Bandra Pumping Station, Bombay: re-design of Bandra influent pumping station

P. B. Clark, E. J. McCann, G. R. Hallowes and S. Spence

ABSTRACT

The Bandra Influent Pumping Station (referred to subsequently as the IPS), at Mumbai (Bombay) in India, is a key element in the Bandra drainage area of Mumbai. Construction of the whole scheme started in the mid 1980s but by the early 1990s had run into construction and financial difficulties. Binnie & Partners (India) Ltd (referred to subsequently in this paper as Binnie and now part of the Black & Veatch group) were commissioned to redesign the IPS, with the assistance of Tata Consulting Engineers of Mumbai (TCE). This paper discusses the details of the changes and the development of what is thought to be a unique layout for a major sewage pumping station. As part of the re-design process, the station was model-tested at the BHr Group laboratories and the model and the modifications required to the station as a result of the testing are also discussed.

Key words | instability, lack of storage, mass oscillation, maximum flows, re-design, sedimentation

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INTRODUCTION

The IPS is a major element of the Bandra sewage collection and disposal scheme. Upstream there are extensive sewerage systems, delivering flows to the IPS via a deep tunnel collector system. The IPS will deliver these flows to a preliminary treatment facility on the coast, from where they will be discharged through an ocean outfall.

Construction of the original scheme, designed by others, commenced in the mid-1980s. Progress on several key elements had almost ceased when Binnie, with TCE, were commissioned in 1991 to undertake a review of all aspects of the project (McCann *et al*. 2000). For clarity, the layout at that stage is referred to as the original design. The conclusions of that review included the recommendation that the IPS should be redesigned. The main technical concerns regarding the original design included:

- sedimentation in the system;
- instability of the pump control systems with large variable-speed pumps drawing from inadequately sized sumps;
- additional complications in the control introduced by mass oscillation effects in the upstream and downstream conveyance systems;
- the lack of storage in the system for purging the outfall;
- the inability of the system to pass the specified maximum flows.

PHYSICAL CONSTRAINTS ON POTENTIAL MODIFICATIONS

The original design of the pumping station is shown in Figure 1. It comprised four shafts excavated in the rock underlying the very constricted site. The collector tunnel entered the riser shaft at low level. The flow was then piped up to a higher level and through a screen shaft before passing through separate tunnels to each of the two pump shafts, which contained identical sumps. Four variable-speed pumps were located in the dry well in each pump shaft.

A constraint on the potential modifications was the requirement to utilise as much as possible of the plant which had already been supplied under a separate contract. This included pumps and motors, variable-speed controllers, valves and pipework, and electrical and control equipment. Also, the four shafts had been excavated

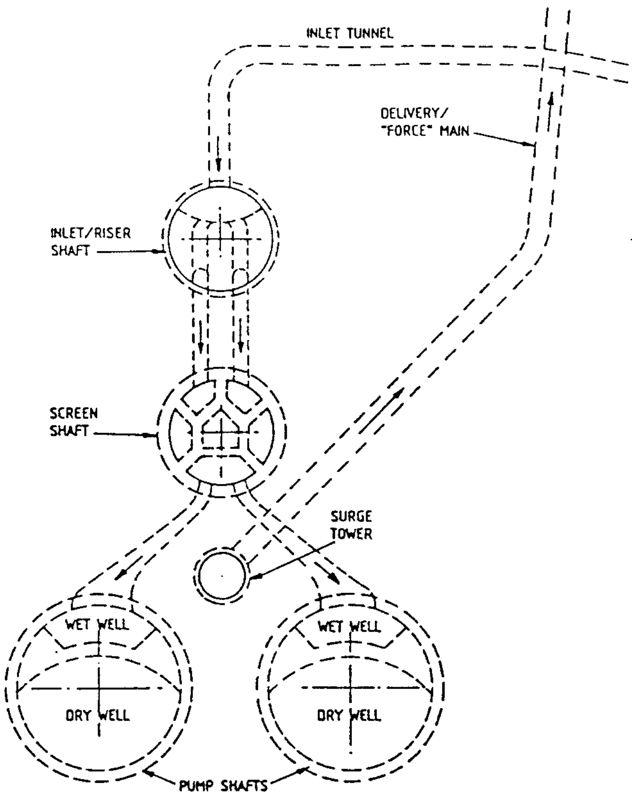

Figure 1 | Original layout of Bandra Influent Pumping Station.

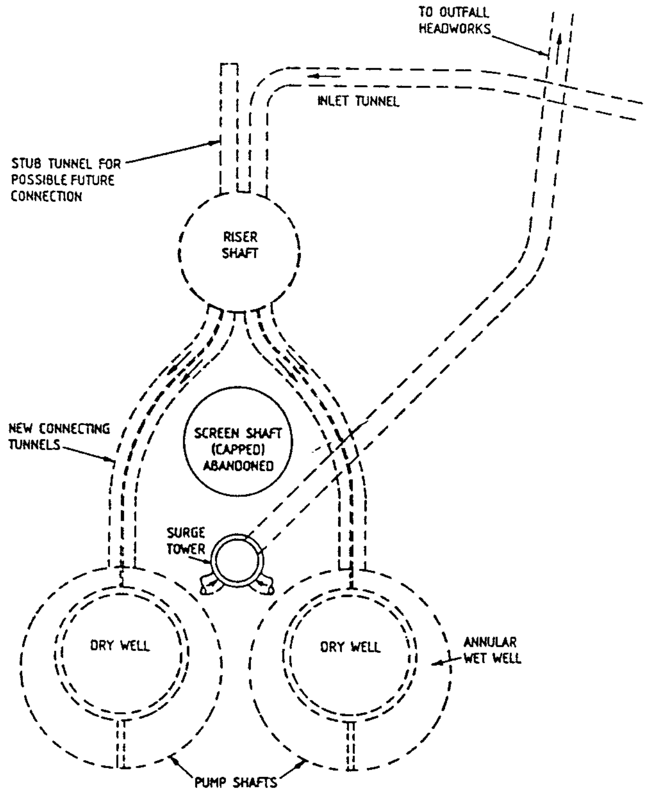

Figure 2 | Modified arrangement of Bandra IPS.

and much of the screen shaft constructed. The collector tunnel system, the surge shaft, and the delivery main had also been substantially completed.

One of the main conclusions of the review was that the pump shafts needed to be deepened to below the level of the tunnels so that the water level could be drawn down periodically and the tunnels flushed through under open-channel flow conditions. Although the bottom floor slabs had been cast in the pump shafts it was possible to break these out and deepen the excavation of these two shafts. However, this was not practicable with the nearly completed screen shaft and it was decided that this element of the works should be abandoned. The revised layout is shown in Figure 2. It comprises an inlet shaft (utilising what was to have been the riser shaft in the original design) containing removable trash screens, tunnels leading directly to the wet wells in the pump shafts, and the two pump shafts each containing two semi-annular wet wells and a dry well for the pumping plant. Each pump shaft contains four pump units, two pumping from each half of the annulus. The screen shaft of the original design is by-passed.

One significant structural modification enabled a complete re-design of the sumps and their hydraulic performance. The original design concept was for each of the pump shafts to be a 'free-standing' structure within the excavation, with non-structural backfill of the space between the outer walls and the rock. By casting the outer walls directly against the rock excavation, and by enlarging the excavation slightly at lower levels, the internal diameters of the shafts could be increased by several metres. Thus not only could the operating depth of the pumps be increased by deepening the sumps but the surface area of the sumps could also be increased significantly. In addition, the pipework and valving of the riser shaft was no longer required and the shaft could become an open inlet shaft, thus adding to the connected surface area of the sumps. The effective surface area of the sumps was thus increased from an original 280 m^2 to about 1,100 m^2 and the potential pump operating volume tenfold or more.

PROPOSED MODIFICATIONS

The enlargement of the shafts also enabled the dry-wells to be formed as circular shafts within the annular wet wells. This has significant structural advantages and has been utilised elsewhere. The Ameria pumping station, which Binnie & Partners had designed as part of the Cairo wastewater project, was an example of such a layout (Grimes *et al*. 1993). That station had the dry-well essentially concentric with the outer wall, with the pump intakes located regularly around the near constant-width annular sump. Although an efficient structural solution, certain hydraulic disadvantages have subsequently been identified with this arrangement. In particular:

- the flow to the rear pumps has to pass intermediate intakes and there can be interference from upstream intakes on the flow approaching an intake further downstream;
- the velocities decrease towards the rear of a concentric annular sump as the abstraction of each pump inlet reduces the flow passing downstream. This increases the risk of sedimentation at the rear.

It was imperative that the modified design for the IPS minimised any risk of sediment deposition. Drawing on the lessons of Ameria, an arrangement for the wet wall was developed in which the circular dry-well shaft is positioned eccentrically within the outer wall and the pumps abstract from separate cells at the rear of the annulus. The internal shaft for the dry well was sufficient to accommodate the existing pumping plant and the necessary pipework and valving. The detailed arrangement of one sump is shown on Figure 3.

Normal operation of the pumping station will be with the water at high level to minimise pumping costs. To flush the upstream collector tunnel, the water level will be drawn down until there are open-channel flow conditions in the tunnels and through the IPS, including the link tunnels between the inlet shaft and the two pump sumps. The annular sumps have been benched at low level so that, under these drawn-down conditions, the velocities around the annulus will be high and not only will sediment from the tunnels be carried through the station but any locally deposited sediment will be re-suspended and carried through to the pumps.

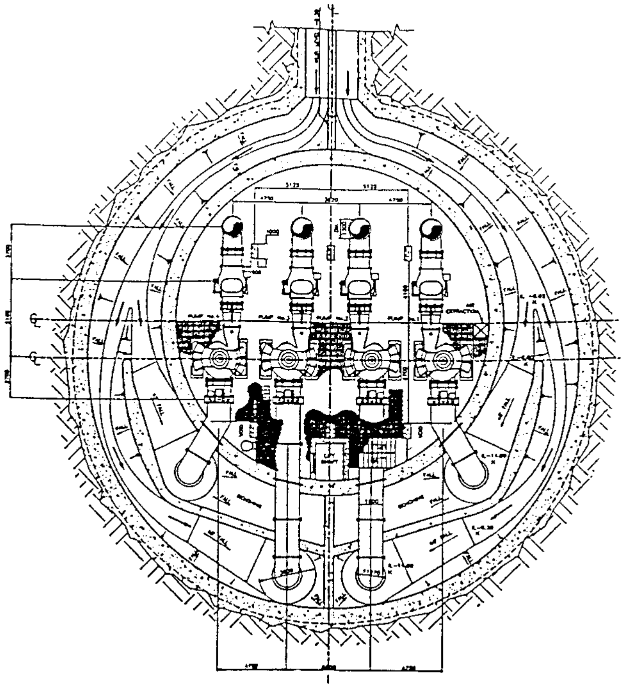

Figure 3 | Detailed layout of re-designed pump shaft.

Division of the annular sump area in each shaft into two wet wells allows two pumps in one shaft to remain in service while maintenance is carried out in the other wet well. However, the horizontal hydrostatic load on the structure of the dry well would be excessive if the maximum water level could occur in one wet well while the other was dry. Therefore the dividing wall between the two wet wells in each shaft terminates at a level which allows water to spill over from one to the other before the unbalanced load becomes excessive. An aperture at a slightly lower level in the dividing wall allows a small flow into the dry wet well before a major overflow occurs, to provide a warning for maintenance workers to evacuate the area before it is flooded.

The flow rates for the station operating in normal mode will range from about 3.0 m^3/s, at the lowest normal operating level with one pump in operation (compared with the nominal 3.4 m^3/s per pump), to 24 m^3/s with seven pumps operating at a lower sump level necessitated by the hydraulic gradient in the upstream tunnel system. In the drawn-down mode required to flush the tunnel system, the discharge from each pump will be reduced under the increased head, with a discharge of 9.6 m^3/s with four of the existing pumps drawing from one pump shaft. The maximum future flow rate is predicted to be 35 m^3/s. To cater for the maximum future flow rate larger pumps will be required. The revised layout allows for these.

The pump inlets are located in deeper wells below the main sump floor. This not only ensures that the velocities approaching the pumps are kept at acceptable levels in the drawn-down mode but also provides the necessary submergence on the intakes. This arrangement has not been utilised before and although the design was developed as far as possible there were several concerns that could not be resolved from a desk study. These included the following:

(i) The flow, during flushing conditions, would be approaching the pumps on a curved path dictated by the annular sump. This could give rise to unacceptable swirl at the pump intakes.
(ii) With the pumps in deep pockets below the main floor level of the sump, the development of flow conditions into the pump inlet might not have been satisfactory.
(iii) It was important for pump control that critical flow conditions could not be set up in the annual channel at the lowest operating level when the water level in the wet wells is low. If this happened it could lead to rapid draw-down of the water level in the operating pump well.

A physical model was constructed, therefore, and tested over the full range of flow conditions likely to be experienced. The contract for the model testing was awarded to the BHr Group and the model was built and tested at their Cranfield laboratories.

THE MODEL STUDY

Objectives

For each of the test configurations the main aspects investigated were:

- the flow patterns throughout the station, particularly in the wet wells and approaches to the pumps;
- the possible formation of free surface and submerged vortices adjacent to the pump intakes, and the existence of pre-rotation of the flow entering the pump suctions;
- head losses through the station;
- the movement of sediment through the station.

The model

A 1:12 scale physical model of the pumping station was constructed from timber, perspex and glass-reinforced plastic. The model included the inlet shaft, containing a drop shaft from a high-level local sewer, and representative lengths of both the existing and a new collector tunnel. The two outlets from the inlet shaft were modelled, one being connected to the twin link tunnels leading to one of the pump shafts and one being connected directly to the suction side of the laboratory pump set, thus enabling the correct flow rates through this outlet to be simulated. The wet well and pump suctions inlets on one side of this pump shaft were modelled accurately, the other half contained two outlets which simulated the flow to the two pump units in the wet well on the other side (Figure 4).

The model was operated at Froudian scale as the predominant forces are gravitational and inertial. Model flow rates were measured using orifice plates located in each line. The magnitude of the swirl angle generated within each pump suction was measured by the speed of rotation of vortometers positioned at two locations within each of the model pump suctions. The first vortometer was immediately downstream of the lobster back bend of the pump suction and the second was installed in the smaller diameter section immediately upstream of the entry to the pump impeller.

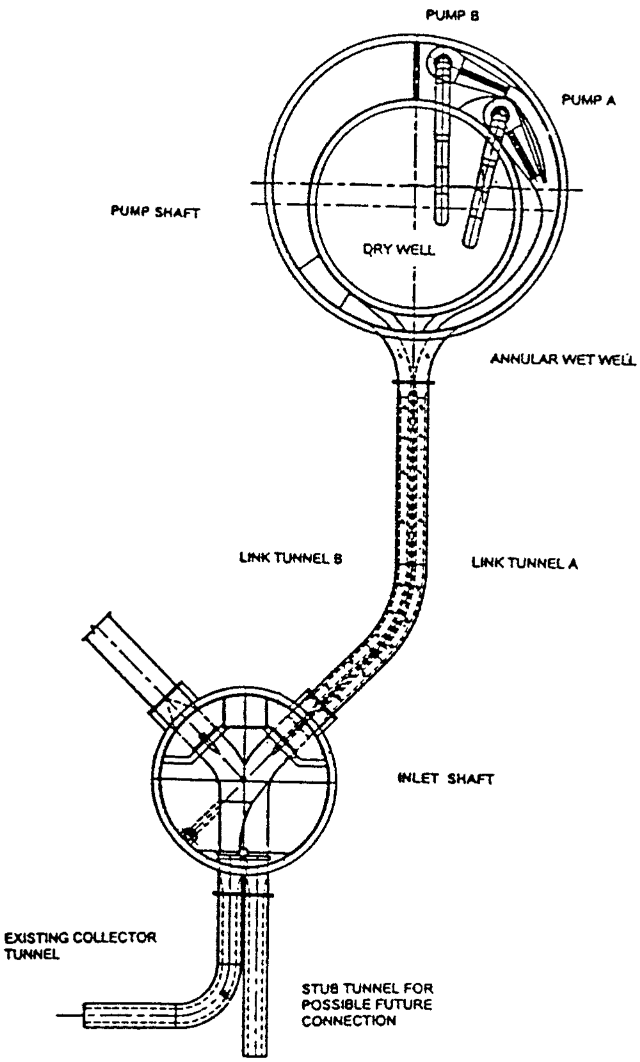

Figure 4 | Extent of physical model of Bandra IPS.

Initial test programme

The initial series of tests demonstrated that the basic hydraulic design of the station was good. The inlet shaft was capable of passing up to the maximum (35 m^3/s) station inflow and there were generally satisfactory flow conditions throughout the rest of the station.

Normal operation

Flow conditions in the inlet shaft were turbulent at times, but this did not appear to have an adverse effect on the overall performance of the inlet structure, and in fact would help to keep sediment in suspension. The turbulence was increased by the aerated discharge from a drop shaft discharging the flow from a high level local sewer. The flow divided satisfactorily between the two link tunnel systems.

In the pump shaft, under all test conditions, there was a strong current along the channel between the outer wall and the section of benching upstream of pumps A and B. At high water levels the strength of this current caused a degree of separation from the top of the steps leading down to the invert level of the two pump sumps, and velocities above the steps and adjacent surfaces were very low, thus creating an ideal area for solids to settle out. When the water level dropped, the velociites were high enough to prevent sedimentation when both pumps were running, but not on single-pump operation under some conditions.

The flow from the link tunnels to the pump sumps was biased to the outer wall of the pump shaft, which resulted in rotational flow approaching the pump inlets. This mass rotation was instrumental in generating pre-rotation of the flow in the suction pipes upstream of the pump impellers. Higher magnitudes of swirl were generally found in pump B, which is beyond pump A where its sump received flow with an increased bias to the outer wall, generating a stronger rotational flow above the pump inlet bellmouth.

Drawn-down operation

In the drawn-down mode of operation, open-channel flow conditions existed in the collector tunnels, inlet shaft, link tunnels and in the channel upstream of the two pump sumps. The flow velocities generated should flush away any sediment deposited; however, there was evidence of small amounts of sediment collecting along the inside edge of the channel upstream of the sump containing the inlet to pump B. This settlement was not excessive and tended to clear eventually.

With the single operation of pump A or pump B, the low wet well level generated supercritical flow from the collector tunnel into the inlet shaft. A hydraulic jump formed in the wider section of the inlet channel and downstream of this the flow was subcritical. Flow issuing from the link tunnels was fully contained within the channel formed by the benching and the outer wall of the shaft.

Deep surface eddies were seen to form and move around the sump, occasionally becoming quite vigorous, but there was no evidence of these developing into air entraining vortices. The rotation of the flow down and into the pump suction pipe resulted in high swirl angles at both vortometer locations in the pump suction.

Increasing the flow rate to the pumps to the maximum produced a standing wave at the diverging section of the approach channel when the water level was drawn right down. This flow regime is likely to have adverse effects on the stability of the water levels above the pumps, causing problems relating to the control of the pumps.

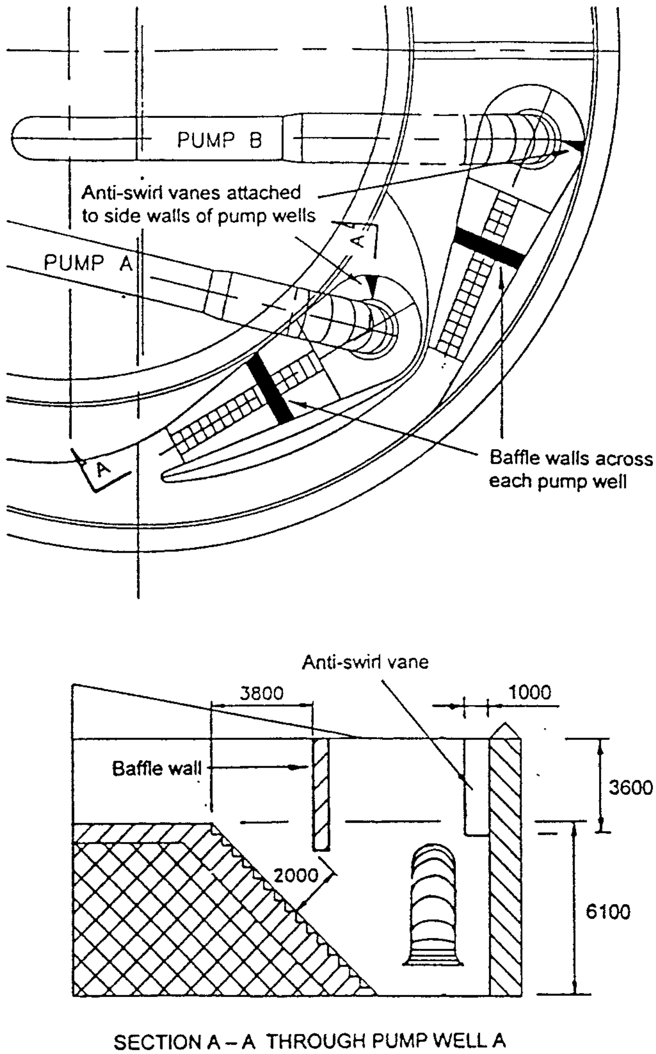

Figure 5 | Details of modifications to pump wells as a result of model testing.

Modifications to station design

Several modifications to the station design were considered as a result of the initial tests. Development tests were carried out to assess them and those found to be most effective were adopted.

Reduction of swirl and sedimentation in wet wells

Three modifications were tested to remedy problems of swirl:

- the invert of the individual pump sumps was raised;
- a vertical baffle was positioned above the steps in each sump;
- vertical baffles were attached to the walls above the intake in each sump.

The invert level of the two pump sumps was raised by 0.2 m to 34.6 m PD and 45° chamfers were added to the bottom perimeter of the sump. The reduced clearance between the sump invert and the inlet bellmouth induced a higher inlet velocity which, although not having a significant effect on the magnitude of swirl within the pump inlets, will help keep solids in suspension and reduce the risk of sedimentation on the invert. The chamfers reduce sedimentation by infilling an area where it would otherwise tend to occur.

Suspended baffle walls were positioned just downstream of the inlets to each sump (Figure 5). Their function is twofold. Firstly they counteract the bias of the flow entering the sumps and generate a more uniform distribution of flow above the pump inlets. Secondly they deflect a proportion of the flow downward over the steps thus preventing sedimentation on the steps and adjacent surfaces. As the operating levels in the wet well increased such that flow could pass above the baffle walls, a re-circulatory flow pattern was again evident. Vertical vanes attached to the sides of the pump sumps helped to disperse the rotating flow and re-establish stable flow conditions within the sumps (Figure 5).

Tests on final arrangement

The full test programme was repeated with all of the modifications described above. The modifications to the station wet well appear to be effective in stabilising the flow conditions in the pump suction pipes upstream of the impellers. A significant reduction in the magnitude of swirl immediately upstream of the pump inlets was observed, with all angles below 3°. Angles measured during the normal operation mode were all below 2° with the exception of one case of 4° for pump B. However, when the wet well is drawn down indicated angles still exceed 3°, immediately downstream of the inlet band, the maximum being 7.2°.

PUMP CONTROL AND OPERATION

The increased sump dimensions, both in area and depth, allowed several significant changes to the control of the pumps. Firstly, the increased surface area greatly reduced the mass oscillation effects on the water levels in the sumps. Thus the control of the pumps was de-coupled from the reactions of the upstream and downstream systems.

Secondly and equally importantly, the increased depth in the sump removed the restriction of 2 m on the total operating level range, imposed by the original design. It was possible to expand that level band and even to raise the level of normal operation to minimise power consumption. The resulting effect of the much larger control volumes available in the sump was to eliminate the need for variable-speed pumping, and it proved possible to design the control system such that the pumps could operate as fixed-speed units responding to a level-cascade control system. This greatly simplified the control system, removed the need for computerised control, eliminated any likelihood of instability in the pump operation and enabled simple manual operation in the event of a failure of the control system.

One other major advantage of the increased sump volume was that it provided storage in the system for the flushing of the delivery main and outfall. Thus the proposed mode of operation of the station will comprise normal operation at high level in response to level changes in the sump. During the dry season and possibly during the monsoon season as well, the sump will be drawn down once a day for a period of about an hour (this period will be confirmed with operational experience) normally at a time during the daily cycle when the inflows are reasonably high. This procedure will allow purging of saline water and sediment from the outfall by high flows as the sumps at the IPS are drawn down, and subsequently flushing of the upstream tunnel system when the water level is low enough to cause high velocity flow through the tunnel.

The model tests showed that when the flow rate to the pumps is increased to the maximum (10 m^3/s through one wet well) a standing wave forms at the diverging section of the approach channel. As this is likely to have adverse effects on the stability of the water levels above the pumps causing problems relating to their control the wet well level should not be less than 43.2 mPD at such flows.

CONCLUSIONS

Remodelling of the Bandra Influent Puming Station was considered essential for several reasons. Despite the considerable constraints imposed by the works already carried out and the mechanical and electrical plant already supplied, it was possible to develop a design that not only met the requirements of the system but also provided a much simpler, more robust solution to the operation and control of this very large station. The hydraulic design that was developed with twin, eccentric, annular sumps is believed to be unique but the model tests confirmed its performance with some relatively minor improvements in the areas of the pump intakes.

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