Mamaroneck Effluent Pumping Station Wet Well Model Study: Necessity or Redundant Design Precaution?

Performing adequate model testing of designs when special circumstances exist may result in the savings of valuable construction time and costs.

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To meet the federal Clean Water Act requirement to provide secondary treatment, the Westchester County Department of Environmental Facilities found it necessary to expand treatment facilities for the Mamaroneck Wastewater Treatment Plant in Westchester County, New York. This expansion required the construction of a complex pumping station that would provide the needed hydraulic head to convey the treated effluent through the outfall during high flow conditions exceeding 40 million gallons per day (mgd) and up to a maximum of 92 mgd. Because the available area to site the expanded facilities was extremely limited, the layout of the expanded plant proved to be a design challenge. The area allocated for the 92 mgd effluent pumping station was, therefore, also extremely limited. The tight available area and constructability issues that dictated three different flow entrance conditions resulted in an effluent pumping station with a wet pit and vertical turbine pumping design. A vertical turbine, wet pit pumping station was selected where the pumps would be suspended into the effluent and the flow conveyed upward through vertical columns. The discharge head, motors and drives were to be installed on a floor above the wet pit or pump wet well.

For these types of pumping stations, the wet well layout remains the controlling factor in the

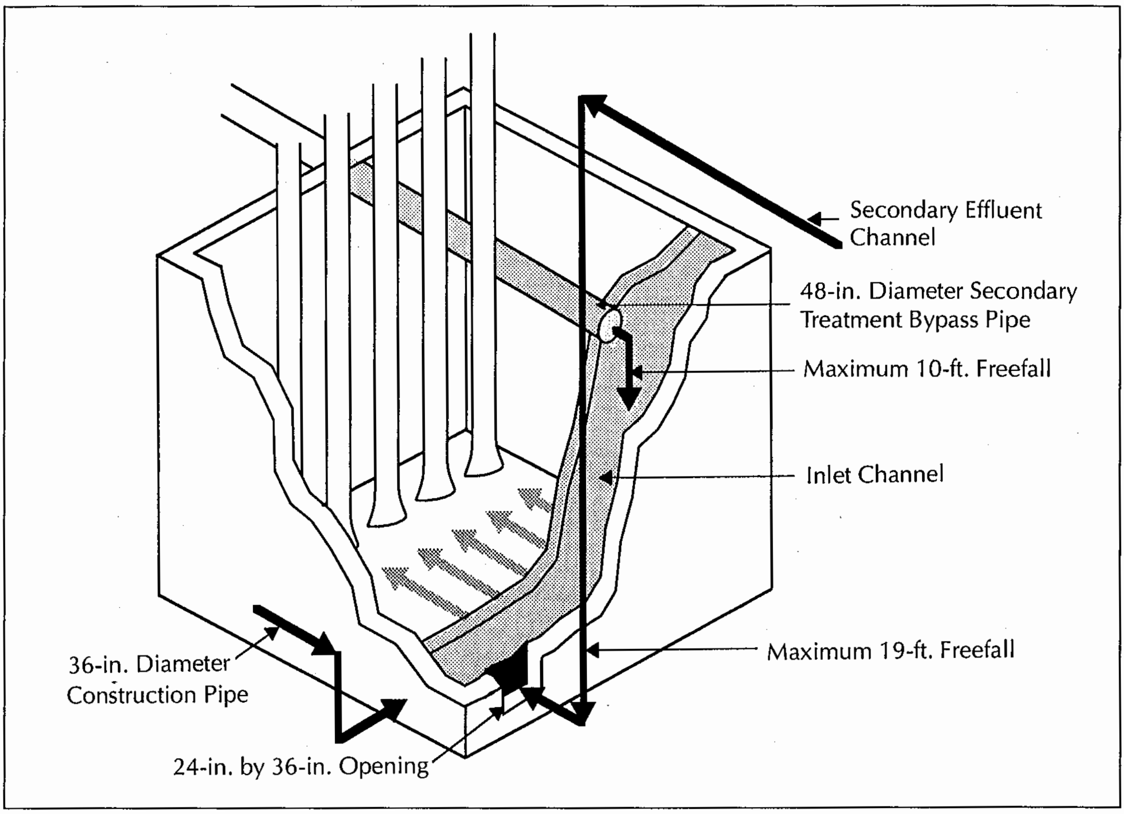

FIGURE 1. Pre-design flow routes.

area required for a proper pumping station design. To a hydraulic specialist, the fact that the available area is limited often means that the design of the wet well and the associated pump suction hydraulics must be addressed with great care. For the pumps to operate properly, the approaching flow to them must be uniformly distributed and be free of any free-surface or submerged vortices that could lead to the severe damage of the pumps and their components. To ensure that the pumping suction hydraulics are adequate for proper pumping operation, the layout of the wet well must rigidly follow accepted design criteria. However, applicable design criteria for this particular wet well design were not available.

To ensure proper wet well hydraulics for this crucial pumping station, the design engineers recommended that a hydraulic study on a reduced scale model be performed. The model study allowed the engineers to test various wet well hydraulic conditions that would occur during the interim construction phase operating conditions as well as during full-scale plant operation.

Initial Wet Well Design

Pre-Design. The pumping station was designed to handle up to 92 mgd using four duty pumps and one standby pump. Because primary effluent is to be handled at certain times, the vertical turbine pumps were required to handle solids. The pumps were controlled by variable frequency drives. The range in wet well water levels was -1.5 to 8.0 feet (msl).

The footprint of the effluent pumping station needed to be limited to 30 by 50 feet because the area available for installation was extremely tight. To see where the problems would occur, the initial design was completed based on shoe-horning the proposed pumping station onto the available site while providing for adequate wet well hydraulics. The initial layout was based on the guidelines set forth by the Hydraulic Institute.[1] These and similar guidelines, however, did not cover the extreme hydraulic conditions caused by non-uniform approach flows that would occur at this pumping station. These unique hydraulic conditions were not completely covered by any previous design criteria found in the literature.

The effluent pumping facility would be required to handle a wide flow range that spanned from 10 to 92 mgd. Pumping would start when flows exceeded 40 mgd. To prevent the excessive cycling of the pumps when the flow receded to 40 mgd, pumping would continue down to 10 mgd. However, during the construction of the treatment facilities, the pumping station would be needed to convey all flows. Flow to the pumping station would be by three separate routes (see Figure 1).

The principal route would accommodate the flow from the secondary clarifiers, which would have a maximum flow or design flow of 40 mgd. The secondary effluent would be conveyed through the secondary effluent collection channel that picked up the flow from the clarifiers. Because of the hydraulic head required to convey flow through the bypass pipe (see Figure 1), the flow from the collection channel would have to freefall downward over a drop of up to 19 feet into a chamber. When pumping would be required as the total of the secondary effluent and bypass flows exceeded 40 mgd, the flow from the chamber would be directed to the pumping station through a 24- by 36-inch opening to the pumping station inlet channel. The flow through the opening accelerated up to ten feet per second (fps) after which it turned 90 degrees into the inlet channel prior to entering the wet well. The steep freefall and the abrupt turn of the flow to the wet well would induce non-uniform approach flows to the pumps that could possibly adversely affect the wet well hydraulics if it were not properly designed.

Because the treatment plant was designed to bypass primary effluent around the secondary facilities at flows exceeding 40 mgd, another flow route was needed to convey this bypass flow to the pumping station. The bypass flow (up to 52 mgd) would be conveyed through a bypass channel that entered a junction box feeding the 48-inch diameter pipeline to the wet well. The freefall required to convey the flow to the wet well could be as high as ten feet. After the freefall, the flow would have to make a 90-degree turn in the inlet channel.

The effluent pumping station was required to convey the primary effluent during the construction of the secondary treatment facilities. During this construction, the primary route to the pumping station would be through the 48-inch diameter pipe. The 48-inch diameter pipe conveyed a maximum flow of 50 mgd during this period. A third route to the pumping station would, therefore, be required to pump flows that exceeded 50 mgd during the construction period of the secondary facilities.

The third route that would only be used during the construction of the secondary facilities directed the flow to enter the pumping station through a 36-inch diameter pipe in a direction perpendicular to the other two flow routes. The 36-inch diameter pipe would convey up to 42 mgd. The freefall needed to accommodate the flow to the pumping station occurred about 50 feet upstream of the pumping station. Air entrainment must, therefore, be addressed for this route as well. The high velocities (up to nine fps) that would occur during maximum flow and the two succeeding 90-degree turns prior to entry of the flow into the wet well would have to be properly addressed to avoid any adverse impact on the wet well hydraulics.

The concerns over the hydraulics of the wet well were twofold. First, the turns in flow would cause uneven distribution of flow toward the pumps. The uneven flow distribution would cause vortices in the wet well. Secondly, excessive air entrainment caused by the freefalls along the flow routes would result in air entering the pumps. Either of these two phenomena could lead to serious operational problems with the pumps. These problems could take the form of bearing failures, as a minimum consequence, and impeller, shaft and column failures, as extreme consequences. Therefore, it was deemed that a scaled-down model of the wet well would provide the means to evaluate the final design of the pumping station in order to avoid such problems.

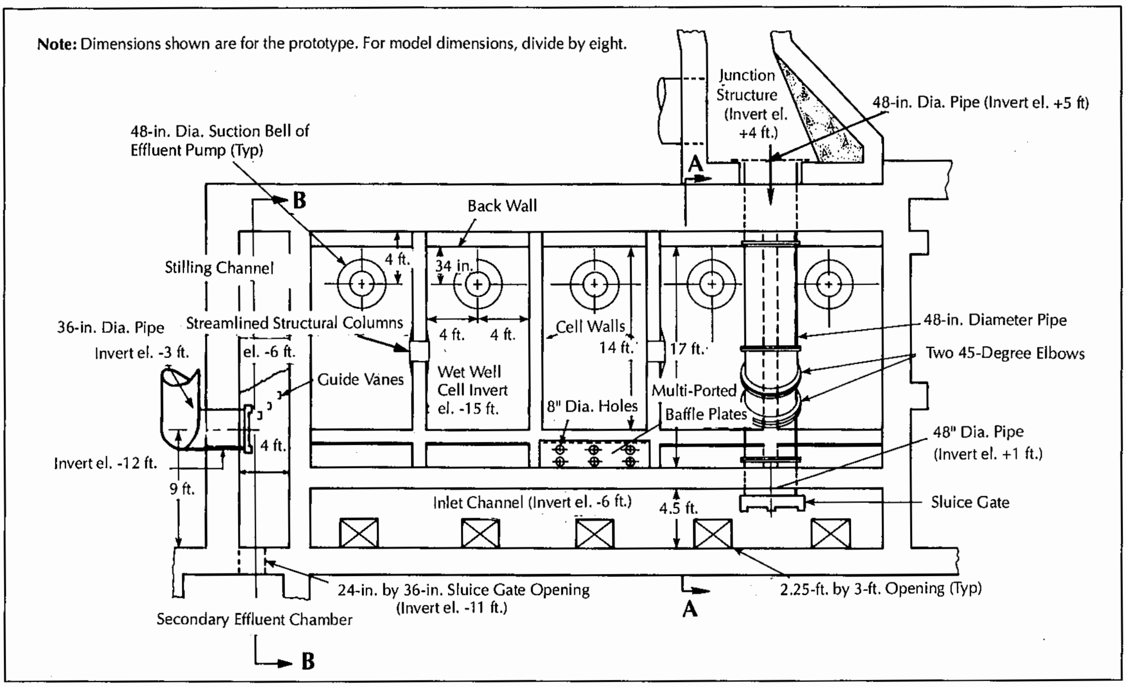

FIGURE 2. Initial model design — plan view.

Initial Design. Prior to the construction of the model of the wet well, an attempt was made to incorporate features into the design that would improve the hydraulics of the wet well using a layout that would best satisfy the limitations of the site while providing adequate hydraulics.

The first step in the model evaluation was to incorporate features into the wet well design that would uniformly distribute flow into the wet well. To this end, the following design features were incorporated into the model (see Figures 2, 3 and 4):

- Two 45-degree vertical bends along the 48-inch diameter pipe
- A deep inlet channel with bottom openings
- Cell walls to isolate the wet wells to each pump
- Multi-ported baffle plates at the entrance to each wet well cell
- A false back wall at each pump
- Streamlining the structural columns that project from the cell walls
- A stilling basin
- Weir walls at the downstream end of the secondary clarifiers' effluent collection channel (secondary effluent chamber)
- Flow guide vanes within the stilling basin

The pump columns were 24 inches in diameter while the suction bell diameter was 48 inches. Based on criteria established by the Hydraulics Institute,[1] the suction bell was installed at a clearance of 24 inches above the wet well floor, while the false back wall was installed to provide a ten-inch clearance from the lip of the suction bell (see Figures 2 and 3).

The two 45-degree bends near the exit of the 48-inch diameter pipe were provided to lessen the freefall as much as possible within the space limitations encountered. A vent was installed upstream of the drop along the 48-inch diameter pipe. The 4.5-foot wide, deep inlet channel was designed to act as a stilling basin that would slow the approach flow as much as possible and that would enhance the stripping of air entrained by the freefall at the exit of the 48-inch diameter pipe. The invert of the inlet channel was positioned below the minimum wet well level to prevent freefall into the wet well. The 2.25- by 3.0-foot openings through the

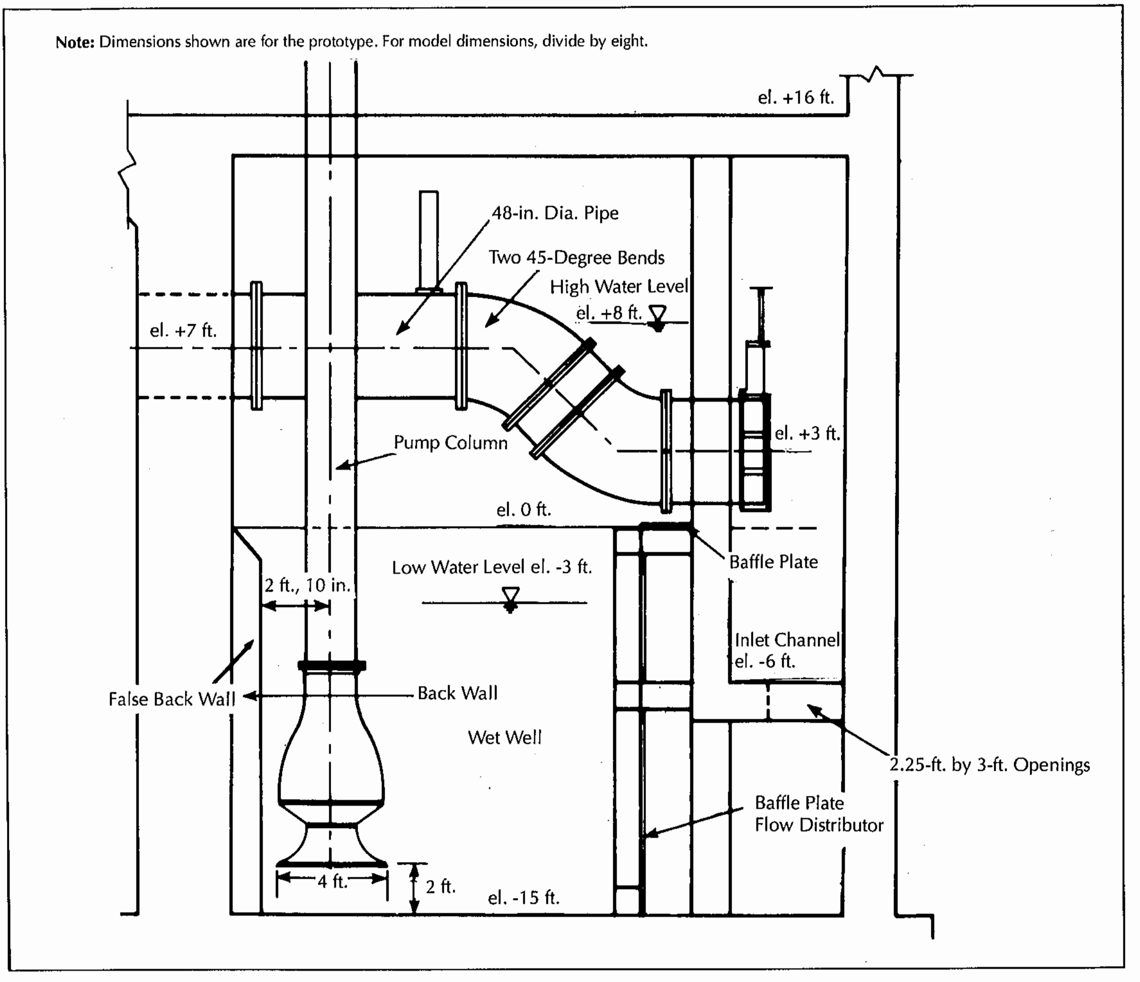

FIGURE 3. Initial model design — section A-A view.

floor of the inlet channel would enhance flow distribution to the individual wet well cells.

Each pump approach was segregated by an eight-foot wide cell. The width and length of the cell were based on Hydraulics Institute criteria.[1] The wet well was segregated into individual cells in order to prevent cross flow among the approaches to the pumps. Without this modification, cross currents would be especially predominant when one or two pumps would be in operation. The flow would tend to enter along the entire width of the wet well regardless of the number of pumps operating. This condition would cause the incoming flow to cross over the wet well approaches to the non-operating pumps and skew the flow toward the active suction bells. The cross flow in the wet well would cause vortices to occur and lead to the improper entry of flow into the pumps. Such conditions should be avoided in order to achieve good wet well hydraulics.

Multi-ported baffle plates were added to straighten the flow toward the pumps and to uniformly distribute the flow throughout each individual cell. Eight-inch diameter ports were selected. The total area of the ports amounted to 13 percent of the plate area. The ports enhanced flow distribution while producing a head loss that could be tolerated by the upstream hydraulics to the pumping station. The multi-ported plates were submerged. Therefore, a short horizontal section of plate with ports was added to the top of each plate.

The suction bells were positioned close to

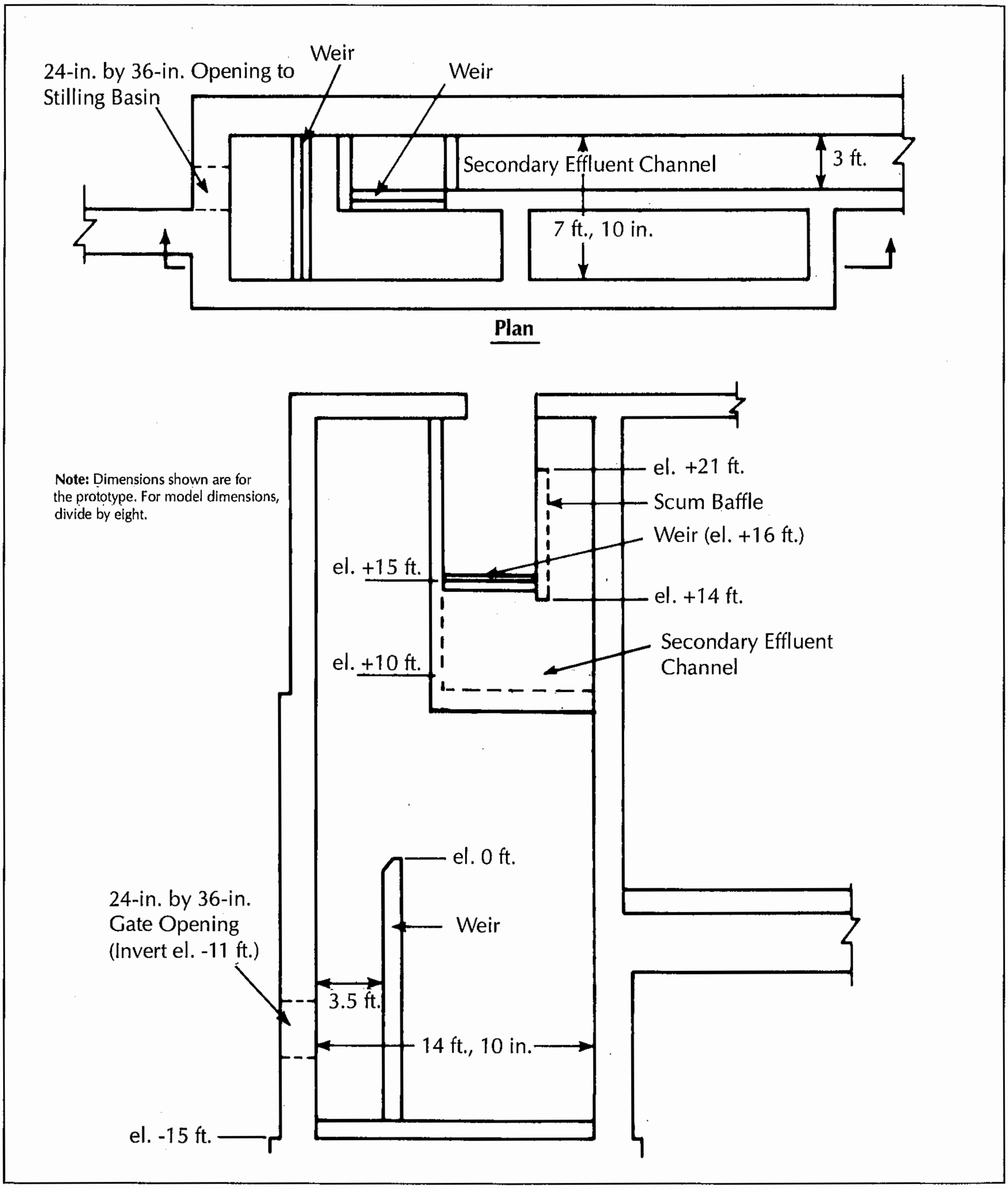

FIGURE 4. Initial model design of the secondary effluent chamber.

the back wall of a wet well in order to minimize the formation of vortices and eddies by allowing the back wall to act as a baffle to any swirling motion. However, because the location of the suction bells in the wet well was governed by the requirements of the drive equipment located above, the suction bells could not be positioned close enough to the back wall as required by the Hydraulics Institute.[1] A false back wall was, therefore, added to allow for the correct positioning of the suction bell (ten inches from the wall).

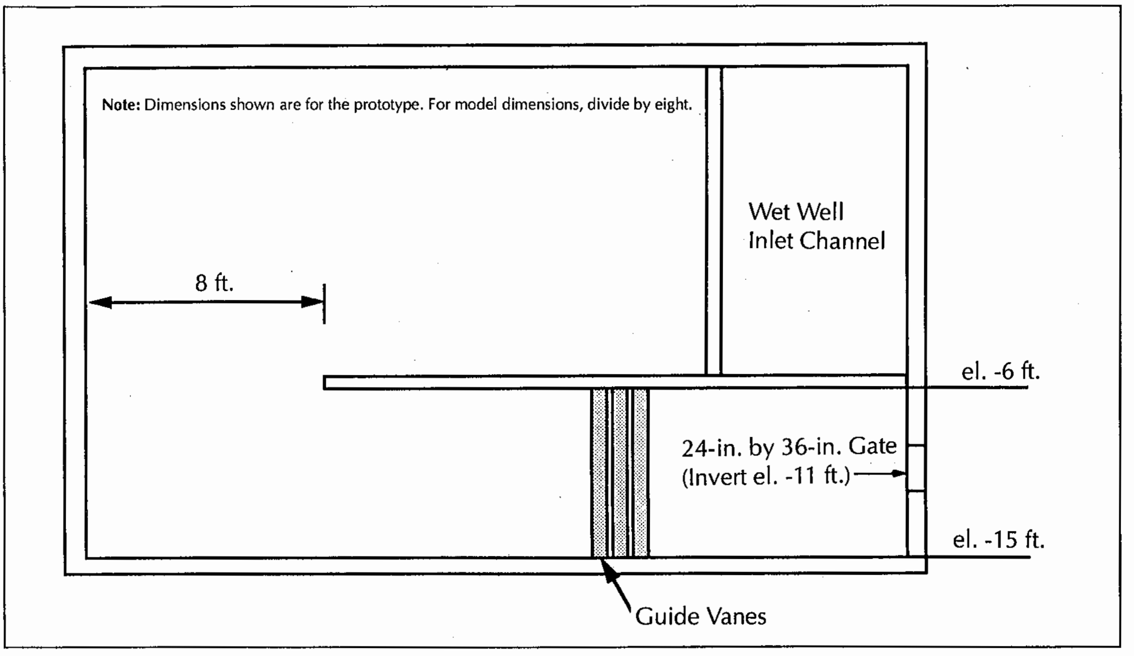

FIGURE 5. Initial model design section view of the stilling basin — section B-B view.

The support columns in the wet well were repositioned to coincide with the cell walls. The columns, however, projected slightly beyond the cell walls. These projections were flared to join the wall in a streamline manner so that they would not cause flow separation and eddies as the flow passes by the projections.

A weir was added at the exit of the secondary clarifiers' effluent collection channel (see Figure 4) to submerge the outlets of the individual effluent launders, thereby minimizing air entrainment along the length of the collection channel. To aid in stripping air caused by the freefall in the secondary effluent chamber, a weir was added to supply a rough air stripping basin prior to the entry of the flow to the pumping station via the 24- by 36-inch opening.

To dissipate high velocities (up to ten fps) through the 24- by 36-inch opening or 36-inch diameter construction pipe, and to strip air from the flow caused by freefall within the secondary effluent chamber and within the 36-inch diameter construction pipe, a stilling well was incorporated into the design. The stilling well was designed as a bi-level basin in order to maximize the detention time and, therefore, maximize air stripping (see Figure 5). Guide vanes were added at the exit of the 36-inch diameter construction pipe to turn the flow and to enhance the uniform distribution of flow in the stilling basin.

After these features were incorporated into the design, fabrication of the scaled model began.

Model Study

Model Similitude. Because the flow regime in the free-surface prototypes are controlled by gravity and inertia forces, the model was designed and operated using similarity between the prototype and the model based on the Froude number. The Froude number in the model, therefore, was kept the same as in the prototype.

The Froude number is a dimensionless number that represents the ratio of inertia and gravitational force. This ratio is defined by the following equation:

$$F = u/(gD)^{1/2}$$

where:

u = the average axial velocity

FIGURE 6. Photograph of the model as seen through its back wall.

g = the gravitational acceleration
D = the suction bell diameter

In preparing a model of a pump wet well to study the formation of vortices, a large enough geometric scale must be selected in order to achieve high Reynolds and Weber numbers. A sufficiently high Reynolds number (30,000) and Weber number (120) will minimize the scale effects of viscosity and surface tension and accurately reproduce the flow pattern toward and around the suction bell.[2,3] When the influence of viscous forces and surface tension on vortexing are negligible, the dynamics involved with similarity are assured in a Froude model.[2,3] A geometric scale for the model of 1/8th of that of the prototype was, therefore, selected.

With the selected geometric scale ratio of 1:8, the respective Reynolds and Weber numbers in the model ranged from 40,000 to 60,000 and 190 to 320, respectively, for the flows corresponding to 23 to 30 mgd per pump. Although adverse scale effects were unlikely to occur with this model, a few selected tests were repeated at 1.5 times the Froude number, as a conservative procedure, in order to allow for any viscosity scale effects.

Based on Froude similitude for the geometric scale of 1/8th of that of the prototype, the velocity and time scale was 1/2.8 and the flow scale was 1/181 of the corresponding values that would be found in the prototype.

In a Froude model at a significant reduced scale, air entrainment cannot be accurately modeled because the air bubbles are not to scale. However, by injecting artificial air bubbles into the channel upstream and downstream of the flow distribution points, qualitative results on the entry of air bubbles into the suction bells can be obtained.

Model Description. No rotating parts of the pump were modeled. Rather, the suction bell was modeled and a swirl meter positioned in the suction pipe where the pump in the prototype would be located. The object of the model study was to determine the flow patterns at the entrance to the pump. Pumps are designed on the premise that the flow pattern towards the pump is uniform, without any significant skewness of the flow pattern nor any pre-rotation. Delivery of the flow to a pump in any other manner than this could cause severe problems.

A model of the wet well was constructed to a length scale ratio of 1:8. The pump columns were fabricated with transparent plastic and swirl meters were installed at the appropriate locations. The suction bells were made from fiberglass. The swirl meters were installed to measure the rotation of flow as it entered the pump. The location of the swirl meters corresponded to the location of the impeller within each prototype pump column.

Rotation of flow into the pump could be caused by eddies and vortices within the wet well. The back wall at the pump side of the wet well was constructed with clear acrylic in order to facilitate observations of flow patterns and vortices. The multi-ported baffle plates were made from sheet metal. The baffle plates were constructed in order to correctly simulate the head losses across them.

Figure 6 represents a photograph taken of the model through its clear acrylic back wall. The swirl meters can be observed above the suction bells as seen through the clear acrylic columns. As previously noted, the swirl meters were located where the pump impellers would be in the prototype. Also, note the multi-ported baffle plates in the background, located at the entrance to the wet well cells.

Model Tests. The model test study was performed in three phases with each phase consisting of selected operating combinations of the pumps. All flows were measured with calibrated orifice meters. Water levels were measured with piezometer taps in order to accurately obtain head loss data.

To evaluate the strength of the free-surface and subsurface vortices within the wet well, a vortex strength scale (shown in Figure 7) was developed and used. This scale indicated the various types of vortices that could be experienced as well as the degree of vortex strength. Subsurface vortices usually emanate from the floor and walls near the suction bell entrance. The vortices were only made visible when dye was injected in these suspect locations.

The magnitude of the swirl that entered the pump was based on the measurements taken by observing the swirl meter. The swirl angle, θ, was calculated according to the following equation:

$$\theta = \arctan (\pi n d/u)$$

where:

u = the axial velocity at the swirl meter location
d = the diameter of the suction pipe
n = the revolutions per second of the swirl meter

The swirl angle represents the average deflection of the velocity vector from the axial direction, and is considered indicative of the strength of the swirl. The tangent of the swirl angle is the ratio of the average tangential velocity, $\pi n d$, indicated by the swirl meter rotations, to the average axial velocity, u.

Short-term swirl angles were calculated based on the average of the number of rotations over a 30-second period in the model, while long-term swirl angles were based on the average rotations over a ten-minute period. In general, free-surface vortices of type 3 or higher, subsurface vortices of type 2 or higher, and swirl angles greater than five degrees are considered objectionable.

Phase 1 Tests. The model was tested at the minimum water levels with one to four pumps operating. The worst cases of vortexing and/or air bubbles entering the suction bells were identified for further testing under the next round of testing.

Even with the use of multi-ported baffle plates, the tests indicated that the flow entering each of the wet well cells was skewed to one

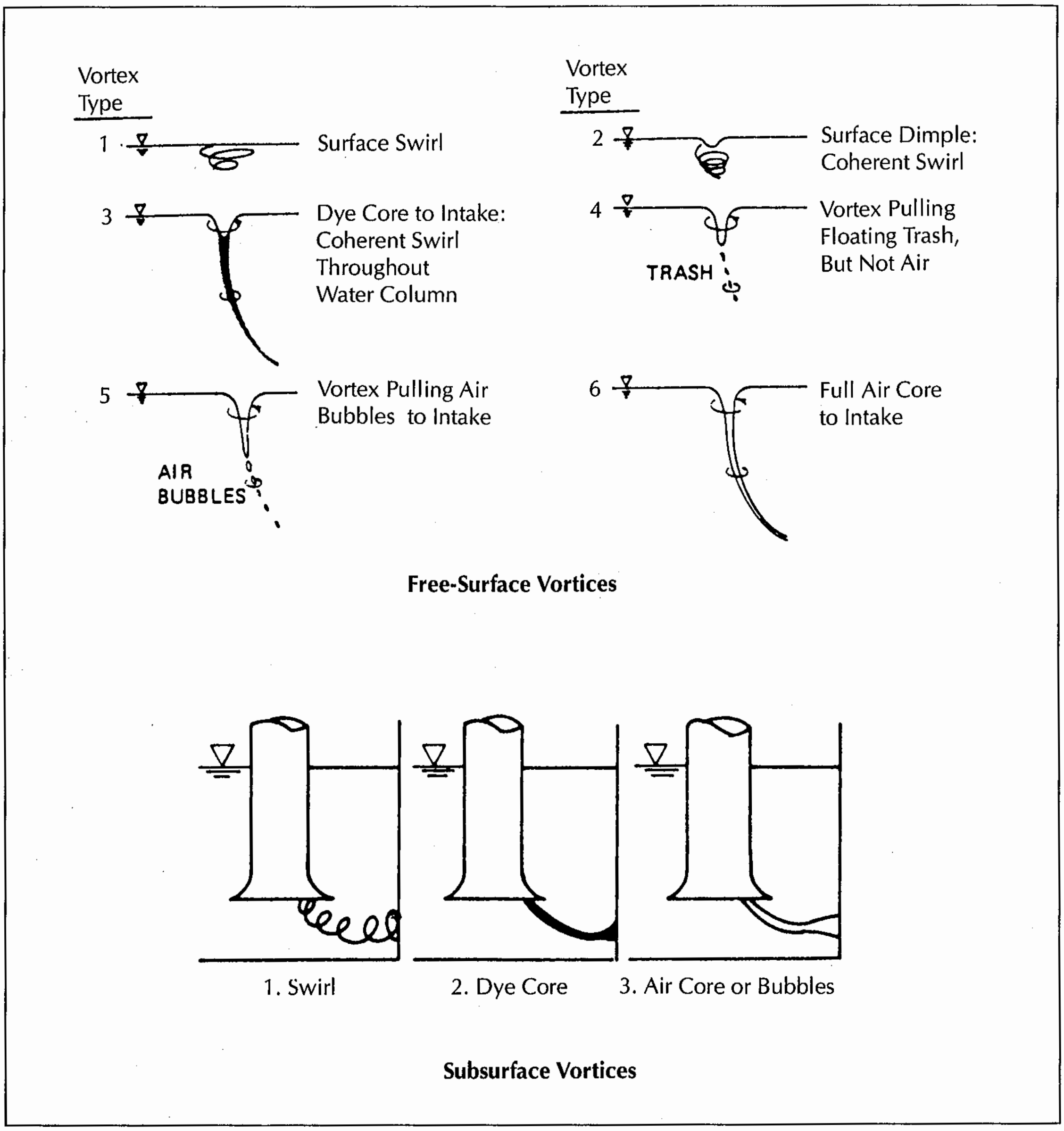

FIGURE 7. Vortex strength scale.

side. The direction of the skewed flow depended on the flow direction in the inlet channel before it entered the openings through the channel bottom. However, the water surface within the wet well cells was turbulent enough to prevent any persistent free-surface vortices.

Some free-surface unsteady vortices with weak, unstable cores of persistencés of less than ten percent were observed in one of the cells during three tests. No air-drawing, free-surface vortices were observed during any of the tests. Objectionably strong subsurface vortices with coherent type 2 cores were observed, however, in all tests. These vortices emanated from the floor of the wet well under the suction bell and from the back wall.

During some of the tests, subsurface vortices were observed emanating from the side walls of the wet well. The subsurface vortices persist-

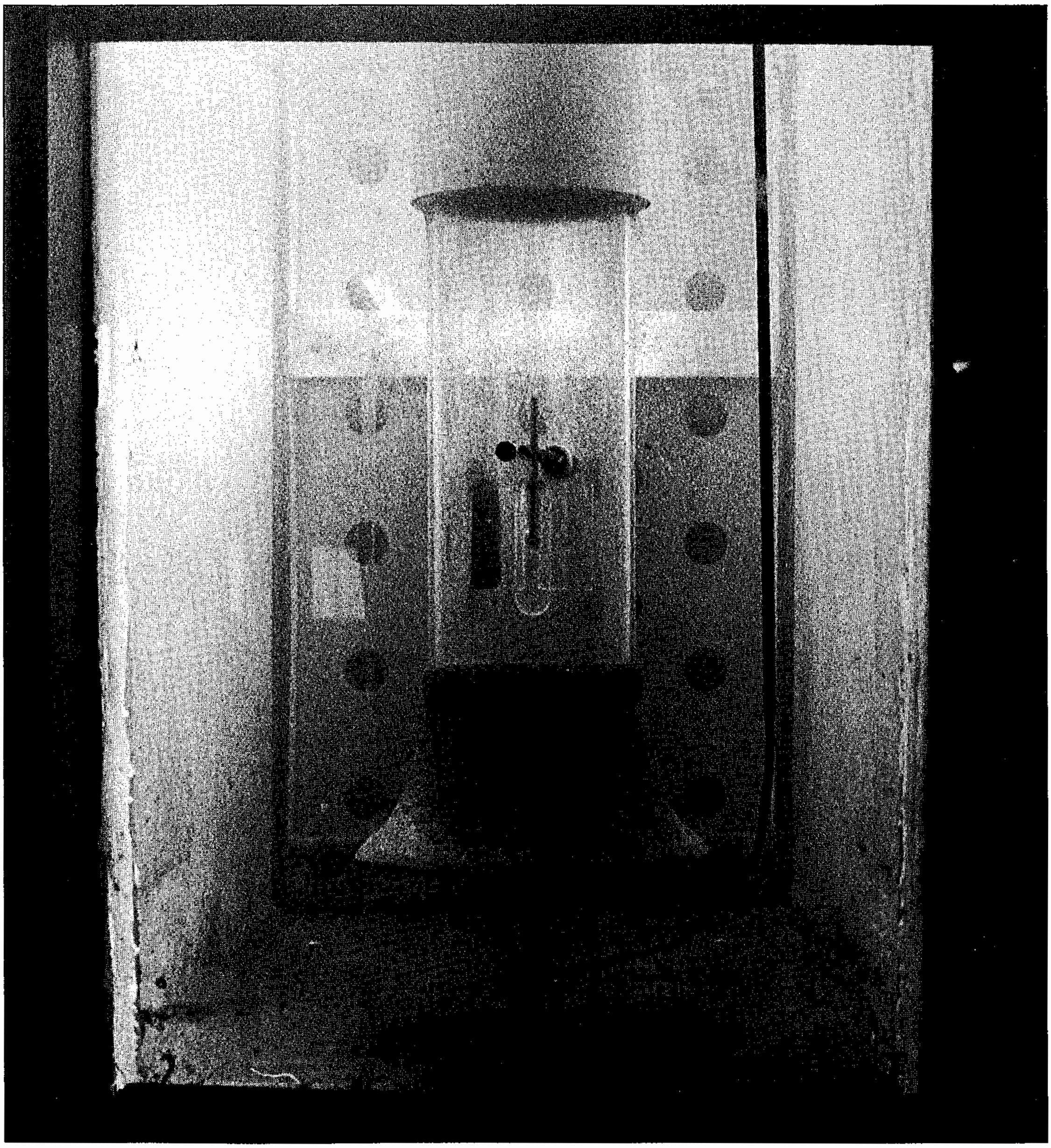

FIGURE 8. Photograph of the suction bell with a subsurface vortex visible.

ed about 75 to 90 percent of the time.

Figure 8 presents a photograph taken of one of the model wet well cells through the clear acrylic back wall. Ink, injected directly under the suction bell, allowed the vortex that was emanating from the floor directly beneath the bell to be seen. Also, note the swirl meter located above the bell and the multi-ported baffle wall located at the entrance of the wet well cell.

Swirl angles higher than five degrees were observed during most of the tests. Both short-term and long-term swirl angles higher than 20 degrees were recorded during some of the tests. The strong subsurface vortices and the skewed approach flow both contributed to the excessive swirling.

The jet of water that issued from the exit of the 48-inch diameter pipe impinged on the far

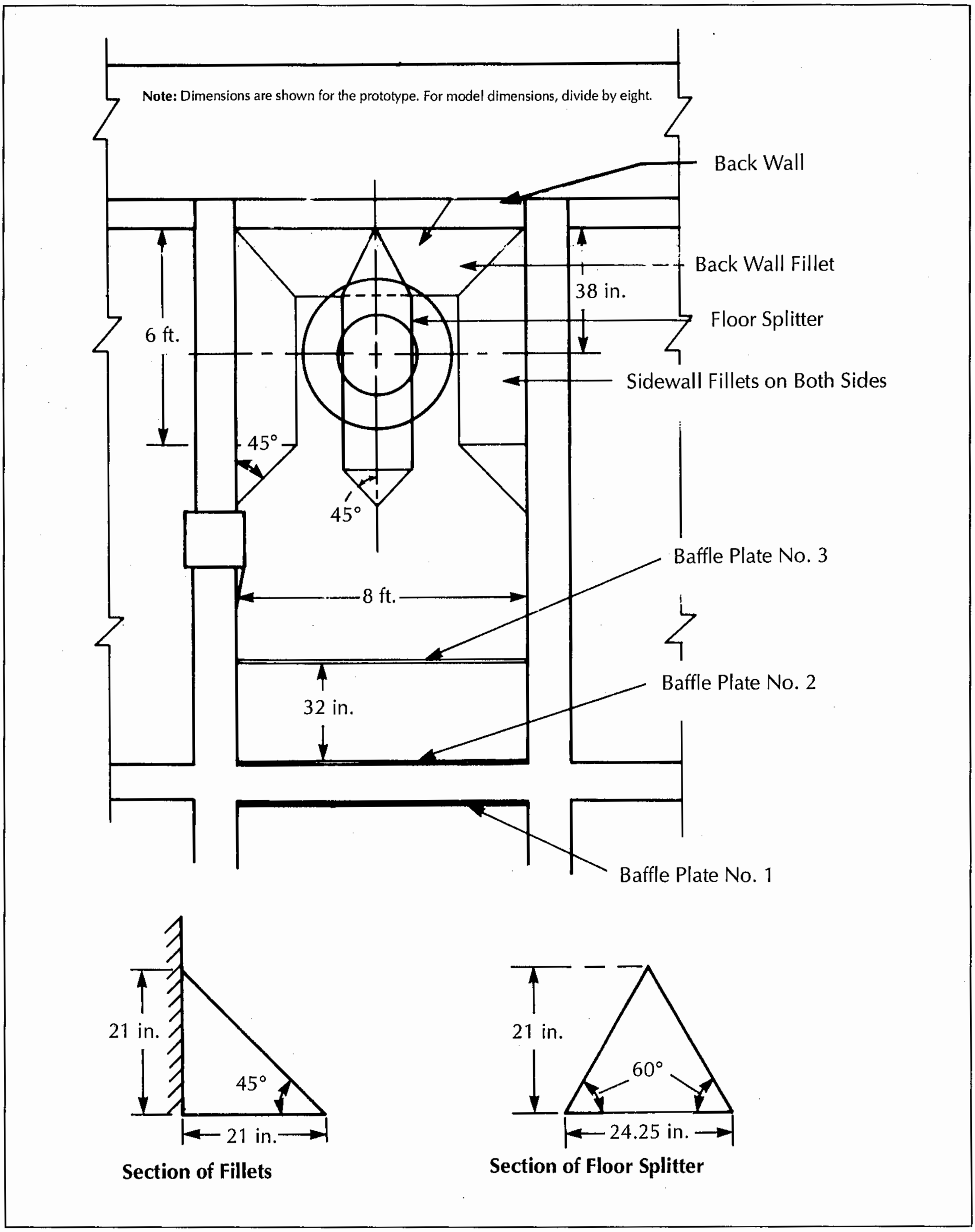

FIGURE 9. The Phase 2 modifications to the wet well cell.

wall of the inlet channel, causing considerable entrainment of large air bubbles at all of the low water levels that were tested. However, all the bubbles that were larger than one millimeter in diameter escaped to the water surface in the inlet channel before the flow entered the wet

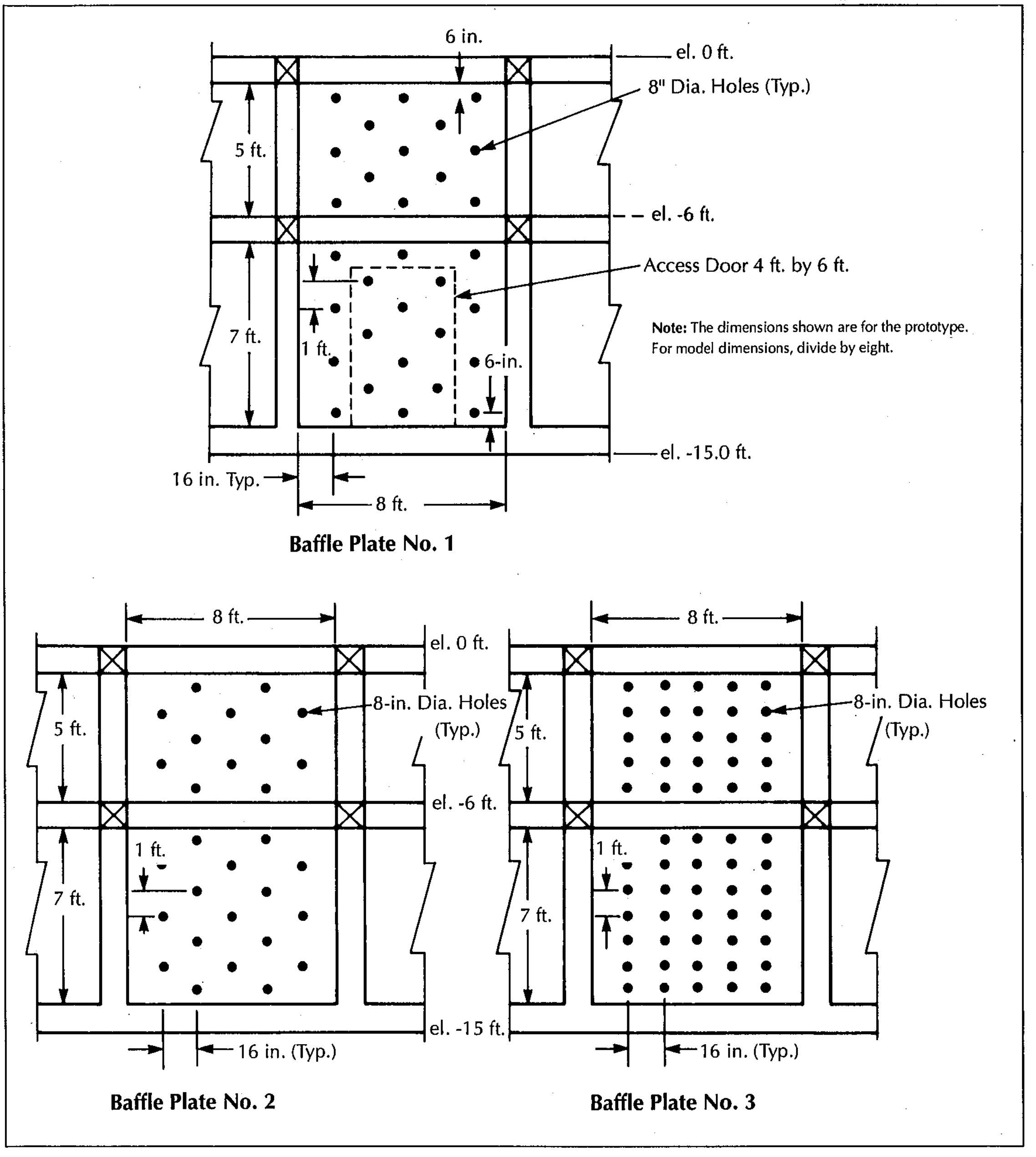

FIGURE 10. The port arrangement through the baffle plates.

well. No objectionable air entered the suction bells from this air source.

The flow through the 24- by 36-inch inlet gate contained much entrained air that was caused by the upstream freefall of water in the secondary effluent chamber. The bubbles larger than one millimeter that were produced by this source were stripped from the water as the flow proceeded through the stilling basin. No objectionable air reached the suction bells from this air source.

Because air bubbles could not be scaled to the scale of the model, further attempts were made to investigate the potential for air to enter the suction bells. To this end, air bubbles were artificially injected using an air pump fitted

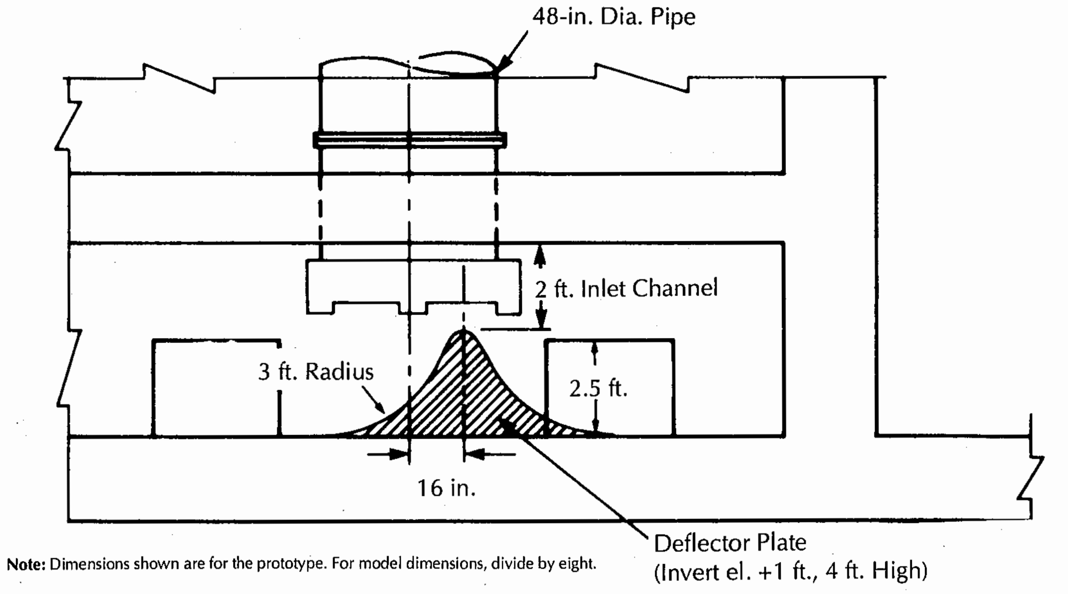

FIGURE 11. Deflector plate.

with a nozzle. The air for this artificial source was injected just upstream and downstream of the multi-ported baffle plates during many of the tests. Only air bubbles less than one millimeter in diameter reached the suction bells. Therefore, entry of objectionable amounts of air was judged not to be a concern.

Phase 2 Tests. Because the high swirl angles proved to be objectionable during the Phase 1 tests, modifications to the wet well of the model were made before proceeding to Phase 2. The modifications to the initial design included the installation of splitters under the suction bells, side and back wall fillets, and additional multi-ported baffle plates at each cell entrance.

Before proceeding to a full round of testing, the modifications were only installed in one of the wet well cells. Tests were conducted on this one cell using the flow condition that proved to be the worst case during the Phase 1 tests. The worst case flow condition was 30 mgd through one pump and at a wet well level of -3.0 feet (msl).

A first attempt to straighten the flow into the wet well cell consisted of changing the arrangement of the ports through the baffle plate to a staggered pattern. This change did not achieve the desired results. Therefore, another multi-ported baffle plate was added downstream of the existing plate. The ports through the second baffle plate were arranged in the same staggered pattern but were offset from the ports through the first plate.

To reduce the strength of subsurface vortices, a combination of floor splitters and back and side wall fillets were installed. The height of the splitter and fillets were selected during tests that focused on these details. During these trials, moving the back wall to 14 inches from the suction bell was found to be beneficial.

After further tests confirmed the effectiveness of these modifications, they were installed in all of the wet well cells. The modifications incorporated into each wet well cell as a result of the Phase 2 tests are shown in Figure 9. Using an adequate mix of test conditions, the results revealed that the strength of the subsurface vortices were mostly reduced to type 1. Any type 2 vortices that were observed proved to be weak and to persist only about ten percent of the time. The swirl angles were found to be less than five degrees for the higher wet well level tests. However, during the low wet well level tests, short-term swirl angles of 12.4 degrees

TABLE 1
Comparison Between Selected Test Results of the Initial and Modified Wet Well Designs

				Maximum Free-Surface Vortex Type**		Maximum Subsurface Vortex Type**		Maximum 30-Sec. Average Swirl Angle (degrees)	
Water Level in Wet Well (ft., msl)	Inflow Details	Pump Operation*	Per Pump (mgd)	Initial Design	Modified Design	Initial Design	Modified Design	Initial Design	Modified Design
-3.0	30 mgd from 48-in. dia. pipe	4	30	2	1	2	1	22.2	1.1
-2.0	36 mgd from 48-in. dia. pipe	1,2,3	12	3	1	2	1	6.4	4.3
-1.5	44 mgd from 48-in. dia. pipe	1,2,3,4	11	3	1	2	1	13.5	2.3
-3.0	30 mgd from 24- by 36-in. gate	1	30	2	1	2	1	18.0	4.3
-2.5	24 mgd from 24- by 36-in. gate	3,4	12	2	1	2	1	14.0	4.3
-2.5	36 mgd from 24- by 36-in. gate	1,2,3	12	2	1	2	1	23.0	6.3

* Numbered from left to right, looking towards the pumps.
** See Figure 7.

and long-term swirl angles of 8.8 degrees had occurred.

To further reduce the swirl angles, a third multi-ported baffle wall was added downstream. To minimize head losses, the third baffle plate was constructed with the same eight-inch ports, but with the total port area increased to 26 percent. The patterns of the ports through all three baffle plates are shown in Figure 10.

As observed during the Phase 1 tests, the flow discharging from the exit of the 48-inch diameter pipe impinged on the far wall of the inlet, causing much splashing. To reduce this splashing (which would also interfere with observation of the wet well of the prototype), a deflector plate was incorporated into the model. The optimum location and dimensions of the deflector plate were determined by trial and error. The deflector plate is shown in Figure 11. The plate caused an additional head loss, but this loss fell within acceptable limits.

Phase 3 Tests. The third and final phase of the tests was conducted in order to study the modifications that were made to the model under 30 selected flow conditions. A few tests were also repeated at a 1.5 Froude number by increasing the flow to 1.5 times the scaled flow while maintaining the same scaled water depth.

The Phase 3 test results showed that the flow pattern into wet well cells possessed a nearly uniform flow toward the suction bells. No objectionable free-surface nor subsurface vortices were observed. Brief, unsteady and sometimes strong type 1 subsurface vortices were observed during many of the tests. These vortices emanated from the back wall where the splitter met the fillet.

Swirl angles were found to be less than five degrees during almost all the tests. During two of the tests, however, swirl angles of up to seven degrees were observed. These higher swirl angles occurred during test conditions that represented the extreme end of operating conditions at minimum wet well levels. In general, the swirl intensities were considered to be within acceptable limits.

The deflector plate effectively reduced splashing from the inlet channel at the exit to the 48-inch diameter pipe. The air entrained by the freefalls along all three flow approaches were effectively prevented from reaching the pumps. Only air bubbles less than one millimeter were drawn into the suction bells.

The modifications that resulted from the Phase 2 tests were judged to be effective and, therefore, were incorporated into the final design of the Mamaroneck Wastewater Treatment Plant's effluent pumping station.

Cost and Duration. The total cost of the model study was about $55,000, including $5,000 for engineering management. The model study took four months from start of construction to final report. However, the information needed to include the modifications in the design was available after three months. The necessary modifications, therefore, were able to be included in the design before the formal model study report was completed.

Conclusions

Table 1 summarizes a comparison of selected test results of the initial wet well design and the modified wet well design. The comparison reveals that the modified wet well design reduced the strength of vortices to non-objectionable levels and reduced the magnitude of the swirl to the pumps to acceptable values.

For the Mamaroneck Wastewater Treatment Plant's effluent pumping station, the decision to model the wet well proved to be critical to the design. Without modeling, any problems that would have occurred would have had to have been corrected after the pumping station became operational. The cost saved by installing the modifications under the initial design is estimated to be between $250,000 and $500,000 based on the approximate costs associated with pump repair, construction delays and additional measures that would have been needed in order to minimize the disruption of the plant operation. And, the modeling and resulting wet well modifications would have still been required. Thus, modeling was definitely a necessity for the proper design of the Mamaroneck effluent pumping station.

NOTE — *The design engineer was Camp Dresser & McKee, Inc., for the Mamaroneck Effluent Pumping Station. Alden Research Laboratory, Inc., was contracted to conduct the hydraulic study on the reduced scale model.*

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