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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 the flow in a canal. Significant water level alterations and hydrodynamic energy losses are generally undesirable not only for CH plan operations, but also for irrigation and flood management operations.

The goal of this study is to better understand the effect of operating individual and arrays of devices on local water operations through field measurements and numerical modeling. A methodology to study the effect of hydrokinetic turbine deployment in a test site in Roza Canal, Yakima, WA, is presented. The methodology comprises detailed water level and velocity measurements to characterize energy gradeline and inflow and wakeflow fields. Results from a preliminary testing are also discussed.

INTRODUCTION

Marine hydrokinetic (MHK) energy technology, often in the form of underwater turbines, is receiving a growing interest. This technology can potentially be deployed in existing US canal system, which comprises tens of thousands of miles of canals. Canal deployment has its own advantages, such as the availability of accurate flow and water level information from the local irrigation district that manages the canal. Despite having this advantage, HK turbine operation can alter water surface elevations and modify the 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.

The Roza Canal, Yakima, WA, USA, is managed by the US Bureau of Reclamation (USBR). USBR also operates the Roza hydropower plant, located five miles downstream the test site, which uses the Roza Canal water flow to drive hydropower turbines. The effect of deploying one or more MHK turbines at the test site on the hydropower plant performance and operation is not yet known. Deployment of a significant number of turbines can potentially cause undesirable effects, such as decreasing the hydropower plant's power generation. In addition, turbine operation can raise the water surface above the limit set by USBR, which requires the water surface in the canal to be at least 1.8' below the canal's freeboard, to minimize the risk of flooding. When the water surface exceeds the freeboard level, the canal's water intake will need to be reduced, which in turn will also reduce the amount of water to be allocated for irrigation and the Roza hydropower plant.

This paper describes a field measurement test plan to investigate the dynamics of water level and velocity in the Roza Canal HK test site due to the deployment and operation of a vertical axis turbine. The plan will be executed during the 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 approximately 1.5 kilometers downstream of the inlet of the canal, which diverts water from the nearby Yakima River. 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, to enable the turbine to be taken completely out of the water when not operating (Figure 2). The turbine is deployed at a straight trapezoidal section of the canal. During the preliminary measurement in 2013, the water surface width and depth at the turbine location were 12.5 m and 3.3 m (Figure 3). The turbine blockage ratio was ~16%. Both canal sidewalls have a slope of 1.25:1 (or 39 degrees from horizontal). The canal bed and sidewalls are made from concrete. The longitudinal slope of the bed is 0.0004. The Froude Number during the measurements was ~0.4. The canal flows are of interest for testing between the spring and fall due to the high flows typically occur during this period. A typical mean velocity in the canal during this period is ~1.9 m/s. The canal flow is significantly reduced in the winter and is not suitable for HK turbine operation.

METHODOLOGY

A set of water level and velocity measurements will be conducted in the vicinity of the turbine in 2014. Pressure transducers were installed in 2013 at several locations within 50 m of the turbine, approximately 1 km upstream of the turbine and 2.5 km downstream of the turbine, to monitor water levels during the measurement campaign. These measurements serve several purposes, to: 1) calculate the water levels in different locations in the canal, when the turbine is deployed and not deployed, 2) monitor the flow steadiness during the measurement period, and 3) calibrate and validate numerical models. The results of (1) will directly apply in determining changes in energy grade line (EGL) and hydraulic grade line (HGL) due to HK turbine operation, which may be analyzed using the energy equation:

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

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)
h_b = Head loss due to turbine blockage (m)

The EGL is a straight line created from two points, a total energy at the upstream location and a 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 a straight line created from the water surface elevations at the two locations, with *x* axis corresponds to the distance between the two locations and the *y* axis corresponds to the water surface elevations.

Inflow velocity will be measured using an acoustic Doppler current profiler (ADCP). Several cross-sections and transects 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. The ADCP will also be used to measure wake velocity field, for studying the wake flow dynamics and wake recovery distance, an important parameter for turbine array design. Measurements will be collected at six cross-sections (CS) downstream of the turbine and along the turbine centerline. A remotely operated survey boat, equipped with a Real Time Kinematic rover-base GPS system (horizontal positioning accuracy within 0.1 m), will be used to deploy an ADCP and an echo sounder for characterizing velocity and bathymetry over a large area within a few hundred meters from the turbine. This information can be used for investigating the effect of geometry changes due to channel meandering and constriction on local and global velocity distributions, which is important for determining the optimal siting location of additional turbines. The velocity and bathymetry measurements can also be used for numerical model boundary condition and validation.

In addition to the water level and velocity measurements, the thrust force acting on the turbine will be derived from strain measurements. A set of coil strain gages will be mounted to the rotating turbine shaft. The measured signal will be transferred to a data acquisition system using a wireless telemetry system. Then, the thrust force acting on the rotor will be derived from the strain measurement, shaft material properties, shaft geometry and shaft dimensions [1]. The measured thrust force can be used to derive a thrust coefficient, a critical input parameter for numerical models to simulate the effect of an HK turbine deployment. In the next phase, the thrust force will be used to simulate the effect of multiple HK devices and array configurations on the local water operation.

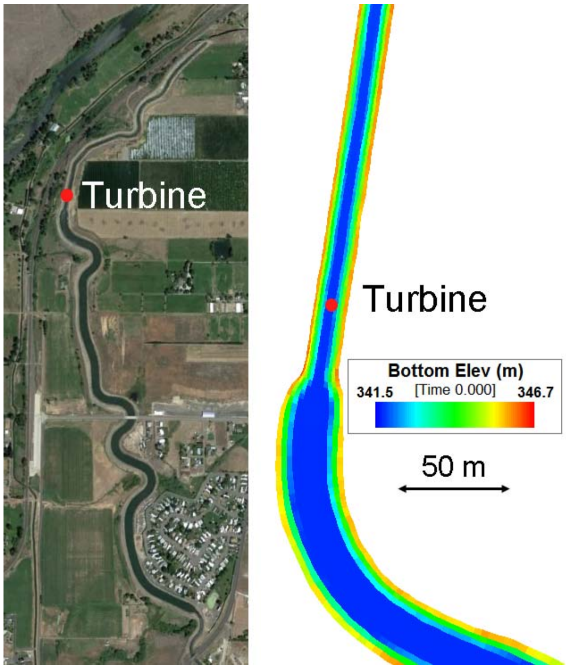

FIGURE 1. ROZA CANAL HK TEST SITE AND BATHYMETRY AT THE TURBINE LOCALITY.

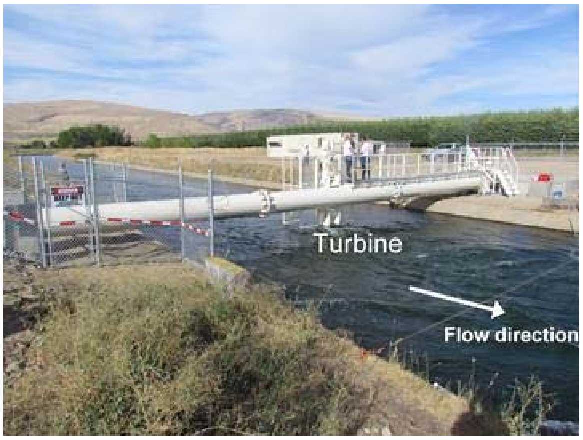

FIGURE 2. THE INSTREAM ENERGY SYSTEM'S TURBINE, IN OPERATIONAL CONDITION.

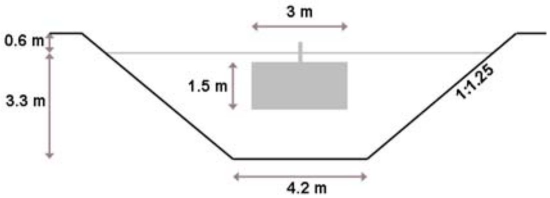

FIGURE 3. A SCHEMATIC VIEW OF THE CROSS-SECTION, SHOWING THE ROTOR SWEPT AREA.

PRELIMINARY RESULTS

A preliminary campaign to measure water level and velocity was conducted in summer 2013 to provide information on the velocity and water level at a flow depth of ~3 m. This information was used to help specs the sensors, e.g. a torque sensor, and design a cableway system for ADCP and acoustic Doppler velocimeter (ADV) deployments that will be used for the 2014 measurements.

Velocity measurements were conducted using an RDI ADCP StreamPro Mode 12 [2], with a sampling frequency of 1 Hz. The measurements were conducted at 12 cross-sections; six cross-sections are located upstream of the turbine and six cross-sections are located 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 with the turbine being located mid-way between CS 6 and CS 7 such that these cross-sections are located 5 m up and downstream from the turbine, respectively. The locations of these cross-sections are illustrated in Figure 4.

Measurements were conducted for two conditions: 1) without the turbine present (baseline), and 2) with the turbine operating at a constant rotation rate. The ADCP, attached to a small catamaran, was traversed along a tagline across the channel in each cross-section (Figure 5). The ADCP was traversed at a speed of 0.1 m/s, or less, resulted in horizontal bin sizes of 0.1 m or less. The size of the vertical bin was set to 0.12 m. Two transects were obtained for each cross-section, which is sufficient for the purpose of this preliminary fieldwork. During the 2014 fieldwork, four transects or more will be measured for each cross-section, with a goal to obtain at least four transects with differences in discharge of equal or less than 5% of the mean of all the samples. This approach is a standard procedure that has been adopted by researchers and engineers, e.g. [3, 4].

A flow discharge was calculated for each cross-section by integrating the velocities over the cross-section area. Due to its measuring methodology, an ADCP cannot measure velocities near hard boundaries (bed and side walls) and near the water surface, due to sidelobe interference and blanking distance. The discharges in these unmeasured regions are either interpolated to the hard boundaries (to zero) or extrapolated to the water surface level using the measured velocities [5]. The discharge calculations are performed within the data collection software WinRiver 2 [3]. A valid comparison between conditions 1 and 2 can be made if the flow discharges between those two conditions are similar. A representative flow discharge of the canal was calculated for each condition by averaging the discharge values of the six upstream cross-sections. A discharge difference of 1.5 % between the two conditions was obtained.

The ADCP velocity measurements upstream of the turbine location, with and without the turbine in the water, are graphically represented in Figure 6, while the same data downstream of the turbine deployment location are shown Figure 7. 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 the one outlined in [6].

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 [7]. 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 [7, 8], such as the locations where the ADCP measurements were taken. Further analyses, such as the spatio-temporal averaging of ADCP transects [9-11], 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 show similar velocity distributions between the cross-sections, with the exception of that at cross-section 11, which has a longer width than the other cross-sections.

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. USBR requires water level measured at the edge of the canal for comparison with freeboard level, therefore, the water level sensors were placed at the edge of the cross-sections. Figure 8 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 9 compares water level measurements in the presence and absence of the turbine. An increase in water level is indicated with a positive difference value and vice versa. These results show 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 measurement. 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.

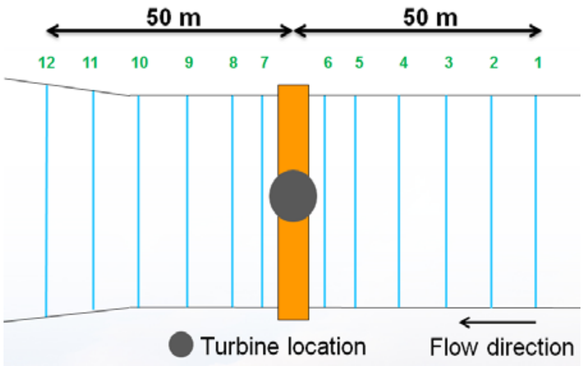

FIGURE 4. THE LOCATIONS OF THE TEST CROSS-SECTIONS, RELATIVELY TO THE TURBINE.

FIGURE 5. ADCP TEST MEASUREMENTS IN AUGUST 2013.

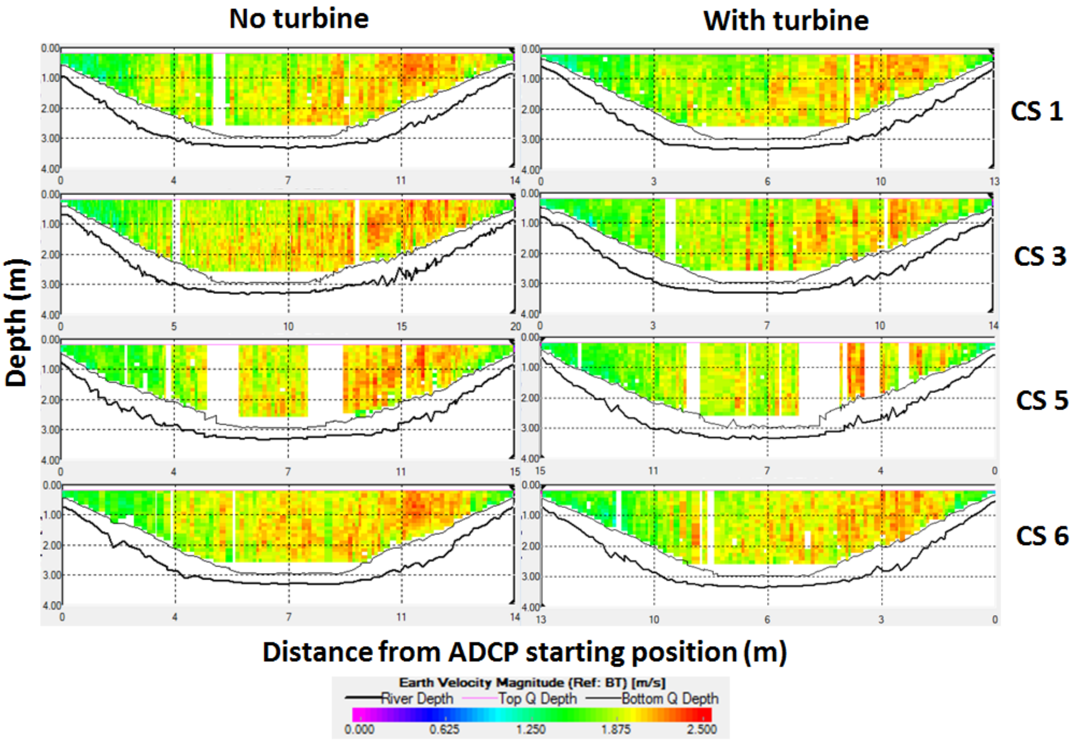

FIGURE 6. CONTOURS OF VELOCITY MAGNITUDE (LOOKING DOWNSTREAM) AT SEVERAL CROSS-SECTIONS UPSTREAM OF THE TURBINE LOCATION. CS 1 IS THE MOST UPSTREAM SECTION. THE TURBINE IS LOCATED BETWEEN CS 6 AND CS 7.

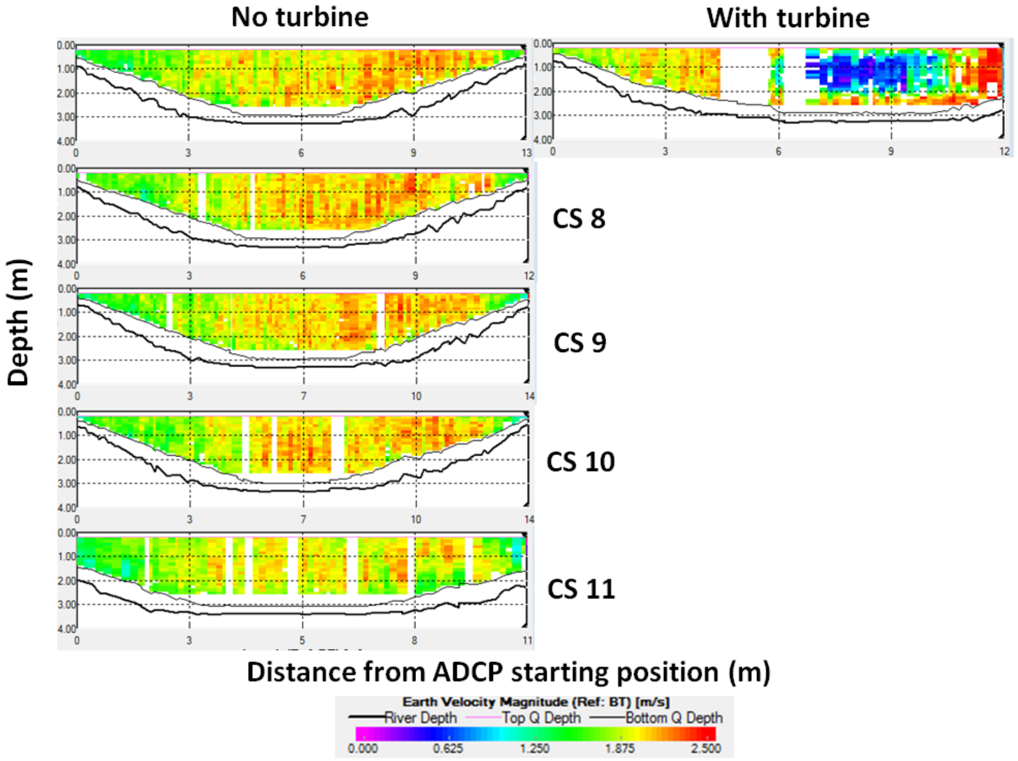

FIGURE 7. CONTOURS OF VELOCITY MAGNITUDE (LOOKING DOWNSTREAM) AT SEVERAL CROSS-SECTIONS DOWNSTREAM OF THE TURBINE LOCATION. THE TURBINE IS LOCATED IN BETWEEN CS 6 AND CS 7. CS 7 WITH TURBINE CONTOUR ONLY SHOWS MEASUREMENTS TO UP TO ¾ OF THE CS LENGTH DUE TO THE BOAT CAPSIZING. MEASUREMENTS WITH THE TURBINE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

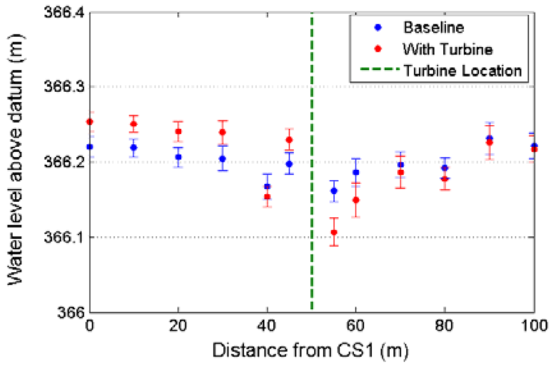

FIGURE 8. TIME-AVERAGED WATER LEVEL MEASUREMENTS FOR THE BASELINE AND WITH TURBINE CASES. USBR DATUM IS USED AS A REFERENCE.

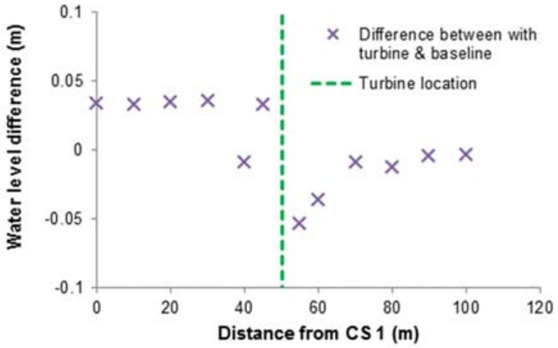

FIGURE 9. WATER LEVEL DIFFERENCE BETWEEN THE WITH TURBINE AND BASELINE CASES.

CONCLUSIONS

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 includes detailed velocity measurements to characterize inflow and wake flow, and water level measurements to quantify the effect of turbine operation on water level, energy grade line and hydraulic grade line. The test plan will be implemented at an 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 and apply appropriate mitigation measures for the negative impacts that may occur.

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REFERENCES

[1] Omega Engineering Inc., 2014, "Positioning strain gages to monitor bending, axial, shear and torsional loads." http://www.omega.com/faq/pressure/pdf/positioning.pdf

[2] Teledyne RD Instruments, 2013, "StreamPro ADCP Shallow Streamflow Measurement System," Data sheet. (http://www.rdinstruments.com/datasheets/streampro_ds_lr.pdf).

[3] Teledyne RD Instruments, 2014, "WinRiver 2 User's Guide," RD Instruments, Poway, CA, USA.

[4] Mueller, D.S. and Wagner, C.R., 2009, "Measuring discharge with acoustic Doppler current profilers from a moving boat." US Geological Survey Techniques and Methods 3A-22, 72p. USGS: http://pubs.water.usgs.gov/tm3a22

[5] Teledyne RD Instruments, 1996, "Acoustic Doppler current profiler, principles of operation, a practical primer." Technical Manual.

[6] Gunawan, B., Sterling, M. and Knight, D.W., 2010, "Using an Acoustic Doppler Current Profiler in a small river," Water and Environment Journal. Vol. 24 no. 2 pp 147-158.

[7] Perkins, H.J., 1970, "The formation of streamwise vorticity in turbulent flow," Journal of Fluid Mechanics, Cambridge University Press, 44 (04): 721-740.

[8] Einstein, H.A. and Li, H., 1958, "Secondary currents in straight channels." Transactions of the American Geophysical Union, Vol. 39, No.6, pp 1085-1088.

[9] Szupiany, R.N., Amsler, M.L., Best, J.L. & Parsons, D.R., 2007, "Comparison of fixed- and moving-vessel flow measurements with an aDP in a large river," Journal of Hydraulic Engineering, ASCE, pp. 1299-1309

[10] Le Coz, J., Gilles, P., Magali, J. & Andre, P., 2007, "Mean vertical velocity profiles from ADCP river discharge measurement datasets," Proceedings 32nd Congress of International Association of Hydraulic Engineering and Research, Venice, Italy.

[11] Gunawan, B., Sun, X., Sterling, M., Shiono, K., Tsubaki, R., Rameshwaran, P., Knight, D.W., Chandler, J., Tang, X. and Fujita, I., 2012, "The application of LS-PIV to a small irregular river for

inbank and overbank flows,“ Flow Measurement and Instrumentation, Volume 24, pp 1–12.