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Free surface vortices at hydropower intakes: – A state-of-the-art review

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ABSTRACT

For years, the study of free surface vortices at hydropower plant intakes has been a topical and intriguing subject among engineers and researchers. This subject will continue to attract attention especially as the world strives to meet the ever-increasing demand for energy. Despite the numerous benefits associated with hydropower, the sustainability of some hydropower plants is being threatened due to low inflows often associated with climate change. Free surface vortices associated with low water levels or submergence at plant intakes can have very detrimental consequences on the operation of hydropower plants if not addressed. Notwithstanding this, free surface vortex flows have also been found to be very relevant in emerging technologies such as the water vortex hydropower plant system. This paper, therefore, presents a state-of-the-art review of the subject including summarised historical findings, but with an emphasis on current developments, findings and research gaps to guide practitioners and researchers. In response to the research gaps identified, the authors make a number of recommendations for further studies which include establishing relationships between free surface vortices formation and turbine efficiency, development of more accurate models for critical submergence and free surface vortices, assessment of free surface vortices at multiple and multi-level intakes, establishing the relationship between free surface vortices and sediment transport at intakes, application of Computational Fluid Dynamics (CFD) shape optimization tools for intake and anti-vortex device optimisation, as well as the continuing development of CFD tools to simulate air-entrained vortices at hydropower intakes.

Introduction

In the midst of the increasing demand for energy, which is driven by industrialisation, urbanisation and population growth, the global community has reiterated the need for sustainable, reliable, affordable and modern energy for all [32,37].

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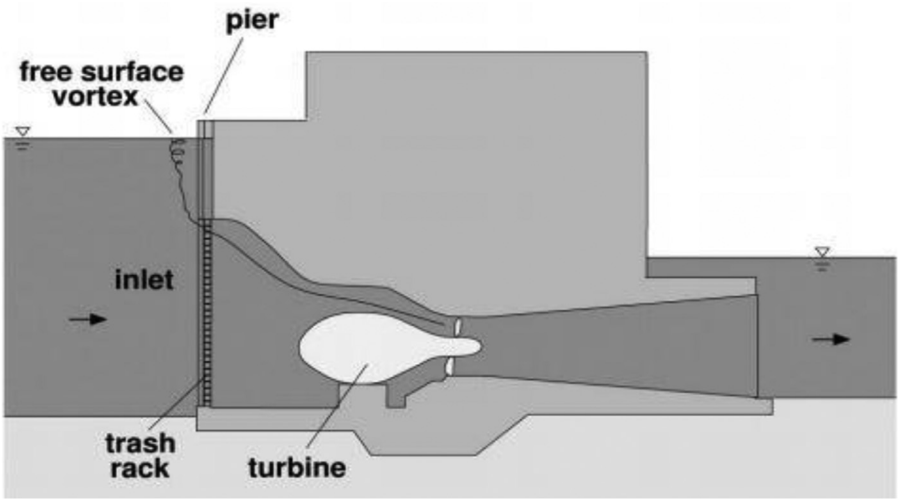

Fig. 1. . Formation of a free surface vortex and its transmission to the turbine (image from [69]).

This goal, which happens to be the United Nations Sustainable Development Goal Seven [79], underpins the significance of renewable energy sources such as solar, hydropower, geothermal, bioenergy and wind in meeting the set target [11].

Hydropower yields about 17% of the electricity generated globally and it has historically been the most common form of sustainable energy [31]. It produces 100 times less greenhouse gases when compared to conventional thermal plants, thus helping in the fight against climate change and its associated impacts [83].

On the other side of the coin, climate change has resulted in reduced inflows into reservoirs in many hydropower facilities in the world, hence threatening the sustainability of such plants [11,20]. The 1020 MW Akosombo Hydropower Plant in Ghana is a classic example of a plant that has experienced perennially low inflows, a situation which has been attributed to climate change impacts [22,26].

Low water levels or submergence, as a result of low inflows, often results in the formation of free surface vortices at hydropower plants intakes (Fig. 1), a situation which could jeopardise the plant if not addressed. Specifically, below a depth called the critical submergence, free surface vortices are initiated. Generally, a turbine intake is designed to admit a smooth transition of flow from a free surface to a pressurised penstock, but the presence of these vortices causes a swirling flow with undesirable flow patterns towards the turbine [57,69]. This situation could negatively affect the efficiency of generation, cause premature structural damages, discharge flow reduction, reduce power output, vibration, surging, reduce performance level and even sometimes result in loss of life [35,47,57,70,77,81].

This makes the specification of submergence and other intake design variables crucial during the design phase of the plant. Free surface vortices are common occurrences in low-head power plant due to low submergence and limited devices for flow alignment. However, free surface vortices can also sometimes be observed in high head power plant especially under low water level conditions [70].

Free surface vortices often form when there is an irregular transition from a free surface (open channel) into a pressurised intake [14]. According to ASCE [9], the major causes of vortex formation are, flow separation and eddy formation, nonsymmetrical approach conditions, insufficient submergence, velocity of approach flow being greater than 0.65 m/s and sudden change in direction of flow.

Notwithstanding the aforementioned issues associated with free surface vortices, free surface vortex flows have also been found to be very relevant in state-of-the-art and emerging technologies such as the water vortex hydropower plant system in which hydropower is harnessed from the activity of a strong full air-core vortex as illustrated in Fig. 2 [44].

When a fluid rotates about a common axis perpendicular to the free surface, this usually results in the formation of a region of vortex with spiral streamlines [36,47,70,81]. Mathematically, vorticity as a vector quantity is expressed as the curl of the velocity vector, $\omega = \nabla \times V$ [28,61]. This phenomenon in the flow field occurs as a result of residual angular momentum [57]. Free surface vortices evolve from the water surface along with angular momentum (swirl) enabling air entrainment [39].

Hydropower plant intakes are often horizontal or vertical. The conventional process of intake design usually involves a preliminary design to ascertain whether there is a need for a physical laboratory model study. The model study, if required, will seek to assess whether hazardous vortices are likely to occur or not. To enhance the preliminary stage of intake design, several design plots have been developed that provide information on submergence levels that avert the formation of free surface vortices. This submergence level is referred to as critical submergence. Critical submergence has generally been found to be site-specific due to the fact that it depends on the approach flow. Due to the influence of the approach flow,

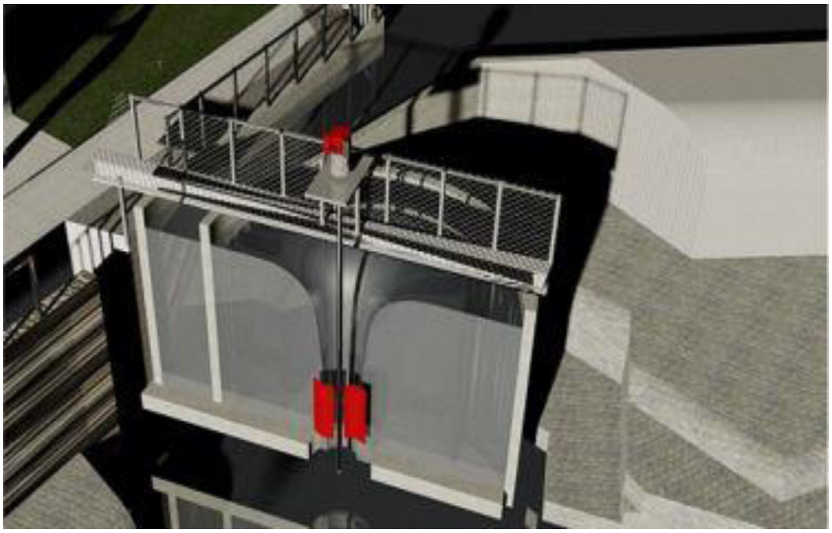

Fig. 2. . Cross-sectional 3D schematic view of a gravitational water vortex hydropower plant (image from [78]).

some designers provide a forebay to minimise high circulation close to the intake. Others also utilise anti-vortex devices to attenuate the impacts of vortices at intakes [57].

The study of free surface vortices has undergone a continuous series of fascinating and rapid developments involving experimental, analytical and numerical studies. Even though numerous studies have been done on free surface vortices at power intakes, it appears from our survey that, to date, there has been no comprehensive state-of-the-art review on the subject. This review paper, thus, seeks to provide researchers and practitioners with relevant state-of-the-art information on free surface vortices at the intakes of hydropower facilities including historical studies and developments, recent studies and findings as well as research trends and gaps for further studies.

The paper will among others seek to address the following questions:

1 Which analytical models have been proposed for free surface vortices?
2 What have been the historical findings regarding studies on free surface vortices?
3 What are the similitude considerations for experiments on free surface vortices?
4 What are the current study findings and trends regarding free surface vortices?
5 Which uncertainties and research gaps in the subject are worth researching into?

Materials and methods

A rigorous keyword-based online search method, recommended by Wilding et al. [84], was used to identify relevant literature on the subject. Our source of literature was made up of peer-reviewed journal articles that have been published on the subject globally. In accordance with the chosen methodology, the keyword search was conducted in major literature databases and library services. Furthermore, the identified papers obtained through the keyword search were further screened to obtain the relevant papers on the subject area. As suggested by Wilding et al. [84], the screening was done through thorough reading and reflection of the identified papers in order to assess their appropriateness for the subject under study.

In accordance with the requirements of this journal, articles published for the past 5 years were given high priority in the study. Those publications will be subsequently discussed in this paper. In order to enhance understanding of the subject matter, other key literature which was published outside the range of years under consideration was also included where appropriate.

The outline of this review paper consists of firstly, the different classifications of free surface vortices, followed by a brief illustration of relevant vortex models, then some discussion of dimensional analysis, design guidelines, similitude requirements for experimental studies involving free surface vortices and then lastly an extensive state-of-the-art review of the subject.

Past studies on free surface vortices at hydropower intakes

Classification of vortices

The basic behaviour of a vortex is governed by the strength of the vortex which is dictated by the circulation, $\Gamma = 2\pi rV_{\theta}$. Γ is in turn affected by the Froude number, F_r and the relative submergence, S/D as well as the reservoir geometry [65].

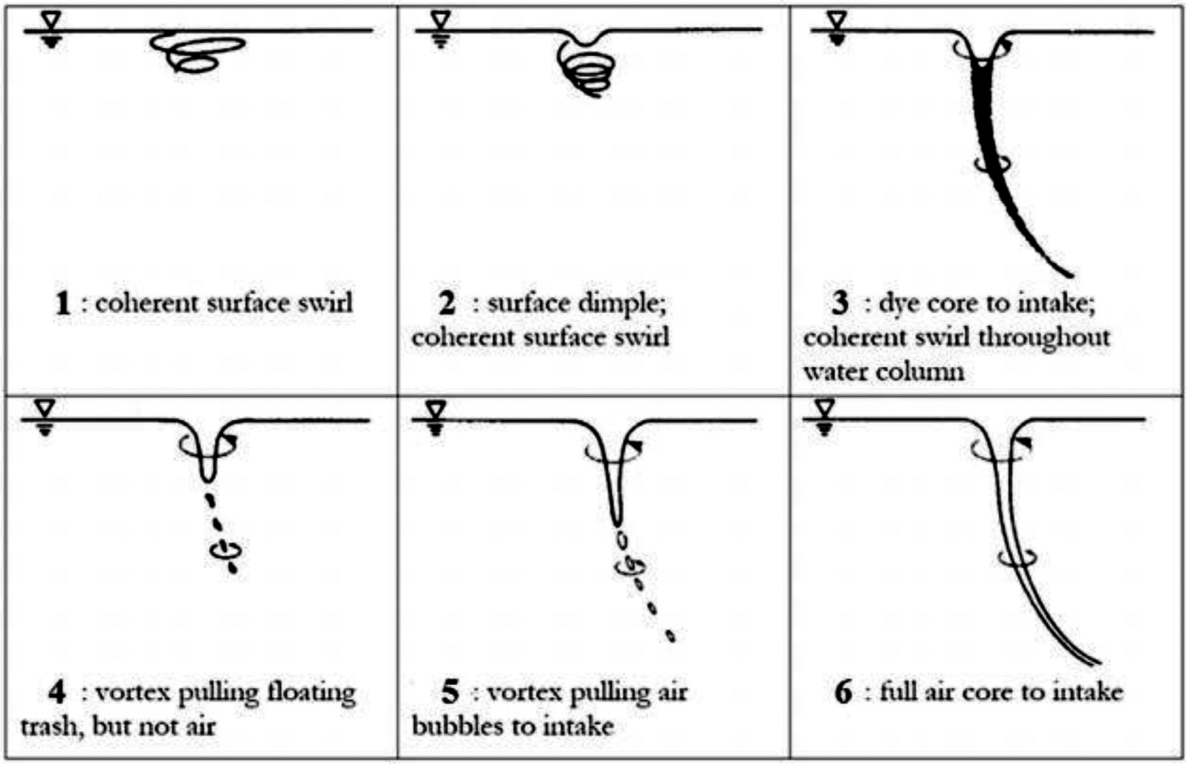

Fig. 3. . Classification of free surface vortices by Hecker [27].

However for a free surface vortex, an additional aspect of the behaviour is the possible formation of an air-core down the centreline of the vortex. Perhaps the earliest research on the classification of free surface vortices was done by researchers in Alden Research Laboratory and reported by Hecker [27]. Their study resulted in the classification of vortices into 6 vortex types with increasing intensity from type 1 to type 6 as illustrated in Fig. 3. Vortex type 1 (VT1) which appears as a coherent swirl has the least impact whilst VT6 associated with full air core has the highest possible impact on hydraulic machinery. The classification was based on the strength and evolution of the vortices [35]. Möller [39] broadened this classification to include VT0 where there is no activity at this stage.

Sarkardeh et al. [67] similarly categorise free surface vortices into three (3) main classes based on their impact on the intake:

Vortex Class A: Associated with entrained air bubbles that extend from the surface of the water to the intake. In the worst case, there is the formation of a stable air-core at the vortex centre which enhances steady transmission of air to the intake. This class is the strongest type and hence must be avoided.

Vortex Class B: Stronger strength and with vortex rotation extending downwards and towards the intake which could pull debris along.

Vortex Class C: Regarded as safe and associated with weak rotation and a slight dimple at the water surface or slight dimple.

Theoretical vortex models

Vortices occur in various artificial and natural systems such as bathtub drains, airplane trailings, swirling flows, tornadoes, tropical cyclones etc. In order to elucidate the mechanisms behind free surface vortices, many researchers have proposed physical models and related mathematical equations to describe their characteristics.

The Potential Vortex Model considers a vortex as consisting of a number of concentric circular streamlines about a point where the speed is constant along any given streamline. The speed, however, varies from one streamline to another and it is also inversely proportional to the radius from the centre. The normalised form of the Potential Vortex Model is given by Eq. (1).

$$V_\theta = \frac{1}{R} \tag{1}$$

Table 1
Vortex models.

Author (s)	Model
Rankine [55]	$V_\theta = \{^{\frac{\Gamma}{2n}\frac{r}{r_m^2}, r < r_m}_{\frac{\Gamma}{2n}, r > r_m}$
Burgers [15] and Rott [59]	$V_\theta = \frac{\Gamma}{2nr}[1 - \exp(-(\frac{r}{r_o})^2)]$; $r_o = 2(\frac{\nu}{a})^{1/2} a = \frac{\partial V_z}{\partial z}$
Odgaard [49]	$V_\theta = \frac{\Gamma}{2nr}[1 - \exp(-1.25(\frac{r}{r_m})^2)]$ $V_r = -k_1 r$ $V_z = 2k_1 z$
Vatistas et al. [80]	$V_\theta = \frac{\Gamma}{2nr_m}\frac{R}{\sqrt{(1+R^4)}}$ $\frac{H_r - H_o}{H} = \frac{2}{n}\arctan(R^2)$
Hite and Mih [29]	$V_\theta = \frac{\Gamma}{2nr_m}\frac{2R}{1+2R^2}$ $V_z = \nu_e \frac{z}{r_m^2}\frac{16}{(1+2R^2)^2}$ $V_r = \frac{-\nu_e}{r_m}\frac{8R}{1+2R^2}$ $\frac{H_r - H_o}{H} = \frac{2R^2}{1+2R^2}$
Chen et al. [16]	$V_\theta = \frac{\Gamma}{2nr_m}\frac{2R}{1+2R^2}(1 + ah_1 z')$ $V_r = \frac{-\nu}{r_m}\frac{8R}{1+2R^2}[1 + (1 + az')]$ $V_z = \frac{16\nu_e}{r_m^2(1+2R^2)^2}[\frac{(1+ah_1 z')}{a} + (1 + ah_1 z')]$ $\frac{H_r - H_o}{h_1} = \frac{2r^2}{r_m^2+2r^2}(1 + az)^2$
Wang et al. [82]	$V_\theta = \frac{\Gamma}{2nr_m}\frac{m_1 R}{1+m_2 R+R^2}$ $m_1 = 0.928$ and $m_2 = -0.7$ $V_r = \frac{-Q}{4ndr_m}\frac{4\times 0.928R}{1-0.7R+R^2}$ $V_z = \frac{-Q}{4nd}\frac{z}{r_m^2}\frac{3\times 0.928}{(1-0.7R+R^2)^2}$ $\frac{H_r}{H_\infty - H_o} = \frac{R^2+0.35R}{R^2+0.35R+1}$

where V_θ is the tangential velocity and R is the normalised radius. The main challenge associated with the Potential Vortex Model is that the vortex centre is singular in terms of the tangential velocity, axial velocity and the static pressure [50].

In order to provide a more reliable model, Rankine [55] provided a hypothesis for a vortex as consisting of an outer circulating area (free vortex or vortex field) and an inner rotating core (forced vortex or vortex core) quantified in terms of the tangential velocity V_θ. A major drawback with the Rankine Model is that at the point of transition between the free mode to a forced mode, there is the issue of discontinuity of velocity derivatives. Following the development of the Rankine model in 1858, other researchers sought to provide an improved model and one such successful model was the Burgers Model which was independently developed by Burgers [15] and Rott [59]. Their procedure assumed constant radial profiles of the azimuthal and radial velocities along the vortex axis. Based on these developments and other analytical and experimental studies, Odgaard [49], Mih [38], Vatistas et al. [80] and Hite and Mih [29] also formulated mathematical models for free surface vortices. Other related studies by Chen et al. [16] and Wang et al. [82] have also yielded a number of empirical equations to describe the vortex phenomenon. The equations proposed by the various authors to describe key vortex characteristics are summarised in Table 1.

In the equations listed in Table 1, V_θ is the tangential, V_r is the radial, and V_z are the axial velocity component, ω is the angular speed of the vortex centre, r is the radius, r_m is the radius at maximum tangential velocity, Γ is the (constant) circulation of the outer zone, ν is the kinematic viscosity, v_e refers to the effective viscosity, a is an axial gradient, k_1 is the factor of proportionality, H is the water surface elevation, H_r refers to the water surface elevation at r, H_o is the water surface elevation at the centre, H_∞ the depth unaffected by the air-core, the dimensionless or normalised radius $R = r/r_m$, h refers to the depth of the air-core as R approaches infinity, h_o is the submergence depth, h_1 is the total depth of air core, $z' = z/h_1$, Q is the discharge and d refers to the intake diameter.

Dimensional analysis

Knauss [35] defined submergence, S, as the vertical distance that stretches between the axis of the intake and the water surface. Critical submergence, S_c, defined as the depth at which the air-core vortex is formed at the intake is a function of a number of variables as given by Eq. (2).

$$S_c = f(V, D, L, \Gamma, g, \rho, \sigma, \mu) \tag{2}$$

where V is the intake velocity, D is the diameter of the intake, L is the measure of the intake geometry, Γ is the circulation, g is the acceleration due to gravity, ρ is the density of water, σ is the fluid surface tension and μ is the dynamic viscosity of water.

Dimensional analysis of Eq. (2) results in Eq. (3) for relative critical submergence, S_{rc} [8,35,67,87].

$$S_{rc} = f\left(\frac{L}{D}, \frac{\Gamma}{VD}, F_r, R_e, W\right) \tag{3}$$

Based on dimensionless groups including the Froude number, $F_r = V/(gD)^{1/2}$, Reynolds number, $R_e = VD/\nu$ and intake Weber number, $W_e = V(\rho D/\sigma)^{1/2}$ which are thus important parameters [43].

In an attempt to elucidate the occurrence of vortices at intakes, many researchers have provided a number of relational equations between the relative critical submergence, S_{rc} and other dimensionless parameters such as Froude number (F_r) and Reynolds number (R_e). In most physical modelling studies, F_r has been employed as the basis for the studies [8]. F_r is also considered by researchers as the most prominent parameter for vortex intensity [7,33].

Critical submergence and design guidelines

From our literature survey, it appears that different researchers viewed critical submergence (S_c) from a different perspective. According to Jain et al. [33], it represents the smallest depth required to avoid the formation of strong and problematic vortices. Odgaard [49] specified S_c as the depth at which the tip of the air-core vortex just reaches the intake. Naderi et al. [47] on the other hand considers it to be the submerged depth between the free surface and intake at which the air-entrained vortex can be clearly noticed. Sarkardeh et al. [67] view critical submergence as the minimum depth that prevents the formation of air-core vortices. From the definitions given by the various authors, it therefore appears that the general consensus on the definition of critical submergence is that the associated vortex must be clearly noticeable and also must have entrained air.

The design of the configuration of the intake depends on multiple factors which include the purpose of the intake and the dam's configuration [57]. In order to ensure a near-perfect upstream flow at intakes, Prosser [52], provided a number of recommendations for the design of intakes as well as the specification for submergence at the intake. For horizontal intakes, the study recommended a 1.5D submergence. Prosser [52] stressed the need for a hydraulic model assessment if there is any deviation on approach flow from the recommendations he provided. Perhaps the earliest design criteria for the design of intakes of hydropower plants was developed by Gordon [24] using data from 29 hydropower intakes. The study yielded Eq. (4) which provides an enveloped region.

$$S = CVD^{0.5} \tag{4}$$

where the coefficient, C is 0.3 and 0.4 for symmetrical and asymmetrical approach flow conditions respectively. When substituted into Eq. (4), one obtains the lower and upper boundaries of the envelope. A major drawback to this criteria is the generic applicability of this guideline in the sense that the parameters used were not dimensionless. Also, only 4 of the installations used to collect data to develop the guideline had vortex challenges.

Based on the results reported in literature and data from Gordon [24], Reddy and Pickford [56] developed a dimensionless intake design graph and design equations Eqs. (5) & (6), where Eqs. (5) & (6) refer to the lower and upper bands respectively. The researchers observed that above the line described by Eq. (5), most intakes experienced free surface vortices implying that critical submergence ought to be always greater than F_r. It was also observed that all critical submergence data were found to lie within the upper band (Eq. (6)) and the lower band (Eq. (5)). The authors highlighted that in the presence of anti-vortex devices, intakes described by Eq. (5) will not experience free surface vortices, and also both equations are only valid in situations where upstream structures do not induce swirl.

A major constraint associated with these findings is that the study lumped together data from both horizontal and vertical intakes without any segregation.

$$\frac{S}{D} = F_r \tag{5}$$

$$\frac{S}{D} = 1 + F_r \tag{6}$$

Humphreys et al. [30] provided a design plot of dimensionless submergence versus intake Froude number based on an experimental study of a vertical intake without a bellmouth. Based on the developed envelope on the graph, the authors postulated that if the dimensionless submergence (S/D) is greater than the square of the intake Froude number, the intake flow will not generate free surface vortices [57].

Based on these historical developments, it became necessary for further research studies to bridge the knowledge gap on intake designs. As a result of this, many of the succeeding research studies aimed at predicting the critical submergence to guide the design of intakes.

Regarding the prediction of critical submergence of intakes, a number of researchers have proposed different empirical equations. Based on physical and experimental model studies, some researchers have proposed equations for S_c in terms of the Froude number, tunnel velocity, v, and tunnel diameter, D. The equations are presented in Table 2.

In Table 2, c is an empirical coefficient that ranges between 3.3 to 3.95. Sarkardeh et al. [67] proposed the relation for critical submergence for Vortex Class A with headwall slope 1: Z. For valid results, Z must range beween 10^6 and 10^{-6}.

Scale effects

The utilisation of reduced-laboratory scale models instead of actual prototypes presents a cost-effective approach for engineers, but results from scaled-down models are only valid within certain limitations. This is as a result of the fact

Table 2
Summary of equations for predicting critical submergence at intakes.

Author (s)	Model
Gordon [24]	$(S_c/D) = 2.3 \times F_r$
Amphlett [4]	$(S_c/D) = c \times F_r^{0.5} - 0.5$
Knauss [35]	$(S_c/D) = \{^{\quad 1.5,\, F_r < 0.5}_{2 \times F_r + 0.5,\, F_r > 0.5}$
Sarkardeh et al. [67]	$(S_c/D)_A = 2(1/Z)^{0.008} F_r^{0.334}$
Denny and Young [18]	$(S_c/D) = 0.151 + 0.305\nu - 0.01\nu^2$
Nagarkar et al. [48]	$(S_c/D) = 4.4 + \nu^{0.54} \times D^{-0.73}$

that the forces that affect vortex characteristics scale differently, hence, the need to ensure thorough similarity in terms of equality of ratios of gravitational, viscous, and surface tension forces to inertia forces between the model and the prototype. In other words it is difficult to satisfy Reynolds, Froude and Weber number scaling at the same time. In most instances, one of these parameters will be used as the basis for the scaling, and the inequality of the other force ratios and their effects will be downplayed ([21,69]; b). When constructing a physical model for intake studies, similarity is often achieved by the use of the Froude law of gravity [85]. Several researchers [7,17,33] have provided suggestions on this phenomenon of scale effects and this will be discussed in the next section.

Surface tension

As already indicated, surface tension, σ is one of the factors that could influence the development of free surface vortices at intakes. Researchers have found out that beyond certain limits, surface tension has negligible impact on the formation of vortices. For instance, σ is considered negligible when the Reynolds number (R_e) is between 3×10^3 and 7×10^5 [17], when $\rho(V^2D/\sigma)$is between 120 and 34,000 for a cylinderical tank [33], when $W_e > 1.5 \times 10^4$ for horizontal and vertical intakes, but considered significant at $W_e < 1.5 \times 10^4$ only when the surface of the water is depressed [6]. Yildirim and Jain [91] also argued that the influence of surface tension is crucial at the vortex core and at low values of circulation.

Viscous effects

According to Rindels and Gulliver [57], most researchers recognise that viscous forces, in general, can be neglected at very high Reynolds number, R_e with the cut-off point for the highest R_e being variable among various authors. For instance, using a vortex tank experiment, Zielinski and Villemonte [94] found that viscous impact on vortex formation can be ignored at $R_e(defined\ as\ V(\frac{D}{\upsilon})) > 1 \times 10^3$ whilst Daggett and Keulegan [17] contend that $R_e > 3.2 \times 10^4$. Using a vortex tank experiment, Anwar [5] concluded that the impacts of viscosity on weak vortex formation can be considered as being negligible for $R_e(defined\ as\ \frac{Q}{\upsilon h})$ greater than or equal to 1000 whereas for strong vortices this limiting value is crucial. However, for a horizontal flume experiment, Anwar et al. [8] observed that the limiting value for this instance was $R_e = 3,000$.

Anti-vortex devices

The options available to address the vortex challenge at intakes once they occur are very limited. Usually, it is economically unwise or practically unfeasible to modify the approach flow conditions or the depth of the intake. This situation suggests the need for anti-vortex devices which operate through any of the following means: disrupting the angular momentum of flow, increasing the area of the outlet, or by compelling the vortices to occur in regions which hinder their formation [57].

In practice, several types of anti-vortex devices exist. Denny and Young [18] and Rutschmann et al. [60] recommended the use of racks, horizontal beams and vertical walls. Other possibilities include solid plates, funnel-shaped plates, a circular flat plate with a porous wall, perforated plates, vane-type vortex suppressors and half-cylinder walls [41,58,74].

On the use of a floating raft as an anti-vortex device, Ziegler [93] found that the best location of the raft is not the water surface but rather a small depth below the surface.

A number of studies also focused on the use of the trash rack as an anti-vortex device [1,12,93]. According to the results from Ziegler [93], the size of the trash rack screens is a dominant factor for vortex formation. In the study by Ables [1], a scaled bar with an expanded width was used to model a trash rack whereas Gwinn [25] used steel deck grating. A vertical wedge-shape anti-vortex device implemented by Song [68] was successfully able to dissipate the angular momentum. An experimental assessment of the use of intake headwall slope as well as a trash rack as an anti-vortex device was performed by Sarkardeh et al. [67] whereas Borghei and Kabiri-Samani [13] considered the use of anti-vortex plates, Roshan et al. [58] looked into anti-vortex walls, the horizontal perforated plates was assessed by Amiri et al. [3], whilst Taghvaei et al. [74] assessed the performance of 13 anti-vortex devices and concluded that the horizontal plate provided the best performance.

Recent studies on free surface vortices at hydropower of intakes

In order to provide an up-to-date review on the subject of free surface vortices at hydropower intakes, a number of recent publications have been reviewed. These publications have been summarised in Table 3. It is notable that Computational Fluid Dynamics (CFD) makes a substantial contribution to many of these publications.

Experimental and physical modelling

A number of physical and experimental studies have been undertaken by researchers with the aim of elucidating the complexity associated with the structure and dynamics of the free surface vortex. In order to better understand features in the flow field surrounding the formation of free surface vortices, flow visualisation techniques and tools such as Acoustic Doppler Velocimetry (ADV) [66,70]. Particle Image Velocimetry (PIV) [34,45,47,69,73,86] and Propeller Velocity meter [10] have been used by various authors. A drawback in the use of a point measurement technique such as ADV is its inability to provide spatial information. However, this drawback can be addressed with the use of PIV [86]. According to Wang et al. [82] and Yang et al. [86], an added advantage of using PIV is that it enables the computation of other turbulence statistics parameters such as Reynolds stresses. Yang et al. [86] used the PIV technique to derive the three velocity components of a spiral movement of an air-core vortex formed over an intake.

In most experimental studies involving flow visualisation techniques, free surface vortices were detected within the region of circulation determined by measuring the tangential velocity [10]. This shows that in general, increase in the depth of submergence often results in decreased vortex strength as well as planar velocities in the reservoir [10]. Regarding the velocity field distribution in the flow field of the vortex, a downward flow with a conical structure towards the intake is observed at the water surface whilst an upward one towards the intake is observed below the axis of the intake [10,66].

It appears from our review that conventional empirical models often used to predict the critical submergence cannot be always fully relied upon for safe intake designs. They could, however, provide some level of guidance during the initial design stage. For instance, from the comparison studies of Sarkardeh [63] and Azarpira et al. [10] on the correlation between empirical models and data from various physical modelling studies in terms of the prediction of critical submergence, the authors found significant discrepancies between empirical predictions and results from physical modelling studies. The empirical model proposed by Sarkardeh et al. [67] provided the best prediction in the case of Sarkardeh [63] whereas Azarpira et al. [10] observed that the models proposed by Sarkardeh et al. [67] and Denny and Young [18] provided the optimal results. It should be noted that the study by Sarkardeh [63] did not take into consideration the models proposed by Denny and Young [18] and Nagarkar et al. [48]. Sarkardeh [63] concluded that models that included features of the intake geometry such as proposed by Sarkardeh et al. [67] provided the best prediction of critical submergence.

On a research study on how free surface vortices are impacted by intake-entrance profiles, Yang et al. [87] concluded that the bell-mouthed intake has lower critical submergence depth compared to the square-edged shape. Also, the presence of nearby sidewalls would increase the critical submergence in the presence of weak circulation. On the impact of sidewalls, Parvaresh and Ghiassi [51] observed that the critical submergence remained the same for type 6 vortices but reduced for type 3 vortices when the angle of intake in the positive trigonometric direction was increased. Considering the constraints involved in physical modelling studies and the varied intake geometries, more studies will be required to develop more robust empirical models that take into consideration crucial elements such as the intake geometry to predict critical submergence.

An experimental research study by Möller et al. [40] provided a guideline for quantifying the amount of air entrainment as well as a methodology for determining the critical submergence which is based on air entrainment rate.

Using an experimental set-up involving two intakes, the rate of sedimentation was found to be directly proportional to the vortex strength. The inclination of the intake also influenced the quantity of sediments transported [34].

Based on a series of experimental data, Gogus et al. [23] formulated an empirical relation for the dimensionless critical submergence in terms of their key dimensionless parameters as well as the influence of scale effects on dimensionless critical submergence.

For subcritical approach flows, the circulation number surrounding a strong free surface vortex has been found to be strongly influenced by the geometry of the approach flow which is in turn characterised by a nondimensional approach flow factor. This inference was based on an experimental study involving data from the geometries of 12 scaled vortex chambers [45].

After the Akkats Power Station had been commissioned, there was an unexpected swirling flow observed at the intake caused by inadequate water level. The problem caused a number of operational challenges such as limitations in electric power output. There was therefore the need for a hydraulic model assessment to gain an understanding of the situation. Based on the understanding from the model study, the optimal countermeasure strategy which entailed the use of a segmented barrier between the dam and the intake was implemented [85].

Taylor Couette flow comparison of turbulent free surface vortex flow was extensively studied by Mulligan et al. [46] using a combination of numerical, experimental and analytical techniques. Results of the study revealed that wall-bounded free surface vortex can be rendered unstable by the centrifugal driving force comparable to the Taylor-Couette flow.

Since air entrainment at intakes is generally sensitive to geometric conditions [69], studies involving experimental testing will continue to be relevant in foreseeable future studies.

Table 3
Summary of recent publications on free surface vortices at intakes.

	Strength	Weakness
Karun III dam	The approach used in the study succeeded in establishing a relationship between the velocity field and the class of vortex formed	The plane velocity fie
	The study was able to detect submerged vortices	The study could not
	The methodology used provided a good agreement between numerical and experimental velocity field measurements	The study could not
of free surface vortices	The semi-empirical model is able to explain how the approach flow and intake geometry influence key vortex characteristics	The proposed model
	The proposed model is capable of explaining how different processes affect the scaling behaviour of the vortex characteristics	Further clarification
	The proposed model by the authors explains how vortex characteristics affect the scaling behaviour of the vortices	Further detail studies
	The study provides an approach by which the impact of intake-entrance profiles on free-surface vortices can be assessed	The direct implicatio
	An appropriate experimental approach to quantify air entrainment rates as well to determine the critical intake submergence has been provided	The influence of the
	An approach to assess the effects of submerged intake angle on the critical submergence depth was been highlighted	Vortex types 1–3 we
	The derived equation for predicting critical submergence requires only the Froude number and the circulation number	The authors admitted
	A detail investigation of the effects of hydraulic parameters on the formation of air-entraining vortices has been provided	The possibility of occ
	A means of studying the impact of vortex formation on sediment transport has been illustrated	A comparison of the
table model	A numeral approach of simulating a strong air-core vortex has been highlighted	There was a significa
onal approach flow factor	The key dependant hydraulic parameters that affect the formation of a strong free surface vortex were identified using the approach	Further measurement
	The use of numerical simulations to compare the performance of anti-vortex devices has been detailed	The study experimen
	The prediction of the critical submergence using the outlined approach does not require information on the whole boundary blockages	The method is genera
	The study revealed the unique velocity structure of an air-core vortex	Information on the t
	The method used in the study was able to reveal the impacts of free surface vortices on the net head and the flow discharge of a tidal power plant	Predicting the accura
ubmergence in relation to the jet	The proposed hydraulic anti-vortex device proved to be an efficient device for suppressing vortices at submerged water intakes	With an increase in t
	The comparison illustrated in the study provides a key guideline for the selection of an appropriate anti-vortex device	The proposed hydrau
	The results obtained on the tangential velocity, radial velocity and water surface profile agreed with the experimental and analytical solutions	The axial velocity res
	A numerical approach capable of estimating air entrainment rates as a result of intake vortices has been highlighted	Compared to the exp
ices	The study revealed the optimal models to be used to predict free surface vortices at intakes	The varying conditio
	A means to identify time-dependant “Taylor-like” vortices in a secondary flow field has been revealed	The study could not
	The jet from the hydraulic-based anti-vortex device provided an external momentum capable of preventing the formation of undesirable vortices	The jet anti-vortex d
ecision-making on the optimal solution to suppress the vortices	The study provided adequate information on using a hydraulic model to address a typical intake flow problems	The study did not loo
	A new method for determining the accurate origin of a vortex at each elevation was proposed in the study	The origin of the air-

Studies related to vortex models

Using a combination of experimental data and the Burgers Vortex Model, an analytical model was formulated that shows how the major vortex characteristics (bulk circulation, radius, depression depth and shape) relates to the geometry of the intake and approach flow conditions ([70]; a). Using this formulated model, Suerich-Gulick et al. [70] proposed an empirical relation that illustrates the influence of viscosity, surface tension and turbulence on the scaling behaviour of free surface vortices. A more recent and simple model that describes key vortex characteristics was proposed by Sun and Liu [73] using a combination of experimental and analytical studies.

Taştan [76] proposed a simplified theoretical approach for determining the critical submergence of dual and isolated intakes by ignoring the whole boundary blockage which had been previously proposed by Yildirim et al. [89], Yıldırım [88] and Yıldırım et al. [90]. The model had a good correlation with available test data.

The continuous development of new models on critical submergence and vortex characteristics through experimental and analytical studies has been motivated by the non-generic application of the models as well as the significant variations observed between experimental and theoretical results [27,73].

CFD-related studies

In practice, the conventional study of vortices has involved the use of experimental and analytical models. Whereas experimental studies have drawbacks such as being costly, laborious, time-consuming as well as issues pertaining to scale effects, analytical models have also been found to be too generic whilst free surface vortex formation in most cases is site-specific. To address some of these challenges, current state-of-the-art studies in this research area have utilised numerical study approaches through the use of CFD tools. Numerical simulation involving CFD provides cost and time-savings. The tool provides good results if appropriate simulation conditions and protocol are adhered to. Compared to physical modelling studies, CFD results can be analysed throughout the domain, hence aiding in-depth analysis [72]. Problems with simultaneous Reynolds and Froude scaling do not arise as CFD models can be set up at realistic scale if needed. Whilst the results from CFD studies require validation with experimental or analytical data, once this has been satisfactorily accomplished the studies can be extrapolated to a range of additional cases.

In CFD simulations, fluid problems are handled by solving the Navier-Stokes Equations (governing equations) of fluid flow in their discretised form, thus providing a spatial and time-dependant solution for the problem under investigation [78]. For a comprehensive review of CFD, readers may refer to Drikakis et al. [19]. Much of the complexity of flow properties involving free surface phenomenon is as a result of the impact of surface tension, gravity, buoyancy and density variation between liquid and gas [2]. As a result of this, authors generally employ the Volume of Fluid (VOF) approach to simulate the free water surface where cells filled with water are assigned a value of 1 whilst those filled with air are assigned a value of 0. Cells which are partially filled with water are given a value between 0 and 1 [54]. The evolution of the interface location is then predicted by the computation of a simple transport equation for this phase fraction α.

Rabe et al. [53], Rabe et al. [54], Sarkardeh [62] and Sarkardeh et al. [64] recommended the use of Large Eddy Simulation (LES) for turbulence modelling of air-core vortices at power intakes due to its unique capability of utilizing a spatial filtration procedure, allowing it to explicitly simulate large scale vortices in the flow. The Shear Stress Transport (SST) model has also been found to be a suitable turbulence model for the simulation of free surface vortices [2,44]. However, in a comparison study involving various turbulent models to simulate strong air-core vortices, the Reynolds stress model outperformed the SST k-ω model, though the SST k-ω model is considered robust and computationally inexpensive in comparison with the Reynolds stress model [44].

Sarkardeh [63] observed that numerical simulations were able to provide a good prediction for critical submergence. Besides this, the tool was able to demystify the entire process involved in the evolution of free surface vortices at intakes [62]. Similarly, in a study by Ahn et al. [2], a free surface vortex formed at the intake of a tidal power plant was numerically simulated and validated thus helping in assessing the vortex impacts on different operating conditions.

CFD tools have also proven to be efficacious in simulating the velocity flow field around the formation of free surface vortices as well as reproducing the spiral motion associated with the formation of free surface vortices [64].

Rabe et al. [54] performed a numerical study of the experimental work of Hite and Mih [29] using FLOW-3D and obtained a good agreement in terms of the radial velocity, tangential velocity and water surface profile of the results of the experimental study and other analytical models.

Sarkardeh [62] found a good correlation between the results of his numerical simulation and experimental study of Möller et al. [40] in terms of quantifying air-entrainment rates. An interesting finding from his study is that the critical submergence could be reduced to about 12% if an air entrainment rate ratio $\beta = 1 \times 10^{-5}$is permitted.

It was also evident from the literature survey that all the numerical studies utilised commercial CFD codes such as FLOW-3D [53,54,62,64] and ANSYS CFX [2,44]. There appears to be a gap in relation to the use of open source CFD tools such as OpenFOAM in simulating free surface vortices at power intakes. The use of open source CFD tools can result in further considerable cost-savings to designers.

With the need to factor in various critical parameters such as intake geometry into empirical models, CFD tools will be very versatile in this perspective. The tool will permit substantial adjustment of crucial geometry parameters in order to observe their impacts on the development of free surface vortices. In this regard, the use of shape optimization tools and algorithms could be the next phase of research.

Studies related to anti-vortex devices

Other authors have focused attention on studies pertaining to anti-vortex devices. Rabe et al. [53] numerically simulated the flow field towards an intake in the presence of a Prosser disc and a funnel anti-vortex device and observed good agreement with experimental data. The study concluded that the funnel type is more effective in mitigating the formation of harmful vortices compared to the Prosser device.

The submerged water jet anti-vortex device hinders the formation of detrimental vortices by providing an external momentum which alters the hydrodynamic pattern of the flow field surrounding the intake, eventually destabilizing any vortex development [41,42,75]. The device has been found to be very flexible and efficient compared to other structurally based anti-vortex approaches [42]. When $F_r$is greater than 1.3, Monshizadeh et al. [41] found out that the efficiency of this type of anti-vortex depends on the vertical distance between the intake axis and nozzle as well as the linear momentum of the jet. The authors also provided a model that is capable of predicting the critical submergence in terms of the nozzle submergence and the linear momentum of the jet. In assessing the optimal inclination of the jet anti-vortex device, Tahershamsi et al. [75] revealed that an inclination with respect to the surface of the water provided better performance. It therefore seems that the current trend in the study of anti-vortex devices is on the development of more efficient anti-vortex devices as well as their numerical simulation.

Research gaps

Although significant progress has been made in the field of study of free surface vortices at power intakes, there still appear to be certain areas of research which are either poorly understood or have not been looked into. It was revealed that all the numerical studies on the subject under consideration utilized commercial CFD codes such as ANSYS and FLOW-3D. With considerable financial savings already associated with numerical studies, the authors believe that the extensive use of open source CFD tools such as OpenFOAM for such studies would provide further significant cost savings to practitioners. Research studies involving the use of open source CFD tools to simulate free surface vortices at hydropower intakes will thus be beneficial to this course.

Engineers and researchers involved in the design and implementation of intakes and anti-vortex devices are more often than not confronted with the challenge of choosing the optimal design option that minimises the development and impacts of free surface vortices from countless choices. This selection has to be made from countless design variations based on several possible parametric shapes and prevailing conditions. One can therefore forecast that, in the future, the use of CFD shape optimisation tools such as Adjoint Optimisation will provide valuable input as well as offer time and cost-savings in attempts to perform shape optimisation of hydropower intakes and anti-vortex devices, especially during the design phase. For instance, the use of the CFD Adjoint Optimisation technique could be used to inform designers on which sections of the intake or anti-vortex device need modification and how that modification should be achieved to obtain the optimal design shape.

Even though most authors held a general consensus on the fact that free surface vortices reduce the turbine efficiency, the relationship between these two factors is either missing or not clearly spelt out.

Conventional design guidelines for intakes are based on models and experimental work from single intakes, however, some authors assert that the formation of free surface vortices will be impacted by the operation of multiple intakes working in groups and even the complexity of impact is further heightened with increase in number and in positions of intakes [81,92]. However, inadequate information still exists on the subject and hence this will be worth considering in the future.

As already indicated, analytical models on critical submergence and vortex characteristics are improved when multiple influential factors are considered. Considering the significant discrepancies that still exist in analytical and experimental results, further experimental and numerical studies in this perspective will be required to bridge the existing gap.

The impacts of vortex formation and sedimentation has received very little attention. Intake sediment transport is a crucial challenge for hydropower plants that draw water from the sea such as tidal power plant [34]. These plants are also often associated with low heads which further compounds the situation by facilitating the development of vortices [2]. Sediment transport has a number of detrimental impacts: blockage of intake, increased boundary roughness, damage to turbines and disruption to power generation etc. [34]. Despite the fact that Khanarmuei et al. [34] identified that the rate of sedimentation is directly proportional to the vortex strength, there is still insufficient information especially regarding models and interrelationship between free surface vortices, sediment transport and remedial interventions. With the expected increase in the deployment of low-head plants which are generally more susceptible to sedimentation and the occurrence of free surface vortices, further studies in this field of research will be crucial.

Conclusions and suggested areas for further research

Hydropower is undoubtedly one of the cleanest energy sources. Optimising hydropower intakes in order to address the destructive impacts of free surface vortices will continue to remain a relevant topic for engineers especially in this era of meeting the ever-increasing global energy demands as well as ensuring considerable cost savings and a sustainable environment. The challenges to this are however enormous: site-specificity and uniqueness of each hydropower project, huge cost and time constraints associated with setting up reduced scale prototype, scale effects relating to differences between models and the actual prototype, uncertainties between empirical models and experimental data, intake sediment transport, the complexity associated with the evolution of vortices as well as significant cost associated with the purchase and licensing of commercial CFD tools etc.

However, as evidenced by the findings of this paper, relentless research and the use of modern tools and technology will help to address many of these challenges and also demystify this area of research. In view of the findings of this state-of-the-art review of the subject, the authors are of the hope that significant gains and insight would be derived if the following areas are considered for further research:

1 A comprehensive study to establish the relationship between the formation of free surface vortices and efficiency of turbines
2 The continuing development of CFD tools to simulate air-entrained vortices at hydropower intakes
3 Continuous development and improvement of models for critical submergence and key vortex characteristics whilst taking into consideration the prominent influencing factors such as intake geometry
4 Free surface vortices in multiple and multi-level hydropower intake system
5 The use of CFD shape optimization tools to optimise the design of intakes and anti-vortex devices
6 Analytical, experimental and numerical study on the inter-relationship between free surface vortices, sediment transport and appropriate remedial measures.

From the above findings, the authors conclude that research studies into the occurrence of free surface vortices at hydropower intakes have had a tremendous impact on the subject. Going forward, numerical simulation involving CFD tools will continue to play a key role in the elucidation of green areas and gaps in the subject area.

Declaration of Competing Interest

None

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