Hydraulic Design of Intake Channels in Drainage Canals of Highly Suspended Sediment Load
Case of “El-Qatee” Lifting Plant
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Abstract
One of the main concepts of design intake structures is to minimize the sediment ingestion into the pump house and guarantee pump efficiency and achieve less frequency of dredging. In most of the cases this concept can be satisfied through the design of a sediment trap within the intake structure to capture most of the sediment load entre the intake. In this paper, the objective of minimizing the sediment load reach to the pump suction point is examined under the case of water ways with highly suspended sediment concentration. It was reported that the intake structure and intake channel for a lifting plant at Fayoum Governorate called “El-Qatee” are suffering from very high sedimentation problems. Sediment accumulates and fill the channel every four months and partially block the entrance and decrease the pump subtraction capacity. The sedimentation process at the channel was simulated and analyzed through the development of a 3-D morphological model using cohesive and non-cohesive sediment modules of Delft3D model. The model was hydro-dynamically and morphologically calibrated against field data collected for the study in May 2015. Different design criteria were checked to minimize the deposition rate. Design that maintain high velocities to prevent the deposition of fine suspended materials gave a good results and prevented the accumulation of the sediment in the channel. Based on the detailed simulation results and analysis, the alignment and dimensions of intake channel with its approaching channel have been modified in order to hydraulically satisfy both the sedimentation problem solving and the suction blocking prevention.

Keywords: Lifting Plant, Cohesive Sediment, Numerical Simulation, Delft3D, Drainage Canals, and Egypt.

1. INTRODUCTION

River side intakes for power-plant, municipal, industrial, and irrigation are often beset by sediment deposition (Tatsuaki, John 1990). Design of the river side intakes requires prevention of bed and suspended load transport. Sedimentation process causes many problems such as reduction in flow discharge capacity in irrigation canals as well as threatening water blockage during low flows. Therefore, the main goal for the design of an intake is to maintain higher flow discharge and low sediment delivery (Mehdi, Mahmood 2010). Blocking of diversion intakes and canals by sediment deposition is a widespread problem in many spate irrigation (flood water farming) systems, sedimentation is a continuous challenge that resulted in 75% reduction of the cultivated land (Tewedros, Yasir 2015). Similarly, the pumping capacity of the lifting plant for the case study of this paper have been decreased by 50 % after four months of operation. The most reliable means for designing intakes that are different in situ conditions is model testing. The reproduction of sediment movement that is geometrically and dynamically similar to the prototype situation is the most important factor (Whittaker 1984). Therefore, Morphological behavior of the sediment movement in the field was observed then morphologically calibrated in the model used in this paper.

Many water intakes were constructed along the Nile River. So, the inlet of these intakes must be designed in an appropriate way to mitigate vortices and/or sedimentation problems. Many researchers as (Fahmy, Esam 2008, Sayed 2013) studied intakes at Nile River where the bed sediment mean diameter, $D_{50}$ varies from 0.29 to 0.45 mm, while, suspended sediment load is minor. In this study the main concern was the suspended load of a mean diameter, $D_{50}$ less than 0.1 mm. Sediment deposition reduces the withdrawal capacity, causes damages to the pumping system and causes partial or full blockage of the intake (Fahmy, Esam 2008).
Mitigation measures for power plant faces sedimentation problems are mainly confined to dredging as in "Rod El-Farag" (Moussa and Ahmed 2010) and submerged vanes as in New Tebbin (Sayed 2013). However, dredging was recommended as a supplementary solution for sediment removal in many pump stations that face sedimentation problem at its intake, still this solution in some cases is not economically effective. Sedimentation problems is relatively common along the Nile River, for example, “MATAI” water intake located near Assiut Barrage faces sedimentation problems due to highly variable flow regime during the year (Sallam 2015). Elsaeed, Bahgat (2016) studied different alternatives to improve the hydrodynamic processes in the vicinity of El Kuraimat power plant intakes and finally changing the topography of the island in the surrounding area showed good results. Within the study case of this research, dredging work was considered as an expensive solution due its repetitively occurring every four months. Therefore, controlling the sediment and minimizing the sediment deposition rate was the technique applied in this study.

The Ministry of Water Resources and Irrigation (MWRI) officials recognized that reuse of agricultural drainage water will be a key solution for meeting increasing demands for water in the next decades (Khater, Kitamura 2014). Lack of experiences in the design of intake channels located at waterways with high suspended load concentration makes these intake channels subjected to severe deposition problems that require continuous dredging.

The objectives of this research is to assess, analyze and mitigate the sedimentation problem inside the intake channel by developing a well calibrated 3D morphological numerical model. Deposition in this intake was recorded from field measurements and calibrated in the model. Four solutions were proposed and tested using Delft3D model to check their efficiency in mitigating the sedimentation problem. Accordingly, sediment deposition was predicted under these different designs of the intake channel. Innovative technique of promoting velocities inside the channel showed a viable solution to minimize sediment deposition rate. The design applied in this study can be disseminated to be used in various intake channels inside Egypt and worldwide.

2. STUDY AREA AND PROBLEM DESCRIPTION

El-Qatee lifting plant withdraws water from “El-Wadi” drainage canal as shown in Figure (1). This earthen agricultural drainage canal is usually subjected to high suspended load flows from the upstream. The lifting plant feeds two canals in El-Fayoum Governorate. The pump units’ maximum capacity is 3 m³ s⁻¹ which decrease gradually due to sedimentation problems. Baraka drain disposes 0.2 m³ s⁻¹ water in “El-Wadi” drain just upstream “El-Qatee” lifting plant as shown in Figure (1). This water is coming from drainage disposal and contain high suspended load. Intake channel size is 25 m width, 50 m length, and 2.5 m depth. Mean velocities in “El-Wadi” drainage canal didn’t exceed 0.5 m s⁻¹ and 0.05 m s⁻¹ inside intake channel.

The intake suffers from a sever sediment deposition problem up to 1.5 m depth every four months. The sediment deposition at the intake reduces pumping capacity to 50%. Several measures were implemented to mitigate this problem and reduce the dredging frequency confined mainly to hydraulic structures that control water level and reduce bed load transport inside the intake channel. However, none of those measures led to sustainable and desirable results. Therefore, it was decided to study the sedimentation problem within this pump intake structure in more details using 3D hydro-morphological model. A study reach of 580 m length was selected where “El-Wadi” drainage canal and “El-Qatee” pump station are located as shown in Figure (1).
Figure 1: Velocity Cross Sections and Bathymetry Cross Sections in The Study Area

(V. S.) stands for velocity cross sections shown in Figure (3), (B.S.) stands for bathymetry sections

3. DELFT3D MODEL

Delft3D numerical model was used to assess the existing sedimentation problems and analyze the subsequent remedial measures. Delft3D-FLOW solves the Navier Stokes equations for an incompressible fluid, under the shallow water and the Boussinesq assumptions. In the vertical momentum equation, the vertical accelerations are neglected, which leads to the hydrostatic pressure equation. In 3D models the vertical velocities are computed from the continuity equation. The set of partial differential equations in combination with an appropriate set of initial and boundary conditions is solved on a finite difference grid (Deltares 2014). In three-dimensional simulations, a boundary fitted (σ-coordinate) approach is used for the vertical grid direction.

A comprehensive knowledge of Delft3D model is necessary to obtain a reliable result for the morphological prediction in the area of interest. Delft3D is shown to perform well in several theoretical, laboratory, and real-life situations (Lesser, Roelvink 2004). Computer modeling of sediment transport patterns is generally recognized as a valuable tool for understanding and predicting

morphological developments (Lesser, Roelvink 2004). This model can be used with good accuracy in the field of the hydrodynamics (Carlos, Roberto 2005). In practice, state-of-the-art computer models are one-or two-dimensional (depth-averaged) and have a limited ability to model many of the important three-dimensional flow phenomena found in nature (Lesser, Roelvink 2004). Sedimentation problem of Rosetta branch of the Nile river in Egypt was investigated using Delt3D model by (Ahmed 2004) and three alternatives were simulated and the proper solution was chosen based on less environmental impact.

A 3D hydrodynamic model was developed by (Ahmed, Abou-Elhaggag 2012) to cover the Gulf of Aqaba which is affected by man-made desalination plants using Delft3D model. The DELFT3D-FLOW module was implemented to validate sediment transport for suspended and bed load transport of non-cohesive sediment by (Lesser, Roelvink 2004) and the model is shown to perform well in several theoretical, laboratory, and real-life situations. (Gessler, Raphelt 1999) developed a 3D model for river morphology, which includes separate solvers for bedload transport and 3D suspended transport. It considers several size fractions of sediment and keeps track of the bed composition and evolution during each time step. Delft3D was capable of simulating the interaction between cohesive (mud) and non-cohesive (sand) modules and showed good results for predicting the combined effect of these two theoretical modelling approaches incorporated in the Delft3D software. This makes the online sediment version of DELFT3D-FLOW especially useful for investigating sedimentation and erosion problems in complex hydrodynamic situations (Lesser, Roelvink 2004).

4. FIELD DATA COLLECTION

Topographic survey was carried out using LEICA, Swiz GPS 500, 1200 and Viva. Bathymetric survey was carried out for 580 m distance covering the study area reach using fiber rubber boats during May 2015 using TAMAYA TDM-9000 Echo Sounder TOKYO, JAPAN. It is a compact and advanced precision echo-sounder and used for measuring the bottom profile. The instrument is connected to a pen recorder for plotting the sea bed configurations with a range of 0.70-100 m and accuracy of ± 0.03 m. Velocity profiles were measured using BRAYSTOCK, England current meter at different places as shown in Figure (1) to fulfill the model calibration. The range of the current meter is 0.02 m s\(^{-1}\) to 4.0 m s\(^{-1}\) and accuracy is ± 0.5 cm s\(^{-1}\). Flow discharges were calculated at “El-Wadi” drain and inside “El-Qttee” intake channel. It was found that “El-Wadi” drain discharge was 4.6 m s\(^{-3}\) and “El-Qttee” lifting plant discharge was 3 m s\(^{-3}\) and decrease gradually after four months of operation due to sediment blockage. Historical data about sediment deposition inside the intake channel and frequency of dredging were collected.

Soil samples from “El-Wadi” drain and inside “El-Qttee” intake channel were collected. Soil samples analysis showed that, “El-Wadi” drain soil mainly consists of coarse sand of D\(_{50}\) equal to 2 mm. While, soil material in “El-Qttee” intake channel consists of 75% silt of D\(_{50}\) equals to 0.02 mm and 25% fine sand with D\(_{50}\) of 0.07 mm. This confirms that sediment deposition occurring inside the channel comes from suspended particles. Sediment concentration at “El-Wadi” drain is 147 ppm and 215 at “El-Qttee” intake channel. The source of sediment is coming from the habits of farmers to release the domestic discharges in “El-Wadi” drain.

5. MODEL SETUP AND CALIBRATION

Three dimensional morphological numerical model was developed to compute and predict sedimentation process. The model covers 580 m length in “El-Wadi” drainage canal and the intake channel of “El-Qatee” pump station as shown in Figure (1). Size of the grid cell is about 1.5 m in the area of interest as shown in Figure (2). The grid was developed to match the layout of the land contours as much as possible. The grid considers the most recent site geometry, as determined from the survey data of the year 2015. In addition, care was taken that the model grid meets all criteria for grid orthogonality and smoothness. The quality of a grid is to a large extent determined by its orthogonality and the rate with which certain properties change over the area to be modelled (smoothness).

A measure for the orthogonality is the angle, or the cosine of the angle, between the grid lines (cos(\(\phi\)) < 0.02), where \(\phi\) is the angle between the grid lines. A measure for the grid smoothness is the aspect ratio of grid cells and the ratio of neighboring grid cell dimensions. The bathymetric data was mapped through an interpolation procedure on the computational grid of the model. In this way, each coordinate of the computational grid of the model was given a depth value. The model time step was
chosen to be 6 seconds. The model boundaries were chosen far from the intake channel, to ensure that the hydrodynamics and sediment dynamics would not get affected. The upstream boundary condition is a constant discharge value of 4.6 m$^3$ s$^{-1}$ and downstream boundary condition is a water level of $-36.1$ m.

The model was calibrated for both hydrodynamic and morphological simulation to ensure its capability of simulating the behavior of sediment as in the field, and then it can compute and predict the morphological changes processes. During the model calibration, the measured water surface slope and the measured depth averaged flow velocities along the measuring cross sections as shown in Figure (1) were compared with the model results as shown in Figure (3). Tuning of the roughness parameter in the model was carried out to obtain the best match between the model and the field measurements. Manning roughness coefficient was taken equal 0.04 along the model area to give the best match between the measurements and model computations. The manning roughness coefficient was high compared to those of the Nile River due to the rough bathymetry of the study area that contain a lot of rocks and rough material in the bed.

For the sake of morphological calibration, comparison of the sediment transport equations of (Rijn, Roelvink 2001) was carried out to investigate the most suitable and reliable predictor in the study area. The analyses of this paper indicated that Van Rijn transport equation computed very high sediment deposition accuracy compared to the field data. Different equations were used inside the model and Van Rijn transport equation gave the best results compared to the measured values. The bed material composition were used as exactly as in the data collected from the field. Then, the model was executed for four months to simulate the same time spent in the field to fill the channel with deposition. The simulation time required to simulate four months was 24 hours in the model. Bed bathymetry at the end of the simulation period inside the intake channel and total amount of sedimentation were analyzed and compared to the field data. Calculated deposition depth at different cross sections within the intake channel was similar to those reported from the field as shown in Figure (4).
Figure 3: Velocity Comparison of Field Data and Model Results at the Selected Cross Sections Shown in Figure (1)
6. RESULTS AND ANALYSIS

In order to find a sustainable solution for the sedimentation problem inside the intake channel of “El-Qatee” pump station, four solutions were proposed as shown in Table (1) and simulated in Delft3D calibrated model. In addition to the objective of minimizing the sediment reaching intake channel, it was necessary for each solution to maintain the water level inside the intake within the required level to guarantee enough head at minimum discharge situation.

Firstly, Solutions focused on minimizing bed load ingress to the intake channel by constructing a weir at the end of the intake channel but they hardly minimized the sedimentation quantity and rate. Low velocities inside the intake channel didn’t initiate the movement of the bed load and the deposition was mainly suspended silt deposited due to low velocities. Secondly, solutions focused on deepening the channel and creating a bigger intake channel within the intake channel, but succeeded only to decrease the dredging frequency. However, the amount of deposited sediment inside the channel was increased and the rate of filling remained exactly the same. Thirdly, thinking was shifted towards constructing an additional intake channel at “El-Wadi” drain to accommodate sediment and guarantee pure water entering the intake channel. However, still enough sediment could fill the two intake channels.
Table 1: Volume of Deposited Sediment and Corresponding Time Span to Fill the Basin under Different Scenarios

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Time to fill the basin (days)</th>
<th>Volume (m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>120</td>
<td>2000</td>
</tr>
<tr>
<td>Firstly (Weir)</td>
<td>120</td>
<td>1800</td>
</tr>
<tr>
<td>Secondly (Deepening)</td>
<td>120 + 60</td>
<td>2000 (Original) + 3000 (Additional)</td>
</tr>
<tr>
<td>Thirdly (Additional Drain)</td>
<td>120 + 120</td>
<td>100</td>
</tr>
<tr>
<td>Fourthly (Higher Velocities)</td>
<td>120</td>
<td></td>
</tr>
</tbody>
</table>

Fourthly, realizing that most of the deposited sediment reaches the channel as suspended load carried by the flow in “El-wadi” drain. And realizing that the design dimensions of the channel 40 m, 25 m and 2.4 m are large enough to lower the flow velocity to 0.05 m s$^{-1}$, thinking for a proper solution was oriented towards the idea of minimizing the amount of suspended load deposited through allowing for a higher velocity inside the channel as shown in Table (2). Settling velocity of 0.02 mm particles size is 0.004 m s$^{-1}$ and requires only 600 second to fully deposit to the bed. Retention time inside the channel is 667 seconds. This leads to 100% capture capacity of suspended load for particles equal to or bigger than 0.02 mm to deposit during its path to the end of the channel. The critical velocity was determined at a value, above which all particles remain in suspension, while at velocities below this critical limit deposition rapidly occurs. Based on the above analysis, the intake design was narrowed to 8.00 m width instead of 25 m as shown in Figure (5). The flow velocities increased to 0.6 m s$^{-1}$. The modified intake design allows the deposition of particles larger than 0.05 mm only with a settling velocity of 0.013 m s$^{-1}$ and time of 154 second. Smaller particles keep suspended and pass through the pumps.

Table 2: Particles Size, Settling Velocity, Time Required for Deposition, Flow Velocity and the Corresponding Retention Time for the Original and Modified Designs.

<table>
<thead>
<tr>
<th>Designs</th>
<th>Particle Size (mm)</th>
<th>Settling Velocity (m s$^{-1}$)</th>
<th>Time required for deposition (Sec)</th>
<th>Flow Velocity (m s$^{-1}$)</th>
<th>Retention Time (Sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original Design</td>
<td>0.02</td>
<td>0.004</td>
<td>600</td>
<td>0.05</td>
<td>667</td>
</tr>
<tr>
<td>Modified Design</td>
<td>0.05</td>
<td>0.013</td>
<td>154</td>
<td>0.6</td>
<td>133</td>
</tr>
</tbody>
</table>

Results as presented in Figures (6, 7) show that after 4 months of simulation time only 20 cm of sediment was deposited inside the intake channel and 6 years were required to full the channel as the original design. The deposition of the sediment was decreased to 9% compared to the original design and the flow carried the deposition to the pumps and moved through the pumps. It is important to note that 100% reduction of all incoming suspended particles is not feasible due to practical limits of storage space, available settling time and frequent dredging cost. Therefore, the efficiency of a containment system is based on the efficiency of sedimentation of a target soil grain size.
Figure 5: Proposed Intake Design, (B.S.) Stands for Bathymetry Sections Proposed Intake Design, (B.S.) Stands for Bathymetry Sections Shown in Figure (6)

Figure 6: Expected Deposited Sediment After 4 Months of Simulation at the Original (Left) and Modified (Right) Designs.
The water to be pumped contains domestic waste and amounts of entrained solids and due to larger quantities of fine sediment passing through the pumps after applying the preferred design. So, pump impeller may get eroded quickly. Erosion damage due to solid particle impingement are usually recognizable and appear as corrosion and erosion. Consequently, special impeller and pump types should be used.

The pumped water contains normal suspended solids concentration like the upstream channel and since the velocities in the channel downstream of the pump station came high to its normal values, so, the suspended solid remains mostly suspended and water can be used for irrigation as normally used in the study area.

7. CONCLUSION

The design of intake channel is strongly relevant to bed and suspended materials characteristics. Design of intake channel in a pure water way like rivers usually have a spacious intake channel prior to the pump units to decrease the velocities at a level that do not allow any movements of bed materials. Since the case study of this paper is located in agricultural drainage canal with high suspended load material concentrations, the traditional design of the intake channel which was applied showed a very high trend for sediment accumulation. Water and bed Samples were collected and analyzed to identify the source of sediment accumulated every four months in the intake channel. Analysis showed that, soil mainly consists of 75% silt of $D_{50}$ equals to 0.02 mm and 25% fine sand with $D_{50}$ of 0.07 mm.
This confirms that sediment deposition which occurred inside the channel comes from suspended soils. Since, the water quality is not the main concern of the lifting plant concerned in this study, it was found acceptable to allow suspended sediment especially when it consists of fine silt and clay particles to pass through the lifting plant. A design approach that allowed for higher velocities inside the channel was applied and showed a positive impact in decreasing the deposition rate. Higher velocities led to less retention time for the water passing through the intake channel. Consequently, coarser suspended sediment could deposit, unlike fine material that remained suspended and safely passed through the pump units. This approach extended the dredging frequency to 6 years instead of 4 months so, it can be applied in agricultural drainage canals with high suspended load. The technique applied in this study can resolve chronic sediment deposition problems in many agricultural drainage canals intake.

8. REFERENCES


