THE EXPERIMENTAL STUDY ON LOCAL SCOUR AROUND A CIRCULAR PIPE UNDERGOING VORTEX-INDUCED VIBRATION IN STEADY FLOW

Bing Yang¹, Tao Yang¹, Jian-Lin Ma¹, and Jin-Sheng Cui²

Key words: local scour, circular pipe, vortex-induced vibration, steady flow, gap-to-diameter ratio.

ABSTRACT

The local scour around a circular pipe undergoing vortex-induced vibration is investigated experimentally in a water flume. The typical characteristic of local scour is analyzed in detail. The influences of initial gap-to-diameter ratio ($e_0/D$), the mode of pipe vibration and the sand type on the local scour are discussed. Experimental results indicate that there exists strong intensity of scour when the pipe moves close to the surface of the sandy bed. The vibration of the pipe results in the rapid development of sandy bed’s scouring. With the increase of gap-to-diameter ratio the distance between the center of the pipe and the position of the maximum scour depth gets larger. The maximum scour depth does not vary monotonically with the gap-to-diameter ratio, but reaches the largest one at certain gap-to-diameter ratio between the values of $e_0/D = 0$ and 2. There is not much difference of the scour profiles around the vibrating pipe between one degree and two degrees of freedom involved in this study.

I. INTRODUCTION

The local scour around a circular pipe in steady flow is a complex coupling problem between fluid, structure and soil, and is also a multi-discipline intersecting problem. Studying the problem has an important significance of engineering and a good scientific value, and therefore, many researchers have paid much attention to it. Kjeldsen et al. [7] conducted experiments in a flume and presented an empirical expression for predicting maximum depth of scour. Based on results by Kjeldsen et al. [7], Bijker and Leeuwestein [1] carried out a series of supplementary experiments in a flume and discussed the effect of mean diameter of sand grain on the scour. Later Ibrahim et al. [5] and Moncada-M et al. [11] further discussed the prediction of maximum scour depth. Sumer et al. [13] made a dimensional analysis on the influencing factors of equilibrium scour depth and investigated the influence of Reynolds number upon the equilibrium scour depth. From the end of eighties in twenty century, the mechanism of the pipe’s suspension attracted the researchers’ interests. Mao [10] stated that the pressure difference between two sides of the pipe with a small embedment on the sand bed will induce seepage flow within the sandy bed. Chiew [2] found that the piping is the main cause of the pipe’s suspension by qualitative experiments. Sumer et al. [17] carried out quantitative experiments about the suspension of the pipe placed on the sandy bed on the basis of the work by Mao [10] and Chiew [2]. They found that the hydraulic gradient ($i$) in the sandy soil is mainly related to the undisturbed flow velocity $U$ (at the top of the pipe), pipe diameter $D$, the initial burial depth $e_0$ and acceleration of gravity $g$. Yang et al. [19] investigated the mechanism of pipe’s suspension by means of numerical simulation. Moreover, the mechanism of scour are also discussed by some researchers [6, 8, 9, 15, 18].

In fact, the pipe may undergo vortex-induced vibration due to the scour under some circumstances. For example, the vortex-induce vibration of submarine pipeline may occur under the action of ocean currents. About this, Sumer [16], Shen et al. [12] and Gao et al. [3] made some preliminary studies. In the work by Sumer et al. [16], two kinds of experiments were conducted. One was to investigate the influence of transverse vibration of the pipe on the scour, and the other was to investigate the influence of scour on the vibration of the pipe. In the second kind of experiment, the pipe was initially maintained stationary for 30 min at a given flow velocity during which scour reached its equilibrium state, and the pipe was subsequently released and vibrated freely above...
the scour hole. Shen et al. [12] primarily investigated the vibration of the pipe with two degrees of freedom (Streamwise and transverse) near an erodible sandy bed. Gao et al. [3] investigated the coupling effects between pipe vibration and sand scour experimentally. They found that the sand scouring will influence the vibration amplitude and frequency of the pipe, and the vibrating pipe may induce a deeper scour hole than the fixed pipe in their examined range of initial gap-to-diameter ratios (-0.25 < e_0/D < 0.75).

Most of the previous studies focus on the local scour around the fixed pipe and only few researchers paid their attention to the local scour around the pipe undergoing vortex-induced vibration. But it has important significance to study this problem, for it can provide the theoretical guideline for the design of submarine pipeline placed on the sandy seabed. Due to its complexity, the underlying mechanism of the coupling interaction between pipe vibration and the scour of sand soil needs to be understood further.

In this paper, the experiments on the local scour around the vibrating pipe are conducted in a flume. The typical characteristic of local scour is described correspondingly. The influences of initial gap-to-diameter ratio, the mode of pipe vibration and the sand type on the scour are discussed.

II. EXPERIMENTAL SET-UP

A special device is used for the present experiments, which is placed in a water flume, as illustrated in Fig. 1. The flume is 0.5 m wide, 0.6 m high and 19 m long, which can produce steady currents with velocity up to approximate 0.6 m/s. The water depth is kept at 0.35 m in this study. The test pipe was attached to the supporting frame by two connecting shafts, two sliding poles and two sets of springs. The sliding poles can move along the four limit wheels, which are connected to the two supportings by four bearings. The pipe can swing around the gemel installed at the lower ends of the sliding pole. The streamwise (in-line) and transverse vibration of the pipe will be modeled in this study. A laser displacement transducer is employed for the non-contact measurement of the vibrating pipe’s displacement. The one with a dynamic resolution of 0.25 mm is used for measurement of vertical displacement and another one with 0.025 mm is for horizontal displacement. The natural frequency of the pipe is obtained by spectrum analysis of free-decay tests in still water.

The time development of scour depth is recorded with a digital camera which is placed at one side of the flume to record the scour profile of the sand bed. The fine and transparent scale paper is pasted on the side wall. When the surface of the sand bed deflects, the value of the variation can be obtained by means of the scale paper. When the scour reaches its equilibrium stage, i.e. the surface of sand bed changes little within ten minutes, the longitudinal scour profile is measured with a depth probe, which can slide along the two side-walls of the flume. The test pipes are 0.032 m and 0.050 m in diameter, 0.47 m in length. Only smooth pipes are considered in this study, i.e. k/D = 0. Two kinds of sandy soil are used, whose grain size distribution are shown in Fig. 2. The mean diameter of the sand grain are d_50 = 0.38 mm with a relative density D_r = 0.66 and d_50 = 0.12 mm with D_r = 0.42. The depth of sandy soil is 15 cm. There are about 15 tests carried out in the experiment, as shown in Table 1.

III. RESULTS AND DISCUSSIONS

1. Dimensional Analysis on the Local Scour

The physical quantities which affect the local scour around the circular pipe undergoing vortex-induced vibration are mainly as follows: the flow velocity U; the kinetic viscosity of fluid ν; the gravitational acceleration g; the mass density of fluid ρ; the mean diameter of sand particles d_50; the mass density of sand grain ρ_s; the relative density of sand soil D_r; the outer diameter of pipe D; the mass of a pipe per meter m;
Table 1. The details of experimental parameters.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>D (m)</th>
<th>U (m/s)</th>
<th>(d_{50})</th>
<th>(e_0/D)</th>
<th>(\theta)</th>
<th>(m^*)</th>
<th>(V_r)</th>
<th>(\zeta)</th>
<th>Type of vibration</th>
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<td>0.66</td>
<td>0.039</td>
<td>1.36</td>
<td>6.6</td>
<td>0.0586</td>
<td>transverse</td>
</tr>
<tr>
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<td>0.255</td>
<td>0.38</td>
<td>0.66</td>
<td>-0.24</td>
<td>0.039</td>
<td>1.36</td>
<td>6.6</td>
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<td>1.36</td>
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<tr>
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<td>0.255</td>
<td>0.38</td>
<td>0.66</td>
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<td>0.255</td>
<td>0.38</td>
<td>0.66</td>
<td>-0.25</td>
<td>0.039</td>
<td>1.97/2.60</td>
<td>0.0386/0.0565</td>
<td>Streamwise and transverse</td>
</tr>
<tr>
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<td>0.255</td>
<td>0.38</td>
<td>0.66</td>
<td>0</td>
<td>0.039</td>
<td>1.97/2.60</td>
<td>0.0386/0.0565</td>
<td>Streamwise and transverse</td>
</tr>
<tr>
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<td>0.255</td>
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<td>0.66</td>
<td>0.34</td>
<td>0.039</td>
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<td>0.0386/0.0565</td>
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<td>1.97/2.60</td>
<td>0.0386/0.0565</td>
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<td>0.0386/0.0565</td>
<td>Streamwise and transverse</td>
</tr>
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<td>7.1</td>
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<td>0.66</td>
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<td>0.039</td>
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</tr>
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<td>0.039</td>
<td>1.97/2.60</td>
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<td>0.12</td>
<td>0.42</td>
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<td>0.039</td>
<td>1.97/2.60</td>
<td>0.0275/0.0543</td>
<td>Streamwise and transverse</td>
</tr>
</tbody>
</table>

Fig. 2. Grain size distribution curves of the sand.

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the natural frequency of pipe in still fluid \(f_n\); the structural damping factor of the pipe \(\zeta\); the roughness of pipe surface \(k\); the initial gap between pipe and sand bed \(e_0\). According to the principle of dimensional analysis, the physical quantities above can constitute some dimensionless parameters, i.e. \(V_r\), \(m^*\), \(K_s\), \(k/D\), \(Re\), \(e_0/D\), \(\theta\), \(Dr\), \(d_{50}/D\), \(s\), where \(V_r\) is the reduced velocity and defined as

\[
V_r = \frac{U}{(f_n D)}
\]

\(m^*\) is the mass ratio, \(K_s\) is the stability parameter, \(Re\) is the Reynolds number, \(\theta\) is the Shields number, \(s\) is the relative density, and they are defined as follows:

\[
m^* = \frac{(4m)l}{(\pi D^2)}
\]

\[
K_s = \frac{(4(m + m_d) \zeta^2 l)}{(\pi D^2)}
\]

where \(m\) is the added mass, and \(m_d = C_d m_g\). \(C_d\) is the added mass coefficient and \(C_d = 1.0\). \(m_g\) is the displaced fluid mass by the pipe per meter and \(m_d = (\pi D^2)/4\).

\[
Re = \frac{(UD)}{\nu}
\]

\[
s = \rho_f / \rho
\]

\[
\theta = \frac{U_f^2}{(s - 1)gd_{50}}
\]
and can be calculated with the Colebrook-White formula, i.e. $U/U_f = 8.6 + 2.5\ln(D/2k_b)$, here $k_b$ is the roughness of sandy bed’s surface and usually taken as $2.5d_{50}$ [14]. Therefore, the equilibrium scour depth ($S$) can be expressed as

$$S/D = f(Vr, m^*, K_*, k_b/D, Re, e_0/D, \theta, Dr, s, d_{50}/D) \quad (7)$$

2. The Typical Characteristic of Local Scour

Fig. 3 shows the typical phenomenon on the dynamic response between the vibrating pipe and the sandy bed. It can be seen from the figure that when the pipe moves close to the surface of the sandy bed, a lot of sand grain is lifted from the surface by the fluid at the wake region. It indicates that there exists strong intensity of scour at the surface of the sandy bed when the pipe contacts to the surface of the sandy bed. The development of scour depth with time for the case of $e_0/D = 0$ and $\theta = 0.039$ is illustrated in Fig. 4. It is indicated from the figure that an inflection point appears at the curve of scour development. The scour develops slowly before the inflection point appears, and after the inflection point the scour beneath the pipe develops quickly. According to the observation of experiments, the time at which the inflection point appears corresponds to the occurrence of the pipe’s vibration.

It indicates that the vibration of the pipe results in the rapid development of sandy bed’s scour. It is seen from Fig. 4 that the scour depth has increased to the value of $0.3D$ when the pipe begins to vibrate. According to the observation, there exist mainly two forms of motion for the sand grain on the surface of sandy bed beneath the pipe during the course of vibrating, as depicted in Fig. 5. The first form is periodical bed load motion of the sand grain at the upstream side of scour hole. When the pipe moves down, the first form of motion appears. When the pipe moves up from the lowest position, the second form of motion (i.e. periodical lift motion of the sand grain at the downstream side of the scour hole) occurs.

3. The Influences of Initial Gap-to-Diameter Ratio ($e_0/D$) on the Local Scour

Fig. 6(a) illustrates the equilibrium scour profile around a transverse vibrating pipe for the case of various gap-to-diameter ratios. The Shields number ($\theta$) is 0.039 in this experiment, which is calculated according to the undisturbed incoming flow. Therefore, the scour far away from the center of the pipe is clear-water scour. The pipe with $m^* = 1.36$ vibrates only in transverse direction. The structural damping factor of the pipe ($\xi$) is 0.0586 and the reduced velocity ($Vr$) is 6.6. It can be seen from the figure that the position of maximum scour depth locates at the downstream side of the pipe’s center for all the gap-to-diameter ratios in this study. With the increase of gap-to-diameter ratio the distance between the center of the pipe and the position of the maximum scour depth gets larger. It is also indicated from the figure that the maximum scour depth does not vary monotonically with the gap-to-diameter ratio, but reaches the largest one at certain gap-to-diameter ratio between the values of $e_0/D = 0$ and $e_0/D = 2$. The vibrating amplitudes corresponding to the equilibrium scour profiles in Fig. 6(a) are plotted in Fig. 6(b). It is observed from the figure that the vibrating amplitude does also not vary monotonically with the gap-to-diameter ratio. According to the results by Yang et al. [20], with the decrease of the gap between the pipe and the sandy bed, the maximum scour depth tends to increase for the case of the local scour around the fixed pipe. Due to the influence of vibration, the variation of maximum scour depth with the gap-to-diameter ratio presents a different law, compared with those for the fixed pipe case. Therefore, the characteristic of local scour is
affected by the combination of gap-to-diameter ratio and the pipe’s vibrating for the case of vibrating pipe. For instance, the maximum scour depth corresponding to $e_0/D = 0$ is smaller than that corresponding to $e_0/D = 0.32$ due to the larger vibrating amplitude of the pipe for the $e_0/D = 0.32$ case. The maximum scour depth corresponding to $e_0/D = 1.00$ is larger than that corresponding to $e_0/D = 2.00$ due to the larger gap-to-diameter ratio for the $e_0/D = 2.00$ case.

Fig. 7 gives the equilibrium scour profiles around the vibrating pipe with two degrees of freedom for various gap-to-diameter ratios. The corresponding vibration amplitudes of the pipe for equilibrium scour profiles of various gap-to-diameter ratios are plotted in Fig. 7(b). It is indicated from the figure that the variation of scour depth with gap-to-diameter ratio for two degrees of freedom case presents a similar law with that for one degree of freedom case.

4. The Influences of Vibration Mode of the Pipe and the Soil Type on the Local Scour

The scour profiles around the vibrating pipe with one and two degrees of freedom are plotted in Fig. 8. The gap-to-diameter ratio in the figure is 0.32. The transverse vibrating amplitude of the pipe with $m^* = 2.08$ and $\zeta = 0.0359$ is 0.84D. The experimental parameters for the pipe with two degrees of freedom are as follows: $m_x = 1.76, \zeta_x = 0.0364, m_y = 2.08, \zeta_y = 0.0521, A_x/D = 0.63, A_y/D = 0.99$. The reduced velocity ($V_r$) is 7.1 and Shields number ($\theta$) which corresponds to the
Fig. 8. The comparison of scour profiles around the vibrating pipe between one degree (transverse) and two degrees of freedom (Streamwise and transverse): $e_S/D = 0.32$; Transverse vibration: $m_x^* = 2.08$, $\xi = 0.0359$, $A_x/D = 0.84$; Two degrees of freedom vibration: $m_x^* = 1.76$, $\xi = 0.0364$, $m_y^* = 2.08$, $\xi = 0.0521$; $A_x/D = 0.63$, $A_y/D = 0.99$; $Vr = 7.1$, $\theta = 0.039$, medium-dense sand.

Fig. 9. Comparison of scour profiles around the vibrating pipe under the condition of different types of sand ($e_S/D = 0$, $m_x^* = 1.97$, $\xi_S = 0.0275$; $m_y^* = 2.60$, $\xi = 0.0543$; $Vr = 7.8$, $U = 0.255$ m/s).

undisturbed incoming flow is 0.039 for the two cases. It can be seen from the figure that there is not much difference of the scour profiles around the vibrating pipe between one degree and two degrees of freedom in this study. The maximum scour depths for the two cases are similar. The maximum scour depth for the case of fine sand is a little larger than that for the case of medium sand. In a whole, the local scour of sandy bed beneath the pipe is influenced weakly due to the difference of sand soil in this study.

5. Comparison with Previous Results

Fig. 10 presents the comparison of development of scour with time between the results by Sumer et al. [16] and those by present study. The Shields number ($\theta$) is 0.039 and the mean diameter of sand grain ($d_{50}$) is 0.38 mm in present study, which means the scour is in the range of clear-water scour. The experimental parameters are $d_{50} = 0.36$ mm and $\theta = 0.1$ in the study by Sumer et al., which means the scour is mobile-bed scour. The initial gap-to-diameter ratio ($e_S/D$) is 0 for both cases. It is observed from the figure that there is a clear inflection point at which the vibration of the pipe begins to occur on the curve of scour development with time in present study, but the inflection point is not clear in the results by Sumer et al. The possible reason may be that the scour in the study by Sumer et al. is mobile-bed scour which blankets the added scour due to the vibration of pipe.

A comparison of present results with previous results by Gao et al. [3], Sumer et al. [16], Hansen et al. [4] and Yang et al. [20] is made in Fig. 11. It is noted that the results by present study, Gao et al. [3] and Sumer et al. [16] correspond to the vibrating pipe case, and those by Hansen et al. [4] and Yang et al. [20] correspond to the fixed pipe case. It can be seen from the figure that the scour depth for the case of vibrating pipe is larger than that for the fixed pipe case. There are some differences between present results and those by Gao et al. [3] and Sumer et al. [16] for the vibrating pipe case. In present study the normalized scour depth ($S/D$) increases with the increasing gap-to-diameter ratio when $e_S/D < 0.44$ and decreases with it when $e_S/D > 0.44$. In the results by Gao et al. [3] and Sumer et al. [16], the dimensionless scour depth...
(S/D) varies monotonically with $e_0/D$ and decreases with the increase of gap-to-diameter ratio. The reason of the difference possibly is that the variation of vibrating amplitude of the pipe with $e_0/D$ is different.

**IV. CONCLUSION**

Most of the previous studies focus on the local scour around the fixed pipe and only few researchers paid their attention to the local scour around the pipe undergoing vortex-induced vibration. The experiments upon the local scour around the vibrating pipe are conducted in a flume in this paper. The main conclusions can be concluded as follows:

1) There exists strong intensity of scour when the pipe moves to the surface of the sandy bed. The vibration of the pipe results in the rapid development of sandy bed’s scour. There exist mainly two forms of motion for the sand grain on the surface of sandy bed beneath the pipe during the course of vibrating, i.e. the periodical bed load motion of the sand grain at the upstream side of scour hole and the periodical lift motion of the sand grain at the downstream side of the scour hole.

2) With the increase of gap-to-diameter ratio the distance between the center of the pipe and the position of the maximum scour depth gets larger. The maximum scour depth does not vary monotonically with the gap-to-diameter ratio, but becomes the largest one at certain value of gap-to-diameter ratio between the values of $e_0/D = 0$ and $e_0/D = 2$. The variation of scour depth with gap-to-diameter ratio for two degrees of freedom case presents a similar law with that for one degree of freedom case.

There is not much difference of the scour profiles around the vibrating pipe between one degree and two degrees of freedom involved in this study.

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