A Hydraulic Model Study of the Water-Intake Structure near River Mile 37 on the Missouri River

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ABSTRACT

A three water-intake structure designed to be built along the right bank of the Missouri River near Chesterfield, Missouri was model-tested at an undistorted scale of 1:5. Although the discharge capacity of each of six pumps to be installed is only 21,000 gpm, the model indicated strong flow circulation and unstable free-surface conditions as flow entered the two-pump bay through a narrow sluice opening at an angle. Strong free-surface vortices were also observed in the model.

The sump modifications developed in the study included an array of baffle bars, a perforated plate, floor splitters, and floor-corner fillets. The solutions developed in this study could be applied to other pump sumps with multiple pump units.

INTRODUCTION

St.Louis Country Water Company in Crave Coeur, Missouri, plans to build a water-intake structure along the right bank of Missouri River near Corps of Engineers River Mile 37 which is located just east of Chesterfield, Missouri. The proposed intake structure, which was designed by Horner and Shifrin, Inc. in St.Louis, Missouri; will consist of three pump bays with two 21,000 gpm vertical pumps in each rectangular pump sump which is 18-ft wide and 24-ft long. The primary objective of the hydraulic model study was indentifying hydraulically objectionable features of the intake design, modifying them to attain satisfactory operation of pumps, and assisting intake designers with useful test information

Some preliminary hydraulic concerns about the proposed intake layout were nonuniform pump-approach-flow conditions as water enters through a narrow sluice-gate opening, a short

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bay length, flow circulation within the intake bay, interaction between two pumps when both are in operation, asymmetric flow distribution when only one pump is in operation, and formation of three-surface and boundary-attached subsurface vortices. Althrough the pumps to be installed were not classified as large pumps, it was anticipated that some of these aforememtioned problems could occur in prototype.

Conventional sump modification to resolve these ploblems include the following flow-straightening devices: an array of deep vanes or baffle bars and/or perforated plate to improve pump-approach-flow distribution; floor and backwall splitters and conor fillets to suppress formation of subsurface vortices; and, horizontal grating or skimmer walls to suppress free-surface vortices. Prior use of these devices is documented by dicmas(1978), Nakato(1984, 1988, and 1989), and Sweeney et al.(1982).

The purpose of this model study is to recommend designs of floor-straightening devices inside the pump sump which provide hydraulically acceptable pump-approach flow to individual pump. In order to test the performance of various designs of such devices, a 1:5-scale geomatrically undistorted hydraulic model was built at the Iowa Institute of Hydraulic Research(IIHR), The University of Iowa. Some of the more specific goals included: uniformly-distributed pump-approach flow in the immediate vicinity of the pump bells; elimination of floor-attached, backwall-attached, or sidewall-attached subsurface vortices and air-entraining free-surface vortices; uniform pump-throat velocity distribution.

II. OVERALL PUMP-INTAKE MODEL

A. Model Layout

The entire model was built at an undistorted geometrical scale of 1:5. The model included pump sump and, approximately 130 ft (26 ft in model) long, river section. Plan and section views of the model are shown in Figure 1.

The model was constructed primarily from timber and plywood. The plywood surface was coated with fiberglass for water proofing. Three walls (two sidewalls and backwall) of the sump were made of transparent lucite to facilitate flow visualization and lighting. Pump bells were machine-formed to scale from lucite, and connected to clear lucite siphon lines. Around the pump bells, four holes were drilled at 45-degree interval to measure the pump-throat velocity distribution using pitot tube.

Flow was supplied to the upstream part of the river section through 10-inch-diameter pipe.

A baffle wall with a horse-hair screen stapled to it was installed immediate downstream of the model diffuser pipe to reduce flow turbulence. This river section provided water to the pump sump through either of two openings(one in the river side, the other in the sidewall; see Figure 1). At downstream of the river section, a simple weir-type tail gate was installed to adjust the river-water level. Flows from the pump were simulated, and withdrawn from the model, by 6-inch-diameter siphon pipes.

B. Similitude Requirements

Undistorted geometric similarity requires that the ratio of all corresponding dimensions in model and prototype be equal. Furthermore, since the flow processes in this study involve free surface, the model should be operated in accordance with the Froude-similarity law. Therefore, it is important that the ratio of gravitational force to inertial force should be preserved. This requires that Froude number, F, be same in model and prototype. The scale ratio for velocity, discharge, and time resulting from the Froude-similarity law for the length scale, Lr, are $Lr^{0.5}$, $Lr^{2.5}$, and $Lr^{0.5}$, respectively, and their values corresponding to $Lr = 1/5$ are 1/2.24, 1/55.9, and 1/2.24, respectively.

C. Criteria for Satisfactory Pump Operation.

IIHR's experience with numerous studies of the present type has led to the following model criteria for satisfactory operation of prototype pump installations:

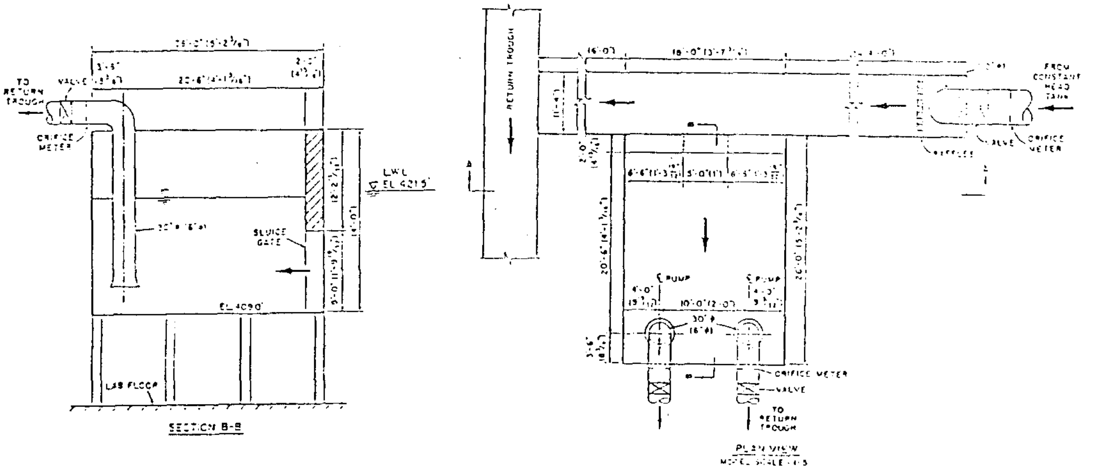


Figure 1. Plan and section view of the initial model

(1) No detectable boundary-attached vortices extending into the pump bells.

(2) No free-surface vortices stronger than type 2 shown in Figure 2.

(3) No velocities measured in the pump throat that vary by more than 10 percent from the average of all local velocities measured in the pump-throat cross section.

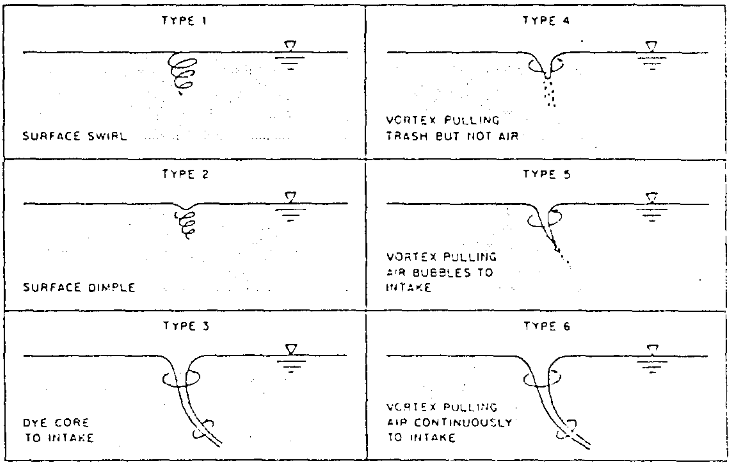


Figure 2. Classfication of free-surface vortices

(4) No detectable, large-scale, persistent "unsteadiness" or "waviness" in the pump-approach flows; no indication of persistent large-scale turbulence; no flow anomalies judged objectionable by investigators experienced with pump-intake model tests.

Ⅲ. TEST RESULTS

A. Preliminary Test

This part of test was conducted by withdrawing intake flow through a 5-feet wide and 9-feet tall river-side sluice to observe general pump-approch-flow conditions as well as around the pump bells. In all the test reported herein, the river stage was maintained at EL 421.5 ft, and the river-flow velocity was set at 2.5 ft/sec in full scale. The 48-inch-diameter pump bells were initially installed 36 in. from the sump floor whose elevation corresponds to 409 ft above MSL.

Under the as-designed condition, three basic problems were found. First, there was a large-scale circulating flow within the sump, as the intake flow entered the pump sump at an angle. Flow separation occurred at the upstream end of the river-side sluice, producing highly concentrated flow along the right sidewall. Second, there were strong floor-attached vortices as well as what weak sidewall-attached and backwall-attached vortices. There was also an abnormal flow pattern in which cross flow existed near the sump floor under the pump bells. Third, there were free-surface vortices (type 3 and type 4 shown in Figure 2) accompanied by unstable, wavy free-surface conditions.

In order to eliminate these undesirable features, it was dicided to first improve lateral distribution of the pump-approach flow and then to fix flow anomalies near pump bells.

B. Developmental Test

At this stage of test, extensive efforts were made in finding proper devices or structures to improve the flow conditions, and in determining their dimensions. Furthermore, efforts were also made to devise a simple, economical and yet practical scheme which would be easy to construct and maintain.

In the first phase of this test, to eliminate large-scale flow circulation in the sump, several devices were tried. After extensive efforts, it was decided to use baffle bars. Three rows of staggered, 12-feet tall, 17.5 in. by 7.5 in. rectangular baffle bars placed at upstream edge of the sidewall-sluice opening (baffle bar design #1)were tested first. Although these baffle bars reduced the intensity of flow circulation, they failed to produce a desired level of uniformity in the lateral flow distribution.

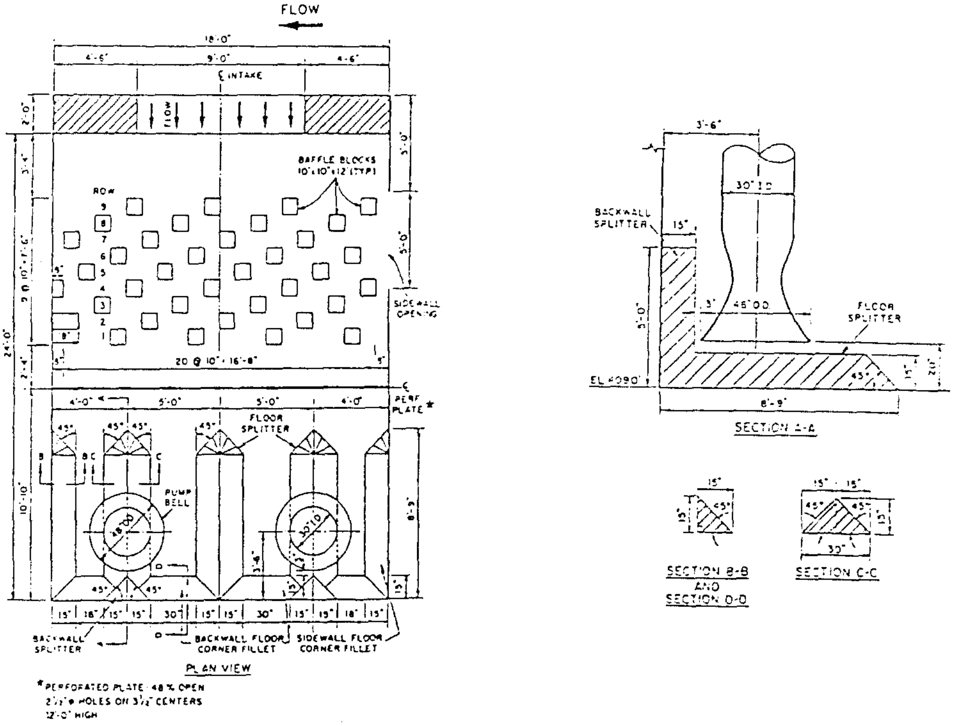
After serveral modifications, it was decided to design a new set of baffle bars in much smaller dimensions. Nine rows of staggered, 12-feet tall, 10 in. by 10 in. square baffle bars (baffle bar drsign #2)were installed immediately downstream from the intake opening. In addition to this set of baffle bars, a 12-feet-tall and 18-feet-wide perforated plate with 48% opening(staggered perforations of 2.5-inch dismeter; 3.5 in. between centers) was placed immediately downstream from the baffle bars for fine tuning. The combunation of the smaller baffle bars and the perforated plate produced smooth pump-approach flow without turbulence, and reduced the intensity of backwall-attached vortices. However, floor-attached and sidewall-attached vortices were still observed even under these modifications. No free-surface vortex was observed under these remedies.

The next phase of the test was to eliminate the submerged, boundary-attached, subsurface vortices. As a first step of this phase, two 20-inch tall and 9-feet 2-inch long floor splitters were designed and installed under each pump bell. Floor-corner fillets were also installed along the sump sidewalls and backwall (splitter design #1). Due to the floor splitters and corner fillets, floor-attached and sidewall-attached vortices were weakened significantly. However, weak floor-attached vortices were still present, possibly because the splitters and sidewall-corner fillets were too close each other. The problem was that the bells were too high for the width of the sump. In general, the floor-splitter height should be at least three fourths of the bell height. In this case, however, the spitter of that height did not allow enough space for smooth flow between splitters and sidewall-corner fillets.

After examining the practical possibility of lowering the bell height, it was decided to lower the bell height to 20 in. from the floor. The new splitter height corresponding to the bell height of 20 in. was 15 in. Furthermore, to help guiding the flow into the bells, another floor splitter was installed between the two bells(splitter design #2). The new set of splitter worked excellently. Most of the vortices disappeared. The only weak vortex left was observed on the right sidewall-corner fillet.

It was believed that this vortex was attributable to the cross flow near the backwall. Therefore, backwall splitters(5-feet tall and 15-inch deep) were installed behind the pump bells(splitter design #3, see Figure 3). These eliminated the vortex completely. Nevertheless, it was decided to make the approach flow more uniform by optimizing the position of the perforated plate, because even the small instabilities, in general, tend to be exaggerated in the prototype. The optimized location of the perforated plate was 2 ft 4 in. from the downstream edge of the baffle bars. This combined layout of baffle bars, a perforated plate, splitters, and floor-corner fillets was considered as the tentative final configuration.

However, it was requested by the client that the river-side-sluice configuration needed to be altered from 5-feet wide by 9-feet high to 9-feet wide by 5-feet high. The tentative final configuration of baffle bars and splitters was tested for the changed sluice opening. By means of dye test, it was observed that the approach flow was non-uniform with stronger flow along the right sidewall, resulting in unstable flow condition at the right corner near pump B. This problem was fixed bv filling the opening between the sidewall and first baffle bar of the second row (see final configuration in Figure 3)



*PERFORATED PLATE 48% OPEN
2½"φ HOLES ON 3½" CENTERS
12'-0" HIGH

Figure 3. Plan and section view of the recommended pump-sump layout

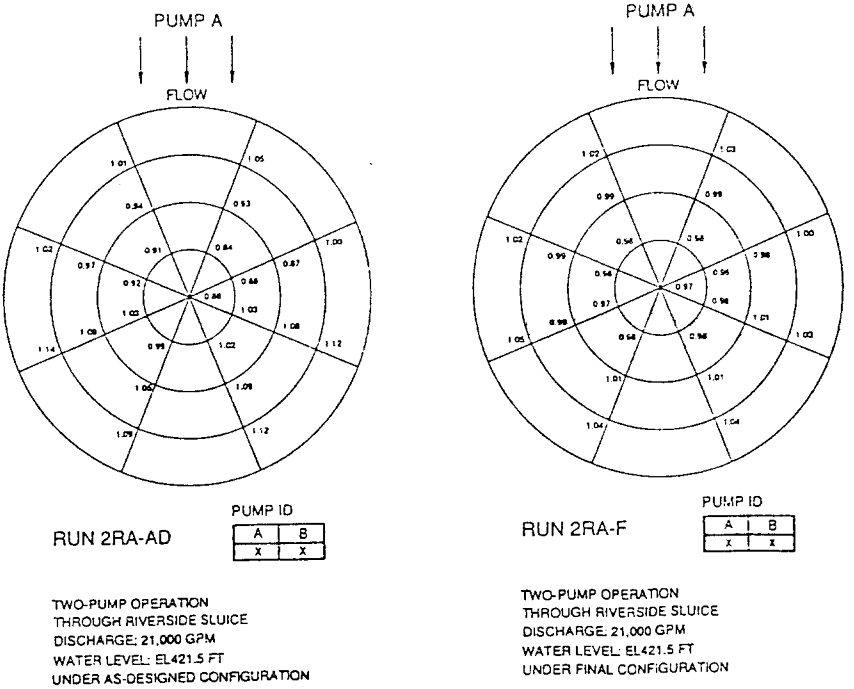
It was also suggested by the client that the baffle bars and perforated plate should be moved downstream by 2 ft 6 in. This modification did not affect performance of baffle bars and perforated plate. Pump-approach flows were uniformly distributed across the sump and no vortex was observed. Finally, the flow condition through the sidewall-sluice opening was tested. No adverse effect was found with this sump configuration. Therefore, this set of baffle bars and perforated plate together with the splitters and corner fillets is proposed as the final recommendation. Figure 3 shows the final configuration.

C. Pump-Throat Velocity Mesurements

The test results presented above are based primarily on visual observation, by means of dye injection, of flow patterns within the pump sump as well as those areas surrounding the pump bells. The more quantitative evidence of improvement in pump-approach-flow distributions by the recommended sump modifications can be shown in terms of the mean axial velocity distribution measured inside each pump throat.

Pump-throat velocities were measured using pitot tube during the final stage of the test.

Velocities were measured at 25 locations at the narrowest section of each pump bell for diffenent operating conditions. In all cases, the average velocity was first calculated, and individual were nomalized by the average value. Comparison of velocity distributions before and after the modification revealed that the flow condition inside the bell throat was improved significantly. The maximum deviation from the average(1.00) was 14% under as-designed condition. After the modification, the maximum deviation was improved to be only 6%. Figure 4 shows the distribution of the nomalized velocities, for a particular pump operation, measured under as-designed and final configurations.



RUN 2RA-AD

TWO-PUMP OPERATION
THROUGH RIVERSIDE SLUICE
DISCHARGE: 21,000 GPM
WATER LEVEL: EL421.5 FT
UNDER AS-DESIGNED CONFIGURATION

RUN 2RA-F

TWO-PUMP OPERATION
THROUGH RIVERSIDE SLUICE
DISCHARGE: 21,000 GPM
WATER LEVEL: EL421.5 FT
UNDER FINAL CONFIGURATION

Figure 4. Pump-throat velocity distribution

Ⅳ. CONCULSIONS

The final recommendations derived from the present study may be summarized as follows:

1. In order to eliminate large-scale flow circulation, and to make uniform pump-approach flows, it is recommended to install nine rows of staggered baffle bars. In addition to baffle bars, a vertical perforated plate is recommended to be installed downstream of the baffle bars to supress flow circulation around the sump, and fine-tune the pump-approach flows.

2. It is recommended to lower the bell height to 20 in. from floor to provide enough space for smooth approach flow from sides.
3. It is recommended to install three floor splitters. The two floor splitters under the pump bells are to suppress floor-attached subsurface vortices, and the middle one is to produce smooth pump-approach flows towards each pump bell.
4. Two backwall splitters are recommended to install behind the pump bells, to eliminate backwall-attached subsurface vortices.
5. Finally, it is recommended to install floor-corner fillets along the sidewalls and backwall. These sidewall and backwall floor-corner fillets are needed to suppress formation of sidewall-attached and backwall-attached subsurface vortices, respectively.

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