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Hydraulic modeling of Mahatma Gandhi (Kalvakurthy) Lift Irrigation Scheme Stage-2

Dr P.V.Chandramohan L. Prabahar*

Abstract

Large Lift irrigation projects are coming up in a big way in the state of Andhra Pradhesh in India. Initial conveyance of water is through tunnels before the water is lifted by large pumps through delivery mains and discharge tunnels. At the meeting point of the tunnel with the pump house, a surge pool is provided. Acceleration and deceleration of the flow during starting or shutting down of the pumps could create unexpected oscillations in the surge pool. It was decided that physical modeling is the effective method to study the oscillations in the pool for various operating parameters. A scaled down hydraulic model of the system was made by M/s Navayuga Engineering Company, Hyderabad, who are carrying out the design and construction of the prototype project, at the site near Kalvakurthy. The model was run for the various operating conditions of the prototype and consequent transients were observed. Salient observations and conclusions of the study are presented in this paper.

Introduction

'Models save millions' is a meaningful saying. This has been proved right many a time. This refers to hydraulic modeling. The flow of water and its interaction with the containing boundaries is a highly complex phenomenon. The shape of a full scale structure once built cannot be altered. So, it is all the more important that trials are taken in a small model where the shape and size are subjects of experiments and varied without much difficulty. But before experiments are conducted in the model, it has to be ensured that the model behaves similar to the full scale structure. The principle underlined in hydraulic modeling is to simulate the flow parameters involved in the actual scenario. Hydraulic modeling needs expertise and experience. Normally this is being done in specialized organizations. But in this instant case, a hydraulic model was constructed and run by Navayuga Engineering Company Ltd and later proceeded with the execution of the prototype project also.

Lift irrigation schemes are similar but reverse of hydro power stations. The components which are similar but reverse are pumps and generators, delivery mains and penstocks, surge pools and surge tanks etc. In most of these schemes, the initial conveyance is through either a tunnel or a canal. This is governed by economic considerations of excavation and existence of good rock to tunnel through.

Wherever, the initial conveyance is through a tunnel, a surge pool is provided as a buffer against oscillations during emergencies. The surge pool also acts as temporary storage during the starting of the pumps. During pump starting and sudden shutdown, surges are produced in the pool. Before implementation of the project, the surge effects on the systems should be analyzed for safety and stability. Analytical solutions for the surge analysis are only a few in the available literature. Either numerical model can be used or physical models to be built and operated to extreme conditions (Chaudhary, 1979) to understand the effects. Even though

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*Navayuga Engineering Company Ltd., 1259, Lakshmi Towers, Road #36, Jubilee Hills, Hyderabad-500033
pvcmohan@gmail.com

numerical models are easy to develop and operate, in most of the cases it may not depict all the salient features of the scheme as generally surge effects are complex and defies numerical simulation. Hence a physical model study is required to understand the salient features of the lift irrigation scheme under various operating conditions to investigate the surge effects.

Function of the Surge Pool

Surge pool in a lift irrigation scheme serves two purposes. Initially when there is no flow, the water levels on both ends of the tunnel will be same. The discharge of the pump will accelerate based on the acceleration in the rpm. The velocity of flow also in the tunnel also has to accelerate to keep up with this. Since the velocity is proportional to the square root of the head, the water level in the pool will slowly lower facilitating a head for the flow to initiate. But the sudden lowering of water level due to pumping will induce a sudden acceleration of water in the tunnel at a time lag giving rise to water level oscillations. The surge pool will act as a buffer to dampen these oscillations. This is not very drastic as only one pump can be started at a time due to the time required for stabilization of the electric current. But in the event of a power failure, all the pumps will shut down simultaneously. The inflow through the tunnel is stopped suddenly. The momentum of the incoming water in the tunnel will manifest in the form of a rise in water level in the surge pool. Besides, the water in the delivery mains will flow back through the pumps and draft tubes into the surge pool resulting in a momentary rise in water level. The total water level rise will have to be accommodated by the surge pool. The pool size will largely depend on the volume of water in the intake tunnel. The crest of the cascade in the cistern will prevent the water in the cistern from flowing back into the pool at power failure. The water level oscillations in the surge pool have to satisfy two criteria. One is that the upsurge of the level should not reach the surface where it would overflow over the top. Similarly, the down surge should not result in emptying of the pool such that operation of the pumps is affected. The second criterion is that the water level oscillations in the pool should be stable. This means that the oscillations should be reducing in amplitude or dampened.

Similitude and Scales

Conditions of flow entering the system, surge pool, pumping, delivery to the cistern etc. are to be carefully considered in the physical modeling (Ruus, 1969; Chaudhry, 1979; IS:1986). With reference to the prototype and the model, a detailed dimensional analysis has to be carried out. Generally the lift irrigation system is open to atmosphere at the inlet, surge pool and the cistern. The dominant force in the system is gravity and the modeling criteria should be based on the Froude number (Streeter et al., 1998; Subramanya, 1993). Hence, here the Froudian similitude law is used for the physical modeling.

The Froude number can be expressed as (Streeter et al., 1998): ; where, V is the velocity of flow m/s, y is the depth of flow in meter and g is the acceleration due to gravity in m/s2. Froudian similarity has to be satisfied between the model and the prototype for the open channel flow. The scales for linear dimensions and the scales for velocity and discharge are decided as per the above mentioned scale. Most of the lift irrigation schemes will have a long longitudinal dimension. This means that this dimension has to be accommodated in the site of construction of the model. Considering the availability of space and other parameters, the model scale was decided (Subramanya, 1993). If S is the scale chosen, using Froudian similitude the scales of various quantities are as follows:

Linear dimensions,; Velocity,; Discharge,; Time, where m represents the model and P represents the prototype.

Physical Model of Mahatma Gandhi (Kalvakurthy) Lift Irrigation Scheme Stage-2

4.1 Lay out of the Scheme

The objective of the broad scheme is to lift 133.3 cumecs of water from the foreshore of Srisailam reservoir for irrigation. This will be lifted in three stages - through a height of 95m in the first stage, 86m in the second stage and 117m in the third stage. The scope of the present package starts from chainage 3975. It starts with a 25m long ramp to the tunnel. The tunnel will convey water to a surge pool. Water will be led into a pump house by draft tubes dug through the rock ledge dividing the surge pool from the pump house. Delivery mains from the pumps will convey the water to an underground manifold, from where a discharge tunnel will convey it to a cistern and into Jonnalaboguda Balancing reservoir.

A lay out of Stage-2 is given below in Fig. 1 and Fig. 2.

The scheme has to convey 113.3 cumecs of water through a horizontal distance of 4795m, lifting it through 86 metres in the process. The starting chainage of the tunnel is 4000 and will join the surge pool at chainage 4680. Incidentally, this is the chainage of a kink in the tunnel alignment. By locating the intake pool at this chainage, the kink in the tunnel is avoided. The intake tunnel will have a length of 680m. Tunnel will have a D-shaped lined cross section of 6.5m diameter. A surge pool of size 80x15m has been located at the end of the tunnel. The pump house is located down the line at a distance for 30m from the surge pool. Both the pool and the pump house have been dug out to a depth of 55m in hard rock. From the surge pool, through the 30m rock ledge, five draft tubes will be drilled to convey water to the five pumps to be installed in the pump house. Stoplog gates and trash racks will be installed to cover each of these draft tube. Five Francis turbine pumps with a motor rating of 30MW are proposed to be installed inside the pump house. Delivery

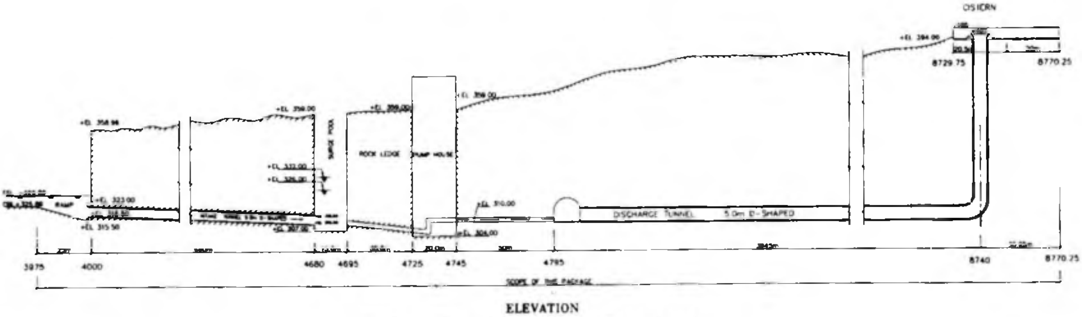

Fig. 1. Elevation of the Prototype

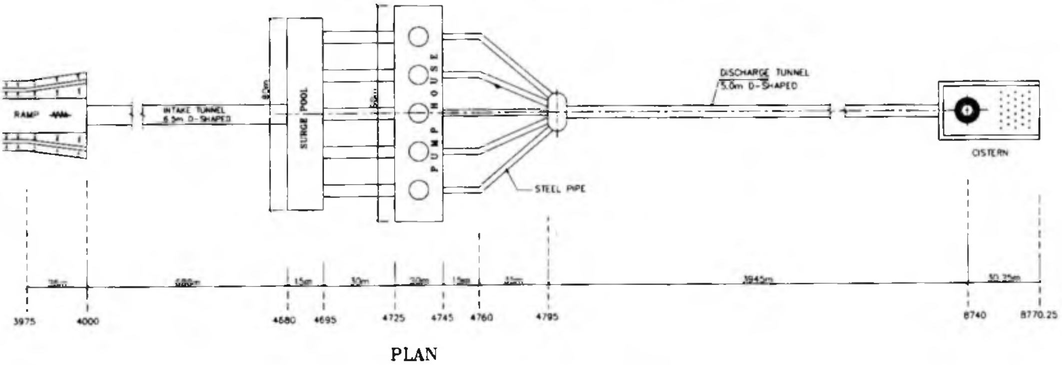

Fig. 2. Plan of the Prototype

mains of 2.5m diameter will carry the discharges of the pumps, converging into an underground manifold. The manifold is connected to a cistern by a discharge tunnel which is D-shaped with a diameter of 5m. The tunnel is horizontal for a length of 3845m ending up in a vertical shaft of 100m. The cistern is in the form of a cascade. The discharge is vertical through a bell mouth and comes down the steps of the cascade, dissipating all the energy before going into the canal beyond. One salient feature is that the discharge through the five delivery mains has been combined into a larger diameter tunnel. This results in reduction of losses due to decrease in length and increase in diameter of the conduit.

Model scales

Considering the availability of space, it was decided to adopt of a scale ratio of 30. Based on this ratio, time ratio worked out to be 5.477. Velocity ratio also came to 5.477. Ratio of discharges was 4929.5. Ratio of areas came to 900. With all these ratios, the velocity in the model tunnel came to 0.927m/s against a prototype velocity of 5.078m/s. The discharge through the model tunnel came to 22.984litre/s against the prototype discharge of 113.3 cumecs.

Construction of the Model

As can be visualized from the drawings, the entire prototype is to be constructed below ground level. But the model has to be above the ground for the sake of construction, operation and observation. A small portion of the approach canal and the inlet ramp were scaled down linearly and fabricated out of steel. The inlet arrangement in the prototype as such could not be reproduced in the model. Source of water in the prototype is from a reservoir which is perennial. The water level is constant. The model has to have a re-circulating system. So the input of water into the model was from an overhead water tank. At the same time water from the cistern was arranged to flow into a sump from where it would be pumped back into the overhead tank. To keep the water level constant in the intake ramp for various conditions of discharge, a valve was provided in the pipeline from the tank to the ramp (Photo 1). An overflow weir was provided near the intake (Photo 2). The level of water was controlled using both the valve and the weir. The tunnel in the prototype had a D-shaped section with a diameter of 6.5m. A D-shape was preferred from the point of view of construction as a bottom flat surface is required for removal of the blasted material through trucks. The tunnel was modeled as a HDPE circular pipe of equivalent area. (Photo 3)The length of 680m in the prototype was scaled down.


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Photo 1 Intake Ramp - Physical Model


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Photo 2 Overflow weir - Physical Model

The surge pool in the prototype is to be dug out in rock. The model of the pool was fabricated out of steel plates. The pool was located entirely above ground level in order to facilitate making observations. The intention of the model studies is also to optimize the size of the pool. So the pool was made such that the size could be varied (Photo 4). Length of the pool was fixed constant. The arrangement was such that the width could be varied. The pool had three sides in masonry and was made with grooves on two sides and at bottom. A movable wall was provided on the fourth side. This wall had transparent perplex at the top half to facilitate easy observations of the water level. Besides, piezometer tubes and automatic water level recorders were attached to the surge pool for accurate reading of levels.

In the prototype, bottom of the surge pool is connected to the pump house through five draft tubes rectangular in cross section. These are tunneled through hard rock. In the model, these were made of steel sheets and were directly connected to pumps (Photo 5), all above ground level. Instead of the vertical Francis turbine pumps in the prototype, ordinary centrifugal pumps with a motor rating of 2.5kW were used in the model. The purpose here is to reproduce the hydraulics of the system and not the pumps.

The delivery mains of 2500mm diameter, scaled down and PVC pipes were installed in the model. Gate valves were provided in each main to control the discharge. The manifold, fabricated of steel and the five PVC pipes was connected to it. The discharge tunnel, which is D-shaped in prototype was scaled down to an equivalent circular pipe and connected to the manifold (Photo 6). The cistern happens to be at an elevated location (Photo 7). The pipe was taken up vertically to enter the cistern from the bottom. The


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Photo 4 Tunnel in prototype

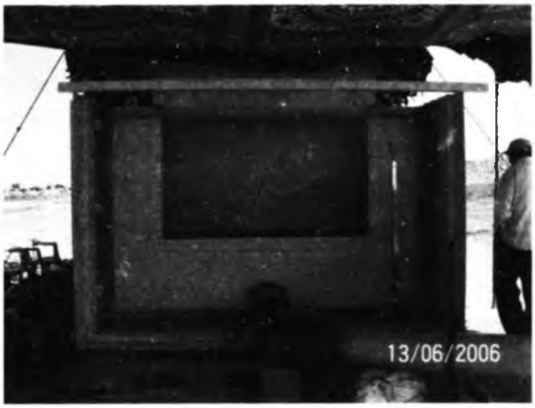
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Photo 5 Surge pool arrangement


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Photo 3 Tunnel arrangement in the model


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Photo 6 Surge pool in prototype

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Photo 7 Draft tubes, pumps & Delivery mains

cistern along with the cascade arrangements were made of brick masonry. The flow back arrangement for the re-circulating system was also installed.

The full discharge of 113.3 cumecs came to be 0.02298 cumecs in the model. The prototype velocity of 3.004m/s in the tunnel became 0.548m/s in the model as per the Froude scale.

Calibration of Model

The first operation is calibration of the model. Initially, when there is no flow, water levels on both ends of the tunnel are same. For a discharge Q by the pumps, the water level in the surge pool has to fall creating a head. This is called draw down. The head difference due to draw down will overcome the friction in the tunnel for that discharge. The draw down for various discharges has been theoretically calculated. This has to be same in the model and the prototype. In case there is any incompatibility, in the frictional characteristics, this will be adjusted using gate openings at the intake of the tunnel. The draw down for a five pump discharge of 113.3 cumecs is 2.335m in the prototype. In the model, these values become 0.023m3/s and 77mm. The draw down is measured by observing the levels at the intake and the surge pool. The discharge is measured by Ultrasonic Flow Meter (UFM)(Krohne, 2003). Besides, discharge through the delivery mains were calibrated by adjusting the opening of the valves.

Results and Discussion

Experiments Conducted

The model was run for various operating conditions of the prototype. The following experiments were carried out in the model. 1) Oscillations (down surge and drawdown) when one pump starts; 2) Oscillations (upsurge) when one pump shuts down; 3) Oscillations (down surge and drawdown) when second pump starts (first pump running); 4) Oscillations (upsurge) when two pumps shut down simultaneously; 5) Oscillations (down surge and drawdown) when third pump starts (first and second pumps running) and 6) Oscillations (upsurge) when three pumps shut down simultaneously; 7) Oscillations (down surge and drawdown) when fourth pump starts (first three pumps running); 8) Oscillations (upsurge) when four pumps shut down simultaneously; 9) Oscillations (down surge and drawdown) when fifth pump starts (first four pumps running); 10) Oscillations (upsurge) when all the five pumps shut down simultaneously. The above experiments were carried out for a surge pool width of 20 metres initially. Since the surge results were found to be satisfactory, another set up was not attempted. The results are discussed below:

Oscillations (down surge and drawdown) when one pump starts

Initially the level at the intake was kept at +339.89 (prototype level). There is no flow as the pumps are shut down. First pump is started. The valve position is already adjusted to the required discharge. All the other four valves are in the shut position. The discharge and the velocity are monitored continuously by means of the UFM. As the flow commences, the level in the surge pool goes down and finally stabilizes at the draw down level for that discharge. But this lowering of the water level is not smooth. As the water in the pool and the tunnel accelerates through the draft tube to meet the sustained discharge of the pump, there will be down surge in the pool followed by low amplitude oscillations. In this case, down surge was observed to be 0.80m below the final draw down level. There was also momentary upsurge also as can be seen from the graph. Steady state conditions were reached after a lapse of 600 seconds. The draw down was found to be 0.093m as the level stabilized at +329.797. The oscillations were recorded by automatic recorder and are shown in Fig 3.

Oscillations (upsurge) when one pump shuts down

In the above situation, due to some reason, if the pump is shut off suddenly, the flow of water through the tunnel is stopped suddenly and it will head up in the pool. Besides, water in the delivery mains will flow back into the pool till the levels in the pool and the shaft equalizes. One superimposed over the other, will give rise to momentary rise in water level. While one pump was running and the water level is in steady state, the pump is shut down. The water level oscillations in the pool were observed. The maximum surge above the draw down level was found to be 1.1m 85 seconds after shut down. Steady state conditions were reached after 1100 seconds. The oscillations were stable. These are given in Fig 4.

Oscillations when fifth pump starts (four pumps running)

The drawdown after starting of fifth pump is given in Fig.5. After stabilization of first pump, second one is started and similarly the third.

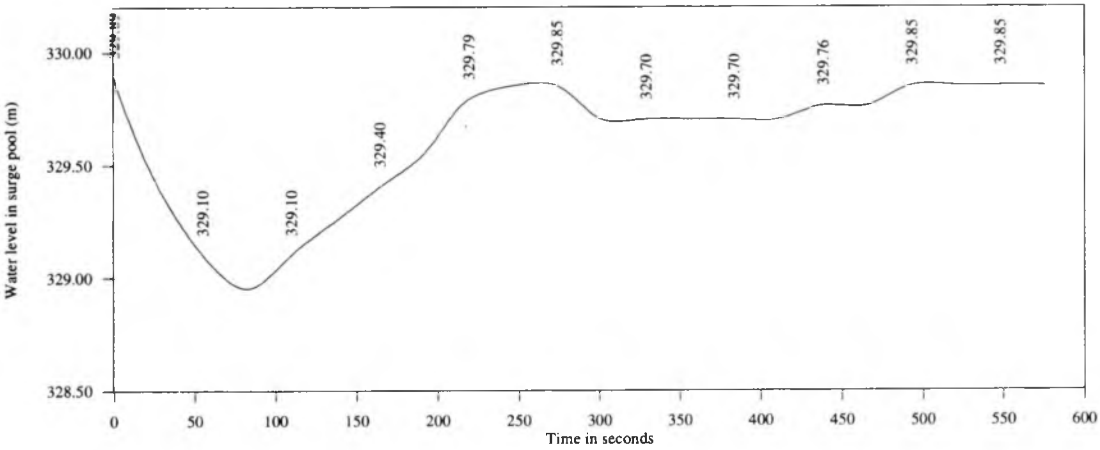

Fig. 3. Water level oscillations when one pump starts

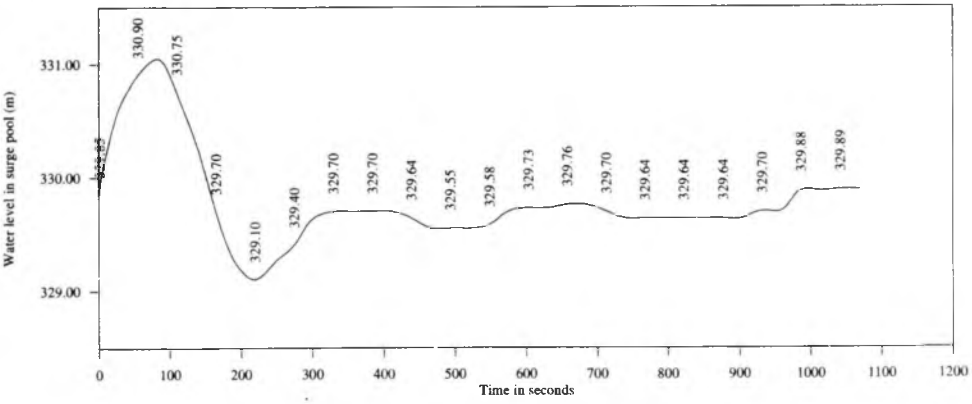

Fig. 4. Oscillations when one pump shuts down

When the fifth pump starts, the draw down due to oscillation is the lowest.

Oscillations when all the five pumps shut down simultaneously

The surge oscillations due to the shutdown of all the pumps at a time, is given in Fig. 6. It can be seen that there is a sudden positive surge and it reduces to original water level at the intake finally. In this case, the surge will be highest. It came to 3.95m above the final steady state level.

Analytical Computations And Comparison

The Bureau of Indian standards in their specification IS : 7936 (Part I) - 1985 'Criteria for Hydraulic design of Surge Tanks Part I Simple, Restricted orifice and Differential Surge Tanks' give formulae for computing surge in water levels in surge tanks. The formula takes into account friction at the boundaries also.

$$\frac{L}{2g\phi\beta^2V_o^2} - \frac{Z_m}{\beta V_o^2} - \frac{L}{2g\phi\beta^2V_o^2} x \left(e - \frac{2g\phi}{L} x \left[Z_m + \beta V_o^2\right]\right) = 0$$

Where,

L - Length of the head race tunnel = 680m

At - Cross sectional are of the head race tunnel = 37.72 m2

Vo - Velocity in the tunnel = 3.00 m/s

β - Coefficient of hydraulic losses in the tunnel.

g - acceleration due to gravity = 9.81 m/s2

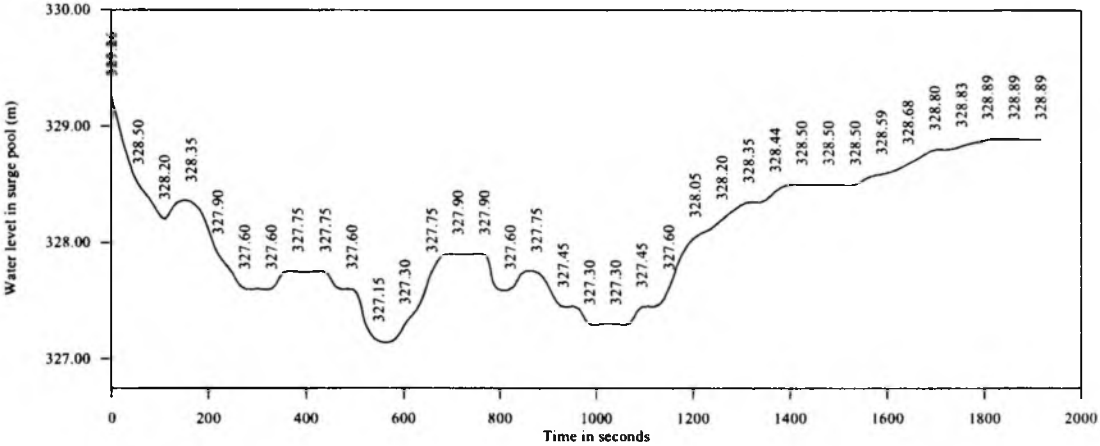

Fig. 5. Oscillations when fifth pump starts (four pumps running)

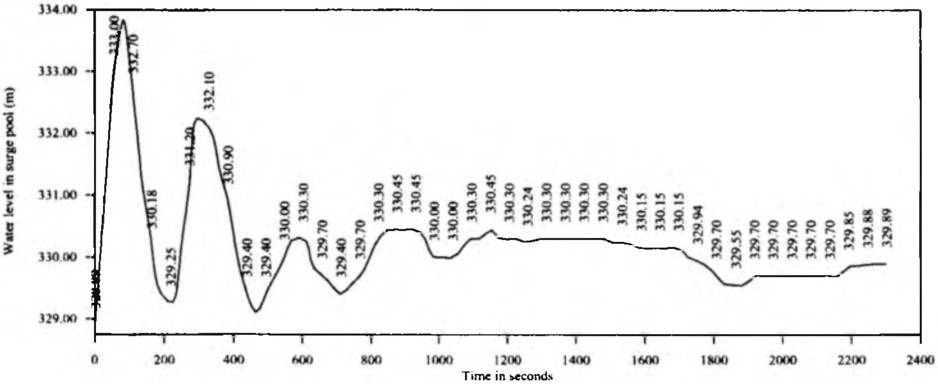

Fig. 6. Oscillations when all the five pumps shut down simultaneously

Tank Size (m)	Discharge (m3/s)	Velocity (m/s)	φ	Beta	Losses (m)	T.length (m)	Surge (m)
80.0 X 15.0	22.66	.60	31.82	-.1090	.04	680.0	1.73
80.0 X 15.0	45.32	1.20	31.82	-.1090	.16	680.0	1.83
80.0 X 15.0	67.98	1.80	31.82	-.1090	.35	680.0	2.01
80.0 X 15.0	90.64	2.40	31.82	-.1090	.63	680.0	2.26
80.0 X 15.0	113.30	3.00	31.82	-.1090	.98	680.0	2.58

$$\phi = \frac{A_s}{A_t} = \frac{1200}{37.72} = 31.81$$

Where As - plan area of the surge pool = 1200 m^2

Z_m - maximum surge

The above equation could be solved for Zm to obtain the surge.

Using the above expression, surge was calculated for various pump discharges ie, at the instant of one pump being shut down, two pumps shut down etc. The values are tabulated below:

As discussed earlier, the flow through the intake tunnel is in the positive direction while the backflow from the cistern through the discharge tunnel is in the negative direction. The surge of water from the tunnel occurs simultaneously with the backflow. But there is a time lag between the peaks of the two. The process is too complex that simple superposition will not yield correct values. The following table gives computed and observed values.

It can be seen that the duration of Backflow varies from 13.20s for only pump discharging and shutting down to 26.90s for five pumps simultaneously discharging and shutting down. This is because the flow back of the same total quantity of water has to pass through only one pump and five pumps respectively. It is interesting to note that movement of water from the intake tunnel and the backflow are simultaneous in time but opposite in direction. When five pumps are discharging, the backflow discharges meeting the tunnel flow are higher. This has given rise to a higher rise than the superimposed value. But in the case of, for example, only one pump discharging, the discharge is low and is confined to only one draft tube emanating into the surge pool. However, it can be seen that the agreement is better in the case of shut down at higher discharges.

Concluding remarks

In lift irrigation schemes, the flow regime is complex on two occasions. During the starting of the pumps, the water body in the pool and the tunnel has to accelerate suddenly to cater for the discharge of the pumps. That is the reason that the Francis turbine pumps used in prototype have guide vanes which open and close at a set slow

Computed values					Observed	
No of pumps	Surge (m)	Rise from Backflow (m)	Total rise in level (m)	Duration of backflow (s)	Rise in level (m)	Period (s)
1	1.73	1.24	2.48	26.90	1.16	85
2	1.83	1.24	3.07	19.60	2.21	85
3	2.01	1.24	3.25	16.40	2.51	80
4	2.26	1.24	3.50	14.60	3.20	85
5	2.58	1.24	3.82	13.20	3.95	85

pace so that the discharge is increased slowly. But in the model, ordinary centrifugal pumps were used and the discharge picks up suddenly. This might create more drastic conditions. However, the oscillations in the pool give a fairly good concept about the down surge and the consequent oscillations. The event of a power failure is an emergency. The pumps shut down together. The backflow through the pumps from the delivery mains is superimposed on the surge of water from the tunnel. But due to the time lag between the peaks of the surge of water from the tunnel and that of the backflow, simple super position is not valid. In long pipelines, the backflow, if allowed, could create runaway speeds of the impeller of the pumps. But in this case, the pipelines are short. The model could be used to optimize the size of the surge pool to economize on the cost and to get an idea about the operating emergencies so that surprises can be avoided.

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