

## STUDY ON LOCAL SCOURING AT SURAMADU BRIDGE PIERS FOR STRUCTURAL INTEGRITY MONITORING

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**ABSTRACT:** Local scour at bridge piers needs to be monitored regularly when the bridge is in-service since it may affect the integrity of the bridge structure and occasionally it can lead to a catastrophe. Scour at bridge piers varies with water depth, flow velocity and duration, pier geometry, and other factors. This paper discusses results of local scour study at piers of Suramadu Bridge, which is at present the longest bridge in Indonesia, for monitoring of its integrity. Field investigations were carried out to obtain sea water current speed and direction, the sea bottom profile, and seabed soil size distribution. Areas at the vicinity of the bridge piers where scouring and sedimentation took place were obtained by comparing results of this study to those of similar study reported earlier. In addition to field investigations, numerical investigation was also conducted in this study to estimate local scour depths occurred at piers of the bridge. Scour depths obtained from the measurements in the field and those numerically computed were compared. Effect of estimated scouring on the bearing capacity of the bridge pier foundation was then investigated. Results of the study showed that the integrity of Suramadu bridge structure was not affected under the estimated scour depth; however, monitoring of the bridge structure requires to be conducted regularly so that its structural integrity can be assured.

**Keywords:** Scouring at bridge pier, bridge monitoring, structural integrity.

### INTRODUCTION

Suramadu bridge is currently the longest bridge in Indonesia. The bridge is 5.4 km long. It is built over Madura strait and connecting the city of Surabaya in Java island and Bangkalan city in Madura island. Main span of the bridge is built using cable stayed system. Upper structure of the bridge main span is supported by two towers (pylons) of 146m high measured from the mean sea water level. Pile foundation having diameters of 0.6m, 2.2m and 2.4m were constructed to support the bridge piers. For the main span 2.2m and 2.4m pile diameters were constructed whereas piles having 0.6m in diameter were installed for other piers except those which are located at Madura island side where 1.0m pile diameter was constructed (Consortium of Chinese Contractors 2006). Figure 1 shows long section of the main span and approach of Suramadu bridge.

Scouring around the bridge piers occurs due to waves, currents and tides. Scouring can affect the bearing capacity of the pier foundation and in turn it may put structural integrity of the structure in danger. Occasionally scouring can lead to catastrophe. Therefore investigation is required to measure the scour depth around bridge piers to assess the structure's integrity so that damages or failure of the bridge can be avoided.

Study on the effect of tide current on scour depth was carried out and reported by e.g. Escarameia (1998), Escarameia et al. (1999) and May et al. (2002). Scour model for single pier with varied flow directions, flow durations, pier cross section shapes and sediment sizes was proposed in (May et al. 2002). Results of their studies showed that effect of sediment diameter on scour depth was not significant and scour depth maximum due to tide type current flow (reversal directional flow) was lower than the depth due to one directional flow for clear water scour (without any sediment). They also noted that one directional flow resulted in deeper and wider scour compared to that of reversal of flow direction. Maximum scour depth occurred at the upstream and downstream of the pier sides for tide type current flow while for one direction flow scouring occurred at downstream of the pier. Results of physical model tests carried out by Escarameia et al. (1999) showed that scour depth ratios due to one directional flow and reversal flow ranged from 49% to 76%. The longer duration of the reversal flow the larger the scour depth; the depth was approaching the maximum scour depth under the one directional flow.

Numerical model for scouring around piles in group due to one directional flow and reversal directional flow

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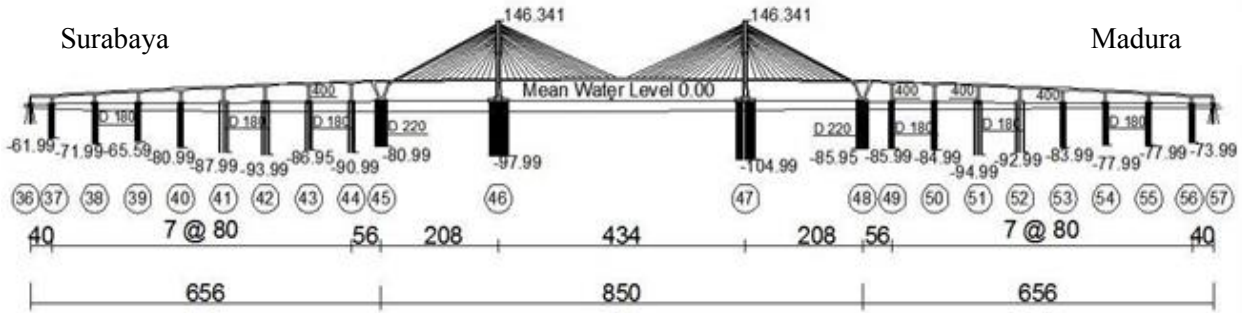


Fig. 1 Long section of Suramadu bridge from pier number 36 (Surabaya side) to pier number 57 (Madura side). The distance and elevation are in meters and pile diameter is in centimeters (Consortium of Chinese Contractors 2006)

was proposed by Vasquez and Walsh (2009). They reported that ratio of maximum scour depth under one directional flow and reversal flow was about 75%. Mohamed et al. (2005) compared 4(four) methods which are frequently used for computing scour at bridge piers. They compared scour depths computed using these methods to the depths recorded at 14(fourteen) bridge locations and those measured in laboratory. They concluded that HEC No. 18 and Larson and Toch methods could estimate the scour depth accurately. Study on 3(three) bridges carried out by Ghorbani (2008) concluded that HEC No. 18 and Hanco methods were excellent methods for predicting the scour depths.

The study reported in this paper was intended to (i) map the surrounding area of Suramadu bridge where scour and sedimentation took place by conducting field investigations, (ii) estimate scour depths around the bridge piers by applying 3(three) scour estimation models, and (iii) assess integrity of the bridge structure by computing the pier foundation bearing capacities due to the effect of scouring.

## METHODOLOGY

In this study field measurements at the bridge site were conducted to measure scour and sedimentation depths at the bridge piers. In addition to confirm results of the field measurements numerical study was carried out for estimating scour depth at piers of the bridge using scour model proposed by Hanco (Gorbani 2008), HEC No. 18 (the US Department of Transportation 2001), and Larsen and Toch method (Mohamed et al. 2005). These models were chosen because they are sufficiently accurate to predict scour occurred around bridge piers (Ghorbani 2008 and Mohamed et al. 2005). Using estimated scour depths obtained from results of this study bearing capacity of foundation at piers of the bridge was calculated and compared to force withstood by the foundation. Thus the bridge structural integrity owing to the effect of estimated scour depths could be determined.

Investigations were carried out in this study to measure scour and sedimentation depths occurred at Suramadu bridge piers. These investigations included bathymetric survey, current and tide survey and sediment material sampling on the sea bed around the piers. The bathymetric survey covered area of 5.0 km x 2x0.1km in the vicinity of the bridge. Result of the survey carried for this study was compared with the result of survey reported in (Consortium of Indonesian Contractors 2005) so that the area around the bridge piers where scouring and sedimentation occurred could be determined.

Measurement for the sea current velocity and direction was conducted in 7(seven) points along the bridge. Moreover 54(fifty four) soil sediment samples were taken at the sea bed around the bridge pier. In addition to data obtained from these investigations data related to the bridge (pier location, pile foundation dimension, and soil properties) were obtained from (Consortium of Indonesian Contractors 2005 and Consortium of Chinese Contractors 2006). Using these data 3(three) methods were applied to estimate scour depth around the bridge pier; these methods included HEC No. 18, Hanco and Larsen and Toch methods. In predicting the scour depth around complex pier foundation HEC 18 accounts for 3(three) components these are pile stem, pile cap and pile foundation, see Figure 2. Scour analysis around bridge complex pier foundation is computed from superposition of these three components; it can be expressed as,

$$y_s = y_{s\ pier} + y_{s\ pc} + y_{s\ pg} \quad (1)$$

$y_s$  = total scour depth,

$y_{s\ pier}$  = pier stem scour depth component,

$y_{s\ pc}$  = pile cap scour depth component,

$y_{s\ pg}$  = pile foundation scour depth component

Detailed explanation regarding computation of these scour depth components can be found in (US

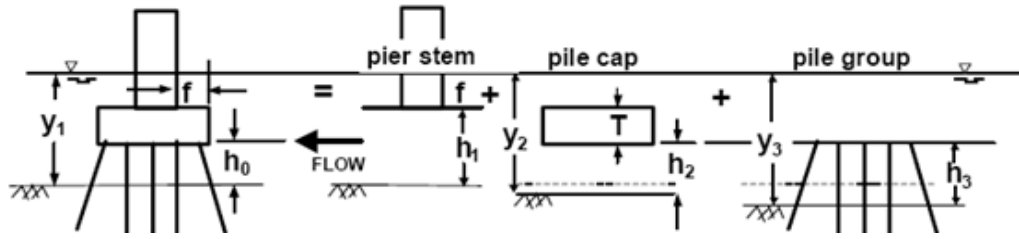


Fig. 2 Components of scour occurs in a complex pier foundation (taken from US DoT, 2001).

Department of Transportation, 2001).

Hanco (Ghorbani 2008) proposed empirical equation for predicting the scour depth,  $y_s$ , as

$$y_s = 3.3 (D_{50})^{0.2} a^{0.67} y_1^{0.13} \quad (2)$$

$D_{50}$  is median size of eroded soil sediment at the sea bed,  $a$  is pier width, and  $y_1$  is water depth in front of the pier. In this study the pier wide is taken to be equivalent to the projection of pile width because pile caps of the bridge pier foundation were constructed above the sea bed.

Larsen dan Toch proposed simple expression for predicting scour depth around the bridge pier (Mohamed et al. 2005). The formula can be written as,

$$y_s = 1.35 a^{0.7} y_1^{0.3} \quad (3)$$

where  $a$  is the pier width, and  $y_1$  is the water depth in front of the pier.

To take into consideration the effect of reversal flows (due to tides, sea current etc) on the computed scour depths, the depths were compared with those proposed by (May and Escarameia 2002 and Vasquez and Walsh 2009) and the score depths measured on-site during the investigations carried in this study. Scour depths obtained from this study was used for assessing bearing capacity of the bridge pier pile foundations so that its effect on the bridge foundation and also the bridge structure could be justified. In this study the loads for the bridge foundation and soil physical properties were taken from study reported in (Consortium of Chinese Contractors, 2006). It was assumed that the soil properties remained the same after the bridge was built.

Bearing capacities of pile foundation under vertical and horizontal loads were computed. Bearing capacity under vertical load can be obtained using (Das 1990)

$$P_u = A_p \cdot q_p + \sum p \Delta L f \quad (4)$$

$A_p$  is cross sectional area of the pile,  $q_p$  is end bearing capacity of the pile,  $p$  is circumference of pile cross section,  $\Delta L$  is the length of pile embedded in soil, and  $f$  is soil friction.

Efficiency of pile bearing capacity can be computed using Converse-Labare equation. Pile bearing capacity under horizontal force is computed using the expression,

$$H = \frac{4EIb^3 y}{(1+bh) \times 10^{-3}} \quad (5)$$

$$b = \left[ \frac{kD}{4EI} \right]^{0.25} \quad (6)$$

$$k = 0.2 \times E_o \times D^{-0.75} \times y^{-0.5} \quad (7)$$

$$l_m = \frac{1}{b \tan^{-1} [bh]^{-1}} \quad (8)$$

$E$  is modulus of elasticity of the pile material,  $E_o$  is soil modulus of elasticity,  $I$  is the moment of inertia of the pile cross section,  $h$  is the length of free-standing for the pile,  $y$  is pile deformation at the sea bottom,  $k$  is coefficient of soil reaction,  $D$  is the pile diameter and  $l_m$  is virtual fixity length.

Force occurs in each pile foundation can be computed using the equation given below,

$$P_v = \frac{V}{n} + \frac{M_y \cdot x}{\sum x^2} + \frac{M_x \cdot y}{\sum y^2} \quad (9)$$

where  $V$  is applied vertical force,  $M_x$  and  $M_y$  are moments about the  $x$  and  $y$  axes,  $y$  and  $x$  are distance measured for the center of gravity of pier pile cap, and  $\sum x^2$  and  $\sum y^2$  are moment of inertia of the pile group.

## RESULTS AND DISCUSSION

As mentioned earlier on-site investigations carried out in this study were bathymetric survey, tides, sea current velocity measurement, and soil sediment sampling. Numerical study was then conducted to estimate scour depths around the bridge pile piers using

3 (three) different methods. Data required for estimating the scour depths were obtained from the investigations conducted in this study.

**Bathymetric Survey**

Results of this survey indicated that the sea water depth around the bridge piers could be divided into three groups, i.e., the depths ranging from 0.0 to -8.0m, -8.0m to -14.0m, and -14.0m to -22.0 m. The deepest area was that around the piers located in the main span of the bridge, viz. piers no 46 and 47. The sea water depth gradually decreased toward the approach bridge

The results were overlaid by measurement results carried out in 2005 to obtain scour and sedimentation depths around the piers. As shown in Figure 3 the scour depths occurred in the vicinity of Suramadu bridge were in the range of 0.0m to 4.0m, while the sedimentation were in the range of 0.0m to 8.0m. Deep scour occurred in the vicinity of Pile No. 27, 28, 29, 38, 39, 40, 41, 42, and 48.

**Sea Current Measurement**

Tide current speed and directions were measured in 7 (seven) locations in the vicinity of Suramadu Bridge piers. The measurement survey showed that the average velocities were in the range of 0,012m/sec to 0,181m/sec and flowed to the East.

**Soil Sediment Sampling**

Seabed soil samples (total 54 samples) were collected from the areas in the vicinity of Suramadu Bridge piers. The samples were tested in the soil laboratory to obtain their grain size distributions by sieve and hydrometer analysis. The results of the analysis showed that the seabed soil consisted of sand, silt and clay. In general, the soil samples was dominated by sand (>60%) except in the samples taken around pile No. 19 and piles No 78 to 87 where they were dominated by silt and clay.

**Numerical Study on Scouring around the Bridge Piers**

To estimate the scour depths in the vicinity of bridge pile piers, a numerical study as described in the methodology was carried out and compared to the results from field observation. Data from field measurements as well as data obtained from other institution were used for numerical inputs. The results of scour in the vicinity of Suramadu Bridge piers obtained using 3(three) methods were depicted in Figure 4.

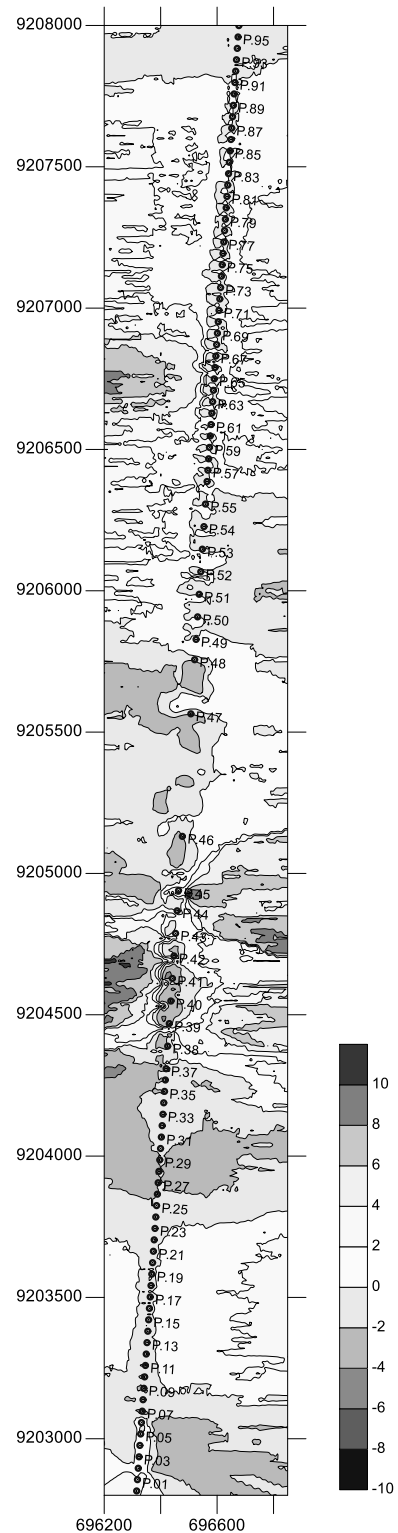


Fig. 3 Contours of scouring and sedimentation depths occurred around Suramadu bridge piers obtained from field measurement conducted for this study.

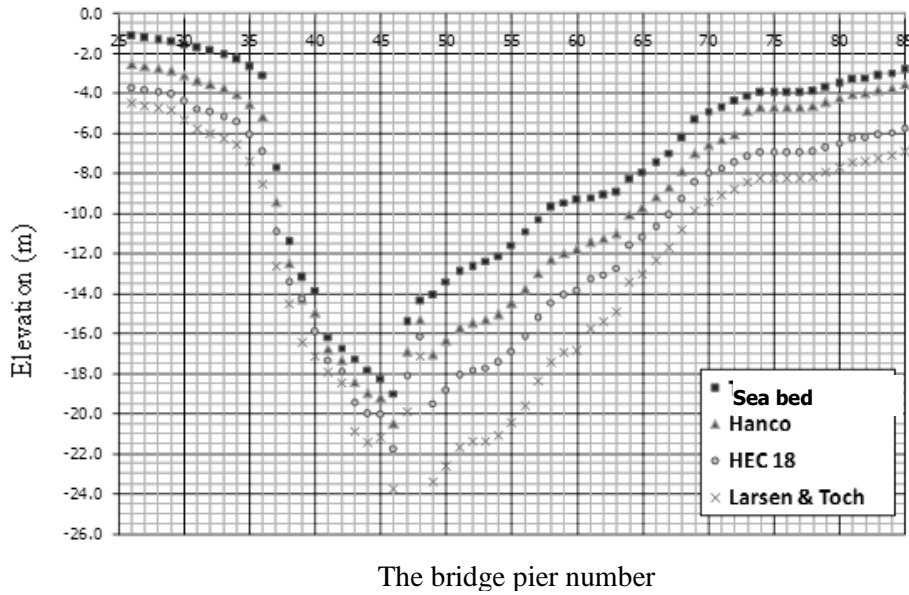


Fig. 4 Scour depths computed using 3(three) different methods by assuming that the flow was uni-directional.

As seen in Figure 4 the scour depths estimated using Larsen & Toch method were deeper than those of Hanco and HEC 18 methods. Large differences (more than 4.0m) were observed in the middle span of the bridge. Scour depths computed using Larsen and Toch method were much higher than field scour observation, therefore this method was not considered in the assessment of pile bearing capacities.

The scour depths estimation using Hanco and HEC 18 methods were in the range of 5.0m to 5.4m; they occurred in the vicinity of pile no 46 to 57. It should be noted that the depth estimation using the above methods consider of one direction flows, while in reality the tide flows in the bridge pile is reciprocal two direction flows with varied speed. The scour estimation method based on two direction flows is not available nowadays. However the estimation using three methods described earlier was intended to obtain initial maximum scour estimation for the bridge piers.

Physical model study by Escarameia (1998) and May and Escarameia (2002) for scouring in the vicinity of single pile with variation of pile shapes, sediment materials, direction and duration of flows due to tidal currents showed that the scour depth was about 49% to 76% of the scour depth estimated by one directional flows. The longer the duration of flows, the closer the estimated maximum scour of two directions to the scour of one directional flow. Therefore, based on the above estimation, a maximum depth of scour in the Suramadu Bridge piers to be used for pile capacity is 4.5m. This value is higher than the depth observed in the field where maximum of 4.0m scour depth was measured. However, as mentioned in the Escarameia (1998) studies above, the maximum depth of two directional flows is 75% of

scour depth from one directional flows. Therefore 75% of 5.4 m is 4.05m which is close to the scour observed in the field.

#### Bearing Capacity of Bridge Pier Foundation

In this study bearing capacities of pile foundation of bridge piers were assessed to investigate the effect of scouring on bearing capacities of the piles. As stated earlier the maximum scour depth used in this study for computation of bearing capacity of the piles was 4.5m. The loads applied to the piles and soil properties were obtained from the report prepared by Consortium of Chinese Contractors (2006). In this study the soil properties were assumed to remain unchanged. In addition the pile cap was stiff so that Eq. (8) could be applied to obtain the forces occurred in the piles. Results of this study showed that allowable bearing capacities of pile foundation were larger than the maximum force occurred in the pile. In addition the pile strength was also larger than the force and moment withstood by the pile foundation; it meant that failure due to buckling that could occur because of increasing free-standing pile length would not take place. For the sake of brevity detailed results of the foundation bearing capacity assessment were not be reported in this paper. This study revealed that most the bridge pier pile foundation was designed by ignoring the soil friction so that scouring would not affect the designed vertical bearing capacity of the foundation. However it would affect the horizontal bearing capacity and the stresses or resistances in the pile foundation material. Therefore scouring occurring in the bridge pier foundations needs to be monitored regularly so that damages, which would lead to failure of the bridge can be avoided.

## CONCLUSION

In this study on-site investigations were conducted to measure scour depths around Suramadu bridge piers. In addition to these field investigations numerical study was also carried out to estimate scour depths around piers of the bridge using methods proposed by three researchers. Results of the field investigations and the numerical study were compared. By taking into account the effect of tides on sea current directions and considering scour measured in the field investigations, scour depth at the bridge pier was determined and utilized for estimating bearing capacity of pile foundations of bridge piers. Thus the effect of scouring to integrity of the bridge structure could be justified. Results of the study showed that the scour depth estimated using methods employed in this study did not affect the integrity of the bridge structure. Nevertheless periodic monitoring of the upper and sub structure of bridge needs to be conducted so that its integrity can be assured during its design life.

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