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FIELD MEASUREMENT TEST PLAN TO DETERMINE EFFECTS OF HYDROKINETIC TURBINE DEPLOYMENT ON CANAL TEST SITE IN YAKIMA, WA, USA

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ABSTRACT

The primary goal of the Department of Energy's Water Power Program is to efficiently develop and utilize the country's marine hydrokinetic (MHK) and conventional hydropower (CH) resources. The program has recently identified the need to better understand the potential for hydrokinetic energy development within existing canal systems that may already have integrated CH plants. Hydrokinetic (HK) turbine operation can alter water surface elevations and modify flow in a canal. Significant water level alterations and hydrodynamic energy losses are generally undesirable for conventional hydropower, irrigation, and flood management operations.

Our goal is to better the effect that individual and arrays of devices will have on local water operations through field measurements and numerical modeling. Here we present a methodology to study the effect of hydrokinetic turbine deployment in a test site in Roza Canal, Yakima, WA. The methodology comprises detailed water level and velocity measurements to characterize energy gradeline and inflow and wakeflow fields. Results from a preliminary measurement campaign are also presented.

INTRODUCTION

Power generation with marine hydrokinetic (MHK) current energy converters (CECs), often in the form of underwater turbines, is receiving growing global interest. Because of ongoing research to enable reasonable investment and maintenance costs, reliability, and environmental friendliness, the technology can contribute to national and global energy markets. Irrigation canals are potential locations for deploying hydrokinetic (HK) turbines. The US canal system comprises tens of thousands of miles of canals, and some have the potential to be developed as a HK energy site.

Canal deployment has its own advantages, such as the availability of accurate information of flow and water level, because these parameters are typically controlled by the local irrigation district. Despite having this advantage, HK turbine operation can alter water surface elevations and modify flow in a canal. Significant water level alterations and hydrodynamic energy losses are generally undesirable for conventional hydropower, irrigation and flood management operations. Little is known about the details of the mechanism that causes these alterations. This lack of knowledge affects the actions of regulatory agencies, the opinions of stakeholder groups, and the commitment of energy project developers and investors. Therefore, there is an urgent need for practical studies and accessible tools to help industry and regulators to evaluate the impact of HK device deployment, especially on water operation and environment, in order to be able to apply mitigation measures and to establish best siting and design practices. This paper proposes a field measurement test plan to investigate the effect of HK device deployment on water operations at a HK energy test site in Roza Canal, Yakima, WA, USA. The test plan comprises a set of comprehensive velocity and water level measurements around a vertical axis HK turbine during the spring and summer of 2014.

Preliminary velocity and water level measurements at the site, conducted in summer 2013, are also presented.

SITE DESCRIPTION

The Roza Canal test site is located at approximately 1.5 kilometers downstream of the canal inlet that diverts water from the nearby Yakima River. The site is owned by the US Bureau of Reclamation (USBR), which also manages the water operations in the canal. Since August 2013, Instream Energy Systems (IES) has been operating a 25 kW 3-blade vertical axis Darrieus turbine at the site. The turbine has a rotor diameter (D_T) of 3 m and a rotor height (H_T) of 1.5 m, and is deployed at the mid-section of the canal (Figure 1), at 1.5 m above the bed. The turbine is mounted on a large cylindrical platform that can be rotated 90 degrees, which enables the turbine to be taken completely out of the water when not operating (Figure 2). The turbine is deployed at a straight section of the canal that has a trapezoidal shape with water surface width of 13 m and 3.4 m water depth. The canal sidewalls have a slope of 1.25:1 (or 39 degrees from horizontal), and are made of concrete. The same material is used for the channel bed. The canal flows are of interest for testing between the spring and fall, with significantly reduced flows and water depth in the winter. High flows typically occur during summer months, with mean and maximum velocities reaching 1.9 m/s and 2.5 m/s, respectively.

METHODOLOGY

A set of water level and velocity measurements is planned in the vicinity of the turbine. Pressure transducers will be installed at several locations within 50 m of the turbine, near the canal inlet, approximately 1 km upstream of the turbine and at 2.5 km downstream of the turbine, to monitor water level during the measurement campaign. These measurements serve several purposes, to: 1) calculate the water level differences when the turbine is deployed and not deployed, 2) calibrate and validate numerical models, and 3) monitor the flow steadiness during the measurement period. The results of (1) will directly apply in determining if the energy grade line (EGL) and hydraulic grade line (HGL) altered by HK turbine operation exceeds the threshold set by the local authority to ensure normal water operation. The energy equation can be expressed as

$$z_1 + y_1 + \alpha_1 \cdot \frac{{V_1}^2}{2g} = z_2 + y_2 + \alpha_2 \cdot \frac{{V_2}^2}{2g} + h_m + h_f + h_t$$

z_1 = Bed elevation at an upstream location, relative to a datum (m)
y_1 = Water surface elevation upstream (m)
α_1 = Coriolis coefficient upstream (-)
V_1 = Mean velocity upstream (m/s)
g = Gravitational acceleration (m/s^2)
z_2 = Bed elevation at a downstream location, relative to the datum used for z_1 (m)
y_2 = Water surface elevation downstream (m)
α_2 = Coriolis coefficient downstream (-)
V_2 = Mean velocity downstream (m/s)
h_m = Minor losses (m)
h_f = Friction losses (m)
h_t = Energy extracted by turbine (m)

The EGL is the straight line created from two points, the total energy at the upstream location, and the total energy at the downstream location minus all the energy losses, with x axis corresponds to the distance between the two locations and the y axis corresponds to the amount of energy. The HGL is the straight line created from the water surface elevations at the two locations.

Inflow velocity will be measured using an acoustic Doppler current profiler (ADCP). Several cross-sections and a transect along the turbine centerline, upstream of the turbine, will be measured to determine the extent of the flow alteration caused by the presence of the turbine. The inflow measurements can be used to estimate resource availability and calculate the power coefficient of the turbine. Additional ADCPs will be used to measure wake velocity field, which will be used to estimate wake flow recovery distance, an important turbine array design parameter. Measurements will be collected at six cross-sections (CS) downstream of the turbine and at a transect along the turbine centerline. In addition, an ADCP and an echo sounder will be deployed using a remotely operated boat to map velocities and bathymetry for a few hundred meters along a section of the canal, to investigate the effect of geometry changes due to channel meandering and constriction on local and global velocity distributions. This information will be used to determine the optimal siting location of additional turbines.

In addition to the water level and velocity measurements, the thrust force acting on the turbine will be derived from strain measurements at the turbine support structure. The measured thrust force can be used to derive thrust coefficient, a critical input parameter for numerical models to simulate the effect of an HK

turbine deployment. Obtaining this parameter allows accurate simulation of the effect of multiple HK devices and array configurations on the local water operation using numerical models.

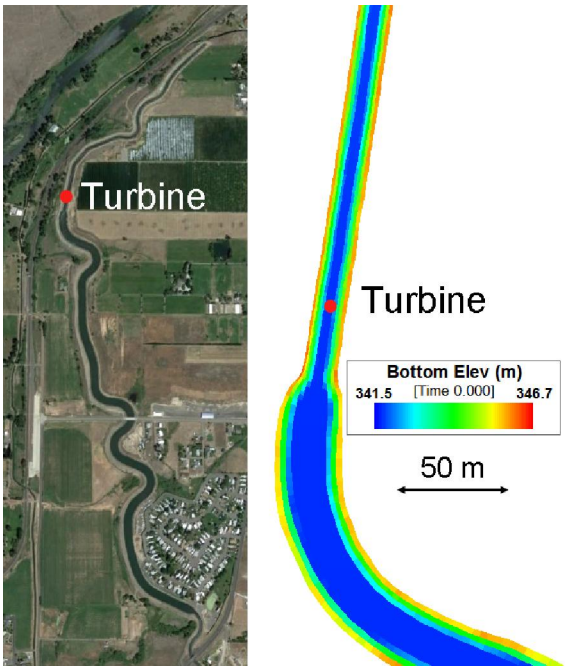

FIGURE 1. ROZA CANAL HK TEST SITE AND BATHYMETRY AT THE TURBINE LOCALITY.

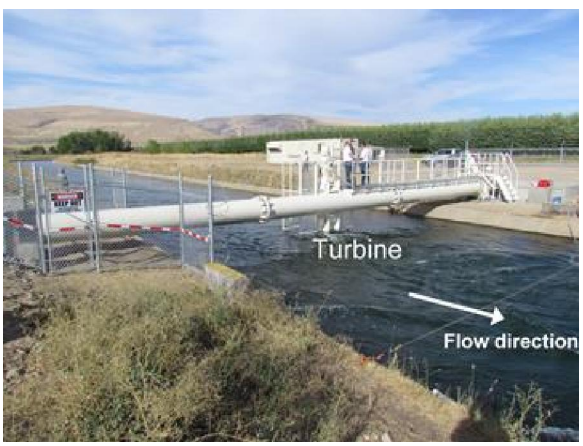

FIGURE 2. TURBINE, IN OPERATIONAL CONDITION.

PRELIMINARY RESULTS

A preliminary campaign to measure water level and velocity was conducted in the summer 2013 to investigate the characteristics of the site. Velocity measurements were conducted using an RDI ADCP StreamPro at 12 CS, 6 upstream of the turbine and 6 downstream of the turbine. Cross-section 1 is the furthest upstream. The turbine is located between cross-sections 6 and 7. All of the cross-sections are evenly spaced 10 m apart beginning 10 m upstream/downstream of the turbine, except for CS 6 and CS 7 which are located 5 m (up and downstream) from the turbine. Measurements were conducted for two conditions: 1) without the turbine present (baseline), and 2) with the turbine operating at a constant rotation rate. Measurements for these two conditions were collected on different days, but the flow conditions were very similar, as indicated by a low difference in flow discharge, of less than 1.5 %.

The ADCP velocity measurements upstream of the turbine location, with and without the turbine in the water, are graphically represented in Figure 3, while the same data downstream of the turbine deployment location are shown Figure 4. The missing data in CS 5, seen as vertical white streaks or gaps in the contour plots, is likely caused by vegetation that grows at the bottom of the canal, causing poor acoustic signal readings. The missing data in CS 7 that included the turbine was a result of the ADCP transducer losing contact with the water. The strong water surface wave in the near-wake caused unstable ADCP boat movement. This condition will be improved by utilizing a larger ADCP boat and a cableway system that can stabilize the boat during high velocity and rough water conditions, such as outlined in [1].

The turbine seemed to have little effect on upstream velocities as the upstream cross sections have similar velocity distributions in absence and presence of the turbine. It is interesting to note that for all cases there is a high velocity core at the right part of the CS. Upstream of the measurement site, the canal curves to the left (Figure 1), which causes superelevation of the water surface on the right side at the measurement location and shifts the high velocity core to the right side downstream of the bend. Secondary flow circulation caused by centrifugal acceleration, which is often termed as the Prandtl secondary flow of the first kind, is known to occur at bends [2]. The ADCP measurements from the preliminary campaigns show an indication of secondary flow cells at the cross-sections upstream of the turbine. It is still unclear if these cells are related only to the secondary flow at the bend, or also influenced by the turbulence driven secondary flow that is known to occur in straight sections of a channel [2, 3], such as the locations where the ADCP measurements were taken. Further analyses, such as the spatio-temporal averaging of ADCP transects [4-6], will be conducted once more measurements are obtained.

Moving the turbine to the high velocity region may significantly increase the rate of power

generation due to the cube relationship between velocity and power. Moving the turbine, however, may not be feasible, because the high velocity region has a shallower depth than the current turbine location, which might result in inadequate clearance between the turbine and channel bottom. Nonetheless, it is important to conduct site-specific full-cross-section velocity measurement, such as the moving-boat ADCP measurement, to identify local hot spots, when designing the deployment strategy for a hydrokinetic turbine.

Furthermore, the baseline measurements for the upstream and downstream CS, with an exception of cross-section 11, have similar velocity distributions. This is because the cross-section geometries are similar for all but CS 11 (which is located far enough downstream to be in the wider section of canal).

The only cross-section measured downstream of the turbine, when the turbine was present, was CS 7. Only ¾ of cross-section 7 was measured before the ADCP boat capsized due to the presence of strong waves at this location. Despite this mishap, the measurement results are encouraging. The ADCP was able to capture the velocity deficit in the near-wake region. The quality of the measured data appears to be acceptable as indicated by the values of signal intensity and correlation, which are very similar to those measured at the other cross-sections. It is expected that with improving ship keeping, future measurements will be attainable in the near and far wake region.

Water levels were measured every 20 seconds at cross-sections 1 – 12 for a period of three days during the field measurement campaign. Due to installation challenges, measurements of water level were recorded at the edge of the cross-sections. Figure 5 shows the time-averaged water level measurements for the baseline and with turbine cases. Both measurements were time-averaged over 1.5 hours. The flow conditions were relatively stationary during the three-day field measurement campaign, indicated by relatively constant water levels during this period at the most upstream cross-section (cross-section 1). During the test period, the water level changes at cross-section 1 never exceeded 0.05 m for the baseline scenario and 0.03 m for the with turbine scenario.

Figure 6 compares water level measurements in the presence and absence of the turbine. Positive values indicate an increase and negative values a decrease in water level when the turbine was present. These results indicate that adding the operating turbine in the canal increased the water surface in the upstream cross-sections by a constant difference of approximately 0.03 m, with the exception of CS 5 (40 m downstream of CS1). Excluding the CS 5 measurement, the HGLs for both the baseline and with turbine cases upstream of the turbine are close to linear. The measurement at CS 5 seems to contain a significant error, as indicated by its much lower measured water level than those at CS 4 and CS 6. This error is possibly caused by the vegetation growth at the bottom of the channel that interferes with the pressure transducer signal. Downstream of the turbine, the water level decreased by 0.05 m at CS 7. The water level difference decreases with distance from the turbine, and diminishes at approximately 40 m downstream of the turbine, or 13.3 turbine rotor diameters. These measurements were made at one canal flow speed with one turbine rotational speed. Future field measurements will include additional flow and turbine conditions, which will provide a more complete picture on the effect of deploying a hydrokinetic energy turbine in a canal system.

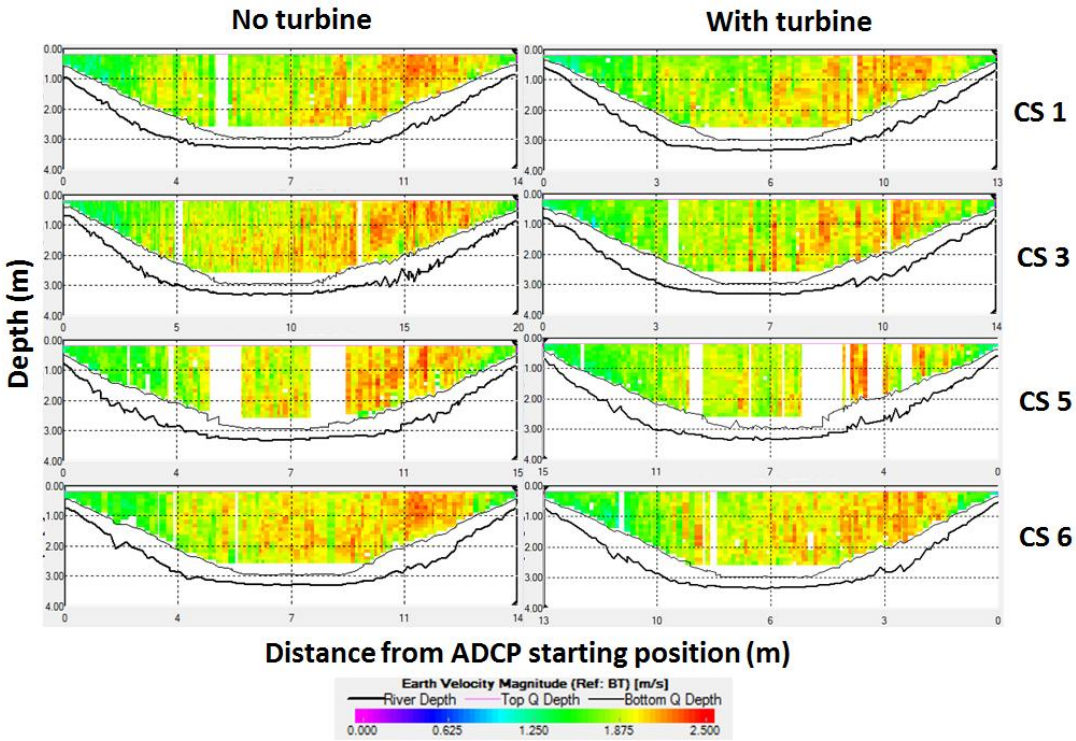

FIGURE 3. CONTOURS OF VELOCITY MAGNITUDE (LOOKING DOWNSTREAM) AT SEVERAL CROSS-SECTIONS UPSTREAM OF THE TURBINE LOCATION. CS 1 IS THE MOST UPSTREAM SECTION. THE TURBINE IS LOCATED BETWEEN CS 6 AND CS 7.

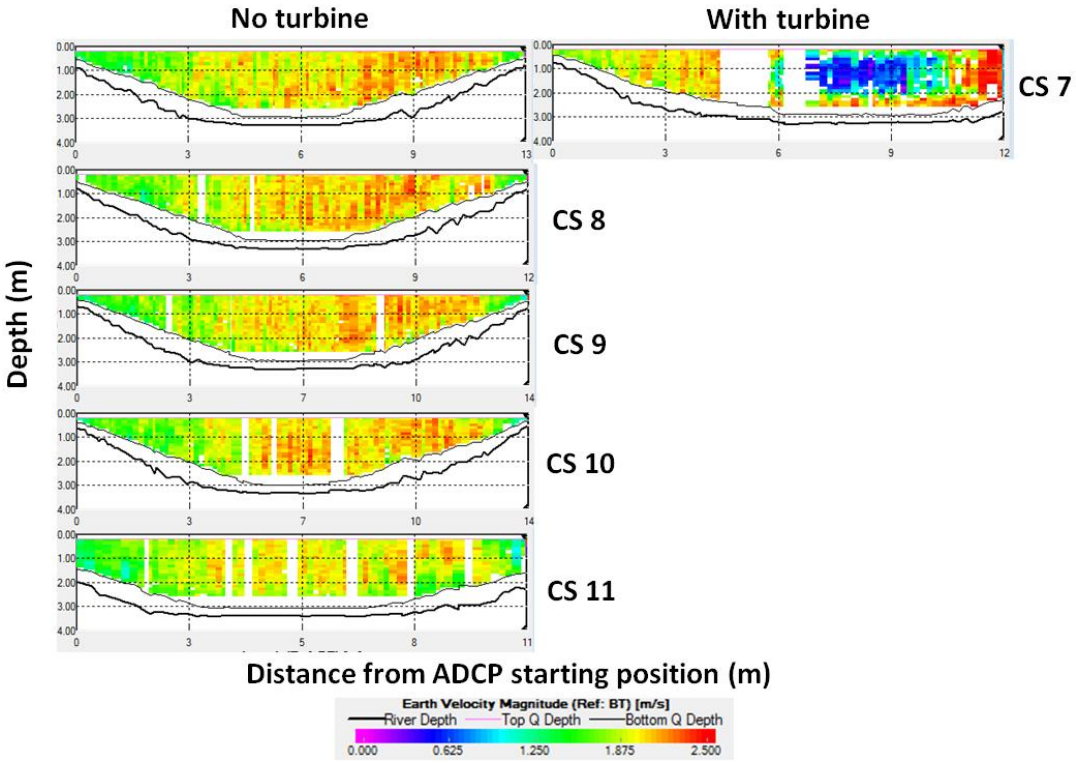

FIGURE 4. CONTOURS OF VELOCITY MAGNITUDE (LOOKING DOWNSTREAM) AT SEVERAL CROSS-SECTIONS DOWNSTREAM OF THE TURBINE LOCATION. THE TURBINE IS LOCATED IN BETWEEN CS 6 AND CS 7. CS 7 WITH TURBINE CONTOUR ONLY SHOWS MEASUREMENTS TO UP TO ¾ OF THE CS LENGTH DUE TO BOAT CAPSIZING. MEASUREMENTS WITH THE TURBINE OPERATING WERE NOT SUCCESSFUL AT CROSS-SECTIONS 8-12 DUE TO BOAT CAPSIZING.

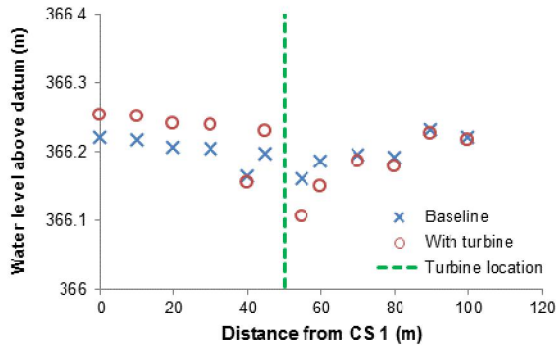

FIGURE 5. TIME-AVERAGED WATER LEVEL MEASUREMENTS FOR THE BASELINE AND WITH TURBINE CASES. USBR DATUM IS USED AS A REFERENCE.

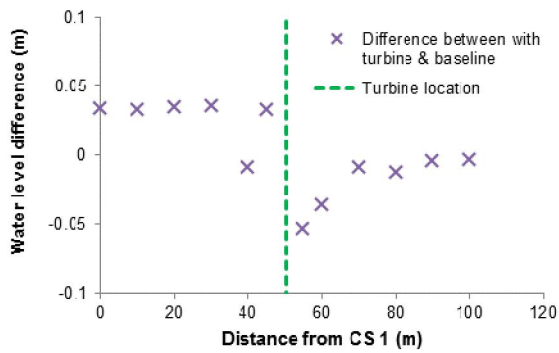

FIGURE 6. WATER LEVEL DIFFERENCE BETWEEN THE WITH TURBINE AND BASELINE CASES.

LESSON LEARNED FROM PRELIMINARY MEASUREMENTS

A comprehensive field measurement test plan to investigate the effect of HK turbine deployment in a canal test site was proposed based on a preliminary observation of velocity and water level measurements around a vertical axis turbine deployed at the site. The test plan comprises detailed velocity measurements to characterize inflow and wake flow and monitoring water level changes due to turbine deployment. The test plan will be implemented at a HK energy test site in Roza Canal, Yakima, WA, USA, in mid-2014. It is expected that the methods used in this study will help industry and regulators evaluate the impact of HK turbine deployment, apply appropriate mitigation measures for the negative impacts that may occur, and ultimately accelerate the commercialization of HK turbines for deployment in canal systems.

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