PAPER 14

Design of Pump Intakes for Desalination Plant and Sewage Stations

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This paper summarises good design practice for pump intakes and cites useful references. For new and/or difficult applications, hydraulic scale-model investigations are the accepted design aid and the basic techniques are described.

Against this background typical requirements for desalination and sewage projects are detailed and the development of satisfactory designs in practical situations is illustrated by case histories from desalination plant and sewage stations in operation or building in the Middle East.

INTRODUCTION

Reliability rates high in the design of rotating machinery. Nevertheless many intrinsically reliable pumps suffer operational damage or failure because insufficient consideration has been given to interactions between the pump and the system in which it is installed. Some examples noted from recent general experience in the pump field serve to illustrate this point.

High-speed, high-pressure, boiler-feed and oil-well injection pumps can suffer cavitation erosion at the impeller eye, if insufficient suction head is available relative to impeller-eye design and system operating conditions; again, these pumps can contribute to severe pipework oscillation by a clash of pump forcing and pipe natural frequencies.

Extraction pumps may risk cavitation damage as a result of poor hydraulic design of pipework between suction vessel and pump; also, in the canister type, they may be exposed to dry running seizures by inadequate venting, or water service arrangements, under start-up or standby conditions.

Low-speed, low-pressure, circulating or transport pumps can experience surging under abnormal operation where long pipe runs are involved; they can also suffer vibration, noise, or even mechanical failure, where approach flow is unsatisfactory.

The last item, while not a new problem, is still manifest, despite considerable attention over the last thirty years. Approach flow problems are most common with high specific speed pumps, ie, large flowrates and low system resistance and, in particular, with the suspended-bowl or axial types drawing direct from a free surface sump.

Controlling the flow of large quantities of water with a free surface is not easy when site conditions and economic pressures dictate the basic civil geometry and split responsibility between pump manufacturer and civil engineer adds a communication problem which, it is hoped, this paper may help to overcome.

INTAKE DESIGN

Examples of the repercussions of bad intake design abound. Messina (1), Bird (2), Paterson on Chang and Prosser (3), Paterson and Campbell (4), and Elder, Hamil and Tullis (5), record site problems covering the trouble spectrum from excessive noise and vibration, through component failure, to complete pump breakdown.

Intakes can be classified as wet well or dry well. In the former the pump is suspended directly in the free-surface sump and is sensitive to flow bias, swirl and air entraining vortices therein, while in the latter intervening pipework can be used to reduce flow bias and swirl emanating from the sump, but air injestion remains a problem.

Design codes exist and Figure 1 from Paterson and Noble (6), summarises the recommendations of the two most used codes, namely the American Hydraulic Institute (7), and the British CIRIA/BHRA publication (8), together with corresponding data from the authors' own experience. In applying these codes it is important to note that the minimum submergencies quoted are based on different criteria.

The Hydraulic Institute states no criteria simply covering all recommended dimensions as composite averages from many pump types and specific speeds.

CIRIA/BHRA define minimum submergence as that at which air entraining vortices form. A margin is therefore necessary for safe operation and no guidance is given on this. Only the minimum submergence given by the authors is the safe site operational limit. Both codes instance good and bad features of intake design and both recommend that, if the code guide-lines cannot be satisfied, hydraulic model tests should be undertaken. Further useful guidance can be obtained, however, by gathering available information in the form of experience graphs. The authors' experience is shown in Figure 2, where submergence is plotted against pump suction velocity, both non-dimensionalised using bellmouth diameter or equivalent. The graph can be separated into four areas:-

Area 1 - Ample submergence ensures satisfactory operation of all but fundamentally bad designs. Excavation costs may dictate lower submergence.

Area 2 - With these submergence levels good intake design principles, experience from similar designs in operation, or Hydraulic-Model-Aided Design (HMAD) is necessary.

Area 3 - Careful detail design local to the pump itself is required in addition to the above in order to operate satisfactorily at these submergences.

Area 4 - Low submergence; unlikely to permit satisfactory operation.

Good intake design must be built in to the civil works from the start for economy and effectiveness.

Approach works must promote equally distributed, uniform, swirl-free flow to the pump sump(s).

Basic geometry, screens, auxiliary walls, and guide vanes should be located and shaped with this in mind. Guide vanes, for example, should intercept flow where it is uniform or be offset at inlet proportional to flow bias. Abrupt changes in area or direction and obstructions in the flow path should be avoided. Sumps should accept flow without introducing bias or separation and channel it to the pump suction, preferably with a smoothly accelerating flow. Flushing curtain walls should be used to avoid vortices being shed from sump dividing wall ends. Pumps should be located in centre-line of individual sumps if possible and close to the end wall. Vortices in the pump wake can be precluded by the use of front curtain walls, submerged roof, or haunching behind the pump.

The pump suction is normally fitted with a convergent bend or bellmouth but, for low submergences, may require additional control vanes or surfaces, which will however incur a slight loss in efficiency.

For unconventional or difficult designs or cases where the design principles noted above cannot be applied, the intake design should be investigated using an hydraulic scale model.

HYDRAULIC-MODEL TECHNIQUES

Pump intake models are normally fixed bed and sufficiently limited in extent to permit adoption of undistorted linear scales. Basic scaling procedures for dynamical similarity are then well established (4,8) but there is an incompatability problem.

The main forces involved with predominantly free surface models are gravitational and viscous, with surface-tension effects of importance only when shallow flow sections and pronounced surface curvatures are involved.

The Froude, Reynolds and Weber force ratios applicable cannot each be satisfied by the same operating velocity with cold water, the pumped fluid in the model and at site.

Gravity governs basic flow patterns and entails a model velocity proportioned as the square root of the scale ratio relative to site.

Viscosity affects flow regime, boundary layer flow, separation, and losses, for which the model velocity should be inversely proportional as the scale ratio.

Surface tension is rarely significant but if so would require a model velocity inversely proportional to the square root of the scale ratio for correct representation.

The basic Froude/Reynolds conflict must be carefully considered in relation to model size, intake geometry, and design criteria applicable in each investigation. The recommended procedure is to run the model at Froude-scale velocities, ensuring that the model is sufficiently large to reproduce the site flow regime and assessing scale effects on separation, vortices, and losses. Increased operating velocities can be used in this assessment provided the basic flow patterns are preserved.

For desalination plant the sea-water pump intakes are normally the only candidates for model investigation though occasionally other services such as product water are sufficiently unique to merit HMAD. The standard procedures outlined cover these investigations.

Sewage applications introduce several factors which need further consideration. Variable inflow to the sump with level controlled pump-out, siltation and sewage settlement in stagnation and low-velocity zones, aeration and release of hydrogen-sulphide gas, all complicate operation of the model and interpretation of the results.

Recommended methods of dealing with these additional factors are discussed and illustrated in the case histories quoted on sewage plant.

DESALINATION PLANT CASE HISTORIES

Dubal Power Station and Desalination Plant: SW Intakes

Three inlet pipes channelled seawater by way of a common forebay to nine SW service pumps and one standby, each in its own sump and individually protected by coarse and travelling-band-type screens. The intake was well designed; inlet pipe and screen ports were submerged; velocities were moderate; transitions were gradual; and design principles, in general, were observed and not compromised to save space.

With multiple pump arrangements such as this, operational requirements usually dictate various combinations of pumps and possibly inlet pipes. Despite thoughtful design the common forebay under these circumstances becomes an area of complex flow patterns. In order to investigate the nature of these flow patterns and establish their effect on flow distribution at entry to each screen chamber a one to thirteen scale model of the approach works was constructed. The S.W. intake arrangement is shown in Figure 3 and the model test facility has been added to illustrate the type of test rig and instrumentation applicable.

Operation with all inlet pipes and all, or the majority, of the pumps gave satisfactory conditions. Flow crossed the forebay in three main streams, diffusing as they approached the screen chamber inlets. Low-velocity reverse circulating flows occurred between streams and along the forebay side walls but flow bias at screen chamber inlets was negligible. Reduction in number of pumps in operation and/or outage of a supply pipe resulted in deflection of the main streams and variation in extent of the associated subsidiary flows, causing a more pronounced bias at entry to certain screen chambers. Quantitative data, in the form of isovelocity plots, were determined using miniature current meters and, in conjunction with flow-pattern plots, used as reference inlet conditions for a larger scale model of one screen and pump chamber. Figure 4 shows the extent modelled. The model test rug has again been added, in this case to illustrate the screen and gate method of varying entry conditions to simulate the extremes applicable to any of the ten pumps, and the techniques used to monitor flow conditions which resulted in the pump chamber. A plot typical of the biased entry flow conditions to be tested is inset.

In many cases it was found that the bias was sufficient to alter the normal sump-flow regime, causing flow down one side to dominate, with the result that mass circulation built-up in one direction at pump inlet and asymmetry in the wake of the pump casing allowed vortices to develop.

Swirl at pump inlet alters impeller-blade and shaft loading and causes mismatch of blade and flow angles while vortices imply intermittent air injestion to pump and system. The combination of increased loading with intermittent air entrainment can cause severe fatigue effects which have in one case resulted in impeller-blade fracture.

Vortex formation behind the pump was prevented by introducing a curtain wall across the sump, upstream of the pump, while any residual swirl around the pump was curbed by fitting vertical control vanes to the wall behind the pump. Flow pattern and modifications are shown inset in Figure 4.

Dubal Power Station and Desalination Plant: Blended Water Intake

The blended-water transfer pumps intake was unusual in that the pumps were located in-line, in a long narrow channel constructed at one end of a reservoir. The reservoir was divided by a central wall such that the pumps could be fed from either or both ends of the channel. Flow to operating pumps inevitably had to pass other operating and stationary pumps.

Since this is not a recommended arrangement an hydraulic scale model was built to examine the approach flow from reservoir to channel and the various flow regimes in the pump suction channel.

The intake is shown in Figure 5. Tests covering the various operational groupings indicated three sources of trouble.

Vortex formation occured at the change of flow direction at channel entry from the reservoir. Coupled with the downward flow through the channel entry port this led to air entrainment by the outermost pumps.

Swirl of varying severity was experienced at the pump inlets, caused by the concentration of flow along the outer wall of the channel.

Surface swirls tended to form in the wake of the pump suspension column under critical flow-past velocities. After considerable experimenting the most effective and least costly modifications were two in number, viz:

Extension of the inner channel wall in the form of a local curtain wall with a vented shelf or ceiling between the wall soffit and stop gate location to control approach flow; and

Splitter vanes upstream and downstream of the pump bellmouths to control swirl at pump inlet.

These modifications are shown inset to Figure 5.

Ras Abu Fontas Desalination Plant: S.W. Intakes

In this arrangement seawater flowed by way of an approach culvert into a stilling chamber with sloping sidewalls. The stilling chamber had five screen chambers along the rear wall leading to a common pump chamber, wherein the pumps were situated along the rear wall separated by narrow piers with gaps between them and the wall, as shown in Figure 6.

Stilling chamber flow was characterised by a wide main stream diffusing from culvert to screen chambers, with lazy reverse circulations at the sides. Even under reduced unit operation, flow into the screen chambers was only slightly biased with negligible effect on flow conditions downstream of the screens.

Conditions in the pump chamber were far from satisfactory however. The offset of screen exits with respect to pumps resulted in asymmetric flow in all cases, aggravated by separation from the pier heads and flow through the gaps at the rear. A typical flow plot is shown inset to Figure 6, the problems of mass circulation round the pumps and vortex formation behind them being obvious.

Fitting a curtain wall flush along the front of the piers, thickening up the piers and closing the gap at the rear, in effect creating individual pump sumps with a large length-to-width ratio, yielded a considerable improvement, but some bias in flow at sump inlet remained in most cases owing to the restricted distance from band screen exit ports to pump sumps. This bias tended to induce surface swirls downstream of the curtain walls and mass circulation at the pumps somewhat higher than normally accepted. Extension of the curtain-wall soffit along the sump and fitting twin control vanes behind the pump as shown inset to Figure 6 removed these residual faults.

SEWAGE-PLANT CASE HISTORIES

Al Ain Pumping Station No. 1

The site layout is shown in Figure 7 and the finally developed layout in Figure 8. Modifications were extensive to solve the hydraulic problems encountered.

It has been the authors' experience that sewage sump design derives little from the recommended codes of practice with regard to pump-suction submergence and associated sump hydraulic design. In order to minimise fluid-retention time sewage sumps are small in comparison to most other pump intakes and hydraulic scale models are frequently made necessary because pump-suction submergence is low, sump inlets are high and there is little directional flow control within the sump.

On the left-hand side of Figure 7 a plan and section of the original site arrangement for this station is shown. Flow entered each half of the sump via twin outfall sewer pipes l a screen chamber. Normal high water level in the sump was low sump inlet invert level. The hydraulic problems encountered re two-fold comprising, first, severe turbulence and the neration of masses of air bubbles in way of pump suctions s. 6 and 3 and, second, problems of swirl and vorticity caused the off-set entry to each half of the sump.

e hydraulic scale model built to study these and other phenomena s of the type indicated on the right-hand side of the diagram. ter was pumped from an underfloor reservoir into a constant-head nk upstream of the model at various flowrates up to the maximum ture handling capability of the station. Abstraction of flow om the model was by a drain/syphon system in which flowrate was asured using calibrated orifice plates and controlled using gate lves downstream of the orifice-plate location.

ferring to the final layout on Figure 8, the first step in the velopment was to isolate the inlet turbulence and associated r bubbles from the inner pump suctions and to produce a more ntrolled approach to all pump suctions. This was done by stalling a long wall along the centre of the sump incorporating streamlined 180-deg turn at each outer end.

oblems of vorticity persisted, however, because of the extremely w pump suction submergencies required. At low water levels the est of each suction bend became uncovered and as flow negotiated is obstacle eddies formed in the lee of each bend and matured to air entraining vortices. These vortices were countered by e installation of short baffle walls which prevented the passage surface flow across the bend crest and thereby prevented eddy edding and consequent vortex formation.

should be noted that when installing such baffle walls cognisance ould be taken of the floating debris in the sump. The walls ould, therefore, be positioned and sized in keeping with the ilosophy adopted for handling such materials.

Ain Pumping Stations W2 and W4

e layouts of these stations were more or less identical and a an and elevation are shown on Figure 9. Incoming water passed om the sewer through a bar screen and down into the sump via section of curved benching. Inlet turbulence was largely confined the area upstream of the inlet chamber dividing wall and stribution to the pump suctions, only one of which was a working it, was through the slot beneath the wall.

ile the hydraulic problems of vorticity and turbulent air bubble trainment were evident, other causes for concern in this vestigation were more specific to sewage projects, namely rbulence and its effect upon the release of hydrogen sulphide s, and silt/solids deposition.

e very nature of the fluid being handled dictates that some drogen sulphide (H_2S) gas will be released regardless of the part the world in which the station is built. In the Middle East, wever, this problem is considered to be more severe than most ing to the concentrated acidity of the sewage.

turbulent flow areas the gas is released and is readily idised by bacteria in the presence of air to sulphuric acid, which is both destructive and a danger to health. Where high level inlets are associated with low sump-water levels, a common feature of sewage-station design, turbulence is unavoidable. Nevertheless, steps should be taken to minimise it where possible. One source of such turbulence on this station was identified as the bar screen. As flow entered the screen chamber area from the sewer it impacted upon and spread across the sloping section of the curved benching, creating a thin film flow through the bar screen. This film separated from the screen bars and generated concentrated "fingers" of flow which did not follow the radius of curvature of the benching but fell directly on to the water surface below, aggravating the turbulence in that area.

In order to eliminate this source of turbulence the shape of the bar screen was altered to curve under the incoming sewer in such a way as to screen bulk flow rather than thin film flow. While turbulence persisted at the foot of the curved benching at low water levels, forthe obvious reason of water-level difference, the severe concentrated turbulence generated by the "fingers" separating from the screen members was eliminated and the residual turbulence equalised over the whole of the enclosed area.

The other problem encountered on this model was one of silt/solids deposition on the apron approaching the pumps' suction.

On the plan view of Figure 9, two sparge pipes can be seen entering the screen chamber area. These pipes were led from the pump discharge pipework and the valves were manually operated to jet the pumped fluid across the apron, to drive the settled materials towards the pump suction and through the pumps. A third sparge pipe can be seen between the pump suctions for clearing the small suction trough. As the pumps were of low capacity and, because they were handling pumped fluid, the sparge pipes had to pass a specified solid/sphere diameter, the jetting velocity was relatively low and tests showed that operating both sparge pipes together at half capacity had little effect upon clearing the deposited materials.

Adjustment of the jetting angle and operation of one pipe at full capacity followed by the second at full capacity, before operating both together, successfully cleared the apron of all settled sand and silt.

It is worth noting that these tests were run on the basis of varying inflows rather than at steady state condition, that is equal inflow and outflow. The model was arranged in a similar fashion to that shown on Figure No. 7, except that butterfly valves were used on the drain/syphon outlets to give a faster reaction time to simulate pumps starting and stopping, much as they would do on site. This permitted conditions to be examined under the influence of less turbulent inflows and less sump water movement, thereby providing a more reliable basis for assessment of likely settlement patterns.

Qatar; West Bay Pumping Station

A further example of the aspects of sewage-pumping-station design which should be taken into consideration is the generation of air bubbles from the high-level inlet waterfall.

The layout shown on Figure 10 is that of the West Bay Pumping Station in Qatar. On the left of the figure, the planview of the station nows the inlet baffled by a metal box upstream of a bar screen. hile this small deflector box served to prevent direct impingement f incoming sewage on top of the first pump suction, turbulence nd the generation of air bubbles occurred at the outlet from the ox and the bubbles were carried towards and into the two upstream uctions.

ne difficulty here is in the assessment of how dangerous this is nd in making such an assessment it must be borne in mind that he air bubbles generated on the model will have venting haracteristics similar to those on site. This being the case, n the higher-velocity environment of the site the bubbles will arry further and more will be transported. Accordingly the roblem was tackled by improving control at inlet in the manner hown on the right of the figure.

he screen was moved upstream and raised and an 'L'-shaped baffle as installed beneath it ensuring that the access opening to the ump was submerged at cut-out water level. As a result of this odification turbulence was contained within the baffled area and hose bubbles which were entrained through the bottom slot vented long the underside of the baffle to the surface before reaching he pumps.

ONCLUSIONS

any pump operational problems have their source in unsatisfactory pproach flow, particularly with low-head, high-flow-rate pumps. ydraulic-model-aided design has proved a useful method of evolving atisfactory designs, as illustrated by the various case histories iscussed.

n desalination plant multiple pump sumps are normal and the complex lows upstream of the pump chambers, occasioned by flexibility f operation, raise the alternatives of adopting space hungry ood design principles, or accepting a more economic arrangement nvolving disturbed flow in the forebay and requiring that the pump ump be made insensitive to this. The latter is practicable with ittle increase in pumping head and is the more favoured arrangement.

ith sewage plants the additional features to be considered are urbulence in relation to hydrogen sulphide release and air bubble njestion, and sudden changes in flow section in relation to silt/ olids deposition. Minimising and isolating turbulence and air rom the pump suctions and avoiding low velocity regions by houghtful introduction of benching are methods of overcoming the roblems.

n all cases early involvement of the pump manufacturer in the ivil works design is important and his experience and advice egarding intake design and the need for model testwork should be ought at this stage.

ACKNOWLEDGEMENTS

The authors wish to thank the directors of Weir Pumps Limited for permission to publish this paper and also the undernoted customers for giving approval to use the material cited in the case histories.

Dubal Aluminium Co Limited, U.A.E.	)	Dubal Power Station and
Weir Westgarth Ltd, UK	)	Desalination Plant
Ministry of Electricity & Water	)	Ras Abu Fontas
Qatar	)	
Ewbank & Partners, UK	)	Desalination Plant
Al Ain Sewage Projects Committee U.A.E.	)	Al Ain Sewage Stations
D. Balfour & Sons, UK & UAE	)	
Ministry of Public Works, Qatar	)	West Bay Pumping Station
Pencol Limited, UK	)	

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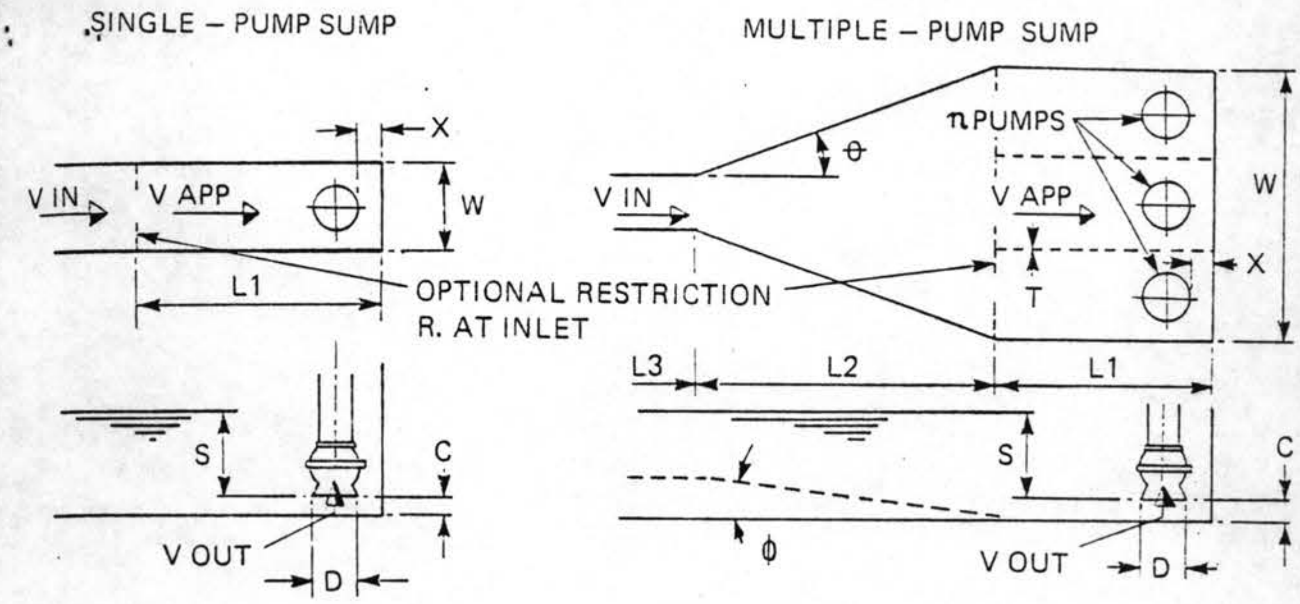


Design Item		Single Pump Sump	Multiple Pump Sump	NOTES
V_{IN} m/s	a	$\ngtr 0.6$	$\ngtr 0.6$	For $V_{IN} > 0.6$ m/s control vanes or L1 increased.
	b	$\ngtr 0.6$	$\ngtr 1.2$	Approach flow uniform, steady, single phase.
	c	$\ngtr 0.6$	$\ngtr 0.6$	Approach flow uniform, steady, single phase.
V_{APP}	a	$\ngtr 0.3$	$\ngtr 0.3$	No turns or obstructions.
	b	$\ngtr 0.3$	$\ngtr 0.3$	No obstructions/abrupt changes in direction/area
	c	$\nless 0.3 \ngtr V_{OUT}$	$\nless 0.3 \ngtr V_{OUT}$	As above + target for smooth progression
V_{OUT} m/s	a	$\ngtr 2.6$	$\ngtr 2.6$	
	b	1.3	1.3	Typical
	c	0.75 to 2.0	0.75 to 2.0	Suction pipes (dry pit) and wet well pumps
C	a	0.4D	0.4D	To be confirmed by pump manufacturer
	b	0.5D to 0.75D	0.5D to 0.75D	To be confirmed by pump manufacturer
	c	0.4D to 0.6D	0.4D to 0.6D	Rounded bellmouth lip also good practice
X	a	$\ngtr 0.35D$	$\ngtr 0.35D$	Avoid axial in-line unless $L > 4D$, $W > 5D$
	b	0.25D to 0.5D	0.25D to 0.5D	Avoid axial in-line unless $L > 8D$, $W > 3D$
	c	$\nless 0.25D$	$\nless 0.25D$	Or min. practicable. In-line as above ÷ baffles
W	a	$\nless 2D$	$\nless 2nD + (n-1)T$	Inter walls if all run. If not gap at rear/omit
	b	2D to 3D	$\nless 2nD + (n-1)T$	Inter walls if inflow skew/$<$n run. Vanes in L1 and L2
	c	$\nless 2D$	$\nless 2nD + (n-1)T$	Inter walls if inflow skew/$<$n run. Vanes in L1 and L2
L	a	$\nless 3D$	$\nless 5.5D$	$\theta \ngtr 45^\circ$ (15° preferred), L large
	b	$\nless 4D$	$\nless 0.7W$ or 4D	$\theta \ngtr 20^\circ$ $\phi \ngtr 10^\circ$. Keep slope turbulence from pump
	c	$\nless 4D$	$\nless 0.7W$ or 4D	$\theta \ngtr 20^\circ$ $\phi \ngtr 10^\circ$. Keep slope turbulence from pump
L (R at inlet)	a	(3W/R) D	(3W/R) D	Pipe/channel. (Use up to W/R = 4)
	b	(5W/R) D	(5W/R) D	Channel/Channel. W/R>2, L = 10D + Vanes
	c	(5W/R) D	(5W/R) D	Channel/Channel. W/R>2, L = 10D + Vanes
S_{MIN}	*a	3D to 2D	3D to 2D	Reduction with size 0.2 m^3/s to 15m^3/s
	b	1.5D	1.5D	Cones or splitters reduce swirl. May affect perf.
	c	3.5D to 0.5D	3.5D to 0.5D	Dependent on V_{OUT}/size/HMAD/experience

a – Reference (7) b – Reference (8) c – Authors

* Min. submergence from flow aspects; NPSH requirements also apply; use whichever greater

FIG. 1 SUMP DESIGN RECOMMENDATIONS

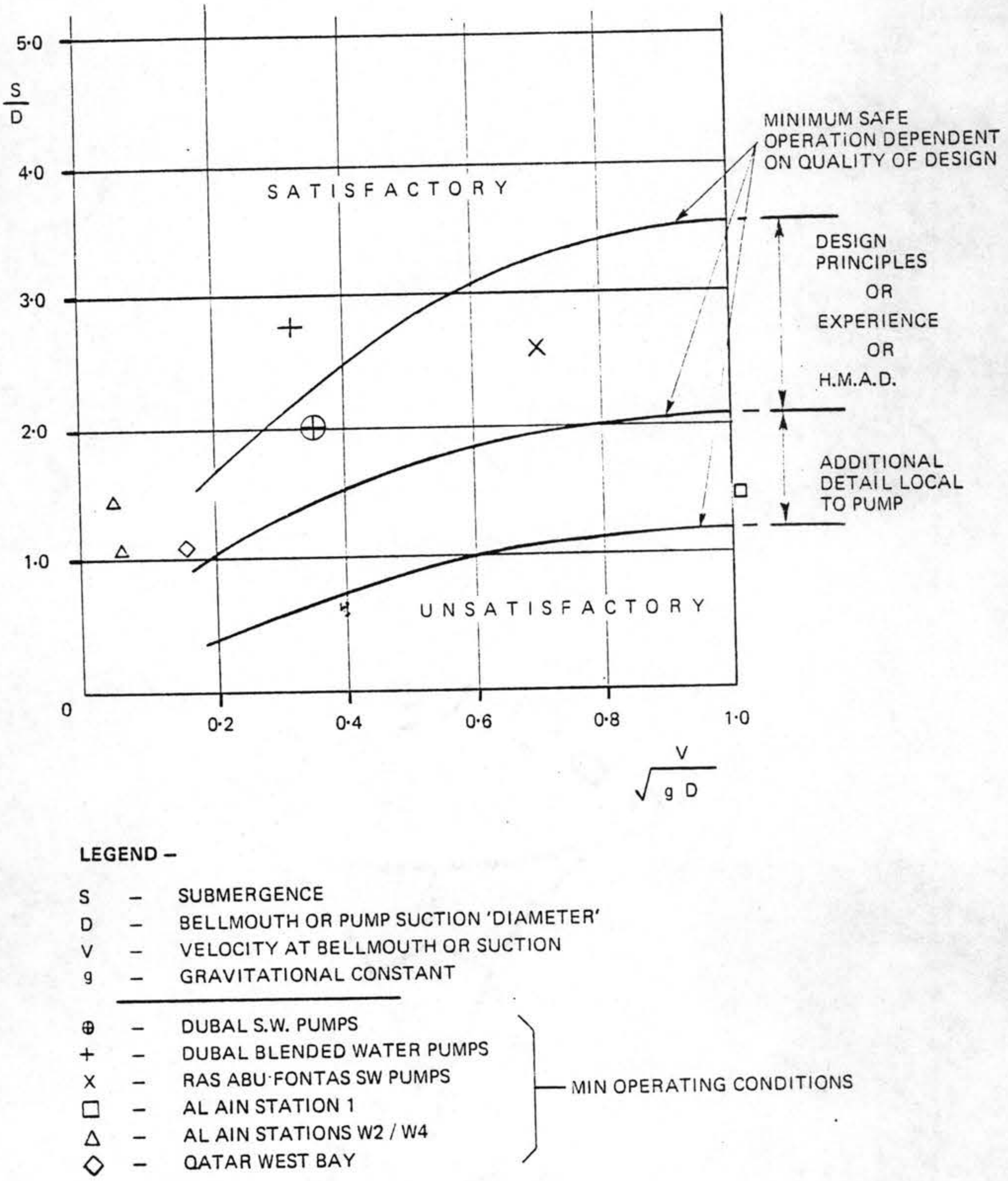


FIG. 2 DESIGN CHART

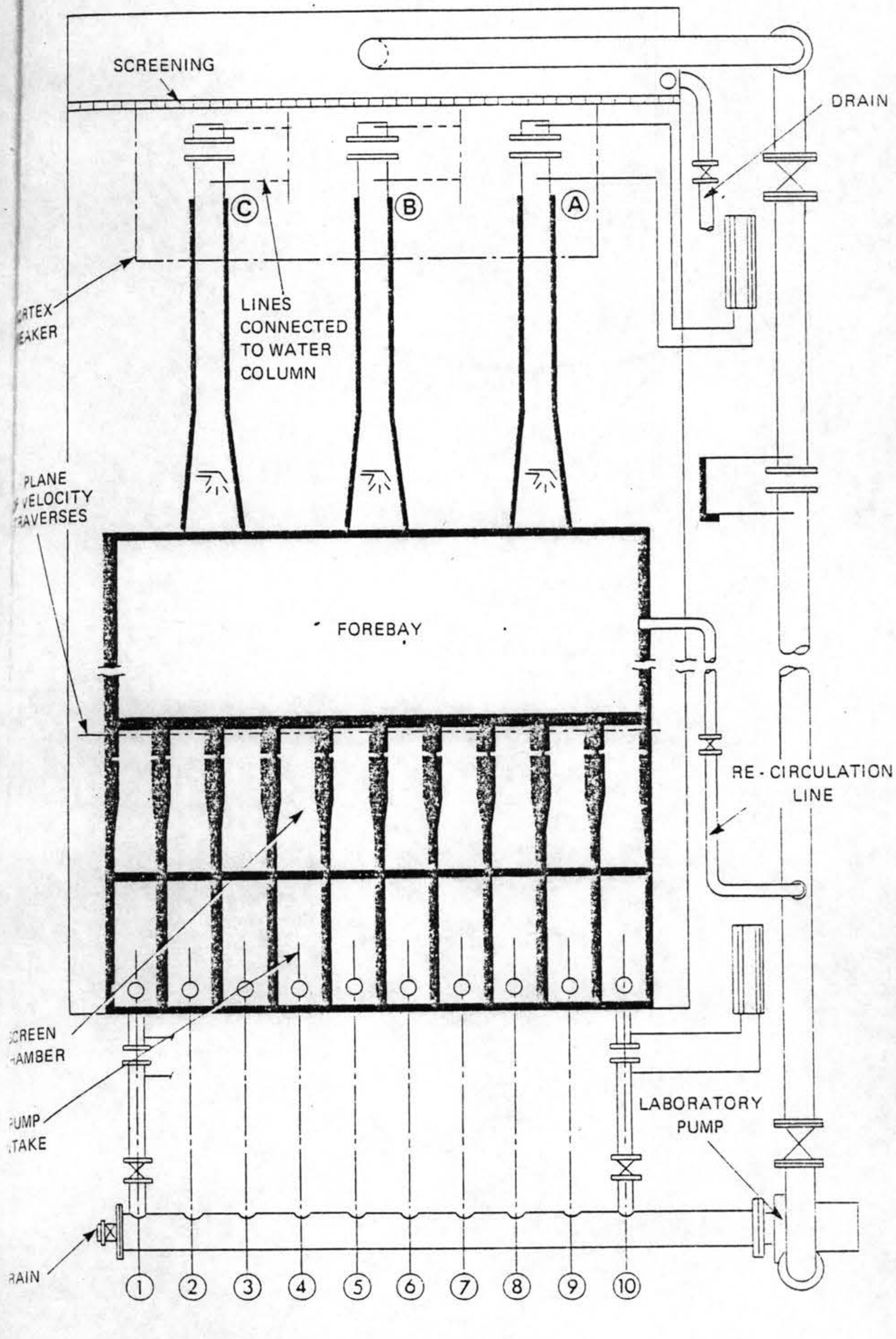


FIG. 3 PLAN OF S.W. INTAKE WITH MODEL FACILITY ADDED

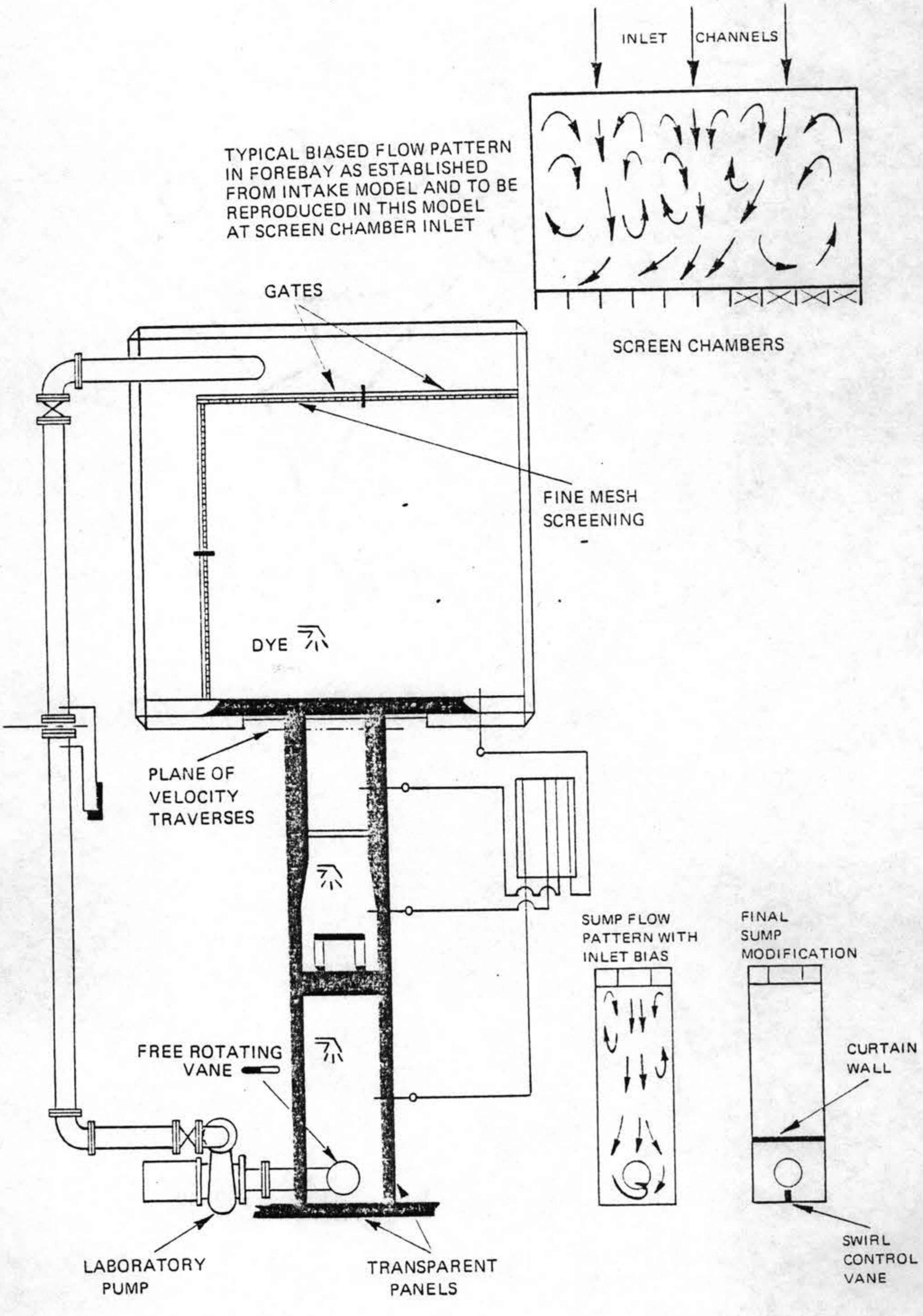
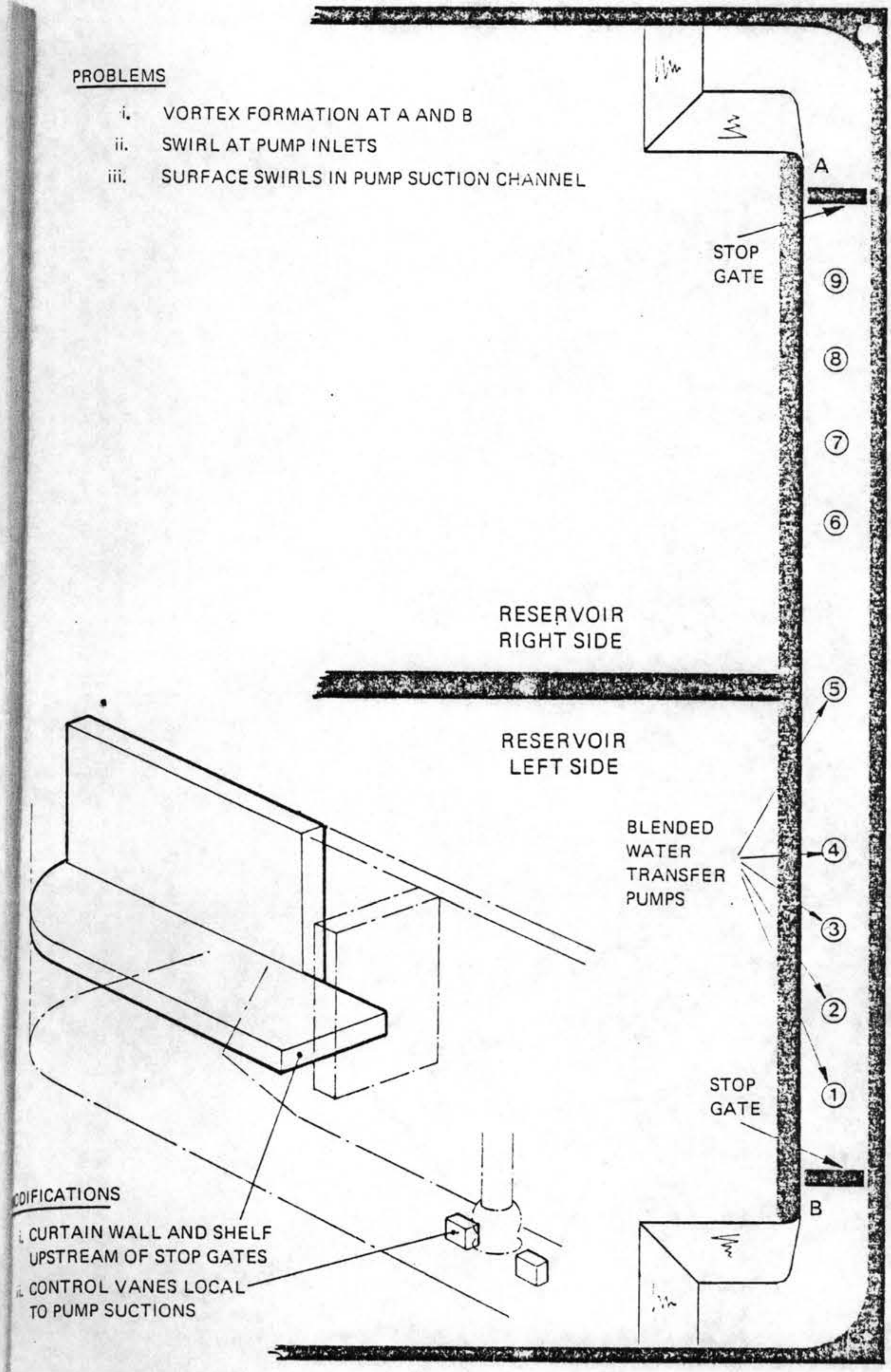


FIG. 4 PLAN OF INDIVIDUAL PUMP/SCREEN CHAMBER WITH MODEL FACILITY ADDED



PROBLEMS

- i. VORTEX FORMATION AT A AND B
- ii. SWIRL AT PUMP INLETS
- iii. SURFACE SWIRLS IN PUMP SUCTION CHANNEL

ODIFICATIONS

- i. CURTAIN WALL AND SHELF UPSTREAM OF STOP GATES
- ii. CONTROL VANES LOCAL TO PUMP SUCTIONS

FIG. 5 BLENDED WATER INTAKE

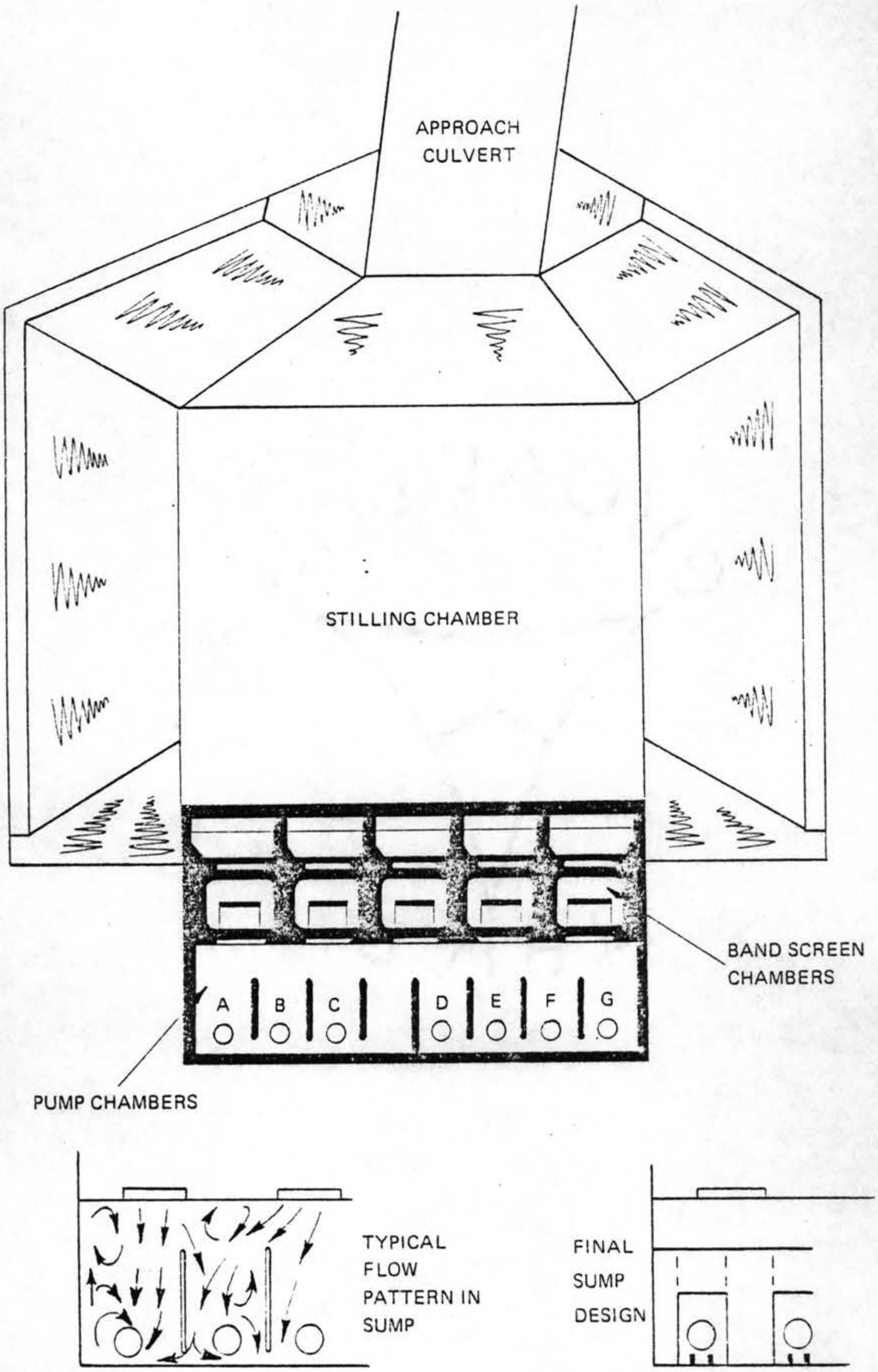


FIG. 6 S.W. INTAKE MODEL

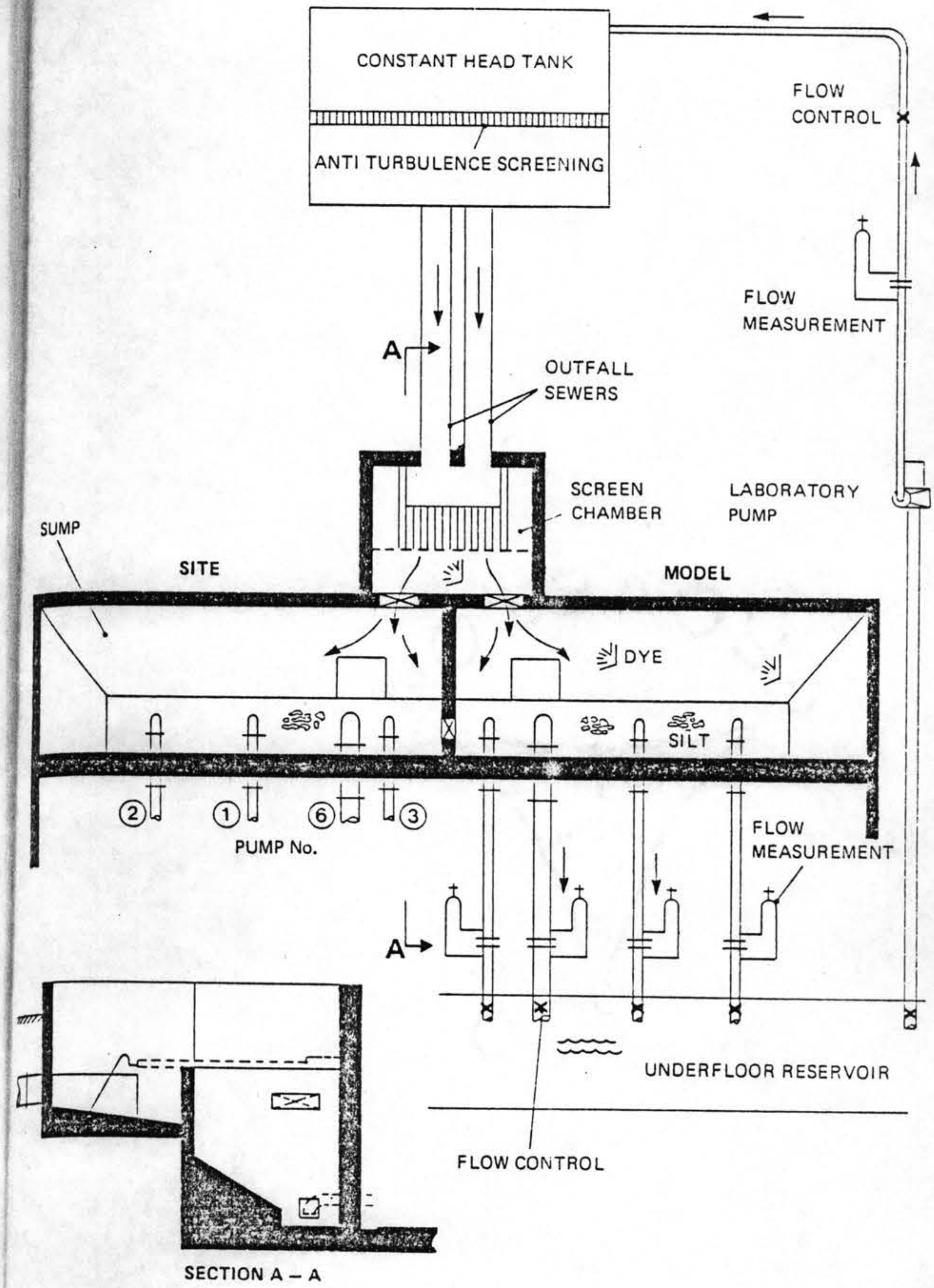
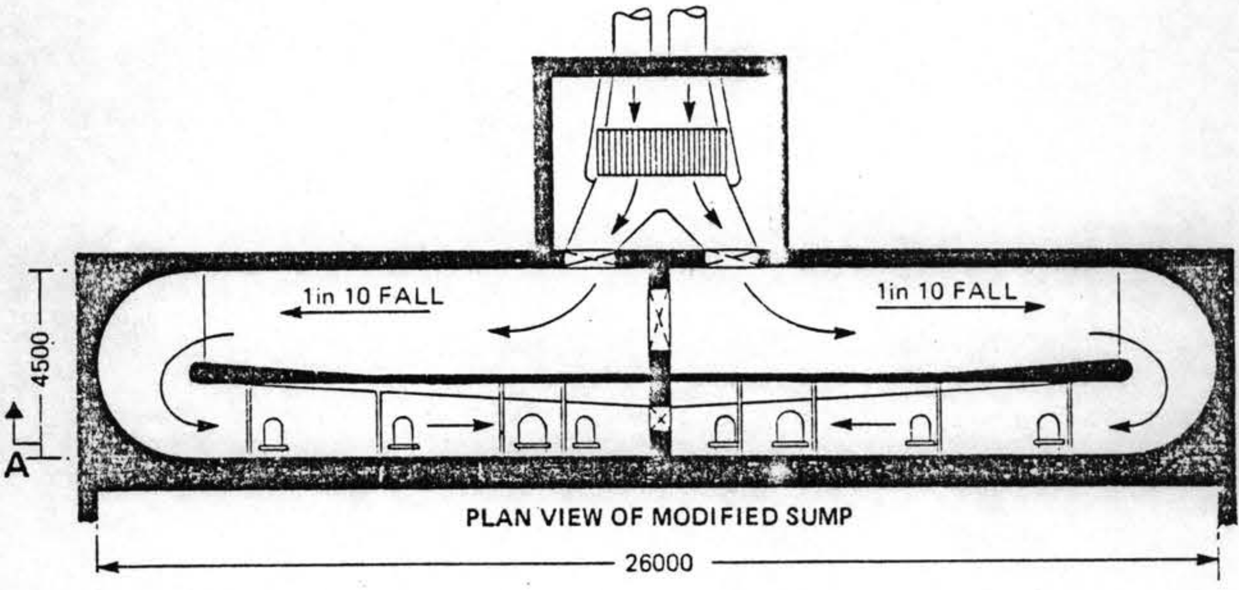
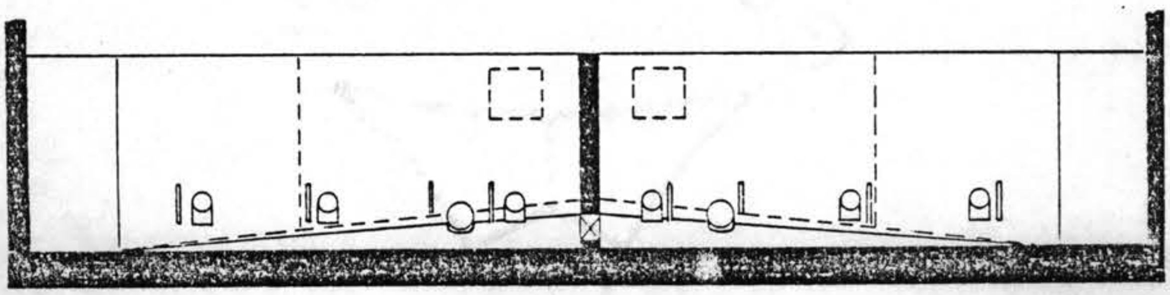


FIG. 7 ORIGINAL LAYOUT OF SEWAGE SUMP



PLAN VIEW OF MODIFIED SUMP



SECTION ON 'A' 'A'

FIG. 8 FINAL LAYOUT OF SEWAGE SUMP

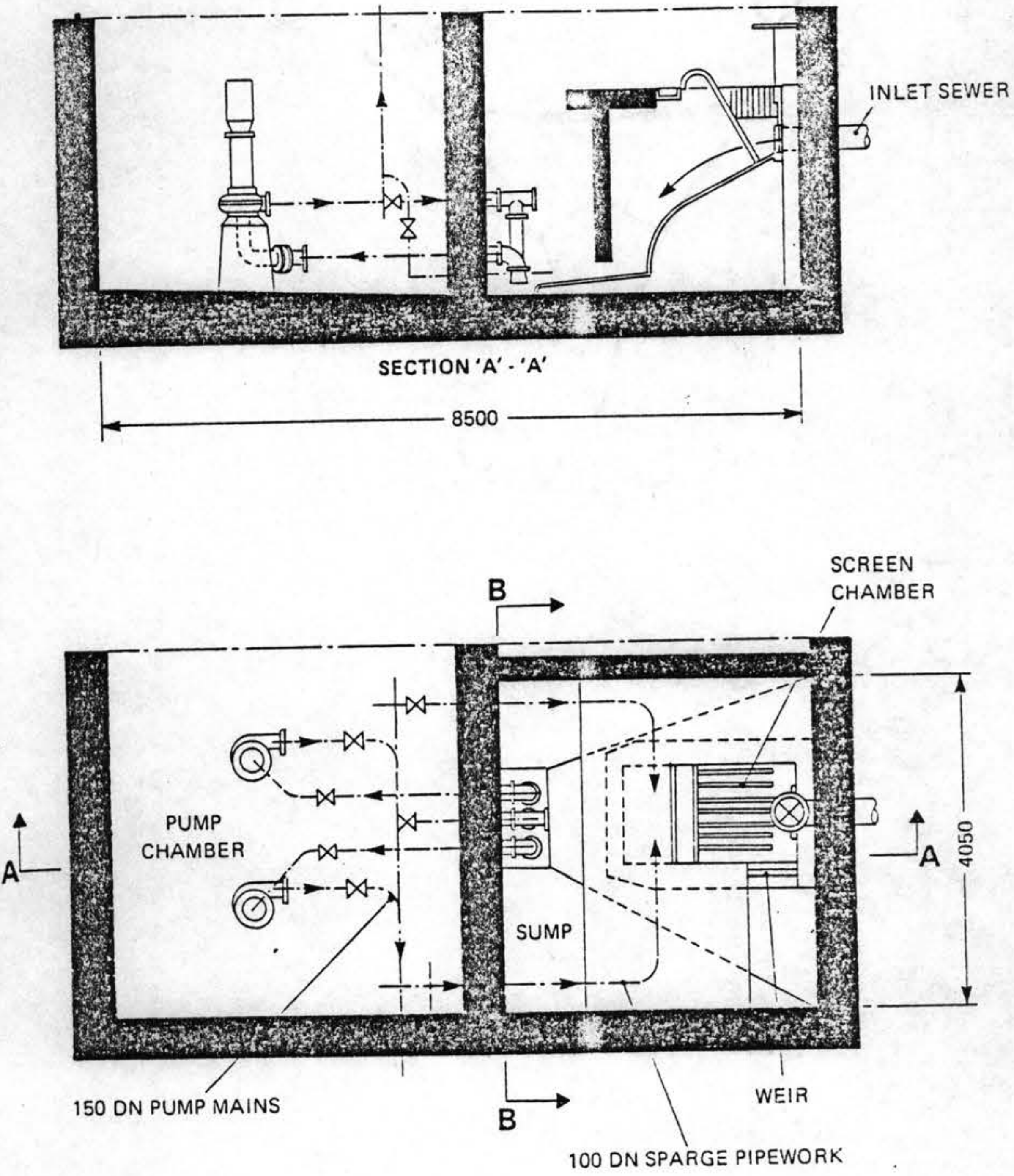


FIG. 9 LAYOUT OF PUMP CHAMBER

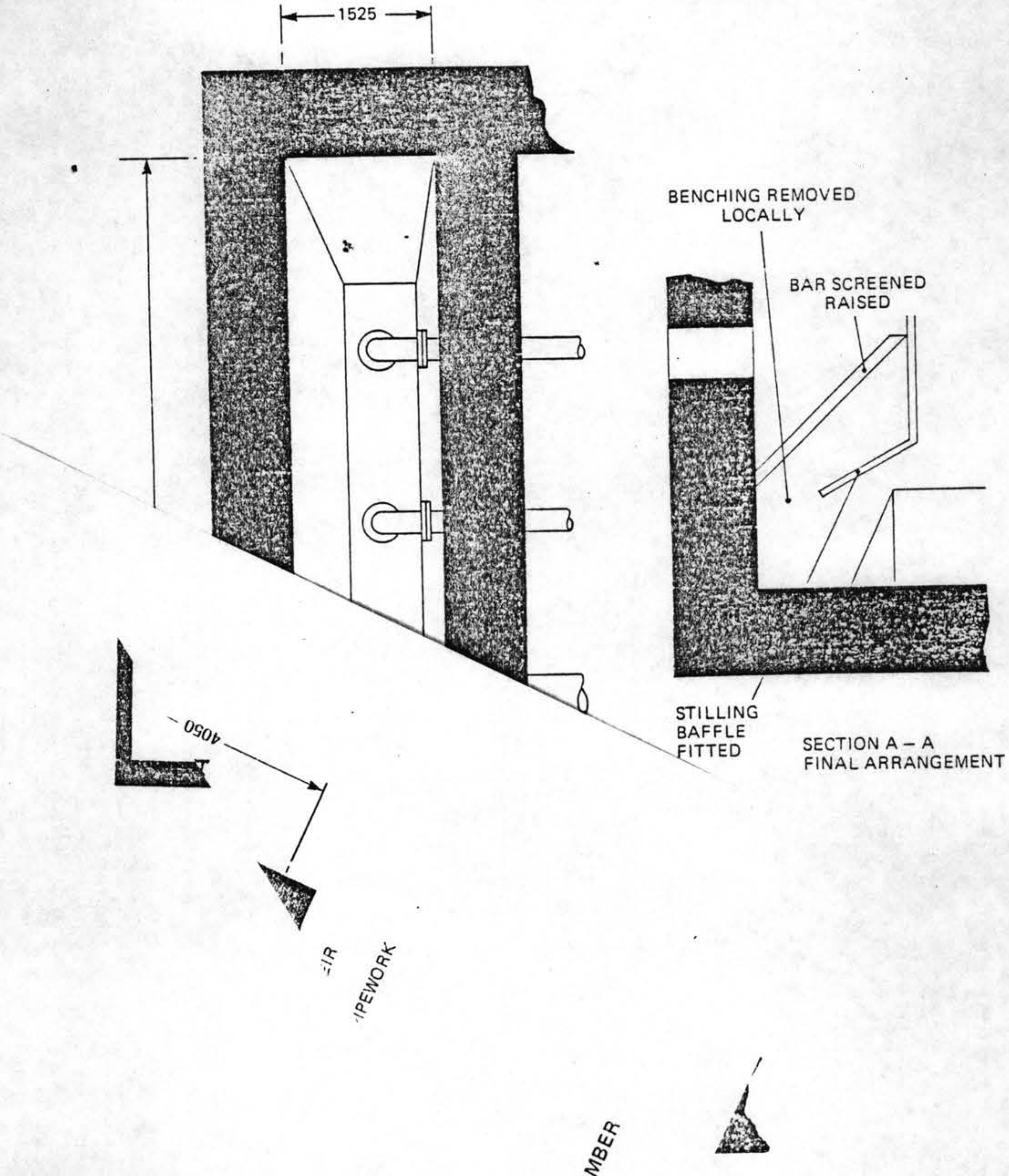


FIG. 8 FINAL LAYOU)F SUMP