Chapter

Application of Vortex Control Principle at Pump Intake

Zambri Harun, Tajul Ariffin Norizan and Wan Hanna Melini Wan Mohtar

Abstract

Vortex flow in a pump intake could affect a pump operation significantly if not treated appropriately. Many researches have been conducted to determine the best control method for vortex flow in pump sumps so that the pump lifespan can be maximized. In this study, a vortex control principle designed to minimize the impact of submerged vortex flow in pump sump on major pump components is presented. This principle employs a device called the plate type floor splitter which serves the function of eliminating vortices formed on the sump floor and reduces the intensity of swirling motion in the intake flow. A pump sump model was built to carry out the study by installing a floor splitter plate sample under the pump suction inlet and the corresponding parameters used to quantify the swirl intensity known as the swirl angle was measured. Procedures for the measurement were conducted based on ANSI/HI 9.8-2018 standard. A numerical simulation was performed to study the flow in a full-scale pump sump. The results showed that the installation of floor splitter plate can eliminate vortices efficiently and reduce swirl angle significantly. However, optimization of floor splitter design is needed to achieve a reduction effect that can reduce swirl angles to an acceptable value of lower than 5° according to ANSI/HI 9.8-2018 standard.

Keywords: vortex flow, pump sump, anti-vortex device, swirl angle, floor splitter

1. Introduction

Pump intake is the part of a pump that draws fluid from the reservoir called the sump as a result of pressure difference generated by the impeller. In most cases, pumped fluid enters the intake in a swirling motion due to geometric features of the sump [1]. Inappropriate sump design such as abrupt changes in sump boundaries, narrow clearance under the pump inlet and asymmetric orientation of the approach channel to the sump will lead to the formation of swirls and vortices [2]. Strong vortices may cause damages to the pump impeller by channelling air to the impeller surface and initiate adverse effects such as cavitation and vibration [3]. On the other hand, excessive swirls in the intake flow can impose imbalance loading to the impeller and even bring resistance to the impeller rotation by introducing swirl rotation in the opposite direction [4]. Due to site condition and operational restrictions, optimal sump design may not be achieved, and therefore local flow correction devices are used as remedial measures.

These devices which are commonly known as anti-vortex device (AVD) come in different shapes and sizes, depending on its application. The conceptual design of

AVD is outlined in ANSI/HI 9.8-2018 [5] standard which is a guideline to assist engineers and designers in optimal intake sump design. Among the AVD types employed in real applications are floor splitter [6], floor cone [7] and corner fillet [8]. These AVD types serve the purpose of eliminating submerged vortices formed at the sump floor. Floor splitters are the most widely used AVD type due to its effectiveness in eliminating vortices and reducing vorticity in the pump intake flow. There are two versions of floor splitter, namely the prism and the plate types. The use of plate type floor splitter is favourable in many applications due to its fabrication friendly-feature and economic design [9]. However, there are a limited number of articles in the literature which discuss the features of floor splitter plate in detail. In this chapter, the characteristics of swirl angle reduction of a floor splitter plate installed in pump sump are studied.

2. Methodology

The study was carried out by both experimental and numerical approaches. A single intake pump sump model, as shown in **Figure 1**, was utilized for the study in which the sample of a floor splitter was installed beneath an intake suction pipe in the sump model. The layout of the sump model test section and the dimensions of the floor splitter installed is illustrated in **Figure 2(a)** and **(b)**, respectively.

2.1 Swirl angle measurement

The main objective of the study is to evaluate the swirling motion in the intake pipe and associated with submerged vortex without and with the installation of floor splitter plate. Initially, the experiment was conducted without the installation of floor splitter plate to capture the initial conditions of the setup. The measurement of the intensity of swirl in the intake pipe was performed according to the procedure described in ANSI/HI 9.8-2018 standard for pump sump model test. The parameter used to quantify the measurement data is the swirl angle θ which is defined in the following equation:

$$\theta = tan^{-1}\left(\frac{\pi dn}{v}\right) \quad (1)$$

where d is the inner diameter of the intake pipe, n is the revolution count of the measurement instrument called the swirl metre and a is the average axial velocity at the location of the swirl metre. The swirl metre consists of a shaft with four straight

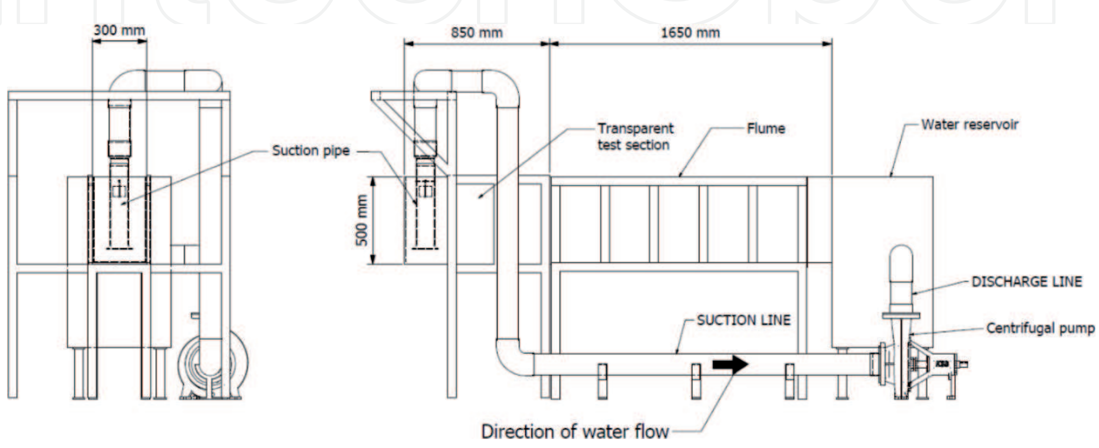

Figure 1.
The experimental rig.

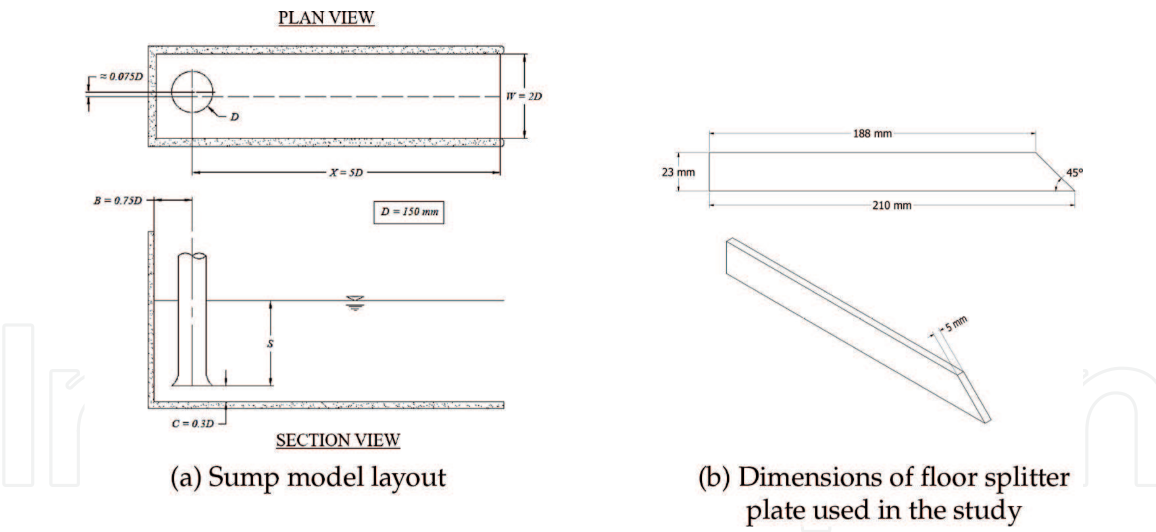

Figure 2.
Main dimensions of the sump model and splitter.

blades used to capture the swirling motion in the intake pipe, and the revolution count of the swirl metre blade is measured using a tachometer. **Figure 3** shows typical swirl metre installation according to ANSI/HI 9.8-2018 standard. Basically, θ is the convention for describing the ratio between the axial velocity and the tangential velocity of the intake flow which characterizes the intensity of the swirling motion in the fluid. The acceptance criteria according to ANSI/HI 9.8-2018 is that the swirl angle must be lower than 5° to prevent excessive swirl in the intake flow.

In order to generate the submerged vortex, the clearance under the pipe was set to 0.3 times the diameter of the inlet D and two types of flow conditioners

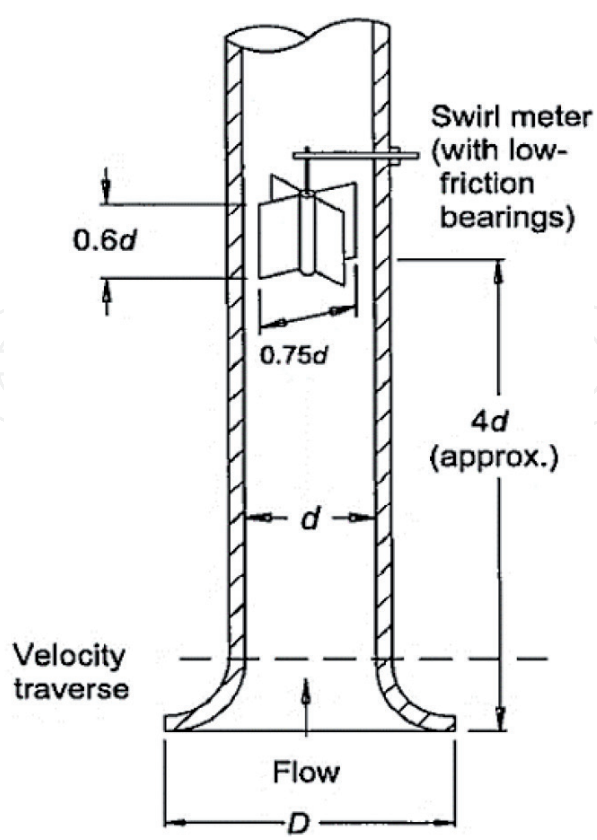

Figure 3.
Swirl metre installation according to ANSI/HI 9.8-2018 standard.

were installed: a sloped floor with an inclination angle of 30° and a sloped wall with the same inclination angle. These flow conditioners were installed at a distance of about 5D from the centre of the intake pipe as shown in **Figure 4(a)** and **(b)**, respectively. The measurement was conducted in a range of pump submergence levels which are normalized by the minimum inlet submergence S_{min}, a threshold value before the occurrence of a surface vortex. S_{min} is calculated by the following equation:

$$S_{min} = D(1 + 2.3Fr_{in}) \tag{2}$$

Fr_{in} is the Froude number at the pipe inlet and is given by:

$$Fr_{in} = \frac{v_{in}}{\sqrt{gD}} \tag{3}$$

where v_{in} is the flow velocity at the inlet and g is the gravitational acceleration. The range of the dimensionless parameter S/S_{min} was set between 0.8 and 1.2.

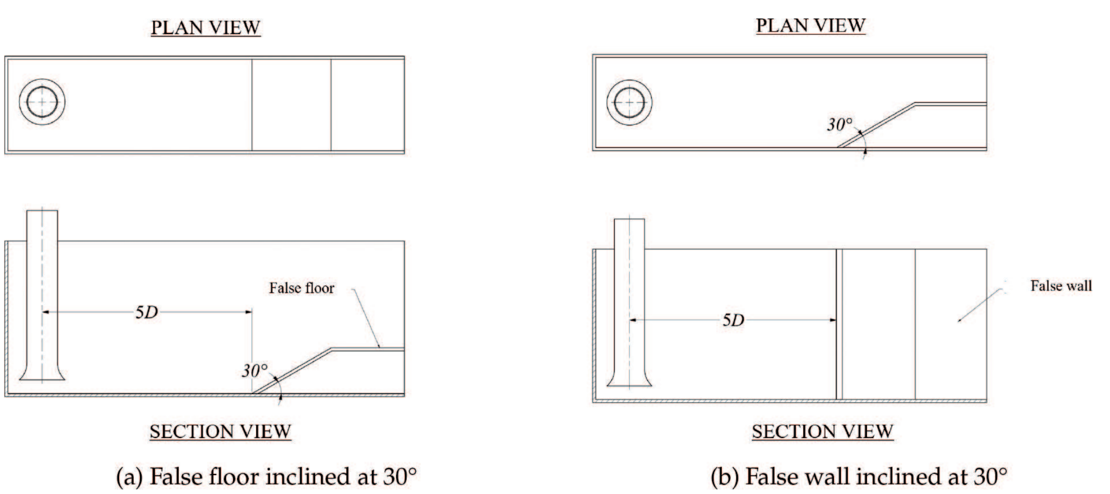

Figure 4.
False floor and false wall arrangements.

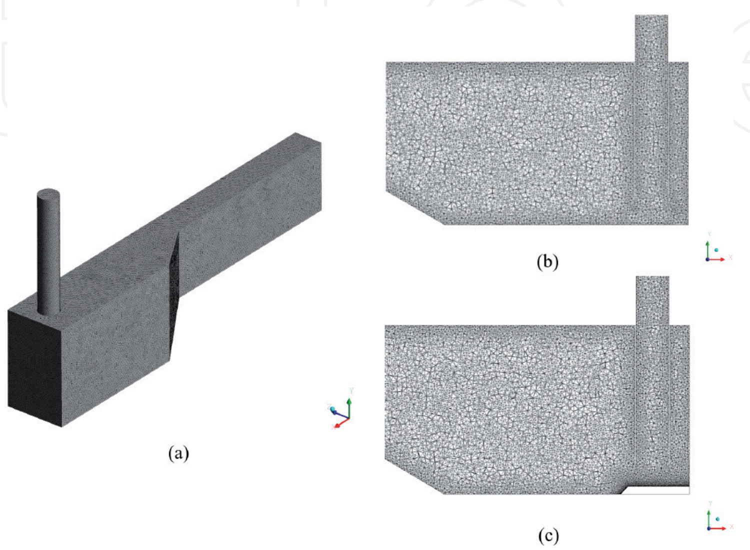

Figure 5.
Numerical model of the full-scale pump sump; (a) the computational domain, (b) model without floor splitter plate, (c) model with floor splitter plate.

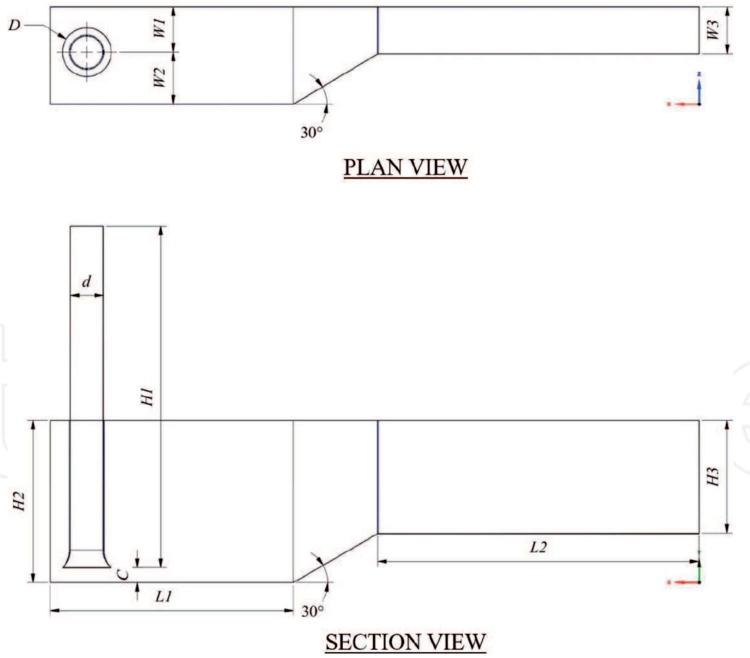

Figure 6.
Dimensions of the full-scale model.

Parameter	Dimension (mm)
Inlet diameter *D*	1275
Pipe diameter *d*	850
Right side distance *W*1	1190
Left side distance *W*2	1360
Water entrance width *W*3	1275
Intake pipe height *H*1	9350
Sump height *H*2	4250
Water entrance height *H*3	2975
Floor length *L*1	6375
Water entrance distance from sloped floor *L*2	8417
Clearance *C*	382.5

Table 1.
Dimension values of the full-scale model shown in **Figure 6***.*

2.2 Numerical simulation of flow in full-scale pump sump

The numerical approach part of the study is set for the simulation of the flow in a full-scale pump sump. As the construction cost for a full-scale pump sump cannot be afforded, a computational fluid dynamics (CFD) simulation was employed as a replacement. The numerical model was validated with experimental data and incorporated with a combined flow conditioner that consists of inclined floor and inclined wall as the ones used in the experiment and built at a scale of 9:1. The flow rate of the pump was set to 2170 l/s, and the pump submergence took the value of S_{min} which is, after the calculation by using Eq. (2), equals to 2678 mm. The mesh structure and the dimensions of the full-scale pump sump are illustrated in **Figures 5** and **6**, respectively, while the values of the model dimensions are listed in **Table 1**.

3. Results and discussion

3.1 Swirl angle evaluation

Figures 7 and **8** show the distribution of swirl angle values at different submergence ratios in the case of false floor and false wall flow conditioner, respectively.

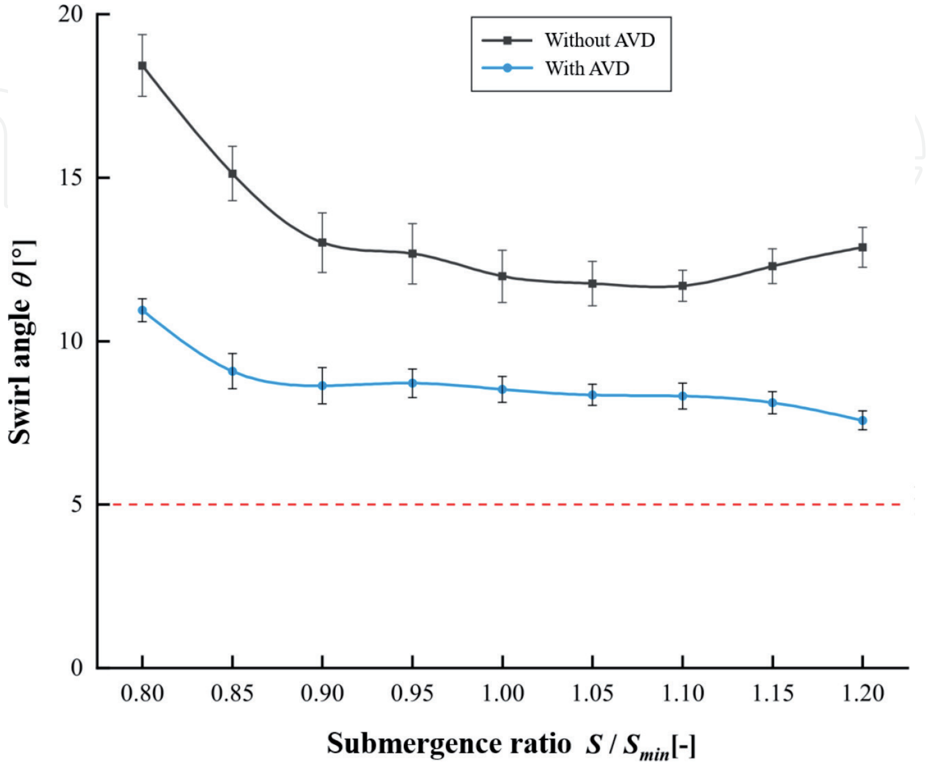

Figure 7.
Swirl angle values at different submergence ratios for the false floor case.

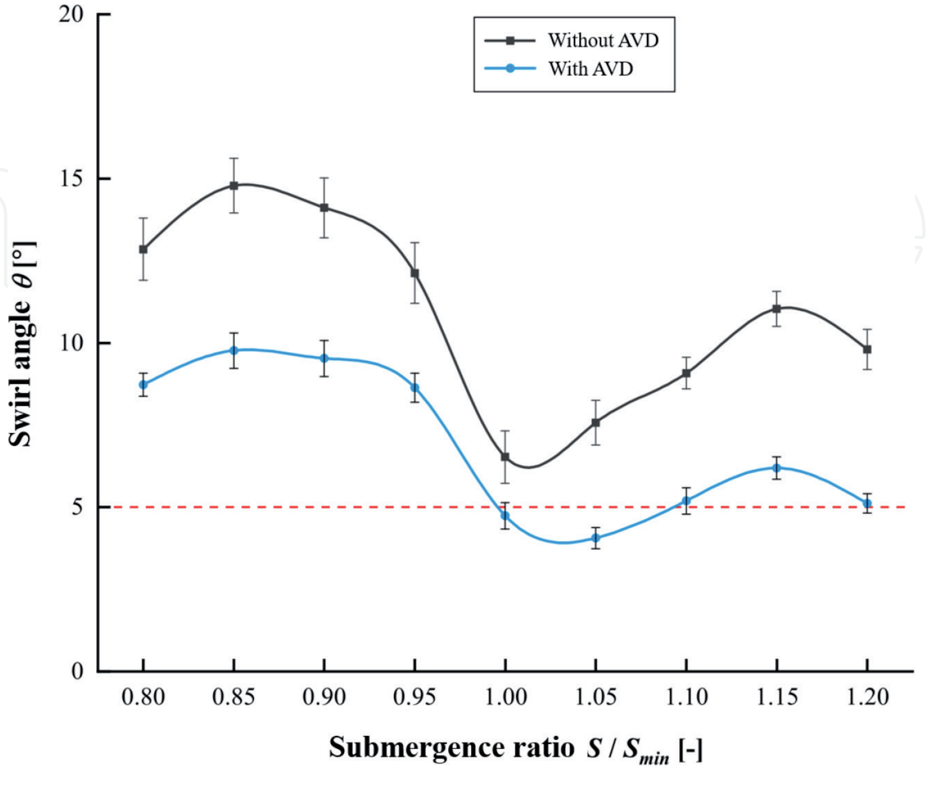

Figure 8.
Swirl angle values at different submergence ratios for the false wall case.

Generally, the installation of floor splitter plate has shown reduction in the swirl angle values. The parameter that can be used to characterize the reduction effect of the floor splitter plate is the swirl angle reduction factor R_θ which is defined as follows:

$$R_\theta = \frac{\theta_{withoutAVD}}{\theta_{withAVD}} \tag{4}$$

In this experiment, the average value of R_θ for the false floor case is 1.53, while in the false wall case, the average value of R_θ is 1.62. In **Figure 7**, the swirl angle values show a decreasing trend with increasing submergence ratio for S/S_{min} greater than 1 when installed with floor splitter plate. This is due to the fact that for S/S_{min} greater than 1, there was only a submerged vortex present in the sump. As the function of floor splitter plate is to eliminate submerged vortices, this result proved that the installation of floor splitter plate has served the purpose. When S/S_{min} is decreased below 1, the swirl angle values increase with decreasing submergence ratio. The inception of free surface vortex at S/S_{min} below 1 has caused bigger fluctuation in swirl angle as can be seen in the larger uncertainties within this region. The higher swirl angle values are contributed by the increase in approach flow velocity at lower water levels. The floor splitter vortex has shown limited swirl angle reduction effect if the submergence ratio is decreased below 1.

In **Figure 8**, the swirl angle values show a sinusoidal trend with increasing submergence ratio for S/S_{min} greater than 1 when installed with floor splitter plate. The trend is contributed by the inception of free surface vortex at S/S_{min} greater than 1. Although the theory behind the minimum inlet submergence S_{min} is that there should be no free surface vortex formed in the sump if the submergence S is greater than S_{min}, this deviation from the theory was contributed by the use of false wall in which the flow has been prerotated at the beginning of the sump. The prerotation has therefore caused the flow to develop a free surface vortex earlier than expected. In the experiment, this situation occurred at $S/S_{min} = 1.15$. As the swirl angle decreases when S/S_{min} decreases below 1.15, the reduction effect of the floor splitter plate can be observed in the decreasing trend of the swirl angle values. Similar to the case of false floor, the swirl angle increases as the submergence ratio decreases due to the increasing approach flow velocity at low water levels.

Despite the swirl angle reduction effect of floor splitter plate, the fulfilment of the requirement of swirl angle reduction below 5° has not been achieved for most of the cases. In the case of false floor, there is no submergence ratio value at which the swirl angle has been reduced below 5°; however, for the false wall case, the reduction of swirl angle values below 5° can be seen between $S/S_{min} = 1.00$ and $S/S_{min} = 1.05$, i.e. the requirement for all submergence ratios when installed with floor splitter plate. This result shows that there is a limiting factor that prevented the swirl angle reduction below 5° and that factor lies on the design of the floor splitter as suggested by Kang et al. [9].

3.2 Simulation of flow in full-scale pump sump model

The first part of the discussion on the result of simulation of flow in full-scale pump sump model is about the vortex elimination by the installation of floor splitter plate. The evaluation is based on the vorticity in the y-axis ω_y due to its influence on the swirling motion of the flow. The value of ω_y is normalized by the ratio of velocity in the suction pipe and the pipe inner diameter ν_d/d. **Figure 9** shows the cross section along x-y plane in which the evaluation of the result in the streamwise direction takes place and its corresponding results which are shown in **Figure 10**.

From **Figure 10**, it can be observed that the core of the vortex, indicated by the high-intensity region extending from the floor towards inside of the pump, has

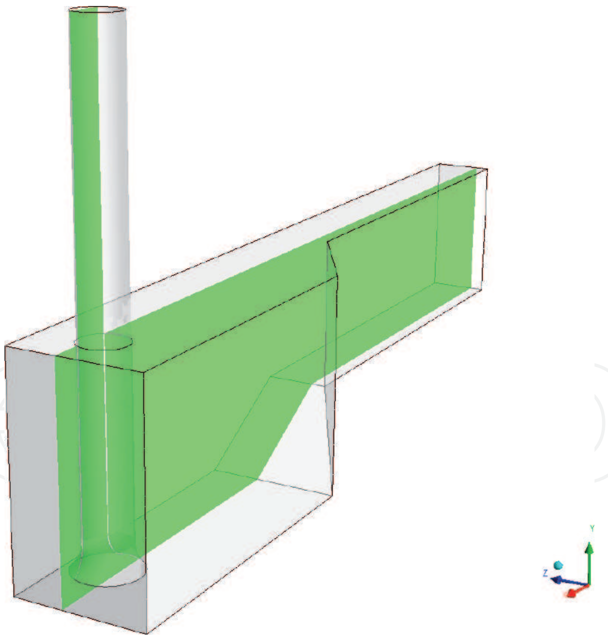

Figure 9.
Evaluation area in x-y plane of the pump sump model (z = 1600 mm).

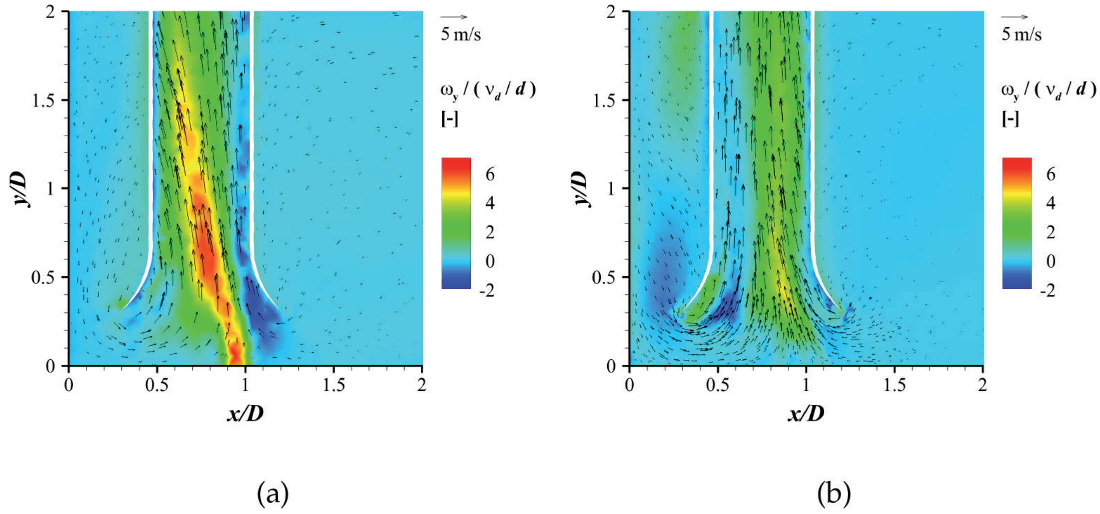

Figure 10.
Contour plot of ωy/(vd/d) at the location of vortex in x-y plane; (a) without floor splitter plate, (b) with floor splitter plate. Dashed circular lines denote pipe diameter.

been eliminated with the installation of floor splitter plate. The vorticity in the pipe has also been reduced which can be seen from the contour colors. The velocity vectors, which appear to point diagonally to the left indicating a strong swirling flow in the pipe, have been straightened in a direction vertically upward towards the direction of suction when installed with floor splitter plate.

When observing the cross section in the spanwise direction (in the plane illustrated in **Figure 11**), similar results are presented. Basically the flow that enters the pump is divided into two regions, namely the right side and the left side flow, due to the geometry of the sump. The flow entrance velocity from the right and the left side of the inlet are nearly the same because of the nearly symmetrical positioning of the pump. The flow entered the pump in a spiral manner without the installation of floor splitter which resulted in vortex formation near to the left side of the pump. When installed with floor splitter plate, the flow is reorganized, and therefore the spiral motion of the flow has been reduced and hence the vortex eliminated. This situation is reflected by the discontinued vortex core shown in **Figure 12** with the installation of floor splitter plate.

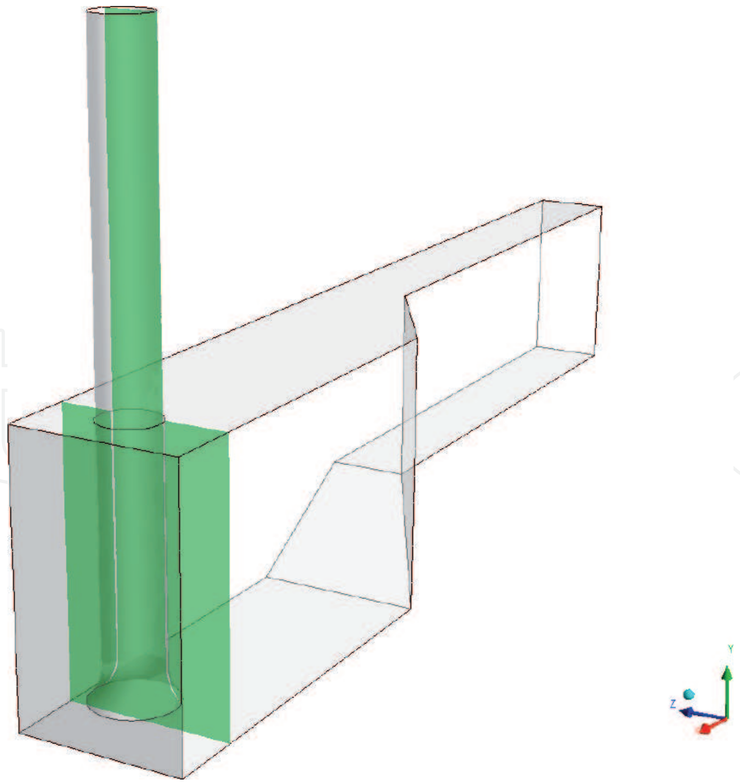

Figure 11.
Evaluation area in y-z plane of the pump sump model (x = 15,860 mm).

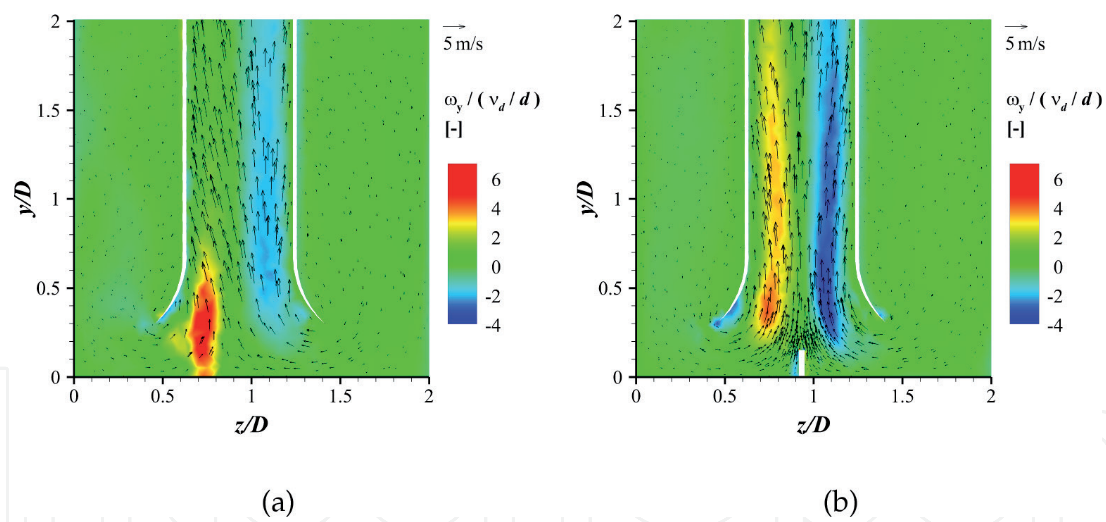

Figure 12.
Contour plot of ωy/(vd/d) at the location of vortex in y-z plane; (a) without floor splitter plate, (b) with floor splitter plate.

As the main function of floor splitter plate is to eliminate vortices formed at the sump floor, an evaluation about the vorticity in the plane at the sump floor is necessary. This location is shown in **Figure 13**. The vortex core is indicated by the spiralling streamline under the pump inlet which can be seen in **Figure 14** in the case without floor splitter plate. As the floor splitter plate was installed, the path of the spiral streamline was interrupted by the plate, and therefore the formation of vortex was prevented. Due to the suction by the pump, a small vortex attached to the side of the floor splitter plate was formed which is inherited from the flow without floor splitter plate as shown in **Figure 14(b)**. However, this vortex constitutes a much smaller vortex core diameter (estimated to be less than 0.1D based on the scale at the x-axis of the graph) and relatively weak compared to the large vortex

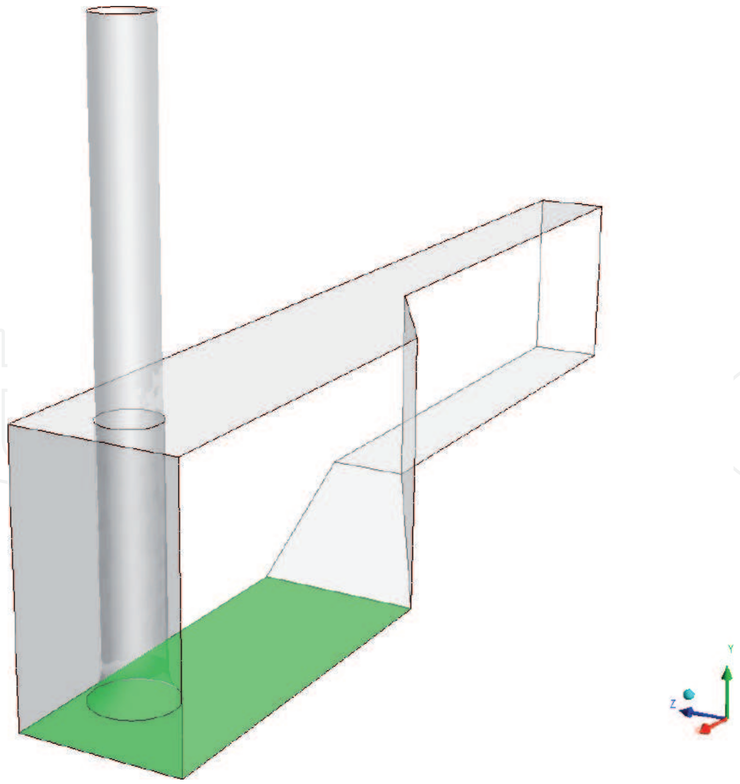

Figure 13.
Evaluation area in z-x plane of the pump sump model (y = 10 mm).

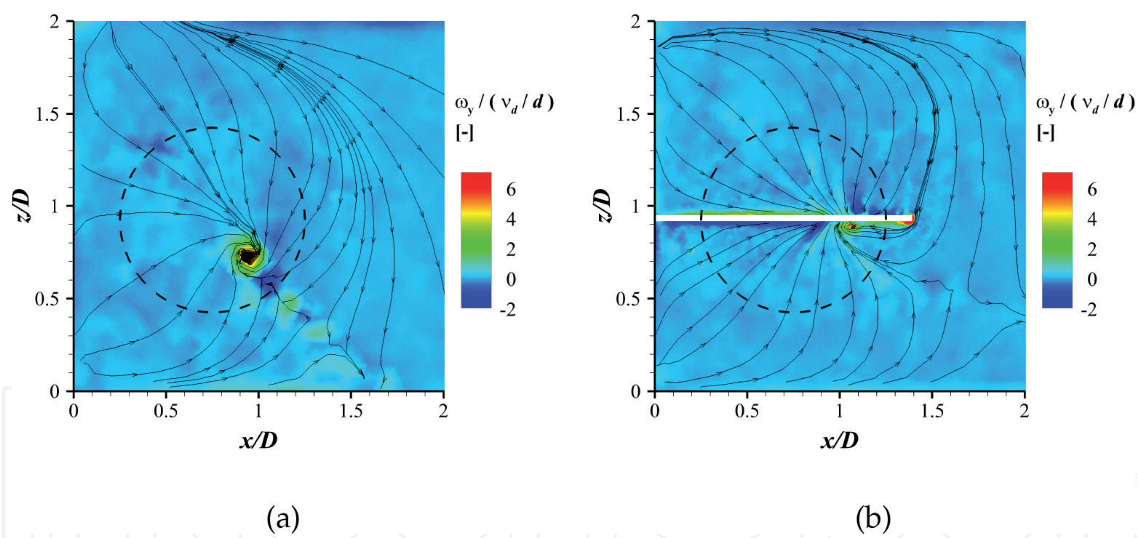

Figure 14.
Contour plot of ωy/(vd/d) at the floor of the sump in z-x plane; (a) without floor splitter plate, (b) with floor splitter plate.

(estimated to be about 0.2D) which can be seen in **Figure 14(a)**, and therefore it can be considered as nondestructive to the pump impeller.

The next part of the evaluation is about the swirl angle reduction characteristics of floor splitter plate installation. For this purpose, an evaluation plane was selected at the position comparable to the installation of swirl metre in the experimental model. The location of the plane is shown in **Figure 15**, and its corresponding results are displayed in in **Figure 16**. The flow at the swirl metre location was rotational with relatively high velocity components as indicated by the velocity vectors. The two visible vorticity regions show the divided inflow field in the pipe as explained in the previous paragraph which is considerably high in reference to the value of ν_d/d as shown in **Figure 16**. With the installation of floor splitter,

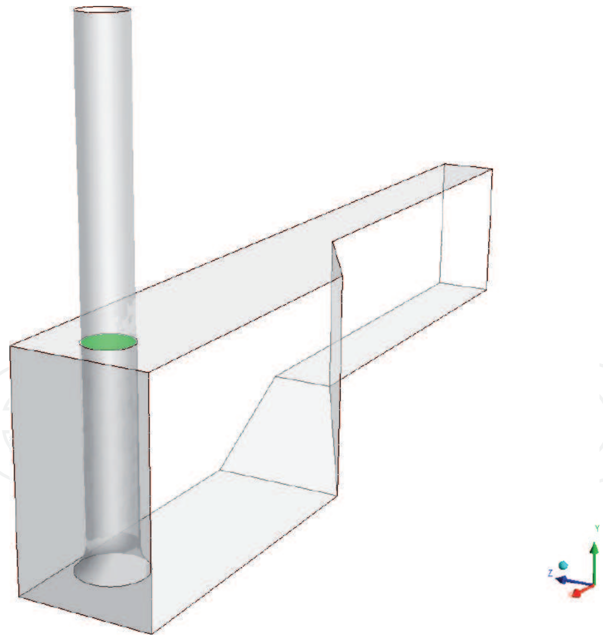

Figure 15.
Evaluation area at the position of swirl metre in z-x plane of the pump sump model (y = 4250 mm).

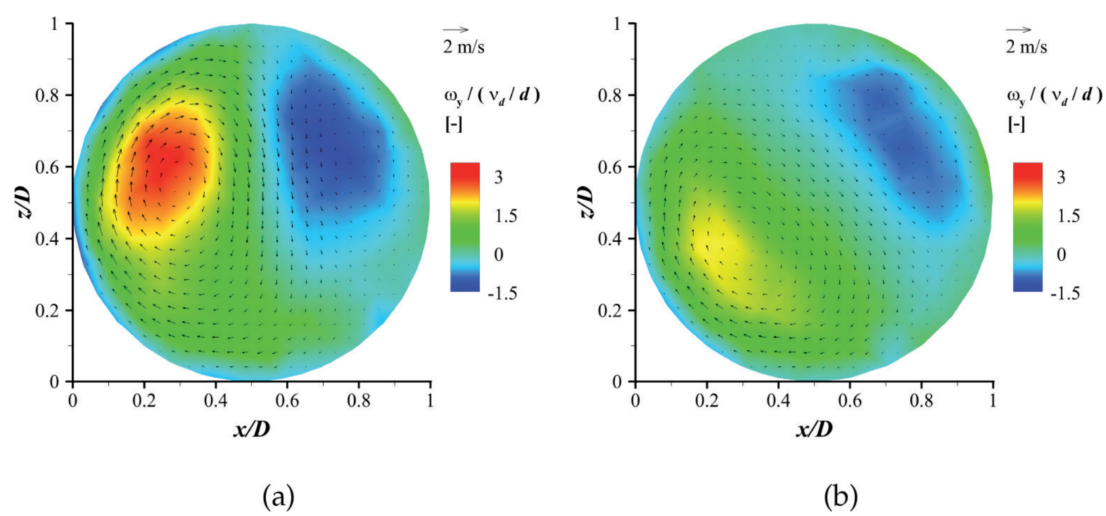

Figure 16.
Contour plot of ωy/(vd/d) at the swirl metre position in z-x plane; (a) without floor splitter plate, (b) with floor splitter plate.

the magnitude of both vorticity regions is significantly reduced and the resulting velocity vectors are also smaller in size compared to the case without floor splitter. This indicates that the spiral flow has been dissolved by the floor splitter plate into a relatively straight flow and the outcome is consistent with the experimental result presented in the previous subsection.

To get a better understanding about the result, a 3D streamline visualization of the intake flow in the sump is illustrated for every case as comparison in **Figure 18**. It can be seen that the intake flow was spiral before the installation of floor splitter plate and as the floor splitter was installed, the spiral motion of the flow was dissolved and went into a relatively straight path. Quantitative values can also be extracted from the result to obtain the associated swirl angle values. The approach for the calculation of swirl angle from the simulation results is based on the principle of Eq. (1) itself where by definition the swirl angle is the angle between the velocity components of the intake flow in the axial and tangential direction. From Eq. (1), the term πdn represents the tangential velocity component, while the term v represents the axial velocity

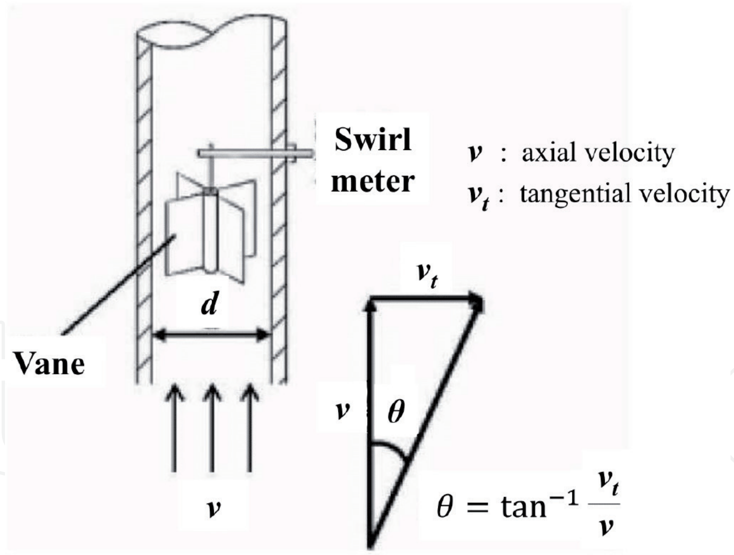

Figure 17.
Swirl angle definition using velocity triangle diagram as shown in Kang et al. [9].

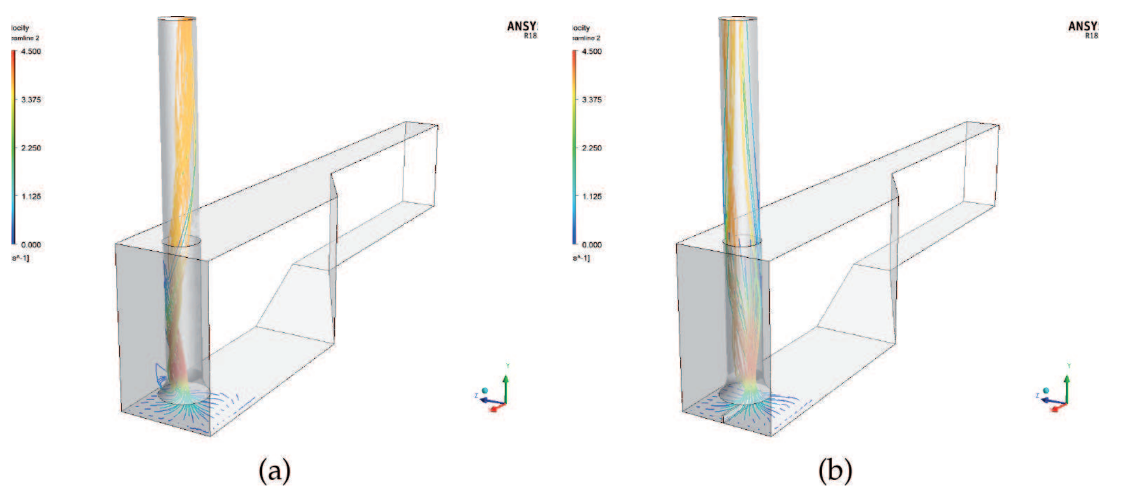

Figure 18.
3D streamline plot showing the intake flow in the sump with the seeding of the flow starts at the floor of the sump; (a) without floor splitter plate, (b) with floor splitter plate.

component; both are at the location of the swirl metre used in the experiment. **Figure 17** shows the velocity triangle diagram which shows the relationship between swirl angle and both of the velocity components in a schematic representation.

Based on this approach in Eq. (1), the velocity components in the axial and tangential direction were derived from the simulation results. As the result was given in vorticity values, the tangential velocity component must be derived from the angular velocity which equals to half of the vorticity [10]. The vorticity of the flow at the position of the swirl metre is calculated by the integration of the vorticity in the plane and divided by the cross section to obtain the vorticity value per unit area. After getting the value of angular velocity, the following correlation is used to calculate the tangential velocity:

$$\nu_t = r \cdot \omega_y \quad (5)$$

The method to derive the value of axial velocity component from the results was based on the same principle in which the integral value of axial velocity component in the plane was extracted and divided by cross-sectional area of the pipe at the swirl metre location to get the velocity per unit area. The reason of performing integration to find the velocity values is that the swirling motion of the intake flow in the pipe constitutes a solid body rotation and the swirl angle value describes the rotation body as a whole [1], and this is where the integration of the velocity across the cross-sectional area becomes the most practical way of calculating the swirl angle in the simulation. After obtaining both velocity values, the swirl angle was then calculated using the velocity triangle diagram as shown in **Figure 17**.

By following the described procedure, the swirl angle value for the case without floor splitter plate installation is 7.58°, while for the case with floor splitter plate, the swirl angle value is 4.09°. Although these values are based on average velocities as the simulation was conducted in a steady-state simulation and therefore are much smaller than the actual swirl angle values, it can be considered as adequate because they are used for comparison purpose and not for the determination of absolute values. Once again, the results are in agreement with the experimental data. This study complements a previous experimental investigation in which the effects of floor splitter heights have been analysed [11].

4. Conclusions

A study on the application of vortex control principle at pump intake was carried out by using an anti-vortex device type called the floor splitter plate. The device was installed in a pump sump model to eliminate vortices formed at the intake and reduce the swirling motion in the intake pipe as a method to improve pump efficiency in actual applications. Evaluation of the effect was conducted based on experimental and numerical approaches. The experimental part comprised swirl angle measurement which was performed according to ANSI/HI 9.8-2018 standard. To complement the results obtained in the experiment, a numerical simulation of the flow in a full-scale pump sump was conducted. The results showed that the installation of floor splitter plate has successfully eliminated the vortex formed at the sump floor and reduced the swirl angle in the intake flow. However, the reduction effect was not sufficient to achieve the criteria set in the ANSI/HI 9.8-2018 standard which requires the swirl angle to be less than 5°, and therefore optimization of the floor splitter plate design is needed. The simulation of flow in a full-scale pump sump produced similar findings with the experimental results. From the contour and streamline plot, it was found that the immersion of the floor splitter plate has disrupted the vortical flow under the pump inlet and provided a flow straightening effect to eliminate destructive vortices and reduce swirl angle in the pump intake.

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Author details

Zambri Harun[1*†], Tajul Ariffin Norizan[1†] and Wan Hanna Melini Wan Mohtar[2†]

1 Department of Mechanical and Manufacturing Engineering, Faculty of Engineering and Built Environment, National University of Malaysia, Bangi, Malaysia

2 Department of Civil Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, Bangi, Malaysia

*Address all correspondence to: zambri@ukm.edu.my

† These authors contributed equally.

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