Proceedings of the 39th IAHR World Congress
19–24 June 2022, Granada, Spain
doi://10.3850/IAHR-39WC2521716X20221013

Three-Dimensional Numerical Modelling of Al-Salam Storm Water Pumping Station in Saudi Arabia

Azin Amini[(1)], Martin Wickenhäuser[(2)] and Azad Koliji[(3)]

[(1)] Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
azin.amini@epfl.ch
[(2,3)] BG Consulting Engineers, Ave de Cour 61, Lausanne, Switzerland
martin.wickenhaeuser@bg-21.com
azad.koliji@bg-21.com

Abstract

The Al-Salam Pump Station will be constructed in the framework of Jeddah Storm water Masterplan (JSWM) in Saudi Arabia. The station discharges the incoming flow from the Al-Salam storm tunnel to the Red Sea. Its structure includes a circular deep wet well (22m diameter and 20m depth below the ground) equipped with six pumps, one weir feed channel (6 m length, 10m width) equipped with four pumps, two pumping channels and two gravity discharge channels.

Simulations have been carried out using CFD numerical modelling (Flow-3D) to verify the hydrodynamic performance of such a structure. The hydraulic analysis focuses on aspects such as flow velocity fields and distribution, water elevations, shear stresses and vorticities.

The numerical simulations allowed to verify the hydraulic operation and design/performance criteria. These criteria include the allowable freeboard, minimum shear stress to transport sand particles and organic materials, the critical submergence of pumps for different hydrological scenarios, and finally the pre-swirl angle of the pumps.

Simulation results show uniform velocity distribution in the wet well as well as in the pumping channels and provide plausible information to confirm design criteria fulfilment.

Keywords: Storm water pumping station; Three-dimensional numerical modeling; Hydraulic performance; Shear stress; Pre-swirl angle

1. INTRODUCTION AND OBJECTIVES OF THE STUDY

In past decades, stormwater management has become an essential component of resilient urban development. Urbanization and land use modification is often associated with replacement of natural pervious areas with impervious surfaces resulting in changes in the characteristics of the surface runoff hydrograph (Goonetilleke et al., 2005), increasing stormwater runoff volumes and peak flows (Barbosa et al., 2012). In the absence of sufficient drainage system, cities are subject to urban flooding caused by extreme runoff with potential loss of life and property damage (Fernández and Lutz, 2010, Weber, 2019, Anni et al., 2020).

The city of Jeddah, in the Kingdom of Saudi Arabia, is generally a dry region with infrequent rainfall patterns. In recent years, cases of sudden intensive rainstorms with urban floods have been reported causing casualties and damages (Subyani and Hajjar, 2016, Abu Abdullah et al., 2019, Farooq & Alluqmani, 2021).

With the aim of improving the safety and ensuring a long-term sustainable development, Jeddah Municipality is investing in Jeddah Stormwater Drainage Program (JSDP) with major planning, engineering, and construction of stormwater management infrastructure. The project includes upstream drainage improvements outside of the city, provision of flood control and drainage shafts within the city, the provision of large storm water conveyance systems and pumping stations to transfer storm water to the coastal zone.

As a part of JSDP, a new pumping station known as Al-Salam Pump station, is planned to discharge the incoming flow from the storm water tunnel to the Red Sea via an outfall and an emergency outfall.

The objectives of the study are to confirm and optimize the layout and the design of the pumping station, the foreseen equipment, and the operation procedures from a hydraulic point of view. The hydraulic conditions, focusing on the streamlines, velocity vectors, water levels and shear stresses are analyzed by CFD modelling using the Flow-3D software. CFD models have been largely used to predict the flow patterns and optimize the hydrodynamic behavior in sumps and forebays of pumping stations. Researchers applied different 3D software packages for this purpose. Xia et al. (2017) applied ANSYS-Fluent software to numerically simulate the front pool flow pattern. While Nasr et al (2021) implemented the ANSYS-CFX software to improve the problem of turbulence in the forebay of a lateral inlet in a multi-unit pumping station. Flow-3D has been also used previously in similar studies (Ha et al. 2019). Recently Yang et al. (2021) carried out numerical investigation of flow pattern and anti-vortex measures of a forebay in a multi-unit pumping station using Flow-3D.

2. PROJECT CHARACTERISAION

2.1. Location and layout

The Al-Salam Pump station is located in the Jeddah coastal zone (Figure 1) and discharges the water from an incoming storm water tunnel into the Red sea.

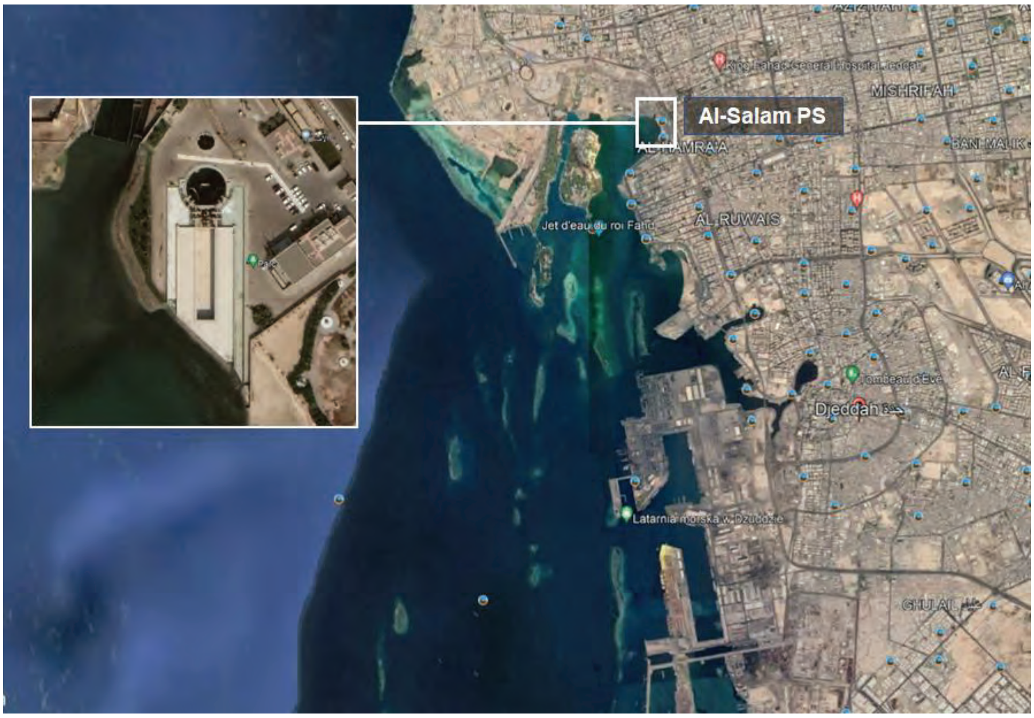

Figure 1. Location of Al-Salam pump station (google.com/map)

As illustrated in Figure 2, the layout for the pumping station foresees:

- One circular deep wet well (area of 380m^2, hydraulic diameter of 22m and depth below ground 20m) equipped with four pumps.
- One weir feed channel (length 63m, width 10m and depth below weir crest 7.5m) also with four pumps.
- Two pumping channels.
- Two gravity discharge channels.

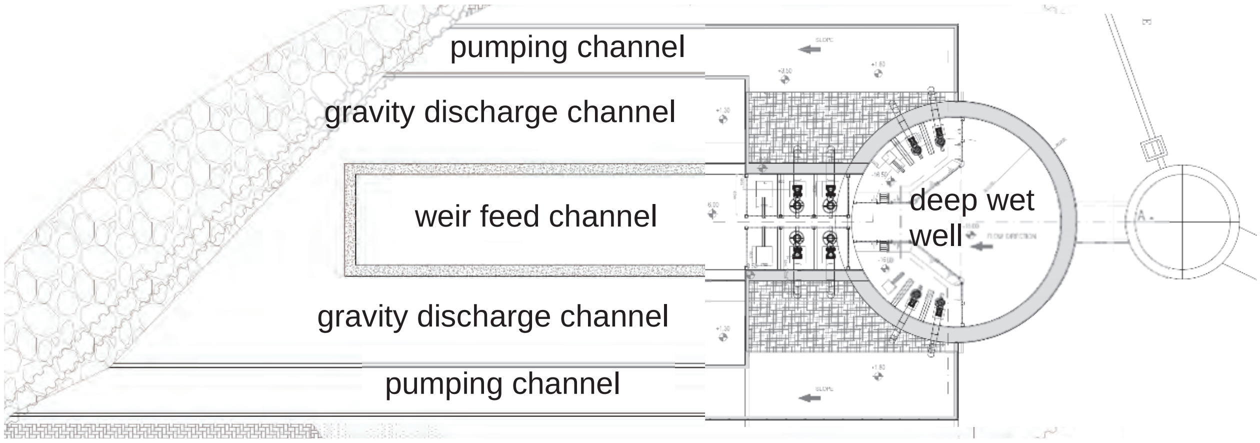

Figure 2: general layout of the pump station

2.2. The hydraulic operation criteria

The hydraulic operation and design/performance criteria are as following:

- The pumping station operation is based on cascade level control with a series of duty start and stop levels following.
- The peak inflow for Al-Salam Tunnel is 12.4 m³/s.
- The individual pump rates of 0.5 m³/s for the wet well pumps and 1.0 m³/s for the weir channel pumps.
- A shear stress of at least 0.6 Pa is required to transport sand particles of 1mm diameter size and density of 2650 kg/m³ and around 1.5 Pa for organic materials with a density of 1050 kg/m³ and diameter of 50mm, respectively.
- The pump operating levels are set with respect to the critical submergence.
- The swirl angles must be less than 5 degrees. However, maximum short-term swirl angles up to 7 degrees may be accepted, if they occur less than 10% of the time or for infrequent pump operation conditions.

2.3. Operational scenarios

The load cases focus on the pumping mode and the drainage mode in steady state conditions:

- Pumping Mode: In this mode, the channel pumps and the wet well pumps are running.
- Draining mode (self-cleansing): In this mode, the wet well pumps are running at specific water level in the well.

3. NUMERICAL MODEL SET-UP

Three-dimensional numerical simulations are carried out using Flow 3D software (v12.0) from “Flow Science” company. This software is used to solve three-dimensional Navier-Stokes equations for any geometry provided as an STL file. The geometry is approximated by the fractal volume method implemented in the Favor algorithm. Flow-3D is particularly suitable for the simulation of free surface flows thanks to the Volume of Fluid algorithm (VOF) allowing to track the shape and position of the fluid interface.

Flow-3D has been initially applied to analyze the hydraulic performance of Al-Salam pump station at an earlier stage of project design (AECOM Jeddah, 2019).

3.1. Simulation parameters

The numerical model takes into account the gravity and turbulence model RNG (Re-Normalized Group). The water is defined to be at 20 degrees Celsius, with a density of 1000 kg/m3, and a dynamic viscosity of 0.001 kg/m/s.

3.2. Geometry and mesh

The model geometry is illustrated in Figure 3. All simulations are preliminary run with a rather coarse mesh of up to 0.4 m cell size. A coarse mesh allows to reduce the computation time and to define the water surface within which Flow3D will calculate the hydraulic parameters. Once a steady state condition is achieved, the mesh is refined and the simulation is relaunched. The final cell size is 0.1 m within the wet well and pumped zone. In order to better simulate the pump pre-swirl and vortices, in the vicinity of the pumps in the wet well nested mesh blocks with very fine cell size (0.05 m) are employed.

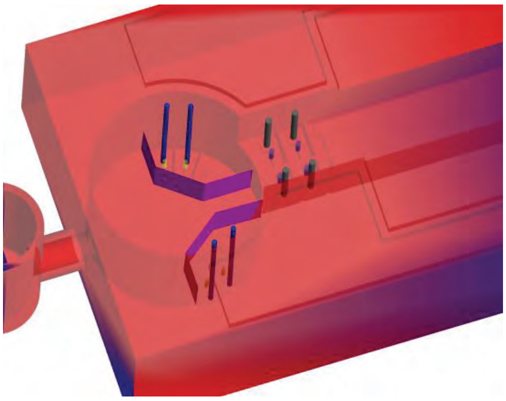

Figure 3: Details of the pump station model, including the pumps, the floor splitters and the protection screens

3.3. Modeling of the protection screens

The protection screens in the wet well and the weir channel are made of stainless steel bars with 0.008m width placed at 0.1 m distance from each other. As mentioned before, the mesh cell size in the numerical model is 0.2 m in the entire model and 0.05 m in the area close to the pumps. In order to model the bars, a highly finer mesh is required, which is not convenient due to significant increase in cell numbers and consequently calculation time. To cope with this problem, the protection screens are introduced into the model as flux surfaces (baffles) with a certain porosity that allows to assimilate the head losses due to the protection screens. Flux surfaces are three-dimensional elements that reside between calculation cells (Figure 4).

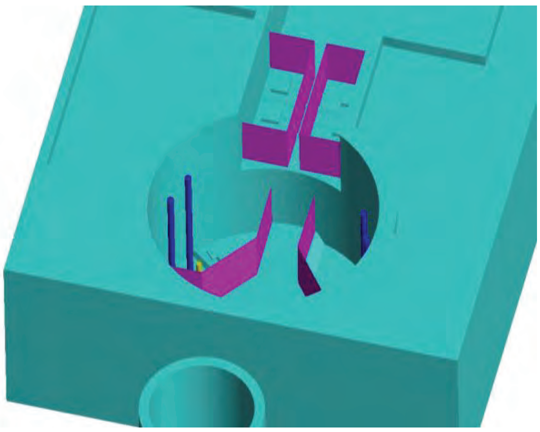

Figure 4: Modelling of the protection screens

The porosity of the flux surface defines the portion of open space in the screen that allows water to pass through this material. In this model, the porosity of the baffles is set to 0.9 and a head loss of 5 cm is assumed for the range of velocities of the simulated load cases. This head loss value corresponds to the case of bar screens which are often cleaned.

3.4. Boundary and initial conditions

For pumping mode scenarios, only the pump discharge channel is simulated. The pumps outlets are simulated as mass momentum sources. The position and inclination of the sources are defined as per final drawings (Figure 5). The mass source has the same diameter as the pipes, e.g. 0.6 m for the wet well pipes and 0.8 m for the weir channel pipes.

For drainage mode scenarios, the model is initiated with wet well filled up to desired water level. The initial and boundary conditions of simulated scenarios are summarized in Table 1.

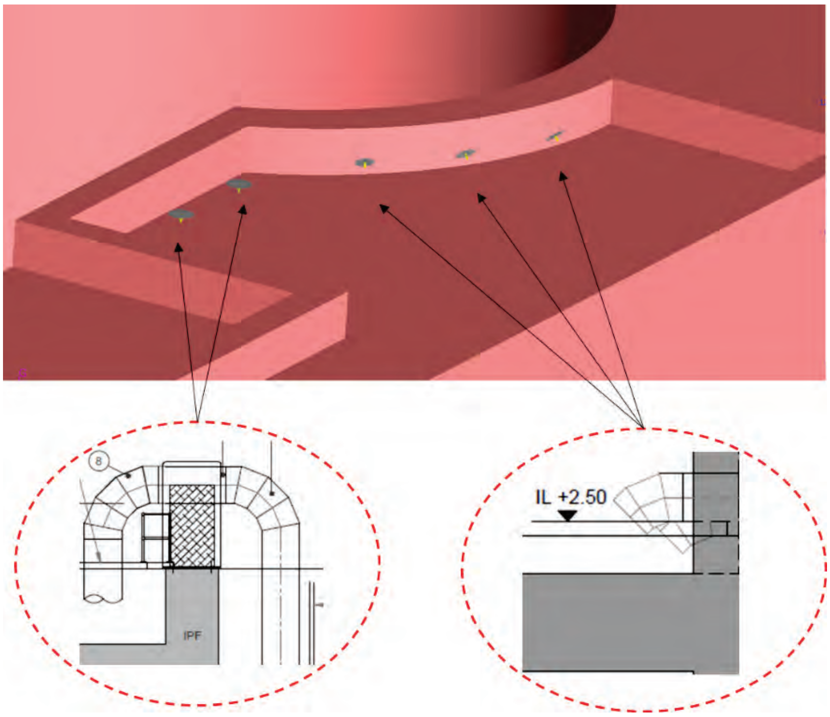

Figure 5: The pump discharge channel with weir channel pump outlets (left) and wet well pump outlets (right) as mass momentum sources

Table 1: Initial and boundary conditions (B. C.) for the simulated scenarios

Simulated mode	**Initial condition**	**Inlet B. C.**	**Outlet B. C.**
Pumping mode:	Dry	Wet well and weir channel pumps as mass momentum sources (discharge of 0.5 or 1 m^3/s)	Outflow boundary with zero gradient at downstream end of the discharge channel
Drainage mode: • Single pump • Three pumps	Initial fluid elevation	Inlet inflow	Wet well pumps and weir channel pumps as mass momentum sinks

3.5. Simulation's duration and finish condition

All simulations are carried out to achieve a steady state of flow in the entire model. The steady-state watch list includes the total mass and the average mean kinetic energy. Once these parameters get to a variation threshold of 1% the steady state is achieved, and the simulation is stopped.

4. SELECTED RESALTS

Some selected results are presented in this chapter.

4.1. Pumping mode

General hydrodynamic behavior

At a first step the velocities and streamlines were extracted for different load cases, in order to understand the hydrodynamic behaviour of the structure. Figure 6 shows the results of the simulated flow velocity (m/s) and streamlines in the pumping channels for the load case with 4 wet well pumps and 4 channel pumps in operation.

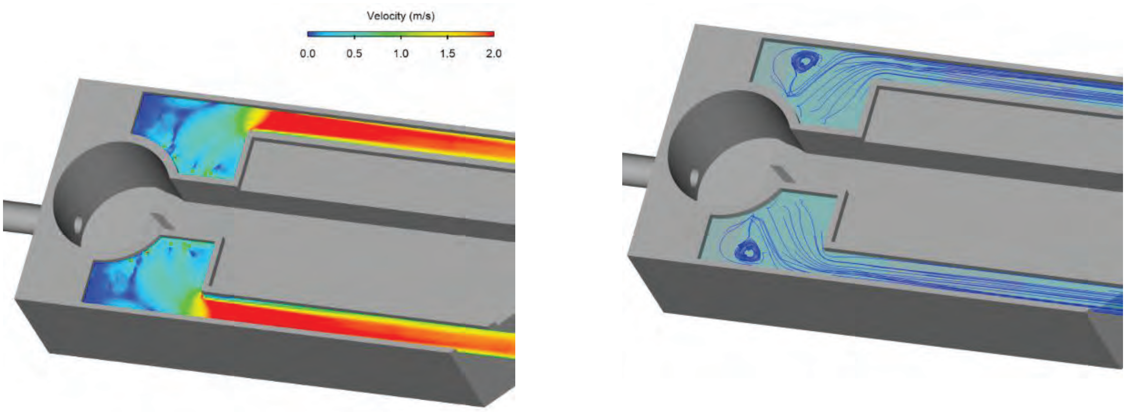

Figure 6: Results for the load case with 4 wet well pumps and 4 channel pumps in operation. Left: Flow velocity (m/s) in the pumping channels; Right: Streamlines in the pumping channels.

Shear stresses

The shear stress values range between 0.25-2.0 Pa within the discharge region and above 2Pa along the pumping channels. The dark blue zones with shear velocities below 0.5Pa are stagnant zones presenting the risk of sediment accumulation.

The shear stress distribution in the pumping channels shows some zone of shear stresses below 0.1 Pa. However, by varying the operation of the pumps, as incorporated in the operating philosophy, all zones of the pumping channels should be exposed to sufficient share stresses to mobilize the sediments.

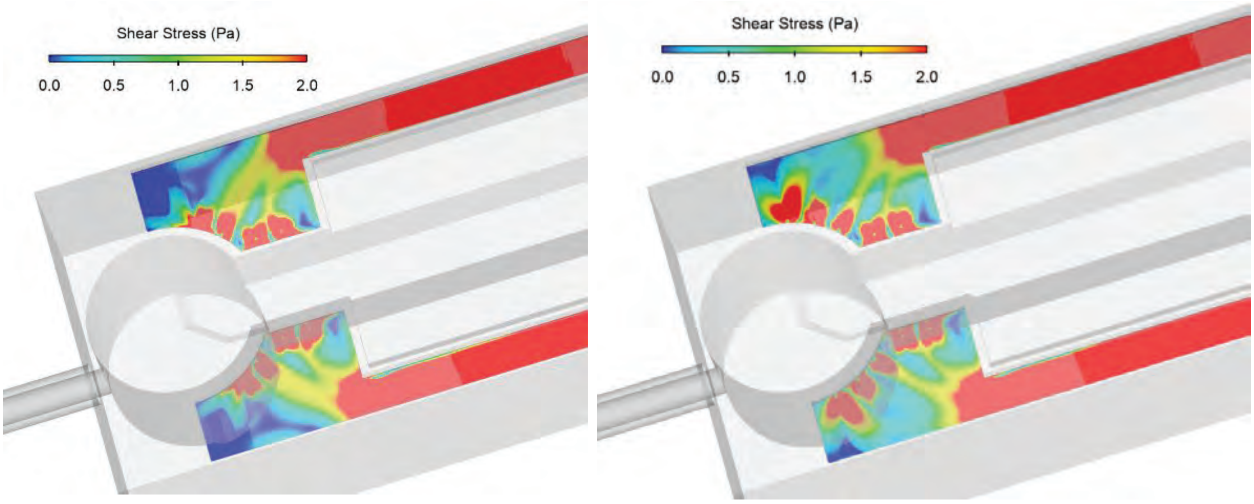

Figure 7: Shear stresses (Pa) in the pumping channels: Left: for the load case with 4 wet well pumps and 4 channel pumps in operation; Right: for the load case with 6 wet well pumps and 4 channel pumps in operation.

4.2 Drainage mode : subsurface vorticities and pre-swirl

Figure 8 present the steam lines and the flow velocity in the wet well during draining mode for one pump in operation (left image) and three pumps in operation (right image).

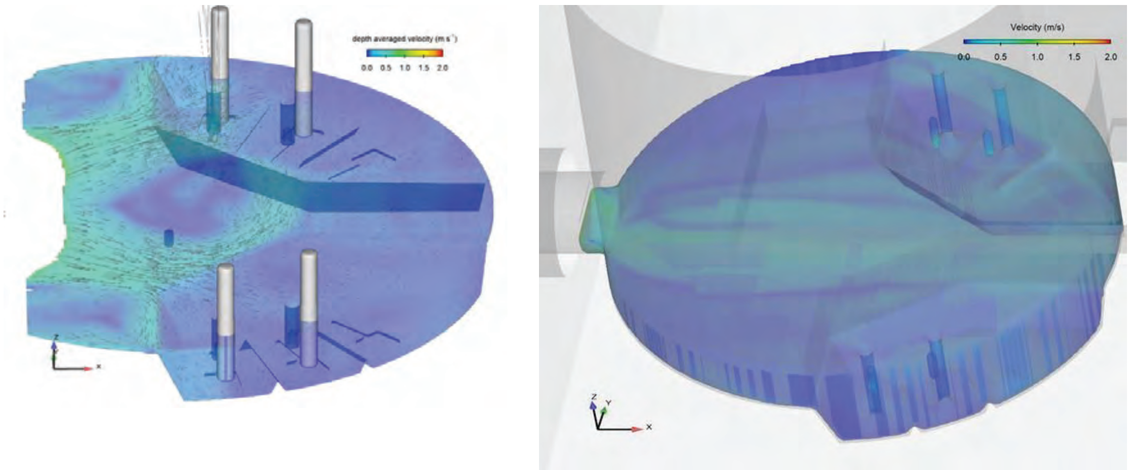

Figure 8: Flow velocity in the wet well during draining mode: Left: one pump in operation; Right: Three pumps in operation.

According to ANSI/HI 9.8 (2018) the most effective way to reduce pre-swirl is uniform approach flow conditions and by providing floor splitters under the pump intake. The following figure presents the positive effect of the pump conditions and the design of the floor splitters for the most critical in draining mode, when only one wet well pump is operating, for pre-swirl action. The swirl angle remains, as required, less than 7 °.

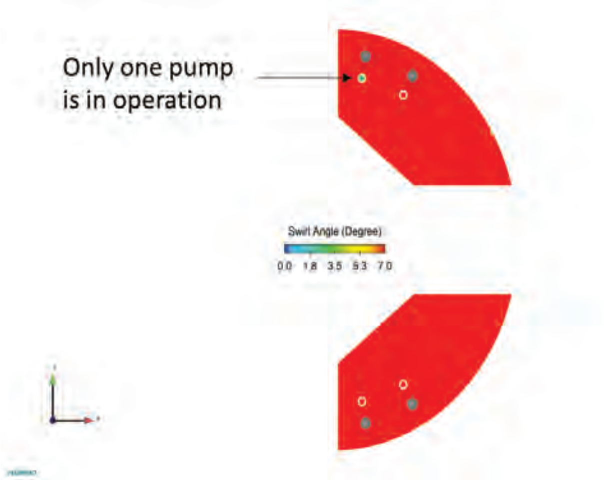

Figure 9: Pre-swirl angle in the wet well while only one pump is in operation

5. CONCLUSIONS

The CFD modelling allowed to validate and optimise the hydraulic design of the pumping station and the equipment and draw the following conclusions:

- The flow velocities, the velocity distribution, and the flow field in the wet well as well as in the pumping channels are acceptable.
- The shear stresses and the shear stress distribution in the wet well as well as in the pumping channels are high enough. Therefore, the station has an acceptable self-cleansing capacity. In addition, by varying the operation of the pumps, as incorporated in the operating philosophy, all zones of the pumping channels should be exposed to sufficient share stresses to mobilize the sediments.
- The minimum pump submergence is confirmed.
- The pre-swirl angles for the investigated load case 3 reach up to 7 degrees. Therefore, it is also recommended to install cruciform flow conditioning devices below the wet well pumps to keep the pre-swirl angles in the acceptable limits.

Therefore, the hydraulic functionality of the Al-Salam storm pumping station and the operation procedure are validated.

Figure 10: Al-Salam Storm pumping station wet well in construction in February 2020 (photo courtesy Abuljadayel Co. for Cont. & Maint,)

6. ACKNOWLEDGEMENTS

The authors appreciate the permission granted by Abuljadayel Co. for Cont. & Maint. to publish the main results of the hydraulic analysis of Al-Salam pumping station and thank Engineer Rateb Jawish and Eamonn Leavey for their special help and support. The authors also acknowledge the contribution of Geotest Ltd and Stunex Ltd on the early stages of the project.

7. REFERENCES

Abu Abdullah, M.M., Youssef, A.M., Nashar, F. and Abu Al Fadail E. (2019). Statistical analysis of rainfall patterns in Jeddah City, KSA: future impacts, *Chapter 9 of: Rainfall - Extremes, Distribution and Properties*, Editors: Abbot J., Hammond, A., Publisher: IntechOpen.

AECOM Jeddah (2019). Al-Salam pumping station CFD modelling, unpublished report.

Anni, A.H., Cohen, S. and Praskievicz, S (2020). Sensitivity of urban flood simulations to stormwater infrastructure and soil infiltration. *Journal of Hydrology*, 588 (9).

ANSI/HI 9.8 (2018). Rotodynamic Pumps For Pump Intake Design

Barbosa, A.E., Fernandes, J.N. and David L.M. (2012). Key issues for sustainable urban stormwater management, *Water Research*, 46 (20).

Farooq, Q.O. and Alluqmani, A.E. (2021). Application of soil based low impact development system for Flash Flood management of Jeddah, Saudi Arabia, *Journal of King Saud University - Engineering Sciences*, (12).

Fernández, D.S. and Lutz, M.A. (2010). Urban flood hazard zoning in Tucumán Province, Argentina, using GIS and multicriteria decision analysis, *Engineering Geology*, 111, 90-98.

Goonetilleke, A., Thomas, E., Ginnc, S, and Gilbert, D (2005). Understanding the role of land use in urban stormwater quality management, *Journal of Environmental Management*, 74, 31-42.

Ha, S.W., Kim, T.W., Choi, J.H. and Park, Y.J. (2019). Study for Flow Phenomenon in the Circulation Water Pump Chamber using the Flow-3D Model, *Journal of the Korea Academia-Industrial,* 20(4), 580-589.

Nasr, A., Yang, F., Zhang, Y., Wang, T. and Hassan, M. (2021). Analysis of the Flow Pattern and Flow Rectification Measures of the Side-Intake Forebay in a Multi-Unit Pumping Station, *Water*.

Subyani, A.M. and Hajjar A.F. (2016) Rainfall analysis in the contest of climate change for Jeddah area, Western Saudi Arabia, *Arabian Journal of Geosciences*, 9 (122).

Weber, A. (2019). What is Urban Flooding? *Natural Resources Defense Council (NRDC)*, https://www.nrdc.org/experts/anna-weber/what-urban-flooding

Xia, C.; Cheng, L.; Zhao, G.; Yu, L.; Wu, M.; Xu, W (2017). Numerical simulation of flow pattern in forebay of pump station with single row of square columns. *Adv. Sci. Technol. Water Resour*. 37, 53–58.

Yang, F., Zhang, Y., Liu, C., Wang, T., Jiang, D. And Jin, Y. (2021). Numerical and Experimental Investigations of Flow Pattern and Anti-Vortex Measures of Forebay in a Multi-Unit Pumping Station, *Water*.

