Review of Operational Challenges and Changing Conditions associated with Offshore Submerged Vertical Pumping Station

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Abstract:

Cooling water system is one of the essential auxiliary systems for a power generating plant. The decision to have an offshore pumping station, instead of onshore station, may have been driven by the scarcity in land area or for direct water supply access. However, the design has several disadvantages such as tendency for sediment intakes, limited condition monitoring activities and inaccessible sump for maintenance and modification.

The paper reviews and lists several potential operational challenges and difficulties experienced with the offshore station. The influences of changing conditions such as varying seawater tide level, clogged intake screen, intake sedimentation issues and marine fouling on the sump walls and structures, are discussed and mitigating solutions are identified. While it is impractical to conduct physical model test for studying flow pattern, the CFD method can be an attractive assessment tools. In addition to this, a review of plant operating parameters can assist in identifying flow anomalies to anticipate potential deterioration. Finally the difficulty in incorporating the solutions to vortex and sediment problems within the sump is highlighted with preference for those which can be managed by limited access or those which are moveable with the vertical pump.

1. Introduction to Cooling Water System for Power Plants

Cooling water system is one of the essential auxiliary systems for a power generating plant. One type of the employed design involves the supply of seawater to a once-through condenser system. For this, a number of pumps would draw water from a reservoir into supply piping system and later discharges back into the sea at downstream of the condenser.

The pumping station can be located onshore or offshore. At onshore, the pumps are located at the mainland with or without a suction piping stretching to the sea for water intake. Its main advantage is the ease of maintenance access. The pump sump can be isolated with stop gate and water drained off for pump overhaul as well as sump cleaning, inspection and rectification. On the other hand, the offshore station would have its structure a few stretches away from the mainland. The sump is bounded by either concrete structures or sheetpiles and submerged vertical pumps or pipes will draw the water needed for the cooling water supply. While the offshore station is normally selected due to limited land area or for direct access to water supply, it is with several disadvantages. These include...
tendency for sediment intakes, limited condition monitoring activities and inaccessible sump for maintenance and modification.

2. Information on Referred Plant

The referred plant, Perai Power Plant uses an offshore pumping station for its supply of cooling water to its once-through seawater cooled condenser. Located 500m from the mainland, the wet well pumping station is a rehabilitated pump house structures for an old plant built in the 1970s. The sump is bounded by sheetpile in a double-trapezium shape with three openings for pump intakes with dedicated 20cm meshed barscreens. The 3 x 35% capacity pumps are of vertical, submerged mixed flow type, each supplying 11,700 m$^3$/hr of seawater to the common discharge header pipe. Refer to Figure 1 for the general assembly of the pumping station in the referred plant. It employs sodium hypochloride dosing at the sheetpile openings for marine fouling prevention. The full plant capacity is achieved with all three pumps placed in service.

![Figure 1: General assembly of the pumping station in the referred plant](image)

This paper reviews and lists several potential operational challenges and difficulties experienced with the offshore vertical submerged pumping station, taking the referred plant as its case study. Emphasis was made to the changing conditions experienced during the operating stage which significantly deviate from the system original design. The issues faced would also apply, fully or partly, to other designs of the offshore pumping station.

3. Changing Conditions

The pumping station is normally designed with a set of parameters that would define its acceptable operating conditions. ANSI/HI 9.8 1998 listed recommended dimensions which include the minimum submergence level, pump sump length and clearances to the floor, side and rear walls [1]. For example, to avoid surface vortex occurrence, the pumping station would be designed to be higher than the critical submergence level, given by,

$$ S_{Cr} = D (1.0 + 2.3 F_D) $$

Where $D$ is the pump intake bell outside diameter and $F_D$ is the Froude number (dimensionless) given by;
\[ F_D = \frac{V}{\sqrt{gd}} \]  

(2)

With \( V \) as the velocity at suction inlet and \( g \) as the gravitational acceleration.

The design parameters are normally good within a few years of operations, but the subsequent years would see these parameters deviate significantly to cause potential problems to the pumping system.

For the offshore pumping station such as the referred plant, several changing conditions have been observed which affect its operations.

3.1. Varying seawater tide level.
Normally the pumping station is designed with sufficient margin for the seawater tide level which can have direct impact to the pump sump water level. Low seawater tide level can influence the sump water level to reach the critical submergence. Surface vortices can start to form, leading to the development of an air core that allows continuous air supply to the pump intake. Surface vortices of ascending strength develop with decreasing sump water level and the minimum water level leading to surface vortex formation is higher with high flow velocity compared with that of low flow velocity [2]. As shown by [3], low submergence level and high flow rate can also lead to subsurface vortex occurrence accompanying the air core vortex. With the vortices, cavitation and imbalance can occur at the pump impeller leading to vibration, noise and damage to some key pump components.

For a normal pumping station, such as the referred plant, the lowest astronomical tide (LAT) level is accounted for during its design, providing sufficient margin for its operations. For the plant, the calculated Froude number is 0.41 and critical submergence at 3.10m. The pump has a minimum submergence of 3.50m against LAT level. Refer to Figure 1.

3.2. Operations with clogged intake screen
Intake screens are installed in front of the pump sump for 2 purposes which are to prevent debris from coming into the sump area and to correct the approach flow. The screens can be either passive type (e.g. meshed barscreen), or active type (e.g. screens with automatic trashraking system). As per ANSI/HI 9.8, they are recommended to be installed at a minimum distance of 6 times the pump bell diameters, 6D. Clogged screen can create severely skewed flow patterns, high velocity jets and severe instability near the pumps [1]. It also has tendency to form eddies which can result in vortex formation with non-uniform approach flow. Localised high velocity jets also have tendency to pull more debris through the screens than it can tolerate [4]. Especially closer to the water surface, small surface vortices can start accompanying the local high velocity spots but these do have significant impact to the pump downstream of the screen provided the recommended distance is adhered. Frequent inspection and cleaning of the screens are recommended to correct the approach flow.

The passive screens at the referred plant are normally clogged with marine organisms (such as jelly fish, seaweed and barnacle) and human pollutants (such as plastic bags and disposed waste). Sample photo of the clogged meshed barscreen from the referred plant is as per Figure 2 of which almost 90% of the flow areas can be clogged up.
Another problem faced with badly clogged screen is the approach flow restriction that can lead to lower pump sump level relative to the seawater tide level. This occurs when the water flow rate through the meshed screen is less than the water being pumped out from the sump. This can lead to surface vortex formation of type 4 which is able to pull floating debris into the cooling water supply piping.

With critical submergence depth, surface vortices of type 6 can be formed with an air core connecting from the free surface to the pump bellmouth with potential to cause cavitation, rotor imbalance and discharge performance degradation. Figure 3 shows the difference in pump sump water level in the referred plant in comparison to the high and low seawater tide levels with the intake screen badly clogged.

![Figure 2: Condition of the meshed barscreen in the referred plant, looking from the pump sump (left) and from the sea (right)](image)

![Figure 3: Comparative trendline for pump sump water level and seawater high and low tide levels. (Note: Intake screen was clogged and cleaned on 9 Sept 2014)](image)
As preventive measure, a monitoring of the sump pump level is done on continuous basis. The measurement is compared to the seawater tide level to assess the required cleaning of the meshed screen.

An evaluation of biofouling was conducted by submerging two sets of pipe specimen in the seawater at the pumphouse in the referred plant. The growth of the marine organisms is monitored on selected days with the first set of specimen. The other set of specimen is meant for control purpose which is lifted up for observation at the end of the monitoring period. Refer to Figure 4. The observation provides insight on the local fouling rate which is very useful to plan for the cleaning frequency of the intake meshed screen.

![Figure 4: A review of marine fouling growth at the pumphouse in the referred plant.](image)

For an onshore pumping station, the installation and operation of the active screens is comparatively better than the offshore station. Stop gate can be installed and crane facility can be made available to allow access for periodic thorough cleaning and maintenance for the screens. For the offshore pumping station, this can be quite challenging and expensive, thus it would not be feasible to do this on frequent basis.

3.3. Intake sedimentation issues

2 types of sedimentation are normally faced for pumping stations, typically referred to as coarse and fine sediments, distinguished by the particulate sizes. For an onshore pumping station, a settling basin can be installed prior to the pump sump to separate the sediments from the water. For an offshore station, to have this would require a relatively larger pumping station and thereby higher capital investment.

Coarse sediment is associated with particulates of size normally larger than medium sand (0.25mm – 0.125mm) [5]. Carryover of coarse sediment can lead to increased sedimentation onto the sump floor. Increased floor level reduces the sump water retention volume which can lead to fast drop in sump water level when the intake screen is badly clogged.
Over a long period, the sedimentation can also be compacted under hydrostatic pressure to produce new permanent floor profile, especially where the flow velocity is low or water is stagnant within the confined pump sump area. This new profile deviates from the earlier intended design for the sump and influences the intake flow field.

As per [6,7], the pump sump design with small clearance between the intake bellmouth and floor is desired to obtain adequate submergence. However, with very small floor clearance, the flow velocity will increase at the pump intake. Based on a study with single pump intake [3], the critical submergences for both air cored surface and sub-surface vortices are proportional to the flow velocity in the sump. As such, both vortices will occur and it would be difficult to apply anti-vortex device within the small clearance.

The new floor profile created by coarse sediment can reduce this clearance over years of operations. Reduced cross-sectional areas with converging profile can be formed, creating high velocity flow and low pressure region under the pump bellmouth. The presence of this low pressure region promotes the formation of sub-surface vortices and cavitation [2]. In addition to this, reduced floor clearance can pull in the coarse particles which can lead to impact and erosion damage of pump and piping components.

On the other hand, fine sediment is associated with fine sand normally with size 0.25mm – 0.062mm and silt of size 0.062mm – 0.004mm [5]. Fine sediment can flow with the pump water intakes and with high particle concentration, it can cause problem with the pump internal flushing and lubricating water system.

A study involving sandy clay composing of very thin particles and 15% fine sand showed that intake of high fine sediment concentration at high flow rate results in higher pump NPSH curve for silt mixture compared to that for water alone. This, being sensitive to viscous flows rather than gravitational forces, accelerates the cavitation occurrence for centrifugal pump [8].

The sediment also adds up to the density of the intake fluid mixture, thereby reducing the pump water discharge capacity and would cause problems for the equipment located downstream such as the heat exchangers and electrolyser plating at the electrochlorination plant. When any one or all pumps are not in service for extended period, the fine sediment settles down to the sump floor and leads to the similar floor issues associated with the coarse sediment.

In the referred plant, the sedimentation level and floor profile are measured and monitored on yearly basis. Diver is sent underwater to take the depth of the top layer of the sedimentation level in the pump sump. Figure 5 and 6 show the measured profile of the floor in the referred plant.
A key disadvantage of an offshore pumping station when compared to an onshore station is its limited accessibility to enable inspection and cleaning of the sediments. Dredging is scheduled periodically to restore the floor profile. Since the work is very expensive, it is prudent for the sub-layers of the floor to be assessed periodically to determine the extent of the sedimentation and the best dredging method to restore the condition. Silts and soft clay layer can easily be removed with suction dredger. More extensive and expensive dredging methods, such as grab, trailer or hopper type dredger, would need to be employed for the removal of thick layers of hard and coarse sand and grades, though not all method can obtain access into the pump sump for the dredging work.

3.4. Marine fouling on pump sump walls and structures
The pumping station would have been designed in the beginning without wall roughness taken into consideration. Model test conducted for pumping station tends to be with clean and smooth walls. Over years of operations, the walls can develop roughness that would affect the flow boundary layers which can influence the flow field and the formation of vortices. For the onshore station, these can be cleaned and cleared during shutdown and overhaul period but it would not be possible for the offshore station.

For the referred plant, the pump sump is surrounded and bounded by sheetpile structures. Within the sump, there are concrete columns including those located between the pumps. Both sheetpile and columns are normally fully covered with marine growth such as barnacle and seaweed.
The effect of wall roughness on flow field inside a single pump intake was investigated through a simulation with the high Reynolds number and a $k - \omega$ model. It was found that wall roughness can reduce the intensity of both surface and sub-surface vortices. The study suggested for potential use of an artificial roughness as vortex suppressor on pump intake [9]. This would work provided the wall roughness can managed and sustained within the stipulated tolerances.

4. Model Test
ANSI/HI 9.8 1998 recommends physical hydraulic model to be done for pump intakes with specific design and operating conditions to ensure the final design produce favourable flow conditions for the pump [1]. Sump design alteration and anti-vortex devices can be incorporated and assessed in addressing any notable vortices and unwanted flow profiles. Physical model tests are mostly done during design stage of the pumping station but may not be suitable for in-service system due to changing conditions and unobtainable information such as on the marine fouling, floor profile and reduced clearance, carryover of sediments and extent of flow restriction by the intake screens which are difficult and complex to evaluate and determine. To model them would be expensive, resource- and time-consuming while the result may not be accurately applied throughout the pump operational period.

Computational fluid dynamic (CFD) methodology is an attractive alternative to study and assess the pumping station with changing conditions. The application of this technique for the study of flow profiles in pump intakes is not new and had found good agreement with the experimental methods [2,3,10,11,12,13] and found good agreement between the two methods. Various topics pertaining to CFD techniques had been studies, such as two-phase modelling [7,14,15,16] and turbulence modelling [17,18,19].

5. Condition Based Assessment
It would be of high value to be able to assess the apparent symptoms of the sump flow problems such as vortex formation and sedimentation issues. There are numerous condition based assessment techniques available, such as vibration analysis, oil analysis, thermography inspection, and motor current signal analysis, to detect pump mechanical. The use of ultrasonic methods which were time of flight, Doppler and imaging techniques, had been studied to detect vortex formation in open volumes and closed ducts and were found successful [20]. However, most of these techniques can only identify the problem when the condition has already worsened.

A review the presence of flow anomalies is attempted with the available operating data such as the sump water level and pump common discharge pressure in the referred plant. Starting with a generic pumping system equation,

$$\dot{Q}_p = \dot{W} = \Delta E_n + \Delta KE + \Delta PE$$

Which is expanded into;

$$\Delta H_p = \Delta H_{F1-2} + \Delta H_{Eq1-2} + \frac{1}{2g} (v_2^2 - v_1^2) + (z_2 + H_2) - (z_1 + H_1)$$
is the pressure increase by the pump while \((\Delta H_{F1-2} + \Delta H_{EQ1-2})\) is the total losses within the pumping system [21].

The data plots for the relationship between the total system losses and the measured sump water level \(z_1\) and pump common discharge head \(H_2\) for the referred plant are given in Figure 7 and 8 for all the 3 pumps in service. The data includes the event of low sump water level as refered in Figure 3 above. Theoretically, energy would be loss in generating vortex flow, thus, the total system losses is expected to be register increasing values at low sump water level which would produce the trend that deviate slightly from the normal straight line. As per the plots, the total loss is inversely directly proportional to both parameters and does not indicate any apparent abnormal losses.

![Figure 7: Relationship between calculated total system loss and measured sump water level \(z_1\) for the referred plant](image1)

![Figure 8: Relationship between calculated total system loss and measured pump common discharge head \(H_2\) for the referred plant](image2)

It can be of valuable future research to further refine and look at the detection methods of flow and other sump problems by analysing the apparent symptoms and reviewing the operational parameters.

6. Prevention of Vortex and Sediment Problems within the Sump

Vortex and sediment problems can be eliminated either by adhering to several published design guidelines for the proper design of the sump, or with the installation of anti-vortex and sediment control devices [1,5,6,22,23]. Solutions for vortex prevention vary based on the sump design and operating conditions. Studies using both the test models and CFD models had been done to check the effectiveness of the various employed solutions such as floor splitter [2], conical device with eight fins [24], sidewall and backwall fillets, centre floor splitters and curtain wall [25] and rectangular bar with trident shaped fixture [26].

Solutions for the vortex and sediment problems are best studied and taken during the design stage and when they occur during the operational stage, the solutions can be very difficult to be incorporated. Most of the design fixes from the guidelines, especially those for eliminating subsurface vortex, would require the access to the major parts of the pump sump and would not be economically practical for the offshore station.

For the offshore station, the preferred solutions are with features that can be managed with limited access or moveable with the vertical pump during its routine overhaul. A study on 3 vortex elimination methods involving bellmouth circle ring, backwall clapboard and approaching vertical clapboard was made using CFD. While the first 2 methods were found beneficial to correct the flow field, the vertical
clapboard was not advised due to its contributing to flow pattern deterioration [27]. This is a potential future research area that would be of beneficial to the offshore station.

7. Conclusion
The paper reviews and lists several potential operational challenges and difficulties experienced with the offshore pumping station. The influences of changing conditions such as varying seawater tide level, clogged intake screen, intake sedimentation issues and marine fouling on the sump walls and structures, are discussed and mitigating solutions are identified. While it is impractical to conduct physical model test for studying flow pattern, the CFD method can be an attractive assessment tools. In addition to this, a review of plant operating parameters can assist in identifying flow anomalies to anticipate potential deterioration. Finally the difficulty in incorporating the solutions to vortex and sediment problems within the sump is highlighted with preference for those which can be managed by limited access or those which are moveable with the vertical pump.

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