Annual Journal of Hydraulic Engineering, JSCE, Vol.49, 2005, February

A METHOD FOR LOCAL SCOUR PREDICTION AT RIVER STRUCTURES CONSIDERING TIME FACTOR

Sanjay GIRI[1] and Yasuyuki SHIMIZU[2]

[1]Student member of JSCE, PhD candidate, Dept. of Hydroscience & Environmental Engineering, Hokkaido University (Kita 13, Nishi 8, Sapporo 060, Japan)
[2]Member of JSCE, D. Eng., Associate Professor, Dept. of Hydroscience & Environmental Engineering, Hokkaido University (Kita 13, Nishi 8, Sapporo 060, Japan)

A generalized method to determine maximum and temporal evolution of scour-depth at river structures, based on large range of data set from independent physical model studies, has been developed. A relative grain-size-like parameter referred to as alpha parameter was proposed. Likewise, a method was proposed to determine time factor in terms of a parameter, so called, sediment Strouhal number that can be employed as a similarity number in any time dependent phenomenon. It is evident that temporal development of local scour can widely be generalized using this parameter. Proposed method can be applied for structures protruding from the river bank (spurs, abutment etc) as well as pier-like structures. This method can be applied for live-bed scouring case as well. The method was verified using large range of laboratory data from independent investigations on maximum and temporal scour. Likewise, method was tested against field investigation on temporal scour development at pier during flood event.

Key Words: *local scour, time factor, alpha parameter, sediment Strouhal number*

1. INTRODUCTION

Presence of structures in river is inevitable despite their impact on hydraulic and geo-morphological changes that may give rise to negative environmental consequences. Construction of several structures like bridge piers, abutments, river training and habitat improvement (spurs, vanes, bend-ways, fish-way etc) is of common practice in river engineering. On the other hand, the stability of river structures should be considered duly so as to get rid of damnification and even fatality caused by the failure of such structures.

There are several investigations that have been performed, to develop methodology to estimate local scour, since long. Commonly, classical design criteria were developed based on maximum local scour (so called "equilibrium scour") in clear water condition. However, it is difficult to quantify equilibrium state of scouring process except for dynamic equilibrium in case of live bed condition. As reported by Melville and Chiew[1], local scour phenomenon significantly depend on time factor and experimental duration less than 10-12 hrs may cause underestimation of scour depth less than 50% of maximum depth. Consequently, criteria based on only apparent equilibrium scour without consideration of time factor may not predict scour depth efficiently.

Earlier, a preliminary method was developed by Giri and Shimizu [2), 3)] to determine development of relative scour-depth. However, it cannot be used to estimate the maximum design scour-depth. The investigations, which were carried out by Melville and Chiew[1] for pier scour and Coleman et al.[4] for abutment scour, are based on extensive experimental observation. Melville and Chiew[1] derived an empirical expression for time factor using extensive data set on pier scour. Moreover, a method was suggested to describe equilibrium time as a function of flow shallowness and flow intensity. However, their formula seems to be valid for only pier scour and clear water case. Besides, it does not follow the dimensional criterion. Recently, similar approach was followed by Coleman et al.[4] for abutment scour. Earlier, Ettema[5] proposed a logarithmic function to identify the evolution of scour at bridge piers. Kothyari & RangaRaju[6] developed a semi empirical method to describe the temporal development of local scour at abutments based on their study on pier scour[7]. Likewise, Yanmaz and Altinbilek[8] proposed a semi empirical model by idealizing the shape of scour hole around pier as an inverted cone. Kuhnle et al.[9] developed an empirical expression for the time development of relative volume of scour near spur-dike. Cardoso and Bettes[10] tested their experiments with existing models. There are several scour prediction methods that do not consider the time factor[11), 12), 13)].

This study is basically originated from the work of Coleman et al.[4]. In this study, all data set from the aforesaid work was used along with the authors' experiments. As a result, a revised and more generalized formulation has been proposed for the maximum and temporal evolution of local scour which is valid for wide range of conditions[14].

2. EXPERIMENTAL LAY-OUT

Study was carried out in a physical model constructed in Laboratory of Hydro-science & Environmental Department of Hokkaido University. A meandering-like flume was used that was constructed on a 30m by 2.5m plat-form having electrical motor mechanism for slope regulation. Flume width was 1m with upstream and downstream straight reaches of 9.8m and 10.5 m respectively. Meandering-like reach with 7.7m wave length consists of three consecutive and opposite bends having constant arc angles of 40^0, 80^0 and 40^0 respectively. The detail on flume lay-out can be found elsewhere[2]. Experimental condition was considered as characteristics of Lowland River with sub-critical flow. The experimental cases and conditions with calculation results are summarized in **Table1**. Study was conducted for non-submerged condition as more often and critical in natural case. Spurs were used with different protrusion length (L) and placed in 35^0 of first bend (**Fig.1**).

The temporal scour depth was measured using an Acoustic Doppler Velocimeter that can remotely detect the movable bed with the accuracy of 0.01 mm. Experiments that have been conducted in University of Auckland since last 30 years were incorporated in this study as well. The detail of all these experiments (series au, d and dd) can be found in a recent publication of Coleman et al.[4]

3. CRITERIAL RELATIONSHIP OF NON-DIMENSIONAL PARAMETERS

In physical modeling of scouring process, usually parameter is defined after having dimensional analysis of the phenomenon, since the consistent mathematical formulation does not exist. For scour phenomenon at structure, in general, parameters that may have effect on scour development is more or less well-known. According to widely held perception, clear-water scour depth around a structure is a function of flow intensity, size of structure, flow depth and shape or geometry factors. Earlier, number of researchers pointed out the fact of sediment size and grading effect, in particular for clear- water scouring at pier and abutment. Laursen[15] suggested to consider

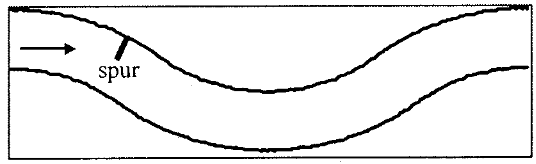


Fig.1 Schematic sketch of bend portion of flume with spur

the particle shear and critical tractive force. Raudkivi and Ettema[16] defined the region in terms of the relative grain size and explained the sediment entrainment mechanism by downflow and horseshoe vortex for each region. Likewise, Melville[13] and Coleman et al.[4] defined an auto-model region for relative sediment size. Consequently, the conventional form of a criterial relationship of non-dimensional parameters for scour prediction at spur-like structures may reads as:

$$\frac{d_{qe}}{L} = f\left(\begin{array}{l}\frac{U}{U_t}; \frac{h}{L}; \frac{L}{d_{50}}; \frac{L}{B}; F_r; shape\ factor; \\ flow\ angle\ of\ attack\end{array}\right) \quad (1)$$

where, d_{qe}= quasi-equilibrium scour depth; U = approach velocity; U_t = threshold velocity corresponding to sediment incipient; h = approach flow depth; L = length (diameter) of structure; d_{50} = median grain size; B = channel width; F_r = Froude number.

However, all earlier formulations appear to have a lack of an important physical parameter so called loading area of lateral pressure[17], i.e. Lh. This parameter can be considered as the index of strength of vortex system near structure which, in turn, can be related with its relative coefficient, i.e. L/h. (or flow shallowness as h/L). Consequently, a new non-dimensional parameter has been proposed as α parameter that considers the loading area of lateral pressure (under square root) normalized with sediment diameter to consider effect of grain-size as well. In this study, the following criterial relationship has been proposed for quasi-equilibrium scour depth:

$$\frac{d_{qe}}{d_{50}} = f\left(\frac{U}{U_t}; \frac{h}{L}; \alpha\right) \quad (2)$$

where, α parameter is proposed to be as follows:

$$\alpha = \frac{\sqrt{Lh}}{d_{50}} \quad (3)$$

Other noteworthy inclusion in this study is the consideration of time factor and widespread generalization of temporal development of local erosion that has significant merit over classical scour prediction methods. Time factor is defined as $T_f = \frac{d_{sT}}{d_{qe}}$; where d_{sT} = scour-depth at a particular time T (temporal scour depth).

Table 1: Experimental conditions

Test	*L* *[mm]*	*h* *[mm]*	*h/L*	d_{50} *[mm]*	*U* *[m/s]*	U/U_t	T_{qe} *[min]*	*alpha* 10^2	*Stqe* 10^4	*dqe* *[mm]*
N-1	88	250	0.35	1.2	0.2216	0.53	4260	12.4	290	124
N-2	80	250	0.32	1.2	0.1825	0.44	1980	11.8	141	45
N-3	88	250	0.35	1.2	0.2216	0.53	5700	12.4	387	143
N-4	88	190	0.46	1.2	0.2216	0.53	4800	10.8	374	115
N-5	88	130	0.68	1.2	0.2216	0.53	3060	8.91	288	64
N-6	75	130	0.58	1.2	0.2600	0.64	6240	8.23	637	139
N-7	65	130	0.5	1.2	0.2246	0.56	5760	7.66	632	87
N-8	105	250	0.42	1.2	0.1857	0.43	2340	13.5	146	79
N-9	95	250	0.38	1.2	0.2053	0.48	4920	12.8	322	123
N-10	75	250	0.3	1.2	0.2600	0.64	7800	11.4	574	201
N-11	65	250	0.26	1.2	0.2246	0.56	6600	10.6	522	137
N-12	65	300	0.22	1.2	0.2246	0.56	8400	11.6	606	173
N-13	65	190	0.34	1.2	0.2246	0.56	5880	9.20	533	109
N-14	75	190	0.39	1.2	0.2600	0.64	7200	9.95	608	177

4. DATA ANALYSIS AND METHOD DEVELOPMENT

In view of all existing approaches, the combined influence of flow shallowness (*h/L*) and relative grain-size on the temporal and maximum scour does not appear to be completely elucidated for its wide implication, e.g. for long river structure. It was found that most of the relations overestimate the scour depth for the significant range of *h/L*, viz. for $0.02<h/L<2$. Consequently, an attempt was made to implement a new parameter (α parameter) as aforementioned Eq.(3).

Local scour evolution is widely conceived as a phenomenon that varies proportionally with the size of structure; hence usually scour-depth is normalized with the same. Nonetheless, it has been shown that using parameter α and having normalized scour depth with median sediment size; the maximum scour depth estimation can be generalized largely for flow shallowness and even for flow intensity (U/U_t) to some extent.

(1) Maximum scour-depth

For all data set presented in **Table 1** as well as presented in work of Coleman et al.[4)], proposed α parameter was calculated. Based on regression analysis of the parameters (**Fig.2**), the following relation for the prediction of quasi-equilibrium (maximum) scour depth can be defined:

$$\frac{d_{qe}}{d_{50}} = a\alpha^{b}\left(\frac{U}{U_t}\right) \tag{4}$$

where, a=1 and b=1.08 for $0.02< h/L \leq 4$; $a=0.6\left(\frac{L}{h}\right)^{0.17}$ and b=1.15 for the combination of parameters U/U_t >0.9 and h/L>2; d_{qe} = quasi-equilibrium scour depth (maximum scour depth as per definition in Coleman et al.[4)]), when T_f tends to be 1; U = average velocity; U_t = threshold velocity, calculated using Melville's method[18)].

For the sake of comparison, result of maximum scour-depth prediction for all but 175 published data points using author's approach and a widely used approach, proposed by Coleman et al.[4)], is depicted in **Fig.3** (shape/slope factor was adopted as recommended by Coleman et al.[4)]).

It was also found that Eq.(4) can be used for live bed condition using the threshold value of flow intensity. In other words, no effect of flow intensity on scour development was found when it exceeds the threshold value. All but 65 data points from various independent investigations on live bed scour were tested (**Fig.4**). It is evident that the Eq.(4) gives satisfactory result. This leads to the conclusion that proper consideration of simultaneous effect of flow depth, length of structure and sediment size, i.e. parameter α may be of significance in predicting maximum scour depth.

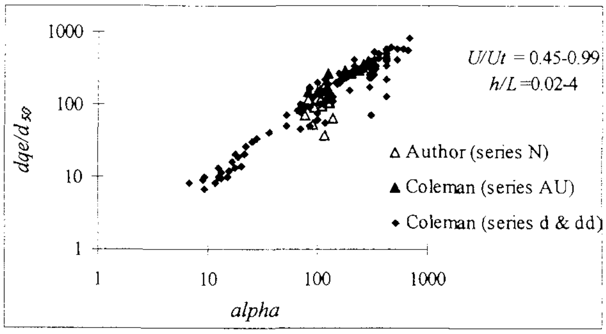


Fig.2 Functional relationship between normalized scour depth and parameter alpha

(2) Time factor, T_f

A non-dimensional parameter referred to as Strouhal number (proposed to be called sediment Strouhal number) has been considered as time similarity criterion for scour evolution as follows:

$$St_* = \frac{U_{*0}T}{\sqrt{Lh}} \tag{5}$$

where, St_* = sediment Strouhal number; U_{*0} = critical shear velocity of sand particle; T = time for scour-hole development.

Analyzing the data set on temporal evolution of scour, it was found that the principal stage of relative scour development follows the similarity of logarithmic growth with high coefficient of determination for the wide range of flow intensity and flow shallowness (**Fig.5**). Consequently, this stage can be expressed with a logarithmic function, whereas initial stage can be expressed using an exponential function as follows:

For initial stage, i.e. $0 \leq St_* < 50$

$$T_f = \frac{d_{sT}}{d_{qe}} = 1 - \frac{1}{\exp(m\,St_*^{\,n})} \tag{6}$$

For principal stage, i.e. $50 \leq St_* \leq St_{*qe}$

$$T_f = \frac{d_{sT}}{d_{qe}} = m_1 Ln(St_*) - n_1 \tag{7}$$

So, temporal scour depth, $d_{sT} = d_{qe}\,T_f$ (8)

where d_{sT} = scour-depth at time T; St_{*qe} = sediment Strouhal number corresponding to quasi-equilibrium condition, when T=T_{qe}= time to attain d_{qe}; m, n, m_1 and n_1 = empirical coefficients (m, n m_1 and n_1 is adopted 0.045, 0.44, 0.13 and 0.34 respectively).

It is noteworthy to be mentioned that a generalized value of St_{*qe}, namely 30000 was adopted. The method was verified using several independent investigations[5), 6), 8), 19), 20)] on temporal development of local scour at spurs, abutments and piers. Some selected results are depicted in **Fig.6** that has revealed satisfactory results.

5. FIELD INVESTIGATION AND MODEL VALIDATION

Field data on temporal effect on local scour depth development is lack due to the sophistication in observing temporal development of scour at bridge structures in field situation. A field observation was made on development of scour around a pier in Akamu bridge at Abbetsu River in Hokkaido during flood event (Typhoon N. 15, 2003). Since bridge pier practically located on flood plane, it could be possible to determine the scour hole development during flood. The field observation on the variation in upstream water level during flood period was made (**Fig.7**). Grain-size distribution of river bed material (**Fig.8**) in upstream region of bridge was available. This enables the verification of developed method to be made for the scour prediction considering time factor. The following data are used for the calculation of temporal scour depth:

Since the flood duration is rather short and maximum h/L is more than 4, at the first approximation, the effective flow depth (h) during flood event was taken as 50% of maximum depth, namely 2.8 m; flood duration was 50 hrs. From grain-size distribution curve, d_{85}/d_{10} can be determined, namely 2.84. Consequently, sediment can be assumed to be uniform with median diameter, d_{50} = 0.289 mm. Width of the pier (L) is 1m. Shape factor was taken as 1 for round nosed pier[18)].

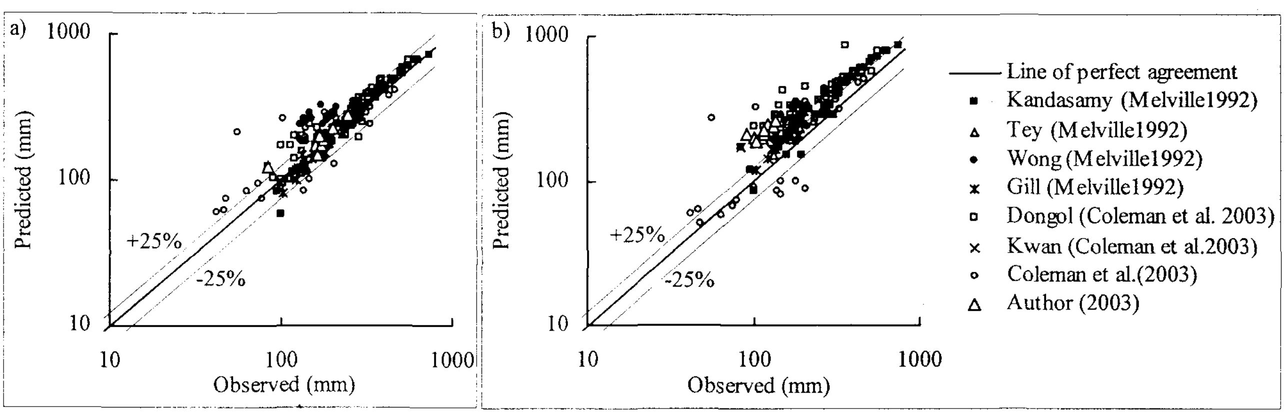


Fig.3 Prediction of maximum scour depth: a) Authors' method; b) Coleman & Melville's method

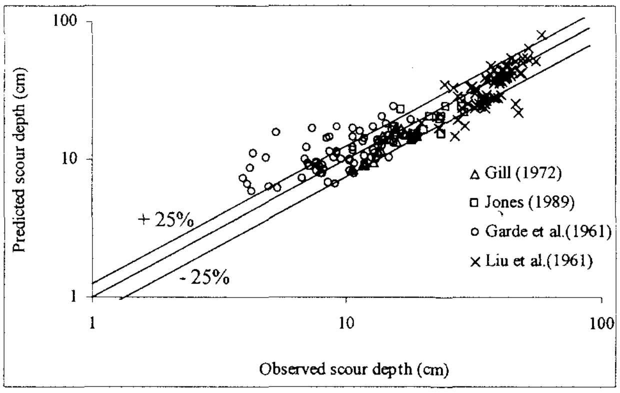


Fig.4 Prediction of scour-depth for live bed condition

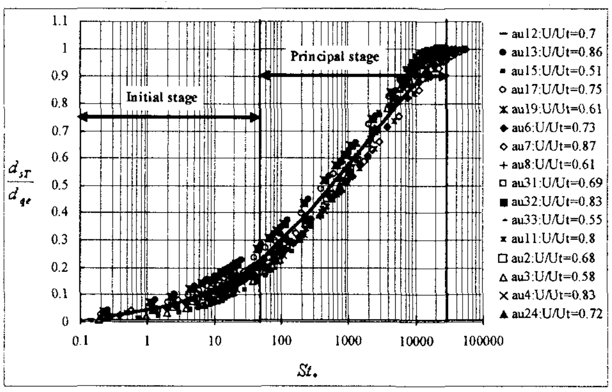


Fig.5 Generalization of temporal evolution of scour depth

In this case, h/L=2.8 > 2, so $a=0.6\left(\frac{L}{h}\right)^{0.17}$ and b=1.15. Since scour occurred in more than threshold condition, so flow intensity U/U_t can be taken as 1.

Time factor T_f can be calculated using Eq.(7), in which St_* can be calculated as follows:

$$St_* = \frac{T\times U_{0*}}{(Lh)^{0.5}} = \frac{50\times 0.014}{(1\times 2.8)^{0.5}} = 1506,$$

$m_1 = 0.13$ and $m_2 = 0.32$

Using Eq.(4) and Eq.(8), temporal scour depth during flood event can be obtained, namely 1.94 m, which is rather closed to measured scour depth (about 1.9m). The scour hole at pier in Akamu bridge after flood can be assessed from **Pic.1.**

6. CONCLUSIONS

A simple method to predict quasi-equilibrium local scour depth was developed. The method has considered various factors like lateral pressure and grain-size (proposed a new parameter as α) as well as time factor which was overlooked in most of the past studies. In addition, an approach was proposed to estimate temporal evolution of local scour based on comprehensive experimental data set. The formulation employed in this study slightly alters general perception; nonetheless the outcome was

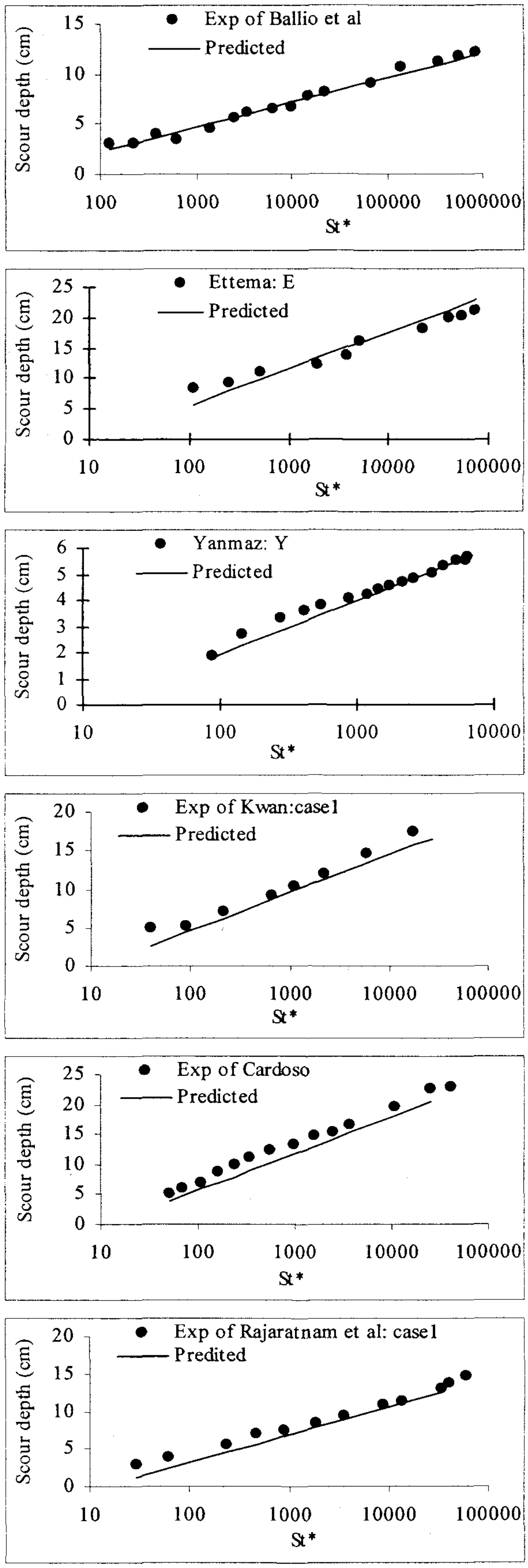


Fig.6 Prediction of temporal evolution of scour depth for various independent experiments on spurs, abutments and piers

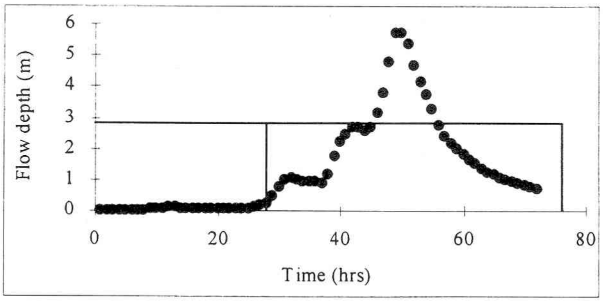


Fig.7 Flow depth variation in flood plane during flood event

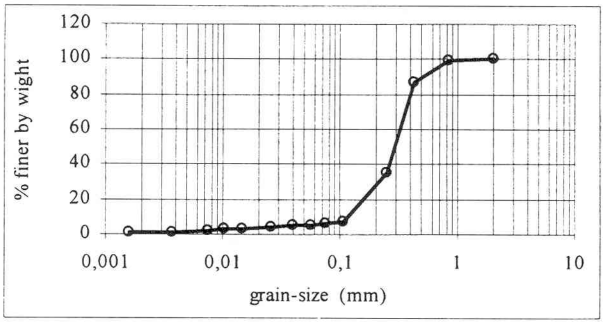
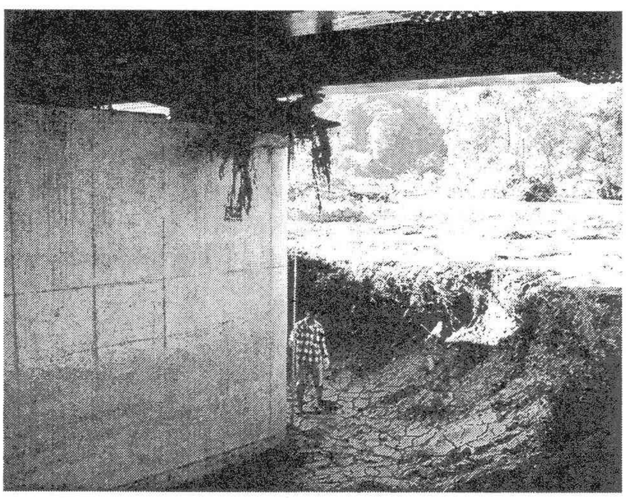


Fig.8 Grain-size distribution curve near Akamu bridge region



Pic.1 Scour hole at Akamu bridge pier after flood event

found to be more precise and generalized that may have wide application. It was shown that the temporal evolution of scour depth can be generalized in terms of sediment Strouhal number.

The method was validated with extensive data sets collected from the various independent sources. Furthermore, a field observation was made on temporal scour depth at bridge pier during flood event and attempt was made to employ the developed method to predict the same. The obtained result appears to be a promising beginning.

REFERENCES

1) Melville & Chiew: Time scale of local scour at bridge abutments, ASCE, Journal of Hydraulic Engineering, Vol.125, No.1, 1999.
2) Giri & Shimizu: Observation on bed variation in a meandering like flume with river training structures, Annual Journal of Hydraulic Engineering, JSCE, Vol.48, 2004.
3) Giri, S. & Shimizu Y.: Structure-induced bed forms and temporal development of local bed in the bend reach of a laboratory flume. 3rd IAHR Symposium on RCEM, Barcelona 2003.
4) Coleman et al.: Clear-water scour development at bridge abutments. Journal of Hydraulic Research., IAHR, Vol. 41, No.5, 2003.
5) Ettema R.: Scour at bridge piers. Rep. No.216, Univ. of Auckland, New Zealand, 1980.
6) Kothyari & Rangaraju: Scour around spur dike and bridge abutments, Journal of Hydraulic Research., IAHR, Vol. 39, No.4, 2001.
7) Kothyari et al.: Temporal variation of scour around circular bridge pier, ASCE, Journal of Hydraulic Engineering, Vol.118, No.8, 1992.
8) Yanmaz & Altinbilek: Study of time-dependent scour around bridge piers, ASCE, Journal of Hydraulic Engineering, Vol.117, No.10, 1991.
9) Kuhnle et al.: Local scour associated with angled spur dikes. ASCE, Journal of Hydraulic Engineering, Vol.128, No.12, 2002.
10) Cardoso & Bettes: Effects of time and channel geometry on scour at bridge abutments, ASCE, Journal of Hydraulic Engineering, Vol.125, No.4, 1999.
11) Gill M.A.: Erosion of sand bed around spur dikes. Proceedings of ASCE, Vol.98, 1972.
12) Garde et al.: Study of scour around spur-dikes, Proceedings of ASCE, Vol.87, HY 6, 1961.
13) Melville B.W.: Local scour at bridge abutments, ASCE, Journal of Hydraulic Engineering, Vol.118, No.4, 1992.
14) Giri S.: Discussion of 'Clear-water scour development at bridge abutment by Coleman, Lauchlan & Melville', Journal of Hydraulic Research., IAHR, (in press), 2004.
15) Laursen E.M.: An Analysis of Relief Bridge Scour, ASCE, Journal of Hydraulic Division, Vol.89, HY 3, 1963.
16) Raudkivi & Ettema: Clear-water scour at cylindrical piers, ASCE, Journal of Hydraulic Engineering, Vol.109, No.3, 1983.
17) Jhuravlyov M. M.: Local scour at bridge piers, M. Transport, Moscow, USSR, 1984 (in Russian).
18) Melville B.W.: Pier and abutment scour: Integrated approach, ASCE, Journal of Hydraulic Engineering, Vol.123, No.2, 1997.
19) Rajaratnam & Nwachukwu: Erosion near groyne-like structures, Journal of Hydraulic Research., IAHR, Vol. 21, No.4, 1983.
20) Ballio & Orsi: Time evolution of scour around bridge abutments, Water Engineering Research, Vol.2, No.4, 2001.

(Received September 30, 2004)