FIELD MEASUREMENT OF MAXIMUM SCOUR DEPTH DURING FLOOD BY INSTALLING NUMBERED BRICKS *

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In order to measure the actual scour depth at piers subject to single or multiple floods, a technique consisting of installing stacks of numbered bricks has been applied around two piers of Shimanto River Bridge (Shikoku Island, Japan) and monitored over the last three years. The main objective was to assess the maximum scour depth upstream of a pier by knowing the number of bricks removed by the flood. Within the period 2001-2003, four main floods were registered, that removed gradually the bricks from the stacks. In conjunction with these investigations and taking into account, the shape of the prototype and the sediment size in the riverbed, flume experiments were carried out with the objective of verifying the effect of the major hydraulic variables on scour at the piers. The results from these investigations lead to the conclusion that the data provided by the numbered bricks follow the same tendency as those from flume experiments and that the experimental data are compatible with the observed field data. Further, the depths indicated by the numbered bricks and those measured at the site are comparable, indicating that the proposed technique is a promising tool for the assessment of the maximum scour depth occurring in the field.

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1 Introduction

Scour around bridge foundations occurs due to the removal of bank material and bed material by the flowing water. All over the world, this process has been recognized as the most common cause of bridge failure, which, in some cases, has led to loss of human life and many economic problems. To avoid these failures, it is necessary to understand well the causes and the processes that result in scour. Earlier studies have resulted in a fair understanding of the mechanism of scour around bridge pier (Jain, 1981; Johnson, 1995, Gotvald, 2003). However, due to the influence of many unaccounted factors on scouring, the bridge designers are still unable to predict with confidence the maximum depth of a scour hole for a given flood. To determine this depth, several formulae have been proposed in the literature, but various studies have shown that, for a given situation, different formulas provide very different estimates (Jain, 1981; Johnson, 1995). Because of this constraint, measurement of actual scour depth in field is a much needed task to assess the laboratory-based scour depth relationships. However, the techniques available for collecting the field data are costly, needing trained personnel and still limited in use. Moreover, the level of difficulty in obtaining such data considerably increases when the depth measurement has to be achieved in a river subject to frequent floods of large magnitude. This is the situation at the Shimanto River Bridge section in the Shikoku Island of Japan, where an advanced local scour processes has been observed. In order to determine the maximum scour depth at the bridge piers, a technique using numbered bricks as scour depth indicators has been attempted and was found to be a reliable approach, the details of which are dealt with in the following sections of this paper.

2 Proposed Technique for Measuring Actual Scour Depth

Since the recognition of the scour process as the main cause for bridge failure, several attempts have been made to measure its exact depth, like the ones proposed by Boehmler & Olimpio (20000) and Gotvald (2003). Although these techniques seem very efficient, they are quite expensive and the results are limited to a certain range of application. In addition, the true depth of scour is usually altered by the sediments transported by the flow, that fill the scour hole when the generating flood subsides. Therefore, what is measured after any flood event is not the true maximum scour depth. The local scour processes at piers are usually divided into two major types: clear water scour and live-bed scour. The first one occurs during the rising stage of the flood. Then, past a critical flow velocity, U_c, a generalized movement of bed material originates the live-bed scour.

The methodology proposed in the present study consists of the installation of stacks of numbered bricks at the upstream and left hand side of two piers. The bricks are stacked so that the last brick would be situated at the riverbed level or just below it (Fig.1). When the flood washes out the riverbed material and the bricks in the stacks, it would be possible to determine the maximum scour depth reached at a pier during a given flood by knowing the number of the brick left not removed and taking into account the angle of repose of the streambed sediment.

3 Study Site

The above-mentioned technique was applied at two piers of Shimanto River Bridge, located in Nakamura City (at 9.5 km from the river mouth), in Kochi Prefecture, Japan. The bridge is 508 m in length and is supported by 13 compound piers; eight of them are settled inside the main channel. The compound pier is formed by two cylindrical piers (4 m in diameter each), joined at their base by a concrete collar (1 m thick), and joined by a concrete block (2 m x 1.5 m x 1.5 m). The total length of this arrangement is equal to 11.2 m and the span between the compound piers is about 54 m.

Due to the particular characteristics of the Shimanto River (Aragão et al. 2003), heavy rainfalls over the area, resultant either from typhoons or from stationary fronts, cause floods at the bridge section with a high peak discharge. As a consequence, the area around the piers has been severely eroded, indicating the need for collecting reliable field data. The technique of the numbered bricks was applied here and periodic investigations were conducted at the bridge site.

4 Field Investigations

To install the numbered bricks, a field investigation at the site was conducted on July 17th 2001, and consisted of the following tasks: verification of the pier shape and conditions, sediment samplings, and data collection on river channel cross-section. During the verification of the pier condition, it was observed that the area surrounding piers 3, 4 and 5 (identified as P3, P4 & P5), was severely scoured and that the concrete collar was completely unearthed by the scouring around the piers. As for sediment sampling, it had the objectives of providing a basis to determine the riverbed roughness at different locations, and to obtain the grain size distribution of the bed material around the bridge. For this purpose, borings were made around P4 and P5 and at sites 20 m upstream (R1) and downstream (R2) from the bridge (Fig. 2). Inside these borings, sediment samplings were done at two different depths. The first level was at 0.30 m below the riverbed and the second one at 0.20 m below the first.

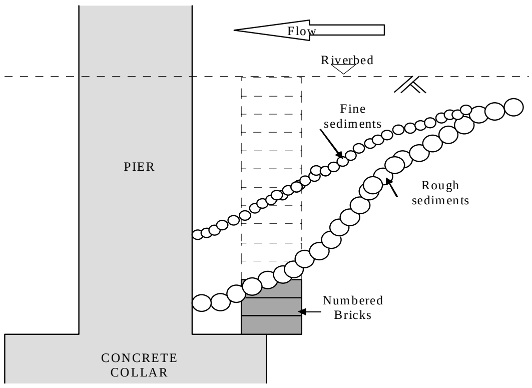

Figure 1. Removal of bricks from a stack.

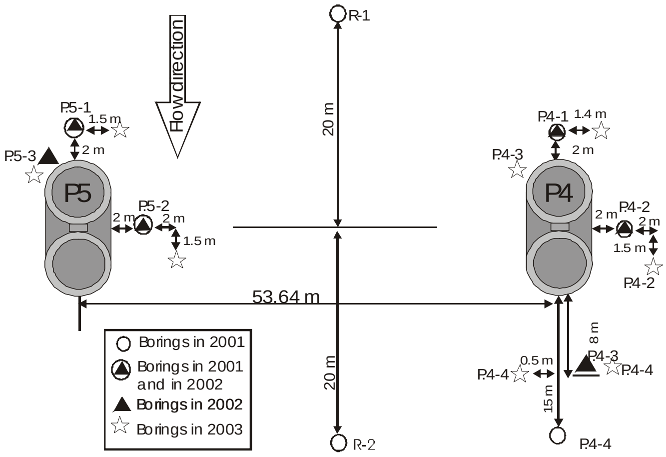

Figure 2. Borings around piers 4 (P4) and (P5).

After the boring and sediment sampling had done, the bricks were installed in the same locations of boring in 2001 as shown in Fig.2. The maximum scour depth can be estimated by brick size (6cm thick) and number of bricks left under the initial bed level after the flood. The bricks can be easily counted on site because the area around the pier is under water only when the flood occurs. At P4, the depths of the holes and the number of bricks installed were the followings: 1.2 m at the upstream face (20 bricks), and 1.2 m on the left side (20 bricks). At P5, the depths and the number of bricks were: 1.5 m deep at the upstream face with 25 bricks and 1.2 m on the left side with 20 bricks.

5 Data Collection and Analysis

After the initial field investigation and within the period of observation (2001-2003), four floods occurred, modifying the bed roughness and removing progressively most of the installed bricks. In these floods, the peak discharge varied from Q_{max}= 2700 m^3/s to Q_{max}= 6700 m^3/s (Table 1, see Sec 5.2). Most of these floods occurred as a consequence of typhoons, motivating periodic field surveys, which consisted of sediment samplings at different locations around the piers, mapping the flushed bricks and measuring the scour depth at the piers. In addition, riverbed levels were measured within an area beginning 20 m upstream from the bridge and ending 250 m downstream of it.

5.1. *Grain Size Analysis*

The grain distributions around P5 after the floods in 2001 and 2002 are shown in Fig.3. The diameter of D_{50} from the samples collected around P4 and P5 are also shown in Fig. 4. As a flood flow begins and flow velocity starts to increase, the small sized particles will be lifted and entrained. Meanwhile, the larger particles will create an armor layer protecting the riverbed against scouring. However, when flow velocity reaches a critical threshold (U_c), even these larger particles will be entrained. The clear-water scour takes places during the first stage of this process (velocity below the critical condition) and after this threshold, the scour condition changes to live bed scour.

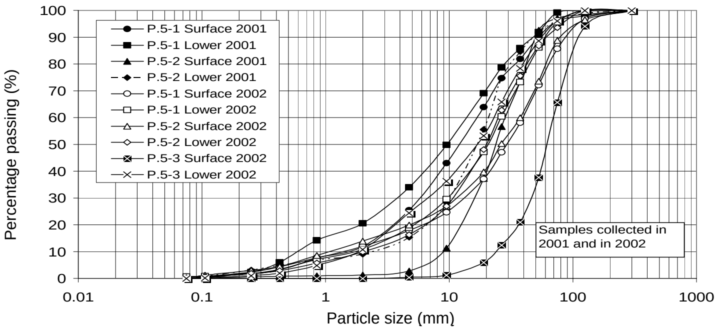

Figure 3. Grain size distribution around P5 before and after the floods in 2001 and 2002.

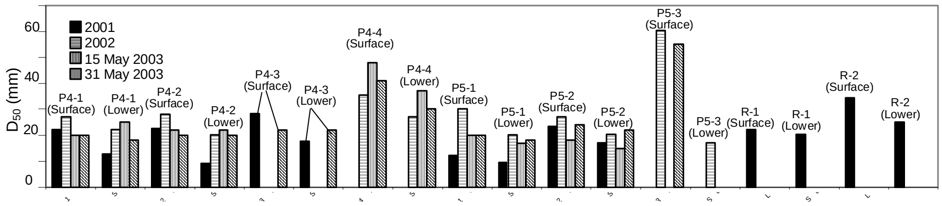

Figure 4. Diameter D_{50} of the sampling within the period 2001-2003.

Table 1 Bricks removed from the stacks at P4 and P5

Date of observation	2001/07/17 (Installation)	2001/09/14	2002/09/01	2003/05/19	2003/05/31
Peak discharge		2700 m^3/s	3100 m^3/s	5700 m^3/s	6700 m^3/s
Max water level		4.0 m	4.90 m	6.07 m	6.98 m
P4-1 P4-2	Upstream (20 bricks) Left side (20 bricks) Maximum scour depth	0 brick 0 brick 3 cm	0 brick 1 brick 9 cm	10 bricks 17 bricks 105 cm	11 bricks 18 bricks 111 cm
P5-1 P5-2	Upstream (25 bricks) Left Side (20 bricks) Maximum scour depth	1 brick 0 brick 40 cm	7 bricks 1 brick 76 cm	19 bricks 20 bricks 148 cm	19 bricks 20 bricks 148 cm

As flood recedes, the larger particles start depositing, followed by the settlement of small sized ones (Fig. 1). This process is verified through the grain size analysis (Figs. 3 and 4). After the floods, it is noticed that for most of the borings surveyed, the diameter at the upper layers was greater than the one in the lower layers, indicating either the lack of fine sediments or their transport away from the bridge. The sediment gradation of the material from the boring P5 after the floods showed a rough sediment composition in which, the material was classified as very coarse gravel to large cobble type.

5.2. *Measurements of Maximum Scour Depth at the Piers*

The reliability of the use of numbered bricks as an indicator of scour depth was verified after the occurrence of the floods previously mentioned, which scoured the lateral and the rear faces of P4 and P5 and removed progressively several bricks, resulting in the scour depths listed in Table 1. In this table, the water level was measured from the mean sea level, having Tokyo Bay as a reference. The discharges and water level registered for each flood at bridge section are listed in Table 1. Vertical averaged velocities associated with the flood events near the bridge were calculated by using the flow depth and the Manning formula (n=0.03) and, according to the order of occurrence, they were: 1.2 m/s, 1.4 m/s, 2.6 m/s, and 3.0 m/s.

With these data, the maximum scour depth at the piers was calculated from the similarity of triangles considering the angle of repose of gravel as follows: As for point P5-1, the sediment was filled up of 34cm on the top of stacks which is the same level as surroundings. As shown in Table 1, 7 bricks were left after the flood so that the calculated scour depth at P5-1 was equal to 76cm (=6cm thick x 7bricks + 34cm = 76cm). From the field observation, the point of actual maximum scour was 1m far from P5-1. Considering with angle of repose ϕ (=35^o), the maximum scour depth is estimated as 76cm+1m x tanϕ = 146cm as a result. The same procedure was taken for the other floods to calculate the maximum scour depth near the piers and these results are discussed with experimental data in the followings.

On the other hand, the results in Table 1 show that, for the same floods, the maximum scour depths at P4 were lower than those at P5. This deviation could be a consequence of the existing inclined flow to the right side of P5 thus increasing the scour depth. It can be seen from the mapping of the removed bricks in Fig. 5a.

5.3. *Contour Map around Piers 4 and 5*

The variations in bed levels around P4 and P5, for the periods 2001-2002 and 2002-2003, are also shown in Figs. 5a and 5b, respectively. Fig. 5a shows that, due to the low flows that occurred in 2001 and in 2002, the flow direction was not straight and forward as expected. Instead, the direction dictated by the sub-channel at the right side of P5 seems to have prevailed, resulting in a non-symmetric scour hole around the piers. However, the contour map in Fig. 5b shows that due to the high discharges in 2003, flow direction was irrespective of the existence of the sub-channel, as indicated by the arrow in Fig. 5b.

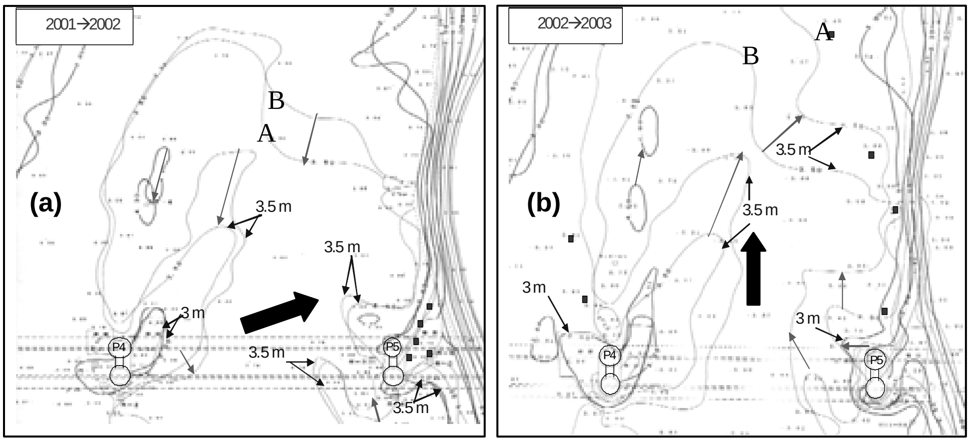

Figure 5. Bed elevation within 2001-2002 (a) and within 2002-2003 (b).

Consequently, the scour holes around the piers were symmetric. These important differences can also be used to explain the position of the removed bricks that settled close to P5 (Fig. 5a) for a small discharge, but were transported further downstream for high discharges (Fig. 5b).

As for bed level variation, observing the contour lines near the piers and the contour lines further downstream of them (named A and B in Fig. 5), one will notice that, in general, no substantial change in bed levels occurred in the interval (2001-2002). On the other hand, in the period 2002-2003, there was a significant degradation farther downstream of P4 and P5, and a substantial scour at P4 and P5, being the depth at P5 influenced by the proximity of the sub-channel.

6 Flume Experiments

Flume experiments were conducted for the clear-water condition to observe the influence of some factors like flow velocity, sediment size, and pier diameter and shape on the scour depth, using the following apparatuses: re-circulating flume (20 m long), a test section (0.75 m long, 0.50 m wide, and 0.20 m deep), filled with sand mixture, and located 12 m downstream from the water inlet; one compound pier model, scaled down the prototype to 4.82 cm in diameter each. The test section was filled with uniform sand (D_{50}=1.42 mm) and non-uniform sand (D_{16}=0.9 mm, D_{50}=2.2 mm, D_{84}=3.4 mm). The applied discharges varied from 5 to 20 liters/s. The different combinations of flow discharges and the opening of the tailgate resulted in different values of the flow velocity and, consequently, resulted in various scour depths. About 130 runs were conducted using both the sand mixtures. A dimensionless index called 'sediment number' of Carsten (1965) defined by:

$$N_s = U / \sqrt{sgD_g} \qquad (1)$$

was used to relate the relative scour depth where, U is the mean flow velocity (m/s), s is the sediment specific gravity (dimensionless), g is the gravitational acceleration (m/s^2), and D_g is the typical grain diameter of the surface particles (m). The D_g of the uniform sand was set equal to D_{50}=1.42 mm and for the non-uniform distribution, the D_g was set to D_{84}= 3.4 mm. The values of N_s for both experimental and field data (Table 1) were calculated and is shown against the respective values of the relative scour depths, (Z_s/D), in Fig. 6. With these data, two types of analyses were made: 1) to verify the closeness of the observed and experimental data with each other, and 2) to determine the flow condition when the bricks were removed in the field. The result is a tendency line, which shows the behavior of scour depth due to changes in velocity. According to this relationship and considering the conditions under which experiments and field measurements were done, it is possible to say that the scour depth due to Q=3,100 m^3/s, occurred under clear-water condition and the one in which Q=6,700 m^3/s existed under live-bed scour. Furthermore, taking into account the limitations of collecting such data, the figure shows that the results from the experiments are compatible with the observed field data.

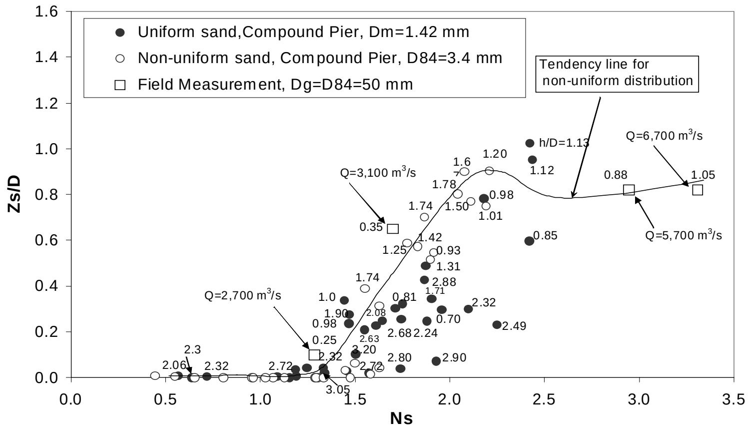

Figure 6. *Zs/D* vs *Ns* for compound piers.

7 Conclusions

The data, collected in the field measurement and from laboratory flume experiments, show that the scouring processes are comparable in the two cases. The observed (measured) values of scour depth at the piers in the field are closely related with the ones determined from the removed numbered bricks. Taking into account the practical difficulties and other limitations inherent in collecting field data, the experimental results could be used to foresee the tendency of scouring in the prototype. Finally, the use of bricks as scour depth indicators could be a very valuable tool, as it can be easily and cost effectively applied at any other bridge site.

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