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Experimental Investigation of the Effect of Splitter Plate Angle on the Under-Scouring of Submarine Pipeline Due to Steady Current and Clear Water Condition

M. J. Emamgholizadeh*[a], A. R. Mostafa Gharabaghi[a], K. Abedi[a], M. H. Sedaaghi[b]

[a]*Faculty of Civil Engineering, Sahand University of Technology, Tabriz, Iran*
[b]*Faculty of Electrical Engineering, Sahand University of Technology, Tabriz, Iran*

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ABSTRACT

Submarine pipelines are appropriate method for transferring oil, gas and other liquids from the seabed. Free spans may occur due to the natural uneven seabed or by under-scouring. Vortex Induced Vibration (VIV) can happen in such free spans at high Reynolds number. Resonance will occur if the frequency of vortex shedding is close to the pipeline's natural frequencyleading to its fatigue that can break the pipeline causing economical and environmental losses. In literature, there are different methods for suppressing the vortex shedding and pipeline vibration and consequent scouring under the pipe such as the usage of splitter plates. In this paper, the effect of splitter plate's angle on the scouring beneath the pipeline is studied experimentally. For this purpose, a new experimental setup is designed and constructed in order to allow for the cylinder to vibrate in both in-line and cross flow directions over an erodible bed. The reduced velocity for the experiments is in the range of 2.45-5.06 with different gap ratios. Experimental results indicate that the relative scour depth is reduced with increasing the ratio of gap to pipe diameter. The relative vibration frequency approaches to a constant value for large gap ratio ($1 < e_D < 2$) and the pipe does not have more effect on the bed. Therefore, the usage of splitter plate with the angle of 0-30 degrees with the horizon reduces the scouring depth below the mean location of the pipe compared with a pipe without splitter plate. Vice versa, the results were reversed for the pipes which used splitter plates with the angle of 60-90 degrees.

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NOMENCLATURE

VIV	Vortex Induced Vibration	St	Strouhal
IL	In-Line	Re	Reynolds number
CF	Cross-Flow	SUT	Sahand University of Technology
FFT	Fast Fourier Transform		

1. INTRODUCTION

Nowadays, due to the great developments in different industries, the demand to the oil and gas has increased enormously. When the pipe is exposed to the flow such as sea currents, the flow regime around it will change, particularly behind the pipe. This will appear as the phenomenon of vortex generation due to the flow separation from the pipe at some special Reynolds number ($R_e > 40$)[1]. These vortices will disperse with a specific frequency (vortex shedding) which applies periodic forces on the pipe. The applied forces can cause the pipe to vibrate in both flow directions and transverse to it which is called as Vortex Induced Vibration (VIV). If the frequency of vortices gets close to the natural frequency of the pipe, it can intensify the pipe vibration. This may lead to the fatigue and finally breakage of the pipe [2].

During the last two decades, the dynamical interaction between the waves, current, pipe and seabed have been studied by several researchers [3-6]. Most of the existing researches on the VIV of pipes have been performed for the pipes with one degree of freedom,

*Corresponding Author's Email: *Javad.Emamgholizadeh@gmail.com* (M. J. Emamgholizadeh)

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mainly cross flow (CF) direction. The research by Khalak and Williamson [7]and Govardhan and Williamson [8]are among those which were concentrated on the CF direction. However, recent model tests on the free-spanning pipeline performed for the Ormen Lange project have proved that the combined CF and in-line (IL) motions are important [9].

Moreover, most of these investigations are concerned with the vibrating pipe near the solid bed or free conditions, without considering the effect of scouring [6]. For instance, the research by Jacobsen et al. [10] and Yang et al. [11] are about the vibrating pipe over the solid bed. It is found that the effect of wall proximity on the VIV is important. This is due to the fact that for small relative gaps from the bed, the pipe is laid in the boundary layer of the bed so its behavior will be different from the free pipe. For small relative gap between the pipe and the bed, the vortex shedding down the pipe may be suppressed [12]. However, in practical cases, usually the seabed is erodible. In literature, there are relatively very few studies about the interaction of vibrating pipe with the erodible bed [6]. The research by Sumer et al. [13]and Gao et al. [6] are a few cases that were performed for investigation of the effect of VIV on the scouring of the sandy bed under the live-bed condition. However, in these researches, the pipe was merely allowed to vibrate in the CF direction. It is found that the sandy bed can make significant effect on the vibration response of the pipe. The main findings by Gao et al. are: (1) the VIV does not happen until the scour depth below the pipeline is large enough; (2) the pipe vibration induces extra scour which gives rise to relatively larger scour depths and scour widthsand (3) scour affects not only the amplitude of the pipeline vibration but also its frequency [6]. There are also a great effort on the two-dimensional soil scour around fixed pipelines in currents, such as the work done by Hansen et al. [14],Sumer et al.[15], and Chiew [16].

Some others have studied this phenomenon numerically. For instance, Zhao et al. [17]investigated the local scour below a vibrating pipeline numerically. They also found that the pipeline vibration enhances the scour depth below the pipeline and the VIV also interacts with the scour process below the pipeline if the pipeline is laid on an erodible sandy bed [18]. Heidarinejad et al.[19] workedon the unsteady two-dimensional reacting flow around a circularcylinder. They found that the non-reacting flows fall within the range of the experimental measurements while the results of the reacting case are qualitatively following the physics. Also Farhanieh et al.[20] investigated the flow properties during the instability condition, the flow pattern, vortex properties and the axial velocity were studied.In literature, there are also several methods to reduce the vibration amplitude of the pipelines [18]. These methods are classified into three categories [21]as follow.

The first category devices are various types of surface protrusions. These can be grouped into two sub-categories; one with the omnidirectional response and the other with the unidirectional response. The omnidirectional devices are the ones which are not influenced by the direction of the flow. These are basically helical strakes, helical wires, etc. The unidirectional devices, on the other hand, are rectangular fins, straight fins extending along the length of the structure, straight wires extending along the length of the structure, etc. The second category devices are various types of shrouds. These include perforated shrouds (with square or circular holes), array of rods encircling the structure, fine mesh gauge, etc.

The third category devices are wake stabilizers such as saw tooth fins, splitter plates, guide plates, etc. Clearly, while the first two category devices act as spoilers to disrupt the boundary layer on the surface of the structure, the third category devices (wake stabilizers) prevents the interaction between the two shear layers, presumably leading to the complete or partial elimination of vortex shedding.

In this paper, the under-scoring of vibrating pipe due to VIV under steady current and clear water condition with and without splitter plate was experimentally investigated. A new set-up system was designed and built that the pipe model can vibrate in both IL and CF directions on the erodible bed. Then the effect of parameters such as the width and angle of splitter plate with horizon, Reynolds number and the reduced velocity on the scoring depth of vibrating pipe was investigated.

2. EXPERIMENTAL DETAILS

2. 1. The Characteristics of Experimental Set-up

The experiments were performed in the hydraulic laboratory of Sahand University of Technology and an elastically mounted rigid cylinder was designed for the pipe model, laid normal to a free stream over an erodible sandy bed that was installed inside the channel. The channel is 10m long, 0.3m wide (this width was decreased to 0.25m in order to place the supporting frame) and 0.46m high (about 0.12 m was filled by sand). The maximum discharge for steady current is 35 l/sec. The experimental set-up is shown in Figure 1. In order to allow the cylinder to vibrate in both CF and IL directions (system with two degrees of freedom) a new supporting frame was designed. The experimental cylinder was connected to the additional wall by four linear springs with the similar stiffness in a cross arrangement at both sides using the designed supporting frame which all weremade from the Plexiglas. For the actual situations, both the mass and natural frequency of the vibrating pipe is the same in the CF and IL directions. Therefore, in the present study, this fact is concerned in the design of the arrangement for the experimental set-up.In addition, two circular end plates between the supporting frame and cylinder were installed in order to prevent the interfering of the vibrating cylinder with related supporting frame.The water depth in all experiments was kept constant and equal to 250mm.

2. 2. The Pipe Model Three smooth Plexiglas cylinders with different diameters (20, 30 and 40 mm) and wall thicknesses (3, 3 and 2mm, respectively) were selected. In the literature it is recommended that in order to avoid the lateral wall effects, the aspect ratio should be greater than 6 (L/D>6) [9], so in these experiments this ratio was 6.25-12.5. In addition, according to the recent studies, for small mass ratio (m*) close to 1, more investigations are needed to be carried out in order to get a better understanding of the physics involved in vortex-induced vibration of such structures[22], so in these experiments this ratio was 1.216-1.754. At both ends of the cylinder, a square plate was mounted to connect the springs to the cylinder. It was also used in order to record the vibrating response of the cylinder. Tables 1 and 2 show some of the dimensionless parameters relevant to the present experiments and the characteristics of the tested models, respectively.

In these tables, U is the undisturbed flow velocity at the center of the cylinder, D is the outer diameter of the cylinder, $f_{nx,y}$ is the natural frequency of the cylinder in still water in x and y directions, U_* is the undisturbedbed shear velocity, that can be calculated from$U_* = \sqrt{\tau_b/\rho}$, in which τ_b is the bed shear stress,$G_s = \rho_s / \rho$ is the specific gravity of sand particles, which is taken as approximately 2.65 for standard sand, g is the gravitation acceleration, $d_s$is the sediment mean diameter (d_{50}), υ is the fluid kinematic viscosity, m is the cylinder mass, ρ is the fluid density, ρ_s is the sediment density, m_a is the added mass that can be estimated from $m_a = C_A m_d$ (m_d is the displaced fluid mass, $C_A = 1.0$ and $m_d = \rho\pi L D^2/4$), $\zeta_{x,y}$ is the structural damping factor in x and y directions and L is the cylinder length.

TABLE 1. Dimensionless parameters related to the present experiments

Parameter	Equation	Definition	Value
$V_{rx,y}$	$\frac{U}{Df_{nx,y}}$	Reduced velocity	$2.45 < V_r < 5.06$
θ	$\frac{U_f^2}{(G_s - 1)gd_s}$	Shields parameter	0.013-0.042
R_e	UD/υ	Reynolds number	$2500 < R_e < 8750$
m^*	$\frac{4m}{\pi\rho D^2}$	the pipeline mass ratio	1.23, 1.42, 1.77
$k_{x,y}$	$\frac{4(m + m_a)\zeta_{x,y}}{\pi\rho D^2}$	The stability parameter	0.1-0.16

TABLE 2. The characteristics of the tested models

pipe	Parameter						
D(mm)	f_{nx}	f_{ny}	ζ_x	ζ_y	m (kg)	k_x	k_y
20	2.64	2.64	0.051	0.058	0.154	0.141	0.160
30	1.83	1.83	0.053	0.049	0.227	0.127	0.118
40	1.46	1.46	0.050	0.045	0.427	0.111	0.100

TABLE 3. The conditions of the experiments and related Reynolds numbers.

D (mm)	No	h (m)	U_m (m/s)	R_e
20	1	0.25	0.183	3660
	2	0.25	0.222	4440
	3	0.25	0.262	5240
	4	0.25	0.286	5720
30	5	0.25	0.183	5490
	6	0.25	0.222	6670
	7	0.25	0.262	7850
	8	0.25	0.286	8580
40	9	0.25	0.183	7320
	10	0.25	0.222	8880
	11	0.25	0.262	10480
	12	0.25	0.286	11440

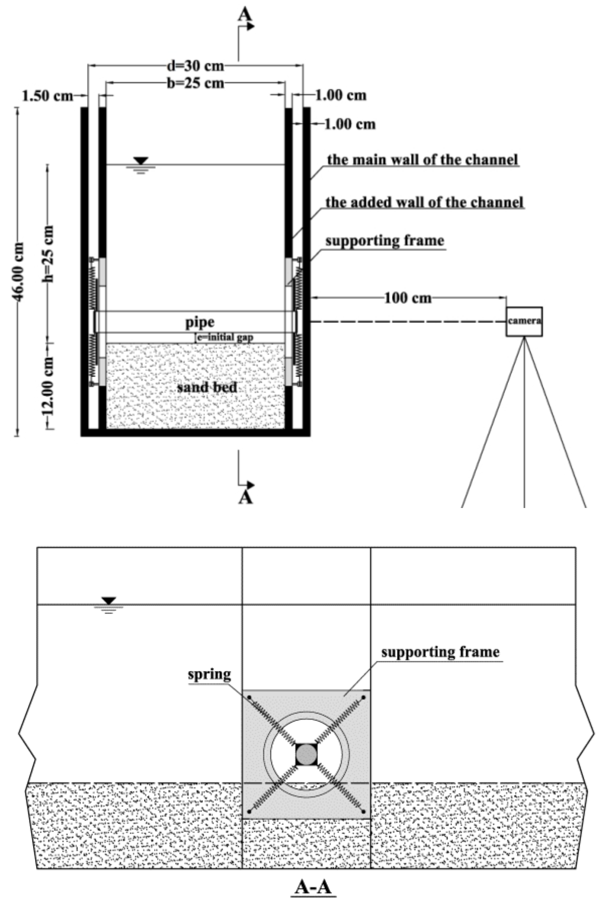

Figure 1. Schematic diagram of experimental set-up and the arrangement of springs with supporting frame and cylinder.

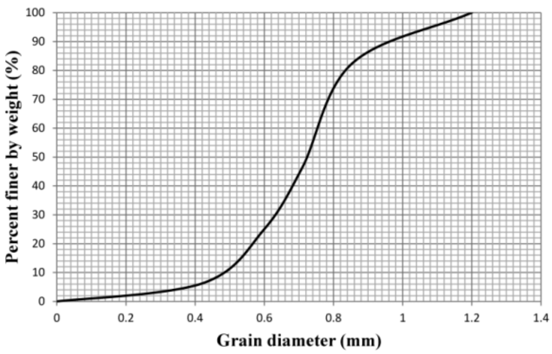

Figure 2. The sand grain size distribution curve.

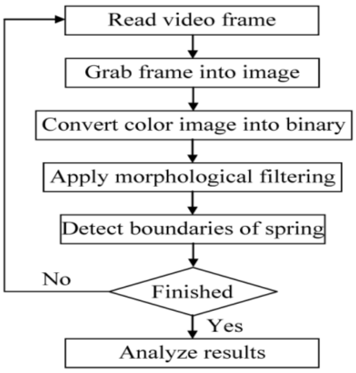

Figure 3. The algorithm of the developed image processing program.

The flow velocity was measured by a micro-propeller current-meter and the natural frequency ($f_{nx,y}$) and the structural damping ($\zeta_{x,y}$) of the cylinders was measured by free decay tests in the stillwater condition. In this study, the cylinder was placed upon an erodible bed at the beginning of the tests. Table 3 shows the conditions of the experiments and related Reynolds number based on the depth averaged velocity (U_m).

2. 3. The Erodible Bed In order to simulate the erodible bed, some parts of the channel were filled by non-cohesive sediments (mean particle diameter $d_{50} = 0.73$ mm, and standard deviation$\sigma_g = (d_{84}/d_{16})^{1/2} = 1.27$). So, the critical shields parameter (θ_{cr}) for the initiation of sediment motion is 0.031.The grain size distribution of erodible bed is shown in Figure 2. The sand gradation was chosen according to the following recommendations; the effect of non-uniformity on the scouring to be omitted, the formation of ripples over the bed to be prevented and the clear water condition to be established [15, 21, 23-25].

In this research, the equilibrium scour depth and related time scale was selected as the scouring depth changes in three consecutive hours is not more than 1mm [25]. For this purpose, a limited number of experiments were performed for about 24 hours and according to the records, it was noticed that the time scale for equilibrium scour depth is about 5 hours. The time scale for recording the vibration response of the cylinder was also chosen about1hour (3600 sec). This was also selected based on the condition that the vibration amplitude ($A_{m_{x,y}}$) of the cylinder reaches to the steady state. After finishing the experiments (300min), the features of the scour hole were measured by the depth probe.

2. 4. Recording the Vibration Response of the Cylinder Image processing technique as a non-contact method was used to measure the vibration characteristics of the cylinder. Since the vibrations of the cylinder are proportional to the displacements of its end plates, these displacements were recorded by a high speed, high resolution video camera (300 frame per second). Figure 3 indicates the algorithm of the program developed in order to process the recorded film into the cylinder's vibration data. The input image (grabbed from a video sequence), which is a color image is firstly converted to a binary image, then morphological filters (including open and close operations with square structuring elements of size 20 and 60) are applied. Finally, the boundaries of the springs were detected. Also, in order to obtain the vibration frequency of the cylinder from the recorded displacements, the response spectrum was estimated by Fast Fourier Transform (FFT). The interested readers are referred to the literature, i.e. Jen Serra [26, 27], Maragos [28], Laurent Najman & Hugues Talbot [29] and Edward R. Dougherty [30].

2. 5. The Splitter Plate In order to reduce the vibrations of the cylinder due to the vortex induced vibrations and subsequently the resulted scouring depth, the controller plates forvortex shedding or splitter plates were used with different widths (L') and angles to the horizon (α). For the reason that the thickness of this plate is not so much important in its performance or the use of thick plates is not economical, only the plates with a constant thickness were used. The characteristics of these plates are presented in Table 4 (see Figure 4).

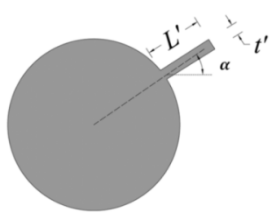

Figure 4. The details of splitter plate

TABLE 4. The characteristics of splitter plates

L' (width of splitter plate)	15, 10, 5 (mm)
α (angle of splitter plate with the horizon)	0, 30, 60, 90 (degree)
t' (thickness of splitter plate)	2 (mm)

3. RESULTS AND DISCUSSION

After starting the experiments, the flow passed over the pipe which was laid over the erodible bed, generated a pressure difference between the upstream and downstream of the pipe. This pressure gradient induced a seepage flow in the sandy bed underneath the pipe. Gradually, this enforced the sand particles to be raised out at the immediate downstream of the pipe leading to the generation of erosion tunnel just beneath the pipe. This condition was continued till the scour hole underneath the pipe was formed.

Obviously, this phenomenon is completely dependent on the interaction between the pipe, fluid and sediment. So in practical cases, after development of the scour hole, the generated free span for the pipe can be followed by the VIV of the pipe, which can also influence the features of the scour hole. In this research in order to provide such a situation, the previously described arrangement for the supporting frame of the cylinder was designed. Hence, by developing the scour hole, the cylinder started to vibrate and this was followed till a steady state condition wasreached. The experiments were performed for different flow velocities and cylinder diameters to get a suitable range of Reynolds number ($2500 < \mathrm{R_e} < 8750$). In addition, all the experiments were performed for the clear water condition ($\theta<\theta_{cr}$). In offshore engineering, the vibration amplitude and frequency of pipeline are important parameters related to its dynamic response. Therefore, after getting the steady state condition, the time history of the pipe vibrations in CF and IL directions was extracted from the recorded film. The equilibrium profile of the scour hole was also measured at the end of each experiment. In the following sections, these results are presented for the cylinder with/ without splitter plates, separately.

3. 1. The Cylinder Without Splitter Plate

Figure 5 shows the time histories and related power spectrum of the CF vibrations of the cylinder with diameter of 40 mm due to different current velocities. At the beginning of the experiments, due to the effect of erodible bed, the vibration of cylinder is affected intensively. But by passing the time and formation of the scouring hole under the pipe, the effect of the bed on the pipe response is eliminated and the pipe vibration reaches to the almost steady manner.

However, it is noticed that unlike the previous studies wherein the pipe is laid over the rigid bed and its response is just affected by the bed, for the erodible bed, in addition to this effect, the pipe vibration also affects the scouring of the bed and the interaction between them is more complex. By comparing these figures, it can be noticed that for velocities of $\mathrm{u} = 0.183{,}0.222\ \mathrm{m/s}$, with related reduced velocity less than 3 ($\mathrm{V_r} < 3.0$), the pipe response is almost negligible as the vibration amplitude is very small. However, as the current velocity increased to $\mathrm{u} = 0.262{,}0.286\ \mathrm{m/s}$, with related reduced velocity more than 3 ($\mathrm{V_r} > 3.0$), the pipe response has been increased. This can be mainly due to the interaction of the pipe and the scour hole which has intensified the lift force leading to the increase of the CF amplitude.

Almost similar results with lower amplification are achieved for IL direction which is not presented in here. In addition, in Figure5 the power spectrum related to each time history has been displayed. The peak value for each spectrum is related to the vibration frequency of the associated experiment. It is observed that for each experiment, the vibration frequency in CF and IL directions is almost the same for all studied velocities.
The results for the vibration amplitude and frequency in CF and IL directions and their ratios are presented in Table 5. Regarding to this table, the IL amplitude is more significant than CF amplitude, for the small reduced velocities ($\mathrm{V_r} < 3$), however by increasing the flow velocity and consequently the higher reduced velocities ($\mathrm{V_r} > 3$), the situation is vice versa. Moreover, their frequencies are almost the same in CF and IL directions for all of the tested current velocities.
In Figure6, the trajectories of the cylinder at different time intervals due to the different current velocities have been shown. The first column figures are related to the whole recorded results (0<time<60), the second column figures are related to the first minute records (0<time<1), and the last column figures are related to the last minute records (59<time<60). In this figure, the horizontal axis (x) is related to the IL displacement and the vertical axis (y) is related to the CF displacement. The flow direction is from the right to the left.It can be observed that for the small velocities ($\mathrm{U} = 0.183$ و $0.222\ \mathrm{m/s}$) with lower reduced velocity ($\mathrm{V_r} < 3$), the cylinder trajectory is almost the same for all the time intervals. However, for higher reduced velocities ($\mathrm{V_r} > 3$), the cylinder trajectory has changed significantly as time passes. For instance, for the last case ($\mathrm{u} = 0.286\ \mathrm{m/s}$), at the first minute, the trajectory direction makes an almost 45 degrees angle with horizon, but at the last minute, it is almost in the CF direction. This performance is related to the time development of the generated scour.

As shown in Figure7 (right), the diagram of time development of relative scour depth (d_s/D) for the cylinder without splitter plate approaches more rapidly to the equilibrium stage for lower reduced velocities ($V_r < 3$). However, as shown in Figure8 (right), this approach is not similar for higher reduced velocities ($V_r > 3$) and even for the last minutes, still the equilibrium stage has not been reached.

Figures 7 and 8 (left) also present the relative equilibrium scour profile measured with the depth probe for the cylinder without splitter plate. It is clear that the dimensions of scour hole have been enlarged by increasing the reduced velocities.

TABLE 5. The relative vibration amplitude and frequency in CF and IL directions due to the current with different velocities for the cylinder with $^{e}/_{D}$ = 0.0 and D = 40 mm.

U	V_r	$\frac{A_{mx}}{A_{my}}$	$\frac{f_x}{f_y}$	$\frac{A_{my}}{D}$	$\frac{f_y}{f_{ny}}$	$\frac{A_{mx}}{D}$	$\frac{f_x}{f_{nx}}$
0.143	2.45	4.302	0.997	0.008	0.695	0.032	0.693
0.174	2.98	1.686	1.008	0.037	0.728	0.063	0.733
0.205	3.51	0.399	1.00	0.222	0.662	0.089	0.662
0.224	3.84	0.338	1.00	0.269	0.638	0.091	0.638

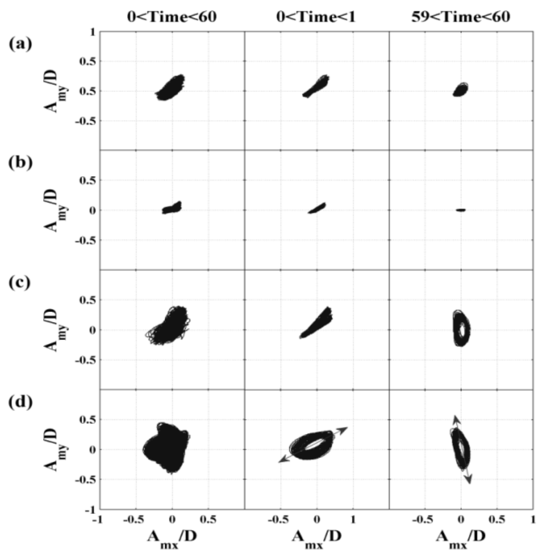

Figure 6. The cylinder trajectories at different time intervals for the cylinder with D = 40mm, $^{e}/_{D}$ = 0.0 due to the current velocity (m/s),(a)U_m = 0.183,(b)U_m = 0.222,(c)U_m = 0.262,(d)U_m = 0.286.

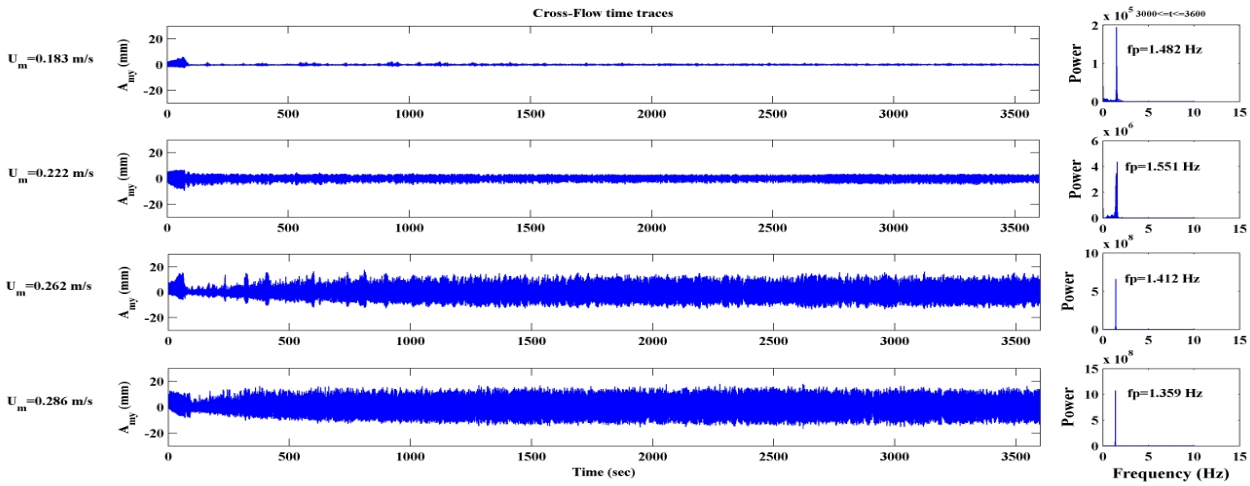

Figure 5. Time history of CF vibration and related power spectrum for cylinder with $^{e}/_{D}$ = 0 and D = 40mm due to the currents with different velocities.

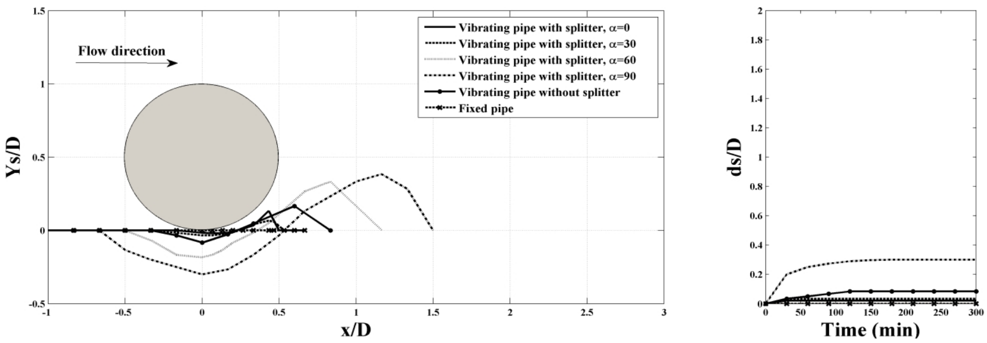

Figure 7. Equilibrium scour profile and related time development of scour depth beneath a vibrating cylinder with different splitter plate angles ($D = 30mm, U_m = 0.183\ ^{m}/_{s}, V_r < 3, \frac{e}{D} = 0.0,\ L' = 10mm,\ \theta = 0.0093 < \theta_{cr}$)

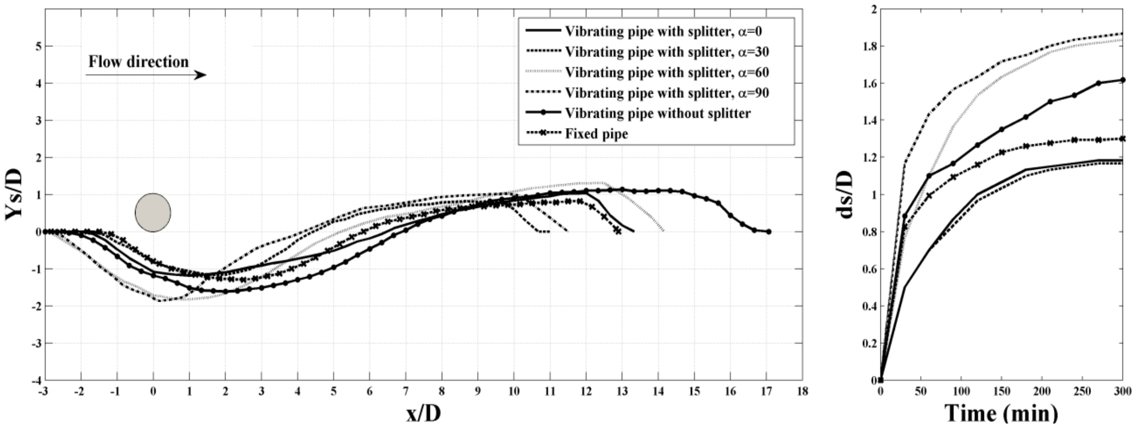

Figure 8. Equilibrium scour profile and related time development of scour depth beneath a vibrating cylinder with different splitter plate angles ($D = 30mm, U_m = 0.286\ ^m/_s, V_r > 3, \frac{e}{D} = 0.0, L' = 10mm, \theta = 0.023 < \theta_{cr}$)

3. 2. The Cylinder with Splitter Plate

Figure 7 and 8as well show the equilibrium scour profile and related time development of scour depth beneath the vibrating cylinder with different splitter plate angles to the horizon (α). It can be noticed that for any value of the reduced velocity, for $\alpha \leq 30^\circ$, the dimensions of equilibrium scour profile reduced significantly compared to the cylinder without splitter plate. Although, these dimensions increased considerably, for $\alpha > 30^\circ$. Moreover, the relative scour depths (ds/D), for $\alpha \leq 30^\circ$, approached more rapidly to the equilibrium stage.

In this study, as splitter plates with different widths were used, so a typical diagram of the time development of relative scour depth (d_S/D) for the case of cylinder with $D = 30mm, L' = 15mm$ is shown in Figure9.

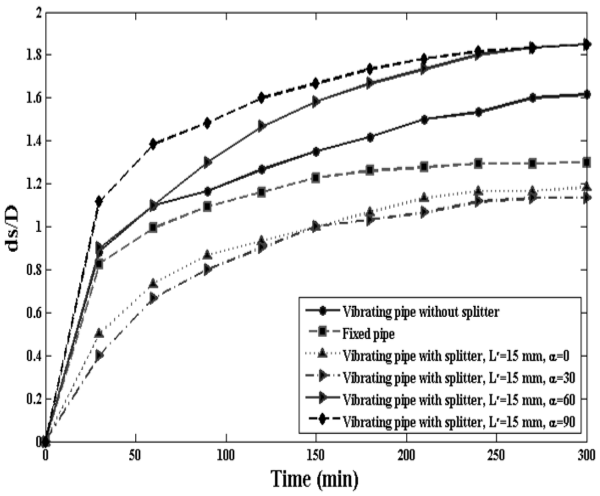

Figure 9. Time development of scour depth beneath a vibrating cylinder with different splitter plate angles, $D = 30mm, L' = 15mm, U_m = 0.286\ m/s, \frac{e}{D} = 0.0$

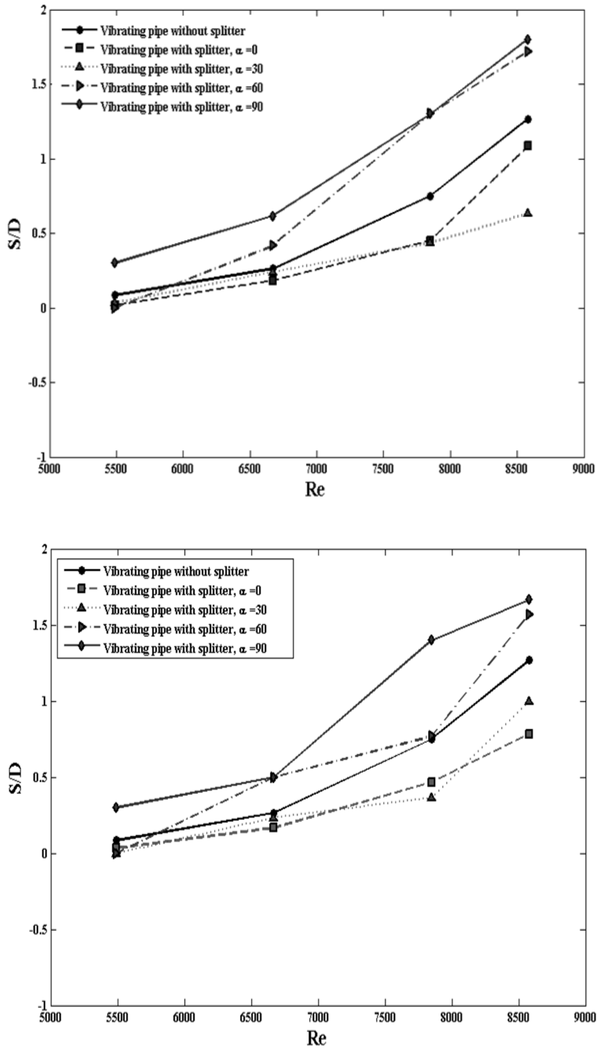

Figure 10. The effect of splitter plate's width and angle to the horizon on the equilibrium scour depth of the cylinder with $D = 30mm$ for different Reynolds numbers, a)$L' = 10mm$, b)$L' = 15mm$.

By comparing these results with the diagram presented in Figure8 (right) which is related to the same cylinder with different splitter plate widths ($L' = 10mm$), it can be concluded that the width of splitter plate does not have a significant effect on the scour depth. However, similar conclusion can be derived for the effect of splitter plate angle.

Similar results were obtained for other widths of splitter plate. In Figure10 all of these results are presented versus different Reynolds numbers for the cylinder with $D = 30mm$. Again, the results show that the equilibrium scouring depth beneath a vibrating cylinder with a splitter plate angle less or equal to 30 degree ($\alpha \leq 30^{\circ}$) is significantly less than the cylinder without a splitter plate. While, inversely, the equilibrium scouring depth related to the cylinder with a splitter plate angle larger than 30 degrees ($\alpha > 30^{\circ}$) is considerably more than the cylinder without a splitter plate. Similar conclusion was obtained for $\alpha = 90^{\circ}$ by Chiew [31].

Actually, the mechanism of splitter plate action is based on the prevention of interaction between two vortices on both sides of the pipe. So, in the cases, where any interaction between the vortices is prevented, a significant reduction in the scouring hole can be observed. However, in the other conditions, the presence of splitter plate has intensified the formation of vortices and their subsequent interaction.In addition, it is obvious that the relative equilibrium scour depth grows by increasing the Reynolds number for almost any width and angle of splitter plate.

4. CONCLUSON

In this paper, the under-scoring of vibrating cylinder due to vortex-induced vibration (VIV) under steady current and clear water condition with and without splitter plate is investigated experimentally. A new set-up system was designed and built that the pipe model can vibrate in both in-line (IL) and cross-flow (CF) directions on the erodible bed. Then the effect of parameters such as the width and angle of splitter plate with horizon, Reynolds number and the reduced velocity on the scoring depth of vibrating pipe was investigated.Based on the performed experiments, the following conclusions are extracted:

1) At the beginning of the experiments, the cylinder is laid on the bed (the air gap ratio=0) and the flow passes over it. This leads to the pressure gradient between the rear and front of the cylinder which can drive the seepage flow underneath the cylinder resulting to the piping. By increasing the current velocity and reaching to the critical value, the erosion tunnel is formed under the cylinder and the condition is provided for the flow passage under it. As a result, the two shear layer up and down the cylinder interacts together and causes its vibration. At this stage, due to the effects of erodible bed, the interaction between the vibrating cylinder and the erodible bed is more complex. By passing the time and formation of the scouring hole under the pipe, the effects of the bed on the pipe response is eliminated and the pipe vibration reaches to the almost steady state.

2) For the small reduced velocities, i.e. $V_r < 3$, the amplitude of IL vibrations is more significant than the CF vibrations, but by increasing the current velocity and consequently the higher reduced velocities, i.e. $V_r > 3$, the situation is reversed. However, their frequencies are almost the same in CF and IL directions for all of the tested current velocities.

3) It was noticed that for all of the current velocities, the trajectory shape of the cylinder is almost the same at the beginning of the experiments. However, the final trajectory shape changes, especially for the higher reduced velocities ($V_r > 3$).

4) The results show that the relative equilibrium scour depth is enlarged with increasing the reduced velocity. Also, the position of maximum equilibrium scour depth moves forward with increasing the reduced velocity.

5) It is noticed that for the cylinder with splitter plate for any value of the reduced velocity, when its angle to the horizon is less or equal to 30 degree ($\alpha \leq 30^{\circ}$), the dimensions of equilibrium scour profile are reduced significantly compared to the cylinder without splitter plate. However, these dimensions are increased considerably, for $\alpha > 30^{\circ}$. Moreover, the relative scour depths (ds/D), for $\alpha \leq 30^{\circ}$, approach more rapidly to the equilibrium stage.

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Experimental Investigation of the Effect of Splitter Plate Angle on the Under-scouring of Submarine Pipeline Due to Steady Current and Clear Water Condition

M. J. Emamgholizadeh[a], A. R. Mostafa Gharabaghi[a], K. Abedi[a], M. H. Sedaaghi[b]

[a]*Faculty of Civil Engineering, Sahand University of Technology, Tabriz, Iran*
[b]*Faculty of Electrical Engineering, Sahand University of Technology, Tabriz, Iran*

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چکيد

خطوط لوله دریایی از جمله راه‌های انتقال نفت، گاز و سایر مایعات از بستر دریا می‌باشد. دهانه های آزاد ممکن است به دلیل آبشستگی بستر و یا ناهمواری طبیعی بستر به‌وجود آید. ارتعاشات ناشی از تشکیل گردابه‌ها (Vortex induced vibration)ممکن است در چنین دهانه‌های آزاد در اعداد رینولدز بالا پیش آید. اگر فرکانس گردابه فرافکنی(Vortex shedding) به فرکانس طبیعی خط لوله نزدیک باشد، پدیده تشدید اتفاق افتاده که منجر به خستگی آن شده و می تواند باعث خرابی و بروز مخاطرات محیطی و اقتصادی گردد. در ادبیات فنی روش‌های مختلفی برای کنترل گردابه‌ها و ارتعاش لوله و آبشستگی زیر لوله ناشی از آن وجود دارد که از جمله این روش‌ها استفاده از صفحات شکافنده جریان(Splitter plate)می‌باشد. در این مقاله تاثیر زاویه-قرارگیری صفحات برروی آبشستگی زیر خط لوله به‌صورت آزمایشگاهی مورد بررسی قرار گرفته است. بدین منظور، چیدمان آزمایشگاهی جدیدی که امکان ارتعاش لوله در دو راستای امتداد جریان و عمود بر آن برروی بستر ماسه‌ای فراهم باشد، طراحی و ساخته شده است. در این آزمایش ها، سرعت کاهش یافته(Reduced velocity) در محدوده‌ی ۵.۰٦–۲.٤٥ می‌باشد و از فاصلههای نسبی لوله از بستر(Gap ratios)متفاوت استفاده شده است. نتایج آزمایشگاهی نشان می‌دهد که عمق نسبی آبشستگی با افزایش فاصله نسبی لوله از بستر کاهش می‌یابد. فرکانس نسبی ارتعاش در فاصله نسبی از بستر بزرگ ($1 < e_D < 2$) مقدار ثابتی را به خود اختصاص می‌دهد و لوله تاثیر زیادی بر روی بستر نمی‌گذارد. در نتیجه، استفاده از صفحات شکافنده جریان تحت زوایای ۳۰–۰ درجه، باعث کاهش عمق آبشستگی در زیر لوله در مقایسه با لوله بدون صفحه شکافنده جریان می‌گردد. درصورتیکه استفاده از صفحات شکافنده تحت زوایای ۹۰–٦۰ درجه، نتیجه عکس دارد.

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