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Evaluation Of Performance Of Empirical Models For The Prediction Of Local Scour At Bridge Piers (Case Study Chanchaga Bridge, Minna, Nigeria)

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Abstract

Scour is the removal of sediment from streambeds and stream-banks and is caused by the erosive action of flowing water. It is more significant during high flow events under high velocity. Due to the complexity of stream dynamics, scour is often exacerbated at bridge piers and abutments, potentially undermining the structure and jeopardizing its stability. The accurate prediction of sediment scour depths near bridge piers under design storm conditions is very important in bridge design, especially when the bridge is located in an un-gauged catchment. The physical processes involved are very complex and difficult to analyze, and, thus, most design scour depth predictive equations are based on laboratory scale experimental results. Here, laboratory study was combined with onsite measurements to obtained relevant parameters. The parameters were fed into empirical models. Subsequently, the best empirical model is determined for estimation of local pier scour at downstream of the Tagwai intake weir among the numerous empirical models. This is achieved by using consistency-correlation analysis which compared the measured depth of scour and calculated depth of scour obtained using selected empirical models.

Keywords: ***Bridge pier, Local scour, empirical models***

1. Introduction

Scour is the removal of sediment from streambeds and stream banks and is caused by the erosive action of flowing water. It can occur at anytime but is more significant during high flow events, when water is moving at a high velocity. Due to the complexity of stream dynamics, scour is often exacerbated at bridge piers and abutments, potentially undermining the structure and jeopardizing its stability (Peggy and Daniel, 1998). This often led to extremely high direct and indirect costs and, in extreme cases, the loss of human lives (Toth and Brandimarte, 2011).

Scour has been discovered in recent time to be the paramount cause of bridge collapse. This is evident in number of bridge that has been reported damaged and subsequently collapse throughout the globe due to scour Peggy and Bilal, (1996). Nigeria has experience her fair share of the devastating effect of scour.

Recently, Busari et al, (2013) evaluates the best probability distribution model for the prediction of rainfall- runoff for Tagwai basin, and suggested appropriate model for the estimation of annual runoff from the basin. The overflow from Tagwai (weir) is the chief source erosion to the downstream channel along which Chanchaga bridge is located. Pagliara and Carnacina, (2011) carried out laboratory experiment to investigate the effect of large woody debris on sediment scours at bridge piers and proposed relationships to predict the effect of drift accumulation on bridge pier scour, both in terms of relative maximum scour and temporal scour evolution.

Scouring has long been acknowledged as a severe hazard to the performance of bridge piers. The total scour at a river crossing consists of three components that, in general, can be added together as explained by Richardson and Davies, (1995). They include general scour, contraction scour, and local scour, on the other hand divided scour into two major types, namely general scour and localized scour. Some other sub-divisions of scour can be found from (Stephen et al. 2003 and Mushair et al. 2004).

Lagasse and Richardson, (2001) shows the flow and scour pattern at a circular pier (figure 1). The strong vortex motion caused by the existence of the pier entrains bed sediments within the vicinity of the pier base. According to Richardson and Davies, (1995) the separation of the flow at the sides of the pier produces wake vortices. These wake vortices are not stable and shed alternately from one side of the pier and then the other. It should be noted, however, that both the horseshoe and wake vortices erode material from the base region of the pier. The intensity of the wake vortices is drastically reduced with distance downstream, such that sediment deposition is common immediately downstream of the pier (Ahmed and Rajaratnam, 1998).

This study evaluates the some empirical models used in estimation of bridge-pier scour, and assesses the empirical models that will provide a reliable design estimate of scour depth. The selected models were found to be adequate for the study area in terms of hydraulic conditions and associated model input parameters. The models evaluated in this study are equations that make use of the principal parameters that constitute the basic entity that influence the occurrence of bridge scour. The accuracy of result obtained from selected empirical models, by subjecting the calculated depth of scour and onsite measured depths of scour to consistency-correlation analysis.

The aim of the study is mainly focus on determination of best empirical model that can be use to estimation of local pier scour at downstream of the Tagwai intake weir among the numerous empirical models. This was achieved by using consistency-correlation analysis on the measured depth of scour and calculated depth of scour. The principal objectives are: firstly, to carry out a much longer duration test than is currently reported at the site with a view to evaluating equations developed in estimation of the local scour at a bridge pier; secondly, to be assessed are common equations that describe the temporal development of pier scour, using correlation analysis to ascertain relativity in terms of accuracy of the some empirical models compare to the measured depth of bridge scour. Finally, to focus on determination and measurement of accurate parameters of the bridge that can be further be used for subsequent research on the bridge.

The accurate prediction of sediment scour depths near bridge piers under design storm conditions is very important in bridge design. Under-prediction can result in costly bridge failure and possibly in the loss of lives, while over-prediction can result in wasted capital during the construction of a single bridge. The physical processes involved are very complex and difficult to analyze, and, thus, most design scour depth predictive equations are based on laboratory scale experimental results.

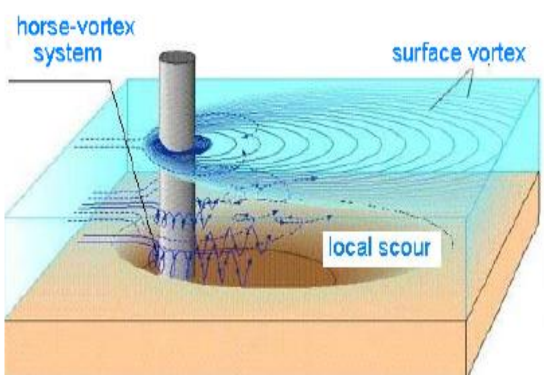

Figure 1: Schematic local pier scour process

2. The Study Area

The Chanchaga Bridge is situated at longitude 6˚ 391-6˚ 441E and latitude 9˚ 34-9˚ 37˚ N across the river Chanchaga south west of Minna. The length of the bridge is about 256m, height of 6.1m and width of 10.5m. Throughout the year, the bridge experiences continuous flow of the water underneath it. This is due to the present of water retaining structure (weir) some few meters from upstream the bridge.

The bridge which was built some 35 years ago to link the state capital to Abuja the Federal Capital Territory, the bridge has contributed immensely to social and political integration of people living in Minna and its environments. The bridge has also contributed to speedily economic growth of Chanchaga environs and Minna by aiding easy transportation of goods, passenger and technology.

The river flowing under the bridge originated from confluence of river Tagwai and Jidno South-west of Minna (see Figure 2). The river is perennial due to presence of a dam upstream the bridge, that help it to retain water during the raining season and discharge it during dry season. The catchment area of the river is about 120km^2. There are secondary vegetation in the area which consists mainly of shrubs and open grass land. The landscape of the Chanchaga river area is made up of flat-lying to undulating terrains. The geology of the area is made up of Precambrian basement complex with varieties of igneous and metamorphic rock and sedimentary basin comprising of Alluvium found along valleys of the project area.

The Chanchaga area has a population of about 12000 – 13000 inhabitants, the majority being the Gwari's. Most of these people in the area are subsistence farmers and fishermen. They practice mixed farming system.

Figure 2: Chanchaga bridge, Minna-Nigeria

The agricultural activities of the farmer is expected to change appreciably with the construction of the dam due to the occurrence of flooding and dry season farming which is expected to occur due to the dam constructed.

3. Framework for analysis

The relation between the depth of scour at a bridge pier y_s, and its dependent parameters can be written as:

$$y_s = f[Flood\ flow\ (\rho, \nu, V, g, y_a),$$

$$Bed\ sediment\ (\rho_s, d_{50}, V_c),$$

$$Bridge\ pier\ \ geometry(a, K_\zeta), Time\ (t)] \quad (1)$$

where $\rho\ and\ \nu$ are fluid density and kinematic viscosity respectively.

V is the mean approach velocity

y_a is mean approach depth of flow and $g$is the gravitational constant

ρ_s is the density of sediment

d_{50} is the bed sample median size

V_c is the critical bed shear velocity

$a,$ is the pier width and

K_ζ is the shape and alignment factor

4. Selected empirical models

Parameters obtained from field combined with the calculate parameters were fitted into the five empirical models adopted for this research to calculate depth of scour. Then, the depth of flow was varied while all other parameters remain unchanged. The depths of scour obtained from these empirical equations were compared with measured scour depth at different depth.

The five empirical equations used in this research to calculate the depth of scour are:

4.1 Richardson Davis Model

The Richardson Davis model for estimating the depth of local scour at pier (HEC 18), colloquially called C.S.U equation, extends back about 35 years and has been updated several times to account for additional influence of the parameters.

The Richardson and Davis equation predict maximum local pier scour depths for both live bed and clear pier scour. The equation is:

$$y_s = 2K_1K_2K_3K_4a^{0.65}y_1^{0.35}F_{r1}^{0.43} \quad (2)$$

where

K_1 = Correction factor for pier nose shape

K_2 = Correction factor for angle of attack of flow

K_3 = Correction factor for bed condition

K_4 = Correction factor for armoring of bed material

a = pier width (m)

y = flow depth directly upstream of the pier (m)

Fr_1 = Froude number directly upstream of the pier

$$F_{r1} \frac{V}{\sqrt{gy}} \quad (3)$$

Table 1: Correction factor for pier nose shape K_1

Shape of pier nose	K_1
Square nose	1.1
Round nose	1.0
Circular cylinder	1.0
Group cylinder	1.0
Triangular	0.9

Source: (Richardson and Davis, 1995)

The correction factor for angle of attack of flow, k_2 is calculated in the equation below:

$$K = [cos\theta + L/a \ sin\theta\ ]^{0.65} \quad (4)$$

Where

L = pier length along the flow line (m)

θ = angle of attack of the flow with respact to the pier

K_3 = 1.1

$$K_4 = 0.4(V_R)^{0.25} \quad (5)$$

$$V_R = \frac{V_i - V_{i50}}{V_{c50} - V_{i90}} \quad (6)$$

$$V_{i50}=0.645[D_{50}/a]^{0.053}V_{c50} \quad (7)$$

$$V_{i90}=0.645[D_{90}/a]^{0.053}V_{c90} \quad (8)$$

V_R = Velocity ratio

V_i = Average velocity in the main channel (m/s)

V_{i50} = approach velocity required to initiate scour at pier for grain size D_{50} (m/s)

V_{i95} = approach velocity required to initiate scour at pier for grain size D_{95} (m/s)

V_{c50} = critical velocity for D_{50} bed material size (m/s)

V_{c90} = critical velocity for D_{90} bed material size (m/s)

$$V_{c50}=K_u y^{1/6} D_{50}^{1/3} \quad (9)$$

$$V_{c90}=K_u y^{1/6} D_{90}^{1/3} \quad (10)$$

K_u = 6.19

Table 2: Correction factor for armoring of bed material (K_4)

Factors	Minimum bed material size	Minimum (K_4) value
K_4	$D_{50} \geq 0.002$mm $D_{95} \geq 0.02$mm	0.4

Source: (Richardson and Davis, 1995)

4.2. The Sheppard- Melville Model

The Sheppard- Melville model builds on the method purposed by Sheppard and Melville, following more or less the same parameter, approach inherent in the Melville (1997) method. The model used an effective pier diameter (a^*) the diameter of a circular pile that will experience the same equilibrium scour depth as the subject structure under the same flow sediments condition. In other words pier shape and alignment factor are used to determine a^* which then is used in the methods equation set. The Sheppard-Melville model comprises of two equations they are:

For clear water scour ($0.4<V/V_c<1$)

$$\frac{y_s}{a^*} = 2.5 f_1\left(\frac{y}{a^*}\right) f_2\left(\frac{V}{V_c}\right) f_3\left(\frac{a^*}{D_{50}}\right) \qquad (11)$$

For the live bed scour range ($1<V/V_c<V_{lp}/V_c$)

$$\frac{y_s}{a^*} = f_i \frac{y}{a^*}\left[\begin{array}{c} 2.2\left[\frac{\frac{V}{V_c}-1}{\frac{V_{lp}}{V_c}-1}\right]+ \\ 2.5\left[\frac{\frac{V_{lp}}{V_c}-\frac{V}{V_c}}{\frac{V_{lp}}{V_c}-1}\right] f_3\left(\frac{a^*}{D_{50}}\right)\end{array}\right] \qquad (12)$$

For live bed scour range above the live peak ($V/V_c> V_{lp}/V_c$)

$$\frac{y_s}{a^*} = 2.2 f_1\left(\frac{y}{a^*}\right) \qquad (13)$$

where

$$f_1 = 2.2\tanh\left(\frac{y}{a^*}\right)^{0.4} \qquad (14)$$

$$f_2 = \left[1 - 1.2\left[\ln\frac{V}{V_c}\right]^2\right] \qquad (15)$$

$$f_3 = \left[\frac{\left(\frac{a^*}{D_{50}}\right)}{0.4\left(\frac{a^*}{D_{50}}\right)^{1.2}+10.6\left(\frac{a^*}{D_{50}}\right)^{-0,13}}\right] \qquad (16)$$

And V_{lp} is the live bed peak velocity, much the same is V_a in the Melville (1997) method.

The sediment critical velocity, V_c is calculated using shield curve

$$V_{lp} = 0.6\sqrt{gy} \qquad (17)$$

Similarly,

$$V_{lp} = 5V_c \qquad (18)$$

a^*= effective diameter

$= 0.86 + 0.97\ [(\propto - \frac{\pi}{4})]^4$

$\propto$ = flow skew angle in radian

4.3. Froehlich David Model

Froehlish equation is based on onsite measurements; the equation predicts the expected maximum depth of local scour at a bridge and suggested safety factor that provides reasonable margin of error for design purposes. The model is described as follows:

$$\frac{y_s}{a} = 0.32 k_s F_r^{\,0.2}\left(\frac{a_p}{a}\right)^{0.62}\left(\frac{y}{a}\right)^{0.46}\left(\frac{a}{D_{50}}\right)^{0.08} \qquad (19)$$

$$a_p = b\sin\theta + a\cos\theta \qquad (20)$$

a_p= projected width of the pier

4.4. Gao Model

The estimate maximum depth of local scour is given by:

$y_s =$

$$0.46k_{\zeta}a^{0.62}y^{0.45}D_{50}{}^{-0.07}\left[\frac{V_i-V'_c}{V_c-V'_c}\right]^{\eta} \quad (21)$$

$$V_c = \left(\frac{y}{a}\right)^{0.14}\left[17.6\left[\frac{\rho_s-\rho}{\rho}\right]D_{50} + 6.05 \times 10^{-7}\left[\frac{10+y}{D_{50}{}^{0.72}}\right]\right] \quad (22)$$

$$V_c{}' = 0{,}645\left[\frac{D_{50}}{a}\right]^{0.53} V_c \quad (23)$$

$$\eta=[V_C/V]^{9.35+2.23\mathrm{Log}D_{50}} \quad (24)$$

where, $V_C{}^1$ = Incipient velocity for local scour at pier and η = 1 for clear water scour<1 for live bed scour.

4.5. Melville Model

The adopted maximum depth of local scour according to Melville is given by:

$$y_s = K_\theta K_{yb} K_i K_d K_S \quad (25)$$

$K_{yb} = 2.4a$ when $y/a > 1.4$

$$K_{yb} = 2(ya)^{0.5} \quad (26)$$

when $0.2 \le y/a \le 1.4$

$K_{yb} = 4.5y$ when $y/a < 0.2$

$$K_i = \frac{V-(V_{lp}-V_c)}{V_c} \quad (27)$$

$$V_{lp} = 0.6\sqrt{gy} \quad (28)$$

$$V_{c50} = K_u Y^{1/6} D_{50}{}^{1/3} \quad (29)$$

5. Methodology

In this research project, the method adopted consists of mainly laboratory experiment on riverbed material granulometry, onsite measurements and desk study.

5.1 Laboratory riverbed grading analysis

The laboratory study involved the sediment size distribution measurement and the specific gravity test.

Particle size distribution can be measured using different methods. The adopted methods are the pipette method, the hydrometer method and the sieve analysis method.

Five samples A, B, C, D, and E were taken from different spots on the site. Sample A, B, C, were taken downstream of the bridge and samples D and E were taken upstream between the weir and the bridge.

$$\%\ \text{mass retained} = \frac{\text{weight of sample on sieve}}{\text{weight of original sample}} \times 100$$

The specific gravity of the soil sample was determined using the density bottle method.

The specific gravity of the soil sample (G_s) is calculated using the following,

$$Gs = \frac{M_2 - M_1}{(M_4 - M_1) - (M_3 - M_2)} \quad (30)$$

Where, M_1 is mass of density bottle

M_2 is the mass of soil sample + density bottle

M_3 is the mass of soil sample + density bottle + distilled water.

M_4 is the mass of water + density bottle

5.2 Onsite measurement

5.2.1 Measurement of Bankfull Discharge

The discharge over the weir was measured and followed the relation:

$$Q = \mu L H^{3/2} \sqrt{(2g)} \qquad (31)$$

where the calibrated coefficient is given by $\mu = {}^{2}/_{3\sqrt{3}} \left[1 + {}^{4x}/_{9+4x}\right]$ and $x = \frac{H}{H_d}$. Several values of the discharges obtained at the weir where used to plot a rating curve and the rating was correlated with measurement result obtained by Saidu, (2007).

The parameters measured in the field are bridge pier geometry, hydraulic properties of the stream and bed sediment.

Consistency-Correlation analysis is then carry out between each of the three results (calculated depth of scour) from three empirical models and the measured depth of scour to ascertain the degree of correlation of each result (calculated scour depth) obtained from three empirical models to the measured depth of scour.

6. Results and discussion

Parameters as measured and required for the estimation of local pier scour are as follows:

L= length of pier= 5.1m, y_1 = = 0.84m

V = approach velocity = 2.01m/s

θ = angle of the flow with respect to the pier = 35°, V_R = Velocity ratio

D_{50} = Grain size = 0.3mm, D_{90} = 0.4mm

a= pier width = 1.24m

*a**= effective diameter = 0.86m

$\propto$ = flow skew angle in radian

V_c= critical velocity

V_{lp} = live bed peak velocity pier shape

ρ_s= 2610 kg/m³.

The computed rating curve obtained from site gauging after calibration is shown in Figure 3. The discharge measurement match well with that measured (Saidu, 2007). Figure (5) showed bed material gradation for five different rainy seasons and the result indicates a sandy bed river of high temporal scale consistency. The d_{50} and d_{90} used in the analysis were obtained as particle size distribution that correspond to 50 and 90% sieve passing of sample respectively

Figure (4), showed the computed maximum scour depth from the empirical equation as compared to the seasonal measured value at the site. It was observed that two of the empirical models(Richardson and Melville overestimate the maximum scour depth.However, the other three empirical models (Sheppard, Gao and Froehlich) provide maximum depth of scour that are relatively close to that of the measured depth of scour. The over-prediction of the calculated scour depth from the aforementioned two models may be associated with time scale of 6 years measurement considered for the study. Their adequacy may be observed in the long term.

The three models under consideration were clearly presented in Figure (6). The estimation of Gao is relatively flat indicate less response to flow depth. More so, Gao model under-estimate and overestimate at respective higher and lower velocities of flows. This could be as a result of roughness induced by channel vegetation resulting in erosion and deposition of bed materials. Similar trend was observed with Froehlich model with low flow gradient, but complete overestimation of scour depth for the given temporal scale.

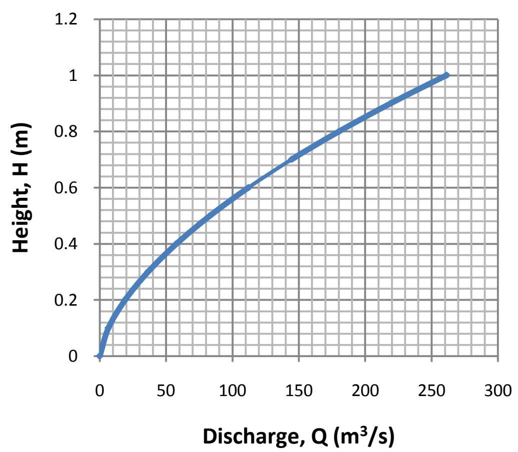

Figure 3: Computed rating curve

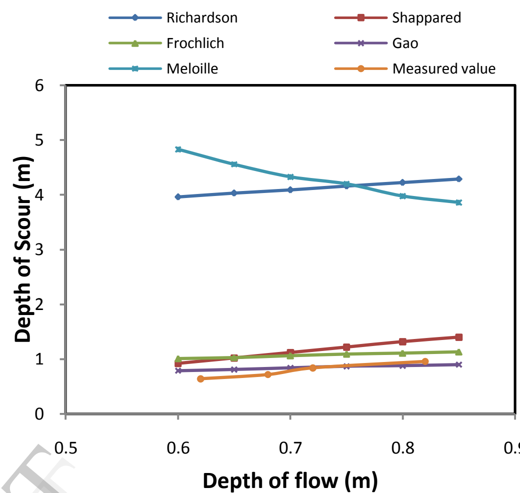

Figure 4: depth of scour against depth of flow

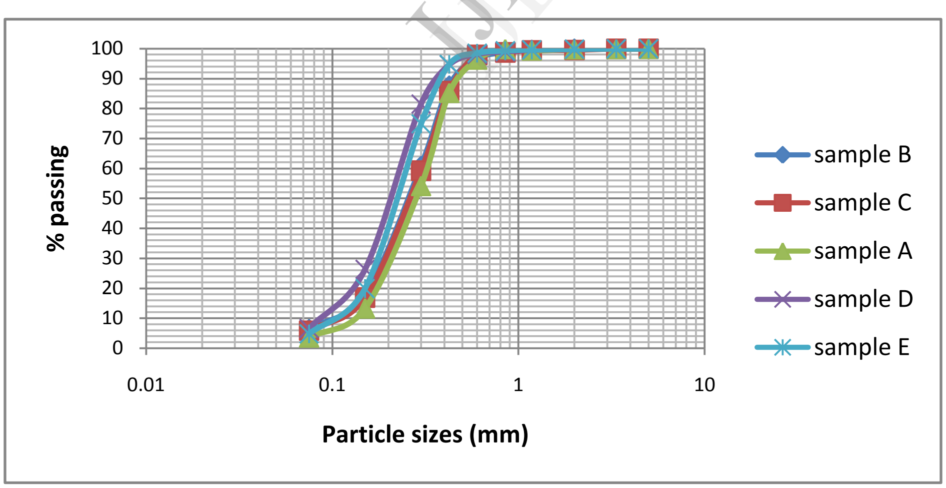

Figure 5: Granulometry curve for the riverbed material (A, B and C are sample taken downstream of the bridge while C and D are the soil sample taken upstream of the bridge)

The trend observed by Sheppard model is most similar to the measured flow depth. Depth of scour increase with increase in velocity in almost linear proportion.

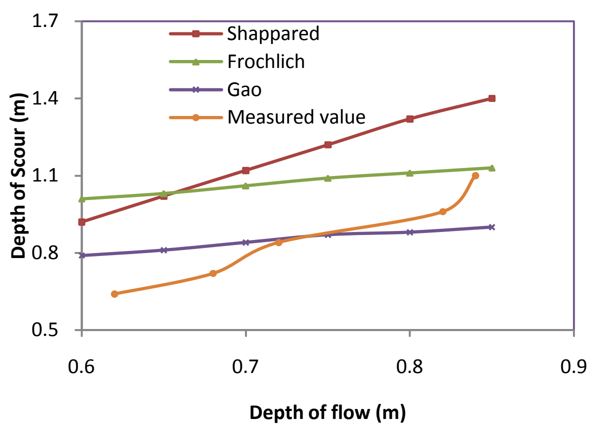

Figure 6: Comparison of calculated and measured scour depth

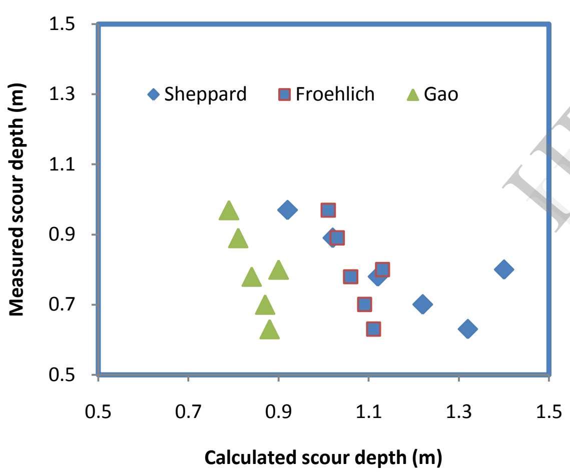

Figure 7: Depth of scour measured and the predicted ones by models

Based on the above discussion, the degree of closeness of three results obtained cannot be ascertained with mere eye as can be observed from Figure (7). The scatter plot suggests a definite positive correlation between measured and calculated scour depth. However, there is possibly slight evidence of non-linearity for calculated values close to zero. However, this is debatable and so we shall move on and consider the other normality assumption.

Due to this fact above, correlation analysis was carry out on each results obtained from the three empirical models with the measured scour depth.

Results (calculated depth of scour) obtained from the three models were compared using consistency – correlation analysis. Measured depth of scour is taken as indeterminate variable is y, and calculated depth of scour which is determinate variable is x.

$$r = \frac{[\Sigma((y-\bar{y}))((x-\bar{x}))]}{\sqrt{\Sigma[(x-\bar{x})^2(y-\bar{y})^2]}} \qquad (32)$$

Considering the correlation coefficient of determination (r) equalled to -0.989, -0.186 and -0.993 for Sheppard model, Froehlich models and Gao model, respectively. The values of r for the three empirical models showed that the Sheppard and Gao empirical models gives results (calculated depth of scour) that are quite strongly correlated with the measured depth of scour.

7. Conclusion

Local scour depth at bridge pier has been estimated using five selected max depth based empirical models. The models results were compared with five years measured scour depth in live-bed conditions. Three models were selected on the basis of closeness to the measured values. Furthermore, consistency-correlation analysis was adopted; Sheppard and Gao models gave a results which are more correlated with the measured depth of scour than results obtained from other empirical models. It should be noted that a lot of uncertainties are associated with measured depth because of noticeable interventions at the site such as water and sediment extraction downstream of the bridge by a block industry. Future study should consider the effect on these interventions on the morphodynamics of the river chanchaga.

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References

1- Ahmed, F. and Rajaratnam, N. 1998. Flow around bridge piers. Journal of Hydraulic Engineering, ASCE, 124(3): 288-300.

2- Busari A.O, Saidu, M and Ajibola, S, (2013). Evaluation of Best Fit Probability Distribution Models for the Prediction of Rainfall and Runoff Volume (Case study Tagwai dam, Minna-Nigeria).International Journal of Engineering and Technology Volume 2 No. 4, January, 2013, UK.

3- Lagasse P.F. and Richardson, E.V. 2001. ASCE compendium of stream stability and bridge scour papers. Journal of Hydraulic Engineering, ASCE, 127(7): 531-533.

4- Mashair, M.B., Zarrati, A.R. and Rezayi, A.R. (2004). Time development of scouringaround a bridge pier protected by collar. 2nd International Conference on Scour and Erosion, Nanyang, Singapore.14th-17th November, 2004.

5- Melville, B.W, (1997). Pier and abutment scour: integrated approach.. Journal of Hydraulic Engineering, ASCE, Volume 123, number 2, 125-136.

6- Pagliara, S and Carnacina, I, (2011). Influence of large woody debris on sediment scour at bridge piers. International Journal of Sediment Research 26 pp 121-136.

7- Peggy, A.J and Bilal, M.A., (1996). Modeling uncertainty in prediction of pier scour. Journal of Hydraulic Engineering, Volume 122 No 2 pp 66-72

8- Peggy, A.J and Daniel, A.D, (1998). Probabilistic bridge scour estimate. Journal of Hydraulic Engineering, Volume 124, No 7, pp 750-754.

9- Richardson, E.V. and Davies, S.R. (1995). Evaluating scour at bridges. Rep. No. FHWAIP- 90-017 (HEC 18), Federal Administration, U.S. Department of Transportation, Washington, D.C

10- Saidu, M (2007). Water demand analysis (A case study of Tagwai channel Minna, Nigeria. M.Eng Thesis, Bayero University, Kano Nigeria.

11- Stephen E. C, Christine S. L, and Bruce, W.M, (2003). Clear-water scour development at bridge abutments. Journal of Hydraulic Research Vol. 41, No. 5, pp. 521–531.

12- Toth, E and Brandimarte, L (2011). Prediction of local scour depth at bridge piers under clear-water and live-bed conditions: comparison of literature models and artificial neural networks. Journal of Hydroinformatics Volume 13 (2) pp 812-824. IWA Publishing.