Imaging of Hydrodynamic Field Around Submerged Objects Regular Wave and Tsunami Conditions

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Abstract. Hydrodynamic particle movement under regular waves and tsunami wave are rarely studied due to its complicated sensors. This research is aimed at investigating flow fields around submerged structures due to regular waves and tsunami wave. A series of experiments were performed at Tsunami Flume Workshop Facility at Tsunami and Disaster Mitigation Research Center (TDMRC) of Universitas Syiah Kuala. The flume has 60 m in length, 2.5 m in width and 1.7 m in height. To model the both waves, a set of electrical paddle and sensors were placed at one end of the flume. This set of equipment is able to mimic any waveform model, in this case a regular wave with three scenarios and the 2004 Indian Ocean Tsunami wave scenario. A submerged structure was placed on the bed of the flume to model underwater structures. To capture the flow fields, we use a Laser Particle Image Velocimetry (PIV) Camera made in Seika. During the experiment, the results showed different vortex field for both simulations, regular wave and tsunami, generated in front of the submerged structure. Regular wave flow has maximum velocities of 0.5 m/s, 0.7 m/s, 0.9 m/s in each paddle amplitude change scenario. The flow field produces an anticlockwise vortex around the pipe with differents pattern. Tsunami wave flow velocity during the maximum amplitude phase is about 0.25 m/s with a complex vortex field around the pipe, a combination of clockwise and anticlockwise. This could be interpreted as more chaotic hydrodynamic fields around the submerged structures under regular wave and tsunami conditions.

1 Introduction

Impacts of waves forces on submerged structures are difficult to observe as these require extensive and complicated sensor systems. Hydrodynamic forces on submerged structures could deliver significant damages on life-line infrastructures, such as pipelines and harbor structures. In the case of a tsunami, or long-waves alike, the forces could displace the pipelines or even detache them. In this condition, long wave orbital velocity could create a long dragging force on the structure. The damage on pipeline during tsunami, storm, or other coastal hazards could disrupt essential logistic and communication services as found in the case of Tonga island tsunami that disconnected the communication for the island state for several weeks [1] and also during the 2011 Great East Japan Earthquake Tsunami that detached gas supply to the affected area.

As tsunamis become a constant threat for the majority of coastal areas in Indonesia, developing the capacity to develop tools/methods in observing the impacts of tsunamis would be essential. Flow fields (map of velocities) around structures could explain the hydrodynamics condition around the submerged structures under tsunami-like conditions. This has been enabled by the existence of the Particle Image Velocimetry (PIV) camera system. The uses of the PIV Camera system in tsunami research have been conducted to estimate the actual tsunami velocity during the 2004 Indian Ocean tsunami, to study characteristics of landslide tsunami, hybrid modeling for Lituya Bay tsunami [2], sedimentation pattern [3], investigate the hydrodynamic performance of a small-scale OWC model [4], simulated the overflow volume and fluid force of tsunami [5] and others. However, it could not be identified with a specific and detailed experiment using the PIV camera system to observe the regular wave and tsunami wavearound submerged structures.

This research is aimed at analyzing hydrodynamic conditions around submerged structures (in this case will be a cylindrical pipe) under regular waves and tsunami wave. The research is expected to demonstrate the use of PIV cameras as an advanced technology to differentiate flow fields under submerged structures in

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the wave flume facilities. The experiments using such advanced techniques have not been reported so far from any research institute/facility in Indonesia. This paper also demonstrates the breakthrough of the advanced techniques in Indonesia that could offer many opportunities for coastal engineering researchers in the region.

2 Materials and Method

2.1 Experimental Setup and Wave Conditions

Wave flume was 60 m in length, 2.5 m in width and 1.7 m in height to perform a series of experiments at Tsunami Flume Workshop Facility at Tsunami and Disaster Mitigation Research Center (TDMRC) of Universitas Syiah Kuala. Forty meters of the flume walls were made from glass. This enables detailed observations of hydrodynamic conditions from the generation to runup. The wave generators were produced by HR Wallingford of the United Kingdom in 2022. Three scenarios of wave amplitudes and frequencies were used in the test as shown in Table 1.

Table 1. Regular wave conditions.

Water Height (H)	Frequency (f) and Amplitude (A) of paddle movement		
0.8 m	f=0.3 Hz, A=0.1 m	f=0.3 Hz, A=0.15 m	f=0.3 Hz, A=0.2 m

The regular waves were generated by a paddle electrical system in 30 seconds at steady state water level conditions of H=80 cm. Each scenario is simulated within 30 second. At the same water level condition, a time series of the 2004 Indian Ocean Tsunami (Fig) were used to demonstrated of tsunami wave. To a model the tsunami waves, a set of pressure tanks and sensors were placed at one end of the flume (Fig).

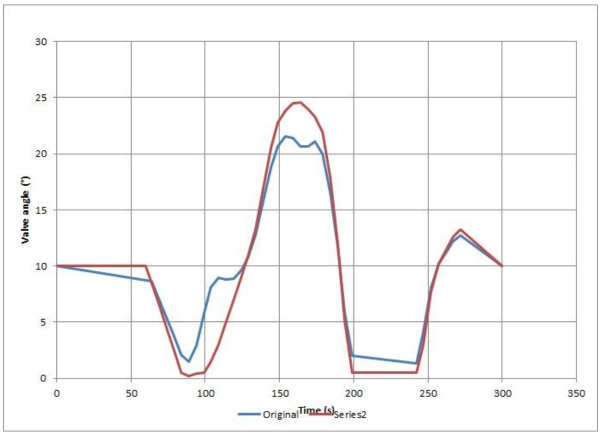


Fig. 1 The 2004 Indian Ocean Tsunami time series

The 2.5 x 2.5 x 4.5 m pressure tank inhales water up to a height of 2.5 m and then releases it to generate tsunami phase waves as shown in Fig. 1. We take the smoother phase for the simulation instead of the original phase. Both scenarios are performed sequentially with the regular wave performed earlier.

A submerged structure was placed on the bed of the flume to model underwater structures. The submerged model is a pipe with a length of 2.5 m and diameter of 0.26 m and was placed on the flume bottom at 35.5 m from the paddle and 38.5 m from the pressure tank (Fig 2).

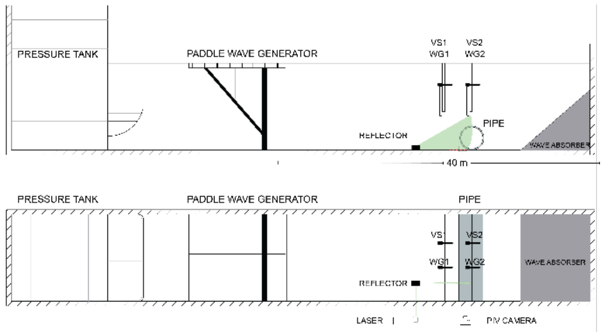


Fig. 2. Experimental setup

2.2 Wave Gauge and Current Meters

Two wave gauges were installed, about 80 cm from the pipe to measure the incoming hydrodynamic condition and above the pipe to measure the hydrodynamic condition above the pipe. At the same positions, two JFE Advantech Current Meters were placed to measure the velocity.

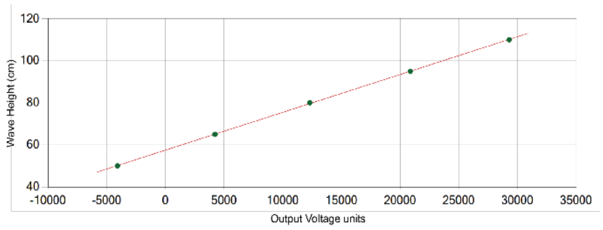


Fig. 3 Wave gauges calibrate response

The water level and velocities measured by the sensors were later used as wave phase references for the measured flow field based on the PIV camera system.

The sensors of WG1 and VS1 were placed at 35 m from the paddle, WG2 and VS 2 were placed on the top of submerged structures about 20 cm into the water, 0.5 m from the WG1 and VS1 (Fig. 1). The calibration of wave gauges was determined by comparing the water level and the scale of the rigid stick sensor at the surface of still water, wave gauges calibrate response shown in Fig. 3. The velocity meters were calibrated to zero level in the still water state to turn down the false flow movement in the water.

2.3 Particle Image Velocimetry

Particle Image Velocimetry (PIV) Cameras were used to capture the 2D flow fields around the submerged structures (pipe). The PIV measurement is considered as two general processes, acquisition and analysis of the capturing image. Polystyrene beads of 0.6 μm diameter are released into the water as floating particles. The displacement of particles is used to calculate their velocities by the time interval. Each particle's velocity is treated as a vector with components in the x and y (2D). Laser system consists of a double impulsion laser and produces the light sheet by the Vlite laser beam with the cylindrical lens. The maximum output energy of 10 mJ – 500 mJ per pulse in the 355 nm wavelength. The light sheet redirects into a flume and reflects in 90° to a pipe. As a glass flume, the PIV camera recorded the flow were placed at the next to the pipe, outside of the flume. The perpendicular camera view of 357 mm x 303 mm was arranged to capture the flow field of the underwater at the surface of the pipe. The 2D flow field data collection and processing are then analyzed by the K2-Lite software to determine particle water displacement by the wave condition (Table 1). These flow visualization techniques can be seen in [4,6–9]

3 Results and Discussion

3.1 Regular Wave Flow Field and Velocity

The velocity measurements were selected to demonstrate the regular wave traveling of each condition. In each experimental run, the maximum amplitude was selected for hydrodynamic analysis around the pipe. The condition refers to the frequency and amplitude of paddle movement, while the wave gauge results are the frequency and amplitude of the waves recorded in the flume.

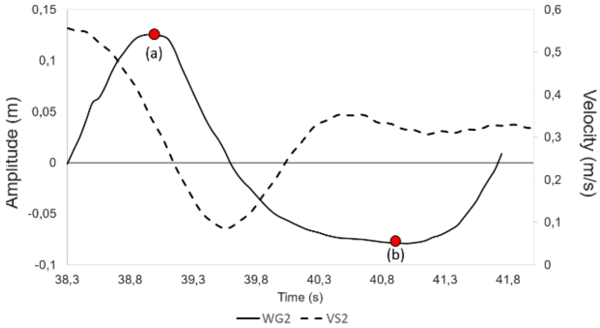


Fig. 4. Regular wave profile with maximum amplitude (black line) recorded by WG2 and velocity recorded by VS2 for conditions of H= 80, f=0.3 Hz, A=0.1 m.

The maximum amplitude recorded by WG2 of each condition is about A=0.12 m; -A=0.08 m (Fig. 4), A=0.25 m; -A=0.12 (Fig.6) and A=0.35 m; -A=0.12 (Fig. 8). Wave amplitudes were compared with the result of the current sensor (dash line) at the same time of wave running. The maximum amplitude (a) and (b) of each condition are selected to determine the forms and velocity of the flow displacement.

As a result, the PIV camera produced 200 images during the paddle wavemaker run. Preliminary experiments demonstrated the repeatability of the regular wave and the distribution of the particles. The arrows (Fig. 5;7;9) represent the magnitude and direction of the velocity vector. The characteristics of regular waves in the maximum amplitude phase tend to move horizontally and then pass through the pipe at the front and top with increasing speed at the top of each scenario. This indicates that the force received by the pipe is mostly above the pipe. The next incoming wave forms anticlockwise around the pipe due to the encounter with the return wave. The position of the vortex observed around the pipe occurs at a water level of 13-15 cm from the bottom of the flume. Then the vortex moves up the pipe as the flow velocity increases and then disappears when the next wave arrives. This process continues to repeat until the number of waves in each scenario has been generated.

The distribution of vectors (Fig. 5) indicates the flow as a wave crest approaches the pipe. In the first condition (H= 80, f=0.3 Hz, A=10 cm), the velocity increases at the top about 0.4-0.6 m/s of the pipe in an uplifting direction at the maximum phase. The minimum movement occurs in the lower half of the pipe ~0.05 m/s. The rotating form in Fig. 4b is due to the confluence of the incoming and return waves with velocity ~0.1-0.25 m/s around the anticlockwise.

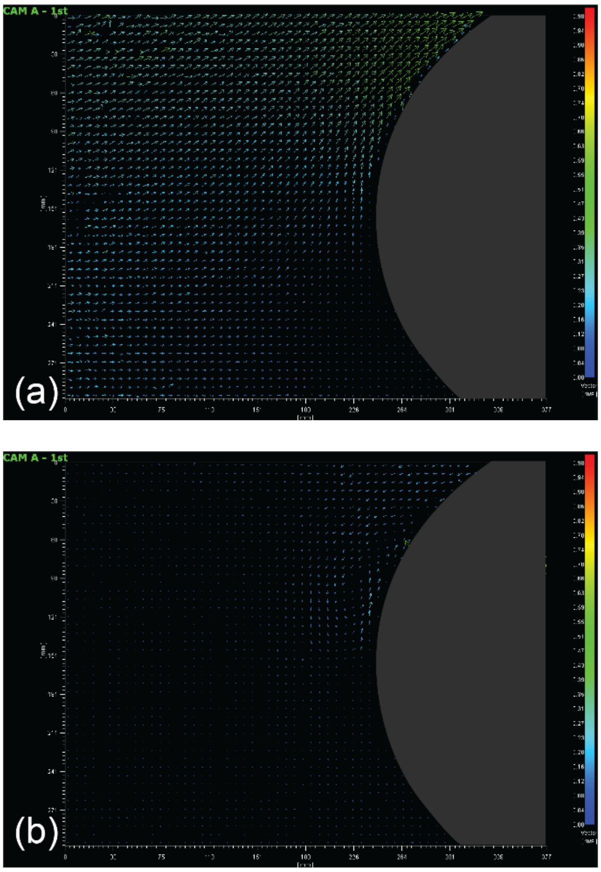


Fig. 5 Velocity fields of regular waves traveling on the pipe by PIV measurements of frequency=0.3 Hz and A=0.1 m.

In the second condition (H= 80, f=0.3 Hz, A=15 cm), the highest velocity are located around the top of the pipe about 0.6-0.8 m/s (Fig. 6a). Anticlockwise form diameter increases (~0.3-0.6 m/s) during wave amplitude change (Fig. 7b) where the position of the circle is most deeply.

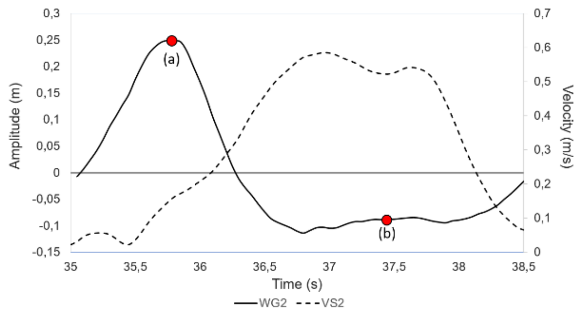


Fig. 6 Regular wave profile with maximum amplitude (black line) recorded by WG2 and velocity recorded by VS2 for conditions of H= 80, f=0.3 Hz, A=0.15 m.

The PIV camera also captures the other particles or air bubbles at the bottom of the flume that move non-uniformly with the coming and returning wave directions. A pre-filtering process was applied to reduce the random motion of the particles. Further analysis is needed in this case, but it does not affect the flow around the pipe.

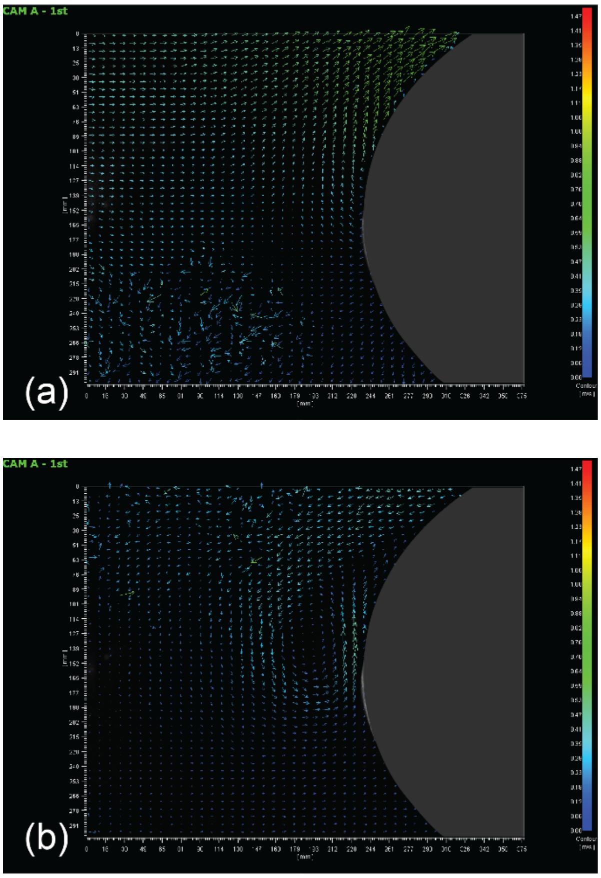


Fig. 7 Velocity fields of regular waves traveling on the pipe by PIV measurements of frequency=0.3 Hz and A=0.15 m.

In the third condition (Fig. 9a) shows the almost uniform direction of displacement with the strongest velocity on the top ~0.8-1.1 m/s. The anticlockwise (Fig 9b) forms deeper and rotates faster (~0.4-0.6 m/s) than the previous two conditions.

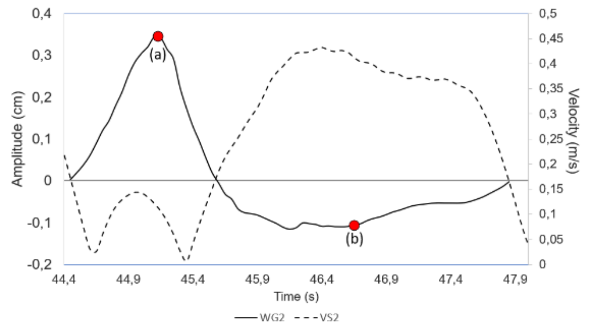


Fig. 8 Regular wave profile with maximum amplitude (black line) recorded by WG2 and velocity recorded by VS2 for conditions of H= 80, f=0.3 Hz, A=0.2 m.

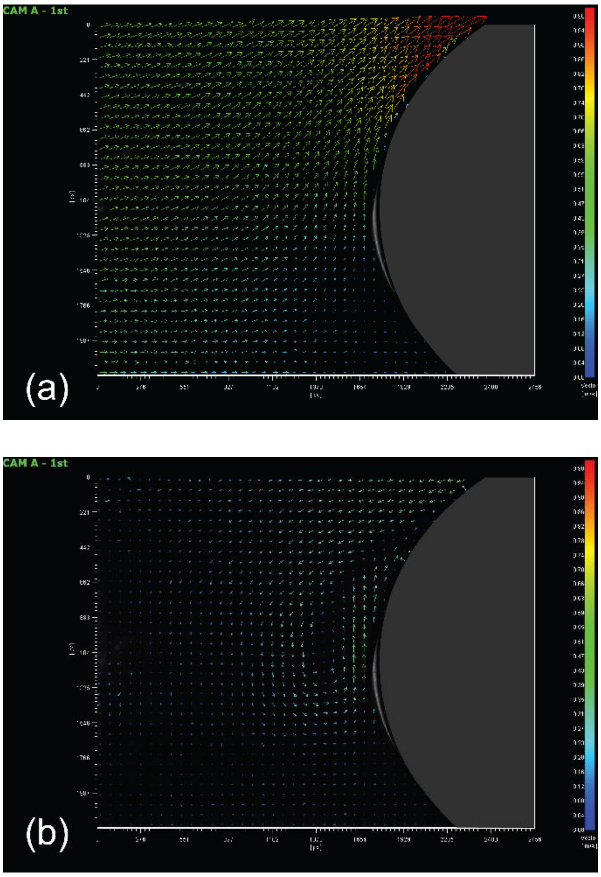
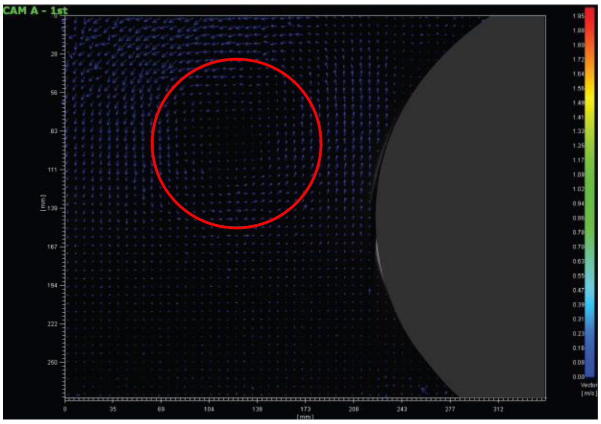


Fig. 9 Velocity fields of regular waves traveling on the pipe by PIV measurements of frequency=0.3 Hz and A=0.20 m.

3.2 Tsunami Wave Flow Field and Velocity

The long wave scenario, the 2004 Indian Ocean tsunami, produces a flow field that is completely different from the regular wave. After 50 seconds, the pressure tank starts to inhale the water, the water flow moves horizontally towards the direction of the pressure tank with a velocity of ~0.05 m/s for 40 seconds. At this stage, the pipe receives flow at the back horizontally.



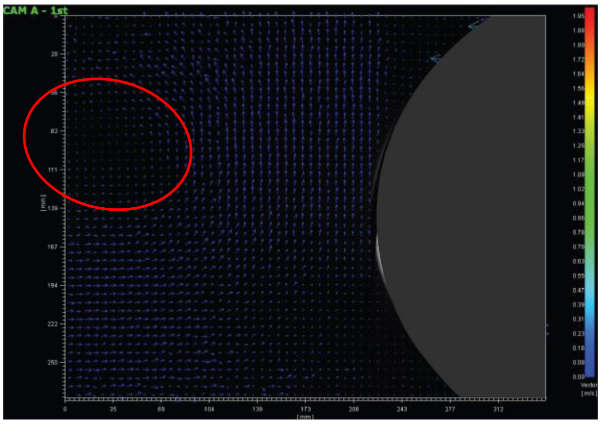


Fig. 10 Velocity fields of the 2004 Indian Ocean Tsunami wave. Red circle captured the vortex posititon.

Water was released at 80 seconds with a maximum velocity of ~0.25 m/s (maximum amplitude). The first anticlockwise vortex is formed around the pipe with a maximum diameter of ~100 mm and a variable velocity at the center of the vortex of <05 m/s and at the sides of 0.08 m/s (Fig. 10). The field forms an anticlockwise vortex direction at the center and vertical up-down at the sides of the vortex. This gives an insight into the presence of pipe lift and pipe compression forces on the pipe.

In the next phase of the second inhalation, the vortex moves towards the pressure tank away from the pipe and then partially dissipates upwards. The second discharge then re-increases the velocity around the remaining vortex to about <0.03 m/s. The vortex forms and direction in the second phase is quite complex where the anticlockwise field and new clockwise formation converge around the pipe. On a larger scale, this affects the durability of the pipe structure in the water.

4 Conclusions

A capturing velocity field has been developed at Tsunami and Disaster Mitigation Research Center Universitas Syiah Kuala. With proper camera and laser setting, PIV technique is effective in the capture of flow fields and measuring the velocity waves.

The flow around the pipe during the regular wave simulation generally moves horizontally toward the top of the pipe repeatedly with average velocities of 0.5 m/s, 0.7 m/s and 0.9 m/s in all three scenarios. Anticlockwise vortices are formed around the pipe with maximum velocities up to 0.6 m/s. A more complex vortex around the pipe occurs during the tsunami wave simulation. The maximum velocity around the pipe is 0.25 m/s. The vortex moves away from and approaches the pipeline in a complex flow field (clockwise and anticlockwise) during the simulation. Both simulations provide insight into the potential damage to submerged structure based on the flow filed of waves and tsunamis on a larger scale.

A more complex experiment can determine the hydrodynamic characteristic, acceleration and vorticity filed with the submerged model then validate the numerical calculation by the PIV measurements. This research has demonstrated the ability of the PIV Camera system to capture vortex dynamics under regular waves and tsunami waves.

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