GREENING MARITIME ENERGY: A SUSTAINABLE APPROACH TO HYDROPOWER GENERATION THROUGH MATHEMATICAL MODELLING IN GRAVING DOCK FLOODING

Miral Michel [(1)i], Omar K. Mahdy [(1)], Omar M. Alkholy [(1)], Kareem M. Yousef [(1)], Yousef M. Shaban [(1)], Amir M. Abu Bakr [(1)] and Ahmed S. Shehata [(1)i]

(1) Marine and Offshore Engineering, College of Engineering and Technology, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt

i) Corresponding authors: Ahmed S. Shehata, e-mail: a_samir@aast.edu
Miral Michel, e-mail: miral.michel@adj.aast.edu

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1. **ABSTRACT:** Dry docking is a common procedure for maritime vessels to enable necessary tasks including maintenance, inspection, and design changes. Since the world is becoming more dependent on renewable energy, the aim of this study is to develop a mathematical model to estimate hydropower generated from the filling process of graving docks. A thorough case study has been conducted with an emphasis on ASRY dry dock No. 1 in order to achieve this goal. By strategically placing hydroelectric turbines throughout the dry dock filling period and utilizing only the natural head difference between sea level and the dry dock level, the study aims to assess the viability and effectiveness of hydropower generation. The case results state that a cost saving of approximately 1 MW per intake line of the dock can be achieved which saves approximately 4572 kg of CO_2 emissions for the whole operation that could have been released into the environment if this power is generated using natural gas.

2. INTRODUCTION

The prevalence of maritime transport, characterized by its safety, cost-effectiveness, and efficiency, has led to a surge in the shipbuilding industry to meet the demands of international trade. Consequently, there is an escalating requirement for additional dock facilities to accommodate ship repairs and other marine operations. This surge in infrastructure development has correspondingly resulted in heightened electricity consumption within docks, concomitant with an increase in emissions. Within this industry, even a little increase in cost-effectiveness or a slight decrease in emissions can have significant consequences on the environmental and economic fronts. Dry docks are essential facilities for shipbuilding and ship repair. Graving docks are first filled with water in this operational cycle to allow a ship to enter for required repairs. Later, the ship is emptied upon docking, allowing engineers and crew to do their duties aboard. When the work is finished, the ship can leave the facility and resume its marine operations because the dry dock is filled once more. One aspect to consider when designing docks is the time it takes to fill them with water. This process involves opening the valves in the gate, allowing water to flow directly into the dock due to the disparity in the head.

The arising interest in innovative technologies with the capacity to generate electricity from sustainable sources has ignited curiosity and investment in ocean and marine research. This field holds significant potential for the future adoption of renewable energy, especially in regions characterized by essential climatic traits, there exists the potential to effectively harness substantial marine energy. Maritime transport stands as one of the most significant and essential industries, dominating a substantial portion of global trade.

This paper aims to harness the water flow used to fill docks during the entry and departure of vessels to generate clean energy that can be used in day-to-day operations. Operating pumps and generators in these dry docks consume a significant amount of energy, leading to elevated emissions detrimental to the environment. A sustainable alternative involves substituting this energy-intensive process with clean energy generated by turbines. Installing turbines at each existing water-flow opening allows for the harnessing of energy from the pressure and velocity of the water, effectively turning the turbines to generate electricity. Most shipyards have at least one dry dock where boats and ships are built, maintained, and repaired. Some dry docks are quite huge to handle enormous ships that require maintenance [1]. The amount of time needed to fill dry docks with water is one of the primary design considerations. Filling time is primarily determined by the features of a flood system, which is usually driven by gravity. Often, the most complex parts of the flooding system are the input channel and the guide walls. Because of variations in sea level caused by tides, hydraulic boundary conditions also change with time. Furthermore, comprehending the relationship between sedimentation, sea hydrodynamics, and dry docks is a crucial component of the design [2]. Water pressure and speed during the flooding procedure are commonly validated by replicating currents within intake pathways as a component of the dry dock flooding examination. The determination of dry dock height involves elevating the water level until it aligns with the sea surface. At each time interval, the discharged water volume is computed. Prior to reaching the floodway, there is a discernible escalation in both water velocity and pressure. Afterwards, as the water level approaches sea level, both water pressure and flowrate experience a corresponding decrease.

Because it occurs consistently and predictably, tidal energy is a tempting renewable resource. Because tides are predictable, energy can be efficiently captured by using streams of water and tidal variations [3]. Several nations have recently shown reluctance to allow tidal barrages. According to N. Guillou et al. [4], calculating the fault rate, availability, and maintainability of the tidal energy system today depends heavily on reliability assessment. V. Khare et al. [5] discovered that in order to optimize the benefits of generating energy while simultaneously satisfying societal expectations, choosing the ideal site for tidal range projects and optimizing their design and operation are crucial elements of these global endeavors. A wide range of design and operational situations can result from the varied design variables of tidal range systems for energy production [6]. Thorough evaluations of tidal stream power supply are necessary to ensure the effective deployment and functioning of equipment in the marine environment. These assessments also aid in improving the design of turbines [7].

Key renewable energy sources, such as hydropower and tidal energy, play a pivotal role in aiding the United Kingdom attain its goal of reaching net zero greenhouse gas emissions [8]. In response to the challenge of climate change, there is a global pursuit of renewable energy sources to reduce reliance on fossil fuels and ensure environmental protection. This quest is being spurred by the globe's exponential population increase and rising energy demand. Undoubtedly, one of the most promising options in the field of renewable energy for supplementing and varying a portion of the energy supply is tidal energy [9].

Wave energy has not yet achieved a commercial viability that would allow it to compete with non-renewable and renewable alternative energy sources in the context of a shifting energy market [10]. Wave energy prototypes have been offered for over a century; however, they are still not fully commercialized. Several factors contribute to this situation, including the diverse operating principles of devices, a range of deployment options spanning onshore, nearshore, and offshore locations, the distinct wave environments at different potential wave energy sites, and the resultant absence of technological convergence and consensus [11]. Systems based on renewable energy have been developed to address the environmental impact of ports and vessels while docked in response to the growing energy demand in harbor regions and the need to minimize pollutant emissions. Ports might be transformed into contemporary energy centers in this way in the upcoming years. Processes have been developed in port regions because of strict objectives implemented by both national and international authorities, measures have been established to reduce carbon emissions in the maritime sector [12]. Hydroelectric dams, wind (offshore and onshore), solar, biomass, geothermal, tidal, and wave energy are just a few examples of the various forms that renewable energy may take. The last ten years have seen a fast development of wind and solar power, making them competitive with fossil fuels [13]. Currently, many sources, depending on the kind of consumer, are used to meet the energy demand at ports [14]. The process of harnessing energy from fossil fuel reservoirs precipitates a notable escalation in carbon emissions thereby substantiating the causal link to global warming. Notably, the exploration of oceanic energy resources presents itself as a discerning alternative, characterized by significant, albeit underexplored, potential [15]. Few renewable energy sources are fully utilized in the ocean, despite its abundance, to minimize the harmful impacts of climate change and transition the global energy industry from fossil fuels to zero-carbon alternatives by the second half of this century therefore investment in developing renewable energy technologies is crucial [16]. In comparison with the preceding thirty years, there was a greater increase in greenhouse gas emissions between 2017 and 2018. The average increase of 2.7% that was seen in 2018 was about 37.1 gigatons of CO_2-equivalents per year [17]. By 2050, the industry is predicted to emit 50% more greenhouse gases than it did in 2018, making up 2.89% of global emissions. Moreover, the sector is accountable for 5 - 10% and 17 - 31% of global emissions of sulphur and nitrogen oxides respectively [18].

As an integral component of the initial International Maritime Organization (IMO) strategy aimed at diminishing greenhouse gas emissions from maritime vessels and with the objective of phasing out such emissions as early as practicable in this century, the maritime industry is actively working towards transitioning into a zero-emissions business [19]. During the period from 2016 to 2019, there was an average annual growth of 2.6% in the energy demand for marine shipping encompassing ports. The increase in energy demand not only leads to a rise in greenhouse gas emissions and other pollutants but also contributes to the escalating costs of energy. In 2018, the shipping industry accounted for 2.89% of air emissions, a rise from 2.76% in 2012, according to the 4th International Maritime Organization (IMO) greenhouse gas assessment [20]. It is anticipated that the shift to a low-carbon economy will spread throughout the economic sectors at a rate determined by the energy intensity, capital intensity, and hegemonic interests of each industry [21].

Historically, the focus in generating renewable energy from marine environments has revolved around capturing energy from waves, currents, or other natural environmental occurrences. There has been comparatively less attention given to integrating the everyday activities of ports and shipyards into efforts aimed at energy production. On the other hand, this paper investigates the potential for producing sustainable energy by utilizing the dock filling cycle. The strategy entails turning turbines positioned at seawater inlets using the water head produced during the dock-filling procedure. The main goals are to calculate the energy produced during dock-filling and investigate the changes in energy production process effectiveness and efficiency over the course of the operation. In order to evaluate the net head, velocity, flowrate, power output, and predicted energy production throughout the process, a mathematical structure must be developed. The filling process is divided into 5% intervals, and in order to approximate the total energy produced, the appropriate variables are calculated for every period. The objective of this evaluation is to assess the model's environmental and economic advantages and ascertain the model's effectiveness over a range of periods.

3. METHODOLOGY

The methodology used in this research is centered on estimating the power generated throughout the dry dock filling process, which is accomplished by carefully positioning turbines near inflow valves. With a focus on graving dry docks, this process entails utilizing scientifically generated equations for precise estimations and meticulously acquiring data. The meticulous processes taken to assess valve flow, head deference, and energy produced at designated intervals are described in the technique. The goal of the research is to offer important new understandings regarding the potential generation of renewable energy in dry docks. This methodology's explanation is supplemented by a graphical representation in the form of a flowchart shown in Figure 1.

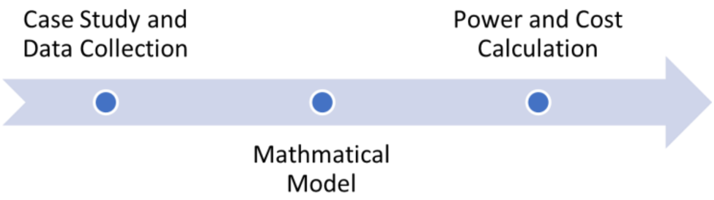

Figure 1: Research Methodology Layout

This flowchart illustrates the methodology's sequential processes, starting with data gathering. Experts with knowledge of the graving dock flooding system provided the information. The equations below show the mathematical model, which is based mainly on Bernoulli's equation.

The filling rate is considered when calculating each time interval. Therefore, by dividing the water volume by the volume flowrate, 19687.5 m^3 of water are required to fill the dock for every 5% step. The remaining computations to determine the duration of each interval are made using this manner.

3.1 Data Collection

The Graving Dock No. 1 at ASRY can accommodate ships with a deadweight tonnage (dwt) of up to 500,000 tons [22]. Having a total length of 375 m, overall width of 75 m and a height of 14 m. The dock is usually filled within 1 - 2 hours which leaves room for the implementation of the system. The dry dock is flooded by an arrangement of 6 valves each having a diameter of 1.5 m.

The water inside the dock (∇) will be estimated by multiplying the length (L), width (W) and depth (D) of the dock, while the density of seawater (ρ) is taken as 1025 kg/m^3 as shown in Eq. (1).

$$\nabla = L \times W \times D \times \rho \tag{1}$$

3.2 Mathematical Model

The main factors influencing the amount of power produced are the valves' cross-sectional area, the water flowrate at a given moment, and the variations in water head. This system must be calculated before it can be put into use in a dry dock. The steps taken in the mathematical model to determine the total power produced by each turbine are shown in Figure 2.

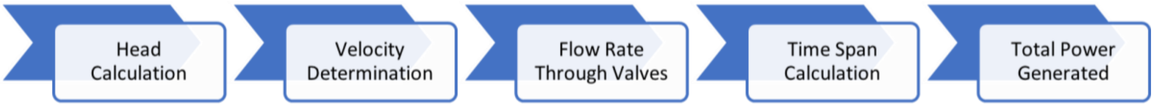

Figure 2: Mathematical Model Layout

Initially, the head difference is used to determine the velocity at a specific time. The velocity and the valves' cross-sectional area are then used to calculate the flowrate while the duration was determined by the dock's filling percentage and flowrate. Finally, a calculation of the generated power is possible.

The water head can be calculated by multiplying the height of the water from the datum point to the graving dock water level (H_d) or the sea level head (H_s), mean sea water level (MSWL) by the gravitational acceleration and water density.

$$H = \rho \times g \times h \tag{2}$$

In contrast, the difference between the head inside the dock (H_d) and the head of the sea level (H_s) is known as the net head pressure (H_n).

$$H_n = H_s - H_d \tag{3}$$

Gravitational acceleration (g) and net head (H_n) are two factors that are used in order to determine water velocity (V).

$$V = \sqrt{2 \times g \times H_n} \tag{4}$$

The flowrate (Q) is calculated by multiplying the velocity (V) and cross-sectional area (A) of the seawater inlet pipe.

$$Q = V \times A \tag{5}$$

To determine the time span for each interval the total volume of water in the dock (∇) is divided by the flowrate (Q) at a certain moment.

$$t = \frac{\nabla}{Q} \tag{6}$$

The net head (H_n), flowrate (Q), cross-sectional area of the seawater inlet valve (A), and turbine efficiency (μ) are used to compute the power generated by the flow as stated by Tian et al. [23]. And the turbine to be used is Francis-Type turbine, while the turbine efficiency is considered to be 85% according to Sánchez, J. (2012) [24].

$$P = \mu \times \rho \times g \times H_n \times Q \tag{7}$$

All these parameters will change depending on the water level in the dock and the time needed to fill it. Thus, they will be calculated based on the filling percentage of the graving dock at 5% intervals.

Once the turbine is added to the waterway, resistance will be more than anticipated during the dock's initial design phase. In consideration of this, the resistance will be recalculated to determine the new flowrate and adjusted in order to prevent any delay in the regular docking process.

The total energy produced for each interval (P_i) will be calculated in kWh by multiplying the power generated (P) by time in hours (T).

$$P_i = P \times T \quad (8)$$

The total energy produced (P_t) will be calculated by summation of energy output from each interval.

$$P_t = \sum P_i \quad (9)$$

To determine the financial cost to produce the energy from natural gas the total energy produced (P_t) is multiplied by the cost of kWh in Bahrain which is 0.0743 $/kWh and to compute the amount of CO_2 to be released into the environment, total energy produced (P_t) is multiplied by 762 g CO_2/kWh as stated by Krarti and Dubey (2018) [25].

4. RESULTS

As shown in Table 1, a clear pattern emerges during the dock filling process, where an increase in water level coincides with a decrease in net head, velocity, and flowrate.

At the beginning of the process, the net head is 12.6 m, velocity is approximately 15.7 m/s, and the flowrate of seawater is 27.8 m^3/s.

By the midpoint of the filling process (50%), there's a slight reduction in velocity to a new value of 11.1 m/s, and the flowrate decreases to 19.6 m^3/s. This progression highlights a consistent relationship between the rising water level and the decreasing values of net head, velocity, and flowrate throughout the filling process.

Table 1. Relationship between main parameters

Water level	*Net head (m)*	*Velocity (m/s)*	*Flowrate (m^3/s)*
0%	12.6	15.7	27.8
5%	12.0	15.3	27.1
10%	11.3	14.9	26.4
15%	10.7	14.5	25.6
20%	10.1	14.1	24.9
25%	9.5	13.6	24.1
30%	8.8	13.2	23.2
35%	8.2	12.7	22.4
40%	7.6	12.2	21.5
45%	6.9	11.7	20.6
50%	6.3	11.1	19.6
55%	5.7	10.5	18.6
60%	5.0	9.9	17.6
65%	4.4	9.3	16.4
70%	3.8	8.6	15.2
75%	3.2	7.9	13.9

80%	2.5	7.0	12.4
85%	1.9	6.1	10.8
90%	1.3	5.0	8.8
95%	0.6	3.5	6.2
100%	0.0	0.0	0.0

It is noticed that the time span increases for each interval at an exponential rate as shown in Figure 3. The total time taken to fill the dock is approximately 1 hour and 17 minutes and it is observed that the time span increases by a higher rate after 90% of the filling process as the flow rate is minimal.

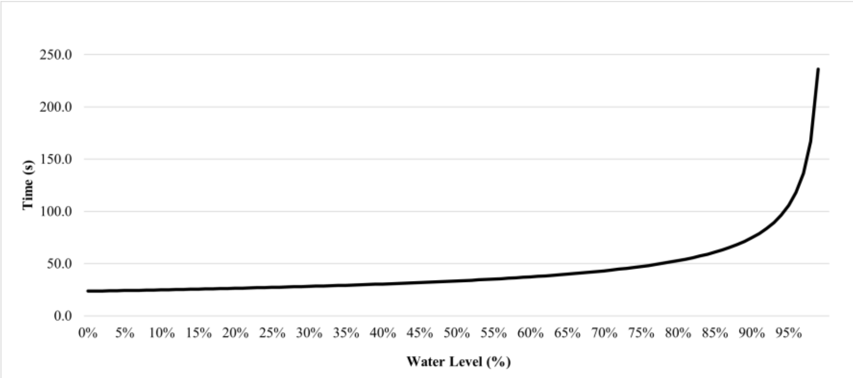

Figure 3: Time Span of Each Interval

The deduction is drawn from the observation that the time span extends with each interval of the filling process. This is attributed to a decrease in flow rate throughout the filling process, owing to the reduction in net head. Specifically, during the initial 5% of the process, approximately 118 seconds are required, while within the range of 25% to 30%, 136 seconds are required.

Progressing further, between 45% and 50%, the time span increases to 159 seconds. Notably, a more pronounced escalation in the time span is evident in later stages from 70% to 75%, it extends to 236 seconds, and notably, from 95% to 100%, it substantially increases to 528 seconds.

As depicted in Figure 4, the turbine initially showcases a pronounced surge in power output, primarily attributed to the maximum flow rate, velocity, and net head.

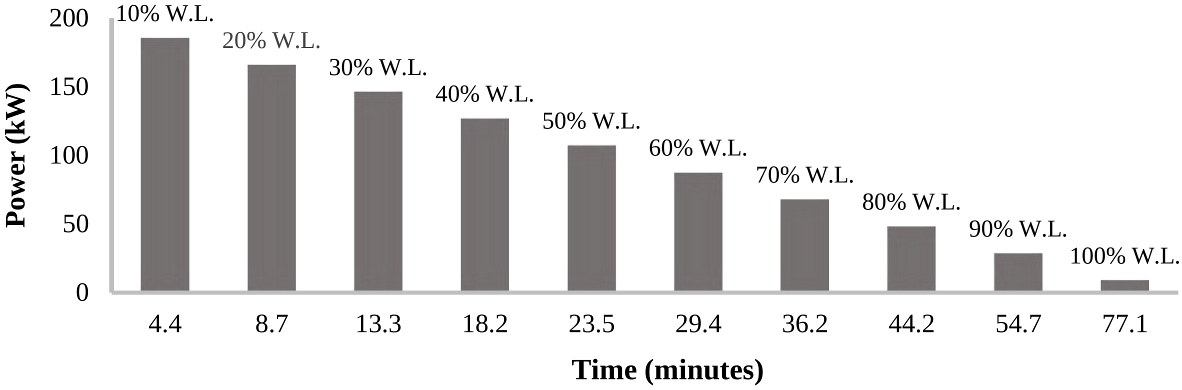

Figure 4: Generated Power Added During the Filling Process

More specifically, during the initial 10% of the 4.4-minute process, the turbine added power is 185.5 kW. Subsequently, as the filling process unfolds, there is a decrease in the generated power. For instance, within the 40% to 50% interval, spanning 5.3 minutes, the turbine produces 107 kW. In the subsequent 90% to 100% interval, encompassing 22.3 minutes, the generated power further diminishes to 8.8 kW. This shows a diminishing trend, where the power generated in each interval decreases due to the reduction in net head.

The temporal evolution is characterized by an initial increment of approximately 4-5 minutes for the first 6 intervals, followed by a substantial escalation in the time required for subsequent intervals. Similarly, the power generated in each interval experiences a notable decline once the water level surpasses the 60% threshold, persisting below 80 kW for the ensuing intervals. This analysis underscores the dynamic relationship between the turbine's power generation, the progression of the filling process, and the associated fluctuations in net head.

Utilizing the computational data provided, the determination of the total energy output in kilowatt-hours (kWh) involves a straightforward calculation: multiplying the power output by the respective time duration. The visual representation in Figure 5 illustrates the comprehensive power generation dynamics during the filling process.

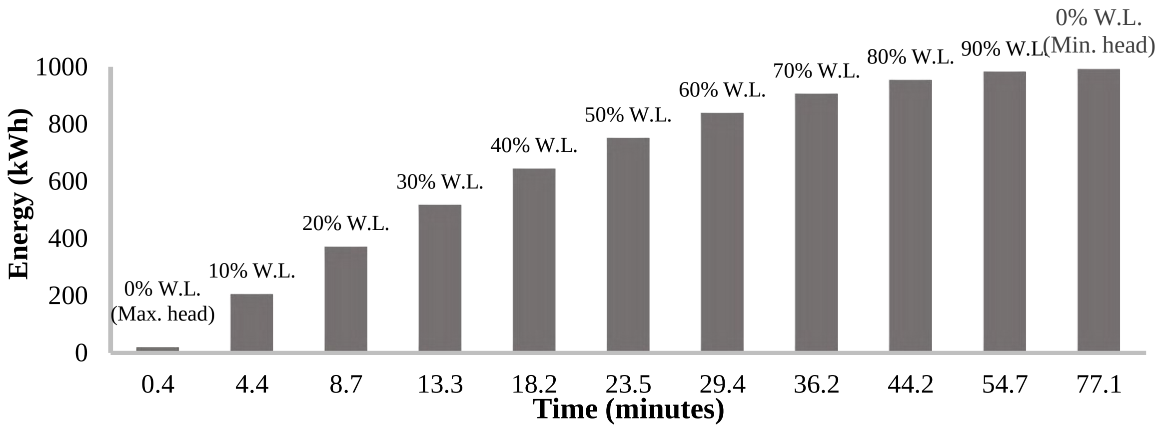

Figure 5: Power Output from the Filling Process

Evidently, the graphical presentation indicates an initial surge in energy production, where an approximate 37% of the total energy is generated within the initial 20% of the filling process, taking approximately 8.7 minutes. This early phase, constituting roughly 11% of the overall operation time, manifests a substantial and swift energy generation rate. Further observation of the graphical representation reveals a significant milestone at the 60% mark of the filling process. At this juncture, more than 80% of the total energy has been generated, occurring within a time span of 29.4 minutes. This specific interval represents approximately 38% of the entire duration of the operation, underscoring a concentrated and efficient energy generation period during the mid-section of the process.

The culmination of the filling operation, reaching 100%, yields the production of approximately 1 megawatt-hour (MWh) of energy. This operation takes a total time duration of 77.1 minutes, equivalent to around 1 hour and 17 minutes. The delineated progression underscores the dynamic nature of energy generation, with discernible phases contributing to the overall efficiency and productivity of the operation.

The calculations suggest that with the operation of the six intake lines, an estimated total of 6 megawatt-hours (MWh) will be generated. The prospective electricity generation derived from the filling process is foreseen to yield financial savings totaling approximately $445, thereby concurrently serving as a proactive measure to avert the emission of 4572 kilograms of carbon dioxide into the environment.

5. CONCLUSION

The primary aim of this paper is to develop a comprehensive mathematical model geared towards accurately assessing the hydropower potential derived from the filling operations of graving docks. Delving into the intricacies of this phenomenon, the study focuses on a specific case study involving the ASRY dry dock no. 1. Important insights have been observed by closely examining the raw energy output created at each stage of the filling process. Interestingly, the analysis finds that each of the dock's six intake lines produces approximately one MWh of power, adding up to an astounding total of almost 6 MWh every fill when all six are operating. This highlights the significant energy-saving potential of using graving dock hydropower while also illuminating the financial advantages of such strategies. Surprisingly, the predicted cost reductions are estimated to be about $445, a significant amount that highlights the feasibility of integrating hydropower alternatives into maritime infrastructure financially. The environmental implications of this alternative source of energy are significant and go above simple financial rewards. This study's analysis of the hydropower production process provides a more sustainable and environmentally friendly energy source than conventional energy generation techniques like natural gas, which include large carbon emissions. In particular, it is shown that 4572 kg of CO_2 would be released into the atmosphere in order to produce the same amount of energy with natural gas. Which serves as a reminder of how urgently we must switch to better power sources. Notwithstanding the encouraging potential for using hydropower from graving docks, it is important to recognize several restrictions and difficulties. The study finds a critical point at which the system's efficacy starts to decline. It is observed that flow resistance increases after 60% of the filling process, causing longer flooding times and reducing the productivity of hydropower generation. Looking ahead, the study uses a multipronged strategy to further hone and build upon its findings. Subsequent research endeavors will involve advanced computational fluid dynamics (CFD) modeling, utilizing state-of-the-art computer programs to further explore the intricacies of flow patterns in graving docks. In addition, the research endeavors to incorporate a wider range of influential elements, such as tidal variations and meteorological characteristics, into its analytical structure. Through the utilization of cutting-edge artificial intelligence methods and experimental models, the research endeavors to obtain a comprehensive comprehension of the intricate features and dynamics that regulate the production of hydropower in maritime environments. With the help of these multidisciplinary projects, the maritime industry's search for innovative and effective sustainable energy solutions is set to soar to new heights as models of dock water flow are examined through simulations, and weather and tide effects are taken into account. Researchers aim to gain a deeper understanding of the operation of hydropower in docks through experimentation and the use of intelligent computer algorithms. This could lead to the discovery of novel applications for sustainable energy in the maritime sector.

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