ESTIMATION OF BRIDGE SCOUR USING HEC 18 AND BD 97/12(A CASE STUDY OF TWIN BRIDGES ALONG BENIN – OFUSO – ORE – AJEBANDELE – SHAGAMU DUAL CARIAGEWAY IN ONDO STATE)

BY

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(CVE/13/1065)

project report submitted to the Department of Civil Engineering

Federal University Oye Ekiti

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ABSTRACT

A bridge is a structure built to span physical obstacles without closing the way underneath such as a body of water, valley, or road, for the purpose of providing passage over the obstacle. There are many different designs that each serve a particular purpose and apply to different situations. Designs of bridges vary depending on the function of the bridge, the nature of the terrain where the bridge is constructed and anchored, the material used to make it, and the funds available to build it. Scour occurs due to the effect of erosive action of flowing water, removing and carrying away soil material from the bed and banks of streams and from around the piers and abutments of bridges.

Bridges can be adversely affected by wind, water, loads on the bridge (traffic), etc. In this project, bridge scour of an existing bridge will be estimated using two (2) bridge scour estimation manuals; BD 97/12 (the Assessment of Scour and Other Hydraulic Actions at Highway Structures), and HEC 18 (Hydraulic Engineering Circular No. 18). Afterwards, an in-situ measurement of the existing scour bridge will be taken to compare which of the bridge scour estimation manual best estimate bridge scour in Nigeria.

CERTIFICATION

This project with the title

ESTIMATION OF BRIDGE SCOUR USING HEC 18 AND BD 97/12(A CASE STUDY OF TWIN BRIDGES ALONG BENIN – OFUSO – ORE – AJEBANDELE – SHAGAMU DUAL CARIAGEWAY IN ONDO STATE)

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Has satisfied the regulations governing the award of degree of

BACHELOR OF ENGINEERING (B.Eng) In CIVIL ENGINEERING,

Federal University Oye-Ekiti, Nigeria

....	29/03/2019
Engr Tochukwu Onuorah Project Supervisor	Date
....	15/04/2019
Dr. Mrs O. I. Ndububa Head of Department	Date

DEDICATION

This report is dedicated to God Almighty who saw me through the course of this project. Without His help, it would not have been achievable.

ACKNOWLEGDEMENT

First of all, I give thanks to God who kept me in His infinite mercies and helped me during the course of my project. Special thanks go to my project supervisor, Eng. Tochukwu Onuorah, for overseeing and coordinating the project as it would not have been a success without his supervision, guidance and advice. I also appreciate Dr. Mrs O. I. Ndububa, the Head of civil Engineering department, Dr. Fapohunda, the departmental project coordinator, Dr. Adetayo, my level advisor, and the entire teaching and non-teaching staff of the Civil Engineering department. I appreciate Eng. Kennedy.I.Ogboko of KIPs Engineering NIG Limited for his interest and financial support on this project. My acknowledgement would not be complete without the mention of the immense contributions of my mother, Mrs. Ojo Funmilayo M, my uncle and his family, Engr. Sunday Siji for their financial support and encouragement and my colleagues for their encouragement. I am really grateful. God bless you all

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CHAPTER 1

1.1 General Background

Scour occurs due to the effect of erosive action of flowing water, removing and carrying away soil material from the bed and banks of streams and from around the piers and abutments of bridges. Different materials at the bed and banks of streams are scour at different speeds. Granular soils that are not tightly jointed are rapidly eroded by flowing water, 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 streams. If there is a constant flow condition, scour depth in sand- and gravel-bed material will reach maximum in hours; cohesive bed material in days; glacial till, sandstones, and shale in months; limestone in years, and dense granite in centuries. Under flow conditions typical of actual bridge crossings, several floods may be needed to attain maximum scour. Accurate judgment on the magnitude of scour is difficult due to the cyclic nature of some scour processes. Scour can be deepest near the peak of a flood, but hardly visible as floodwaters recede and scour holes refill with sediment.

Scour can occur in both riverine and coastal areas. In riverine environments, flow is in one direction (downstream) resulting into scour. In coastal areas, highways that cross waterways and/or encroach longitudinally on them are subject to tidal fluctuation and scour may result from flow in two directions. (Arneson, Zevenbergen, Lagasse, & Clopper, 2012)

Plate 1.1: Local scour damage at piles on the Logan River

In planning a new bridge design, or the evaluation of the structural stability of an existing bridge, scour around the piers of the bridge should be given high attention. Scour is a continuous process by which the streambed is lowered or degraded through natural or human induced ways. This degradation is a consequence of the following increase discharge, decreased bedload, or decreased bed material size. (Galay, 1983). Obstruction of the bridge opening by debris also results in decreased flow area and may cause or increase contraction scour at a site. (Butch, 1991).

Local scour, which occurs in response to continuous fluid migration carrying away badmaterial from the pier, is the most important. This is because it obstruct the flow of water, therefore causing scour due to the increase in velocity of flow, horse shoe, down-flow, and shear stress and wake vortices create hole (Chow V. , 1959; Shen, River Mechanics, 1971; Raudkivi & Melville, 1977). The depth of the scour hole is typically much larger than that resulting from general or contraction scour, often by a factor of 10 (Fischenich & Landers, 2000).

1.2 Brief Description of the Route (Preliminary Investigations)

The existing twin bridges are on Ore – Ajebandele – Shagamu Expressway. The road has a length of 96.15Km and takes off from Ajebandele (Ondo State) to Shagamu (Ogun State). It lies within the South West part of Nigeria in Ogun and Ondo States. The existing road is a double lane dual carriageway that link the Five (5) Geopolitical Zones to South West Nigeria. It is clearly an important route for transporters travelling to and fro the nation's business capital of Lagos and vice versa.

Plate. 1.2 Scouring of Bridge Foundations

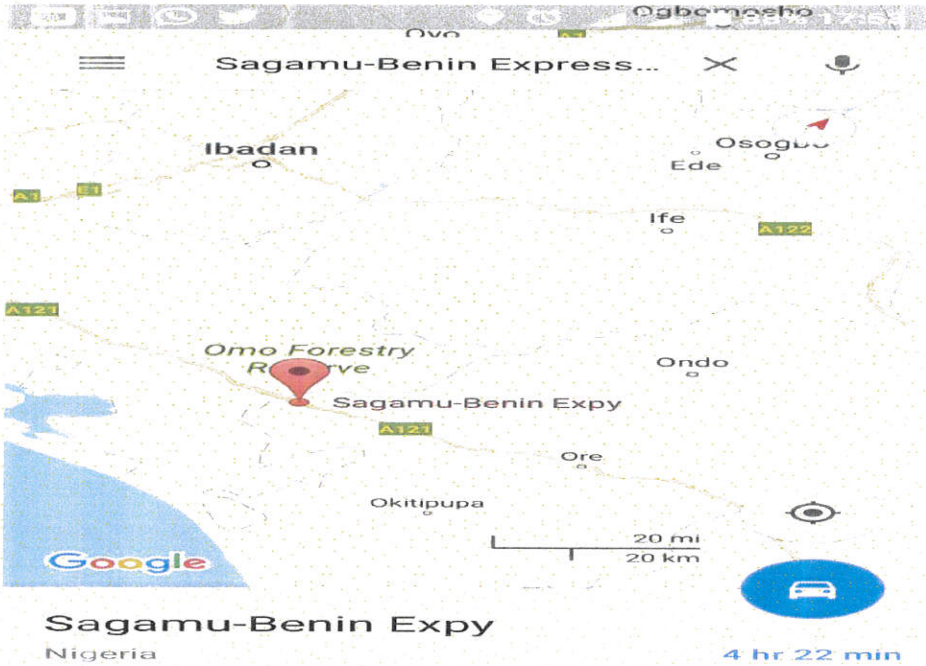


Plate.1.3 Map showing sagamu-benin Express road (Googlemap)

1.3 Problem Statement:

Bridge failure affects the free flow of traffic therefore causing deteriorating in the economy of the area at which the bridge failure had happened. This also affects negatively the social and governing life of the public as well as the cost implication of replacing the bridges. Example is the collapse of Wairoa river Bridge in 1988, this impede the movement of vehicles within the wairoa Town therefore causing losses in the economy within the surrounding community and the cost of reconstructing the bridge was reported to be 50% less than the cost of providing temporary palliative measures for traffic flow in 1990.

Plate 1.4; the collapsed Wairoa River Bridge, New Zealand, 1988.

Because of the high flood of 2012 in Nigeria, the Federal Highway Department in Nigeria was forced to do review on the designs they have prepared for the construction of bridges including Loko-Oweto Bridge across River Benue. River Ekulu Bridge was threatened by scour as shown below in Plate 1.5.

Plate 1.5; Ekulu River Bridge in Nigeria; pier foundation threatened by scour.

1.4 Justification of the study

This study is considered very important as it will investigate the most applicable manual that can be used to estimate bridge scour in Nigeria by considering a case study of twin bridges along benin – ofuso – ore – ajebandele – shagamu dual cariageway in ondo state.

1.5 Aim and objectives:

1.5. Aim

The purpose of this research work is to investigate the best scour assessment method that can be used in Nigeria to estimate scour at bridges.

1.5.2 Objectives:

The objectives of the project are to:

i. Estimate bridge scour using HEC 18 ;
ii. Estimate bridge scour using BD 97/12
iii. Evaluate the two assessment methodology with respect to in-situ measurement of the scoured twin bridge at benin – ofuso – ore – ajebandele – shagamu dual cariageway in ondo state.

BD 97/12 (the Assessment of Scour and Other Hydraulic Actions at Highway Structures).

HEC 18 (Hydraulic Engineering Circular No. 18 (HEC-18)-Evaluating Scour at Bridges.

1.6 Scope of study:

Through time, there has been manuals with formulas used in estimating scour at bridges, part of this formula are discoursed in the following manuals; BD 97/12 (the Assessment Of Scour And Other Hydraulic Actions At Highway Structures) And HEC-18 (Hydraulic Engineering Circular No. 18 -Evaluating Scour at Bridges), (Richardson and Davis, 2001). In this study, local scour at bridge piers will be examined using the formula provided in both standard listed above. The result of the estimation using this formulas will be compared with an in-situ measurement of the pier affected by local scour to know which one of this formula best estimate local scour at bridges in Nigeria

CHAPTER 2

2.0 Literature review

2.1 Total scour

Total scour at a highway crossing considers three primary components:

1. **Long-term degradation** of the river bed
2. **Contraction scour** at the bridge
3. **Local scour** at the piers or abutments

These three scour components are added to obtain the total scour at a pier or abutment. This assumes that each component occurs independent of the other. Considering the components additive adds some conservatism to the design. In addition, there are other types of scour that occur in specific situations as well as lateral migration of the stream that must be assessed when evaluating total scour at bridge piers and abutments. (Arneson, Zevenbergen, Lagasse, & Clopper, 2012)

2.1.1 Aggradation and Degradation

Aggradation and Degradation are changes in the height of streambed as a result of natural or man-induced caused. Aggradation is as a result of the speed of the flow river therefore transporting (eroding) streambed material from the bridge upstream reach. Degradation is the deficiency in the amount of bed-material transported from the upstream of a river to its downstream, which causes lowering of the stream bed. Even in the absences of bridge or other hydraulic structure, degradation is the lowering of streambed because of flood actions. (Arneson, Zevenbergen, Lagasse, & Clopper, 2012)

2.1.2 Contraction Scour

Contraction scour occurs because of the obstruction in the flow of water in a floodplain, this constriction may be because of rock found in the river part or the availability of hydraulic structure, thereby reducing the area of the stream, and increasing the pressure of the flowing fluid and bed shear stress. Contraction scour results from contraction (or constriction) of the flow, which results in removal of material from the bed across all or most of the channel width. The difference between contraction scour and long term degradation is that contraction scour occurs around the hydraulic structure while long-term degradation does not. Lowering of the bed elevation causes an increases in the flow area therefore causing the velocity and shear stress to be reduced till a stable point is reached; i.e. the bed shear stress decreases such that no sediment is transported out of the reach. (Arneson, Zevenbergen, Lagasse, & Clopper, 2012). In contraction scour, the depth of scour can be more at some point compared to other points. (Department of Transport and Main Roads, 2013)

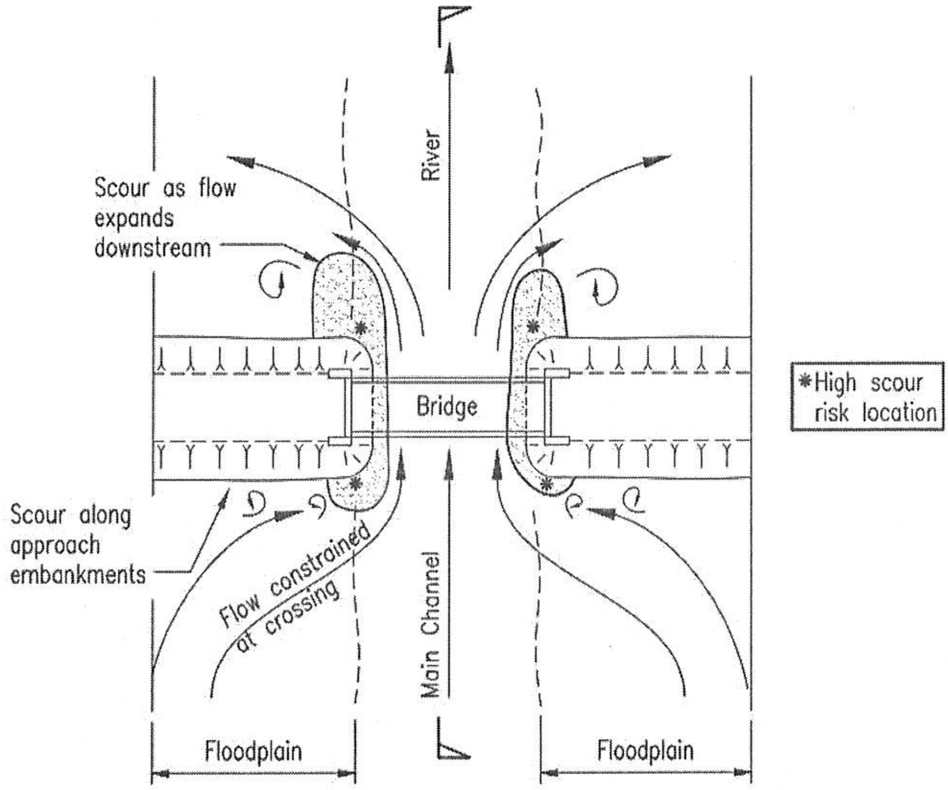


Plate 2.1: Contraction scour and high risk locations

2.1.2.1 Clearwater scour

When there is no bed material transported from the upstream reach, to the downstream reach, it is referred to as Clearwater scour. In other words the velocity of the river is less than the critical velocity of the bed material in the river (i.e. $v/v_c < 1$). Clearwater scour occurs until the flow velocity (V) or the shear stress (τ_o) on the bed equals the critical velocity (V_c) or the critical shear stress (τ_c) of a certain particle size (D) in the bed material. At this point the velocity of the flowing liquid is low in its force to move bed material from the scour area. (Department of Transport and Main Roads, 2013)

2.1.2.2 Live bed scour

Live-bed contraction scour is just the direct opposite of Clearwater scour. Therefore the stream velocity is greater than the critical velocity of the bed material ($v/vc > 1$). Now in live-bed scour, equilibrium is reached when the amount of sediment transported is equal to the amount of sediment transported to the scour area. Live-bed contraction scour is typically cyclical and due to the high suspended sediment load, more abrasive. For example, the bed scours away during the rising stage of a runoff event and fills on the falling stage. The cyclic nature of contraction scour causes difficulties in determining contraction scour depths after a flood. As such, this is why scour depths need to be calculated and why post flood inspections are necessary. (Department of Transport and Main Roads, 2013)

2.1.3 Local Scour

Local scour which is the remover of bed material from around the hydraulic structure (piers, abutments, spurs, and embankments) as a result of acceleration of flow and resulting vortices by the obstruction of flow. Vortices will form within the separated layer. Plate 2.2A and Plate 2.2B show the processes behind localized scour at piers and abutments. Vortices form upstream and downstream of pier and abutment Flow around vertical cylinders, such as bridge piers will be turbulent. The resulting vortex system will consist of flows moving in a downward direction in front of the pier. The velocity of the flow will push the vortex system around the pier. When observed in plan view the vortex system resembles a horseshoe. Horseshoe vortices will become stable only after an equilibrium scour depth has formed. Hydrodynamically shaped piers help reduce the generation of turbulent flow. (Arneson, Zevenbergen, Lagasse, & Clopper, 2012)

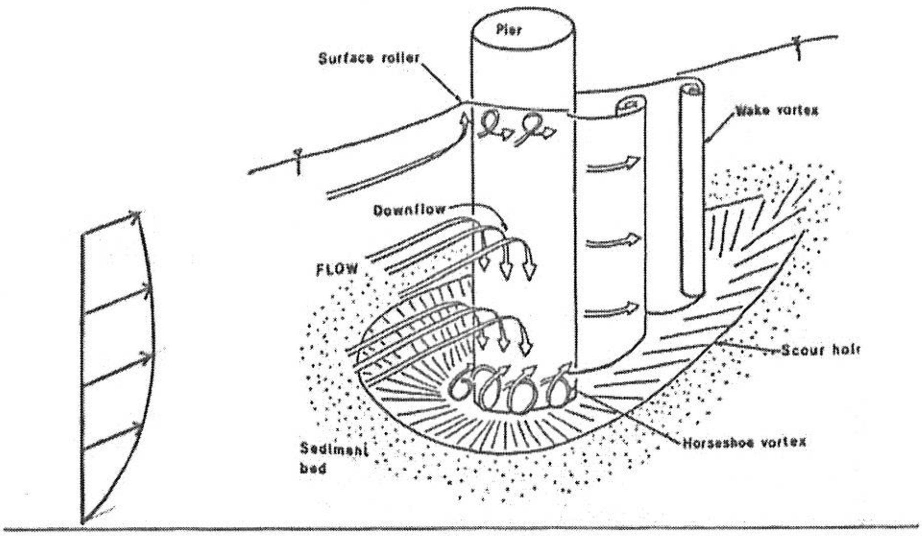


Plate 2.2A: Scour at a bridge pier (HEC-18, 2012)

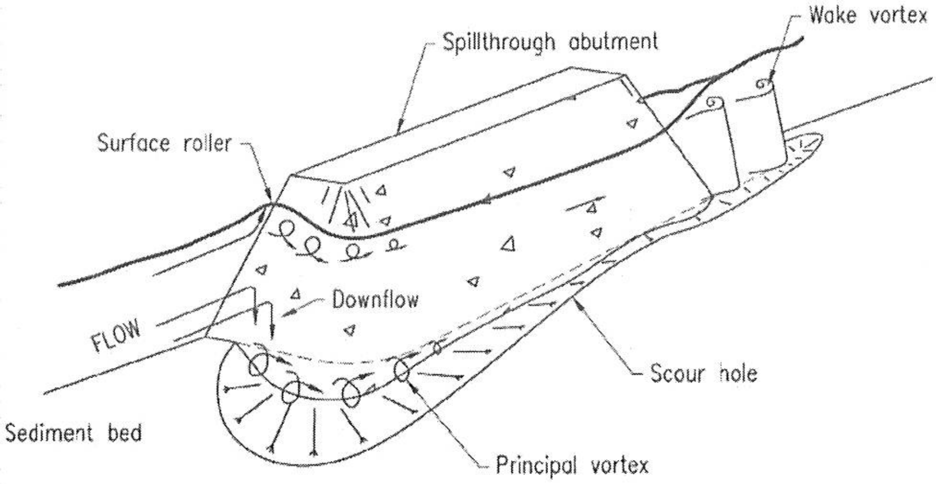


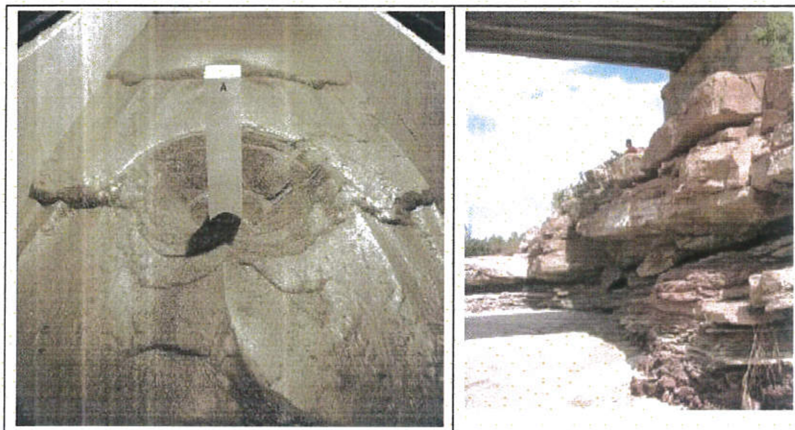
Plate 2.2B: Scour at a bridge abutment (HEC-18, 2012)

2.1.4 Other Types of Scour

Other scour conditions such as flow around a bend where the scour may be concentrated near the outside of the bend, scour resulting from stream planform characteristics, scour at confluences, or a variable downstream control can also influence the total scour in a bridge reach. (Arneson, Zevenbergen, Lagasse, & Clopper, 2012)

2.2 Soils, rock, and geotechnical considerations

According to Arneson elal, one very important point to be considered in evaluating bridge scour is the component involved in the scour process. The components are the earth material (SOILS, ROCK) and the flowing water that acts on the earth material. The hydraulic force of the water can be considered as the load while the geotechnical property of the earth material is considered the resisting force agains the force of the liquid. This fact necessitate enginers involed in bridge design to know the geotechnical property of the earth available insite. (Arneson, Zevenbergen, Lagasse, & Clopper, 2012)



a. Scour in soil (sand) | b. Scour in rock (sandstone)

Plate 2.3. Photographs of scour in soil and rock.

2.2.1 Cohesionless Soils and Cohesive Soils

Cohesive soil can be explained as the soil that is bounded together strongly by high cohesive force, while cohesionless soil are soil that are not bounded together by strong cohesive force. Due to the bounding force of the soil particles, the rate at which different particles are washed away varies from one to the other. Soil particles in cohesionless soil are easily washed away within hours or even days which makes the design consideration in construction of bridge on a cohesionless soil to be a single flood event. But for a cohesive soil, the rate at which the soil particles are washed away is slower. The soil particles in cohesive soil may take days, months, or even years due to the fact that the washing away of the soil particles is done particle by particles or block by block. Cohesive soil is therefor time bound while cohesionless soil is not time bound. (Arneson, Zevenbergen, Lagasse, & Clopper, 2012)

2.2.2 Rock

In determining scour in rocky foundations, there is high consideration given to both the force of the liquids that acts on the rock and the resisting property of the rock that is in consideration. The disintegration of rock by the effect of hydraulic force does not occur in a single way but in the following ways. (National Cooperative Highway Research Program, 2011e):

1. Dissolution of soluble rocks
2. Cavitation
3. Quarrying and plucking of durable, jointed rock
4. Abrasion and grain-scale plucking of degradable rock

2.2.3 Erodibility

Erodibility involves both the hydraulic conditions that create erosive forces, and the properties of the geomaterials to resist erosion when exposed to those conditions. There are concepts and equations used to define and quantify erosive conditions of flow and the erosion resistance of soils and rock, the combination of which results in predictive methods for estimating erodibility under a wide range of flow conditions and geomaterials. (Arneson, Zevenbergen, Lagasse, & Clopper, 2012)

Erodability is explained by what, how and why the erosive force (condition that created the erosion force), and the resisting ability of the soil material. Below are the conditions evaluated before the erodibility of a soil is determined.

2.2.3.1 Velocity

Velocity is dependent on slope and cross-section of the channel, the smoothness of the sides of the channel, the total discharge of the river at any given period of time. It is expressed as;

$$V = \frac{Q}{A} \quad \text{Eq7}$$

Where Q is the total discharge (ft3/s or m3/s) at a given time, and A is the cross-sectional area of flow in ft2 (m2). Note, velocity is not the same though out a river channel, it can be high at upstream and low at the middle and lower at the downstream depending on the gradient of the river.

2.2.3.2 Shear Stress

Shear stress is expressed as follows:

$\tau = K_b \gamma R S_f$...Eq8

Where

T= Design shear stress, lb/ft2 (N/m2)

K_b= Bend coefficient (dimensionless) Unit weight of water, lb/ft3

Y= Unit weight of water, lb/ft3

R= Hydraulic radius (area divided by wetted perimeter), ft (m)

S_f= Slope of the energy grade line, ft/ft (m/m)

2.2.3.3 Devices to Measure Erodibility

Piston-Type Devices: Piston-type devices are laboratory devices that measure the erosion of a sample of soil or rock exposed to flowing water in a relatively small flume under controlled conditions.

Rotating-Type Devices: Rotating-type devices measure the rate at which geomaterials erode as a function of the shear stress applied by the flowing water.

Submerged Jet-Type Devices: An apparatus that can be used in the laboratory or field to evaluate soil erodibility is the submerged jet erosion device.

2.3 Soil properties

Scour and erosion of soils is a soil-water interaction phenomenon. These properties are grain size distribution, plasticity, density, strength, and hydraulic conductivity. (Arneson, Zevenbergen, Lagasse, & Clopper, 2012)

2.4 Stream stability and migration

Scour causes an evolution in the look of a river channel by the effect of the water that acts on the earth material of the river, thereby affecting the size and shape of the river. As water moves through a river channel, if the channel is straight, the water that washes the sand of the river channel will cause the river channel to state widening up, causing a meandering effect on the channel until a relatively stable point is reached. Until a stable point is reached, the shape of the river channel will keep changing. See Plate 2.4A (Department of Transport and Main Roads, 2013)

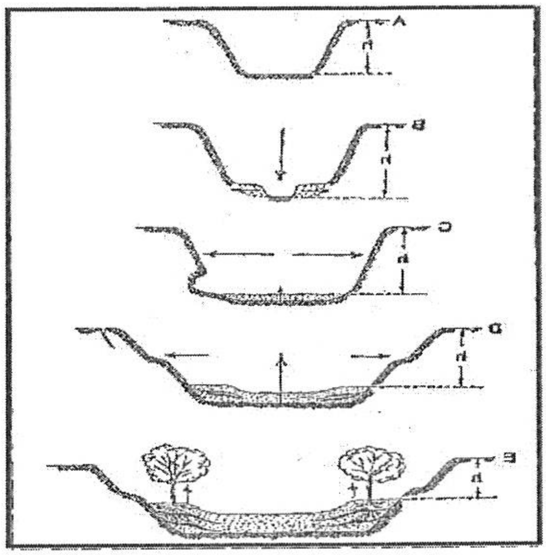


Plate 2.4A: Evolution of incised channel from initial incision (A, B) and widening (C,D) to aggradation (D,E) and eventual relative stability (Schumm, Harvey, & Watson, 1984)

Plate 2.4B below shows the different classification of channel stability which is influenced by the shape, size and load of the river. Stability of a river is a function of the degree to which the configuration (shape) of a river can easily the affected.

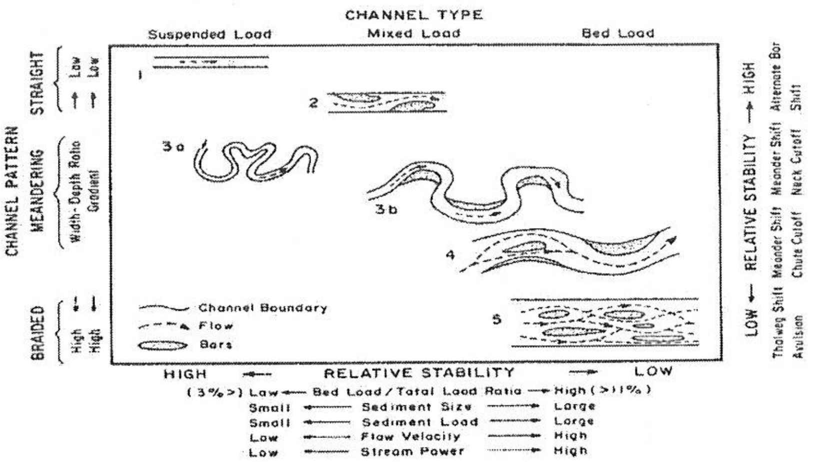


Plate 2.4B: Channel pattern and relative stability (Shen, S.A, & J.D, Methods for Assessment of Stream Related Hazards to Highways and Bridges, 1981)

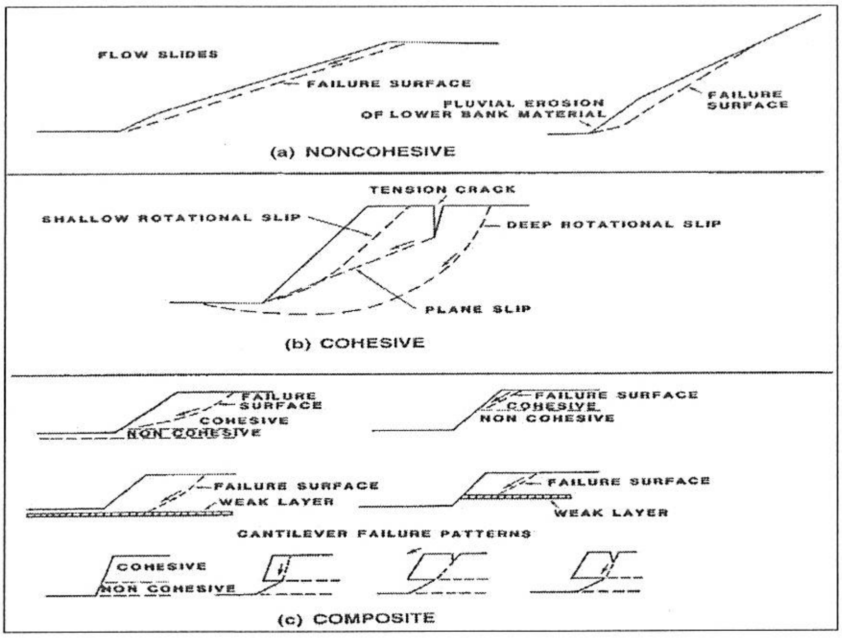


Plate 2.4C: Typical bank failure surfaces: (a) non-cohesive, (b) cohesive, and (c) composite (Brown, 1985)

2.4.1 Bend Scour

(Department of Transport and Main Roads, 2013)Straight channels are highly unstable, so natural streams have bends or meanders. As the flow direction changes at a bend, the force of the water can cause scour. Scouring of the bend causes the channel to move. Migration of meandering channels can be quite significant. The movement of a meander may lead to the failure of nearby infrastructure, such as a bridge.

Plate 2.4D is a plan view of a typical meandering stream and the hydraulic features associated with bends in channels.

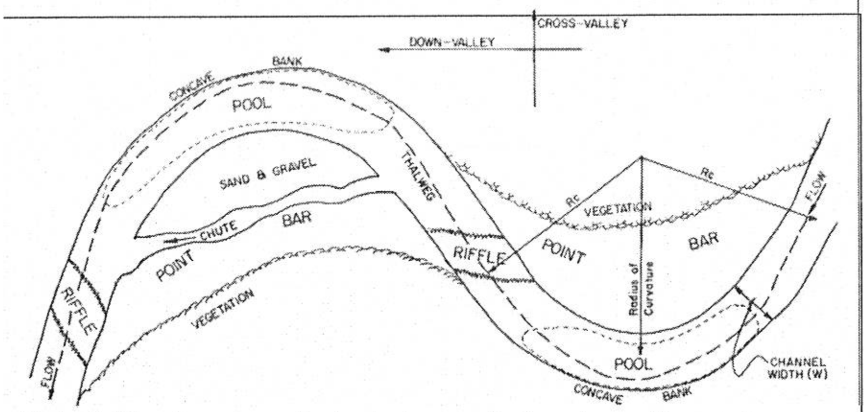


Plate 2.4D: plan view of a typical meandering stream (Lagasse, Zevenbergen, & W.J., 2012)

2.4.2 Cutback Scour

Cut-back scour occurs when the stream bed is lowered at one location by scour or dredging of the bed is carried out. This situation results in a step in the stream bed gradient. To return to a more uniform gradient and energy head the stream will cut back the bed upstream and in so doing will lower the bed level from a maximum at the scour hole or dredging location. If a bridge is located upstream of a scour hole or dredging location there is a risk that the bed levels at the bridge will be lowered. The implications for a bridge will depend on the depth of scour and the foundation levels or the pile embedment length. (Department of Transport and Main Roads, 2013)

2.5 Bridge Pier Flow Field

To understand pier scour, it is necessary to understand the flow field at a pier, and how the flow field varies with pier size and shape, as well as with flow depth and foundation material.

(Arneson, Zevenbergen, Lagasse, & Clopper, 2012) Considering the width, a, and the depth of flow, y, pier can be classified as follows:

1. Narrow piers ($y/a > 1.4$), scour is deepest at the pier face

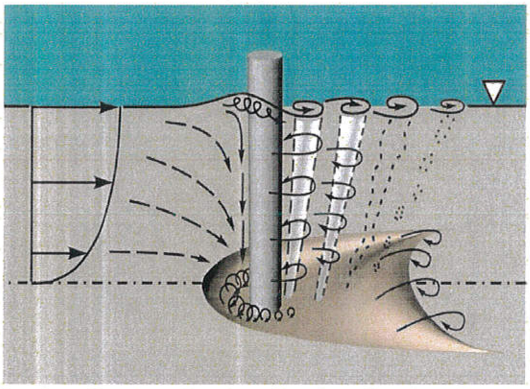


Plate 2.5. The main flow features forming the flow field at a narrow pier of circular cylindrical form (National Cooperative Highway Research Program, 2011e).

2. Transitional piers (0.2 < y/a < 1.4)
3. Wide piers (y/a < 0.2), scour is deepest at the pier flank

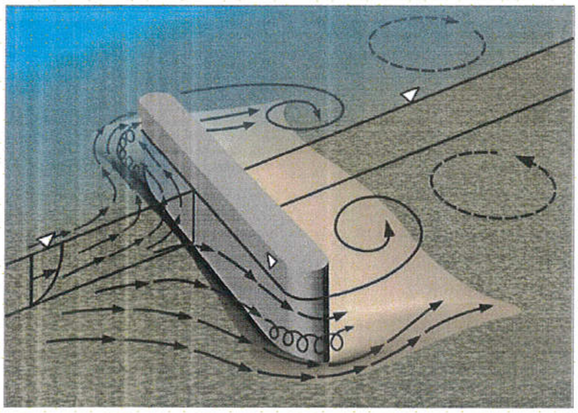


Plate 2.6. Main features of the flow field at a wide pier (y/a < 0.2) (National Cooperative Highway Research Program, 2011a).

The pier flow field may become more complicated if the pier has a complex shape, such as a column supported on a pile cap underpinned by a pile cluster. Additionally, the close proximity of an abutment and/or a channel bank further complicates the flow field.

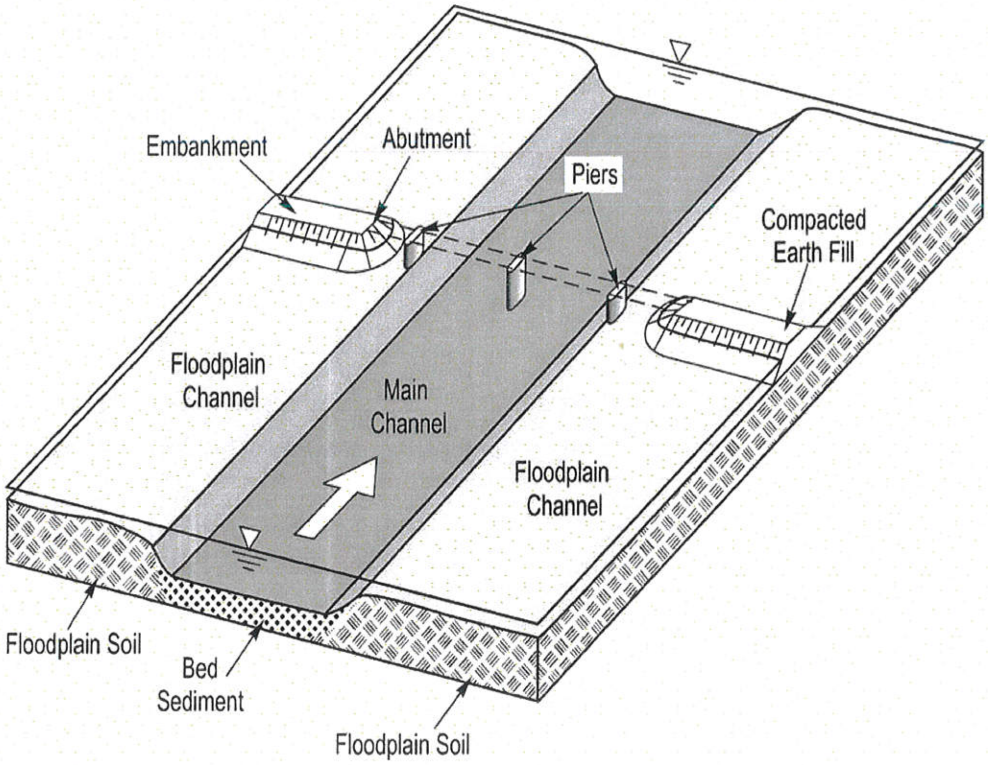


Plate 2.7. Variation of soil and sediment types at a bridge crossing (NCHRP 2011a and b).

2.6 Scour assessment methods:

The two principle manual/standards:

i. BD 97/12 the Assessment Of Scour And Other Hydraulic Actions At Highway Structures And

ii. Hydraulic Engineering Circular No. 18 (HEC-18)-Evaluating Scour at Bridges, (Richardson and Davis, 2001).

2.6.1 Review of bd 97/12 scour assessment (Melville & Coleman, 2000):

Assessment of a structure should be carried out in levels of increasing complexity, with the object of efficiently determining its adequacy. Level 1 Assessment comprises simple methods, including the use of engineering judgment, to identify structures that are not at risk from scour or where the risk is tolerably low. Provided a structure is shown to be adequate at Level 1 then the assessment is complete. Where a Level 1 assessment does not show that a structure is adequate, then the assessment should progress to Level 2.

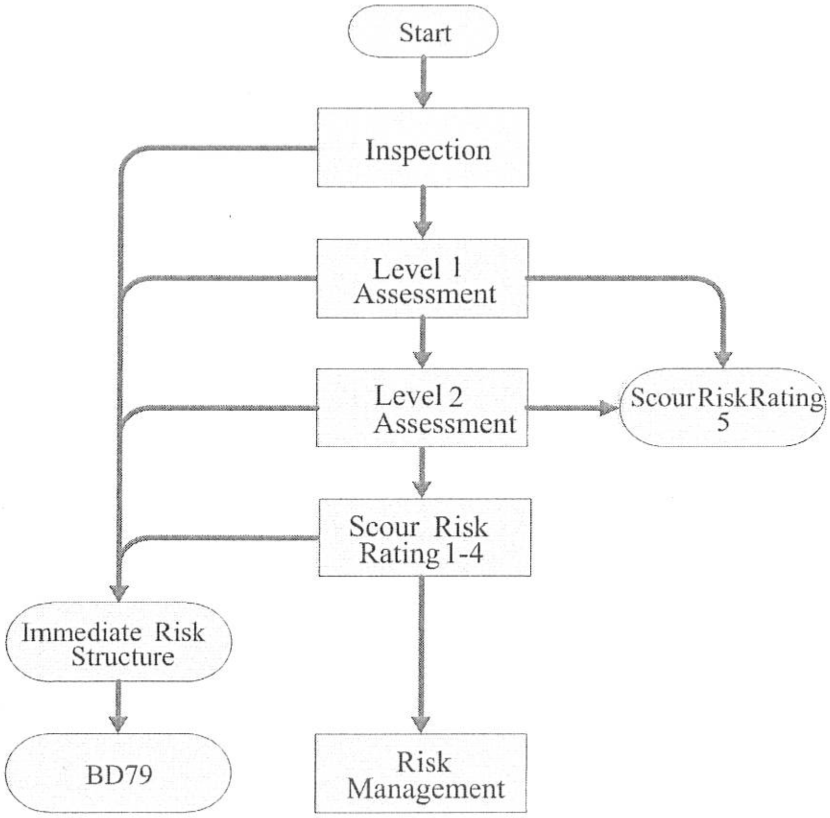


Figure 2.8 – Scour Assessment Process

The purpose of the inspection is to gather information to be used in the scour assessment, including information regarding the structure and its foundations, the waterway and its bed, any protection measures or flood relief measures, and evidence of changes or erosion. Existing records should also be sought and compiled for consideration in the assessment. Note should be made of any changes to the watercourse near the structure location (upstream and downstream). The extents of the distance to be considered should be determined and agreed by the teams carrying out the inspection and the level 1 assessment, and should be no less than 30 times the average width of the channel in each direction.

2.6.1.1 Level 1 Assessment

The Level 1 Assessment considers the risk of scour damage, the stability of the waterway and the robustness of the structure under flood conditions.

Aspects to be considered at Level 1 include the following:

(i) Probability of scour affecting the foundation of the bridge;

(ii) Level of the danger that the channel embankment is facing due to flood;

(iii) Debris possibility;

(iv)Occurred during a flood, the level of is stability

Examples of structures for which a Level 2 assessment will be necessary include the following:

(i) structures currently experiencing scour or those which have a history of scour problems as identified, for example, from inspection and maintenance records, but which do not have adequate scour protection;

(ii) structures that do not have adequate scour protection and which have design features that make them more likely to be vulnerable to scour, such as:

- i piers and abutments founded on shallow spread footings in the river channel;
- ii bridges on unstable river channels;
- iii bridges on fast flowing steep channels;
- iv bridges on or immediately downstream of bends in the river;
- v piers subject to an oblique angle of attack from the flow (note: this can be a particular problem if there is an upstream obstruction as, for example, another bridge with piers aligned at a different angle to the bridge under consideration causing the flow to be directed obliquely towards the bridge being assessed);
- vi abutments that protrude into the river channel;
- vii open spans of such lengths that the abutments or piers cause significant contraction of the river channel;
- viii Relatively small bridge openings or bridges with debris screens or obstructions that could easily be blocked by floating debris.

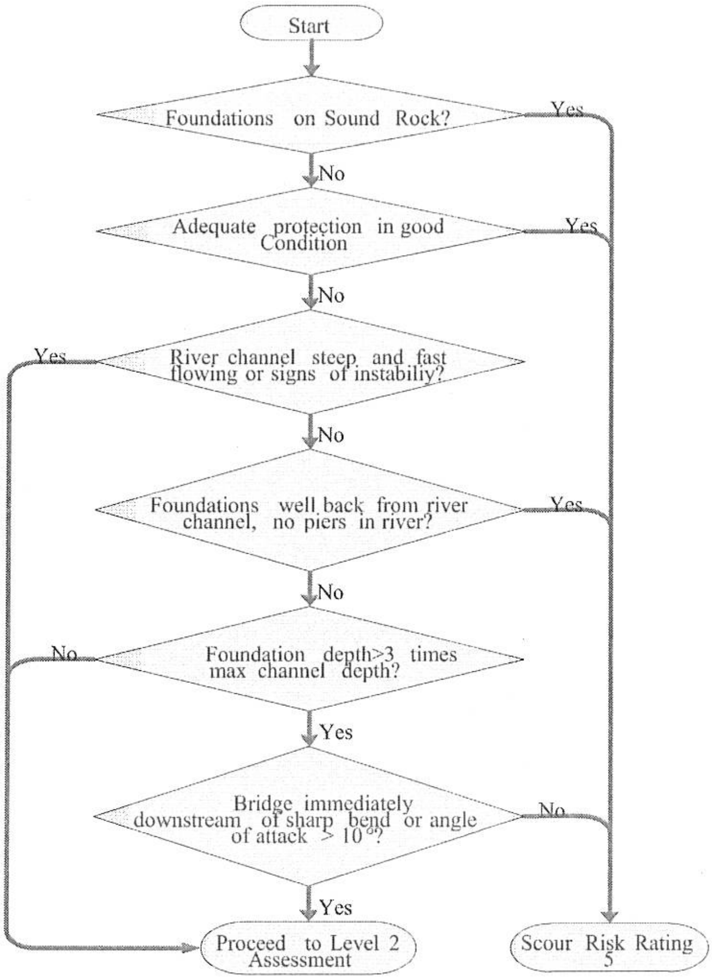


Figure 2.9 – level 1 Assessment decisions

2.6.1.2 Level 2 scour assessment

The primary purpose of the Level 2 Assessment is to calculate the estimated scour depth corresponding to the Assessment Flow, and to compare this with the foundation level. The scour risk rating can then be determined.

2.6.1.2.1 Calculation of depth of local Scour

Based on the geometry of pier, local pier scour estimation should done based on the maximum probability of scour depth. Maximum local scour depth is given as:

$D_{l,pier} = 1.5W_p f_{ps} f_{PA} f_y$ ……………………………………………………………….Eq30

Where :

Wp is the width of the pier,

fPS is a shape factor,

fPA is a factor depending on the angle of attack of the flow,

and

fy a factor depending on the relative depth of the approach flow to the pier width

The shape factor fPS should be taken from Plate 2.17, except where the angle of attack exceeds 10°, when it should be taken as 1.0.

The angle of attack factor, fPA should be calculated as:

$$f_{PA} = \left(\cos\alpha + \frac{L}{W_P}\sin\alpha\right)^{0.65} \quad \text{.......Eq31}$$

Where L is the pier length, Wp is the pier width, and α is the angle between the flow direction and the pier centerline.

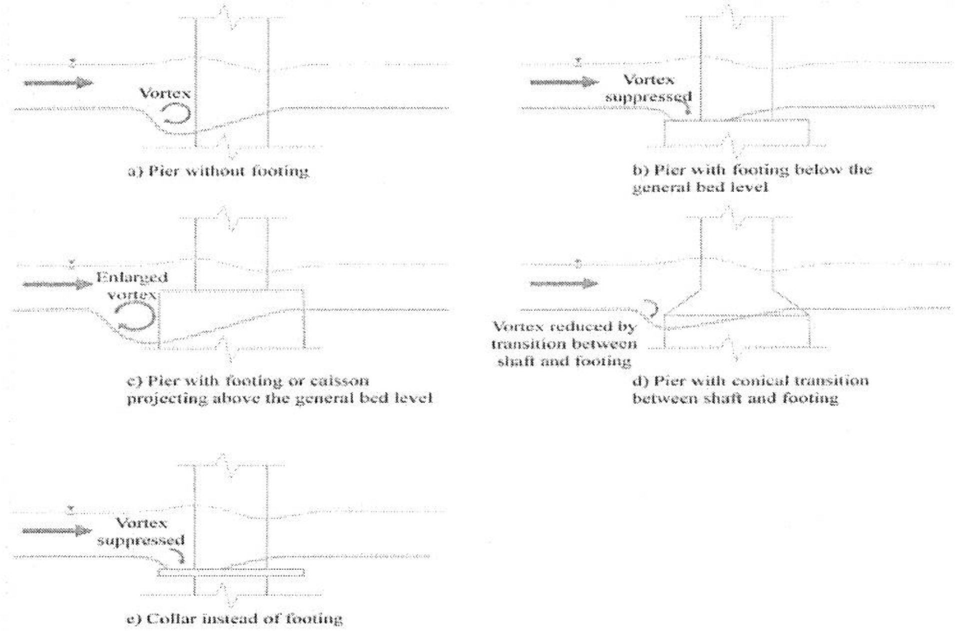


Plate 2.10 – effect of Pier Footings on local Scour (based on figure in 'Guide to bridge Hydraulics', TAC)

The depth of flow factor fy should be taken as:

(i) 1.0 where the depth at the pier including constriction scour y_{sp} exceeds 2.6 times the pier width, where $y_{sp} = y_B + D_c$ Eq32

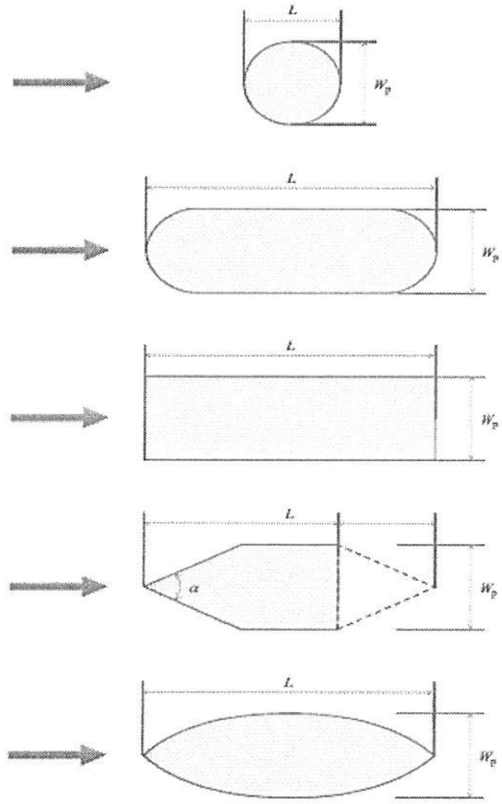
(ii) In other cases, $f_y = 0.78\left(\frac{y_{sp}}{W_P}\right)^{0.255}$ Eq33

For piers comprising a line of columns then the local scour may be calculated based on the following:

(i) If the columns are in line with the flow then the local scour should be based on 1.15 times the depth for a single column

(ii) If the columns are not in line with the flow and the spacing exceeds 5 column diameters then the local scour should be based on 1.2 times the depth for a single column.

(iii) Otherwise the line of columns may be approximated as a solid rectangular pier.



Plan shape of nose	L/W_p	Shape Factor
Circular	1.0	1.0
Rounded	All values	1.0
Rectangular	< 2	1.2
	2 - 6	1.4
	> 6	1.2
Triangular		
$\alpha = 60°$	All values	0.8
$\alpha = 90°$	All values	1.2
Lenticular	2	0.9
	3	0.8
	4	0.7

Plate 2.11 – Pier Shape Factors

2.6.2 Review of pier scour assessment using hec18 (Arneson, Zevenbergen, Lagasse, & Clopper, 2012):

The equation provided in HEC 18 as been proven to be of great advantage in the calculation of local scour at piers for both clear water scour and live bed scour. This equation predicts the maximum pier scour of a bridge pier. It can be used to solve complex scour conditions and for wide piers.

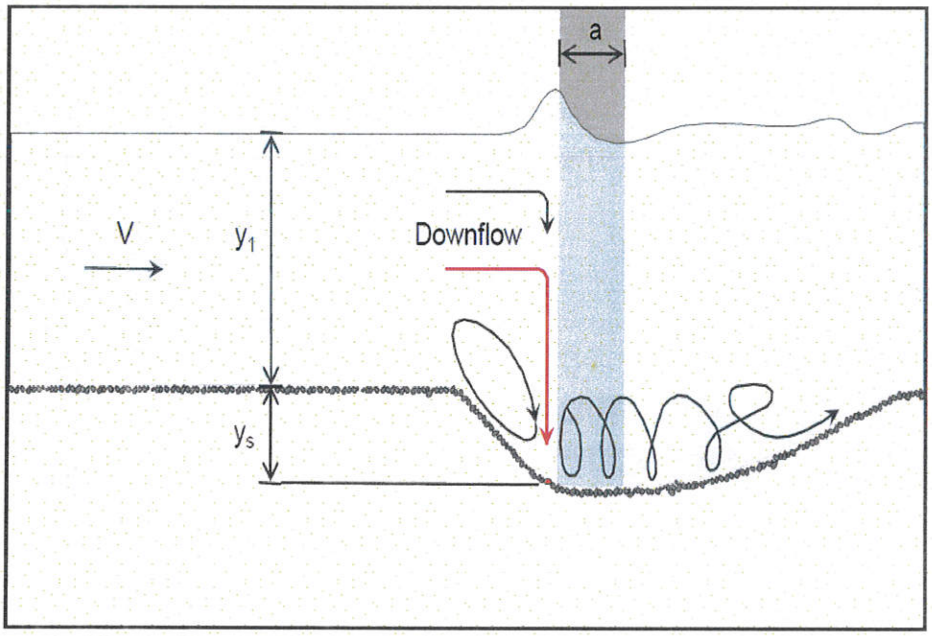


Plate 2.12 Definition sketch for pier scour.

2.6.2.1 The HEC-18 equation is:

$$\frac{y_s}{y_1} = 2.0k_1k_2k_3k_4k_w\left(\frac{a}{y_1}\right)^{0.65} F_r^{\ 0.43} \quad \text{.......Eq34}$$

As a Rule of Thumb, the maximum scour depth for round nose piers aligned with the flow is:

ys $\leq$ 2.4 times the pier width (a) for Fr $\leq$ 0.8 ....Eq35a

ys $\leq$ 3.0 times the pier width (a) for Fr > 0.8..Eq35b

$$\frac{y_s}{a} = 2.0k_1k_2k_3k_4k_w\left(\frac{y_1}{a}\right)^{0.35} F_r^{\ 0.43} \quad \text{.......Eq36}$$

In terms of $\frac{y_s}{a}$, Equation is:

y_s = Scour depth, ft (m)

y_1 = Flow depth directly upstream of the pier, ft (m)

K_1 = Correction factor for pier nose shape from Table 2.6

K_2 = Correction factor for angle of attack of flow from Table 2.7 or Equation 37

K_3 = Correction factor for bed condition from Table 2.8

a = Pier width, ft (m) L = Length of pier, ft (m)

Fr_1 = Froude Number directly upstream of the pier = $V_1/(gy_1)^{1/2}$

V_1 = Mean velocity of flow directly upstream of the pier, ft/s (m/s)

g = Acceleration of gravity (32.2 ft/s^2) (9.81 m/s^2)

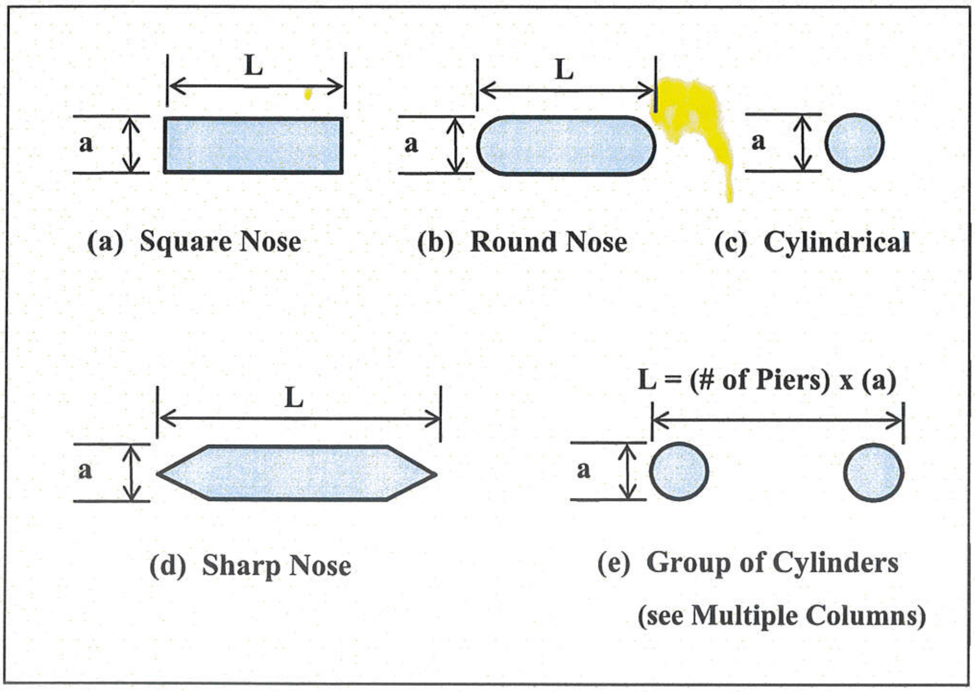


Plate 2.13 Common pier shapes.

The correction factor, K_2, for angle of attack of the flow, 2, is calculated using the following equation:

$$k_2 = \left(\cos\alpha + \frac{L}{a}\sin\alpha\right)^{0.65} \quad \text{.......Eq37}$$

If $\frac{L}{a}$ is larger than 12, use $\frac{L}{a} = 12$ as a maximum in Equation 37 and Table 2.7. Table 2.7 illustrates the magnitude of the effect of the angle of attack on local pier scour.

Table2.1Correction Factor, K1, for Pier Nose Shape.

Shape of Pier Nose	K_1
(a) Square nose	1.1
(b) Round nose	1.0
(c)Circular cylinder	1.0
(d)Group of cylinders	1.0
(e) Sharp nose	0.9

Table 2.2 Correction Factor, K_2, for Angle of Attack, 2, of the Flow.

Angle	L/a=4	L/a=8	L/a=12
0	1.0	1.0	1.0
15	1.5	2.0	2.5
30	2.0	2.75	3.5
45	2.3	3.3	4.3
90	2.5	3.9	5.0

Table 2.3 increase in equilibrium pier scour depths, k_3, for bed condition.

Bed Condition	Dune Height ft	K_3
Clear-Water Scour	N/A	1.1
Plane bed and Antidune flow	N/A	1.1
Small Dunes	$10 > H \geq 2$	1.1
Medium Dunes	$30 > H \geq 10$	1.2 to 1.1
Large Dunes	$H \geq 30$	1.3

1. If the angle at which the water force hit the bridge is less than or equal to 5 degree, **K1** should be taken from table 1 above. But if the angle of attack id greater than 5 degree, **K2** will be given preferences than K1 and K1=1. If L/a is larger than 12, use the values for L/a = 12 as a maximum in Table 2.7 and Equation 37.
2. For the following conditions, K2 should not be used: (1) the abutment is blocking the flow of the water from directly affecting the bridge pier; or (2) if the direction of water is been redirected by an abutment or by another peir. The table above gives the limit to K2 that is max of 5.0

3. K3 is used to cater for the limitation of the equation 34. The equation 34 can give value that is less than the maximum pier.
4. Piers set close to abutments (for example at the toe of a spill through abutment) must be carefully evaluated for the angle of attack and velocity of the flow coming around the abutment.

2.6.2.2 Scour for complex pier

To calculate scour of complex pier, the explained procedure below should be used, (Jones & Sheppard, 2000). But, for accurate judgment, the density of traffic, traffic type, the value of the high way, cost of failure (potential loss of life and dollars), and the increase in cost that would occur if the most conservative scour depth is used, should be considered by the engineer in charge of the estimation.

2.6.2.2.1 Superposition of Scour Components Method of Analysis

The flow of moving water around bridges can be obstructed by the components of the bridge which are referred to as scour producing component. This components includes, the pier, the pile cap, and the pile group. (Salim & Jones, Effects of Exposed Pile Foundations on Local Pier Scour, 1995) (Salim & Jones, Scour Around Exposed Pile Foundations , 1999) (Salim & Jones, Scour Around Exposed Pile Foundations, 1996), said most research have focus on solid pier without putting into consideration the scour producing component.

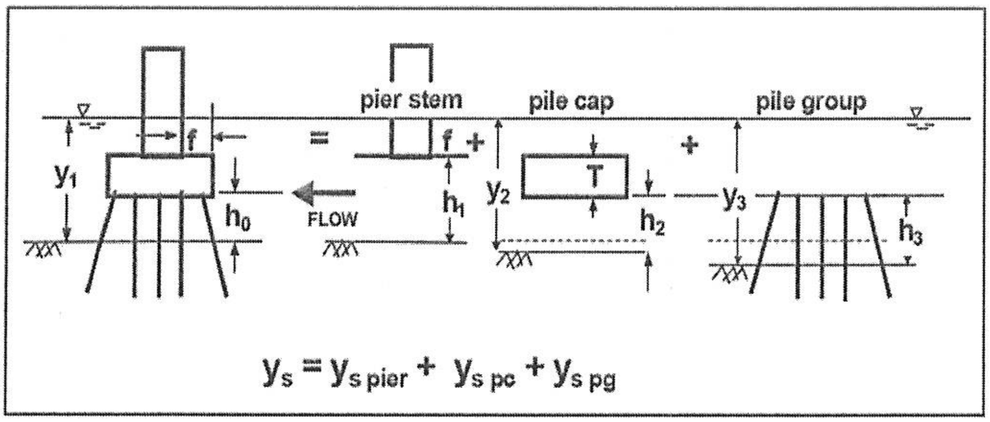


Plate 2.14. Definition sketch for scour components for a complex pier (Jones & Sheppard, 2000)

The variables illustrated in Plate 2.14 and others used in computations are as follows:

f = Distance between front edge of pile cap or footing and pier, ft (m) h_o = Height of the pile cap above bed at beginning of computation, ft (m) $h_1 = h_o + T$ = height of the pier stem above the bed before scour, ft (m) $h_2 = h_o + y_{s\,pier}/2$ = height of pile cap after pier stem scour component has been computed, ft (m)

$h_3 = h_o + y_{s\,pier}/2 + y_{s\,pc}/2$ = height of pile group after the pier stem and pile cap scour components have been computed, ft (m)

S = Spacing between columns of piles, pile center to pile center, ft (m)

T = Thickness of pile cap or footing, ft (m)

y_1 = Approach flow depth at the beginning of computations, ft (m)

$y_2 = y_1 + y_{s\,pier}/2$ = adjusted flow depth for pile cap computations ft (m)

$y_3 = y_1 + y_{s\,pier}/2 + y_{s\,pc}/2$ = adjusted flow depth for pile group computations, ft (m)

V_1 = Approach velocity used at the beginning of computations, ft/sec (m/sec)

$V_2 = V_1(y_1/y_2)$ = adjusted velocity for pile cap computations, ft/sec (m/sec)

$V_3 = V_1(y_1/y_3)$ = adjusted velocity for pile group computations, ft/sec (m/sec)

Total scour from superposition of components is given by:

$y_s = y_{s\,pier} + y_{s\,pc} + y_{s\,pg}$ Eq55

where:

y_s = Total scour depth, ft (m)

$y_{s\,pier}$ = Scour component for the pier stem in the flow, ft (m)

$y_{s\,pc}$ = Scour component for the pier cap or footing in the flow, ft (m)

$y_{s\,pg}$ = Scour component for the piles exposed to the flow, ft (m)

2.6.2.2.1.1 Determination of the Pier Stem Scour Depth Component

Computing the pier scour component is necessary if the pile cap, and the pier stem are in the flow:

$$\frac{y_{spier}}{y} = 2.0k_1k_2k_3k_{hpier}\left(\frac{a_{pier}}{y_1}\right)^{0.65} F_{1r}{}^{0.43} \quad \text{...Eq56}$$

Where:

k_{hpier}

$= coefficient\ to\ account\ for\ height\ of\ pier\ stem\ above\ bed\ and\ shielding\ effect\ by\ pile\ ca$

$$k_{hpier}\ a\ function\ of\ {}^{h_1}/_{a_{pier}}\ and\ {}^{f}/_{a_{pier}}$$

Overhang distance "f" in front of pier stem

2.6.2.2.1.2 Determination of the Pile Cap (Footing) Scour Depth Component

It is required to calculate the pile cap scour if the pile cap is in the flow or as a result of scour cause the bridge pier component. In determine the pile cap scour, there are two different cases that can be experienced:

Case 1: The bottom of the pile cap is above the bed and in the flow either by design or after the bed has been lowered by scour caused by the pier stem component. The strategy is to reduce the pile cap width, a_{pc}, to an equivalent full depth solid pier width, a^*_{pc}, using Plate 2.22. The equivalent pier width, an adjusted flow depth, y_2, and an adjusted flow velocity, V_2, are then used in Equation 1 to estimate the scour component.

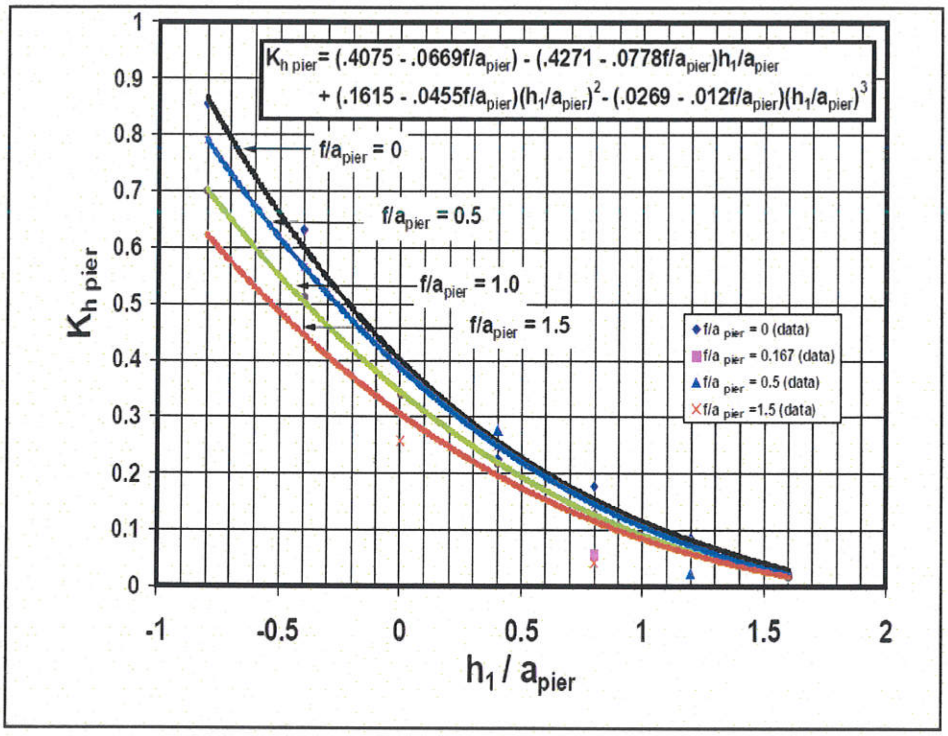


Figure 2.15 Suspended pier scour ratio (Jones & Sheppard, 2000).

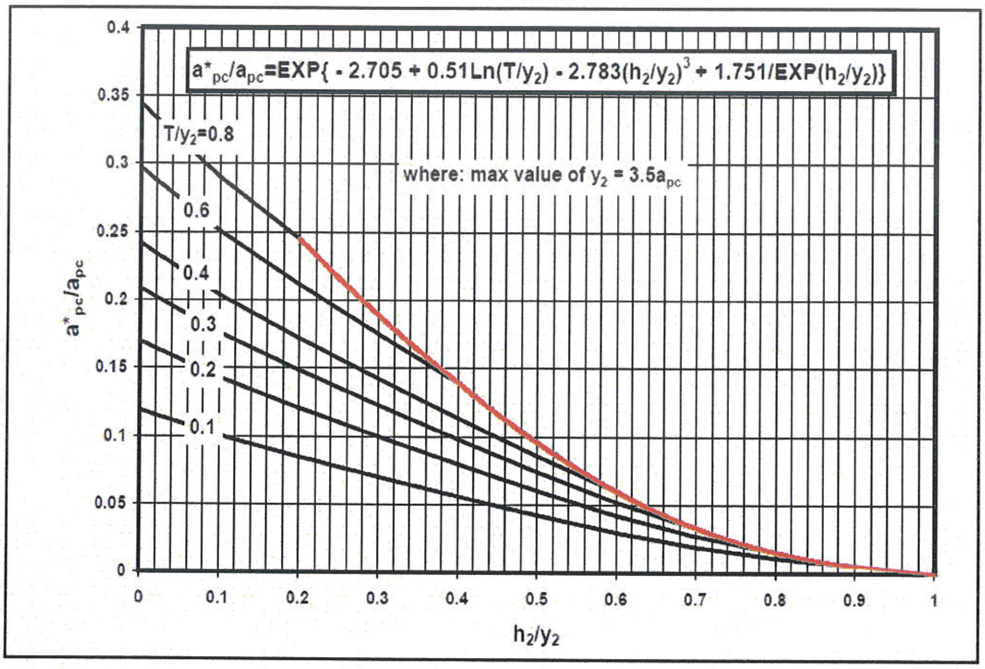


Figure 2.16 Pile cap (footing) equivalent width (Jones & Sheppard, 2000).

Case 2: The bottom of the pile cap or footing is on or below the bed. The strategy is to treat the pile cap or exposed footing like a short pier in a shallow stream of depth equal to the height to the top of the footing above bed. The portion of the flow that goes over the top of the pile cap or footing is ignored. Then, the full pile cap width, a_{pc}, is used in the computations, but the exposed footing height, y_f, (in lieu of the flow depth), and the average velocity, V_f, in the portion of the profile approaching the footing are used in Equation 1 to estimate the scour component.

An inherent assumption in this second case is that the footing is deeper than the expected scour depth so it is <u>not necessary</u> to add the pile group scour as a third component in this case. If the bottom of the pile cap happens to be right on the bed, either the Case 1 or Case 2 method could be applied, but they won't necessarily give the same answers. If both methods are tried, then engineering judgment should dictate which one to accept.

Details for determining the pile cap or footing scour component for these two cases are described in the following paragraphs.

Case 1. Bottom of the Pile Cap (Footing) in the Flow above the Bed

T = Thickness of the pile cap exposed to the flow, ft (m)

$h_2 = h_o + y_{s\ pier}/2$, ft (m)

$y_2 = y_1 + y_{s\ pier}/2$, = adjusted flow depth, ft (m)

$V_2 = V_1(y_1/y_2)$ = adjusted flow velocity, ft/s (m/s)

where:

h_o = Original height of the pile cap above the bed, ft (m)

y_1 = Original flow depth at the beginning of the computations before scour, ft (m)

$y_{s\ pier}$ = Pier stem scour depth component, ft (m)

V_1 = Original approach velocity at the beginning of the computations, ft/s (m/s)

Determine a^*_{pc}/a_{pc} from Figure 2.16 as a function of h_2/y_2 and T/y_2 (note that the maximum value of $y_2 = 3.5\ a_{pc}$).

Compute $a^*_{pc} = (a^*_{pc}/a_{pc})\ a_{pc}$; where a^*_{pc} is the width of the equivalent pier to be used in Equation 1 and a_{pc} is the width of the original pile cap. Compute the pile cap scour component, $y_{s\ pc}$ from Equation 1 using a^*_{pc}, y_2, and V_2 as the pier width, flow depth, and velocity parameters, respectively. The rationale for using the adjusted velocity for this computation is that the near bottom velocities are the primary currents that produce scour and they tend to be reduced in the local scour hole from the overlying component. **For skewed flow use the L/a for the original pile cap as the L/a for the equivalent pier to determine K_2.** Apply the wide pier correction factor, K_w, if (1) the total depth, $y_2 < 0.8\ a^*_{pc}$, (2) the Froude Number $V_2/(g\ y_2)^{1/2} < 1$, and (3) $a^*_{pc} > 50\ D_{50}$.

The scour component equation for the Case 1 pile cap can then be written:

$$\frac{y_{spc}}{y_2} = 2.0K_1K_2K_3K_w\left(\frac{a^*{pc}}{y_2}\right)^{0.65}\left(\frac{V_2}{\sqrt{gy_2}}\right)^{0.43} \qquad \text{Eq57}$$

Next, the pile group scour component should be computed.

Case 2. Bottom of the Pile Cap (Footing) Located On or Below the Bed.

One limitation of the procedure described above is that the design chart in Figure 2.22 has not been developed for the case of the bottom of the pile cap or footing being below the bed (i.e., negative values of h_2). In this case, use a modification of the exposed footing procedure that has been described in previous editions of HEC-18. The previous procedure was developed from experiments in which the footing was never undermined by scour and tended to be an over predictor if the footing is undermined.

As for Case 1:

Y_2 = $y_2 + y_{s\ pier}/2$, ft (m)

$V_2 \quad = \quad V_2(y_2/y_2)$, ft/s (m/s)

The average velocity of flow at the exposed footing (V_f) is determined using the following equation:

$$\frac{V_f}{V_2} = \frac{\ln\left(10.93\frac{y_f}{K_s}+1\right)}{\ln\left(10.93\frac{y_2}{K_s}+1\right)} \quad \text{.........Eq58}$$

Where:

Vf = Average velocity in the flow zone below the top of the footing, ft/s (m/s)

V2 = Average adjusted velocity in vertical of flow approaching the pier, ft/s (m/s)

In = Natural log to the base e

Y_f = $h_l + y_{s\ pier}/2$ = distance from the bed (after degradation, contraction scour, and pier stem scour) to the top of the footing, ft (m)

ks = Grain roughness of the bed (normally taken as the D_{84} for sand size bed material and 3.5 D_{84} for gravel and coarser bed material), ft (m)

Y_2 = Adjusted depth of flow upstream of the pier, including degradation, contraction scour and half the pier stem scour, ft (m)

See Figure 2.23 for an illustration of variables.

Compute the pile cap scour depth component, $y_{s\ pc}$ from Equation 1 using the full pile cap width, a_{pc}, y_f, V_f as the width, flow depth, and velocity parameters, respectively. The wide pier factor K_w should be used in this computation if (1) the total depth $y_2 < 0.8\ a_{pc}$, (2) the Froude Number $V_2/(gy_2)^{1/2} < 1$, and (3) $a_{pc} > 50\ D_{50}$. Use y_2/a_{pc} to compute the K_w factor if it is applicable. The scour component equation for the case 2 pile cap or footing can then be written:

$$\frac{y_{spc}}{y_f} = 2.0K_1K_2K_3K_w\left(\frac{a_{pc}}{y_2}\right)^{0.65}\left(\frac{V_f}{\sqrt{gy_f}}\right)^{0.43} \quad \text{.........Eq59}$$

In this case assume the pile cap scour component includes the pile group scour and compute the total scour depth as:

of pile rows and a height factor to account for the pile length exposed to the flow. Guidelines are given for analyzing the following typical cases:

1. Special case of piles aligned with each other and with the flow. No angle of attack.
2. General case of the pile group skewed to the flow, with an angle of attack, or pile groups with staggered rows of piles.

The strategy for estimating the pile group scour component is the same for both cases, but the technique for determining the projected width of piles is simpler for the special case of aligned piles. The strategy is as follows:

1. Project the width of the piles onto a plane normal to the flow.
2. Determine the effective width of an equivalent pier that would produce the same scour if the pile group penetrated the water surface.
3. Adjust the flow depth, velocity and exposed height of the pile group to account for the pier stem and pile cap scour components previously calculated.
4. Determine pile group height factor based on exposed height of pile group above the bed.
5. Compute the pile group scour component using a modified version of Equation 34.

Projected width of piles

For the special case of aligned piles, the projected width, a_{proj}, onto a plane normal to the flow is simply the width of the collapsed pile group as illustrated in Figure 2.24.

Smith attempted to derive weighting factors to adjust the impact of piles according to their distance from the projection plane, but concluded that there was not enough data and the procedure would become very cumbersome with weighting factors. A reasonable alternative to using weighting factors is to exclude piles other than the two rows and one column closest to the plane of projection.

Effective width of an equivalent full depth pier

The effective width of an equivalent full depth pier is the product of the projected width of piles multiplied by a spacing factor and a number of aligned rows factor (used for the special case of aligned piles only).

$a^*_{pg} = a_{proj} K_{sp} K_m$ Eq61

Where:

aproj = Sum of non-overlapping projected widths of piles

Ksp = Coefficient for pile spacing

Km = Coefficient for number of aligned rows, m, (note that K_m is constant for all S/a values when there are more than 6 rows of piles)

Km = 1.0 for skewed or staggered pile groups

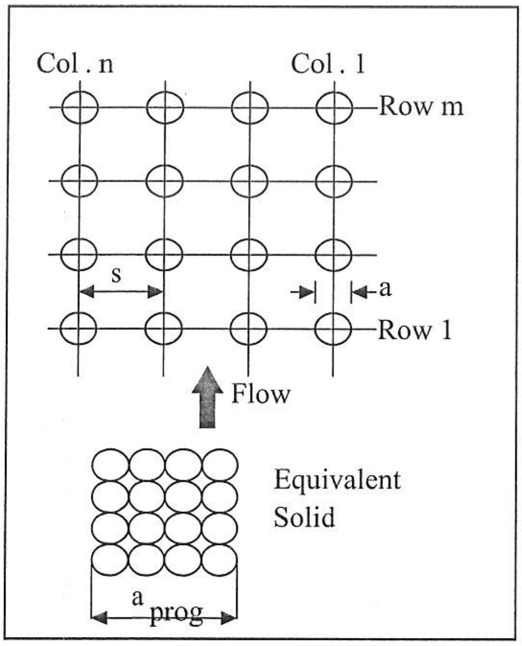


Plate 2.18 Projected width of piles for the special case of aligned flow.

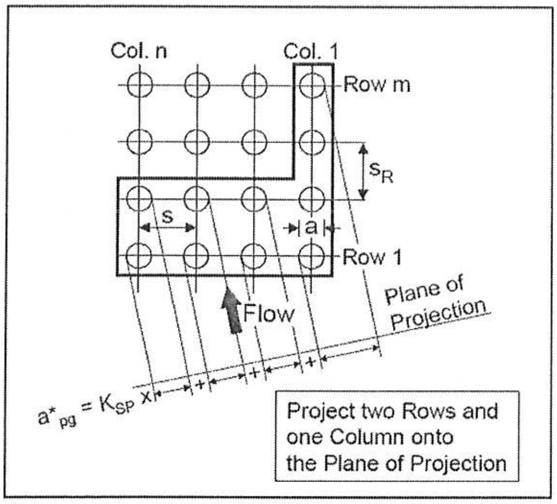


Plate 2.19 Projected width of piles for the general case of skewed flow.

The number of rows factor, K_m, is 1.0 for the general case of skewed or staggered rows of piles because the projection technique for skewed flow accounts for the number of rows and is already conservative for staggered rows.

<u>Adjusted flow depth and velocity</u>

The adjusted flow depth and velocity to be used in the pier scour equation are as follows:

$y_3 = y_1 + y_{s\ pier}/2 + y_{s\ pc}/2$, ft (m) Eq62

$V_3 = V_1(y_1/y_3)$, ft/s (m/s) Eq63

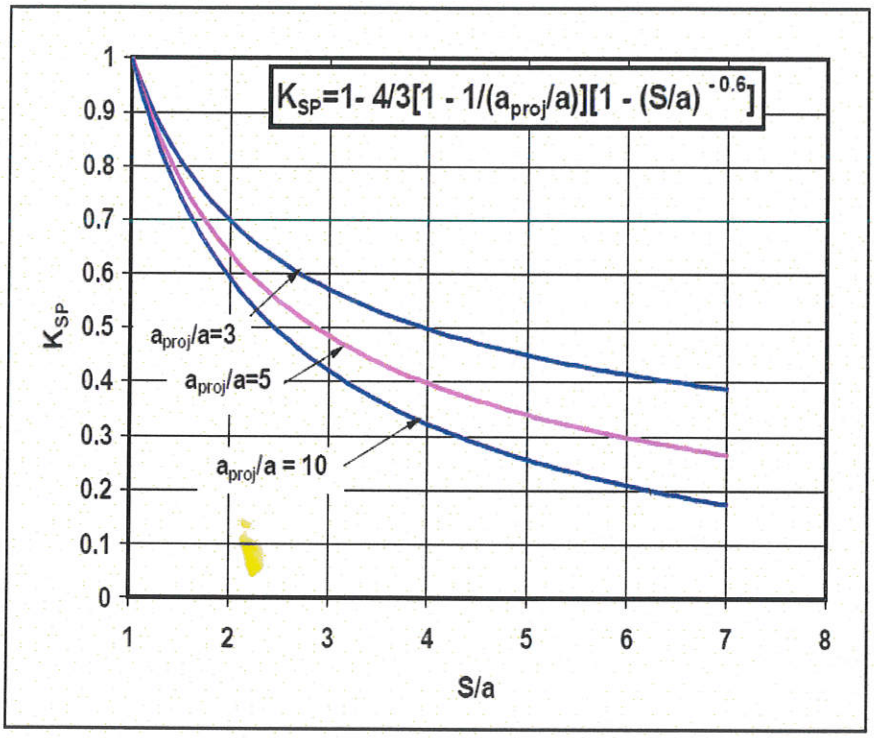


Figure 2.20 Pile spacing factor (Sheppard, 2001).

The scour equation for a pile group can then be written as follows:

$$\frac{y_{spc}}{y_3} = 2.0K_1K_3K_{hpg}\left(\frac{a^*{}_{pg}}{y_3}\right)^{0.65}\left(\frac{V_2}{\sqrt{gy_3}}\right)^{0.43} \quad \text{..Eq64}$$

where:

K_{hpg}= Pile group height factor given as a function of h_3/y_3 (note that the maximum value of $y_3 = 3.5\ a^*_{pg}$)

h3 = $h_0 + y_{s\ pier}/2 + y_{s\ pc}/2$ = height of pile group above the lowered stream bed after pier and pile cap scour components have been computed, ft (m)

K_2 from Equation 1 has been omitted because pile widths are projected onto a plane that is normal to the flow. The quantity in the square brackets is the scour ratio for a solid pier of width, a^*_{pg}, if it extended to the water surface. This is the scour ratio for a full depth pile group.

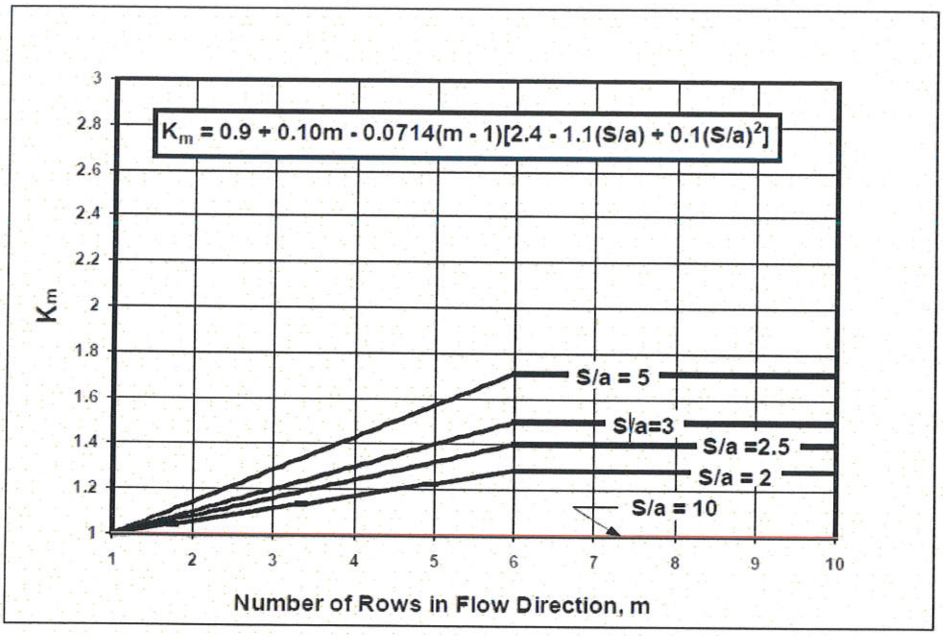


Figure 2.21 Adjustment factor for number of aligned rows of piles (refer to Sheppard 2001).

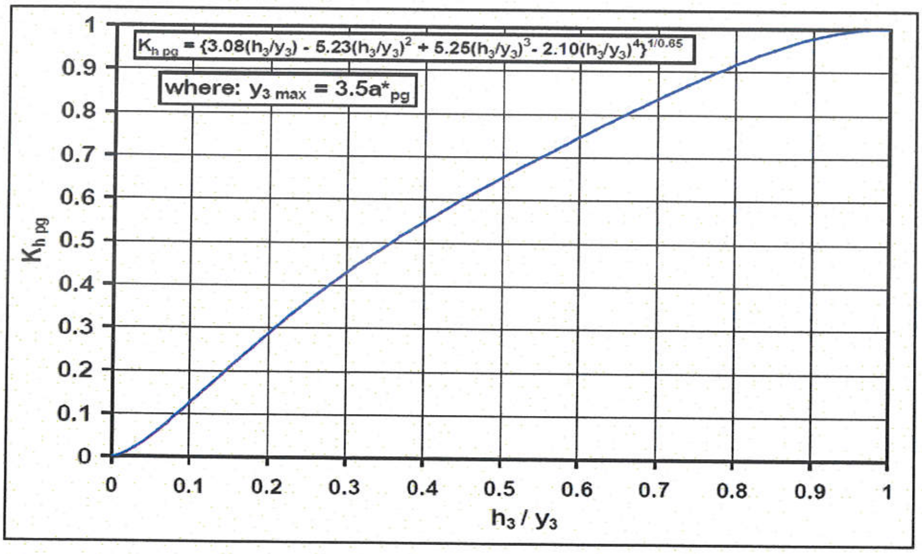


Figure 2.22 Pile group height adjustment factor (refer to Sheppard 2001).

2.6.2.2.1.4 Determination of Total Scour Depth for the Complex Pier

The total scour for the complex pier from Equation (55) is:

$$y_s = y_{spier} + y_{spc} + y_{spg}$$

2.6.2.3 SCOUR FROM DEBRIS ON PIERS

Debris can be define as the ruins of plant or structure. The accumulation of this ruins on a bridge substructure causes the effective width of the bridge substructure to the be wider than its normal size.

Plate 2.23 Woody debris at a bridge pier. Note how debris can be much wider than the pier itself (also note debris on lower chord of bridge deck). Source: NCHRP Web-Only Document 48 (see NCHRP 2010a).

2.6.2.3 Debris Size and Shape

NCHRP Report 653, "Effects of Debris on Pier Scour," (NCHRP 2010a) provides extensive insight into scour processes at piers when debris loading is present. The primary variables involve the shape of the debris blockage, and the dimensions of the debris mass compared to the pier width.

The shape of debris accumulations can be generally idealized as either rectangular or triangular. Rectangular shapes represent a more extreme blockage of flow, and therefore they create more scour. Triangular debris shapes are somewhat streamlined, and create a flow pattern that is not as severe at the base of the pier. However, both shapes result in more blockage compared to a pier without debris, and therefore both result in additional scour. Figures 7.16 and 7.17 illustrate the idealized dimensions as described in NCHRP Report 653.

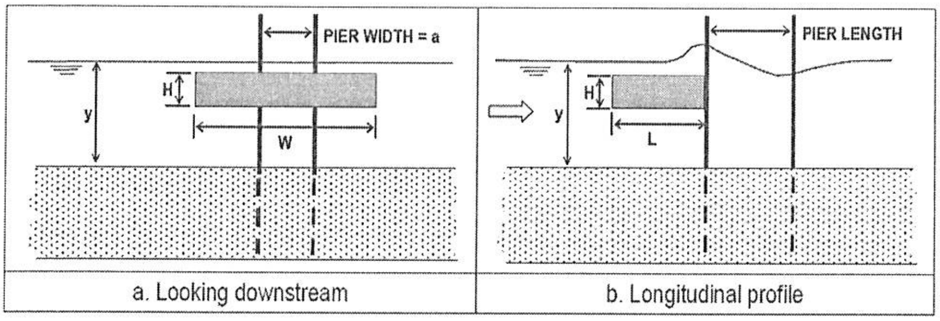


Figure 2.24 Idealized dimensions of rectangular debris accumulations (modified from NCHRP Report 653).

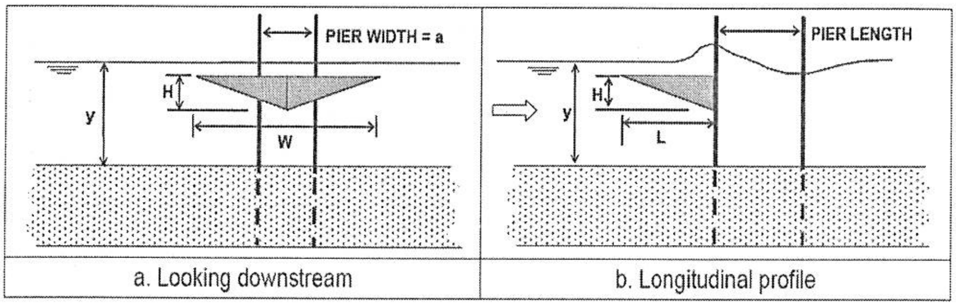


Plate 2.25. Idealized dimensions of triangular debris accumulations (modified from NCHRP Report 653).

Perhaps the most important result from the NCHRP research is the fact that the greatest amount of debris-induced scour at the pier occurs when the length of the debris in the upstream direction (dimension "L" in the above figures) is equal to the approach flow depth. When the debris accumulation has grown to this dimension, the plunging flow created by the debris is focused at the base of the pier, reinforcing the horseshoe vortex.

During the NCHRP study, it was also found that when debris floats at the water surface during a flood event, all of the approach flow is forced to plunge beneath the debris, with no flow going over the top. Therefore, the guidance developed for estimating pier scour with debris assumes that the debris is floating at the surface during a flood, which is a very likely condition during the peak of a flood event.

Effective Pier Width with Debris

$$a^*_d = \frac{K_1(HW)+(y-K_1H)a}{y} \quad \text{.......Eq65}$$

where:

a^*_d = Effective width of pier when debris is present,ft(m)

a = Width of pier perpendicular to flow, ft (m)

K_1 = 0.79 for rectangular debris, 0.21 for triangular debris

H = Height (thickness) of the debris, ft (m)

W = Width of debris perpendicular to the flow direction, ft (m)

Y = Depth of approach flow, ft (m)

2.7 RELATED WORKS

2.7.1 Bridge Scour and its Monitoring Using GSM Enabled Sensors – a Laboratory Study

The study presents an in-situ lab scour monitoring mechanism by using the Global System for Mobile (GSM) under clear water condition on cohesionless bed material. Circular pier with collar and another round nosed pier model at 5 different angles are considered for these experiments with GSM enabled sensors monitoring the scour. Monitoring devices connected to GSM enabled sensors are installed near the bridge pier. Using the scour data provided by GSM unit, an alert is sounded for the local administration regarding the real time safety condition of the bridge. The purpose of this project is to measure the scour depth using ultrasonic sensor and IR sensor. As an addition facility temperature and humidity sensors are also connected. This scour depth is processed by microcontroller and sent to the user over GSM mobile. For none of the test, time to equilibrium condition was defined and hence all tests were stopped after 24 hours. Flowchart showing flow of data is shown using Figure 5.the result of his experiment was that In 24 hrs period, the scour rate dropped from 171 mm/hr to 0.27 mm/hr. In this case, 60% of scour was observed in 16% of the time and 80% of scour in about 50% of the time. The maximum scour was exactly on the pier front nose in case of plain pier and that on the downstream side away from pier collar. This is the major advantage of collar. The GSM enabled sensors which continuously monitored the real time scour have clearly demonstrated that the river flow simulated for 24 hrs duration, is insufficient to develop maximum scour threating the bridge safety if 3D collar is fitted to the pier.

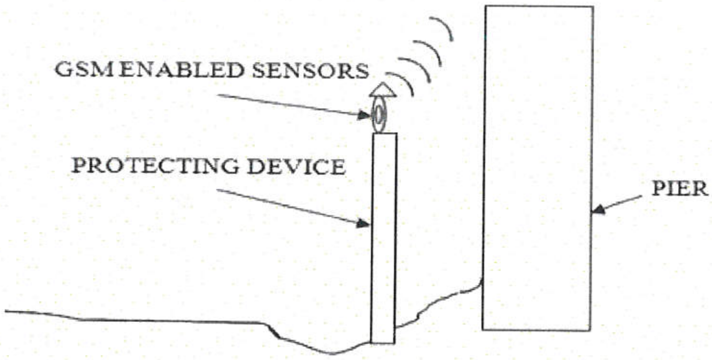


Plate 2.26 Schematic diagram of the setup with sliding pole / protective device

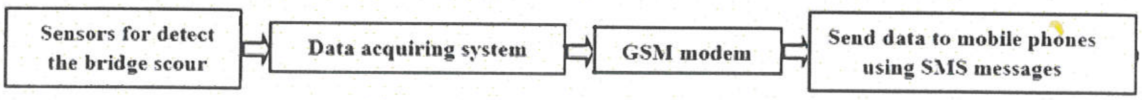


Plate 2.27 Flow of data

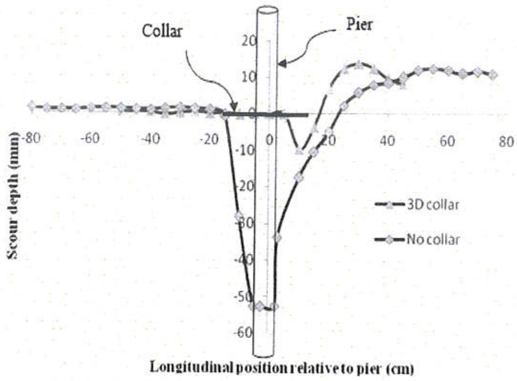


Plate 2.28a Longitudinal profile of scour hole its area for a case of plain pier

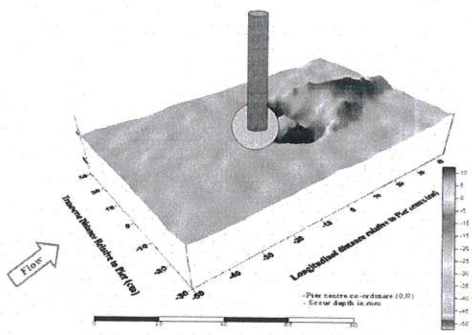
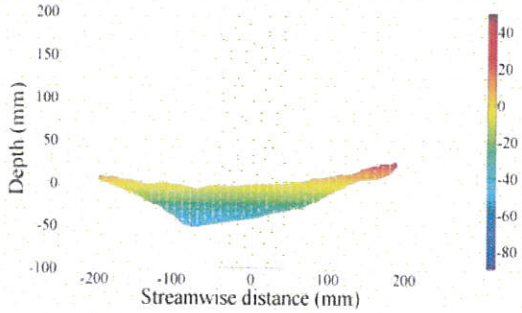


Plate 2.28b 3D view of scour and surrounding

He concluded by say; The GSM enabled sensors allow for continuous monitoring of stream bed elevations and scour conditions. The GSM monitoring unit were placed at critical point where maximum scour is likely to occur. After comparing the result using GSM Scour monitoring unit with standard point gauge the maximum variation of scour was found to be around 8 %. The GSM based monitoring sensors can be quickly designed and installed and it is cost-effective system. (Umesh & Shetty, 2014)

2.7.2 Laboratory modeling of bridge scour Comparison of three techniques for scour depth measurement: photogrammetry, echosounder profiling and a calibrated pile

The report considered three method of scour depth estimation, photogrammetry, Echosounder profiling, and a Calibrated pile. In the result, it was stated that photogrammetry provides the best method for the estimation except for it refraction deficiency.



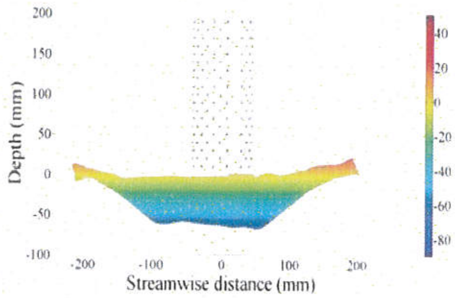


Figure 2.29a Side elevation of 3D echosounder profile **Figure 2.29b Side elevation of 3D photogrammetry profile**

A novel underwater camera measurement system was presented. The main conclusions of the paper are:

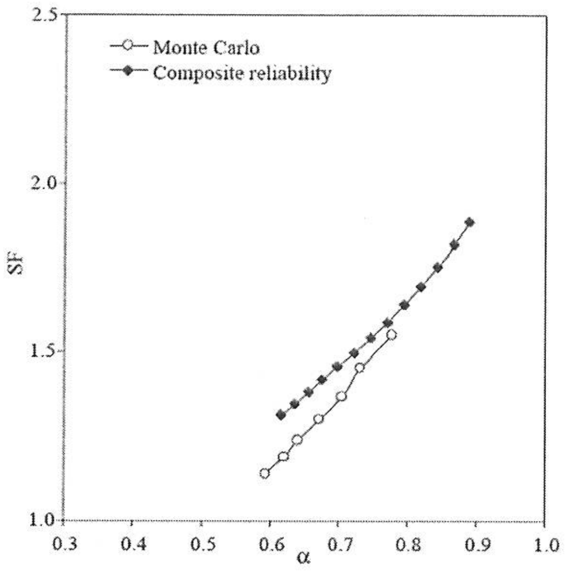
1. Result gotten from photogrammetry is in conformity with the standard techniques
2. It was observed that the result of echosounder device reduced for a sloppy section
3. Echosounder measurements of scour holes in the laboratory should be treated with caution especially where an echosounder with similar or lower specifications has been applied at a comparable scale to this study.
4. Photogrammetry gave precise 3d scour hole profiles. For this reason, scour is better understood using photogrammetry than the other two methods. (Kate, Richard, & John, 2014)

2.7.3 Statistical reliability model

Deterministic scour prediction equations for bridge abutments consider only the effects of hydraulic parameters and do not take the uncertainties of scouring parameters into account. Treatment of these uncertainties would provide the means for risk evaluation in bridge foundation design. Herein, a static reliability model is developed for the assessment of local scouring reliability around bridge abutments having relatively short lengths. This model is based on resistance-loading interference incorporating dependent parameters. In the model, the relative abutment footing depth, which can be considered at least the relative maximum scour depth, and the linear combination of the relative approach flow depth and Froude number are defined as the system resistance and external loading, respectively. By examining the statistical randomness of extensive laboratory data, a bivariate lognormal distribution is found to represent the joint probability density function of dependent resistance and loading. Reliability expressions are developed in terms of resistance. In an example, it is shown that the results of the proposed model and a Monte Carlo simulation are in good agreement. It is also observed that the execution of this model is less time consuming than the Monte Carlo simulation. In the model, the linear combination of the relative approach flow depth and the Froude number is considered to represent the external loading, x. The relative bottom elevation of abutment footing, which is obtained from the maximum possible depth of scour at an abutment, y, is regarded as the system resistance. The relationships between the resistance and loading for vertical and wing wall abutments are given by Eqs. (14) and (15), respectively. The statistical analysis of the data indicates that x and y are dependent and their joint PDF can be represented by a bivariate lognormal distribution. (YANMAZ & CELEBI, 2003)

$$y = 0.5976 \ln x + 0.7871 \quad 0.346 < x < 4.171$$

$$y = 0.8276 \ln x + 0.9484 \quad 0.465 < x < 1.783$$



2.7.4 Prediction of the Local Scour at the Bridge Square Pier Using a 3D Numerical Model

(Thanh, Chung, & Nghien, 2014)In this paper, the problem on local scour around a single square pier was studied by using both the numerical and physical models. The numerical model for the study is FSUM (Flows with Substance transport and Bed Morphology) developed by Chung, D.H. based on a finite-difference method to solve the Reynolds averaged Navier-Stokes equations (RANS) and the equations for suspended sediment concentration and bed morphology. The computed result was verified through data measured in the experimental flume with a sand bed. In general, the typical features of local scour around the pier were successfully simulated by FSUM, such as stream flow, bow flow, down flow, horseshoe vortex. The comparison between the computation and experiment data shows a quite good fitness. Both numerical model and experiment results show that the maximum scour depth occurs at two front edges of the pier. Although the computed result shows a little bigger scour depth in comparison with the measurement in the physical model, it still confirms the reliability of numerical model in some measure. The time duration of about 4 hours for such an experiment is enough to investigate in more details the process of erosion around a pier. Time variation of the maximum scour depth indicates that 90% of equilibrium scour depth occurs in the first two hour. Especially, this remark is very important for prediction with numerical model. From the longitudinal profile of stream lines it shows the important mechanism of local scour around the pier, the decisive factor of which is due to the sudden change of flow direction in front of a barricade, especially, the flow direction downwards to the bed. Finally, through this study, it also shows that the ability of application of numerical model in practice to predict the scour depth under various conditions is completely possible.

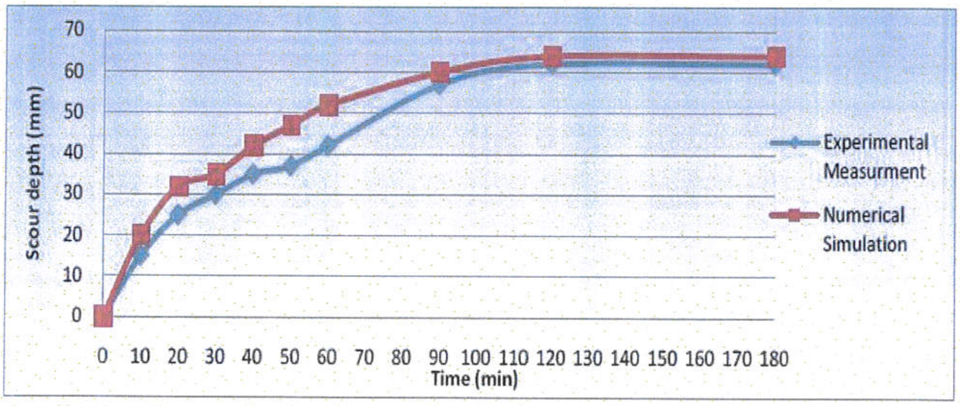


Figure2.30 shows an interesting comparison on the development of the maximum scour depth versus time between the numerical model and experiment.

The behavior of erosion evolution around the pier by the numerical model is quite suitable with the experiment. The correlation coefficient between observed and predicted values was 0.98. This also confirms the correctness of the proposal on the local treatment on bed roughness calculation in FSUM.

2.7.6 Field measurement of bridge scour

2.7.6.1 INVESTIGATION OF BRIDGE SCOUR AT SELECTED SITES ON MISSOURI STREAMS

(LAWRENCE, 1994)In this experiment, several scour formula where used to estimate scour at streams in Missouri. Flood as occurred for atleast 2 to 50 years at the considered bridges. The depth of scour ranges from 0.5 to 7 feet. All the formula did not gave a 0.5 level of significance, but Froehlich equation without a safety factor provided the "best fit" estimates of the equations considered. The answers gotten from the equations where compared statistically, and graphically to know how applicable they are to the Missouri stream, Froehlich equation proved to be most suitable for scour estimation.

Froehlich (1987) used multiple-linear-regression analysis to develop a prediction equation for local live-bed scour

$$\frac{d_s}{b} = 0.32b\phi Fr^{0.2}\left(\frac{b_e}{b}\right)^{0.62}\left(\frac{h}{b}\right)^{0.46}\left(\frac{b}{d_{50}}\right)^{0.08} + 1$$

This scour was largely attributable to contraction scour; however, woody debris that partially blocked the bridge opening also was a contributing factor. A bridge failure attributable to contraction scour occurred near Lebanon, Missouri, during 1990 that further demonstrates the potential, detrimental effect of bridge scour.

2.7.6.2 Research on Identification Method of Scour Depth for Bridge Based on ERA and SVM

(Xiaozhong, Wenjuan, & Bo, 2014)In this paper, an identification method on scouring damage of bridge structure based on ERA and SVM was established through theoretical derivation. And this method was verified in terms of identification accuracy and robustness under environmental excitation condition through real bridge test.

Conclusions are as follows: (1) the identification method on scouring damage of bridge structure based on ERA (*Eigensystem Realization Algorithm*) and SVM (support vector machine) can well identify the scouring depth of bridge substructure (underwater section) owing to its excellent testability on upper structure. (2) According to the real bridge test, the method proposed in this paper has higher identification accuracy and convenient practicality. (3) The analysis on identification method of scouring damage of bridge structure based on ERA and SVM provided a new approach for monitoring the scouring depth of cross-river bridges and cross-sea bridges. The real bridge test was conducted under good environment condition, while in practical operation, current bridges are surrounded with complex environment conditions with bigger noise. Therefore, how to eliminate the noise effect during data testing has become the next research direction. In addition, before this method is promoted into practical production, the issue of effectively transmitting data under field environment is still needed to be addressed, which will be a tough topic needed to be overcome in the future.

2.7.6.2 A Field Study of Scour at Bridge Piers in Flood Plain Rivers

For the study, 6 bridges on 3 rivers where considered. datas where collected from the field. The hydraulic effects of flow depth and velocity, sediment characteristics such as specific gravity, internal friction angle, particle size, and particle size distribution, and bridge pier geometry were considered. The aim of the study was to present a general view of the scouring process at bridge piers on the ground. For the purposes of this study, datas where subsequently analyzed using statistical and physico-mathematical methods. Field observations and photographic methods were also utilized. Due to the flood that occur in the November 1986 during the study, three of the bridges were damaged, which resulted into great lost and high cost of repair. As sediment particle size increased, the depth of local scour decreased. A comparison of scour equations with field measurements revealed that Hanco, CSU, Veiga, and Neill equations exhibited good agreement with the field data; however, Indian and Inglis equations overestimated scour depth (GHORBANI, 2007).

2.7.6.2.1 Equations used to carry out the report above for calculating scour

There exist many empirical equations that describe local scour depth as a function of other factors. (Neill, 1965) Suggested the following equation for computing scour depth, *ds*, at rectangular piers in live bed conditions for $\alpha = 0$:

$$\frac{d_s}{b} = 1.5\left(\frac{d}{b}\right)^{0.3}$$

Where ds = local scour depth, V = mean upstream velocity, Vc = critical mean velocity, d= upstream depth of flow, b = pier width, and D_{50} = median size of bed material.

(Breusers, H.N.C, Nicollet, & Shen, 1977) Recommended an equation for a general case in which sediment particle

Size is explicitly included for d/b > 1, and D50 = 0.5, 2, and 5 mm:

$$\frac{d_s}{b} = 3.3\left(\frac{D_{50}}{b}\right)^{0.2}\left(\frac{d}{b}\right)^{0.13}$$

An equation based on the CSU equation is suggested for both live bed and clear water local scour depth (Richardson, E.V., Simons, & Julien, 1990), which is currently provided in the HEC-18 manual (NHI, 2001):

$$\frac{d_s}{b} = 2.0k_1k_2k_3k_4\left(\frac{d}{b}\right)^{0.35} F_{1r}{}^{0.43}$$

where $K1$ = the correction factor for pier nose shape (1.0 for round noses and cylindrical piers and 1.1 for square noses), $K2$ = the correction factor for flow angle of attack (1.0 for a zero degree angle of attack and a range of L/b = 4-12, where L is pier length), $K3$ = the correction factor for bed conditions (1.1 for clear water scour and nearly 1.0 for live bed scour), $K4$ = the armoring correction factor, and Fr = the Froude number of the approach flow. More details of Eq. (6) can be found in the HEC-18 manual (NHI, 2001).

Veiga (1970) reported the following equation for estimating the scour depth in a live bed scour condition for a circular pier and 0.5 < d/b < 4, in which the influence of grain size was considered to be negligible for D < 0.5 mm on ds/b:

$$\frac{d_s}{b} = 1.35\left(\frac{d}{b}\right)^{0.13}$$

An alternative relation is given by Indian experiments for Model Bridge piers set in a sand bed for live bed scour conditions (Laursen, 1962):

$$\frac{d_s}{b} = 1.8\left(\frac{d}{b}\right)^{0.75} \quad 0 < ds/b < 7.6 \text{ and } 0 < d/b < 7$$

There is also another Indian experimental equation expressed by (Inglis, 1949.) in which the Froude number is brought into consideration as follows:

$$\frac{d_s}{b} = 4.2\left(\frac{d}{b}\right)^{0.78} F_{1r}{}^{0.52} \; 0 < d/b < 7 \text{ and } Fr < 1$$

Where Fr is the Froude number, which is written as Fr = V/(gd)1/2, where g = acceleration of velocity, and V = mean flow velocity. The abovementioned equations represent only a few samples of the many that have been derived to predict sour depth at bridge piers.

2.9.6.3 COMPARISON OF FORMULAE FOR THE PREDICTION OF SCOUR DEPTH AT PIERS

(Gaudio, Grimaldi, Tafarojnoruz, & Calomino1)Synthetic and original field data were used to estimate local scour at bridges. The formulas selected for the study are as written below. The pier considered is a circular type. The results show that different formulae produce significantly different predictions. The selected formulae were also tested on a field dataset in the case of uniform bed sediments, confirming that their ability to assess the maximum scour depth at equilibrium is not satisfactory.

2.9.6.3.1 SELECTED FORMULAE

The selected formulae are presented below.

a) (Breusers, H.N.C, Nicollet, & Shen, 1977) formula (hereinafter BR) for clear-water and live-bed scour conditions:

$$\frac{d_{se}}{b} = 2\left[2\frac{U}{U_e} - 1\right] \tan h\left(\frac{h}{b}\right) k_s k_\theta$$

Where d_{se} is the maximum scour depth in equilibrium condition, b the pier width, U the approaching flow velocity, U_e the critical velocity for sediment motion – computed with the Neill (1973) equation.

b) (Jain & Fischer, 1979)formula (hereinafter JF) for clear-water and live-bed scour conditions:

$d_{se} = 1.84b\left(\frac{h}{b}\right) Fr_c^{0.25}$ Valid for *Fr-Frc*<0 in clear-water conditions;

$d_{se} = 2.0b\left(\frac{h}{b}\right)^{0.5} (Fr - Fr_c)^{0.25}$ valid for *Fr-Frc*≥0.2 in live-bed conditions

Where $Fr = (\frac{u}{gh})^{0.5}$ and $Fr_c = (\frac{u_c}{gh})^{0.5}$ are the Froude number and the critical Froude number, respectively. For $0 < Fr - Fr_c < 0.2$ the largest value which is obtained from the two equation above is to be taken.

c) (Froehlich, 1988) formula (hereinafter FL) for live-bed scour condition:

$$d_{se} = 0.32b\phi Fr^{0.2}\left(\frac{b_e}{b}\right)^{0.62}\left(\frac{h}{b}\right)^{0.46}\left(\frac{b}{d_{50}}\right)^{0.08}$$

Where b_e is the width of the bridge pier projected orthogonally to the approach flow, φ a coefficient based on the shape of the pier nose and d_{50} the median grain size.

d) (Kothyari, Garde, & Ranga Raju, 1992) formula (hereinafter KR) for clear-water scour condition:

$$\frac{d_{se}}{b} = 1.0\left(\frac{b}{d_{50}}\right)^{-0.25}\left(\frac{h}{d_{50}}\right)^{0.16}\left[\frac{U^2 - U^2{}_{ep}}{\frac{\Delta\gamma_s}{\rho_f}d_{50}}\right]^{0.4}\alpha^{-0.3},$$

$$U^2{}_{ep} = 1.2\left(\frac{\Delta\gamma_s}{\rho_f}d_{50}\right)\left(\frac{b}{d_{50}}\right)^{-0.11}\left(\frac{h}{d_{50}}\right)^{0.16}, \qquad \Delta\gamma_s = \gamma_s - \gamma_f$$

Where U_{ep} is the critical velocity for the motion of sediment particles at the pier nose, γ_s the sediment specific weight, γ_f the fluid specific weight, ρ_f the fluid mass density and *α*=(*B*-*b*)/*B* the opening ratio, *B* being the flume width or centreto- centre spacing between two piers. In this study, *B* was assumed to be much greater than *b* and, therefore, its effect was neglected.

e) (Melville B. , 1997) formula (hereinafter ML) for clear-water and live-bed scour conditions:

$$d_{se} = k_{hb}k_ik_dk_sk_\theta k_G$$

Where $k_{hb}, k_i, k_d, k_s, k_\theta$ *and* k_G are coefficients taking into account the depth scale, the flow intensity, the sediment size, pier shape, pier alignment and channel geometry effects on scour depth, respectively; k_{hb}, k_i *and*k_d, can be calculated as follows:

$$k_{hb} = \begin{cases} 2.4b & for \quad {}^{b}/_{h} < 0.7 \\ 2\sqrt{hb} & for \quad 0.7 < {}^{b}/_{h} < 5.0 \\ 4.5h & for \quad {}^{b}/_{h} > 5.0 \end{cases} \quad k_i$$

$$= \begin{cases} \frac{U}{U_c} \quad for \quad \frac{U}{U_c} < 1 \\ 1 \quad \frac{U}{U_c} \geq 1 \end{cases} \quad k_d$$

$$= \begin{cases} 0.57log\left(2.24\frac{b}{d_{50}}\right) \quad for \quad \frac{b}{d_{50}} \leq 1 \\ 1 \quad \frac{b}{d_{50}} > 1 \end{cases}$$

Factors k_s *and* k_θ can be also calculated by using the tables proposed in Melville (1997). In addition, $k_G = 1$ for piers.

f) FHWA (HEC-18) formula (hereinafter HC) for clear-water and live-bed scour conditions:

$$\frac{d_{se}}{b} = 2.0k_1k_2k_3k_4k_w\left(\frac{b}{h}\right)^{0.35} F_r^{\ 0.43}$$

Where k_1, k_2, k_3, k_4 *and* k_w are correction factors accounting for pier nose shape, flow angle of attack, presence of bed forms, bed armouring and wide piers in shallow flows, respectively (Richardson & Davis, Evaluating scour at bridges, 2001).

He concluded that in most conditions the agreement between formulae is weak, being good at best in 55% of the analysed cases. The formulae were also tested on a field dataset available in the literature for uniform sediments, producing unsatisfactory results. The HC formula in both clear-water and live-bed scour and the FL formula in live-bed condition predicted the measured scour depths better than the other selected formula. This study evidences that none of the selected formulae accurately predicts the maximum equilibrium scour depths in the field and that high result variations are often obtained by using different pier scour formulae. Further research is needed to give a more comprehensive evaluation of pier scour formulae.

2.7.7 Vulnerability of bridges to scour: insights from an international expert elicitation workshop

(Rob, Willy, Henry, & Thorsten, 2017)Stated the important factors that should be considered when assessing scour risk to bridges?

Group	**Proposed factors**	**Comments**
Characteristics of the bridge structure	– Foundation depth –Foundation type - Structure span - Construction date - Existence of scour protection - Flow constriction at the bridge -Bridge type	Relate to static characteristics of the structure
History and uncertainty about information	– Application of scour assessment and monitoring procedures – Whether there is a history of scour problems – Whether or not foundation depth is known – Number of floods in the last 5 years – History of debris accumulation	Broad group of factors reflecting how much is known about scour vulnerability at a bridge, including evidence from past events (especially previous occurrence of scour) and also whether the bridge characteristics are well known.

Change factors	– Sand/gravel extraction in the reach near the bridge – Weir has been removed near bridge	Changes at the bridge or elsewhere in the watercourse that could lead to changes in susceptibility to scour.

Table 2.4 Proposed vulnerability factors.

2.7.8 Factors Effecting Local Scour (RICHARDSON & RICHARDSON)

1. Effect of pier width: wide pier width cause the space passed by water to reduce, therefore causing an increase in the velocity of the flowing water to maintain continuity. This results in increase in the depth of scour.
2. Effect of projected length of abutment: an increase in the projected width of an abutment will cause an increase in the depth of scour. Compared to the ratio of the flow in the main channel to flow in the overbank, the length of an abutment may not be so important.
3. Effect of the length of pier: the length of pier as no effect on the depth of scour except the pier of the bridge is at an angle to the flow of water. If the pier is at an angle, the depth of scour can be increased by 33 present.
4. The flow depth also as a direct effect on the depth of scour, there is an increase in the scour depth by a factor of 2 and more for a pier, and for an abutment, the increase ranges from 1.1 to 2.15.
5. (Jain & Fisher, 1979), have proven that scour depth increases with an increase in Froude numbers. Meaning the more the velocity, the more the depth of scour.
6. Bed size of bed materials as no effect on the depth of scour, except the fact that time at which maximum scour will b reach varies from one bed material to the other due to it size.

7. Angle of attack of the flow to the pier or abutment has a large effect on local scour as was pointed out in the discussion of the effect of pier length above. The effect on piers will not be repeated here. With abutments the depth of scour is reduced for

embankments angled downstream and is increased if the embankments are angled upstream. According to the work of Ahmad, (Richardson, Simons, Karaki, Mahmood, & Stevens, 1975) the maximum depth of scour at an embankment inclined 45 degrees downstream is reduced by 20 percent.

Whereas, the scour at an embankment inclined 45 degrees upstream is increased about 10 percent.

8. The shape of piers and abutments have a significant effect on scour. With a pier, streamlining the front end reduces the strength of the horseshoe vortex and reduces scour depth. Streamlining the downstream end of piers reduces the strength of the wake vortices. However increasing the angle of attack will decrease or negate the decrease of scour depth which would be realized by streamlining the piers. A square-nose pier will have maximum scour depths about 20 percent larger than a sharp-nose pier, and 10 percent larger than a cylinder or round-nose pier. Abutments with vertical walls on the stream side and upstream side, will have scour depths about double that of spill slope abutments.

CHAPTER 3

3.0METHODOLGY

BD 97/12 (the Assessment of Scour and Other Hydraulic Actions at Highway Structures), and HEC 18 (Hydraulic Engineering Circular No. 18-Evaluating Scour at Bridges, (Richardson and Davis, 2001)) methodologies will be used in this study for the estimation of bridges case study that has been affected by scour. The study will involve comparing the result of both approaches i.e. BD 97/12 and HEC 18, in estimating local scour at bridge piers. Afterwards, an in-situ measurement of the existing scour bridge will be taken to compare which of the bridge scour manual best estimate bridge scour in Nigeria.

Synthetic data from Monte Carlo simulation technique, labouratory data, or field data can be used for this experiment, but, strictly field data will be used to carry out this experiment.

3.1.0. CASE STUDY OF A BRIDGE

TWIN BRIDGES ALONG BENIN – OFUSO – ORE – AJEBANDELE – SHAGAMU DUAL CARIAGEWAY IN ONDO STATE WILL BE INVSTIGATED.

3.2.0. ESTIMATION OF SCOUR USING BD 97/12

3.2.1. ESTIMATION OF SCOUR DEPTHS

Calculation of depth of local Scour

The depth of local scour for piers should be based on the maximum potential scour depth, which depends primarily on the geometry of the pier. The maximum local scour depth is given by:

$D_{l,pier} = 1.5W_p f_{ps} f_{PA} f_y$……………………………………………………….Eq32

Where Wp is the width of the pier, fPS is a shape factor, fPA is a factor depending on the angle of attack of the flow and fy a factor depending on the relative depth of the approach flow to the pier width.

The shape factor f_{PS} should be taken from Figure 2.18, except where the angle of attack exceeds 10°, when it should be taken as 1.0.

The angle of attack factor, f_{PA} should be calculated as:

$$f_{PA} = \left(\cos\alpha + \frac{L}{W_P}\sin\alpha\right)^{0.65} \text{..........} \text{Eq31}$$

Where L is the pier length, Wp is the pier width, and α is the angle between the flow direction and the pier centerline.

The depth of flow factor f_y should be taken as:

(i) 1.0 where the depth at the pier including constriction scour y_{sp} exceeds 2.6 times the pier width, where $y_{sp} = y_B + D_c$ Eq32

(ii) In other cases, $f_y = 0.78\left(\frac{y_{sp}}{W_P}\right)^{0.255}$ Eq33

3.3.0. ESTIMATION OF USING HEC 18

3.3.1 The HEC-18 equation FOR Calculating scour at bridge pier is:

$$\frac{y_s}{y_1} = 2.0k_1k_2k_3k_4k_w\left(\frac{a}{y_1}\right)^{0.65} F_r^{\;0.43} \text{..........} \text{Eq34}$$

As a Rule of Thumb, the maximum scour depth for round nose piers aligned with the flow is:

ys ≤ 2.4 times the pier width (a) for Fr ≤ 0.8 ....Eq35a

ys ≤ 3.0 times the pier width (a) for Fr > 0.8..........Eq35b

$$\frac{y_s}{a} = 2.0k_1k_2k_3k_4k_w\left(\frac{y_1}{a}\right)^{0.35} F_r^{\;0.43} \text{..........} \text{Eq36}$$

In terms of $\frac{y_s}{a}$, Equation is:

y_s = Scour depth, ft (m)

y_1 = Flow depth directly upstream of the pier, ft (m)

K_1 = Correction factor for pier nose shape from Figure 2 and Table 1

K_2 = Correction factor for angle of attack of flow from Table 2 or Equation 34

K_3 = Correction factor for bed condition from Table 3

a = Pier width, ft (m) L = Length of pier, ft (m)

Fr_1 = Froude Number directly upstream of the pier = $V_1/(gy_1)^{1/2}$

V_1 = Mean velocity of flow directly upstream of the pier, ft/s (m/s)

g = Acceleration of gravity (32.2 ft/s^2) (9.81 m/s^2)

The correction factor, K_2, for angle of attack of the flow, 2, is calculated using the following equation:

$$k_2 = \left(\cos\alpha + \frac{L}{a}\sin\alpha\right)^{0.65} \text{..........Eq37}$$

If $\frac{L}{a}$ is larger than 12, use $\frac{L}{a}$ = 12 as a maximum in Equation 37 and Table 7.2. Table 7.2 illustrates the magnitude of the effect of the angle of attack on local pier scour.

3.3.2 SCOUR FOR COMPLEX PIER

Superposition of Scour Components Method of Analysis is used in estimating scour for complex pier. The method involves determining the scour depth for each component and adding the results:

Total scour from superposition of components is given by:

$$y_s = y_{s\,pier} + y_{s\,pc} + y_{s\,pg} \text{..........Eq55}$$

Where:

y_s = Total scour depth, ft (m)

$y_{s\,pier}$ = Scour component for the pier stem in the flow, ft (m)

$y_{s\,pc}$ = Scour component for the pier cap or footing in the flow, ft (m)

$y_{s\,pg}$ = Scour component for the piles exposed to the flow, ft (m)

3.3.2.1 Determination of the Pier Stem Scour Depth Component

$$\frac{y_{spier}}{y} = 2.0k_1k_2k_3k_{hpier}\left(\frac{a_{pier}}{y_1}\right)^{0.65} F_{1r}^{\ 0.43} \text{..........Eq56}$$

3.3.2.2 Determination of the Pile Cap (Footing) Scour Depth Component:

The determination of pile cap scour depth is of two cases which are as discoursed in chapter two above

Case 1. Bottom of the Pile Cap (Footing) in the Flow above the Bed

$$\frac{y_{spc}}{y_2} = 2.0K_1K_2K_3K_w\left(\frac{a^*_{pc}}{y_2}\right)^{0.65}\left(\frac{V_2}{\sqrt{gy_2}}\right)^{0.43} \quad \text{...Eq57}$$

Case 2. Bottom of the Pile Cap (Footing) Located On or Below the Bed.

$$\frac{y_{spc}}{y_f} = 2.0K_1K_2K_3K_w\left(\frac{a_{pc}}{y_2}\right)^{0.65}\left(\frac{V_f}{\sqrt{gy_f}}\right)^{0.43} \quad \text{...Eq59}$$

In this case assume the pile cap scour component includes the pile group scour and compute the total scour depth as:

$y_s = y_{s\,pier} + y_{s\,pc}$ (For case 2 only) Eq60

3.3.2.3 Determination of the Pile Group Scour Depth Component

$$\frac{y_{spc}}{y_3} = 2.0K_1K_3K_{hpg}\left(\frac{a^*_{pg}}{y_3}\right)^{0.65}\left(\frac{V_2}{\sqrt{gy_3}}\right)^{0.43} \quad \text{...Eq64}$$

The total scour for the complex pier from Equation (55) is:

$$y_s = y_{spier} + y_{spc} + y_{spg}$$

3.3.3 SCOUR FROM DEBRIS ON PIERS

Floating woody debris (drift) that lodges and accumulates at bridge piers creates additional obstruction to flow, and transforms the pier geometry into one that is effectively wider than if debris were not present. Thesame formula in equation 34 is used in calculating for bridges with debris except for the width. The width is calculated as:

Effective Pier Width with Debris

$$a^*_d = \frac{K_1(HW)+(y-K_1H)a}{y} \quad \text{..Eq65}$$

where:

a^*_d = Effective width of pier when debris is present,ft (m)

a = Width of pier perpendicular to flow, ft (m)

K_1 = 0.79 for rectangular debris, 0.21 for triangular debris

H = Height (thickness) of the debris, ft (m)

W = Width of debris perpendicular to the flow direction, ft (m)

Y = Depth of approach flow, ft (m)

CHAPTER 4

4.0 ANALYSES, ASSESSMENT OF SCOUR AT BRIDGE AND DISCUSSION OF RESULTS

4.1 ESTIMATION OF LOCAL SCOUR AT PIER USING HEC 18 AT:

ANGLE 0(60m):

Determination of the Pier Stem Scour Depth Component

$$\frac{y_{spier}}{y} = 2.0k_1k_2k_3k_{hpier}\left(\frac{a_{pier}}{y_1}\right)^{0.65} {F_{1r}}^{0.43}$$

$$\frac{y_{spier}}{8.1} = 2.0 * 1.1 * 1 * 1.1 * 1\left(\frac{0.5}{8.1}\right)^{0.65}\left(\frac{9.05}{\sqrt{9.81 * 8.1}}\right)^{0.43}$$

$$y_{spier} = 2.42 * 0.164 * 1.15 * 8.1 = 3.69m$$

Bottom of the Pile Cap (Footing) in the Flow above the Bed

$$\frac{y_{spc}}{y_2} = 2.0K_1K_2K_3K_w\left(\frac{{a^*}_{pc}}{y_2}\right)^{0.65}\left(\frac{V_2}{\sqrt{gy_2}}\right)^{0.43}$$

$$h_2 = 4.6 + \frac{3.39}{2} = 6.45m$$

$$y_2 = 8.1 + \frac{3.39}{2} = 9.95m$$

$$v_2 = 9.05\left({}^{8.1}/_{9.95}\right) = 7.37$$

$$\frac{T}{y_2} = \frac{1}{9.95} = 0.1$$

$$\frac{h_2}{y_2} = \frac{6.45}{9.95} = 0.65$$

$$since\ y_2 > 0.8a^*D_c, k_w = 1$$

$$a_{pc}{}^* = 0.03 * 5 = 0.15$$

$$\frac{y_{spc}}{9.95} = 2.0 * 1.1 * 1 * 1.1 * 1 \left(\frac{0.15}{9.95}\right)^{0.65} \left(\frac{7.37}{\sqrt{9.81 * 9.95}}\right)^{0.43}$$

$$y_{spc} = 2{,}42 * 0.075 * 0.92 * 8.1 = 1.35m$$

Determination of the Pile Group Scour Depth Component

$$\frac{y_{spc}}{y_3} = 2.0K_1K_3K_{hpg}\left(\frac{a^*{}_{pg}}{y_3}\right)^{0.65}\left(\frac{V_2}{\sqrt{gy_3}}\right)^{0.43}$$

$$h_3 = 4.6 + \frac{3.39 + 1.35}{2} = 7.12m$$

$$y_3 = 8.1 + \frac{3.39 + 1.35}{2} = 10.62m$$

$$v_3 = 9.05\left({}^{8.1}/_{10.62}\right) = 6.18m/s$$

$$a_{proj} = 4.4m$$

$$\frac{s}{a} = \frac{1.5}{0.45} = 3.33$$

$$\frac{a_{proj}}{a} = \frac{4.4}{0.45} = 9.77$$

Therefore, $k_{sp} = 0.4$, $k_m = 1.5$

$$a_{pg}{}^* = 0.4 * 1.5 * 4.4 = 2.64$$

$$\frac{h_3}{y_3} = \frac{7.12}{10.62} = 0.67$$

$$k_{hpg} = 0.8$$

$$\frac{y_{spg}}{10.62} = 2.0 * 1.1 * 1.1 * 0.8\left(\frac{2.64}{10.62}\right)^{0.65}\left(\frac{6.18}{\sqrt{9.81 * 10.62}}\right)^{0.43}$$

$$y_{spg} = 1.79 * 0.4 * 0.81 * 10.62$$

$$y_{spg} = 6.16m$$

ANGLE 10(60m):

Determination of the Pier Stem Scour Depth Component

$$\frac{y_{spier}}{y} = 2.0k_1k_2k_3k_{hpier}\left(\frac{a_{pier}}{y_1}\right)^{0.65} F_{1r}^{\;0.43}$$

$$K_2 = [cos10 + 6sin10]^{0.65} = 1.58$$

$$\frac{y_{spier}}{8.1} = 2.0 * 1 * 1.58 * 1.1 * 1\left(\frac{0.5}{8.1}\right)^{0.65}\left(\frac{9.05}{\sqrt{9.81 * 8.1}}\right)^{0.43}$$

$$y_{spier} = 3.48 * 0.164 * 1 * 8.1 = 4.6m$$

Bottom of the Pile Cap (Footing) in the Flow above the Bed

$$\frac{y_{spc}}{y_2} = 2.0K_1K_2K_3K_w\left(\frac{a^*{}_{pc}}{y_2}\right)^{0.65}\left(\frac{V_2}{\sqrt{gy_2}}\right)^{0.43}$$

$$h_2 = 4.6 + \frac{4.6}{2} = 6.9m$$

$$y_2 = 8.1 + \frac{4.6}{2} = 10.4m$$

$$v_2 = 9.05\left({}^{8.1}/{}_{10.4}\right) = 7.05$$

$$\frac{T}{y_2} = \frac{1}{9.95} = 0.09 \cong 0.1$$

$$\frac{h_2}{y_2} = \frac{6.9}{10.4} = 0.66$$

$$since\ y_2 > 0.8a^*D_c, k_w = 1$$

$$a_{pc}{}^* = 0.025 * 5 = 0.13$$

$$\frac{y_{spc}}{10.4} = 2.0 * 1 * 1.58 * 1.1 * 1\left(\frac{0.13}{10.4}\right)^{0.65}\left(\frac{7.05}{\sqrt{9.81 * 10.4}}\right)^{0.43}$$

$$y_{spc} = 3.48 * 0.058 * 0.87 * 10.4 = 1.57m$$

Determination of the Pile Group Scour Depth Component

$$\frac{y_{spc}}{y_3} = 2.0K_1K_3K_{hpg}\left(\frac{a^*{}_{pg}}{y_3}\right)^{0.65}\left(\frac{V_2}{\sqrt{gy_3}}\right)^{0.43}$$

$$h_3 = 4.6 + \frac{4.6 + 1.57}{2} = 7.69m$$

$$y_3 = 8.1 + \frac{4.6 + 1.57}{2} = 11.19m$$

$$v_3 = 9.05\left({}^{8.1}/_{11.19}\right) = 6.55m/s$$

$$a_{proj} = 3.8m$$

$$\frac{s}{a} = \frac{1.5}{0.45} = 3.33$$

$$\frac{a_{proj}}{a} = \frac{4.4}{0.45} = 8.44$$

$$k_{sp} = 1 - 1.33[1 - {}^{1}/_{a_{pro}/a}][1 - [{}^{S}/a]^{-0.6}]$$

$$k_{sp} = 1 - 1.33[1 - {}^{1}/_{8.44}][1 - 3.33^{-0.6}]$$

$$k_{sp} = 1 - 1.33[0.88][0.51] = 0.4$$

$$a_{pg}{}^* = 0.4 * 3.8 = 1.52$$

$$\frac{h_3}{y_3} = \frac{7.69}{11.19} = 0.69$$

$$k_{hpg} = 0.82$$

$$\frac{y_{spg}}{11.19} = 2.0 * 1 * 1.1 * 0.82\left(\frac{1.52}{11.19}\right)^{0.65}\left(\frac{6.55}{\sqrt{9.81 * 11.19}}\right)^{0.43}$$

$$y_{spg} = 1.804 * 0.27 * 0.82 * 11.19$$

$$y_{spg} = 4.5m$$

ANGLE 15(60m):

Determination of the Pier Stem Scour Depth Component

$$\frac{y_{spier}}{y} = 2.0k_1k_2k_3k_{hpier}\left(\frac{a_{pier}}{y_1}\right)^{0.65} {F_{1r}}^{0.43}$$

$$K_2 = [cos15 + 6sin15]^{0.65} = 1.82$$

$$\frac{y_{spier}}{8.1} = 2.0 * 1 * 1.82 * 1.1 * 1\left(\frac{0.5}{8.1}\right)^{0.65}\left(\frac{9.05}{\sqrt{9.81 * 8.1}}\right)^{0.43}$$

$$y_{spier} = 4 * 0.164 * 1 * 8.1 = 5.18m$$

Bottom of the Pile Cap (Footing) in the Flow above the Bed

$$\frac{y_{spc}}{y_2} = 2.0K_1K_2K_3K_w\left(\frac{a^*{}_{pc}}{y_2}\right)^{0.65}\left(\frac{V_2}{\sqrt{gy_2}}\right)^{0.43}$$

$$h_2 = 4.6 + \frac{5.18}{2} = 7.19m$$

$$y_2 = 8.1 + \frac{5.18}{2} = 10.69m$$

$$v_2 = 9.05\left({}^{8.1}/_{10.69}\right) = 6.86m/s$$

$$\frac{T}{y_2} = \frac{1}{10.69} = 0.093 \cong 0.1$$

$$\frac{h_2}{y_2} = \frac{6.9}{10.69} = 0.67$$

$$since\ y_2 > 0.8a^*D_c, k_w = 1$$

$$a_{pc}{}^* = 0.025 * 5 = 0.125$$

$$\frac{y_{spc}}{10.69} = 2.0 * 1 * 1.82 * 1.1 * 1\left(\frac{0.125}{10.69}\right)^{0.65}\left(\frac{7.05}{\sqrt{9.81 * 10.69}}\right)^{0.43}$$

$$y_{spc} = 4 * 0.055 * 0.84 * 10.69 = 1.98m$$

Determination of the Pile Group Scour Depth Component

$$\frac{y_{spc}}{y_3} = 2.0K_1K_3K_{hpg}\left(\frac{a^*{}_{pg}}{y_3}\right)^{0.65}\left(\frac{V_2}{\sqrt{gy_3}}\right)^{0.43}$$

$$h_3 = 4.6 + \frac{5.18 + 1.98}{2} = 8.18m$$

$$y_3 = 8.1 + \frac{5.18 + 1.98}{2} = 11.68m$$

$$v_3 = 9.05({}^{8.1}/_{11.68}) = 6.28m/s$$

$$a_{proj} = 5.7m$$

$$\frac{s}{a} = \frac{1.5}{0.45} = 3.33$$

$$\frac{a_{proj}}{a} = \frac{5.7}{0.45} = 12.67$$

$$k_{sp} = 1 - 1.33[1 - {}^{1}/_{a_{pro}/a}][1 - [{}^{S}/a]^{-0.6}]$$

$$k_{sp} = 1 - 1.33[1 - {}^{1}/_{12.67}][1 - 3.33^{-0.6}]$$

$$k_{sp} = 0.38$$

$$a_{pg}{}^{*} = 0.38 * 5.7 = 2.2$$

$$\frac{h_3}{y_3} = \frac{8.18}{11.68} = 0.7$$

$$k_{hpg} = 0.83$$

$$\frac{y_{spg}}{11.68} = 2.0 * 1 * 1.1 * 0.83\left(\frac{2.2}{11.68}\right)^{0.65}\left(\frac{6.28}{\sqrt{9.81 * 11.68}}\right)^{0.43}$$

$$y_{spg} = 1.804 * 0.34 * 0.79 * 11.68$$

$$y_{spg} = 5.7m$$

ANGLE 20(60m):

Determination of the Pier Stem Scour Depth Component

$$\frac{y_{spier}}{y} = 2.0k_1k_2k_3k_{hpier}\left(\frac{a_{pier}}{y_1}\right)^{0.65} F_{1r}^{\ 0.43}$$

$$K_2 = [cos20 + 6sin20]^{0.65} = 2.04$$

$$\frac{y_{spier}}{8.1} = 2.0 * 1 * 2.04 * 1.1 * 1\left(\frac{0.5}{8.1}\right)^{0.65}\left(\frac{9.05}{\sqrt{9.81 * 8.1}}\right)^{0.43}$$

$$y_{spier} = 4.49 * 0.164 * 1 * 8.1 = 5.82m$$

Bottom of the Pile Cap (Footing) in the Flow above the Bed

$$\frac{y_{spc}}{y_2} = 2.0K_1K_2K_3K_w\left(\frac{a^*{}_{pc}}{y_2}\right)^{0.65}\left(\frac{V_2}{\sqrt{gy_2}}\right)^{0.43}$$

$$h_2 = 4.6 + \frac{5.82}{2} = 7.51m$$

$$y_2 = 8.1 + \frac{5.82}{2} = 11.01m$$

$$v_2 = 9.05\left({}^{8.1}/_{11.01}\right) = 6.6m/s$$

$$\frac{T}{y_2} = \frac{1}{10.69} = 0.09 \cong 0.1$$

$$\frac{h_2}{y_2} = \frac{7.51}{11.01} = 0.68$$

$$since\ y_2 > 0.8a^*D_c, k_w = 1$$

$$a_{pc}{}^* = 0.02 * 5 = 0.1$$

$$\frac{y_{spc}}{11.01} = 2.0 * 1 * 2.04 * 1.1 * 1 \left(\frac{0.1}{11.01}\right)^{0.65} \left(\frac{6.66}{\sqrt{9.81 * 11.01}}\right)^{0.43}$$

$$y_{spc} = 4.49 * 0.05 * 0.83 * 11.01 = 2.05m$$

Determination of the Pile Group Scour Depth Component

$$\frac{y_{spc}}{y_3} = 2.0K_1K_3K_{hpg} \left(\frac{a^*{}_{pg}}{y_3}\right)^{0.65} \left(\frac{V_2}{\sqrt{gy_3}}\right)^{0.43}$$

$$h_3 = 4.6 + \frac{5.82 + 2.05}{2} = 8.54m$$

$$y_3 = 8.1 + \frac{5.82 + 2.04}{2} = 12.04m$$

$$v_3 = 9.05\left({}^{8.1}/_{12.04}\right) = 6.09m/s$$

$$a_{proj} = 6.5m$$

$$\frac{s}{a} = \frac{1.5}{0.45} = 3.33$$

$$\frac{a_{proj}}{a} = \frac{6.5}{0.45} = 14.44$$

$$k_{sp} = 1 - 1.33[1 - {}^{1}/_{a_{pro}/a}][1 - [{}^{S}/_{a}]^{-0.6}]$$

$$k_{sp} = 1 - 1.33[1 - {}^{1}/_{14.44}][1 - 3.33^{-0.6}]$$

$$k_{sp} = 0.36$$

$$a_{pg}{}^{*} = 0.36 * 6.5 = 2.34$$

$$\frac{h_3}{y_3} = \frac{8.54}{12.04} = 0.7$$

$$k_{hpg} = 0.83$$

$$\frac{y_{spg}}{12.04} = 2.0 * 1 * 1.1 * 0.83 \left(\frac{2.34}{12.04}\right)^{0.65} \left(\frac{6.09}{\sqrt{9.81 * 12.04}}\right)^{0.43}$$

$$y_{spg} = 1.83 * 0.34 * 0.78 * 12.04$$

$$y_{spg} = 5.84m$$

ANGLE 25(60m):

Determination of the Pier Stem Scour Depth Component

$$\frac{y_{spier}}{y} = 2.0k_1k_2k_3k_{hpier}\left(\frac{a_{pier}}{y_1}\right)^{0.65} F_{1r}{}^{0.43}$$

$$K_2 = [cos25 + 6sin25]^{0.65} = 2.23$$

$$\frac{y_{spier}}{8.1} = 2.0 * 1 * 2.23 * 1.1 * 1\left(\frac{0.5}{8.1}\right)^{0.65}\left(\frac{9.05}{\sqrt{9.81 * 8.1}}\right)^{0.43}$$

$$y_{spier} = 4.91 * 0.164 * 1 * 8.1 = 6.36m$$

Bottom of the Pile Cap (Footing) in the Flow above the Bed

$$\frac{y_{spc}}{y_2} = 2.0K_1K_2K_3K_w\left(\frac{a^*{}_{pc}}{y_2}\right)^{0.65}\left(\frac{V_2}{\sqrt{gy_2}}\right)^{0.43}$$

$$h_2 = 4.6 + \frac{6.36}{2} = 7.78m$$

$$y_2 = 8.1 + \frac{6.36}{2} = 11.28m$$

$$v_2 = 9.05(^{8.1}/_{11.28}) = 6.49m/s$$

$$\frac{T}{y_2} = \frac{1}{11.28} = 0.088 \cong 0.1$$

$$\frac{h_2}{y_2} = \frac{7.51}{11.28} = 0.69$$

$$since\ y_2 > 0.8a^*D_c, k_w = 1$$

$$a_{pc}{}^* = 0.02 * 5 = 0.1$$

$$\frac{y_{spc}}{11.28} = 2.0 * 1 * 2.23 * 1.1 * 1\left(\frac{0.1}{11.28}\right)^{0.65}\left(\frac{6.49}{\sqrt{9.81 * 11.28}}\right)^{0.43}$$

$$y_{spc} = 4.91 * 0.046 * 0.81 * 11.28 = 2.06m$$

Determination of the Pile Group Scour Depth Component

$$\frac{y_{spc}}{y_3} = 2.0K_1K_3K_{hpg}\left(\frac{a^*{}_{pg}}{y_3}\right)^{0.65}\left(\frac{V_2}{\sqrt{gy_3}}\right)^{0.43}$$

$$h_3 = 4.6 + \frac{6.36 + 2.06}{2} = 8.81m$$

$$y_3 = 8.1 + \frac{6.36 + 2.06}{2} = 12.31m$$

$$v_3 = 9.05(^{8.1}/_{12.13}) = 5.95m/s$$

$$a_{proj} = 7.7m$$

$$\frac{s}{a} = \frac{1.5}{0.45} = 3.33$$

$$\frac{a_{proj}}{a} = \frac{7.7}{0.45} = 17.11$$

$$k_{sp} = 1 - 1.33[1 - {}^{1}/_{a_{pro}/a}][1 - [^{S}/_{a}]^{-0.6}]$$

$$k_{sp} = 1 - 1.33[1 - {}^{1}/_{17.11}][1 - 3.33^{-0.6}]$$

$$k_{sp} = 0.399$$

$$a_{pg}{}^{*} = 0.399 * 7.7 = 3.07$$

$$\frac{h_3}{y_3} = \frac{8.81}{12.31} = 0.72$$

$$k_{hpg} = 0.83$$

$$\frac{y_{spg}}{12.04} = 2.0 * 1 * 1.1 * 0.83\left(\frac{3.07}{12.31}\right)^{0.65}\left(\frac{5.95}{\sqrt{9.81 * 12.13}}\right)^{0.43}$$

$$y_{spg} = 1.83 * 0.41 * 0.77 * 12.31$$

$$y_{spg} = 7.11m$$

ANGLE 30(60m):

Determination of the Pier Stem Scour Depth Component

$$\frac{y_{spier}}{y} = 2.0k_1k_2k_3k_{hpier}\left(\frac{a_{pier}}{y_1}\right)^{0.65} F_{1r}^{\ 0.43}$$

$$K_2 = [cos30 + 6sin30]^{0.65} = 2.4$$

$$\frac{y_{spier}}{8.1} = 2.0 * 1 * 2.4 * 1.1 * 1\left(\frac{0.5}{8.1}\right)^{0.65}\left(\frac{9.05}{\sqrt{9.81 * 8.1}}\right)^{0.43}$$

$$y_{spier} = 5.28 * 0.164 * 1 * 8.1 = 6.84m$$

Bottom of the Pile Cap (Footing) in the Flow above the Bed

$$\frac{y_{spc}}{y_2} = 2.0K_1K_2K_3K_w\left(\frac{a^*{}_{pc}}{y_2}\right)^{0.65}\left(\frac{V_2}{\sqrt{gy_2}}\right)^{0.43}$$

$$h_2 = 4.6 + \frac{6.84}{2} = 8.02m$$

$$y_2 = 8.1 + \frac{6.84}{2} = 11.52m$$

$$v_2 = 9.05\left({}^{8.1}/_{11.52}\right) = 6.36m/s$$

$$\frac{T}{y_2} = \frac{1}{11.52} = 0.086 \cong 0.1$$

$$\frac{h_2}{y_2} = \frac{8.02}{11.52} = 0.69$$

$$since\ y_2 > 0.8a^*D_c, k_w = 1$$

$$a_{pc}^{*} = 0.02 * 5 = 0.1$$

$$\frac{y_{spc}}{11.52} = 2.0 * 1 * 2.4 * 1.1 * 1\left(\frac{0.1}{11.52}\right)^{0.65}\left(\frac{6.36}{\sqrt{9.81 * 11.52}}\right)^{0.43}$$

$$y_{spc} = 5.28 * 0.046 * 0.81 * 11.52 = 2.24m$$

Determination of the Pile Group Scour Depth Component

$$\frac{y_{spc}}{y_3} = 2.0K_1K_3K_{hpg}\left(\frac{a^{*}{}_{pg}}{y_3}\right)^{0.65}\left(\frac{V_2}{\sqrt{gy_3}}\right)^{0.43}$$

$$h_3 = 4.6 + \frac{6.84 + 2.24}{2} = 9.14m$$

$$y_3 = 8.1 + \frac{6.84 + 2.24}{2} = 12.54m$$

$$v_3 = 9.05\left({}^{8.1}/_{12.54}\right) = 5.79m/s$$

$$a_{proj} = 8.8m$$

$$\frac{s}{a} = \frac{1.5}{0.45} = 3.33$$

$$\frac{a_{proj}}{a} = \frac{8.8}{0.45} = 19.56$$

$$k_{sp} = 1 - 1.33[1 - {}^{1}/_{a_{pro}/a}][1 - [{}^{S}/a]^{-0.6}]$$

$$k_{sp} = 1 - 1.33[1 - {}^{1}/_{19.56}][1 - 3.33^{-0.6}]$$

$$k_{sp} = 0.39$$

$$a_{pg}^{*} = 0.399 * 8.8 = 3.4$$

$$\frac{h_3}{y_3} = \frac{9.41}{12.54} = 0.73$$

$$k_{hpg} = 0.85$$

$$\frac{y_{spg}}{12.54} = 2.0 * 1 * 1.1 * 0.85 \left(\frac{3.4}{12.54}\right)^{0.65} \left(\frac{5.79}{\sqrt{9.81 * 12.54}}\right)^{0.43}$$

$$y_{spg} = 1.87 * 0.43 * 0.76 * 12.54$$

$$y_{spg} = 7.66\ m$$

ANGLE OF ATTACK	TOTAL DEPTH OF LOCAL SCOUR
0	11.2
5	11.2
10	10.67
15	12.86
20	13.71
25	15.53
30	16.74

Table 4.1 calculation summary of 60m span bridge using HEC18

ANGLE 0(45m):

Determination of the Pier Stem Scour Depth Component

$$\frac{y_{spier}}{y} = 2.0 k_1 k_2 k_3 k_{hpier} \left(\frac{a_{pier}}{y_1}\right)^{0.65} F_{1r}^{\ 0.43}$$

$$\frac{y_{spier}}{8.8} = 2.0 * 1.1 * 1 * 1.1 * 1 \left(\frac{0.5}{8.8}\right)^{0.65} \left(\frac{5.875}{\sqrt{9.81 * 8.8}}\right)^{0.43}$$

$$y_{spier} = 2.42 * 0.164 * 0.82 * 8.8 = 2.79m$$

Bottom of the Pile Cap (Footing) in the Flow above the Bed

$$\frac{y_{spc}}{y_2} = 2.0 K_1 K_2 K_3 K_w \left(\frac{a^*{}_{pc}}{y_2}\right)^{0.65} \left(\frac{V_2}{\sqrt{g y_2}}\right)^{0.43}$$

$$h_2 = 4.9 + \frac{2.79}{2} = 6.29m$$

$$y_2 = 8.8 + \frac{2.79}{2} = 10.19m$$

$$v_2 = 9.05\left({}^{8.8}/_{10.19}\right) = 5.08m/s$$

$$\frac{T}{y_2} = \frac{1}{10.19} = 0.09 \cong 0.1$$

$$\frac{h_2}{y_2} = \frac{6.29}{10.19} = 0.6$$

$$since\ y_2 > 0.8a^* D_c, k_w = 1$$

$$a_{pc}{}^* = 0.035 * 4 = 0.14$$

$$\frac{y_{spc}}{10.19} = 2.0 * 1.1 * 1 * 1.1 * 1 \left(\frac{0.14}{10.19}\right)^{0.65} \left(\frac{5.08}{\sqrt{9.81 * 10.19}}\right)^{0.43}$$

$$y_{spc} = 2.42 * 0.062 * 0.75 * 10.19 = 1.15m$$

Determination of the Pile Group Scour Depth Component

$$\frac{y_{spc}}{y_3} = 2.0 K_1 K_3 K_{hpg} \left(\frac{a^*{}_{pg}}{y_3}\right)^{0.65} \left(\frac{V_2}{\sqrt{g y_3}}\right)^{0.43}$$

$$h_3 = 4.9 + \frac{2.79 + 1.15}{2} = 6.87m$$

$$y_3 = 8.8 + \frac{2.79 + 1.15}{2} = 10.77m$$

$$v_3 = 5.875\left({}^{8.8}/_{10.77}\right) = 4.8m/s$$

$$a_{proj} = 3.4m$$

$$\frac{s}{a} = \frac{2.5}{0.45} = 5.55$$

$$\frac{a_{proj}}{a} = \frac{3.4}{0.45} = 7.53$$

Therefore $k_m = 1.7$

$$k_{sp} = 1 - 1.33[1 - {}^{1}/_{a_{pro}/a}][1 - [{}^{S}/_{a}]^{-0.6}]$$

$$k_{sp} = 1 - 1.33[1 - {}^{1}/_{7.55}][1 - 5.55^{-0.6}]$$

$$k_{sp} = 0.26$$

$$a_{pg}{}^{*} = 0.26 * 1.7 * 3.4 = 1.5$$

$$\frac{h_3}{y_3} = \frac{6.87}{10.77} = 0.64$$

$$k_{hpg} = 0.77$$

$$\frac{y_{spg}}{10.77} = 2.0 * 1 * 1.1 * 0.77 \left(\frac{1.5}{10.77}\right)^{0.65} \left(\frac{4.8}{\sqrt{9.81 * 10.77}}\right)^{0.43}$$

$$y_{spg} = 1.694 * 0.28 * 0.72 * 10.77$$

$$y_{spg} = 3.68m$$

ANGLE 10(45m):

Determination of the Pier Stem Scour Depth Component

$$\frac{y_{spier}}{y} = 2.0k_1k_2k_3k_{hpier}\left(\frac{a_{pier}}{y_1}\right)^{0.65} F_{1r}{}^{0.43}$$

$$K_2 = [cos10 + 6sin10]^{0.65} = 1.58$$

$$\frac{y_{spier}}{8.8} = 2.0 * 1 * 1.58 * 1.1 * 1\left(\frac{0.5}{8.8}\right)^{0.65} \left(\frac{5.875}{\sqrt{9.81 * 8.8}}\right)^{0.43}$$

$$y_{spier} = 3.48 * 0.164 * 0.82 * 8.8 = 4.02m$$

Bottom of the Pile Cap (Footing) in the Flow above the Bed

$$\frac{y_{spc}}{y_2} = 2.0K_1K_2K_3K_w\left(\frac{a^*{}_{pc}}{y_2}\right)^{0.65}\left(\frac{V_2}{\sqrt{gy_2}}\right)^{0.43}$$

$$h_2 = 4.9 + \frac{4.02}{2} = 6.91m$$

$$y_2 = 8.8 + \frac{4.02}{2} = 10.81m$$

$$v_2 = 5.875\left({}^{8.8}/_{10.81}\right) = 4.78$$

$$\frac{T}{y_2} = \frac{1}{10.81} = 0.09 \cong 0.1$$

$$\frac{h_2}{y_2} = \frac{6.91}{10.81} = 0.64$$

$$since\ y_2 > 0.8a^*D_c, k_w = 1$$

$$a_{pc}{}^* = 0.035 * 4 = 0.14$$

$$\frac{y_{spc}}{10.81} = 2.0 * 1 * 1.58 * 1.1 * 1\left(\frac{0.14}{10.81}\right)^{0.65}\left(\frac{4.78}{\sqrt{9.81 * 10.81}}\right)^{0.43}$$

$$y_{spc} = 3.48 * 0.06 * 0.72 * 10.81 = 1.63m$$

Determination of the Pile Group Scour Depth Component

$$\frac{y_{spc}}{y_3} = 2.0K_1K_3K_{hpg}\left(\frac{a^*{}_{pg}}{y_3}\right)^{0.65}\left(\frac{V_2}{\sqrt{gy_3}}\right)^{0.43}$$

$$h_3 = 4.9 + \frac{4.02 + 1.63}{2} = 7.73m$$

$$y_3 = 8.8 + \frac{4.02 + 1.63}{2} = 11.63m$$

$$v_3 = 5.875\left({}^{8.8}/_{11.63}\right) = 4.45m/s$$

$$a_{proj} = 2.9m$$

$$\frac{s}{a} = \frac{2.5}{0.45} = 5.55$$

$$\frac{a_{proj}}{a} = \frac{4.4}{0.45} = 6.44$$

$$k_{sp} = 1 - 1.33[1 - {}^{1}/_{a_{pro}/a}][1 - [{}^{S}/a]^{-0.6}]$$

$$k_{sp} = 1 - 1.33[1 - {}^{1}/_{6.44}][1 - 5.55^{-0.6}]$$

$$k_{sp} = 1 - 1.33[0.84][0.64] = 0.28$$

$$a_{pg}{}^{*} = 0.28 * 2.9 = 0.812$$

$$\frac{h_3}{y_3} = \frac{7.73}{11.63} = 0.66$$

$$k_{hpg} = 0.8$$

$$\frac{y_{spg}}{11.19} = 2.0 * 1 * 1.1 * 0.8\left(\frac{0.28}{11.63}\right)^{0.65}\left(\frac{4.45}{\sqrt{9.81 * 11.63}}\right)^{0.43}$$

$$y_{spg} = 1.76 * 0.089 * 0.69 * 11.63$$

$$y_{spg} = 1.26m$$

ANGLE 15(45m):

Determination of the Pier Stem Scour Depth Component

$$\frac{y_{spier}}{y} = 2.0k_1k_2k_3k_{hpier}\left(\frac{a_{pier}}{y_1}\right)^{0.65} F_{1r}{}^{0.43}$$

$$K_2 = [cos15 + 6sin15]^{0.65} = 1.82$$

$$\frac{y_{spier}}{8.8} = 2.0 * 1 * 1.82 * 1.1 * 1 \left(\frac{0.5}{8.8}\right)^{0.65} \left(\frac{5.875}{\sqrt{9.81 * 8.8}}\right)^{0.43}$$

$$y_{spier} = 4 * 0.164 * 0.82 * 8.8 = 4.62m$$

Bottom of the Pile Cap (Footing) in the Flow above the Bed

$$\frac{y_{spc}}{y_2} = 2.0K_1K_2K_3K_w \left(\frac{a^*{}_{pc}}{y_2}\right)^{0.65} \left(\frac{V_2}{\sqrt{gy_2}}\right)^{0.43}$$

$$h_2 = 4.9 + \frac{4.6}{2} = 7.21m$$

$$y_2 = 8.8 + \frac{4.6}{2} = 11.11m$$

$$v_2 = 5.875\left({}^{8.8}/_{11.11}\right) = 4.65m/s$$

$$\frac{T}{y_2} = \frac{1}{11.11} = 0.09 \cong 0.1$$

$$\frac{h_2}{y_2} = \frac{7.21}{11.11} = 0.65$$

$$since\ y_2 > 0.8a^*D_c, k_w = 1$$

$$a_{pc}{}^* = 0.03 * 4 = 0.12$$

$$\frac{y_{spc}}{11.11} = 2.0 * 1 * 1.82 * 1.1 * 1 \left(\frac{0.12}{11.11}\right)^{0.65} \left(\frac{4.65}{\sqrt{9.81 * 11.11}}\right)^{0.43}$$

$$y_{spc} = 4 * 0.053 * 0.45 * 11.11 = 1.06m$$

Determination of the Pile Group Scour Depth Component

$$\frac{y_{spc}}{y_3} = 2.0K_1K_3K_{hpg} \left(\frac{a^*{}_{pg}}{y_3}\right)^{0.65} \left(\frac{V_2}{\sqrt{gy_3}}\right)^{0.43}$$

$$h_3 = 4.9 + \frac{4.62 + 1.06}{2} = 7.74m$$

$$y_3 = 8.8 + \frac{4.62 + 1.06}{2} = 11.64m$$

$$v_3 = 5.875(^{8.8}/_{11.64}) = 4.44m/s$$

$$a_{proj} = 4.1m$$

$$\frac{s}{a} = \frac{2.5}{0.45} = 5.55$$

$$\frac{a_{proj}}{a} = \frac{4.1}{0.45} = 9.11$$

$$k_{sp} = 1 - 1.33[1 - {^1}/{_{a_{pro}/a}}][1 - [^s/_a]^{-0.6}]$$

$$k_{sp} = 1 - 1.33[1 - {^1}/{_{9.11}}][1 - 5.55^{-0.6}]$$

$$k_{sp} = 0.24$$

$$a_{pg}{}^{*} = 0.24 * 4.1 = 0.984$$

$$\frac{h_3}{y_3} = \frac{7.74}{11.64} = 0.66$$

$$k_{hpg} = 0.8$$

$$\frac{y_{spg}}{11.64} = 2.0 * 1 * 1.1 * 0.8 \left(\frac{0.984}{11.64}\right)^{0.65} \left(\frac{4.44}{\sqrt{9.81 * 11.64}}\right)^{0.43}$$

$$y_{spg} = 1.76 * 0.2 * 0.69 * 11.64$$

$$y_{spg} = 2.83$$

ANGLE 20(45m):

Determination of the Pier Stem Scour Depth Component

$$\frac{y_{spier}}{y} = 2.0k_1k_2k_3k_{hpier}\left(\frac{a_{pier}}{y_1}\right)^{0.65} F_{1r}{}^{0.43}$$

$$K_2 = [cos20 + 6sin20]^{0.65} = 2.04$$

$$\frac{y_{spier}}{8.8} = 2.0 * 1 * 2.04 * 1.1 * 1 \left(\frac{0.5}{8.8}\right)^{0.65} \left(\frac{5.875}{\sqrt{9.81 * 8.8}}\right)^{0.43}$$

$$y_{spier} = 4.49 * 0.16 * 0.82 * 8.8 = 5.18m$$

Bottom of the Pile Cap (Footing) in the Flow above the Bed

$$\frac{y_{spc}}{y_2} = 2.0K_1K_2K_3K_w \left(\frac{a^*{}_{pc}}{y_2}\right)^{0.65} \left(\frac{V_2}{\sqrt{gy_2}}\right)^{0.43}$$

$$h_2 = 4.9 + \frac{5.18}{2} = 7.49m$$

$$y_2 = 8.8 + \frac{5.18}{2} = 11.39m$$

$$v_2 = 5.875\left({}^{8.8}/_{11.39}\right) = 4.54m/s$$

$$\frac{T}{y_2} = \frac{1}{11.39} = 0.087 \cong 0.1$$

$$\frac{h_2}{y_2} = \frac{7.49}{11.39} = 0.66$$

$$since\ y_2 > 0.8a^*D_c, k_w = 1$$

$$a_{pc}{}^* = 0.03 * 4 = 0.12$$

$$\frac{y_{spc}}{11.39} = 2.0 * 1 * 2.04 * 1.1 * 1 \left(\frac{0.12}{11.39}\right)^{0.65} \left(\frac{4.54}{\sqrt{9.81 * 11.39}}\right)^{0.43}$$

$$y_{spc} = 4.49 * 0.052 * 0.69 * 11.39 = 1.83m$$

Determination of the Pile Group Scour Depth Component

$$\frac{y_{spc}}{y_3} = 2.0K_1K_3K_{hpg} \left(\frac{a^*{}_{pg}}{y_3}\right)^{0.65} \left(\frac{V_2}{\sqrt{gy_3}}\right)^{0.43}$$

$$h_3 = 4.9 + \frac{5.18 + 1.83}{2} = 8.41m$$

$$y_3 = 8.8 + \frac{5.18 + 1.83}{2} = 12.31m$$

$$v_3 = 5.875\left({}^{8.8}/_{12.31}\right) = 4.19m/s$$

$$a_{proj} = 5.2m$$

$$\frac{s}{a} = \frac{2.5}{0.45} = 5.55$$

$$\frac{a_{proj}}{a} = \frac{5.2}{0.45} = 11.55$$

$$k_{sp} = 1 - 1.33[1 - {}^{1}/_{a_{pro}/a}][1 - [{}^{s}/_{a}]^{-0.6}]$$

$$k_{sp} = 1 - 1.33[1 - {}^{1}/_{11.55}][1 - 5.55^{-0.6}]$$

$$k_{sp} = 0.22$$

$$a_{pg}{}^{*} = 0.22 * 5.2 = 1.144$$

$$\frac{h_3}{y_3} = \frac{8.41}{12.31} = 0.68$$

$$k_{hpg} = 0.83$$

$$\frac{y_{spg}}{12.31} = 2.0 * 1 * 1.1 * 0.83\left(\frac{1.144}{12.31}\right)^{0.65}\left(\frac{4.19}{\sqrt{9.81 * 12.31}}\right)^{0.43}$$

$$y_{spg} = 1.83 * 0.21 * 0.66 * 12.31$$

$$y_{spg} = 3.12m$$

ANGLE 25(45m):

Determination of the Pier Stem Scour Depth Component

$$\frac{y_{spier}}{y} = 2.0k_1k_2k_3k_{hpier}\left(\frac{a_{pier}}{y_1}\right)^{0.65} F_{1r}{}^{0.43}$$

$$K_2 = [cos25 + 6sin25]^{0.65} = 2.23$$

$$\frac{y_{spier}}{8.8} = 2.0 * 1 * 2.23 * 1.1 * 1\left(\frac{0.5}{8.8}\right)^{0.65}\left(\frac{5.875}{\sqrt{9.81 * 8.8}}\right)^{0.43}$$

$$y_{spier} = 4.91 * 0.164 * 0.82 * 8.8 = 5.67m$$

Bottom of the Pile Cap (Footing) in the Flow above the Bed

$$\frac{y_{spc}}{y_2} = 2.0K_1K_2K_3K_w\left(\frac{a^*{}_{pc}}{y_2}\right)^{0.65}\left(\frac{V_2}{\sqrt{gy_2}}\right)^{0.43}$$

$$h_2 = 4.9 + \frac{5.67}{2} = 7.74m$$

$$y_2 = 8.8 + \frac{5.67}{2} = 11.64m$$

$$v_2 = 5.875\left({}^{8.8}/{}_{11.64}\right) = 4.44m/s$$

$$\frac{T}{y_2} = \frac{1}{11.64} = 0.086 \cong 0.1$$

$$\frac{h_2}{y_2} = \frac{7.74}{11.64} = 0.66$$

$$since\ y_2 > 0.8a^*D_c, k_w = 1$$

$$a_{pc}{}^* = 0.03 * 4 = 0.12$$

$$\frac{y_{spc}}{11.64} = 2.0 * 1 * 2.23 * 1.1 * 1\left(\frac{0.12}{11.64}\right)^{0.65}\left(\frac{4.44}{\sqrt{9.81 * 11.64}}\right)^{0.43}$$

$$y_{spc} = 4.91 * 0.051 * 0.69 * 11.64 = 2.01m$$

Determination of the Pile Group Scour Depth Component

$$\frac{y_{spc}}{y_3} = 2.0K_1K_3K_{hpg}\left(\frac{a^*{}_{pg}}{y_3}\right)^{0.65}\left(\frac{V_2}{\sqrt{gy_3}}\right)^{0.43}$$

$$h_3 = 4.9 + \frac{5.67 + 2.01}{2} = 8.74m$$

$$y_3 = 8.8 + \frac{5.67 + 2.01}{2} = 12.64m$$

$$v_3 = 5.875(^{8.8}/_{12.64}) = 4.09m/s$$

$$a_{proj} = 6.2m$$

$$\frac{s}{a} = \frac{2.5}{0.45} = 5.55$$

$$\frac{a_{proj}}{a} = \frac{6.2}{0.45} = 13.78$$

$$k_{sp} = 1 - 1.33[1 - {}^{1}/_{a_{pro}/a}][1 - [{}^{s}/_{a}]^{-0.6}]$$

$$k_{sp} = 1 - 1.33[1 - {}^{1}/_{13.78}][1 - 5.55^{-0.6}]$$

$$k_{sp} = 0.21$$

$$a_{pg}{}^{*} = 0.21 * 6.2 = 1.302$$

$$\frac{h_3}{y_3} = \frac{8.74}{12.64} = 0.69$$

$$k_{hpg} = 0.83$$

$$\frac{y_{spg}}{12.64} = 2.0 * 1 * 1.1 * 0.83 \left(\frac{1.302}{12.64}\right)^{0.65} \left(\frac{4.09}{\sqrt{9.81 * 12.64}}\right)^{0.43}$$

$$y_{spg} = 1.83 * 0.23 * 0.65 * 12.64$$

$$y_{spg} = 3.46m$$

ANGLE 30(45m):

Determination of the Pier Stem Scour Depth Component

$$\frac{y_{spier}}{y} = 2.0k_1k_2k_3k_{hpier}\left(\frac{a_{pier}}{y_1}\right)^{0.65} {F_{1r}}^{0.43}$$

$$K_2 = [cos30 + 6sin30]^{0.65} = 2.4$$

$$\frac{y_{spier}}{8.8} = 2.0 * 1 * 2.4 * 1.1 * 1\left(\frac{0.5}{8.8}\right)^{0.65}\left(\frac{5.875}{\sqrt{9.81 * 8.8}}\right)^{0.43}$$

$$y_{spier} = 5.28 * 0.164 * 0.82 * 8.8 = 6.12m$$

Bottom of the Pile Cap (Footing) in the Flow above the Bed

$$\frac{y_{spc}}{y_2} = 2.0K_1K_2K_3K_w\left(\frac{a^*{}_{pc}}{y_2}\right)^{0.65}\left(\frac{V_2}{\sqrt{gy_2}}\right)^{0.43}$$

$$h_2 = 4.9 + \frac{6.12}{2} = 7.96m$$

$$y_2 = 8.8 + \frac{6.12}{2} = 11.86m$$

$$v_2 = 5.875\left({}^{8.8}/_{11.86}\right) = 4.36m/s$$

$$\frac{T}{y_2} = \frac{1}{11.86} = 0.08 \cong 0.1$$

$$\frac{h_2}{y_2} = \frac{7.96}{11.82} = 0.67$$

$$since\ y_2 > 0.8a^*D_c, k_w = 1$$

$$a_{pc}{}^* = 0.025 * 4 = 0.1$$

$$\frac{y_{spc}}{11.86} = 2.0 * 1 * 2.4 * 1.1 * 1\left(\frac{0.1}{11.86}\right)^{0.65}\left(\frac{4.36}{\sqrt{9.81 * 11.86}}\right)^{0.43}$$

$$y_{spc} = 5.28 * 0.046 * 0.77 * 11.86 = 2.18m$$

Determination of the Pile Group Scour Depth Component

$$\frac{y_{spc}}{y_3} = 2.0K_1K_3K_{hpg}\left(\frac{a^*{}_{pg}}{y_3}\right)^{0.65}\left(\frac{V_2}{\sqrt{gy_3}}\right)^{0.43}$$

$$h_3 = 4.9 + \frac{6.12 + 2.18}{2} = 9.05m$$

$$y_3 = 8.8 + \frac{6.12 + 2.18}{2} = 12.95m$$

$$v_3 = 5.875\left({}^{8.8}/_{12.95}\right) = 3.94m/s$$

$$a_{proj} = 7.1m$$

$$\frac{s}{a} = \frac{2.5}{0.45} = 5.55$$

$$\frac{a_{proj}}{a} = \frac{7.1}{0.45} = 15.78$$

$$k_{sp} = 1 - 1.33[1 - {}^{1}/_{a_{pro}/a}][1 - [{}^{s}/_{a}]^{-0.6}]$$

$$k_{sp} = 1 - 1.33[1 - {}^{1}/_{15.78}][1 - 5.55^{-0.6}]$$

$$k_{sp} = 0.19$$

$$a_{pg}{}^{*} = 0.19 * 7.1 = 1.35$$

$$\frac{h_3}{y_3} = \frac{9.05}{12.95} = 0.69$$

$$k_{hpg} = 0.83$$

$$\frac{y_{spg}}{12.95} = 2.0 * 1 * 1.1 * 0.85\left(\frac{1.35}{12.95}\right)^{0.65}\left(\frac{3.99}{\sqrt{9.81 * 12.95}}\right)^{0.43}$$

$$y_{spg} = 1.83 * 0.23 * 0.64 * 12.95$$

$$y_{spg} = 3.49\ m$$

ANGLE OF ATTACK	TOTAL DEPTH OF LOCAL SCOUR
0	7.62
5	7.62
10	6.91
15	8.51
20	10.13
25	11.14
30	11.79

Table 4.2 calculation summary of 45m span bridge using HEC18

4.2 ESTIMATION OF LOCAL SCOUR AT PIER USING BD 93/12

ANGLE 0

$D_L = K.W_P.f_{PS}.f_{PA}.f_y$

Where K = 1.5 (constant empirical factor)

W_P = 0.5m (width of the pier)

$L/W_P = 6/0.5 = 6 = 6.0$ (rectangular shape of pier) so, $f_{PS} = 1.4$

$f_{PA} = (\cos\alpha + L/W_P \sin\alpha)^{0.65}$ (factor depending on angle of attack)

Where $\alpha = 0^o$

$f_{PA} = (\cos 0^o + 6\sin 0^o)^{0.65} = 1$

For $f_y = 1.0$ ($y_{sp} = y_B + D_c > 2.6W_P$)

$D_L = 1.5 \times 0.5 \times 1.4 \times 1.0 \times 1.0 = 1.05$m

ANGLE 5

$D_L = K.W_P.f_{PS}.f_{PA}.f_y$

Where K = 1.5 (constant empirical factor)

W_P = 0.5m (width of the pier)

$L/W_P = 6/0.5 = 6 = 6.0$ (rectangular shape of pier) so, $f_{PS} = 1.4$

$f_{PA} = (\cos\alpha + L/W_P \sin\alpha)^{0.65}$ (factor depending on angle of attack)

Where $\alpha = 5^o$

$f_{PA} = (\cos 5^\circ + 6\sin 5^\circ)^{0.65} = 1.31$

For $f_y = 1.0$ ($y_{sp} = y_B + D_c > 2.6W_P$)

$D_L = 1.5 \times 0.5 \times 1.4 \times 1.31 \times 1.0 = 1.38$m

ANGLE 10

$D_L = K.W_P.f_{PS}.f_{PA}.f_y$

Where K = 1.5 (constant empirical factor)

$W_P = 0.5$m (width of the pier)

$L/W_P = 6/0.5 = 6 = 6.0$ (rectangular shape of pier) so, $f_{PS} = 1.4$

$f_{PA} = (\cos\alpha + L/W_P \sin\alpha)^{0.65}$ (factor depending on angle of attack)

Where $\alpha = 10^\circ$

$f_{PA} = (\cos 10^\circ + 6\sin 10^\circ)^{0.65} = 1.58$

For $f_y = 1.0$ ($y_{sp} = y_B + D_c > 2.6W_P$)

$D_L = 1.5 \times 0.5 \times 1.4 \times 1.58 \times 1.0 = 1.659$m

ANGLE 15

$D_L = K.W_P.f_{PS}.f_{PA}.f_y$

Where K = 1.5 (constant empirical factor)

$W_P = 0.5$m (width of the pier)

$L/W_P = 6/0.5 = 6 = 6.0$ (rectangular shape of pier) so, $f_{PS} = 1.4$

$f_{PA} = (\cos\alpha + L/W_P \sin\alpha)^{0.65}$ (factor depending on angle of attack)

Where $\alpha = 15^\circ$

$f_{PA} = (\cos 15^\circ + 6\sin 15^\circ)^{0.65} = 1.58$

For $f_y = 1.0$ ($y_{sp} = y_B + D_c > 2.6W_P$)

$D_L = 1.5 \times 0.5 \times 1.4 \times 1.83 \times 1.0 = 1.92$m

ANGLE 20

$D_L = K.W_P.f_{PS}.f_{PA}.f_y$

Where K = 1.5 (constant empirical factor)

$W_P = 0.5$m (width of the pier)

$L/W_P = 6/0.5 = 6 = 6.0$ (rectangular shape of pier) so, $f_{PS} = 1.4$

$f_{PA} = (\cos\alpha + L/W_P \sin\alpha)^{0.65}$ (factor depending on angle of attack)

Where $\alpha = 20^o$

$f_{PA} = (\cos20^o + 6\sin20^o)^{0.65} = 2.04$

For $f_y = 1.0$ ($y_{sp} = y_B + D_c > 2.6W_P$)

$D_L = 1.5 \times 0.5 \times 1.4 \times 2.04 \times 1.0 = 2.142m$

ANGLE 25

$D_L = K.W_P.f_{PS}.f_{PA}.f_y$

Where K = 1.5 (constant empirical factor)

$W_P = 0.5m$ (width of the pier)

$L/W_P = 6/0.5 = 6 = 6.0$ (rectangular shape of pier) so, $f_{PS} = 1.4$

$f_{PA} = (\cos\alpha + L/W_P \sin\alpha)^{0.65}$ (factor depending on angle of attack)

Where $\alpha = 25^o$

$f_{PA} = (\cos25^o + 6\sin25^o)^{0.65} = 2.23$

For $f_y = 1.0$ ($y_{sp} = y_B + D_c > 2.6W_P$)

$D_L = 1.5 \times 0.5 \times 1.4 \times 2.23 \times 1.0 = 2.352m$

ANGLE 30

$D_L = K.W_P.f_{PS}.f_{PA}.f_y$

Where K = 1.5 (constant empirical factor)

$W_P = 0.5m$ (width of the pier)

$L/W_P = 6/0.5 = 6 = 6.0$ (rectangular shape of pier) so, $f_{PS} = 1.4$

$f_{PA} = (\cos\alpha + L/W_P \sin\alpha)^{0.65}$ (factor depending on angle of attack)

Where $\alpha = 30^o$

$f_{PA} = (\cos30^o + 6\sin30^o)^{0.65} = 2.4$

For $f_y = 1.0$ ($y_{sp} = y_B + D_c > 2.6W_P$)

$D_L = 1.5 \times 0.5 \times 1.4 \times 2.4 \times 1.0 = 2.52$

ANGLE OF ATTACK	TOTAL DEPTH OF LOCAL SCOUR
0	1.05
5	1.38
10	1.66
15	1.92
20	2.14
25	2.35
30	2.52

Table 4.3 calculation summary using BD97/12

4.3 DISCUSSION OF THE RESULT OF ANALYSES

From the analysis above, the angle of attack was varied from 0° to 30°, using the formula provided in HEC 18 and BD 97/12 for evaluating local scour at bridge pier. The variation in the angle of attack caused changes in the total local scour around bridge piers, as shown in the table above.

See the graphical presentation below for further explanation:

4.3.1 HEC 18 result analysis

At the 60m span bridge, the following where the observation gotten from the calculation:

i. When the angle at which water attack the bridge pier was 0°, the local scour of the bridge was calculated as 11.2m.
ii. When the angle at which water attack the bridge was increased to 10°, a decrease in the calculated depth of local scour was observed, which is from 11.2m to 10.67m
iii. Further increase in the angle of attack of flow water from 10° to 15° was observed to give an increase in the calculated depth of the local scour. The value gotten (12.86m) is higher than the value gotten from angle 0° (11.2m).
iv. For further investigation, the angle of attack of the flow was further increased from 15° to 20°, 25°, and 30°. This steady increase in the angle of attack gave a steady increase in the calculated local scour depth from

12.86m to 13.71m, 15.53m, and 16.74m in respect to the increase angle of attack.

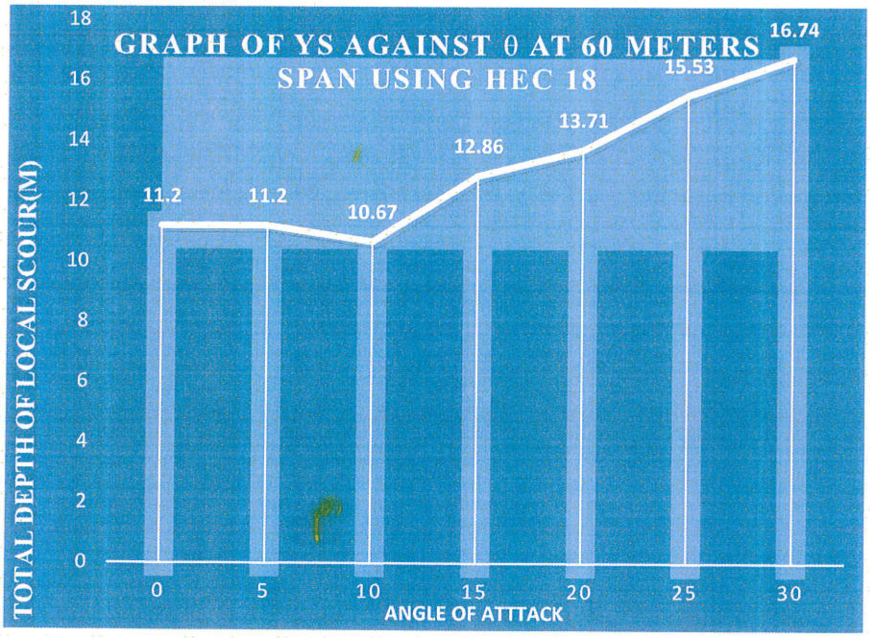


Figure 4.1 Graph of Y_s against θ at 60 meters span using HEC 18

At the 45m span bridge, the following where the observation gotten from the calculation:

i. When the angle at which water attack the bridge pier was 0°, the local scour of the bridge was calculated as 7.62m.
ii. When the angle at which water attack the bridge was increased to 10°, a decrease in the calculated depth of local scour was observed, which is from 7.62m to 6.91m
iii. Further increase in the angle of attack of flowing water from 10° to 15° was observed to give an increase in the calculated depth of the local scour. The value gotten (8.5m) is higher than the value gotten from angle 0° (7.62m).
iv. For further investigation, the angle of attack of the flow was further increased from 15° to 20°, 25°, and 30°. This steady increase in the angle of attack gave a steady increase in the calculated local scour depth from 12.86m to 10.13m, 11.14m, and 11.79m respectively.

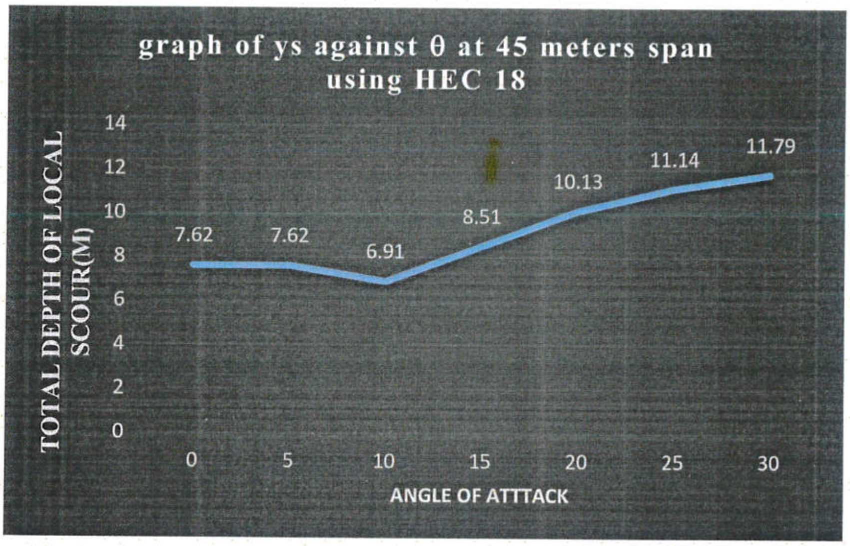


Figure 4.2 **Graph of Y_s against θ at 45 meters span using HEC 18**

4.3.2 BD 97/12 result analysis

On like HEC 18, BD 97/12 show a continuous increase from 0° to 30°. it is observed that at 0°, the scour depth is 1.05m and with further increase in angle, at 5°, the scour depth increased to 1.38m, at 10°, it increased to 1.66m, at 15°, the depth further increased to 1.92m, at 20°, the scour depth increased to 2.14m, at 25°, the scour depth increased to 2.35m, and at 30°, the scour depth increased to 2.52m.

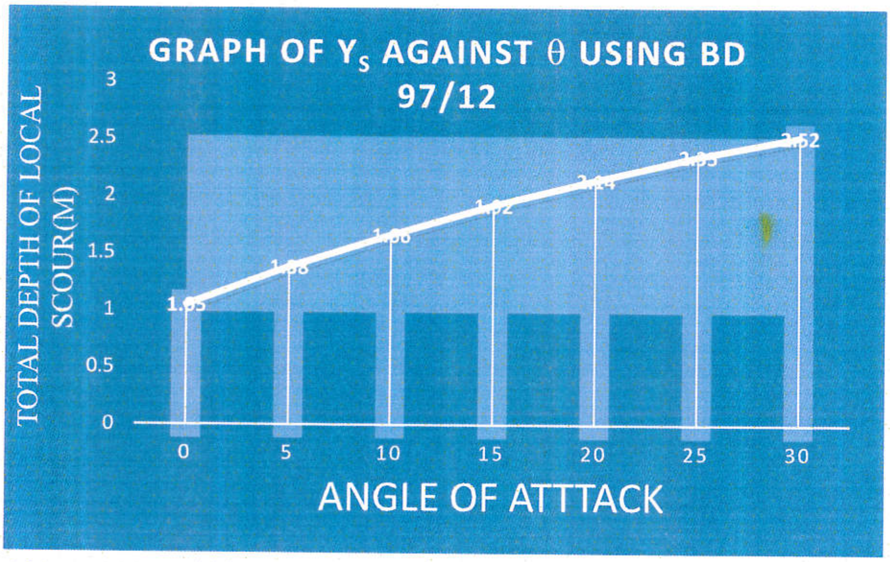


Figure 4.3 Graph of Y_s against θ using BD 97/12

4.3.3 What causes increase in the angle of attack?

Scour causes an evolution in the look of a river channel by the effect of the water that acts on the earth material of the river, thereby affecting the size and shape of the river. As water moves through a river channel, if the channel is straight, the water that washes the sand of the river channel will cause the river channel to start widening up, causing a meandering effect on the channel until a relatively stable point is reached. Until a stable point is reached, the shape of the river channel will keep changing. See figure 2.4A on page 13.

The angle of attack of flow for piers is the angle between the flow direction and the major axis of the pier alignment. The depth of local scour for all shapes of pier, except cylindrical, depends strongly on the alignment to flow. The depth of scour is a function of the projected width of the pier (Fig. 2.20 a, b), i.e. the width normal to the flow (Breusers and Raudkivi 1991), where the projected width of the pier is the width normal to the flow direction. As the angle of attack increases, the scour depth increases due to the increase in effective frontal width of the pier (Melville and Coleman, 2000) and the point of maximum scour depth moves along the exposed side of the pier towards the rear, and the scour depth at the rear becomes greater than that at the front face of the pier. The angle of attack, for which the scour becomes deeper at the rear, depends on the ratio of the length of the pier to its width. Values of alignment factor *Ke* for piers given by Richardson *et. al.* (2001) are reasonably consistent with the widely used Laursen and Toch. (1956) curve. In practice, the angle of attack at bridge crossings may change significantly durmg floods for braided channels, and it may change progressively over a period of time for meandering chaimels (Melville and Coleman 2000).

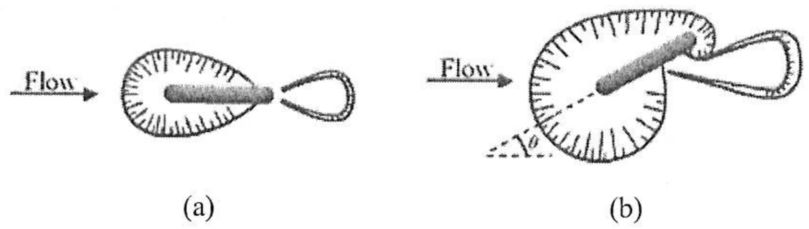


Plate 4.4 Diagrammatic scour shapes at round - nosed rectangular pier (a) aligned with the flow (b) at an angle of attack

4.4 OBSERVATION:

4.4.1 Differences observed between HEC18 and BD 97/12

BD 97/12 provided formula for finding scour of a simple pier without considering other foundation components like the pile cap, and the pile group, while HEC 18 did.

Comparing the values gotten for the pier scour at the bridge, HRC 18 provided results that are higher in values than that gotten from BD 97/12

HEC 18 considered froud number as part of the parameters needed to estimate the local pier scour at bridges, BD 97/12 doesn't.

4.4.2 Similarities observed in HEC 18 and BD 97/12

Both formulas shows an increase in scour with respect to increase in the angle of attack except at angle 10 using HCE 18, where there is a decrease in the scour hole. See explanation above in figure

4.4.3 Other observations:

Mining activity: it was observed that there are some people that illegally mine the available soil at the river banks to sell.

CHAPTER 5

5.0 SUMMARY

The outline of the project report id as stated below:

Chapter one which is the background of the study define scour, and brief discussion on scour problem. It presented the bridge to be considered which lies within the south west part of Nigeria in ogun and ondo states. This same chapter gave the problem statement, talking about places affected by scour, loss in the economy of such state, and comparing the amount needed for demolition and reconstruction to maintans. The aim and objectives of the project was declared in this chapter, the scope of the project is not left out.

The chapter two, which is the literature review of the project report spelt out the type of scour, Geotechnical considerations needed for scour estimation, stream stability and migration, bridge pier flow field. This part of the project report also review two principal manuals available for determining scour at bridges, putting all of the attention on local scour at bridges. Likewise, investigation on local scour done by other persons where considered.

The methodology of the project is stated in chapter 3, it spelt out the formula from both manuals required for the calculation of local scour at bridge piers.

Chapter 4 is the analysis of the project. This part of the write up has the calculation done on scour estimation, and the result (observations).

Chapter 5 is the summary of the project, the conclusion, and limitation of the project.

5.1 CONCLUSION

The project involve going to a bridge site to obtain data's. The data gotten from the bridge site was used in the analysis compiled in the chapter 4 above. The formula used for the analysis is gotten from BD 97/12 and HEC 18. From BD 97/12, the following parameters were counted important for the estimation of local bridge scour; W_p [width of pier], and α[Angle of attack]. While, HEC 18 presented the following parameter to be of great important in estimating local bridge pier; a [width of pier], y_1 [depth of approaching flow], θ[angle of attack], v [velocity of approaching flow].

It was observed that the values gotten from the estimation of scour using HEC 18 gave outrageous result even though it consider every component of a complex pier, while BD 97/12 can only be used for the estimation of simple pier.

5.2 LIMITATION AND RECOMMENDATION

1. HEC 18 has two methodology available for calculating ;
   (a) Simple bridge for pier, and
   (b) Complex bridge pier.

   While there is just a single methodology provided by BD97/12 which is for a simple bridge. But the bridge considered in this project is a complex pier bridge; therefore, another approach that considers a complex pier bridge should be used on the bridge considered in this project, and the result should be compared together with those of HEC 18.
2. The Federal government should enforce the embargo against illegal mining of sand, especially around the river banks, for this activity affects the design life of the constructed bridge.

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