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Novel approach for hydrokinetic turbine applications

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ABSTRACT

By 2017, Egypt is expected to finish its sixth hydropower plant which is associated with the new Assiut barrage. Based on any hydraulic structure's design, there is enormous kinetic energy created downstream of the gates. This super power water jet generated under dams/barrage gates creates a destructive scouring effect downstream of the gates. In this work, a novel approach for hydrokinetic energy application is presented. The new approach proposes installing a farm of hydrokinetic turbines on the stilling basin of the spillways of the barrage's gate. This approach does not only magnify the total electric energy which was untapped in the past but also dissipates the enormous kinetic energy downstream of the gates. The total expected captured electric power from the barrage reaches 14.88 MW compared to 32 MW rated value of the existing hydropower plant.

Introduction

Hydro power is considered one of the economical and uncontaminated sources of power generation in Egypt, the hydropower generation in Egypt started firstly with the construction of Aswan dam to control the Nile water flow for irrigation, navigation and industrial purposes. In 1967, the high dam hydropower plant with total capacity of 2.1 GW was commissioned, followed by the startup of Aswan 2 power plant in 1985. Meanwhile, the Ministry of Water Resources and Irrigation constructed new barrages along the Nile River such as: new Esna barrage and its hydropower plant was constructed and completed in 1994, new Naga-Hammadi barrage and its hydropower plant was constructed and completed in year 2008 and finally the new Assiut barrage. Recently, the hydropower plant of the new Assiut barrage is under construction and expected to be completed in 2017. The total power that is generated from the hydropower of new Esna, Naga-Hammadi and Assiut barrages are 90, 64 and 32 MW respectively (Hydraulics Research Institute, 1991, 1997, 2014). According to the Ministry of Electricity & Energy (2012), the total share of hydropower generation in Egypt to the total generation represents about 8.9% in 2012/2013.

Several research papers have introduced schemes to increase the energy extracted downstream (far away) powerhouses of dams with different principals, criteria of applied approach and expected harnessed energy (Yue and Daniel, 2014; Arango, 2011). The main objective of this paper is to present a novel development for the conventional dams/barrages design to increase the total harnessed energy from them. The proposed approach suggests the utilization of the super power water jet downstream dams/barrage gates by means of installing a hydrokinetic turbines farm downstream the gates on the stilling basin of the spillways. Such power is not only an untapped power, but also it is a problematic issue for civil engineers/designers since dissipation of this power requires sometimes lengthening of the stilling basin and sometimes adding concrete structures to dissipate or at least deviate some amount of this power away from the river bed (Peterka, 1984).

The proposed approach may be an ambitious idea, notably if the recorded water velocities under gates may exceed 8–12 m/s for certain water discharge flow. The associated problems are mainly relevant to mechanical issues that if these ultra-speeds are suitable for installing hydrokinetic turbines or not. Another question primarily related to hydraulic engineers is raised: Is this proposal a real solution for super-jet water flow problem and is there any need of another way for energy dissipation? All these questions and others will be open for discussion with all involved fields of engineering.

In the succeeding sections, a brief comparison between hydrokinetic and conventional hydropower turbines is introduced; problem overview

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is fully presented in Problem overview, followed by methodology of investigation and case study description in Methodology and case study description. Results presents the achieved results. Challenges and potentials are fully described in Challenges and potentials, and conclusions are finally drawn.

Hydrokinetic turbines vs. conventional hydropower turbines

River streams, tidal waves, marine stream currents, and other artificial channels have potential for generating electric power through various hydrokinetic energy technologies. This nascent class of renewable energy technology is being strongly considered as an exclusive and unconventional solution falling within the area of both in-land water resource and marine energy.

The terminology of 'Hydrokinetic Turbine' has been alternately used with other terms such as: 'Marine Current Turbine' (MCT) (Verdant Power Canada, 2007; Garman, 1986), 'Ultra-low-head Hydro Turbine' (Radkey and Hibbs, 1981), 'Free Flow/Stream Turbine' (Geraldo and Tiago, 2003), or 'In-stream Hydro Turbine' (Dixon, 2007). Like wind energy, hydrokinetic turbines are employing both horizontal and vertical schemes and are currently being explored deeply. Such devices can be deployed in pre-selected water channels in a modular/array pattern without significantly disturbing the natural path of the stream (Khan et al., 2009). As inspired by wind energy conversion systems, the global scheme for a grid-connected hydrokinetic energy conversion system (HECS) is similar to wind energy conversion system (WECS) and given in Fig. 1. Same methodologies for modeling resource, turbine, and electric generators for WECS can be used for HECS (Khan et al., 2011; Lago et al., 2010). For HECS, water is the flowing fluid; however the total kinetic power in a MCT is governed by the following equation (Guney and Kaygusuz, 2010):

$$P_{HECS} = \frac{1}{2}\rho A V_{wr}^3 \tag{1}$$

where: P_{HECS} is the total hydro power that can be collected from the turbine, ρ is the water density (1000–1025 kg/m^3), A is the turbine swept area while V_{wr} is the water velocity. A hydrokinetic turbine can only yield a fraction of this power owing to hydrodynamic behavior and thus Eq. (1) is modified as follows:

$$P_{Mech} = \frac{1}{2}C_p \rho A V_{wr}^3 \tag{2}$$

where: P_{Mech} is the shaft power harnessed by hydrokinetic turbine, and C_p is the power coefficient that indicates to the power losses due to energy conversion through turbine shaft.

The aforementioned principle is different for conventional hydropower plants; *hydraulic turbines* derive the potential energy of the fluid into kinetic energy and convert into useful shaft torque. In another words, hydraulic turbines derive torque from the force exerted by a head of water coming from reservoir. These turbines are classified into two main classes: impulse turbines and reaction turbines (IEEE Std). A conventional hydro power plant depends mainly on natural topology of the site. So it requires huge infrastructure buildings and massive capital investment contrary to HECS. The mechanical power developed by the turbine is proportional to the product of the flow rate, the head and the efficiency. The power is controlled by adjusting the flow into the turbine by means of wicket gates on the reaction turbines and by a needle on the impulse turbine. The nominal power is given by the following equation (IEEE Std):

$$P_{hyd} = \rho g Q H \eta \tag{3}$$

where: P_{hyd} is the mechanical power developed by the turbine, Q is the flow rate, H is the head, g is the gravitational acceleration while η represents the actual utilization of the available potential energy of the system. The turbine efficiency is defined as the ratio of mechanical power transmitted by the turbine shaft to the absorbed power from fluid flow and depends on the water flow rate and the turbine operating characteristics.

Problem overview

Dams and barrages are structures created across a river or a natural water channel for diverting water into a canal for the purpose of irrigation or water supply, or into a channel or tunnel for generation of electricity. However, and despite their similarities, there are differences in these two structures. A barrage is considered as a type of dam consisting of a series of large gates (sluice gates or spillways) that can be closed or opened to control/manage the amount of water passing through it. These gates are mainly predestined for adjusting and stabilizing the water flow for irrigation, navigation and industrial purposes. One key difference between a dam and a barrage is that while a barrage is built for diverting water, a dam is constructed for storing water in a reservoir/basin to raise the water level significantly. A barrage is usually constructed where the surface is flat across rivers (Mott MacDonald, 2014).

Based on barrage design, flow over spillways or underneath gates has an enormous potential energy value, which is converted into kinetic energy downstream control structures. This phenomenon is called *hydraulic jump*; such terminology is a well-known term for hydraulic structure engineers. Hydraulic jumps are natural phenomena that occur owing to the flow discrepancy between the upstream and downstream regimes affecting the same reach of a channel (Abdelazim et al., 2010).

For example, as demonstrated in the sketch of the hydraulic jump shown in Fig. 2, if the upstream control causes supercritical flow, then a hydraulic jump is the only means to resolve this transition by forming significant turbulence and dissipating the energy (Abdelazim et al., 2010). Where V is the flow velocity, M is the velocity head in height of water column, P represents the pressure, h_L is the energy head loss and L_j is the length of the hydraulic jump. Subscript 1 refers to the upstream, while subscript 2 refers to the downstream of the gates. In

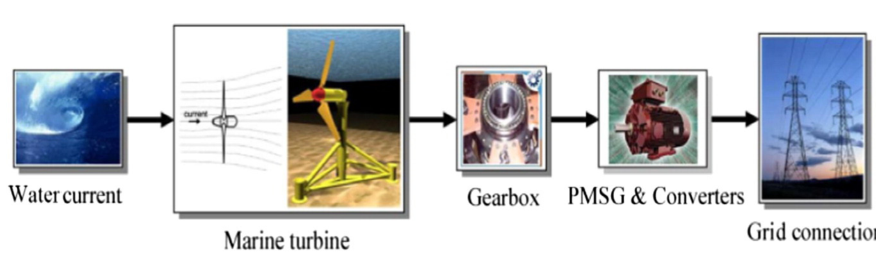

Fig. 1. HECS global block diagram.

other words, hydraulic jump will occur when the supercritical flow, in which the Froude Number is greater than unity, can be transformed into a subcritical flow ($F_{r1} < 1$) (Habibzadeh et al., 2011). The Froude Number could be calculated from the following formula:

$$F_{r1} = \frac{V_1}{\sqrt{g y_1}} \tag{4}$$

where g is the gravitational acceleration; and y is the depth of water.

As per dams/barrages design standards, this energy should be dissipated to minimize the probability of excessive scouring of the downstream waterway bed/stilling basin, reduce erosion and prevent weakening of structures. Same effect – in case it wasn't healed correctly – will jeopardize the structure safety (Peterka, 1984). There are many methods to dissipate such undesired energy; one of them is the controlling of the hydraulic jump itself as it consumes considerable amount of kinetic energy by producing turbulent flow across it (Abdelazim et al., 2010). Meanwhile, the hydraulic jump can be controlled by different methods. The objective of these methods is to ensure the formation of the hydraulic jump within the stilling basin and to manage its position for all probable operating conditions.

In other words, “to control” means to force the occurrence of the jump and to control its position, hence, reducing the risk of bed scour after the hydraulic structures. The design of such controlling structures should consider three interrelated parameters: jump position, tail water level and jump type. Mainly, there are two different categories to control the hydraulic jump: control by adding structures in the stilling basin and control by stilling basin modifications (Abdelazim et al., 2010).

One of the different techniques to reduce local scour that have been employed in previous studies is the use of splitter plates or collars (Fahmy, 2013). In the same framework, *baffle blocks* installed on stilling basins have been also utilized to stabilize the formation of the jump and increase the turbulence, thereby assisting in the dissipation of energy. The term “baffle block” can be denoted as one of a series of standing obstructions constructed to dissipate energy as in the case of a stilling basin or drop structure and usually made by concrete, constructed in a channel or stilling basin to dissipate the energy of water flowing at high velocity as shown in Fig. 3, where w_1 is the block width, w_2 is the spacing between two blocks; B is the stilling basin width while L is the distance between two rows of blocks (The Federal Highway Administration (FHWA), 2014).

Methodology and case study description

The implemented case study in this paper work is the new Assiut barrage Project. Referring to Fig. 4, the new Assiut barrage project components are: spillway with 8 radial gates 17 m wide each, low head hydropower plant with 4 turbine units of total energy of 32 MW

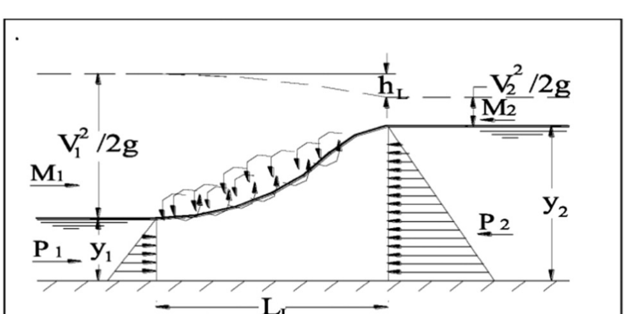

Fig. 2. Definition sketch of the hydraulic jump.

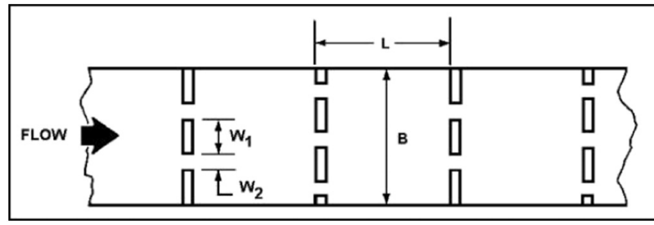

Fig. 3. Installed baffle blocks on a stilling basin.

and new two navigation locks with chamber of 160 × 17 m. Besides, the closure dam will be constructed to close the Nile River. The water flow discharges expected to pass through the barrage gates during a year are shown in Fig. 5 (Mott MacDonald Ltd. Fichtner GmbH & Co. KG, Inros-Lackner AG., and CES Consulting Engineers, 2005).

Accordingly, the proposed approach is tested by the data of 2D spillway physical model of the new Assiut barrage shown in Fig. 6 which has been built in the hydraulic laboratory of the Hydraulics Research Institute (HRI), Delta Barrage, Egypt. This physical model simulates the actual structure of the new Assiut barrage with scaling factors. These scaling factors are specified for the new Assiut barrage model as follows:

$$Q_{act} = Q_{model} \times 21^{(2.5)} \tag{5}$$

$$V_{act} = V_{model} \times 21^{(0.5)} \tag{6}$$

$$S_{act} = S_{model} \times 21 \tag{7}$$

where: Q_{act} and Q_{model} are the water flow discharge for actual and scaled model respectively, while V_{act} and V_{model} are the corresponding water flow velocity, and finally S_{act} and S_{model} are the actual and scaled model lengths along the stilling basin respectively.

In the same context, the same model was utilized to simulate all water discharges shown in Fig. 5 – passing annually through the barrage gate – to obtain the physical equations representing the water flow downstream barrages' gate. Fig. 7 is one sample of the data obtained experimentally by the 2D model at certain water discharges. In addition, and by the aid of the experimental results for the hydrokinetic turbine effects on the water flow which are demonstrated in (Arango, 2011; Gunawan et al., 2012), complete water flow equations with the existence of a hydrokinetic farm (installing on the spillway's stilling basin)

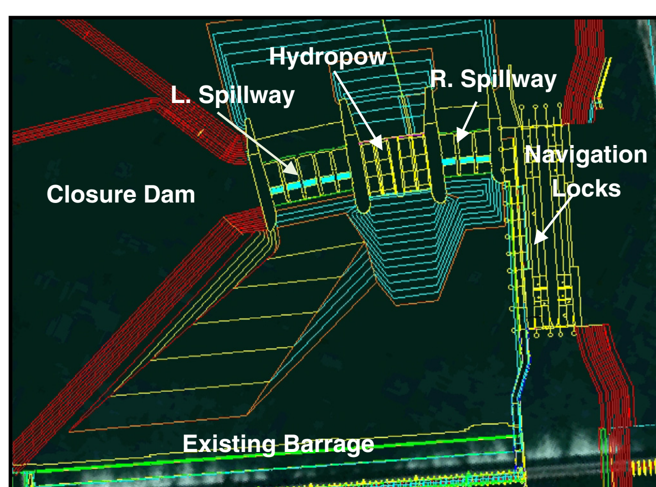

Fig. 4. New Assiut barrage layout.

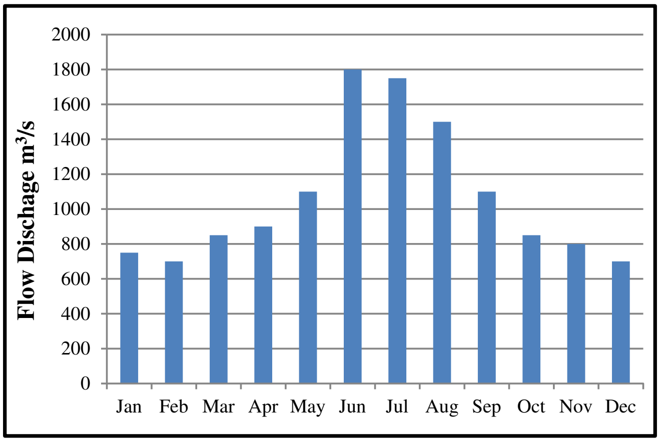

Fig. 5. Yearly total flow discharge passing through new Assiut barrage' gates.

are obtained and therefore the total captured power from the installed turbines can be calculated.

In Fig. 7, the flow velocity was measured at ten cross sections, the distance between each two sections equals 0.5 m. Six cross sections were located on the apron area and three sections were located downstream the apron. There was one cross section located upstream the gate. The velocity values were measured at five depth points along the water depth at relative distances from water surface of 0.2, 0.4, 0.6 and 0.8 above the bed (all actual velocity values should be multiplied by model scale).

According to (Fahmy, 2013), the floor blocks should occupy between 40% and 55% of the floor width and the most favorable conditions are achieved when the baffles are placed perpendicular to the incoming flow. For similar basis, the proposed approach basically depends on removing concrete baffle blocks placed on the stilling basin and installing a farm of hydrokinetic turbines. From hydraulics engineering's point of view, the installed turbines should be placed away from the gate opening to prevent total blockage of spillways which will in turn affect the calculated gate opening and structure operation (The Federal Highway Administration (FHWA), 2014). Other reasons for turbines implementation quite far away from gate opening should be highlighted as follows:

1- To avoid eddy/disturbing flow caused by hydraulic jump. As shown in Fig. 2, the hydraulic jump pattern is always in upward direction, therefore, such proposed allocation avoids eddies and disturbed water flow caused by hydraulic jump to be entered to the turbine (which may jeopardize turbines operation).
2- As per (Winter, 2011), the thrust force applied on the turbine blades will have large values. The same is expected due to the super-jet flow velocity just downstream gates; this may cause total failure of the turbine blades.
3- Flow discharge under gates may be accompanied with reefs and sediment (Fahmy, 2013); it will also affect the turbines' operation and may lead to blades' failure.

Fig. 6. The 2D physical model of spillway of a new Assiut barrage showing the installed baffle blocks.

For this paper work, the proposed number of turbines is set as one turbine per one row. Each row of turbines is placed at 30 m spacing distance and the first row is 20 m from gate opening, thus forming 3 rows. The hydrokinetic turbine diameter is 10 m; its coefficient of performance is 0.48 which is relatively low since the constricting walls and the blockage effect can increase the turbine power coefficient (Lalander and Leijon, 2011). Finally, overall system efficiency of all the cascaded stages is given as follows:

$$\eta_{sys} = \eta_{drv} \times \eta_{gen} \times \eta_{con}. \tag{8}$$

Consistent with (Couch and Bryden, 2004), typical values of these different efficiencies: gearing–bearing efficiency (η_{drv}), generator efficiency (η_{gen}), and power converter efficiency (η_{con}) are 0.90, 0.875 and 0.875 respectively.

Results

By the assumption that the water discharge flow is 700 m^3/s divided equally between all barrage's spillways, two water regimes are demonstrated in Fig. 8, one with turbines implementation and the other without implementation. As shown, the flow velocity decreases immediately downstream of the turbine (approximately 42.4% of water retardation occurs with turbines installation). In addition to the retardation effect of the hydraulic jump itself, the resultant flow velocity is retarded along the channel length and the same is expected due to the artificial energy extraction of power absorbed by the installed hydrokinetic turbines. These results are matched with the results obtained in (Gunawan et al., 2012; Qinetiq Ltd., 2004).

The power extracted from the water flow decreases dramatically; the same can be explained by the aid of Eq. (2), where the power is proportional with the cubic value of water velocity. Such result is also significant with respect to hydraulic purpose where the super-jet water flow under gates is retarded without the aid of the baffle blocks. The calculated values of water velocity and power extracted at different rows are shown in Table 1.

The demonstrated results are only shown for one spillway (Assiut barrage contains 8 spillways). Accordingly, the total expected captured power form the barrage – under 700 m^3/s flow discharge – will be 14.88 MW (1.86 MW × 8). Nonetheless, the calculated results actually depend on specific conditions of water flow rate, gate opening value and coefficient of performance along the installed rows of turbines. These results can basically highlight the new proposed idea.

As shown, the number of installed turbines, rows and turbine diameter are proposed ones, however, an optimization problem shall be exercised including detailed water flow models, cost of installation, different water flow rate along the year and corresponding gate openings. Meanwhile all these factors shall be further included to ensure exact system modeling and guarantee optimum results.

Challenges and potentials

Although the proposed approach magnifies the total energy harnessed at dams/barrages by implementing hydrokinetic turbines downstream gates of dams/barrages structures, some uncertainties

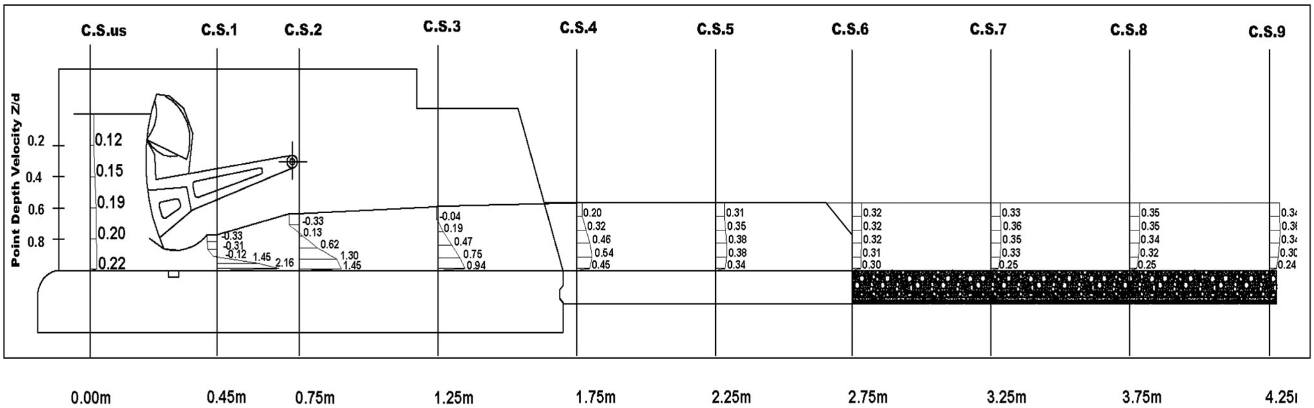

Fig. 7. The 2D physical model velocity distribution at different locations along the stilling basin (@ 900 m^3/s flow discharge).

and challenges associated with developing and deploying such idea are highlighted here:

- *Loading on the turbines blades*: Loading and blades design are major issues and should be studied by designers because of the enormous thrust forces acting on the turbine blades. In (Martin and Brian, 2011), a guide for blade design of hydrokinetic turbines is introduced.
- *Large fluctuations and turbulences*: As turbine blades will be exposed to large fluctuations and turbulences in water flow as a result of the hydraulic jump, it is necessary that rotor speed is controlled during operation precisely. If the rotor speed is permitted to rise higher than the standard operational rotational speed with considerable value, there is a possibility that the rotor will produce serious high thrusts. It is known that three marine turbine developers (*MCT*, *OpenHydro* and *Verdant Power*) have experienced blade failure. By considering this issue, challenges for blades design and control systems must be taken into consideration in the future (Winter, 2011).
- *Eddies and disturbing flow*: Non-uniform flow is a problematic issue for turbine control system operation. For eddies, the turbine controllers (grid side converter, machine side converter or even yaw system for horizontal axis turbine) may take undesired or false actions which in turn may lead to inefficient performance of turbines.

Referring to the reasons mentioned in Section 5 for turbine implementation away from gate opening, the hydraulic jump pattern is always in upward direction (it facilitates turbines implementation on the apron of the stilling basin); such proposed allocation avoids eddies and disturbed water flow. Besides, it allows utilizing maximum flow velocity just downstream gates (refer to Fig. 7). Another tool may help in regulating the flow streams by means of augmentation channels/tubes (Khan et al., 2009).

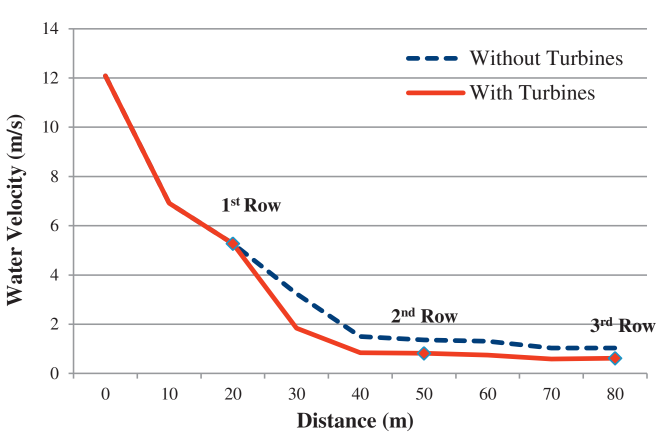

Fig. 8. Flow velocities along the stilling basin length.

- *Spillways width limitation*: Spillway width is a significant issue for turbine blades design. As highlighted above that blockage ratio of the stilling basin shall not exceed 60%, thus, deploying horizontal axis hydrokinetic turbines will be more complex due to manufacturing restrictions. Allowable blade radii shall fulfill the blockage ratio conditions. Implementing vertical axis hydrokinetic turbines may override the blockage ratio problem by increasing the blades height. However, such proposal needs careful investigation because the velocity distribution along the turbine blades will be non-uniform (refer to Fig. 7). This irregular profile of flow velocity shall be considered in case of blade design or control system design.

One the other hand, the approach presented herein has a number of distinct potentials; some of them can be listed as follows:

- Water flows are predictable many years in advance with small variations. Thus, the hydrokinetic turbines would require less rigorous fast acting control and protection methods (Yue and Daniel, 2014).
- The outflow of dams/barrages is unidirectional and the deploying of hydrokinetic turbines with fixed orientations would be suitable for most of its applications (Yue and Daniel, 2014).
- There is no impact on the visual amenity as hydrokinetic turbines are under water.
- The expediency of electricity grid connection would be another advantage for the proposed approach compared to distributed renewable energy sources. It requires minimum grid interconnectivity or transmission line facilities. It would be able to employ the existing grid interconnection infrastructure at the site of barrages/dams. It doesn't require expensive infrastructure upgrades or new transmission line installations (Yue and Daniel, 2014).
- One important potential of the proposed approach is the dissipation of the enormous kinetic energy downstream the gates. Hence, minimizing the probability of excessive scouring of the downstream waterway bed/stilling basin reduces erosion and prevents weakening of structures.

Table 1
Power and velocity at different rows.

	Velocity (m/s)	Power (kW)
1st row (20 m)	5.2721	1850.6904
2nd row (50 m)	0.8183	6.9194
3rd row (80 m)	0.6189	2.9942
Sum of power		1860.6039

• The system generates power 24 h a day and 365 days/year and consequently there is no need for power storage. Besides, it has a very low maintenance cost, therefore the produced kWh is much cheaper than any wind turbines or photovoltaic solutions.

Conclusions

In this work, a novel approach for hydrokinetic turbine application is presented. Proposed idea suggests utilizing super-jet water flow under gates of a barrage or dams by means of hydrokinetic turbines implemented along the spillway stilling basin. This idea has not generated additive electric power only, but also may solve the problem related to dissipation of water jet to prevent river bed scouring downstream the barrage structure. In other words, such power is not only an untapped power, but also it is a problematic issue for civil engineers/designers since dissipation of this power requires sometimes lengthening of the stilling basin and may be achieved by adding concrete structures to dissipate or at least deviate some amount of this power away from the river bed.

The proposed approach depends on removing concrete baffle blocks placed on the stilling basin and installing a farm of hydrokinetic turbines. By the aid of the data generated by the 2D spillway physical model of the new Assiut barrage, actual water flow characteristics are studied and turbine performance could be investigated. The reported results show promising outcomes for both captured power and water retardation. For example, the total expected captured electric power from the barrage reaches 14.88 MW compared to 32 MW rated value of the existing hydropower plant. This investigation was performed under 700 m^3/s water discharge flow; meanwhile the captured power is expected to be changed according to the water flow rate.

Generally, the outlined results ensure the proposed idea validation. Besides, approximately, 42.4% of water retardation occurs with turbine installation absorbing some of the enormous kinetic energy created downstream gates in such useful way, not just the dissipation of energy like previous techniques.

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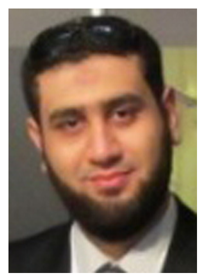

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