a limiting rate of scour is approached asymptotically.

(iii) Scour with Continuous Sediment Supply: The inflow of sediment from upstream may be smaller or greater than the rate of sediment removal from the scour hole. If the sediment supply discharge is greater than the amount being eroded away from the scour hole

> the depth of scour will decrease with time. Conversely, the reverse situation will occur when the supply rate is less than the erosion rate and the depth of scour will increase, reach a maximum and eventually vary aperiodically with time about an equilibrium value due to the passage of dunes through the scoured zone.

The distinction between Cases (ii) and (iii) is shown in Fig. 2.2.

The scouring processes described above are conveniently represented by the following relationship suggested by Laursen (1952):

$$\frac{dQ_s}{dt} = q_{s1} - q_{s2} \tag{2.1}$$

wherein $\frac{dQ_s}{dt}$ is the rate of local scour in volume per unit time; q_{s1} is the capacity of the flow to transport sediment out of the scour hole in volume per unit time; and q_{s2} is the rate at which sediment is supplied to the scour hole by the undisturbed flow. With this relationship the three cases are then summarized as follows:

(i) $q_{s1} = q_{s2} = C$ represents stable scour. When $C = 0$ there is no scour.

(ii) $q_{s1} >> q_{s2} \cong 0$ represents clear-water scour.

(iii) $q_{s1} \geq q_{s2} > 0$ or $q_{s1} \leq q_{s2} > 0$ represents scour with continuous sediment supply.

This study was limited to case (ii) of clear-water scour.

CHAPTER III

MECHANISM OF LOCAL SCOUR AND THE SCOURING PROCESS

3.1 Interaction Between Pier and Flow Field

Local scour at a bridge pier is caused by a system of vortices or eddies which develop around the pier. Depending on the type of pier and free-stream conditions, the eddy-structure near a pier can be composed of any, all, or none of the following three basic systems: the horseshoe-vortex system, the wake-vortex system and the trailing-vortex system (Roper et al, 1967). The so-called "horseshoe" vortex system is, however, the dominant cause of scour at the nose of a bridge pier. The axis of this vortex is horizontal and the term "horseshoe" is derived from the shape that the vortex system takes as it wraps around the upstream base of the pier and tails downstream (see Fig. 3.1).

The magnitude of a locally scoured hole depends, among other factors, on the shape of the pier as it reflects the strength of the horseshoe-vortex at the base of the pier. Depending on the geometry and the angle of attack of the undisturbed flow piers are, therefore, classified as either blunt-nosed or sharp-nosed (Breusers et al, 1977). The three pier shapes investigated in this study all behaved as blunt-nosed in this sense.

3.2 Blunt-Nosed Piers and the Horseshoe-Vortex System

A blunt-nosed pier causes the greatest scour depth as it induces a horsehoe-vortex of the greatest strength. Tison (1961) attributed the formation of the horseshoe-vortex to the downward flow in the front of the pier; he showed that this vertical velocity component existed as a result of the horizontal curvature of the streamlines in front of the pier and the reduced velocity near the bed by friction. Shen and others (1966), however, have stated that the mechanism which forms the horseshoe vortex system is a pressure field induced by the pier. If the pressure field is sufficiently strong the approaching boundary layer separates ahead of the pier and rolls up to form the horseshoe-vortex, as illustrated in Fig. 3.1 for a circular pier. A sufficiently large pressure gradient is required to initiate this process and a blunt-nosed pier is defined as one capable of inducing such a pressure field.

In the vicinity of a blunt-nosed pier scour begins when the horseshoe-vortex system develops enough shear stress to dislodge and suspend the bed material. The combined actions of the vortex and the convergence of streamlines due to increased horizontal velocity near the pier then carries the scoured material a short distance downstream with the flow, that is, until the action of viscosity and/or adverse pressure gradients sufficiently dissipate the vortex system.

As the scouring process continues, the material adjacent to the scour hole starts to slide into the hole as a result of reduced lateral support. With time, the scour hole extends both downwards and outwards due to the complementary processes of material removal and sliding. Eventually the whole process tends to equilibrium.

At equilibrium the shear stress developed in the scoured zone is no longer sufficient to move the bed material. In cases where there is general sediment movement on the bed (live-bed situations) the equilibrium condition would be characterized by equal rates of sediment supply to and sediment removal from the scour hole.

3.3 Sharp-Nosed Piers

A sharp-nosed pier is defined as one which causes only a weak separation of the boundary layer on approaching the pier, and hence prevents the formation of a strong horseshoe-vortex system. This type of pier is illustrated in Fig. 3.3. The curvature of the flow streamlines near the upstream end of the pier is said to be the major factor that determines the magnitude and, also, the location of maximum scour when the major axis of the pier is aligned with the flow (Shen et al, 1966). Thus streamlining the front end of the pier reduces the strength of the horseshoe-vortex, thereby reducing the scour. However, a sharp-nosed pier in straight flow could behave like a blunt-nosed pier if the flow is at an angle of attack. For instance, a sharp-nosed pier aligned at a skewed angle with the flow has been observed by Roper et al (1967) to induce a strong horseshoe-vortex system and develop a large scour hole at the nose of the pier as a result.

3.4 Other Vortex Systems

The wake-vortex system has a vertical axis and develops because of partial blockage of the flow by the pier (Simons and Şentürk, 1977). As outlined by Roper and others (1967) the wake-vortex system is formed by the rolling up of the unstable shear layers generated at the surface of the pier. These shear layers are then shed alternately from the pier and convected downstream. The strength of the wake-vortex system depends on the pressure gradients over the rear whose strength is in turn dependent on the shape of the tail of the pier. The wake system suspends the scoured material which is then carried a limited distance downstream from the pier. For most piers, however, very little additional scouring is caused by wake vortices.

The other type of vortex system is called the trailing-vortex system.

> 'The trailing-vortex system usually occurs only on completely submerged piers and is similar to that which occurs at the tips of finite lifting surfaces in finite wing theory. It is composed of one or

> more discrete vortices attached to the top of the pier and extending downstream. These vortices form when finite pressure differences exist between two surfaces meeting at a corner, such as at the top of the pier.'
> (Breusers et al, 1977)

Again, this system of vortices contributes little or no scouring in addition to that caused by the horsehoe-vortex system.