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# Substantiating Significance of Pump Thrust on Stability Analysis of River Intake Structures

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**ABSTRACT:** River intake structures are critical for efficient water resource utilisation in various sectors. The stability of these structures is of paramount importance to ensure their longevity and safe operation. In conventional design practice, the stability analysis only considers the impact of incident wind and flood forces, along with the external loads transferred by the pump to the foundation. However, the influence of pump thrust, which is a reactive force exerted as a result of fluid expulsion during the pump operation, has been largely overlooked and is not deemed a significant factor when evaluating the structure's stability. This hydrodynamic force, resulting from a sudden directional change of water between the discharge line and the header pipe, tends to be unbalanced, and is a crucial facet in the design of River Intake Structures. With higher-head pumps becoming the norm, this unbalanced force is significantly more powerful in the present-day context and must be accounted for as an external force contributing to instability. This paper presents a comprehensive theoretical exploration and substantiates the importance of pump thrust in ensuring the stability of river intake structures and contrasts it with the incident wind force.

**KEYWORDS:** River Intake Structure, Stability Analysis, Pump Thrust (Hydrodynamic Force), Wind Force.

## I. INTRODUCTION

During stability analysis of river intake structures, engineers place significant emphasis on evaluating the effects of local external loads that originate from the weight of the pump and are transmitted to the foundation. To conduct this analysis, engineers rely on the specifications provided by the manufacturer.

In a river intake structure when high-pressure water from the pump flows through the discharge line, it enters the header pipe at a sharp  $45^\circ$  to  $90^\circ$  angle (**Fig.1**). This sharp directional change of the water flow creates an unbalanced force due to the sudden change in momentum and direction. In structures of this nature, thrust blocks are strategically placed to counteract this reactive force which is then treated as having been passed to the foundation through the floor.

In the past, pumped water supply systems were typically located in close proximity to their water sources. The shorter distances between the water sources and the pumping stations resulted in lower-heads (vertical distance between the water source and the point of discharge). Nowadays, as urban areas have expanded and water demands have increased, it has become necessary to transport water over longer distances. This has led to the emergence of pumped water supply systems with higher-heads, that are required to overcome the increased elevation and longer distances involved in delivering water to its destination.

While these pumps offer advantages in terms of increased pumping capacity, however, the use of higher-head pumps has led to a rise in hydrodynamic forces. This can be particularly problematic as the unbalanced forces can induce significant stress that may lead to structural instability. When the structure is not adequately designed to withstand or distribute these forces, it may potentially cause the entire structure to overturn. Thus, it is imperative to account for the increased hydrodynamic force as an external force acting on such structures.

Pump thrust is a constant force during pump operation. During normal and low river flows, it is a significant contributing factor to the overturning of the intake structure, in some cases, it may exceed even the force exerted by wind on the structure. By carefully considering and accounting for the increased hydrodynamic force in the stability calculations of the design, engineers can ensure long-term functionality and reliability of the structure, by minimising the risks associated with additional stress levels on the structural elements.

## II. LITERATURE REVIEW

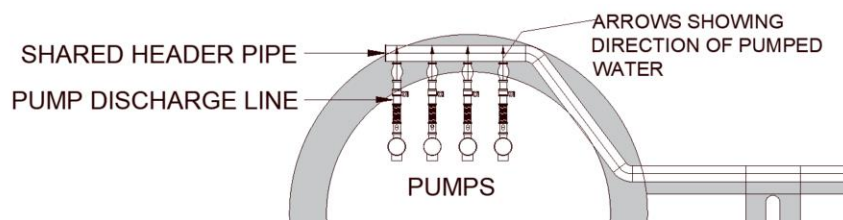
Indian Standard Institution, “Design Loads (Other than Earthquake) for Buildings and Structures – Code of Practice (Part 3 Wind Loads)”, IS: 875 (Part-III) 2015 (Reaffirmed 2020), is a comprehensive code that provides guidelines for the calculation of static and dynamic wind forces on buildings and structures in India [1].

American Water Works Association, “Steel Pipe – A Guide for Design and Installation”, Manual of Water Supply Practices (M11) Fifth Edition, guides the design and installation of steel pipes in water supply systems. The manual notes the importance of considering the hydrodynamic force that the operation of the pump generates [2].

## III. EXPERIMENTAL EXPLORATION

While wind force is incidental and short-term (occurs intermittently and for limited durations), the pump thrust is a persistent force that remains active as long as the pump is operating. In a pumping system, each individual pump contributes to the overall hydrodynamic force exerted. This force is generated by the movement of water being pumped from each pump into a shared header pipe, the hydrodynamic force grows proportionally with the pumping head (**Fig.1**).

At a higher pumping head, the hydrodynamic force becomes significantly greater and eventually surpasses the wind force incident on the structure. Moreover, the hydrodynamic force acts above the pump floor, which has important implications for stability as it increases the moment arm (perpendicular distance from the base of the structure i.e., pivot point, to the line of action of the force). By increasing the moment arm, the force exerted by the pumped water has a greater mechanical advantage, enhancing the likelihood of overturning the structure if the combined forces are not properly accounted for.



(Fig.1) Illustrative figure showing Pump Assembly inside the River Intake Structure (Plan)

### Wind Force Analysis for Structures

The susceptibility of a structure to wind force is determined by various factors, including its geographical location, surrounding terrain, local topography, proximity to obstructions, and structural characteristics. These elements collectively influence how the wind interacts with the structure and the resulting forces it exerts upon it.

The wind force mentioned in the paper adheres to the guidelines set forth by the Indian Standard Institution, specifically IS: 875 (Part-III; Wind Loads) 2015 (Reaffirmed 2020). Importantly, the code recognises the need to consider the impact of high wind speeds during cyclonic events. It incorporates relevant factors that allow for adjustments to the design wind speed, taking into account the criticality and importance of the structure being designed.

### Hydrodynamic Force in Pumping Systems

The hydrodynamic force resulting from the action of pumped water can pose a significant risk to structural elements, potentially leading to increased stress, in a worst-case scenario, causing the intake structure to overturn. It is crucial for engineers to carefully design the structure to ensure its stability under the anticipated hydrodynamic force. In the context of this paper, the connection between the discharge line and the header pipe is established through a T-junction configuration. This specific configuration gives rise to an unbalanced force that remains constant during pump operation and contributes to the overall hydrodynamic force experienced by the structure.

To accurately assess and account for the pump thrust and the associated hydrodynamic force, in this study the calculations outlined in the American Water Works Association's Manual of Water Supply Practices (M11), Fifth Edition are utilised. This manual provides standardised procedures and guidelines for determining pump thrust, allowing for the accurate estimation of the hydrodynamic force acting on the structure due to the pumped water.

To quantify the impact of pump thrust, the below problem statement is developed, incorporating real-world scenario of river intake operation. It aims to highlight the pivotal role of pump thrust when evaluating the stability of the intake structure which in this case holds more significance in comparison to the wind force.

**PROBLEM STATEMENT: IMPACT OF WIND FORCE AND PUMP THRUST ON RIVER INTAKE STRUCTURES**

**Plan Dimensions of Intake Structure (Fig.2): Cylindrical Well + Rectangular Pump House**

**Cylindrical Well:**

Height of well: **25.0 m**

Diameter of well: **20.0 m**

**Rectangular Pump House:**

Length of pump house: **20.0 m**

Breadth of pump house: **18.0 m**

Height of pump house: **10.0 m**

**Total Height of Structure (h): 35.0 m**

**Site:**

**Location:** Coastal Orissa (Central India) indicated in (Fig.3)

**Nearest sea-coast:** 70 km

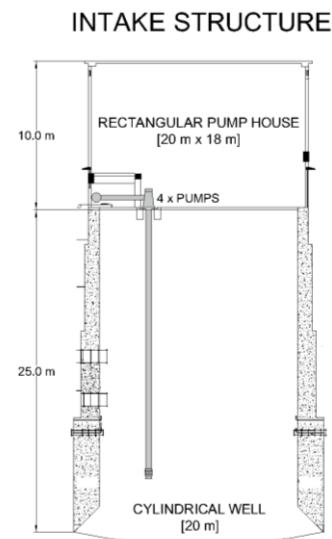
**Nature:** Open terrain with no obstructions (open sea-coasts)

**Upwind Slope:**  $\Theta < 3^\circ$

**Structure:**

**Class:** Post-cyclone importance for emergency services

**Design Life:** 100 years



(Fig.2) Layout of Intake Well (Elevation)

**Calculation of Wind Force according to IS: 875 (Part-III) 2015 (Reaffirmed 2020)**

**Check for Dynamic Effect of Wind [Clause 9.1]:** Flexible structures that meet any of the two criteria below must be examined for the dynamic effects of the wind as they may experience wind-induced oscillations.

(a) Closed structures with height-to-minimum lateral dimension ratio exceeding 5.0:

$$\frac{h}{b} = \frac{35}{18} = 1.94 < 5.0$$

(b) Structures with a first-mode natural frequency below 1.0 Hz:

$$T^* = \frac{0.09 \times \text{Total height of structure}}{\sqrt{\text{Maximum base dimension}}} = \frac{0.09 \times 35}{\sqrt{20}} = 0.70$$

$$F = \frac{1}{T} = \frac{1}{0.70} = 1.43 > 1.0 \text{ Hz}$$

\*Fundamental time period (T) is computed rationally, but can also be established by experiments on similar structures.

Since neither of the above two criteria are met, the static method can thus be adopted for wind force calculations.



**A. Wind Force by Static Method**

**1. Design Wind Speed ( $V_z$ ) [Clause 6.3]**

As the basic wind speed ( $V_b$ ) (Fig. 3) is tied to specific reference conditions, the following modification factors are defined to assess the design wind speed.

$$V_z = V_b k_1 k_2 k_3 k_4 \tag{Eq. 1}$$

Where;

$V_z$  = Design Wind Speed at Height  $z$  (m/s)

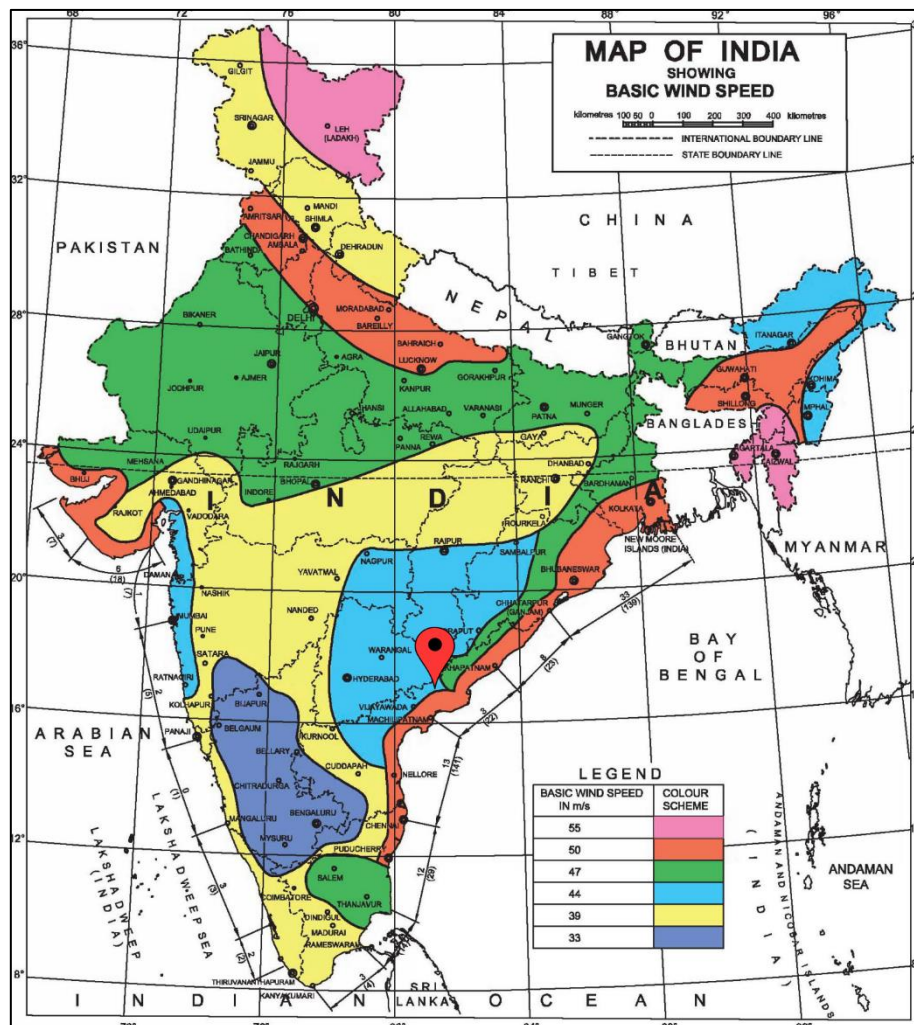
$V_b$  = Basic Wind Speed (m/s) (Fig.3)

$k_1$  = Probability factor (Risk coefficient) Table 1. (Clause 6.3.1)

$k_2$  = Terrain Roughness and Height factor Table 2. (Clause 6.3.2)

$k_3$  = Topography factor (Clause 6.3.3)

$k_4$  = Importance factor for Cyclonic Region (Clause 6.3.4)



(Fig.3) Basic Wind Speed in m/s (50-Years Return Period)\* with Location of Intake Structure

\*Based on wind data collected from anemograph stations provided by the Indian Meteorological Department (IMD).



The below excerpt from **Table 1** displays factor  $k_1$  for varying basic wind speeds. It is calculated using statistical principles that consider structural importance, desired level of reliability and the number of years that the structure will be exposed to wind.

**Table 1. Risk Coefficients for Different Classes of Structures in Different Wind Speed Zones (Clause 6.3.1)**

Class of Structure	Mean Probable Design Life of Structure in Years	$k_1$ Factor for Basic Wind Speed (m/s) of					
		33	39	44	47	50	55
Important buildings and structures such as hospitals, communication buildings, towers and power plant structures	100	1.05	1.06	1.07	1.07	1.08	1.08

The following excerpt exhibits the factor  $k_2$  for calculating wind speeds at heights in different terrain categories, as outlined in **Table 2**. The code defines four categories (Clause 6.3.2.1) based on terrain characteristics and the average height of surrounding objects. The intake structure falls in **Category 1** having exposed open terrain with few or no obstructions.

**Table 2. Factors to Obtain Design Wind Speed Variation with Height in Different Terrains (Clause 6.3.2.2)**

Height (z) (m)	Terrain and Height Multiplier ( $k_2$ )			
	Terrain Category 1	Terrain Category 2	Terrain Category 3	Terrain Category 4
30	1.15	1.12	0.06	0.97
50	1.20	1.17	1.12	1.10

Linear interpolation is employed for the intermediate values of height  $z$  and terrain category 1, given that the total height of the intake structure is 35 m, as specified in the problem statement, the terrain and height multiplier will be;

$$k_2 = y_1 + \frac{(x - x_1)}{(x_2 - x_1)} \times (y_2 - y_1) = 1.15 + \frac{(35 - 30)}{(50 - 30)} \times (1.20 - 1.15) = 1.16$$

The basic wind speed is solely based on the height of the site above sea level, without considering any local topographical characteristics that may influence wind speed in their vicinity. To account for enhancement in wind speed resulting from topographical features, factor  $k_3$  is utilised if the upwind slope ( $\theta$ ) exceeds  $3^\circ$ . In our case, the slope is less than  $3^\circ$ , so it is assumed that the topography has no significant impact on wind speed, and the factor is taken as **1.0**.

The factor  $k_4$  is determined by the significance of the structure, with the highest value assigned to structures that are considered of utmost importance following the cyclone. The importance factor for intake structure in the problem statement based on its class is illustrated in the excerpt from **Table 3** below.

**Table 3. Risk Coefficients for Different Classes of Structures in Different Wind Speed Zones (Clause 6.3.4)**

Class of Structure	$k_4$ Importance Factor for Cyclonic Region
Structures of post-cyclone importance for emergency services (such as cyclone shelters, hospitals, schools, communication towers, etc.)	1.30

$$\text{Thus, } V_z = V_b k_1 k_2 k_3 k_4 = 44 \times 1.07 \times 1.16 \times 1 \times 1.30 = 71 \text{ m/s}$$

This design wind speed has been assessed from the wind force conditions specific to the site of the intake structure and takes into consideration the sufficient safety margins, the impact of wind flow characteristics at the location, potential changes in wind patterns, as well as the heightened risk and severity of wind forces on the intake structure.

**2. Design Wind Pressure (Pd) [Clause 7.2]**

$$P_d = K_d K_a K_c P_z$$

(Eq. 2)

Where;

 $P_d$  = Design Wind Pressure ( $N/m^2$ ) $K_d$  = Wind Directionality factor (Clause 7.2.1) $K_a$  = Area Averaging factor Table 4. (Clause 7.2.2) $K_c$  = Combination factor (Clause 7.3.3.13) $P_z$  = Wind Pressure at Height  $z$  ( $N/m^2$ )

To account for the random wind directionality and the fact that pressure or force coefficients are established for specific wind directions, circular and axisymmetric sections are assigned a factor  $K_a$  having the value of **1.0** as they offer uniform resistance, irrespective of the wind direction. This includes regions impacted by cyclones where it is also considered 1.0.

When a tributary area (the surface area where wind forces transfer to the structure) flows over an increased area, local eddies are generated, which reduces the correlation of measured values leading to a decrease in pressure. To account for this, the area reduction factor  $K_a$  is introduced as a multiplier for pressures on the structure. In our example, the tributary area is greater than  $100 m^2$  and thus the factor is **0.8** referring to Table 4.

**Table 4. Area Averaging Factor  $K_a$  (Clause 7.2.2)**

Tributary Area (A) $m^2$	Area Averaging Factor $K_a$
$\leq 10$	1.0
25	0.9
$\geq 100$	<b>0.8</b>

Structures subjected to pressure under wind force can have discrepancies between the outside and inside pressure. To accommodate this pressure difference, a factor  $K_c$  having a value of **0.90** is utilised. This is crucial to ensure that the structure can endure the wind force without experiencing any damage.

$$P_d = K_d K_a K_c P_z = 1.0 \times 0.8 \times 0.9 \times P_z = \mathbf{0.72 P_z}^*$$

\*As stated in clause 7.2, the value of  $P_d$  shall not be taken as less than  $0.70 P_z$ .

The wind pressure at any elevation above the average ground level with the typical atmospheric pressure and air temperature conditions in India can be calculated using;

$$P_z = 0.6 V_z^2 = 0.6 \times (71)^2 = 3025 N/m^2$$

$$\text{Therefore, } P_d = 0.72 P_z = 0.72 \times 3025 = \mathbf{2178 N/m^2}$$

**NOTE: Wind Force on Cylindrical Sections [Clause 7.3.3.7]**

For cylindrical structures with circular cross-sections (lower section of the intake structure), the force coefficient exhibits noticeable changes, and thus to express the external pressure coefficients, a non-dimensional parameter called the **Reynolds number\*** is used. It considers the air velocity, kinematic viscosity, and member diameter. Since the kinematic viscosity of air remains relatively stable in most natural settings in India, IS: 875 (Part-III) employs only the diameter of the member and design hourly mean wind speed.

$$Re = DV_d = 20 \times 44 = \mathbf{880 < 10000}$$

\*Calculating external pressure coefficients is only appropriate when the Reynolds number exceeds 10,000.

### 3. Design Wind Force (F) [Clause 7.4]

When an object obstructs the flow of wind, it generates pressure on the object's surface in the direction of the wind. This pressure multiplied by the corresponding surface area yields a force called 'drag'. The provided force coefficients aid in determining the overall force on the structure for designing and assessing the structure's stability. When multiplied by the effective frontal area ( $A_e$ ) of a structure and the design wind pressure ( $P_d$ ), the force coefficients represent the total wind force exerted on the entire structure.

$$F = C_f A_e P_d \tag{Eq. 3}$$

Where;

$F$  = Total Wind Force acting in a direction normal to the structure (N)

$C_f$  = Force coefficient for the structure (Drag coefficient) (Fig.4) (Clause 7.4.2.1) & Table 5 (Clause 7.4.2.2)

$A_e$  = Effective Frontal Area ( $m^2$ )

$P_d$  = Design Wind Pressure ( $N/m^2$ )

**Cylindrical Well:**

Height of Well above HFL = 1.0 m

Height of Structure above HFL (h)\* = 11 m

**Rectangular Pump House:**

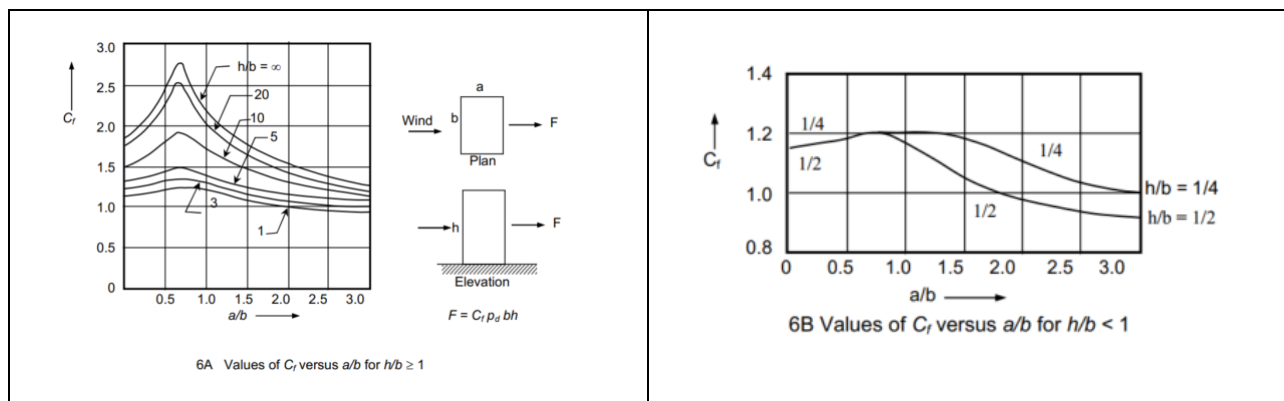
Height = 10.0 m

Breadth = 18.0 m

Length (b) = 20.0 m


From (Fig.4);  $\frac{h}{b} = \frac{11}{20} = 0.55 < 1$

And the ratio;  $\frac{a}{b} = \frac{18}{20} = 0.9 < 1$



(Fig.4) Force Coefficients ( $C_f$ ) for Rectangular Structures (Clause 7.4.2.1)

Table 5. Force Coefficients ( $C_f$ ) for Structures with Circular Cross-sections (Clause 7.4.2.2)

Plan Shape	$V_z$ m <sup>2</sup> /s	$C_f$ for Height / Breadth Ratio		
		$\leq 2$	10	$\geq 20$
	< 6	0.7	0.9	1.2
	≥ 6			
Smooth	≥ 6	0.5	0.5	0.6

\*It's worth noting that the presence of water can still indirectly affect the building's structural response to the wind. The interaction between wind and water can generate waves and currents, which may apply additional dynamic forces on the submerged portions of the building and potentially affect the stability of the structure.



Due to the composite design of the intake structure, consisting of a rectangular top and cylindrical bottom, we will determine the effective force coefficient by taking the average.

$$F = C_f A_e P_d = \frac{1.2+0.7}{2} \times (11 \times 20) \times 2178 = 455202 \text{ N} = 46 \text{ t (tonnes)}$$

From (Fig.6); Rock Level = 270.0 m

Point of action of wind force above the Pump House Floor (290.0 m) is determined to be at 3.0 m

Therefore, *Moment Arm for Wind* = 293.0 – 270.0 = 23 m

**Overturning Moment due to Wind Force** = 46 × 23 = 1058 t – m (tonne – meter)

**B. Hydrodynamic Force (T) [M11 (AWWA) 2018 (Fifth Edition), Chapter 8]**

$$T = p A_0 \tag{Eq. 4}$$

Where;

*T* = Hydrodynamic Force (Pump Thrust) (kg)

*p* = Maximum Internal Pressure (kg/cm<sup>2</sup>)

*A*<sub>0</sub> = Cross-sectional Area of the Pipe (cm<sup>2</sup>)

$$T = p \times A_0 = 25 \frac{\text{kg}}{\text{cm}^2} \times \left(\frac{\pi}{4} \times 35^2\right) \text{ cm}^2 = 24050 \text{ kg} = 24 \text{ t}$$

Therefore, for 4 Pumps = 24 × 4 = 96 t (tonnes)

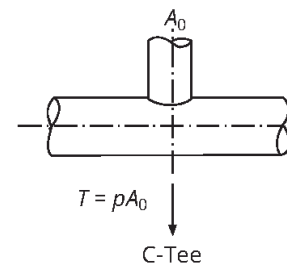
From (Fig.6) Rock Level = 270.0 m

Top Level of Cylindrical Well = 290.0 m

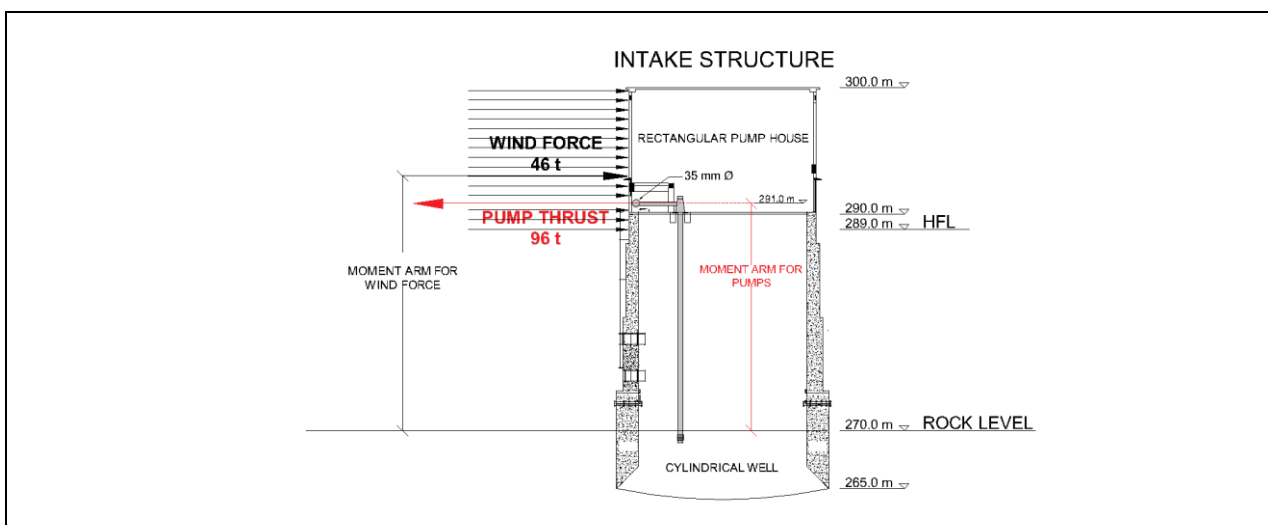
Height of Header Pipe above Pump House Floor = 1.0 m

Therefore, *Moment Arm for Pumps* = 290.0 – 270.0 + 1.0 = 21 m

**Overturning Moment due to Pump Thrust** = 96 × 21 = 2016 t – m (tonne – meter)

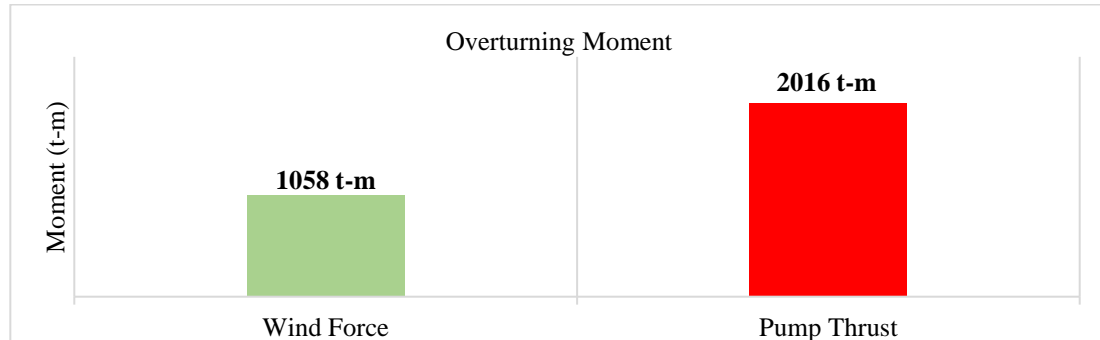


(Fig.5) Hydrodynamic Force (T)



(Fig.6) Moment Arm and Loading Diagram for River Intake Structure

#### IV. RESULTS AND DISCUSSIONS



(Fig.7) Graph showing Comparison of Overturning Moment due to Wind Force and Pump Thrust

Based on our findings, and as evident from the graphical representation above, the pump thrust plays a more prominent role in the overturning of the intake structure compared to the wind force, exhibiting a strength nearly twice as great. It is essential to enhance current design practices and guarantee the stability of the intake structure by ensuring that the resisting moment provided by the foundation of the structure exceeds the overturning moment.

#### V. CONCLUSIONS

1. This study advances the understanding of pump thrust and its impact on the stability analysis of intake structures and contributes to the development of more robust and reliable design practices.
2. It underscores the necessity of incorporating pump thrust in future stability assessments along with flood force<sup>[3]</sup> and wind force, ensuring the safety of intake structures in the face of evolving hydraulic and operational challenges.

#### VI. ACKNOWLEDGEMENTS

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- [3] Abhilash Vishwakarma, "Examining Engineering Estimations in ascertaining Flood Force on River Intake Structures", International Journal of Innovative Research in Science, Engineering and Technology, Volume 11, Issue 8, 2022.

#### BIOGRAPHY



**Abhilash Vishwakarma** is an experienced Engineer with a proven record of successfully managing a wide range of projects in the civil engineering industry. His particular area of interest is in the detailed engineering of water infrastructure projects. As a professional, he has published studies and actively shares his expertise on water engineering as an editor on his blog, *waterengineeringdaily.com*. Beyond his professional pursuits, he actively participates in community service and has a history of service that includes serving as President of the Rotaract Club of RCOEM and Zonal Rotaract Representative under District 3030. When not working, he enjoys spending time with his family and friends while exploring personal interests in cooking, maintaining aquariums and engage in studying various aspects of chess.



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