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Ms Lyndsay Troyer
Science Editor
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Dear Lyndsay

TECHNICAL PAPER FOR CONSIDERATION FOR PUBLICATION
Visualization of flow field around a vibrating pipeline within an equilibrium scour hole

My co-authors and I are grateful for the excellent suggestions of the editor and reviewers. We have carefully read the critiques and suggestions and amended the manuscript accordingly.

We are pleased to submit herewith a revised manuscript entitled "Visualization of flow field around a vibrating pipeline within an equilibrium scour hole" for consideration for publication in the journal. As previously discussed, part of this manuscript was already published in an archival journal, which is cited in the manuscript.

Thank you for your consideration. Please inform us what the next stage of the publication stages are.

Yours sincerely

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TITLE:

Visualization of Flow Field Around a Vibrating Pipeline Within an Equilibrium Scour Hole

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KEYWORDS:
Sediment transport, local scour, flow measurements, pipeline-fluid-seabed interaction, particle image velocimetry, multiple-time-interval, forced vibration, wavelet transform.

SUMMARY:
The goal of the protocol is to enable visualization of the detailed flow fields and determination of the near-boundary shear and normal stresses within an equilibrium scour hole induced by a vibrating pipeline.

ABSTRACT:
An experimental method is presented in this paper to facilitate visualization of the detailed flow fields and determination of the near-boundary shear and normal stresses within an equilibrium scour hole induced by a vibrating pipeline. This method involves the implementation of a pipeline vibration system in a straight flume, a time-resolved particle image velocimetry (PIV) system for pipeline displacement tracking and flow fields measurements. The displacement time-series of the vibrating pipeline are obtained by using the cross-correlation algorithms. The steps for processing raw particle laden images obtained by using the time-resolved PIV are described. The detailed instantaneous flow fields around the vibrating pipeline at different vibrating phases are calculated by using a multiple-time-interval cross-correlation algorithm to avoid displacement bias error in the flow regions with a large velocity gradient. By applying the wavelet transform technique, the captured images that have the same vibrating phase are accurately cataloged before the phase-averaged velocity fields are obtained. The key advantages of the flow measurement technique described in this paper are that it has a very high temporal and spatial

resolution and can be simultaneously used to obtain the pipeline dynamics, flow fields, and near-boundary flow stresses. By using this technique, more in-depth studies of the 2-dimensional flow field in a complex environment, such as that around a vibrating pipeline, can be conducted to better understand the associated sophisticated scour mechanism.

INTRODUCTION:

Subsea pipelines are widely used in offshore environments for the purpose of fluid or hydro-carbon products conveyance. When a pipeline is placed on an erodible seabed, a scour hole around the pipeline is likely to form because of the waves, currents or dynamic motions of the pipeline itself (forced-vibration or vortex-induced-vibration)[1,2]. To improve the understanding of the scour mechanism around a subsea pipeline, measurements of the turbulent flow fields and estimations of the bed shear and normal stresses within the pipeline-fluid-seabed interaction region are essential in addition to measurements of the scour hole dimension[1-7]. In an environment where the bed shear and normal stresses are extremely difficult to be determined because the flow field is unsteady and the bottom boundary is rough, measured instantaneous near-boundary stresses (at approximately 2 mm above the boundary) could be used as their surrogate[8,9]. In the past few decades, scour around a vibrating pipeline has been studied and published without quantitatively presenting the values of the sophisticated flow fields around the pipeline within the scour hole[3-5,10-18]. Therefore, the goal of this method paper is to provide a novel experimental protocol for visualizing the detailed flow fields and to determine the near-boundary shear and normal stresses within an equilibrium scour hole induced by a forced vibrating pipeline. It should be noted that the pipeline-fluid-seabed interaction process in this study is in a quiescent water environment rather than those with unidirectional currents and waves.

This experimental method consists of two important components, namely, (1) simulation of pipeline (forced) vibrations; and (2) measurements of the flow fields around the pipeline. In the first component, the vibrating pipeline was simulated in an experimental flume by using a vibrating system, which has a servo motor, two connecting springs, and pipeline supporting frames. Different vibration frequencies and amplitudes can be simulated by adjusting the motor speed and location of the connecting springs. In the second component, the time-resolved particle image velocimetry (PIV) and wavelet transform techniques were adopted to obtain high temporal and spatial resolution flow field data at different pipeline vibration phases. The time-resolved PIV system consists of a continuous wave laser, a high-speed camera, seeding particles, and cross-correlation algorithms. Although PIV techniques have been widely used in obtaining steady turbulent flow fields[19-25], applications in complex unsteady flow field conditions, such as cases of pipeline-fluids-seabed interaction, are relatively limited[8,9,26,27]. The reason probably is because traditional single-time-interval cross-correlation algorithm of PIV techniques is unable to accurately capture the flow features in unsteady flow fields where a relatively high velocity gradient is present[9,20]. The method described in this paper can solve this problem by using the multiple-time-interval cross-correlation algorithm[9,28].

PROTOCOL:

1. Laboratory safety check

1.1. Review the safety rules relating to the use of the laser and flume system.

1.2. Ensure that the safety training requirements of the laboratory have been met.

NOTE: In this experiment, a set of 5W air-cooling continuous wave laser with a wavelength of 532 nm and a glass-sided straight flume (**Figure 1**) with dimensions of 11 m length, 0.6 m width, and 0.6 m depth are used. The basic safety recommendations for these two apparatuses are as follows:

1.2.1. Check the potential reflection surfaces in the laser line-of-sight prior to testing; wear safety goggles when operating the laser device.

1.2.2. Avoid having eyes at the level of the laser beam during the experiments and be careful of reflected laser lights when handling the optical elements or reflective tools.

1.2.3. Ensure that the water hose does not fall off and that there is always no water overflowing from the flume.

2. Flume and seabed model setup

2.1. Prepare the erodible seabed model located in the middle of the flume.

NOTE: The sediment material used in this study was a uniformly distributed medium sand with a median grain size d_{50} = 0.45 mm, relative submerged particle density Δ = 1.65 and geometric standard deviation σ_g = 1.30.

2.2. Compact and level the seabed using a sand leveler.

2.3. Slowly fill the flume with a water hose and make sure that a flat seabed surface is intact during the filling process; stop filling when the water level has reached a depth of 0.4 m above the seabed.

2.4. Clear the flume top platform and glass for setting up the pipeline model and PIV system.

3. Pipeline model and vibration system setup

3.1. Use a prefabricated pipeline model in the form of an acrylic cylinder with a diameter of 35 mm and a length of 0.56 m.

3.2. Mount the pipeline model on an aluminum supporting frame, which, in turn, is connected by two springs to a moveable pole on another fixed frame that is locked on the top rails of the flume, as illustrated in **Figure 2**. Fix the supporting frame inside the fixed frame by using four bearings to ensure that the supporting frame could freely vibrate only along the vertical direction (**Figure 2**).

3.3. Use a connecting rod to tie the moveable pole to a servo motor mounted on the top of the fixed frame. In this study, the weight of the assembled vibrating system, including the pipeline model and the aluminum frames, is 1.445 kg, which has an equivalent mass ratio (m^*) of 2.682; a natural frequency (f_N) of 0.82 Hz; and damping ratio (ζ) of 0.124.

3.4. Adjust the moveable pole and the supporting frame to obtain a certain gap ratio between the pipeline and seabed. In this study, G/D =1, where G is the vertical distance between the bottom of the pipeline and initial seabed surface; and D is the pipeline diameter.

3.5. Turn on the servo motor to induce a forced vibration on the pipeline; adjust the supporting frames and four bearings to ensure that the pipeline vibration is along the vertical direction. Turn off the servo motor when adjustments of the supporting frames have completed.

3.6. Compact and level the seabed again before running the experiment if the seabed model is disturbed in 3.5.

4. PIV setup

4.1. Place the laser device on the top of the flume and install the laser sheet forming optics.

4.2. Turn on the laser device and adjust the laser sheet forming optics so that an illuminated flat sheet inside the field-of-interest is formed.

NOTE: In this study, the illuminated green laser sheet is 1.5 mm thick, parallel to the flume glass walls and is cast downward into the water along the centerline of the flume. The field-of-interest of this study refers to the interaction region of the pipeline-fluid-seabed and is confined to the right half side of the pipeline. The shadow of the pipeline will be seen on the left half side of the pipeline.

4.3. Set up the high-speed camera.

NOTE: For this study, a high-speed camera with 3-gigabyte-memory storage and a maximum resolution of 2.3 Mpx (1920×1200) is used (e.g., Phantom Miro 120). The detailed operation procedures are as follows:

4.3.1. Mount the lens with appropriate focal length on the high-speed camera. Screw the high-speed camera onto a height-adjustable tripod; adjust the camera to the level of the observation region with its axis perpendicular to the illuminated laser sheet.

NOTE: This study uses a 60 mm prime lens at its maximum aperture of f/2.8.

4.3.2. Connect the camera to the computer by using an Ethernet cable and turn on the camera control software (e.g., Phantom PCC 2.6); turn on the camera and connect it to the computer in the camera control software interface.

4.3.3. Adjust the tripod to ensure that the field-of-view of the camera covers the pipeline-fluid-seabed interaction region; level the camera using the built-in bubble level on the tripod; tune the focus ring on the lens to ensure that the laser sheet is clear on the focal plane.

5. Experimental setup optimization and calibration

5.1. Add PIV seeding particles to the test section of the flume.

NOTE: The seeding particles used in this study were aluminum powders with a diameter of 10 μm and a specific density of 2.7.

5.2. Enhance the light intensity of the laser sheet if necessary.

5.3. Verify the focus of the camera by observing the illuminated seeding particles on the laser sheet through a live camera view on the computer; fine-tune the focus ring, if necessary, to ensure that the seeding particles are sharp and in focus.

5.4. Place a calibration ruler inside the field-of-view on the plane of the laser sheet and capture one calibration image.

NOTE: The adopted resolution of the image in this study was 1600 × 1200 pixels.

5.5. Select a proper sampling rate for data collection.

NOTE: The chosen sampling rate should ensure that the seeding particle displacement within a pair of images is less than 50% of the maximum interrogation window length. In this study, the maximum interrogation window size is 32 × 32 pixels and the adopted sampling rate is 200 frames per second.

5.6. Turn off the laser and camera when steps 5.1-5.5 are completed.

6. Running the experiment and data collection

6.1. Place a transparent acrylic plate (20 mm thick) below the laser source and on the water surface, to suppress water surface fluctuations, and ensure tranquil optical access for the laser light.

6.2. Turn on the servo motor to induce forced vibrations on the pipeline model.

NOTE: In this study, the induced frequency of the servo motor is f_0 = 0.3 Hz.

6.3. Keep the vibration system running for (t =)1440 min to obtain a quasi-equilibrium scour hole beneath the vibrating pipeline.

6.4. Turn on the laser and adjust the output power to the optimized intensity. Turn on the camera and camera control software and apply the calibrated settings to the camera. Turn off the background lights in the laboratory.

6.5. Start recording the seeding particle-laden flow field image with the sampling rate selected in 5.6 by clicking the **Capture Bottom** in the camera software control software.

NOTE: For every single recording in this study, the camera storage allows 1,000 images to be captured.

6.6. Once the data collection is completed, review the recorded image quality and check if the seeding particle density per interrogation window (32×32 pixels) is greater than 8. Save the recorded file if satisfied, otherwise, the seeding density is increased by slowly injecting seeding solutions in the observation region, and repeat steps 6.3-6.5.

6.7. Repeat steps 6.3-6.5 to collect more data sets.

NOTE: For this study, more than 20,000 images were taken to ensure that enough raw data are obtained for calculating the flow velocities, vorticities, turbulence, and near-boundary stresses.

6.8. Turn off the laser device, camera, and server motor when all the data collections are completed; turn on the background lights in the laboratory.

7. Data processing

7.1. Open the software; click the **File folder** button on the toolbar and load the calibration image taken in step 5.4.

NOTE: Use the data processing program for pipeline displacement tracking and flow field calculations software (e.g., PISIOU).

7.2. Click the **Scale setup** button on the toolbar; measure a known distance on the calibration image to calculate the scale of the image.

NOTE: The calculated image scale was 0.1694 mm/pixel.

7.3. Click the **Origin** button on the toolbar; set the origin of the coordinates on each image.

7.4. Extract the displacement time-series of the vibrating pipeline from the recorded images.

7.4.1. Load the raw images taken in step 6.

7.4.2. Apply the **Low pass filter** in the **Image filter** menu.

NOTE: This operation will allow the edge of the pipeline (target to be tracked) to be readily recognized on the processed images (see **Figure 3a**).

7.4.3. Click the **Object tracking** button on the toolbar; select the target region (i.e. the pipeline) on the processed image and track the displacement of the vibrating pipeline from consecutive processed images; record the displacement time-series, $\eta(t)$, of the vibrating pipeline for subsequent flow field data processes (see **Figure 4**).

7.4.4. Export and save the pipeline displacement time-series data for further calculations.

7.5. Determine instantaneous velocity fields from the recorded images.

7.5.1. Open the **Parameter panel** on the toolbar; specify the velocity vector calculation parameter.

NOTE: In this study, a multi-pass iteration process is adopted as the interrogation windows, which started from 32 × 32 pixels, then passed with 16 × 16 pixels, and ended with 8 × 8 pixels; all passes use a 50% overlap between adjacent sub-windows.

7.5.2. Apply the **Laplacian filter function** in the **Image filter** menu to the raw images to highlight the seeding particles and filter out undesirable scattering light (see **Figure 3c**).

7.5.3. Click the **Boundary** button on the toolbar, set the geometric mask on the images to exclude the seabed region for further calculation.

7.5.4. Click the **Run** button on the toolbar to calculate the instantaneous velocity fields for different vibrating phases using the cross-correlation method.

NOTE: In this study, a multi-time interval algorithm is adopted to reduce the bias error due to high velocity gradient in the flow field (see **Figure 5**). The adopted multiple-time intervals for cross-correlation calculations are Δt, $3\Delta t$, $9\Delta t$ and $21\Delta t$ (Δt = 5 ms). The satisfactory correlation criterion is greater than 70%.

7.5.5. Export and save the instantaneous velocity fields data for further analysis.

7.6. Determine the phase-averaged velocity fields from the calculated instantaneous velocity fields with the algorithm as described in *Newland* 1994[29,30] and *Hsieh* 2008[28].

NOTE: The calculation procedures for this step is described as follows:

7.6.1. Apply the wavelet transform function to the displacement time-series, $\eta(t)$, of the vibrating pipeline to obtain the instantaneous phase for each instantaneous velocity field. The wavelet transform function is defined as:

$$W_\psi = \frac{1}{\sqrt{\alpha}} \int_{-\infty}^{\infty} \eta(t) \left[\psi\left(\frac{t-\beta}{\alpha} \right) \right]^* dt \qquad (1)$$

where W_ψ is wavelet coefficient; α and β are the scale and translation parameters, respectively; the function ψ is the Morlet function and is calculated as $\psi(t) = e^{2\pi t i} e^{-t^2/2}$; the superscript "*" denotes the complex conjugate. The instantaneous phases, Φ, of the vibrating pipeline that correspond to the different pipeline displacements can be calculated from:

$$\Phi(\alpha, \beta) = \arg\left(W_\psi\right) \qquad (2)$$

7.6.2. Average the instantaneous velocity fields with the same phase to obtain the phase-averaged velocity fields.

7.6.3. Determine the flow vorticity, ω_z, in the calculated phase-averaged velocity fields from:

$$\omega_z = \partial \overline{v} / \partial x - \partial \overline{u} / \partial y \qquad (3)$$

where $\overline{u}$ and $\overline{v}$ are phase-averaged velocities along x and y directions.

7.7. Load the calculated phase-averaged velocity and vorticity data in Tecplot software for visualization.

7.8. Determine the near-boundary shear and normal stresses from the calculated instantaneous velocity fields with the algorithm as described in *Hsieh et al.* 2016 [9]. The calculation procedures for this step is described as follows:

7.8.1. Extract the near-boundary velocity data (0-5 mm above the seabed) from the calculated phase-averaged velocity flow fields.

7.8.2. Compute the near-boundary shear stresses, τ_s and normal stresses, τ_n, along the scour profile (approximately 2 mm above the scour hole boundary) for different phases within one vibrating cycle. Note: The calculation equations are as follows:

$$\tau_s = \mu \frac{\partial u_p}{\partial n}, \qquad \tau_n = \mu \frac{\partial u_n}{\partial n} \qquad (4)$$

where, μ = dynamic viscosity of the fluid (herein taken as 1×10^{-3} Pa·s); u_p = near-boundary velocity parallel to the bed; u_n = near-boundary velocity perpendicular to the bed; n = normal distance from the bed.

7.9. Load the calculated near-boundary shear and normal stresses data in a software (e.g., Tecplot) for visualization.

REPRESENTATIVE RESULTS:

An example of the comparison between the raw image and processed image of the pipeline displacements tracking and instantaneous velocity calculation is shown in **Figure 3**. As shown in **Figure 3b**, the seeding particles and noise in the raw image are filtered out and the shining pipeline edge is retained to obtain the displacement time series. As shown in **Figures 3c**, light scatters/reflections around the seeding particles, pipeline edge and seabed surface are filtered out by the Laplacian filter. An example of the displacement time-series of the vibrating pipeline is shown in **Figure 4**. The vibration of the pipeline is almost sinusoidal, and the vibrating frequency and amplitude are 0.3 Hz and ~50 mm, respectively.

Figure 6 shows an example of the image of the quasi-equilibrium scour profile and vibrating pipeline at t = 1440 min, in which the origin of the coordinate (x-O-y) of this study is set at the intersection point of the original seabed surface and the pipeline vertical centerline. As shown in **Figure 6**, in addition to the seeding particles, very few suspended sediment particles can be observed in the flow; therefore, the raw image quality was not compromised. This also indicates that a quasi-equilibrium stage was reached for the pipeline scour process.

Examples of the visualized phase-averaged velocity field and vorticity dynamics are shown in **Figure 7**. It should be noted that because of the shadow of the pipeline during the PIV measurements, the region on the left side of the pipeline has no data (see subplots in **Figure 7**). As seen in **Figure 7**, nine discrete phases of the flow field within one cycle of vibration are presented. During the pipeline falling phases ($0 \leq t_0/T < 0.5$, where T is the vibration period and t_0 is the time varies from 0 to T), a pair of vortices with symmetrical patterns is generated from the shear layers on both sides of the vibrating pipeline. Immediately after the pipeline has reached the scour trench bottom ($t_0/T = 4/8$), the counter-clockwise vortex is distorted and sucked into the scour trench as the pipeline rises from the seabed. For the period of the pipeline ascending phases ($0.5 \leq t_0/T < 1$), another pair of vortices with opposite rotating directions to those in the descending phase is symmetrically generated around the top edge of the pipeline. For a better observation of the flow dynamics in **Figure 7**, a corresponding video (**Video 1**) made of 72 phases (frames) of flow fields for one cycle of pipeline vibration is provided.

An example of the near-boundary shear stresses, τ_s and normal stresses, τ_n evolution along the scour profile within one vibrating cycle is presented in **Figure 8**. Since the flow field is symmetrical about the y axis, the near-boundary shear stresses and normal stresses presented in this study are confined to the right half of the scour profile ($0 < x < 5$). As shown in **Figure 8**, these two stresses are normalized by the value of the critical bed shear stress, τ_c (obtained from Shields' curve as 0.243 Pa) of the sand particles on a plane bed condition. The absolute values of τ_s and τ_n within the scour trench and beneath the vibrating pipeline increase significantly when the pipeline is falling to the bed or ascending from the bed. The regions where τ_s and τ_n exhibit the maximum and minimum values are consistent with the evolution of flow fields between the vibrating pipeline and scour boundary as shown in **Figure 7**.

FIGURE AND TABLE LEGENDS:

Figure 1: Schematic of the experimental flume.

Figure 2: Schematic of the pipeline model and vibration system set-up. (**a**) Section view, (**b**) Side view. This figure has been modified from[8].

Figure 3: Example of the comparison between raw and processed images. (**a**) the raw image, (**b**) the processed image for pipeline displacements tracking, and (**c**) the processed image for instantaneous velocity calculation.

Figure 4: Example of the displacement time-series of vibrating pipeline at *t* = 1440 min.

Figure 5: Comparison between single-time and multi-time interval cross-correlation algorithm. This figure is reproduced from[9].

Figure 6: Example image of the quasi-equilibrium scour profile at *t* = 1440 min.

Figure 7: Examples of visualized phase-averaged velocity field and vorticity dynamics. This figure is reproduced from[8].

Figure 8: Example of evolutions of τ_s and τ_n along the scour profile within one vibrating cycle. The touchdown and liftoff times refer to the times when the bottom of the pipeline just touches and rises from the scour hole boundary, respectively. This figure is reproduced from[8].

Video 1: Flow field evolution around the vibrating pipeline within the equilibrium scour hole. The video is made from 72 phases (frames) of flow fields for one cycle of pipeline vibration. This video is reproduced from[8].

DISCUSSION:

The protocol presented in this paper describes a method for visualization of the two-dimensional flow fields and determination of the near-boundary flow stress fields around a forced vibrating pipeline in an equilibrium scour hole by using the PIV techniques. Since the designed pipeline motion is one-dimensional along the *y* direction, preparing and adjusting the pipeline model and vibration system to fulfill this objective are critical prerequisites for a successful outcome. Any undesirable motions of the pipeline along the *x* direction may induce asymmetrical flow fields and scour hole formation around the vibrating pipeline. Besides the apparatus effects, the selection of vibration frequency and amplitude of the pipeline for the experiments is also important for inducing a symmetrical flow field around the pipeline. In fact, in a quiescent water condition, Lin et al.[31] showed that the structure of flow recirculation behind an impulsively started circular cylinder can maintain its symmetry when the non-dimensional time $T_D = t_D U_D / D$ < 5, where t_D = cylinder moving time; and U_D = cylinder speed. For the condition when T_D > 5, the oblique vortex shedding may occur around the cylinder. In this study, the maximum pipeline speed can be estimated as $2\pi f \cdot A_0$, and the cylinder moving time can be taken as $1/2f$, thus the maximum non-dimensional time $T_D = \pi A_0/D = 4.48$.

During the PIV setup stage, the laser sheet and camera adjustments and the seeding particle selection are the critical protocol steps for obtaining high quality flow field data. The camera shooting direction must be perpendicular to the laser sheet, otherwise, perspective distortions will be shown in the captured images. As this method aims to obtain the near-boundary flow stresses in an unsteady flow field, the intensity of the laser and the position of the field-of-view should be properly set to avoid strong light reflection of the boundary. The chosen seeding particles need to effectively scatter the illuminating laser sheet and be able to follow the flow streamlines without excessive settlement[20]. Based on this consideration, the seeding particles used in this study were aluminum powders, whose settling velocity was estimated to be 92.6 μm/s using Stoke's law. This settling velocity is negligible compared to the flow velocities (0.1-0.2 m/s) near the vibrating pipeline. To optimize the experimental setup, verifying the focus of the camera and determining the camera sampling rate are also crucial steps for reliable measurements.

For the data process stage, there are two challenges for obtaining high quality phase-averaged flow fields and near-boundary flow stresses: (1) accurately calculate the instantaneous flow fields and avoid the displacement bias error in the flow regions with a large velocity gradient; and (2) accurately catalogue the captured images that have the same vibrating phase. For calculating the instantaneous flow fields, the traditional PIV cross-correlation method [19] determines the velocity vector between two consecutive images with a fixed time interval Δt (See **Figure 6a**). This traditional method may not be suitable for this study because the calculated flow field may have significant displacement bias errors near the vibrating pipeline and seabed boundaries. To overcome this problem, a multi-time-interval algorithm is adopted in this study (See **Figure 6b**). By using this method, image interrogations are executed reiteratively on different image pairs for different selected intervals. The velocity vector at each grid point is determined based on the estimations of suitable time interval[9,27,28]. It should be noted that when using this method, the raw image datasets should be acquired by a time resolved PIV with a high sampling rate camera and continuous wave laser. To overcome the second challenge, this paper provides a wavelet transform technique. By applying the wavelet transform function to the displacement time-series of the pipeline, the instantaneous phase of each captured image can be accurately calculated. This method can also be applied to investigate vortex induced vibration processes, such as pipeline vibration induced by asymmetry vortex shedding[15,27,32].

The key advantages of the flow measurement technique described in this paper are high temporal and spatial resolution and the capacity to simultaneously obtain the pipeline dynamics, flow fields, and near-boundary flow stresses. By using this technique, more in-depth studies on pipeline scour in complex environments can be carried out and the complex mechanism of scour around the vibrating pipeline could be better understood.

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DISCLOSURES:

The authors have nothing to disclose.

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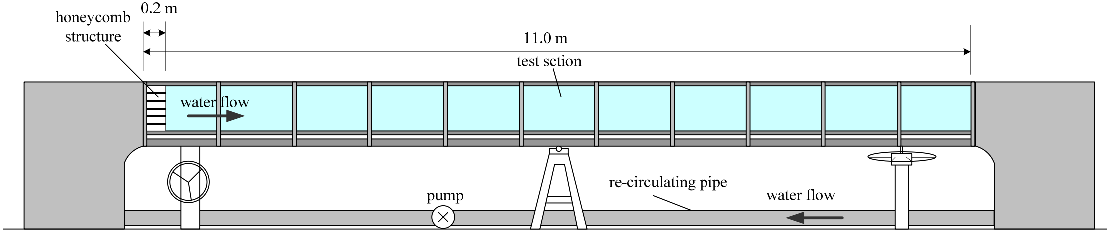

honeycomb
structure
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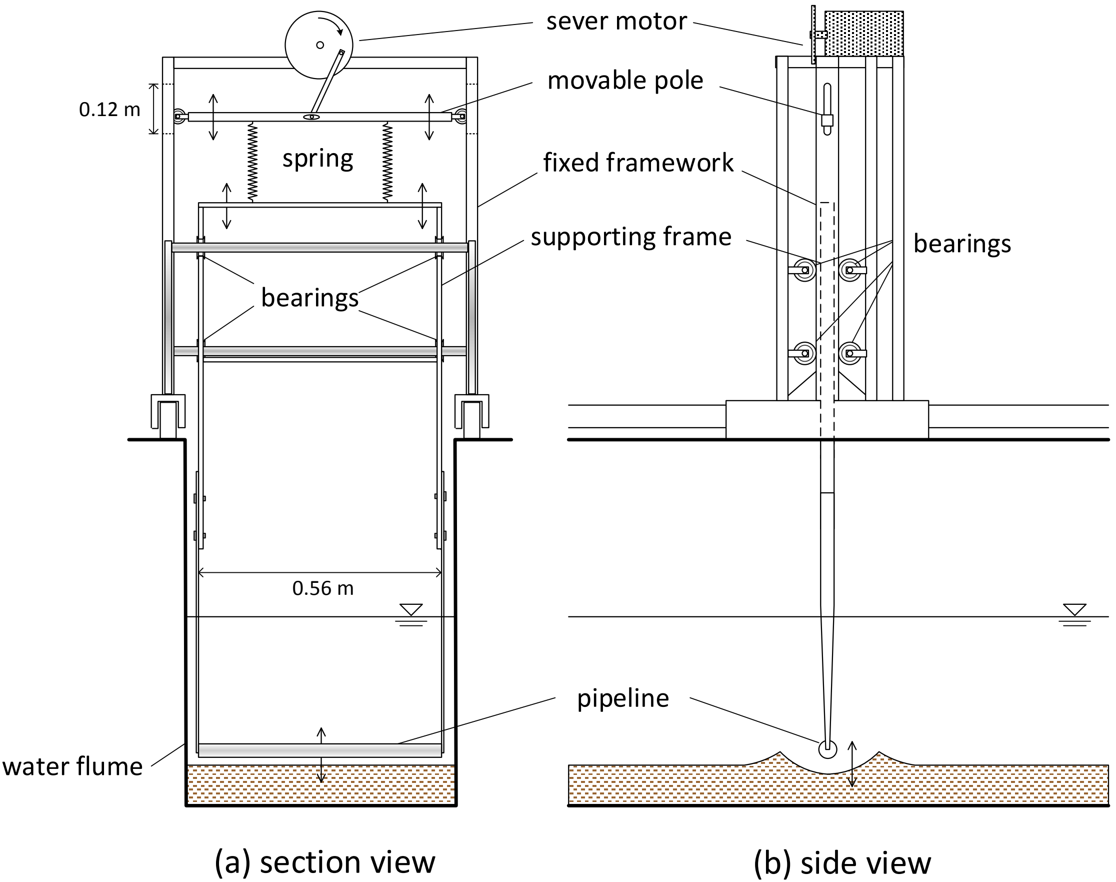
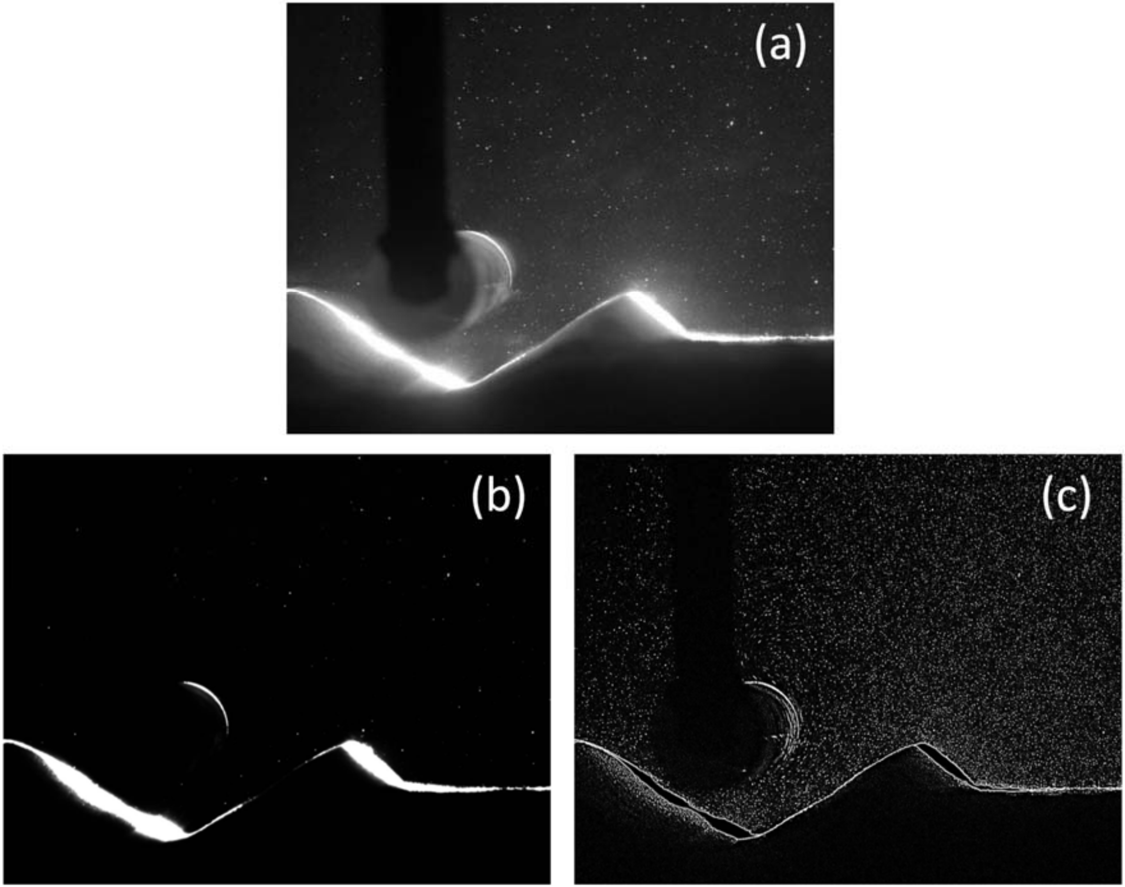
water flow



sever motor
movable pole
0.12 m
spring
fixed framework
supporting frame
bearings
bearings
0.56 m
pipeline
water flume
(a) section view
(b) side view


(a)
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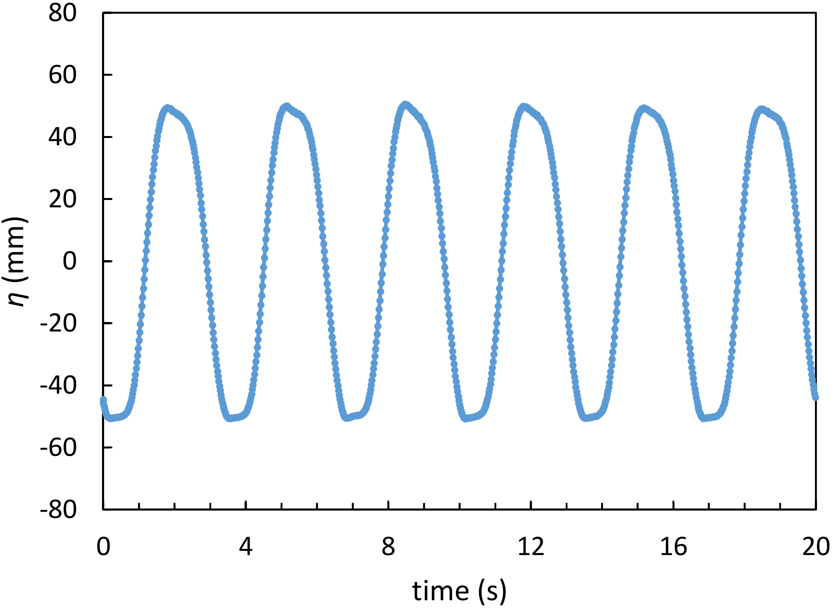
(c)



80
60
40
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-20
-40
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4
8
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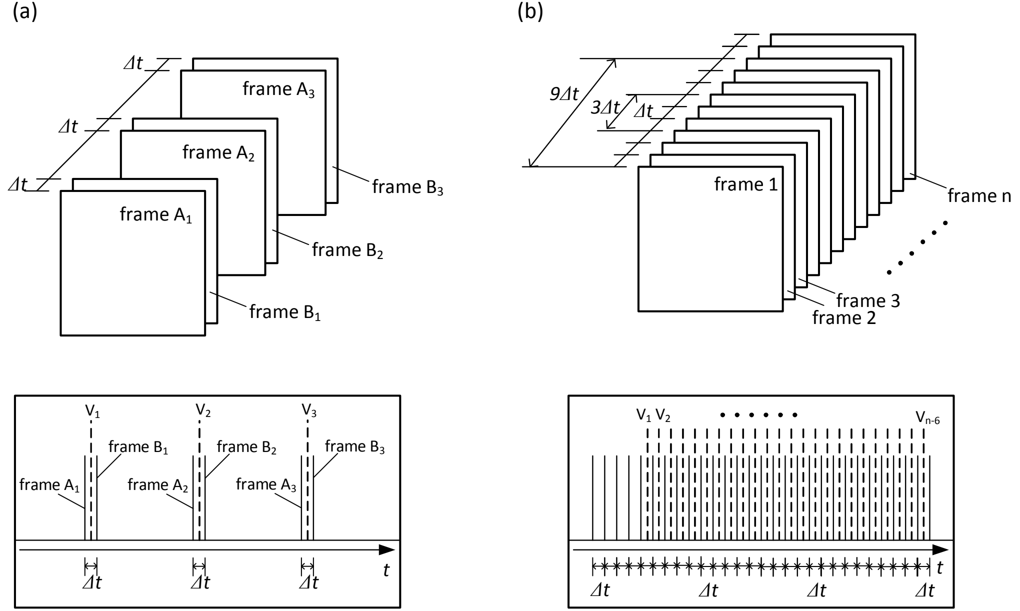
16
20
time (s)



(a)
Δt
Δt
Δt
frame A3
frame A2
frame A1
frame B3
frame B2
frame B1
(b)
9Δt
3Δt
Δt
frame 1
frame n
frame 3
frame 2
V1
V2
V3
frame B1
frame B2
frame B3
frame A1
frame A2
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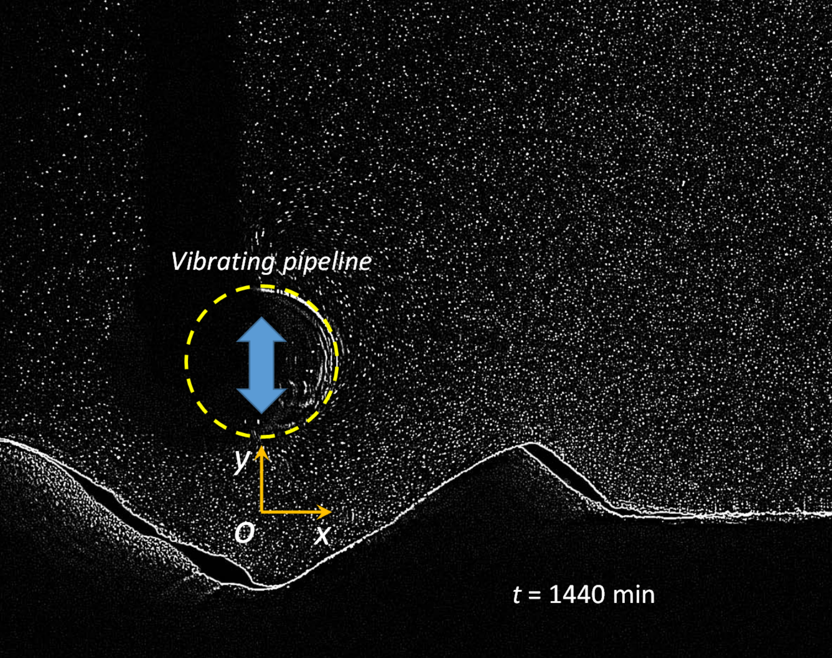
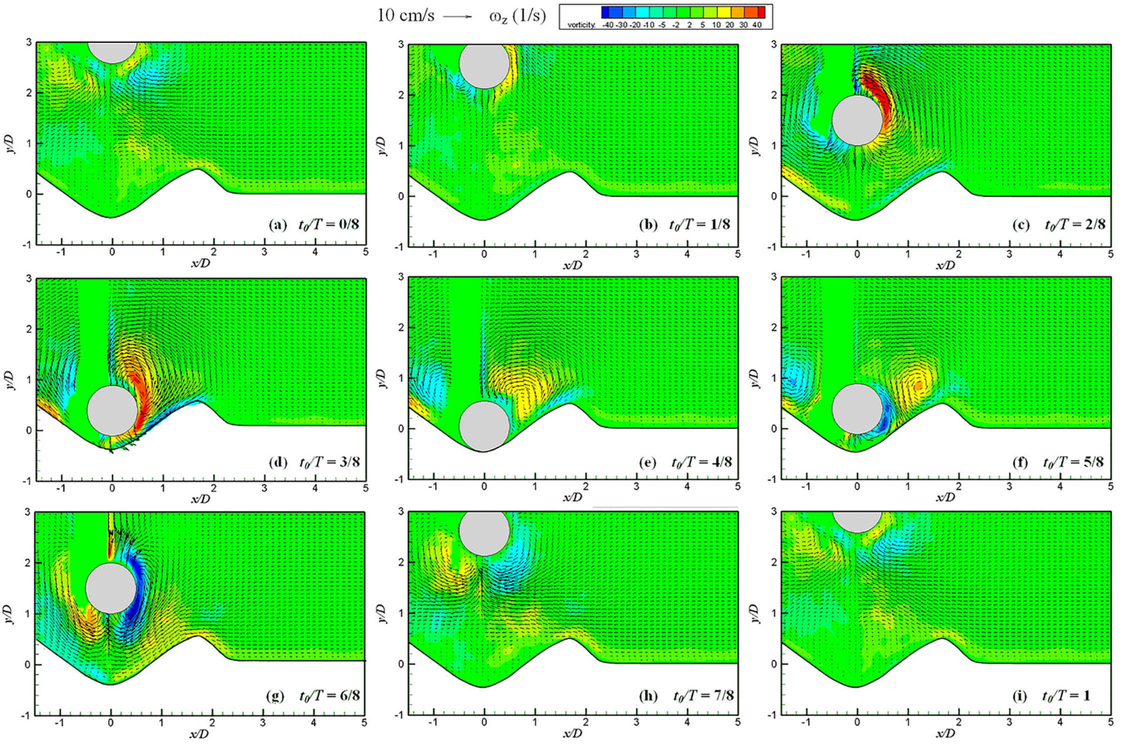

Vibrating pipeline
y
O
x
t = 1440 min



10 cm/s
ωz (1/s)
vorticity: -40 -30 -20 -10 -5 -2 2 5 10 20 30 40
(a) t0/T = 0/8
(b) t0/T = 1/8
(c) t0/T = 2/8
(d) t0/T = 3/8
(e) t0/T = 4/8
(f) t0/T = 5/8
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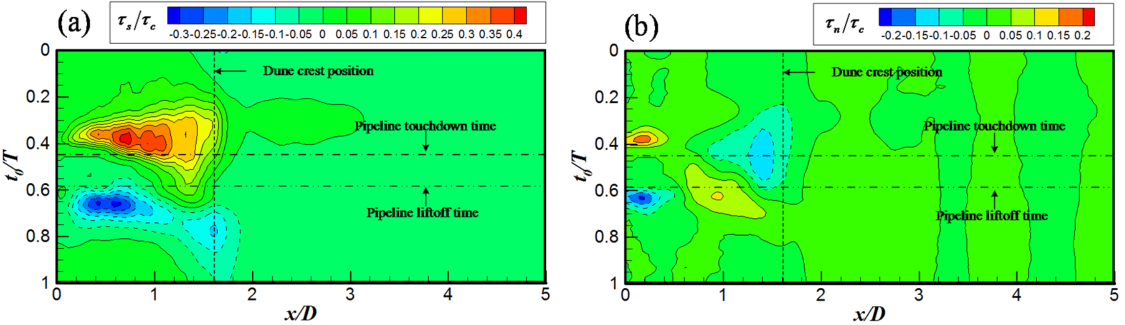
(i) t0/T = 1
x/D
y/D


(a)
τ_s/τ_c
-0.3 -0.25 -0.2 -0.15 -0.1 -0.05 0 0.05 0.1 0.15 0.2 0.25 0.3 0.35 0.4
Dune crest position
Pipeline touchdown time
Pipeline liftoff time
t_0/T
x/D
(b)
τ_n/τ_c
-0.2 -0.15 -0.1 -0.05 0 0.05 0.1 0.15 0.2
Dune crest position
Pipeline touchdown time
Pipeline liftoff time
t_0/T
x/D

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Video or Animated Figure

Video1.mp4

Name of Material/Equipment	Company	Catalog Number
Camera control software	Vision Research	Phantom PCC 2.6
Camera lens	Nikon Chiyoda	
Continuous wave laser	Beijing Laserwave optoelectronics technology co. ltd.	
High-speed camera	Vision Research	Phantom Miro 120
Laser sheet forming optics	Thorlabs Inc	
Pipeline model	ZONCEPZ SOLUTIONS	
Pipeline vibration system	ZONCEPZ SOLUTIONS	
PIV calcuation software	AXESEA Engineering Technology Limited Co.	PISIOU
PIV seeding materials	Shimakyu	
Recirculating flume	SZU ENGINEERING PTE LTD	
Tri-pod	MANFROTTO	SKU MT190GOC4US 410

Comments/Description

Camera control, image data acquisition and processing
Nikor 60mm, f=2.8 prime lens

PIV Laser source; Nd:YAG laser, 532 nm; air-cooling
Image data recording
Transform the point laser to a thin laser sheet
Acrylic cylinder with a diameter of 35 mm
Consists of a sever motor, two connecting springs and pipeline supporting frames.
Image data processing for obtaining flow fields and pipeline displacements
Aluminum powder with a diameter of 10um
Glass-sided, 11 m long, 0.6 m wide, and 0.6 m deep
Camara supporting

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Author(s):	Dawei Guan, Yee-Meng Chiew, Maoxing Wei, Shih-Chun Hsieh

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Department:	School of CEE
Institution:	Nanyang Technological University
Title:	Visualization of flow field around a vibrating pipeline within an equilibrium scour hole
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Authors: The overall goal of this method have been clearly stated in the introduction section as:

"The goal of this method paper is to provide a novel experimental protocol for visualizing the detailed flow fields, and to determine the near-boundary shear and normal stresses within an equilibrium scour hole induced by a forced vibrating pipeline." See lines 70-73 of the revised manuscript.

5. Please revise the Protocol to contain only action items that direct the reader to do something (e.g., "Do this," "Ensure that," etc.). The actions should be described in the imperative tense in complete sentences wherever possible. Avoid usage of phrases such as "could be," "should be," and "would be" throughout the Protocol. Any text that cannot be written in the imperative tense may be added as a "NOTE." Please include all safety procedures and use of hoods, etc. However, notes should be used sparingly and actions should be described in the imperative tense wherever possible. Please move the discussion about the protocol to the Discussion.

Authors: The manuscript has been thoroughly revised according to this comment.

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Reviewers' comments:

Reviewer #1:

Manuscript Summary:

Decent paper. The topic of this paper is interesting and has drawn wide attention in the last decades. The PIV, which has been widely used for flow measurement, is a good technical method to help understanding the scour mechanism around a subsea pipeline. But, there are limited studies on this topic due to inaccurate capture of the flow shear layers in high-velocity-gradient areas. Single-time-interval cross-correlation algorithm of PIV techniques is inappropriate for this kind of measurement. Instead, the authors used the multiple time-interval cross-correlation algorithm to solve this problem. In the test case, a pipeline vibration system and a time-resolved particle image velocimetry (PIV) system were sued simultaneously. Steps for processing raw particle laden images were described. This experimental method is reliable, and the results about the detailed flow fields seem quite promising. The main innovation of this paper is that the proposed flow measurement technique has a very high temporal and spatial resolution. Both the writing and structure of the manuscript are good. Recommend to be accepted.

Major Concerns: none.

Minor Concerns: Only one suggestion that the authors should give more descriptions about the pipeline engineering background in the section of introduction in order to make this paper more readable.

Authors: We thank Reviewer #1 for the constructive comments, which have helped us improve the paper. We have revised the introduction section to make this method paper more readable. Several latest references related to this study have been added to the paper.

Larsen Bjarke, E., Fuhrman David, R. & Sumer, B. M. Simulation of wave-plus-current scour beneath submarine pipelines. Journal of Waterway, Port, Coastal, and Ocean Engineering. 142 (5), 04016003, (2016).

Guo, Z., Jeng, D.-S., Zhao, H., Guo, W. & Wang, L. Effect of seepage flow on sediment incipient motion around a free spanning pipeline. Coastal Engineering. 143 50-62, (2019).

Zhu, Y., Xie, L. & Su, T.-C. Visualization tests on scour rates below pipelines in steady currents. Journal of Hydraulic Engineering. 145 (4), 04019005, (2019).

Lu, L. & Sick, V. High-speed particle image velocimetry near surfaces. JoVE. (76), e50559, (2013).

Kim, J.-T., Kim, D., Liberzon, A. & Chamorro, L. P. Three-dimensional particle tracking velocimetry for turbulence applications: Case of a jet flow. JoVE. (108), e53745, (2016).

Reviewer #2:

Manuscript Summary:

The manuscript presents a laboratory testing protocol to (a) create a realistic scour hole beneath a 2D section of pipeline and (b) visualise the flow mechanics within the scour hole using particle image velocimetry (PIV). The protocol covers setup and calibration of the PIV system, initial development of a scoured trench due to forced (spring-mounted) actuation, PIV data collection and results post-processing. The manuscript is relatively well written, with some grammatical and spelling issues, but not significant. However, the discussion and testing descriptions are not general and are very specific to a particular application.

Authors: We thank Reviewer #2 for the constructive comments, which have helped us improve the paper. The replies to his/her comments are as follows:

1. Major Concerns: The manuscript presents the method of testing reasonably well, but does not provide sufficient details to the mechanical aspects of the testing to allow the setup to be reproduced exactly. For instance, no information is given on the stiffness of the springs or their mechanical setup. There is also a lack of information on the railings and connections to the bearings in the actuation system (this would seem important as the ability to reproduce this setup would be a novel contribution of the paper). This reviewer also thinks that the description of the testing process is very case-specific to the testing approach consider (i.e. problem, geometry, etc. specific). These could be excluded in the protocol section as the main enterprise is to do with the actuation setup and the PIV testing and post-processing methods. The paper would have more general impact if the descriptions of how to reproduce this testing setup were more general, although it is acknowledged that the testing was conducted for a specific purpose. This reviewer believes the paper would be better formulated if the test actuation rig setup was described in more specific detail as this is the more novel part of the setup in this reviewer's opinion.

Authors: Thank you for this comments. We agree that selection of the mechanical setup do affect the experimental results. However, the goal of this method paper is to provide a novel experimental protocol for visualizing the detailed flow fields, near-boundary shear and normal stresses distribution within an equilibrium scour hole induced by a forced vibrating pipeline. Thus, the emphasis of the method paper is related to how the flow fields and near-boundary stresses around a vibrating pipeline are obtained rather than how to simulate a vibrating pipeline. The related information of the mechanical setup has been given in Steps 3.4 and 3.6.

Minor Concerns: Minor concerns are listed below:

2. - define 'near boundary' in the introduction

Authors: Definition of "near-boundary" has been added in the introduction. See line 67 of the revised manuscript: "measured instantaneous near-boundary stresses (at approximately 2 mm from the boundary)".

3. - 'servo' is spelled as 'sever' throughout. This appears incorrect.

Authors: This typo has been corrected throughout the paper.

4. - It is very highly recommended that a note on use of safety goggles be included in the safety check section, and in particular that goggles need to be specific acquired for the laser wavelength in use

Authors: One step (1.2.1) for wearing goggles has been added to the protocol.

5- It is recommended that potential reflection surfaces in the laser line-of-sight be checked for prior to testing

Authors: One step (1.2.1) for checking potential reflection surfaces has been added to the protocol.

6 - There is some casual language used, e.g. 'Look out at all times for'

Authors: The casual language "Look out" has been revised as "Ensure that the water hose does not fall off and that there is no water overflowing from the flume at all times" (Step 1.2.3).

7 - Define the gap (G) either schematically or textually

Authors: The definition of G has been added in Step 3.4.

8 - A note of caution is needed in section 4 with regards to adjust the laser with respect to safety and use of goggles. Never look at laser light without appropriate safety goggles (even indirectly). More discussion on how to adjust the laser safely is needed - e.g. how to line up the laser parallel

Authors: One step (1.2.1) for wearing goggles has been added to the protocol.

9 - what is the MPx of the 7 used?

Authors: 2.3MPx; 1920x1200. This has been added in line 169 of the revised manuscript.

10 - 10 micrometer particles seems to be rather large - refer to Raffel et al. (2007) for discussion on particle size effects with respect to fluid flow lag; - Importantly, the seeding particle appear not to be neutrally buoyant. Surely this is important for modelling the flow. Please explain.

Authors: The explanation on the selection of seeding particles has been included in the DISCUSSION section (lines 427-430 of the revised manuscript).

11 - Is the calibration image (with ruler) supposed to be taken with the laser on? If so, how can the image of the ruler (parallel to the laser) be illuminated?

Authors: Yes, the calibration image with the ruler is taken with the laser on. At the same time, the background light is also on. This allows the scale on the ruler to be clearly seen. We have revised Step 5.

12 - How to check calibration over the field of view?

Authors: The ruler is long enough to cover the full length of the field of view.

13 - It is not clear that specifics, such as the % overlap of interrogation windows or the px size of windows should be specified in a general testing protocol.

1.1. Authors: To make it clear, Step 5.5 has been revised as: "Select a proper sampling rate for data collection. Note: The chosen sampling rate should ensure that the seeding particle displacement within a pair of images is less than 50% of the maximum interrogation window length. In this study, the maximum interrogation window size is 32×32 pixels and the adopted sampling rate is 200 frames per second."

14 - How to suppress/eliminate bubble beneath the acrylic plate?

Authors: The thickness of the acrylic plate used in the test is actually 20 mm (we have corrected this typo in line 211 of the revised manuscript). Since the water surface did not have significant motions during the entire test, no bubble was observed beneath the acrylic plate.

15- Was any external verification of the displacement time-series conducted?

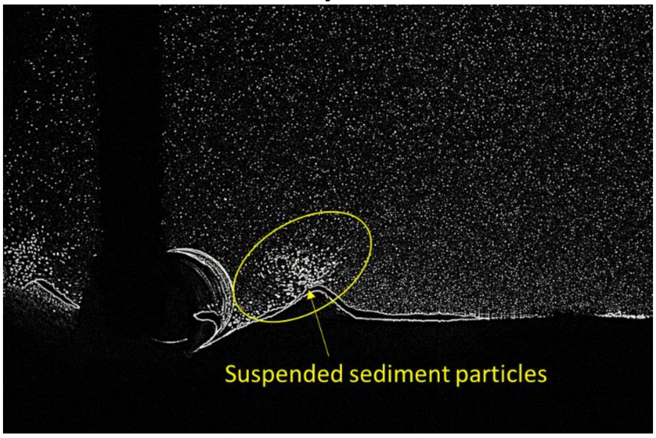
Authors: In this study, the displacement range of the pipeline is from -50 mm to +50 mm, while the accuracy of PIV measurement is about 0.16 mm. Therefore, the quality of the recorded displacement time-series data can be guaranteed.

16 - Can advice be provided on satisfactory correlation criteria for the PIV convergence?
Authors: The satisfactory correlation criteria is greater than 70%. This has been added in Step 7.6.4.

17- If the post-processing algorithm for multiple-time interview analyses is important to the process, this should be explain in more detail. If not important, this should be excluded.
Authors: The comparison between traditional PIV cross-correlation algorithm (single-time interval algorithm) and the present multi-time interval cross-correlation algorithm is clearly given in Figure 5. For the detail explanation of this algorithm, the readers could refer to the published references below.
Hsieh, S.-C., Low, Y. M. & Chiew, Y.-M. Flow characteristics around a circular cylinder subjected to vortex-induced vibration near a plane boundary. Journal of Fluids and Structures. 65 257-277, (2016).

18 - A point of note should be made about asymmetry of the flow field and the effect of ensemble-averaging a temporally asymmetric field.
Authors: The discussion on the symmetry of the flow field is provided in lines 412-418.

19 - Figure 6 does not really indicate that no suspended sediment particles were present.
Authors: Sediment particles and seeding particles can be easily distinguished on the image, as they have obvious differences in sizes and brightness. Please see the image (taken at t = 30 mins) below. In Fig. 6 of the revise manuscript, all the illuminated particles appear to be the same kind, indicating that almost no suspended sediment particles were present at the equilibrium scour stage. In addition, observation with the naked eyes confirmed this.



20 - How were the seeding particle motions compared in the images?
Authors: The sentence has been deleted.

21 - Figure 3 - the pipe does not appear to be parallel to the camera.
Authors: It is parallel. The reason of this visual illusion is that the pipeline was not placed in the middle of the image.

Reviewer #3:

Review of manuscript no. JoVE59745, "Visualization of flow field around a vibrating pipeline within an equilibrium scour hole", by Guan, Chiew, Wei, and Hsieh

This manuscript presents a protocol to realize experiments where pipeline scour is triggered by the pipe vibration in a still water, and to measure the velocity field in longitudinal sections by PIV. The manuscript is in general clear and of potential interest for JoVE readers. The experimental setup and representative results seem suitable for a video article. I suggest several amendments below.

Authors: We thank Reviewer #3 for the constructive comments, which have helped us improve the paper. The replies to his/her comments are as follows:

1. As a general comment, I found striking that the protocol does not include a procedure to measure the profile of the mean equilibrium scour profile that can be measured from images like those of figure 3. A portion of the protocol devoted to this measurement could be added.

Authors: In this study, the equilibrium scour profile on the raw image is clearly designated by the shining seabed shining boundary (see Fig. 3a). After applying the Laplacian filter function to the raw images, the undesirable scattering light on the seabed boundary is filtered, and the equilibrium scour profile can be clearly displayed on the processed image (see Fig. 3c). Therefore, there is no need to measure the profile of the mean equilibrium scour profile.

2. Second general thing is that I would probably remove figures 1 and 2. The experimental setup will be starring in the video article, so sketches are probably useless in the written paper.

Authors: To make the written paper more comprehensive and readable, the authors would like to keep these two figures. Some recent PIV method papers published in JoVE also have figures showing their experimental setups, for example:

Kim, J.-T., Kim, D., Liberzon, A. & Chamorro, L. P. Three-dimensional particle tracking velocimetry for turbulence applications: Case of a jet flow. JoVE. (108), e53745, (2016).

Lu, L. & Sick, V. High-speed particle image velocimetry near surfaces. JoVE. (76), e50559, (2013).

3. Third, the symmetry of the process (line 373) is never shown here. Rather, the camera placement seems such that the pipeline does not appear in the middle of the images (figure 3). So the statement of a symmetric process is not supported here. I suggest providing some evidence.

Authors: The symmetry of the process has been discussed in the DISCUSSION section. Please see <u>lines 412-418</u> of the revised manuscript.

"In a quiescent water condition, Lin et al.[28] found that the structure of the flow recirculation behind an impulsively started circular cylinder can maintain its symmetry when the non-dimensional time $T_D = t_D U_D / D$ < 5, where t_D = cylinder moving time; and U_D = cylinder speed. For the condition that T_D > 5, the oblique vortex shedding may occur around the cylinder. In this study, the maximum pipeline speed can be estimated as $2\pi f \cdot A_0$, and the cylinder moving time can be taken as $1/2f$, thus the maximum non-dimensional time $T_D = \pi A_0 / D = 4.48$.".

The placement of the camera is determined by the location of the interested or desired observation region in the experiments. In this study, if the pipeline were to appear in the middle of the field of view (image), the interested flow region around the pipeline will be partially blocked by the vibrating pipeline during filming. This is because the laser sheet is located on the centerline plane of the flume rather than on the side glass wall. Since the flow pattern and scour trench are almost symmetry in this study, we scarified half side of pipeline to obtain a completed view of the other side. This operation is quite common in PIV operation. In Step 4.3, we have stated that: "Set up the high-speed camera and adjust the field-of-view of the camera to cover the desired observation region." The desired observation region is confined to the half-side of the pipeline in this study.

Line-by-line comments

4 -Summary and abstract, and throughout the paper: I find "near boundary" at line 32, "near-bed" at 38, and so on. Style of these "near-something" should be made uniform.

Authors: Thank you for this comment. We have unified the term "near-boundary" throughout the paper.

5 -Line 41 lists the same features that appear at line 38. Repetition could be avoided.

Authors: The two sentences have been revised to avoid repetition. Please see lines 38-40 of the revised manuscript.

6 -Line 43: why mentioning a "recirculation" flume? This is irrelevant here as there is no flow.

Authors: The "recirculation flume" has been revised as "straight flume". Please see line 41 of the revised manuscript.

7 -Lines 45-47: I would invert the order of these two statements.

Authors: The order of the two sentences has been inverted. Please see lines 42-44 of the revised manuscript.

8 -Line 53: "which" sounds used wrongly here.

Authors: The word "which" has been revised as "and". Please see line 50 of the revised manuscript.

9 -Introduction: just today I received the content alert of JHE, where a paper by Zhu et al entitled "Visualization Tests on Scour Rates below Pipelines in Steady Currents" appears. Could be worth having a look at it and possibly add to the literature review.

Authors: This reference has been added in the literature review.

10 -Lines 88-93: written in this way, this text seems to suggest that high velocity gradients are absent in turbulent flow fields; this is not the case, I think. Suggest rephrasing.

Authors: The sentence has been revised. Please see lines 88-91 of the revised manuscript.

11 -Step 1.2: here and at other instances, details for the present experimental setup are given. When I wrote a paper for JoVE few years ago, such content was written in a "NOTE". Not sure if the style shall be the same in this case.

Authors: Thank you for pointing out this issue. We have revised the whole paper to ensure that any text that cannot be written in the imperative tense is added as a "NOTE."

12 -Step 2.3: it is not clear what the top platform of the flume is, please clarify.

Authors: The top platform of the flume can be seen in the video.

13 -Step 3.1: well, I guess that the pipeline model is built once for all the tests. Suggest rephrasing as "Use a prefabricated pipeline model...".

Authors: The sentence (Step 3.1) has been revised as suggested by the reviewer.

14 -Step 3.5: "strictly" is generic, should be clarified. It should be also mentioned how the check of having only vertical motion is performed.

Authors: The sentence (Step 3.5) has been revised as: "adjust the supporting frames and four bearings to ensure that the pipeline vibration is along the vertical direction."

15 -Step 3.6: if one has to wait that the predetermined response is obtained, there must be some measurement here? Needs to be clarified. Second, what is intended with "record"?
Authors: This sentence is deleted. Selection of the initial condition is not a necessary step of this protocol. In other words, different induced frequencies may be used in a similar research if one follows this protocol.

16 -Step 4.2: when I read this, I wondered about the pipeline shadow. Actually the authors mention it later, could be wise to add a NOTE here promising that something will be said later on this issue.
Authors: The sentence has been revised as suggested by the reviewer. Please see Step 4.2 in the revised manuscript.

17 -Step 4.3.1: there seem to be two spaces after "90°". How is this angle measured? Please add.
Authors: The sentence (Step 4.3.1) has been revised as: "adjust the camera to the level of the observation region with its axis perpendicular to the illuminated laser sheet." This is a common procedure in PIV experiments.

18 -Step 4.3.2: please define f.
Authors: The definition of f (aperture) has been added.

19 -Step 4.3.3: shouldn't this camera levelling be performed before one ensures that it is perpendicular (4.3.1)?
Authors: The order of these two steps has been reversed.

20 -Step 5.1: these particles are quite heavy. Nothing is mentioned about how they are maintained in suspension. Will it be just by the vibration of the pipeline? Please clarify.
Authors: The explanation relating to the selection of seeding particles is now included in the DISCUSSION section (lines 427-430 of the revised manuscript).

21 -Step 5.2: how should one check that the sheet is parallel to the wall? Please clarify. Second, shouldn't this be done before the camera is placed (since the camera must be perpendicular to the sheet, 4.3.1)?
Authors: This sentence has been deleted as it has been stated in Step 4.3. This is a common procedure in PIV experiments.

22 -Step 5.6: I find this "within 50% overlap between adjacent interrogation window" confusing. Please rephrase for clarity.
Authors: This step has been revised as: 5.5 Select a proper sampling rate for data collection. Note: The chosen sampling rate should ensure that the seeding particle displacement within a pair of images is less than 50% of the maximum interrogation window length. In this study, the maximum interrogation window size is 32×32 pixels and the adopted sampling rate is 200 frames per second.

23 -Step 6.1: I guess that the vibration of the pipeline will trigger some surface waves. By contrast, the thickness of this plate is small. Has it some walls to prevent water from passing over it?
Authors: The acrylic plate used in the test is actually 20 mm think (we have corrected this typo in line 211 of the revised manuscript). Since the water surface did not have significant motions during the whole test, the situation commented by the reviewer did not occur.

24 -Step 6.5: suggest using "the sampling rate selected in 5.6".
Authors: The sentence has been revised as the reviewer suggested.

25 -Step 6.6: based on what shall one decide that seeding particle density is "sufficient"?

Authors: Step 6.6 has been revised as: Once the data collection is completed, review the recorded image quality and check if the seeding particle density per interrogation window (32×32 pixels) is greater than 8. Save the recorded file if satisfied, otherwise the seeding density should be increased by slowly injecting seeding solutions in the observation region, and repeat Steps 6.3-6.5.

26 -Line 240: "are" should be "were" for consistency with other text.

Authors: The correction has been made as the reviewer suggested. Please see line 235 of the revised manuscript.

27 -Step 6.8: lab lights on again?

Authors: Yes. The sentence "turn on the background lights in the laboratory room." has been added to Step 6.8.

28 -Step 7.1.3: is this "cross-correlation method" called like this in the processing software?

Authors: Step 7 has been thoroughly revised.

29 -Step 7.2.2: how does this differ from 7.1.2?

Authors: Step 7 has been thoroughly revised.

30 -Step 7.2.3: I think that this "mask" has not been mentioned before. Please clarify.

Authors: This is a normal procedure in PIV data process. The masked region on the image is not included in the calculation.

31 -Step 7.2.4: I find this confusing, please rephrase for clarity. It is not clear why these changes are made.

Authors: This is a normal procedure in PIV data process. Please refer to Raffel et al. (2007).

32 -Step 7.3.1: not clear what a "phase image" is. Second, how are the scale and translation parameters determined?

Authors: To avoid confusion, this step has been revised. Please see Step 7.7 of the revised manuscript. For the detail algorithm of wavelet transform analysis, please refer to *Newland (1994a, b)* and *Hsieh (2008)*.

Hsieh, S.-C. Establishment of high time-resolved piv system with application to the characteristics of a near wake flow behind a circular cylinder, National Chung Hsing University, (2008).

Newland, D. E. Wavelet analysis of vibration: Part 1—theory. Journal of Vibration and Acoustics. 116 (4), 409-416, (1994a).

Newland, D. E. Wavelet analysis of vibration: Part 2—wavelet maps. Journal of Vibration and Acoustics. 116 (4), 417-425, (1994b).

33 -Step 7.4.2: I think that these equations would need some support. The equation for tau_s is the Newton law, whose validity in non-laminar conditions should be argued. The second one is even more puzzling.

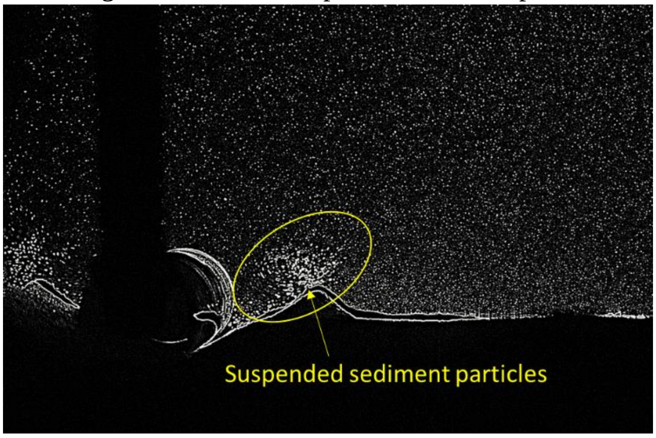
Authors: We named them as "near-boundary shear stresses" to distinguish from the well know "bed shear stresses". This has been explained in the INTRODUCTION section (see lines 64-67 of the revised manuscript).

34 -Line 334: the first statement of this section is not a result. By the way, I already suggested to remove these figures.

Authors: This sentence has been deleted.

35 -Lines 343-345: I suggest to remove this text, since (1) these are not results and (2) the figure has been already reference in step 7.2.5.
Authors: This sentence has been deleted.

36 -Lines 351-352: I do not see how this last statement is supported by the text above. please clarify.
Authors: Sediment particles and seeding particles can be easily distinguished on the image, as they have obvious differences in sizes and brightness. Please see the image (taken at t = 30 mins) below. In Fig. 6 of the revised manuscript for example, all the illuminated particles look the same, indicating that almost no suspended sediment particles were present at the equilibrium scour stage.



37 -Line 355: why is the pipe shadow on the left rather than below, as one would expect for a laser source above? Some clarification is needed.
Authors: Because the Laser source is not placed directly above the top of the pipeline and the field-of-interest of this study is confined to the right half side of the pipeline. This has been clarified in Step 4.2.

38 -Line 357: this check of the velocity data continuity is not mentioned in the protocol. Did the authors do it? If yes, a step should be added above.
Authors: This sentence has been deleted.

39 -Line 358-359: also this comparison is not mentioned in the protocol above.
Authors: This sentence has been deleted.

40 -Line 373: do not think that "along" is the proper word here.
Authors: The word “symmetrical along” has been revised as “symmetrical about”. Please see line 360-361 of the revised manuscript.

41 -Line 377: which equation has been used as representative of the Shields diagram?
Authors: Obtaining the critical shear stress by using the Shields diagram is a very basic knowledge in the field of sediment transport.

42 -Lines 380-381: this statement of consistency between velocity and tau results sounds trivial, as the stresses are computed as velocity derivatives. Therefore, it cannot be used to argue that the measurements are "valid" (line 382). Suggest rephrasing.
Authors: To avoid confusion. The sentence “This means that the measured results are valid and can be used for analyzing the scour mechanism beneath a pipeline subjected to forced vibration.” has been deleted.

43 -Line 418: I suggest to replace "stresses" with "stress fields".
Authors: The "stresses" has been replaced with "stress fields". Please see line 405 of the revised manuscript.

44 -Line 425: suggest starting with "In fact, ".
Authors: The revision has been made as suggested by the reviewer. Please see line 412 of the revised manuscript.

45 -Line 428: moving time and speed are not well defined, since the pipe is moving continuously and its velocity is not constant.
Authors: This definition is from a previously published paper (Lin et al. 2019).

46 -Line 434: I guess that this seeding particle selection is also performed once for the entire campaign. So it is not a protocol step, strictly speaking.
Authors: We do not quite understand this question. Discussion of the seeding selection is necessary for this protocol.

47 -Line 438: I guess that "x>0" means to the right of the pipe. Why does it need to be specified here?
Authors: The "x>0" has been deleted.

48 -Line 442: I suggest to add a brief comparison of this velocity with the typical water velocities around the pipe.
Authors: The typical water velocities around the pipeline in this study is about 10-20 cm/s. This has been added in lines 429-430 of the revised manuscript.

49 -Line 457: my understanding is that each velocity vector may be measured with reference to a different frame rate. If this is correct, it should be explicitly declared. Then, it may be also mentioned that the velocity values are further averaged, that should reduce the impact of the time interval used for the single PIV measurements.
Authors: This calculation is done by using a PIV software. For the detailed explanation of this algorithm, please refer to references below:
Hsieh, S.-C., Low, Y. M. & Chiew, Y.-M. Flow characteristics around a circular cylinder subjected to vortex-induced vibration near a plane boundary. Journal of Fluids and Structures. 65 257-277, (2016).

50 -Figure 3: in the end, there seem to be two scour profiles in panel (c). Why? This should be briefly discussed at line 347.
Authors: These are the outlines of the illuminated scour boundary, not two scour profiles. The illuminated scour boundary normally has a thickness (as shown in Fig. 3a). The scour profile is taken as the upper shining line. This is quite common in PIV tests.

51 -Figure 8: touchdown and liftoff times need to be defined. They are the times at which the pipeline is at minimum and maximum elevation, I guess.
Authors: The definition has been added to the caption of Fig. 8. The touchdown and liftoff times refer to the time when the bottom of the pipeline just touches and rises from the scour hole boundary, respectively (see lines 392-296 in the revised manuscript).

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