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HYDRAULIC PERFORMANCE OF LARGE SUBMERSIBLE PUMPS

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SYNOPSIS

Submersible pumps are commonly used in wet-wells of pumping stations along sewage collection systems. The geometry and alignment of the areas immediately upstream of the pumps are closely tied to the requirements of the specific site such that it is difficult to standardize their design. Due to underground space limitation, the pump configuration and approach area must often be evaluated on a case by case basis to determine their impact on the hydraulic performance of the pumping station. This paper presents a case study of a particular wet well with large submersible pumps. The study illustrates how through laboratory hydraulic model testing, a preliminary design can be modified within the site constraints to insure a proper hydraulic performance.

INTRODUCTION

Physical models remain the best available tool to evaluate the hydraulic performance of pumping stations. These structures are often associated with hydraulic problems (cavitation, vibration, and operation problems) that cannot be eliminated simply on the basis of analytical solutions or previous investigations. Flow problems associated primarily with flood control or water supply pumping stations have been widely reported in the literature (Dicmas (7), Fraser (15), Hattersley (16), Larsen and Padmanabhan (21), Sweeney *et al.* (29), Triplett *et al.* (30), Tsou *et al.* (31) and Tullis (32)).

Hydraulic flow problems in flood control or water supply pumping stations have largely been attributed to: 1) uneven flow distribution in the approach area causing a net flow circulation around the pump column; 2) large scale turbulence generated in the approach flow to the pump; 3) vorticity generated by flow past pier noses, screen supports, and other structural members; 4) vorticity generated at fluid shear zones formed at discontinuous flow boundaries in the vicinity of the pump such as the corners of a rectangular basin; 5) vorticity generated in the boundary layer at the walls and floor; and 6) vorticity generated by flow past the pump column (Fletcher (10), EPRI (9), Sweeney *et al.* (29) and Tullis (32)).

Few studies however, have been published on the use of submersible pumps in wet wells along sewer lines. These pumps appear to experience similar hydraulic flow problems that are often related to the well design rather than to mechanical imperfections. As pump size and flow rate are continually increasing, these problems become more significant as the cost of replacing a large pump becomes prohibitively expensive while the cost of a model study is a small percentage of the total project cost.

Conceptually, hydraulic flow problems in sewer pumping stations are likely to be attributed to similar causes as flood control or water supply pumping stations. While these causes have been well established, their solutions have not. Different approaches to prevent vorticity, provide even flow distributions, and mitigate the effects of large scale turbulence have been developed primarily through experimental studies using physical models. The various approaches involve the utilization of flow guidance and distribution structures (such as beams, vanes, screens, ramps, flow splitters) to provide satisfactory flow conditions. However, no definitive design criteria have been developed.

Design guidelines provide recommendations on the size and configuration of pump stations, based on either the suction bell diameter or the anticipated flow rates (Flygt (14), HIS (18), Knauss (20), Prosser (26) and US Army (35)). None of these guidelines guarantees satisfactory flow conditions because they are based primarily on empirical information obtained from laboratory tests creating a lack of a theoretical basis for determining an optimal layout for pumping stations. Indeed, several surveys have documented the severity and prevalence of inadequate performance of pumping stations that were designed in accordance to recommended design guidelines (Fletcher (10) and EPRI (9)). The EPRI (9) study noted the apparent lack of generalized criteria for designing pump stations and Fletcher (10) concluded that about 50 percent of the flood control stations managed by the US Army Corps of Engineers have experienced flow problems that warrant improvement.

As such, physical modeling remains necessary and perhaps the only means, to evaluate the performance of a pumping station design and derive appropriate modifications that could alleviate potential hydraulic deficiencies. This paper presents an evaluation of the hydraulic performance of submersible pumps in a wet well sewage pumping station. The station's preliminary design was evaluated through physical model tests. Modifications were developed within the site constraints to insure a proper hydraulic performance. The general applicability of design features in the selected modifications are discussed.

THEORETICAL CONSIDERATIONS

Complete similarity between model and prototype is obtained by maintaining geometric, kinematics, and dynamic similarity. A uniformly scaled reproduction of the prototype ensures geometric, and to a large extent, kinematics similarity (Paterson and Campbell (25)). Dynamic similarity however, involves the reproduction of gravitational, viscous, and surface tension effects which can be accomplished by satisfying the Froude, Reynolds, and Weber criteria as expressed by:

$$(N_F)_m = (N_F)_p\,; \quad \text{or} \quad (V^2/gL)_m = (V^2/gL)_p \tag{1}$$

$$(N_R)_m = (N_R)_p\,; \quad \text{or} \quad (LV/\nu)_m = (LV/\nu)_p \tag{2}$$

$$(N_W)_m = (N_W)_p\,; \quad \text{or} \quad (\rho LV^2/\tau)_m = (\rho LV^2/\tau)_p \tag{3}$$

where m, p = subscripts for model, prototype; N_F = Froude number; N_R = Reynolds number; N_W = Weber number; V = fluid velocity; g = gravitational acceleration; L = characteristic length; ν = kinematics viscosity; ρ = fluid density; and τ = fluid surface tension. Assuming that water is the liquid used in both model and prototype, Eqs. 1 to 3 can be reduced to the following:

$$V_m = (L_m/L_p)^{+1/2}\, V_p \tag{4}$$

$$V_m = (L_m/L_p)^{-1}\, V_p \tag{5}$$

$$V_m = (L_m/L_p)^{-1/2}\, V_p \tag{6}$$

Since open channel flow dominates upstream of wet well pump intakes, reproducing gravitational effects (Froude criterion) becomes essential. Clearly, the other two criteria (Reynolds and Weber) cannot be satisfied simultaneously which may introduce performance deviations, referred to as *scale effects,* between model and prototype. Scale effects can be neglected so long as the model is large enough to maintain a fully turbulent flow and avoid shallow water at all critical sections hence minimizing viscous and surface tension forces (Anwar *et al.* (2), Daggett and Keulagan (3), Dicmas (6), Hecker (17), Jain *et al.* (19), Padmanabahn and Hecker (24) and Rindels and Gulliver (28)). Excess viscous and surface tension forces could affect the formation and strength of vortices at which time the Reynolds and Weber criteria cannot be neglected.

Maintaining a Weber and Reynolds number greater than 120 and $5x10^4$, respectively, will generally eliminate the effects of viscous and surface tension forces (Daggett and Keulegan (3), Jain *et al.* (19) and Zielinski and Villemonte (36)). Although testing at higher than Froude-scaled velocities has been suggested in several studies to overcome potential scale effects (Denny (4), Dicmas (5), Durgin and Hecker (8) and Zajdlik (35)), it should be avoided because it results in exaggerated flow rates which can create different approach flow patterns and erroneous circulation in the model compared to the prototype (Padmanabhan and Hecker (24)).

PROJECT DESCRIPTION

The pump station which is equipped with four submersible pumps, is located in Louisville, Kentucky and is used to transport wastewater along sewer mains. Similar stations have been constructed along the same sewer main and have experienced cavitation and air entrainment problems. The objective of the present project is to identify potential hydraulic deficiencies and eliminate or minimize them through hydraulic model testing.

The station's initial design was prepared by Tenney Pavoni Associates, Inc. of Louisville, Kentucky in 1991. It comprised an influent screening and gate channels with two openings each leading into a baffle chamber with two bottom rectangular openings. The wet well includes side fillets and a pedestal on which four submersible pumps are mounted. The pumps are separated by a divider wall with a gated square opening. Figs. 1a and 1b illustrate the station's initial design.

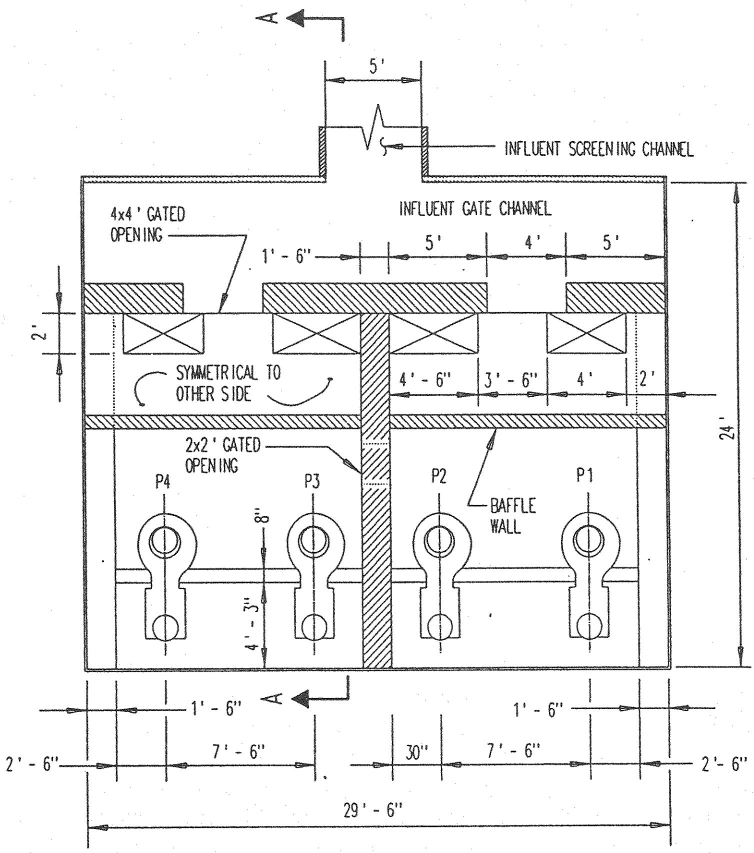

Fig. 1a. Preliminary design layout-plan view

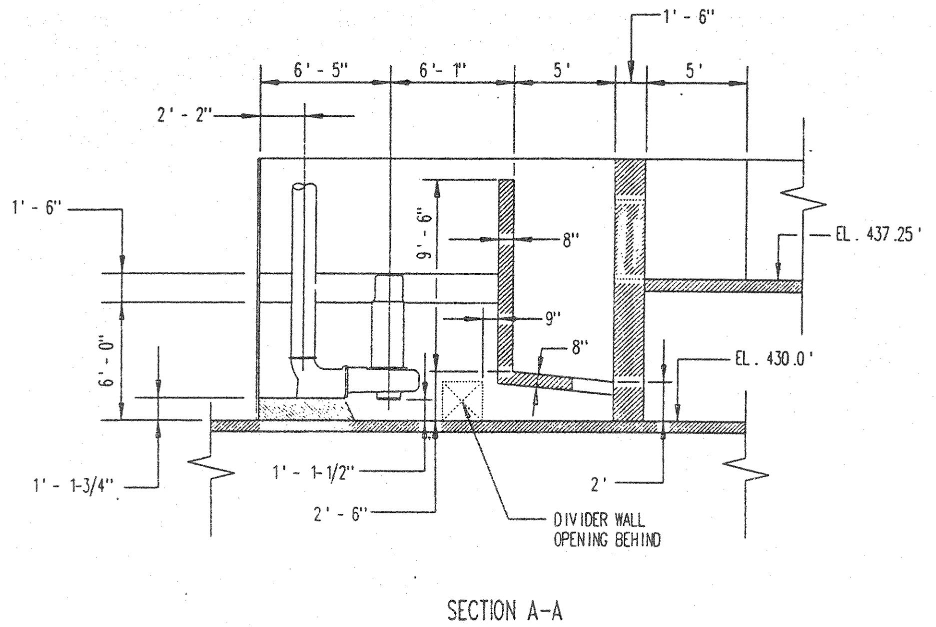

Fig. 1b. Preliminary design layout-cross section

PHYSICAL MODEL

Hydraulically significant components of the pumping station were reproduced through physical modeling in accordance to a linear undistorted scale ratio of 1:5 model to prototype. The scale ratio was selected on the basis of a compromise between cost and theoretical considerations minimizing potential scaling effects and reproducing accurate prototype behavior.

The outside walls of the modeled wet well were made of transparent plastic to facilitate flow visualization. Pump mock-ups included suction pipes fabricated out of transparent tubing and equipped with four-leaf vortimeters to measure rotational tendencies of incoming flows. The model was equipped with a recirculating system and flow measuring instrumentation. Each of the four pump suction lines is valved to allow operation of any combination of pumps. Pre-calibrated orifice plates are used to measure flow rates. The model layout is illustrated in Fig. 2.

MODEL ACCEPTANCE CRITERIA

Hydraulic performance of the wet well and flow conditions in the approach to the pump suction inlets were evaluated in terms of qualitative and quantitative parameters. Qualitatively, flow patterns throughout the model were examined using water colorant to aid in defining the extent and location of rollers, eddies, stagnant areas, uneven flow distributions, swirls, and surface and sub-surface vortices. Quantitatively, water levels were measured and corresponding vortimeter rotations were counted.

The efficiency of a pumping station depends on model acceptance criteria which included: 1) a uniform and steady flow pattern in the approach to the pump suction inlets; 2) total elimination of all vorticity (surface or sub-surface); and 3) ten or less rotations per minute (rpm) as measured with the four-leaf vortimeters at the pump suction bell. In addition, although air entrainment is not accurately reproduced in a Froude Law model, a qualitative assessment of aeration processes was conducted in terms of air bubble visual size and relative quantity using the criteria described in Table 1. Only *low* quantity of *small* size bubbles were deemed acceptable.

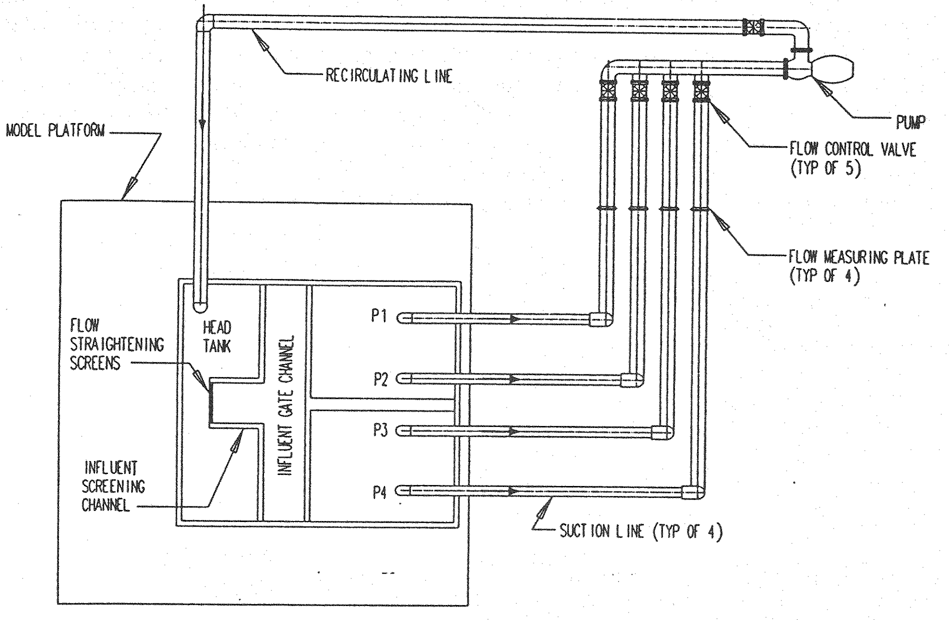

Fig. 2. Physical model layout (TYP = TYPICAL)

Table 1. Criteria for assessing air entrainment

Bubble Size	Model observation at suction bell: Diameter cm (in)	Bubble Quantity	Model observation at suction bell: Appearance
Small	0.13 (0.05)	*Low*	small scattered
Medium	0.25 (0.1)	*Medium*	small to medium clumps or large scattered
Large	0.38 (0.15)	*High*	large clumps

PRELIMINARY DESIGN TESTING

Testing of the preliminary design covered the full range of anticipated operating conditions of the wet well pumping station. Tests included combinations of one, two, three, and four-pump operation with pumps operating at rated flows ranging from 4,400 to 7,200 gallons per minute (gpm) or 0.28 to 0.45 cubic meters per second (m^3/s) and water depths ranging from the prescribed minimum submergence of 0.91 meters (m) or 3 feet (ft) to a maximum anticipated water level of 3.05 m (10 ft).

Model tests identified several hydraulic deficiencies. Air entrainment was a problem for all conditions tested. The drop from the floor of the influent gate channel to the bottom of the baffle chambers generated significant aeration and caused air bubbles to reach the suction inlets. The air entrainment varied from a *high* at a water depth of 0.91 to 1.83 m (3 to 6 ft) to a *medium* for depths exceeding 1.83 m (6 ft).

Subsurface vortices were evident for all conditions tested and surface vortices were observed in tests at a water depth of 0.91 m (3 ft). Swirl varied with pumps in operation and water level. Vortimeters rotated at more than 10 rotations per minute (rpm) for more than half of the tests conducted. The opening on the divider wall increased vortimeter rotations in excess to 50 rpm at the pump immediately downstream of the opening and adversely affected flow patterns within the well in tests with three-pump operation.

The flow through the influent channel gates was skewed towards the far side of the openings for all conditions tested. The areas of the influent gate channel downstream of the gates exhibited stagnant flow conditions which is conducive to solids settlement. Finally, the model showed that closure of the divider wall gate raises the water elevation in the influent channel and creates a differential in the water level inside the sumps which otherwise remains the same. Typical flow patterns for the initial design with a three pump-operation are depicted in Fig. 3. The design was modified on the basis of model test observations. Structural changes were made to improve hydraulic performance within the site constraints imposed by operational requirements.

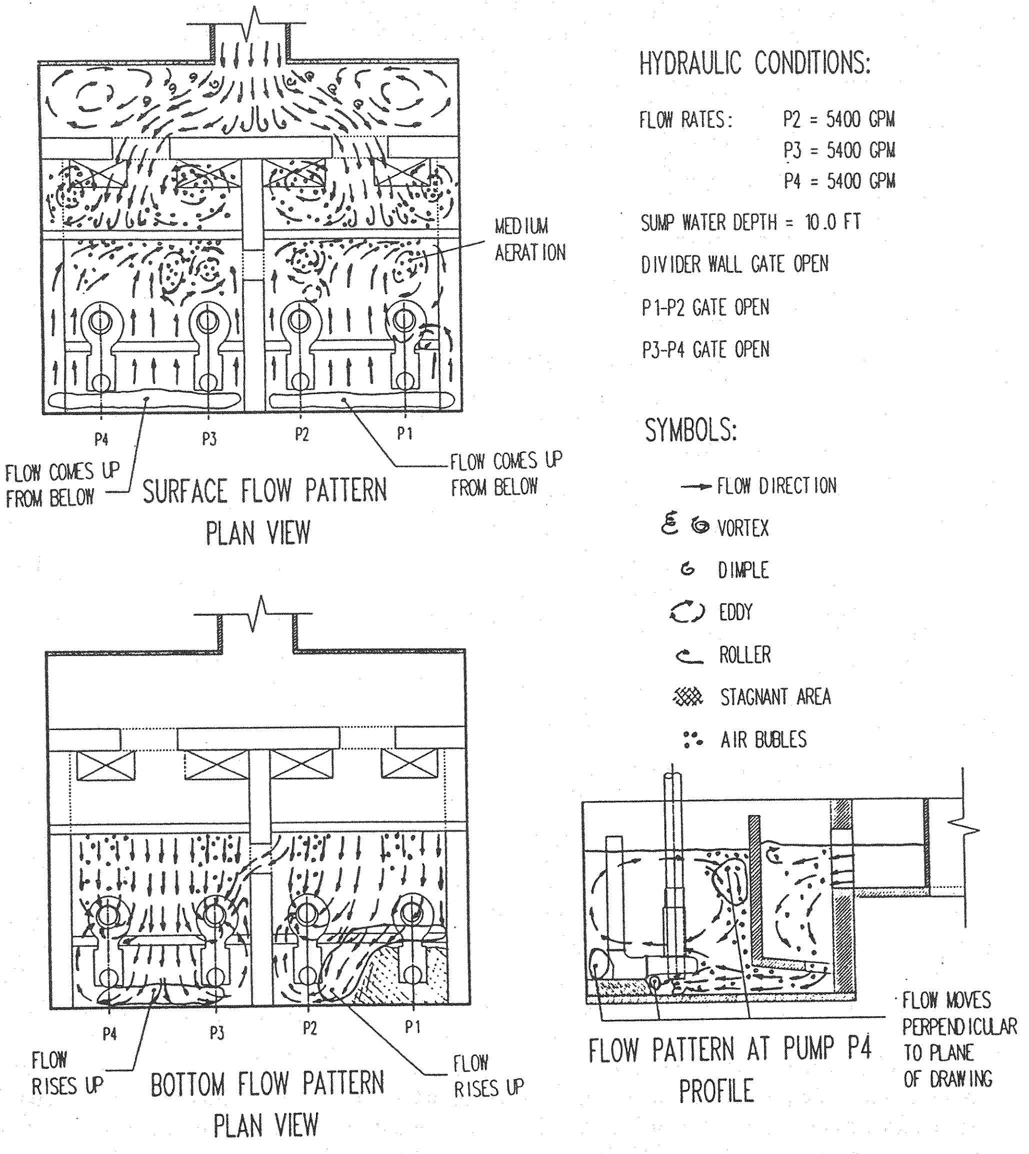

Fig. 3. Preliminary design typical flow patterns

DESIGN MODIFICATIONS

Model tests were conducted to eliminate or minimize the hydraulic deficiencies observed during the initial tests of the preliminary wet well design. During these tests modifications with different dimensions were used including baffle walls, flow guidance elements, flow splitters under the suction bells, vanes, floor fillets, divider walls, and horizontal beams. A combination of structural and operational modifications was necessary to achieve a satisfactory hydraulic performance under all conditions tested.

The structural modifications needed to produce the most satisfactory flow conditions are: 1) lowering the floor of the influent gate channel to place the air-entraining drop further away from the pumps; 2) lowering the invert of the influent channel gates to better utilize the flow area afforded by the square openings and reduce flow velocities at the entrance to the baffle chambers; 3) bringing the end walls of the influent gate channel close to the gated openings to eliminate potential solid deposition areas and help guide the flow through the openings; 4) adding wedge-shaped flow splitters under the suction inlets to break subsurface vortices; 5) changing the location of the divider wall gated opening from the well to the baffle chamber area to minimize the adverse effects of flows moving through the opening during three-pump operation; 6) a wall under the baffle chamber floor between the two openings on the floor; and 7) a horizontal beam between the vertical baffle wall and the pumps. The modified design with structural details are illustrated in Figs. 4a, 4b and 4c.

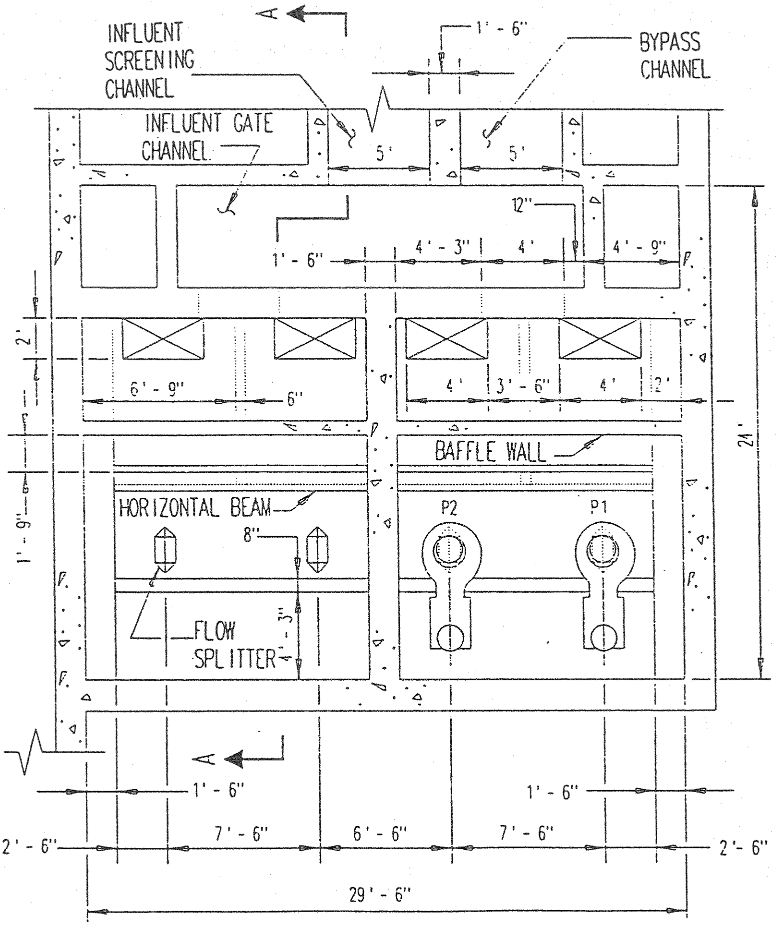

Fig. 4a. Modified design layout-plan view

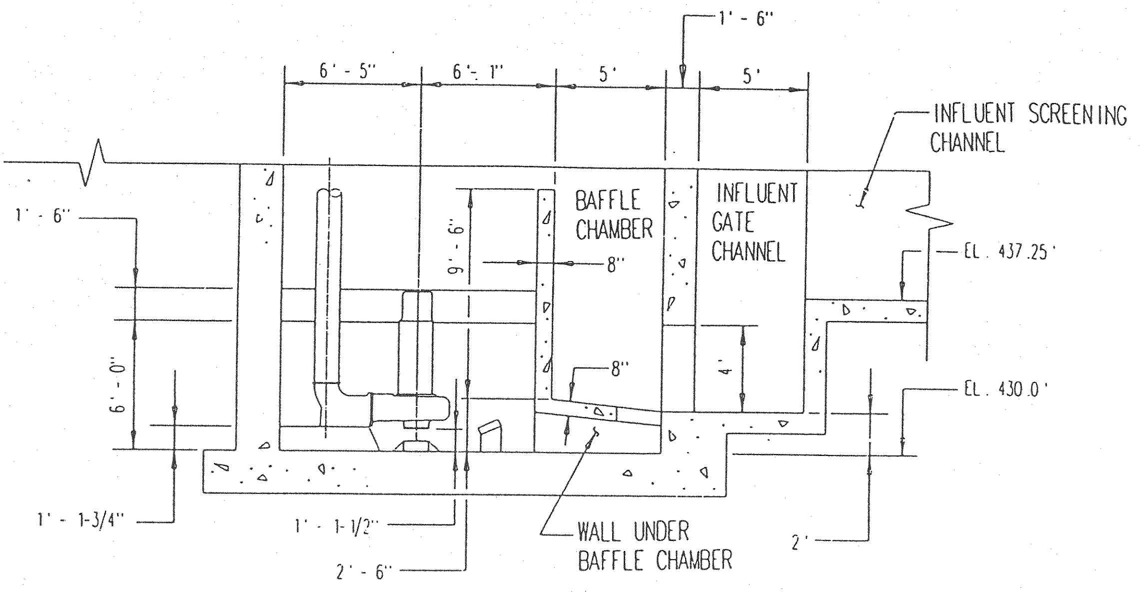

Fig. 4b. Modified design layout-cross section

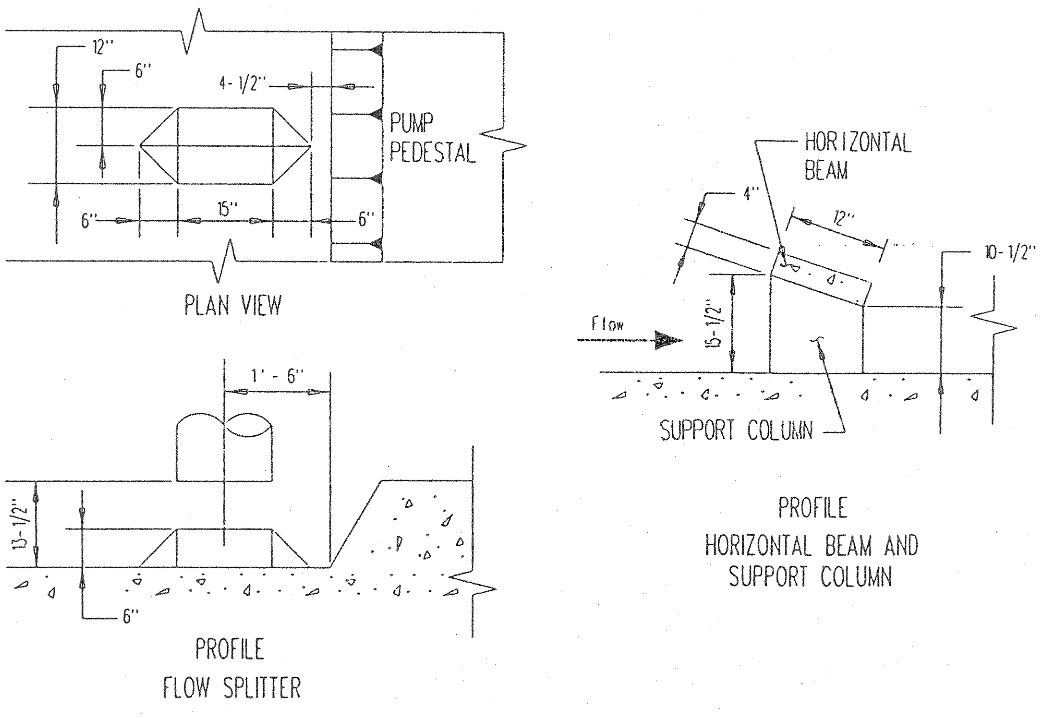

Fig. 4c. Design modification details

After implementing the design modifications, a final series of tests was performed to verify and document the hydraulic performance of the modified design. The design performed satisfactorily for all anticipated operating conditions. It eliminated the need to favor one pump over another within one sump, and also provided satisfactory performance with two pumps operating within one sump.

The final design tests were used to establish the minimum water level at which different combinations of pumps will operate normally with minimal air entrainment as presented in Table 2. Vortimeter rotations and a qualitative assessment of air entrainment at the pump suction inlets for final design tests are also included in Table 2. Although the acceptibility criterion of ten vortimeter rotations per minute is satisfied, the difference exhibited between the pumps can be attributed primarily to the unevenness in the approach flow conditions particularly that the distance between the inlet gate channel and the pump basin is relatively small and does not provide sufficient travel time for the flow to even itself out. Water surface elevations measured throughout the wet well are presented in Table 3. Note that, the tests presented in Table 3 were used to document only water elevations and not flow vorticity or air entrainment.

Table 2. Final design parameter measurements water depth, vortimeter rotation and air entrainment

Test No.	Pump(s) in Operation	Pump Flow Rate m^3/s (gpm)	Minimum Water Depth m (ft)	Vortimeter Rotation at Pump rpm P1	P2	P3	P4	Air Entrainment at Pump(s)
1	P3	0.28 (4,400)	1.22 (4)			1		none
2	P3	0.45 (7,200)	1.22 (4)			1		low
3	P4	0.28 (4,400)	1.22 (4)				1	none
4	P4	0.45 (7,200)	1.22 (4)				3	low
5	P1 & P3	0.39 (6,250)	1.83 (6)	3-5		3-5		low
6	P1 & P4	0.39 (6,250)	2.13 (7)	2			2	low
7	P2 & P3	0.39 (6,250)	1.83 (6)		6-8	6-8		low
8	P3 & P4	0.39 (6,250)	2.44 (8)			6	0	low
9	P1, P3 & P4	0.34 (5,400)	2.44 (8)	4-7		2-3	7-9	low
10	P1, P3 & P4	0.34 (5,400)	3.05 (10)	4		5	3	none

Table 3. Final design parameter measurements water surface elevation throughout the pump station (NM = Not Measured)

			Water Surface Elevations m						
			Influent Screen Channel	Gate Channel		Baffle Chambers		Pump Sumps*	
Test No.	Pump(s) in Operation	Pump Flow Rate m^3/s (gpm)		P1-P2 Side	P3-P4 Side	P1-P2	P3-P4	P1-P2	P3-P4
11	P3	0.28 (4,400)	133.43	132.34	132.31	132.34	132.31	132.34	132.28
12	P3	0.45 (7,200)	133.49	132.39	132.36	132.39	132.34	132.39	132.28
13	P1 & P3	0.39 (6,250)	133.58	132.65	132.65	132.65	132.65	132.60	132.60
14	P2 & P3	0.39 (6,250)	133.58	132.94	132.94	132.94	132.94	132.92	132.92
15	P1 & P4	0.39 (6,250)	133.58	133.20	133.20	133.20	133.20	133.18	133.18
16	P3 & P4	0.39 (6,250)	133.61	NM	133.60	NM	133.56	NM	133.50
17	P1, P3 & P4	0.34 (5,400)	133.62	133.57	133.56	133.56	133.55	133.53	133.50
18	P1, P3 & P4	0.34 (5,400)	134.23	134.21	134.20	134.20	134.17	134.17	134.13

* Floor sump, elevation = 131.06 m. Floor of baffled chambers sloped from 131.83 to 131.67 m. Floor of influent gate channel, elevation = 131.67 m. Floor of influent screening channel, elevation = 133.27 m.

As indicated in Table 2, in terms of swirl and air entrainment at the pump suction inlets, the minimum water level for satisfactory hydraulic performance vary for different pump combinations. Any one pump operates well at water depths in the sump of four feet and higher. Any three pumps or two pumps in the same sump operate well at water depths of eight feet and higher. Two pump operation in separate sumps requires depths of six feet when the center pumps (P2 and P3) are activated and of seven feet when either of the corner pumps (P1 or P4) is in operation. Typical flow patterns for the modified design with a three pump-operation are shown in Fig. 5.

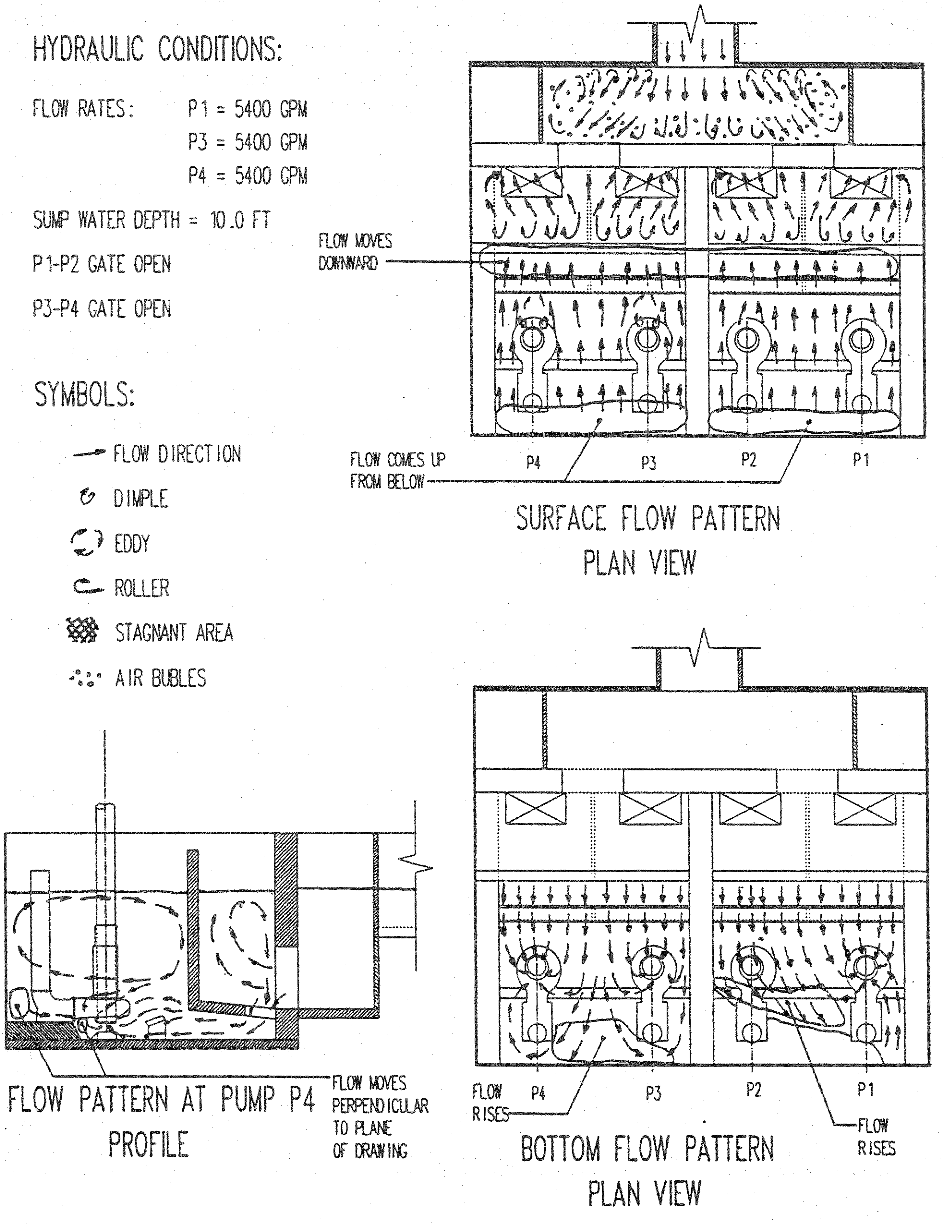

Fig. 5. Modified design typical flow patterns

PRACTICAL APPLICATIONS

In general, design guidelines have been developed in a way that relates the suction bell diameter to sump geometric dimensions or the pump flow rate. While this approach is acceptable to develop a preliminary design, but it has been demonstrated to be inadequate in eliminating many hydraulic deficiencies due primarily to approach flow conditions and pump configuration. Therefore, structural elements (a combination of baffles, beams, ramps, flow splitters, and corner fillets) are introduced to eliminate/minimize these hydraulic deficiencies. The location and number of these elements can be determined best by experimentation via a physical model and is not a function of the suction bell diameter or the pump flow rate. They depend rather on the pump configuration and the approach area. Due to space limitations in underground pumping facilities, the approach area plays a more significant role particularly with respect to air entrainment. The lack of a theoretical basis for a general design dictates that physical modeling has to be used to arrive at a satisfactory design.

A generalized design may be attainable and may require significant deviations from current practices. The vortex suppression and flow guidance characteristics of baffles, beams, ramps, and flow splitters would have to be enhanced by elements of the generalized design to make the resulting structure independent of approach flow conditions. An alternative considered in developmental and testing stages, is the formed *suction intake*, also referred to as *suction scoop* or *inverted draft tube*. (Antunes and Holman (1), Fletcher (12, 13), Nakato (22), Rahmeyer and Tullis (27), Tullis (32), Triplett *et al.* (30) and Urroz and Tullis (33)). It is used mainly on vertical pumps in flood control pumping stations and essentially it turns the area in front of the pump bell into a conduit that smoothly transitions from a vertical rectangle into a horizontal bell shape. Different configurations of the formed suction intake have reportedly been implemented at some installations (Fletcher (11) and Nakato (23)), but additional research and systematic testing which involves adequate variability in configuration of the device, are still required to arrive at a generalized design (Tsou *et al.* (31)).

SUMMARY AND CONCLUSIONS

Existing design guidelines provide recommendations on the size and configuration of pump stations but do not guarantee satisfactory flow conditions because they are based primarily on empirical information obtained from laboratory tests creating a lack of a theoretical basis for determining an optimal layout for pumping stations. A satisfactory design for one installation may not perform adequately for another one. Therefore, physical modeling is necessary to evaluate the performance of a pumping station design and derive appropriate modifications that would alleviate potential hydraulic deficiencies.

Few studies on the use of large submersible pumps have been published. A hydraulic model study was conducted to evaluate the hydraulic performance of a preliminary design of a wet well pumping station. The station is equipped with large submersible pumps and is used to pump wastewater from sewer mains.

Model tests identified hydraulic problems and deficiencies (air entrainment, surface and subsurface vortices, and uneven flow distribution) and served as a benchmark in the development and evaluation of design modifications. The model was also used to define operational parameters including the determination of water levels upstream of the pump station and within the wet well for which various combinations of pumps will operate satisfactorily.

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APPENDIX - NOTATIONS

The following symbols are used in this paper:

N_F = Froude number (dimensionless);

N_R = Reynolds number (dimensionless);

N_W = Weber number (dimensionless);

L = characteristic length (L);

V = fluid velocity (L/T);

g = gravitational acceleration (L/T^2);

ρ = fluid density (M/L^3);

τ = fluid surface tension (M/T^2); and

ν = kinematic viscosity (L^2/T).

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