Experimental study of flow around a pole standing in a scour

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Abstract. The characteristics of fluid flow and fluid force of the pole standing in scour were investigated with several different scour depths conditions by using a wind tunnel. The scour was modeled into a mortar, with an inverted circular cone. The diameter of the pole was 40 mm and the scour depth was changed from H/D (= depth / diameter of the pole) 0.25 to 1.75. The free stream velocity was 16 m / s, making the Reynolds number 4.2×10^4 . Flow visualization was carried out using a surface oil-film method and smoke-wire method. The surface pressure distributions on the pole and the scour were measured and the drag coefficient acting on the pole was determined by integrating the surface pressure distribution on the pole. The characteristics of the flow around the pole and the drag acting on the pole standing on the scour were clarified. The results show that as the scour depth become deep, the flow around the pole is extremely characteristic and the drag coefficient has a maximum value at $Z/D = 0.25$ and a minimum value at about the midpoint between the ground level and the bottom of the scour.

1 Introduction

Local scour is defined as the abrupt decrease in bed elevation near a pole due to the erosion of bed material induced by the local flow structure in the vicinity of the pole. Local scour around bridge pier is one of problem in civil engineering field as shown in figure 1. The scour around a pole standing on the sand and snow has the same problem too.

It is well known that the horseshoe vortex system largely dominates the flow field around a pole in scour [1, 2], the flow around a pole is dominated by the three vortex systems; a horseshoe vortex system, a wake vortex system and a trailing vortex system. The horseshoe vortex surrounding a cylindrical pole has been captured in computation [3]. It was found that two distinct horseshoe vortices influence the scour formation. Recently the flow and horseshoe vortex characteristics are cleared by several modern manners, a particle image velocimetry (PIV) [for example 4], an acoustic doppler velocimetry (ADV) [for example 5 and 6] and a simulation [for example 7].

Figure 1. Typical example of the bridge pier scour.

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On the other hand, the progress of local scour is time dependent [8 and 9]. Figure 2 shows the distinction in depth between the clear water scour condition and the scour with continuous sediment motion. The depth approaches a limit asymptotically with the clear water scour, while there is a periodic oscillation in the scour depth with continuous sediment motion. The flow around the pole and the fluid force acting on the pole are changed with time.

In this study we focus on flow and fluid force acting on a pole standing in a scour under the clear water scour condition. In the clear water scour condition, the radius and depth of the scour both grow up at the same time, the scour slope keeps constant angle as shown in figure 3 (a). In this study, we consider the special case that only the depth increase as shown in figure 3 (b). We can extremely sometimes observe it, for example, the pole standing on the partially paved or hard ground. So that, we carried out the experimental wind tunnel study.

Figure 2. Time variation of scour depth; (a) clear water scour and (b) scour with continuous sediment motion

2 Experimental apparatus and method

The flow geometry and coordinate system for the experiments are shown in figure 4. The pole, with diameters D of 40 mm, was made of acrylic resin. The configuration of a real scour is complicated, so we simplified the scour and made the inverted circular cone model. Seven different depths of scour models were used for this investigation: H/D (depth / diameter of the pole) = 0.25, 0.5, 0.75, 1.0, 1.25, 1.5 and 1.75. The radius of the scour, R , was constant value of 90 mm. The scours were made of wood.

Experiments were performed in a low speed wind tunnel with a 400 mm high, 300 mm wide and 1000 mm long working section. The free stream velocity, U , was 16 m/s and the Reynolds number, Re , based on D was 4.2×10^4 .

Figure 3. Progress type of scour; (a) R and H both increase and (b) R keep constant, H increase.

Figure 4. Flow geometry and coordinate system.

The surface pressure on the pole and scour were measured by a multi-tube pressure manometer connected to 0.6 mm diameter pressure taps arranged along a spiral arrangement at ten-degree intervals from the surface of the pole and scour. The pressure measurement system is shown in figure 5. The entire pole and scour surface pressure can be determined by rotating the model on its center axis. The fluid forces acting on the pole were then obtained by integrating the pressure distribution of the pole.

The flow visualization of the pole and scour was performed using an oil-film method and a smoke-weir method. The oil-film method is available in order to allow for the observation of the time averaged flow behavior around the structure. The oil film is white oil mixed with oleic acid, titanium oxide, and liquid paraffin. The surface of the flow visualization model was painted black in order to provide the highest possible contrast with the white oil film.

3 Results and discussion

3.1 Flow visualization

Figure 6 shows the surface oil-flow pattern on the pole and scour at various depths. In $H/D = 0.25$, the oil flow pattern of the pole is similar to the two dimensional flow pattern of a single circular cylinder. In $H/D \geq 0.75$, the effect of the scour depth appears on the oil flow pattern on the pole. This fact shows that the flow around the pole changes in the certain condition of $0.25 < H/D \leq 0.75$. On the scour surface, a circular separation lines are observed in all condition. These are caused by a horseshoe vortex.

Figure 7 describes the peculiarity of the surface oil flow pattern on the pole. The flow around the pole in the scour is dominated by the horseshoe vortex system. On the front face, there are the two stagnant points ($F.St_2$ and $F.St_1$) and the interactive line ($i.L.$), which can be attributed to the interaction of the two horseshoes vortices shown in the flow schematic. One horseshoe vortex is large and rotates clockwise, and another is small and rotates counter clockwise as refer to figure 8. On the side and rear faces, we can observe the concentrate point ($C.P.$), the rear stagnant point ($R.St.$) and the rear separation area ($R.S.$).

Figure 5. Pressure Measurement system.

Figure 6. Oil flow pattern on the pole and scour surface ($Re = 4.2 \times 10^4$);
(a) $H/D = 0.25$, (b) $H/D = 0.75$, (c) $H/D = 1.25$ and (d) $H/D = 1.75$.

Figure 7. Description of the oil flow pattern on the pole

We back to the figure 6. In $H/D \geq 0.75$, on the pole, the interaction line (*i.L.*) appears on the front face, the oil flow patterns on the side and back faces are remarkable. These are the concentrate points (*C.P.*) are formed on both side of the rear separation area (*R.S.*), which are caused by interaction of the horseshoes vortices and the roll-up vortex. The roll-up vortex is the spiral vortex can be observed behind the pole [11]. Graf and Istiarto [6] and Pasiok and Stilger-szydlo [7] call this vortex the wake vertical vortex. The deeper the scour, the larger the rear separation area.

3.2 Pressure distribution on the pole and scour

Figure 9 shows the pressure coefficient contours on surface of the pole. The numbers on the contours show the values of the pressure coefficient. In $H/D = 0.25$, the contours show approximately the two-dimensional pressure distribution of a circular cylinder, because the scour is extremely shallow. In $H/D \geq 0.75$, the depth of the scour hardly influence to the surface pressure of the pole. In $H/D = 0.75$, the high pressure areas appear in front and back of root of the pole. The high pressure areas expanded with increasing the depth of the scour. In $H/D = 1.75$, the high pressure areas surround the root of the pole. In $H/D \geq 0.75$, there are the lowest pressure areas in $\theta = \pm 120 - \pm 150$ degree at $Z/D = 0$. These point and the concentrate points (*C.P.*) in figure 6 correspond.

Figure 8. Horseshoe vortices in front of the pole
($H/D = 1.5$, $Re = 4.2 \times 10^4$)

C.P. : concentrate point
F. St : front stagnation point
R. St : rear stagnation point

H.V.(C.W.) : horseshoe vortex (clockwise)
H.V.(C.C.W.) : horseshoe vortex (counter clockwise)
i.L. : interactive line

Figure 9. Pressure coefficient contour on the pole ($Re = 4.2 \times 10^4$); (a) $H/D = 0.25$, (b) $H/D = 0.75$, (c) $H/D = 1.25$ and (d) $H/D = 1.75$.

The pressure coefficient contours on the scour are presented in figure 10. In $H/D = 0.25$, generally the pressure on the front and back area of the pole are positive and negative respectively, just in front of the pole, the pressure has maximum value. In $H/D = 0.75$, the negative pressure area in the back of the pole decrease. The negative pressure areas on the scour decrease with increasing the depth of the scour. In $H/D \geq 1.0$, the positive pressure area spreads out in back of the pole and the whole scour becomes the positive pressure area.

Figure 11 presents the pressure coefficient distribution along the centerline of the pole and scour. The inside and outside from the outline of the pole indicate negative and positive pressure areas, respectively. The upper and lower side from the ground level and the scour outline indicate negative and positive pressure areas, respectively.

Figure 10. Pressure coefficient contour on the scour ($Re = 4.2 \times 10^4$); (a) $H/D = 0.25$, (b) $H/D = 0.75$, (c) $H/D = 1.25$ and (d) $H/D = 1.75$.

Figure 11. Pressure coefficient distribution of the pole and scour surface on the centerline ($Re = 4.2 \times 10^4$); (a) $H/D = 0.25$, (b) $H/D = 0.75$, (c) $H/D = 1.25$ and (d) $H/D = 1.75$.

Figure 12. Local drag coefficient of the pole

Figure 13. Local drag coefficient of the pole under the ground level

The pressure coefficient distribution on the front face of the pole, C_{pf} , has a minimum value at the middle point of the scour depth. On the rear face, in $H/D \geq 1.25$ the back pressure coefficient, C_{pb} , reaches a maximum value on the root, which is the rear stagnation point. The value of C_{pb} decreases as it moves up because of the wake vertical vortex. At the root of the pole and the bottom of the scour, the positive pressure area enlarges with the scour depth, because the pole was surrounded with the horseshoe vortices.

3.3 Drag force acting on the pole in the scour

The local drag coefficient of the pole, CD_z , was obtained by integrating the pressure coefficient distribution on the pole surface. The CD_z is plotted against Z/D in figure 12. In $H/D = 0.25, 0.5$ and 0.75 , There is little influence of the scour depth in the distributions. In $D/H \geq 1.0$, the distributions of CD_z have the same tendency. That is to say, the distribution has a maximum value at about $Z/D = 0.25$ and a minimum value at $Z/D = -1.0 \sim -0.3$, which is approximately the middle of the scour depth. The concentrate points (C.P.) and the minimum C_{pf} position are related to the maximum and minimum value of CD_z .

Figure 13 shows the change of CD_z with scour depth under the ground level. In $H/D = 0.25, 0.5$ and 0.75 , the change of CD_z by the depth is small. In $D/H \geq 1.0$, the

distributions are arc shapes with the minimum value at about $Z / H = -0.5$ which is the midpoint between the ground level and the bottom of the scour.

4 Conclusions

The characteristics of fluid flow and fluid force of the pole standing in scour were investigated with several different scour depths by using a wind tunnel. As a result, the relation between the flow and pressure fields was clarified.

According to the flow visualization and the pressure counter, the flow around the pole changes in the certain condition $0.25 < H / D \leq 0.75$. The effect of the horseshoe vortex and the roll-up vortex was given and the effect of the scour depth appears on the surface flow of the pole and scour in $H / D \geq 0.75$.

The effect of the scour depth appears on the local drag coefficient of the pole remarkably in $H / D \geq 1.0$. The distributions of the drag have the same tendency. That is to say, the distributions have the maximum value at $Z / D = 0.25$ and are arc shapes with the minimum value at about $Z / H = -0.5$ which is the midpoint between the ground level and the bottom of the scour.

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