Analysis of water hammer in irrigation pipelines networks due to pump power failure

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It has long been known that the severity of transients in pipelines networks is underestimated. In irrigation networks, transient flow still needs more investigation. The objective of the present study is to determine and draw the profile of maximum and minimum heads along the pipelines of the irrigation networks due to pump power failure. In this case, protecting the irrigation pipelines networks against water hammer is of great importance. Therefore, the present study aims to investigate the effect of using a protection device; one-way surge tank; on the network. To achieve this goal, basic partial differential equations based on one-dimensional homogenous flow model are formulated and solved by the method of characteristics. A computer model written in Fortran language is prepared considering several boundary conditions to define the irrigation pipelines networks. Three different case studies are investigated considering pipelines networks feeding pivot irrigation systems in Toshka project in Southern Egypt. The results show that using the proposed one-way surge tank as a protection device proved to be effective for limiting the minimum head values.

إن ظاهرة الطرق المائى فى شبكات المواسير لم تأخذ حق قدرها الا قريبا. فى شبكات الرى مازالت هذه المشكلة تحتاج المزيد من الدراسة. و الهدف من هذا البحث هو حساب ورسم منحنى أقصى و أقل ضغوط تحدث على امتداد خطوط المواسير فى شبكات الرى نتيجة إنقطاع التيار الكهربى عن الطلمبات. فى هذه الحالة يكون من الضرورى التفكير فى طريقة لحماية الشبكة. لذلك فإن البحث الحالى يهدف أيضا إلى دراسة أحد وسائل الحماية من المطرقة المائية مثل إستخدام صهريج التمُور ذوى الاتجاه الواحد لحماية هذه الشبكات. و لتحقيق هذا الهدف تم إستخدام طريقة الميزات العددية لصياغة و حل معادلات السريان المتجانس الاحادية الابعاد التى تمثل ظاهرة الطرق المائى و تم عمل برنامج بلغة الفورتران يشتمل على عدة شروط حدية لتمثيل هذه الشبكات. و تم دراسة الطرق المائى على ثلاثة شبكات رى بمنطقة جنوب الوادى بتوشكى و أوضحت النتائج أن إستخدام صهريج التمُور ذوى الاتجاه الواحد له تأثير فعال للحد من قيم الضغوط السالبة التى تحدث فى مواسير شبكات الرى.

Keywords: Transient head, Irrigation networks, Pump failure, One way-surge tank, Characteristics method, Water hammer

1. Introduction

Computerized transient flow models are used with great success in the analysis of water hammer in topologically simple pipelines systems. There are many well documented results in the literature describing the performance of such models, mostly for various types of pumping plants connected to a series pipeline. As early as 1937, Schnyder conducted comparisons between computed and observed water hammer pressures in pumping plants. Chaudhry presents test results for hydroelectric power plants (Chaudhry and Portfors [1]), pumping plants (Chaudhry [2]), and makeup cooling-water-supply- lines (Chaudhry, Cass and Bell [3]), Simpson and Wylie [4] give test results for transients with water column separation, Hancox and Banerjee [5] present an implicit finite-difference model and test results for a two-phase flow in nuclear-power-plant piping systems. Although these systems may be complex in a physical or a behavioral sense, they lack the topological complexity typical of many branched and looped pipe networks.

Little is known about the transient-flow behavior of complex pipe systems. There are many unsubstantiated arguments, and as many unresolved issues surrounding this important topic. For example, how is the predicted transient behavior influenced by a one-way-surge tank protection? What is the nature of dissipative forces, such as junction and other minor losses, water distribution networks.

2. Governing equations

Two equations are used to model transient flow in closed conduits: the momentum equation and the equation of mass conservation, [e.g., Chaudhry [2], Wylie and Streeter [6]. If x is the distance along the centerline of the conduit, t is time, and partial derivatives are represented as subscripts, these equations can be written as:
Continuity equation:

$$\rho a^2 v_x + P_t + vP_x = 0\,. \tag{1}$$

Momentum equation:

$$v_t + vv_x + \frac{1}{\rho}P_x + g\sin\theta + \frac{f}{2D}|\,v\,|\,v = 0\,. \tag{2}$$

In which, $P = P(x,t)$ = pressure; $v = v(x,t)$ = fluid velocity; D = inside pipe diameter; f = Darcy-Weisbach friction factor; a = wave speed; θ = slope angle of the pipe; and g = acceleration due to gravity. Eqs. (1 and 2) are valid if the flow is one-dimensional, the conduit properties (diameter, wave speed, temperature, etc.) are constant and the friction force can be approximated by the Darcy-Weisbach formula for steady flow. In addition, it is usually assumed that the friction factor f is constant during the transient analysis.

The Method Of Characteristics (MOC) is a simple and numerically efficient way of solving the unsteady flow equations. In essence, the MOC combines the momentum and continuity expressions to form the following equation in the velocity (v) and piezometric head (h):

$$\frac{dv}{dt} \pm \frac{g}{a}\frac{dh}{dt} \mp \frac{g}{a}v\sin\theta + \frac{f}{2D}v\,|\,v\,| = 0.0\ . \tag{3}$$

Eq. (3) is valid only along the so called C^+ and C^- characteristic lines defined by $dx/dt = v \pm a$. To satisfy these characteristic relations, the x-t grid is usually chosen to ensure $\Delta t \le \dfrac{\Delta x}{\max|a+v|}$ (see fig. 1.). Once the initial conditions and the space-time grid have been specified, eq. (3) can be integrated along mP and nP in fig. 1. to give the following equations in its final form:

$$C^+\ :\quad v_p = C_P - C_a h_p\ . \tag{4}$$

$$C^-\ :\quad v_p = C_N + C_a h_p\,. \tag{5}$$

In which:-

$$C_P = v_m + \frac{g}{a}h_m + \frac{g}{a}\Delta t\, v_m \sin\theta - \frac{f\,\Delta t}{2D}v_m|\,v_m\,|$$

$$C_N = v_n - \frac{g}{a}h_n - \frac{g}{a}\Delta t\, v_n \sin\theta - \frac{f\,\Delta t}{2D}v_n|\,v_n\,|$$

$$C_a = \frac{g}{a}\,.$$

The unknown values of $h_m, v_m, h_n,$ and v_n can be estimated by using linear interpolation with the help of the known values at the grid points.

Once the boundary conditions are established, then velocities and heads at all grid points at $t = \Delta t$ can be calculated. Then values at $t = \Delta t$ are used to write new equations to solve for values of (h) and (v) at the next time step where $t = 2\Delta t$. This process is repeated continuously ahead in the (x – t) plane until the required time of analysis.

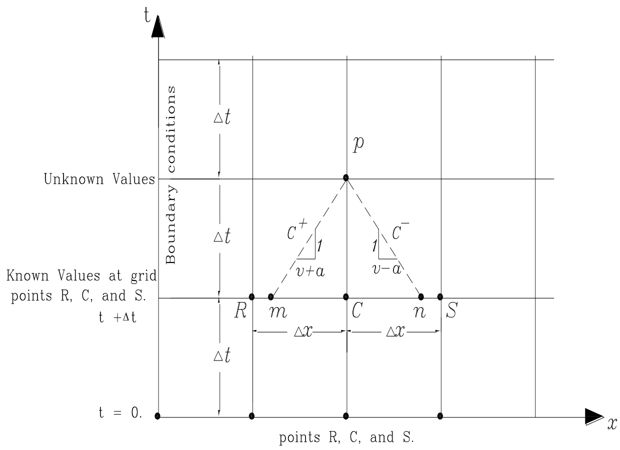

Fig.1. Interpolation of (h) and (v) values on the (x - t) grid.

3. Boundary conditions

3.1. Junction of sprinkler

Sprinkler discharge is a function of the pressure at each individual sprinkler. The equation of discharge can be represented as an orifice discharging to the atmosphere. The relationship is written in the following form:

$$Q_{spr} = C_{spr}\left(H_{spr}\right)^{0.5} . \qquad (6)$$

Where H_{spr} = pressure head at the sprinkler inlet; C_{spr} = sprinkler discharge coefficient.

Sprinkler manufacturers provide tables for pressures and corresponding discharges for different type of sprinklers. So for a certain type of sprinkler the value of C_{spr} can be easily calculated at the steady-state condition and its value is kept constant for the rest of the transient analysis.

The following significant assumptions must be considered when this equation is used:

- For practical use, the losses in the sprinkler riser as well as the losses between the sprinkler riser inlet and the main pipe have been neglected to avoid extra computational effort.
- If the head at the sprinkler inlet during the transient analysis is less than zero, no air is allowed to enter in the sprinkler and the junction will be dealt with as an interior junction between two series pipes without any external demand.

3.2. Junction of pump

The analysis is concerned with a common pump power failure. The pipeline is provided with a check valve in the pump discharge line, as well as a low-loss bypass line around the pump station. The new rotational speed (N) over a time increment (Δt) can be calculated from the following relation:-

$$N_{t+\Delta t} = N_t - \frac{60}{2\pi I} T_t \Delta t . \qquad (7)$$

Where, T_t = the decelerating torque of the pump at an earlier time interval; I = the total rotational moment of inertia of the rotating parts of the pump. The following assumptions are made when modeling the pump:

- The decelerating torque is constant over the time interval (Δt) and its value is known at the previous instant of time.
- The pump characteristics curves are linearized.
- All the pumps fail simultaneously.
- The head loss across the pump discharge column is neglected
- When the pump head is less than the sump water level, the pump bypass will be opened.
- When the velocity at the pump is negative, it will be set to zero as a result of the check valve existence.

3.3. Junction of one-way-surge tank

In pressured pipelines, the one-way surge tank is commonly used because the elevation of HGL is usually too far above the pipeline. The one-way surge tank is used to prevent downstream low pressures. The energy equation is written as:

$$Q_s = C_s A_{pi} \sqrt{2g(H_s + Z_s - h)} . \qquad (8)$$

Where, Q_s = discharge from the tank; C_s = the loss constant for the connecting pipe between the surge tank and the pipe; Api = the cross-sectional area of the connecting pipe; H_s = height of water in the tank; z_s = elevation of the junction of the tank; h = transient piezometric head at the junction.

The values of C_s can be calculated from the more readily available values for the losses coefficients of the components of the tank connection. For a very well designed connection, C_s could be as large as 0.90. For a poorly designed connection, C_s may be as low as 0.40 (Watters (2000) [7]).

4. Case studies

A pivot network constructed to feed 6500 faddans serving from branch two in Toshka is analyzed. A sketch for this network is shown in fig. 2. The network consists of nine booster pump stations fed from an open channel.

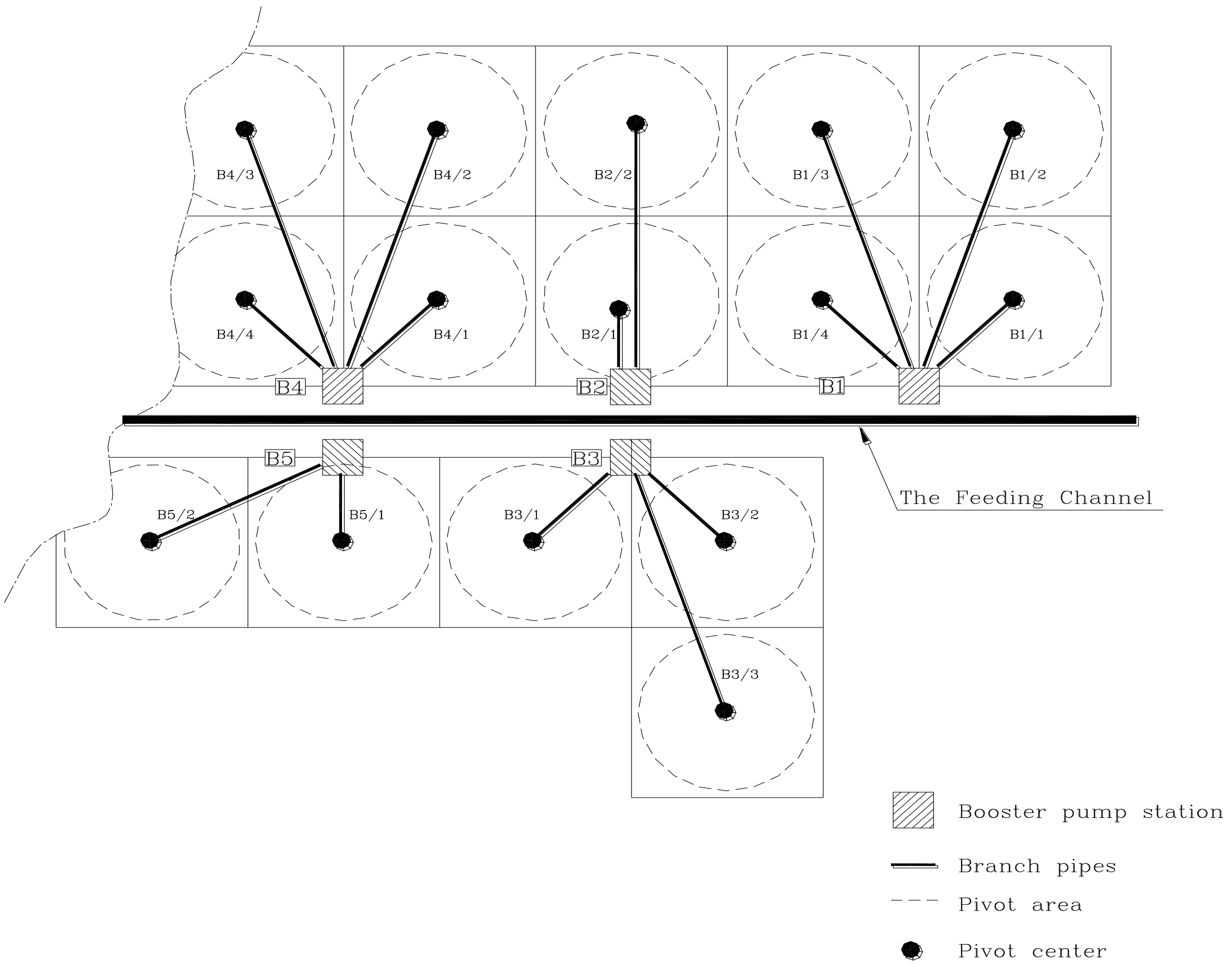

Fig. 2. A sketch of the case study.

Each booster station has its own branch UPVC pipes. Each branch pipe ends with pivot line.

4.1. Hydraulic analysis

The major analysis is performed to examine the network against the pump power failure. This analysis is performed on the network considering two cases:-

- Case (1): The first case is without any protection.
- Case (2): The second case using a one way surge tank as a protection device located at downstream side of the pump.

In the analysis, the pivot line is composed of 216 sprinklers spaced at a distance of 1.80 m, with a dead end. The steady state discharge of each sprinkler varies according to the distance from the pivot centre.

The analyzed booster pump stations are stations 2, 3 and 4. In the next section, each booster station is analyzed alone to give the results for each.

The characteristics of the one-way-surge tank used in the network are shown in table1:

4.2. Booster pump station two (B2)

It consists of two branches (B21 and B22 of total lengths 421.0 and 1162.0 m, respectively) supplied by one pump as shown in fig. 2. Each branch ends with a pivot line. A control valve is installed at the beginning of each branch to adjust the flow. Minor losses are considered in the calculations.

table 1
Characteristics of one-way-surge tank

H_s (m)	Diameter (m)	A_{pi} (m^2)	C_s
12.0	1.80	0.049	0.90

Figs. 3 and 4. Show the envelope of minimum pressure head values along branch pipe (B21) and (B22) respectively due to power failure for the two cases considered.

4.3. Booster pump station three (B3)

It consists of three branches (B31, B32 and B33 of total lengths 570.0, 592.0 and 1293.0 m respectively) supplied by two pumps as shown in fig. 2. Each branch ends with a pivot line. A control valve is installed at the beginning of each branch to adjust the flow. Minor losses are considered in the calculations.

Figs. 5, 6 and 7. Show the envelope of minimum pressure head values along branch pipe (B31, B32, and B33) respectively due to power failure for the two cases considered.

4.4. Booster pump station four (B4)

It consists of four branches (B41, B42, B43 and B44) of total lengths 575.0, 1282.0, 1194.0, and 589.0 m respectively) supplied by two pumps as shown in fig.2. Each branch ends with a pivot line. A control valve is installed at the beginning of each branch to adjust the flow. Minor losses are considered in the calculations.

Figs. 8, 9, 10 and 11. Show the envelope of minimum pressure head values along branch pipe (B41, B42, B43 and B44) respectively due to power failure for the two cases considered.

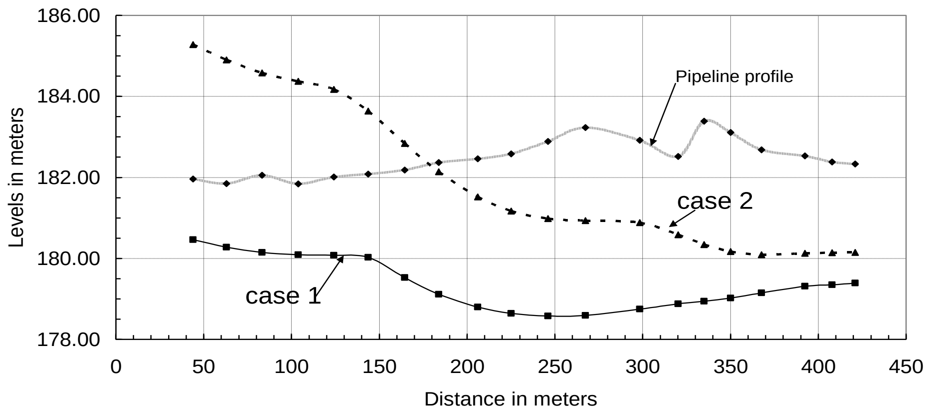

Fig. 3. Distance versus levels.

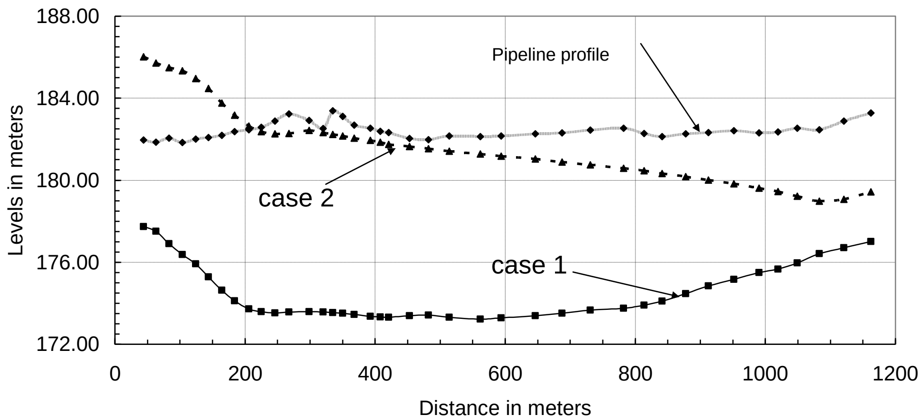

Fig. 4. Distance versus levels.

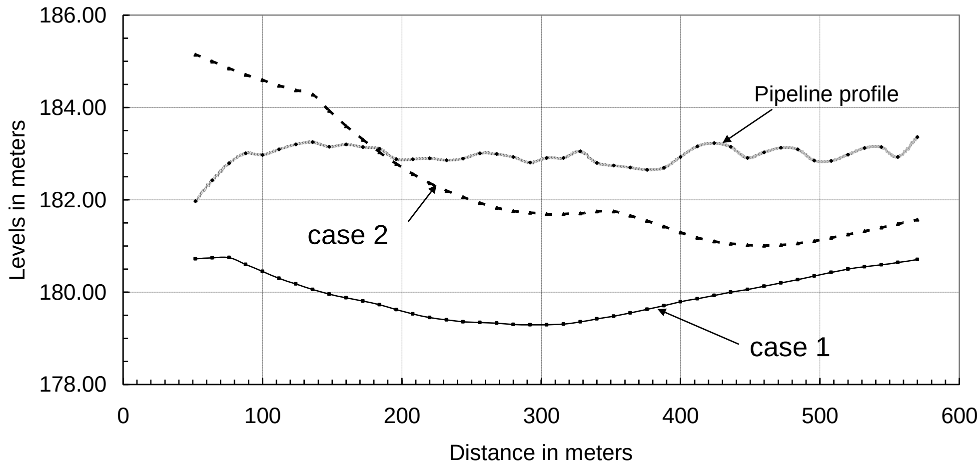

Fig. 5. Distance versus levels.

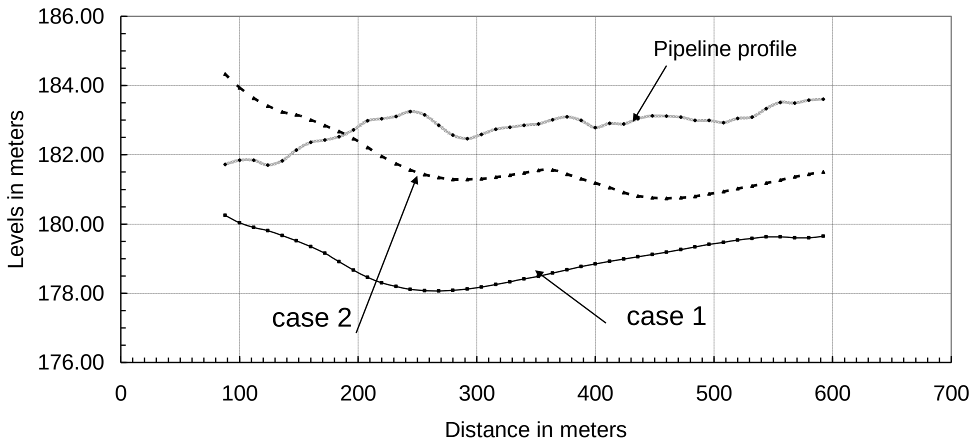

Fig. 6. Distance versus levels.

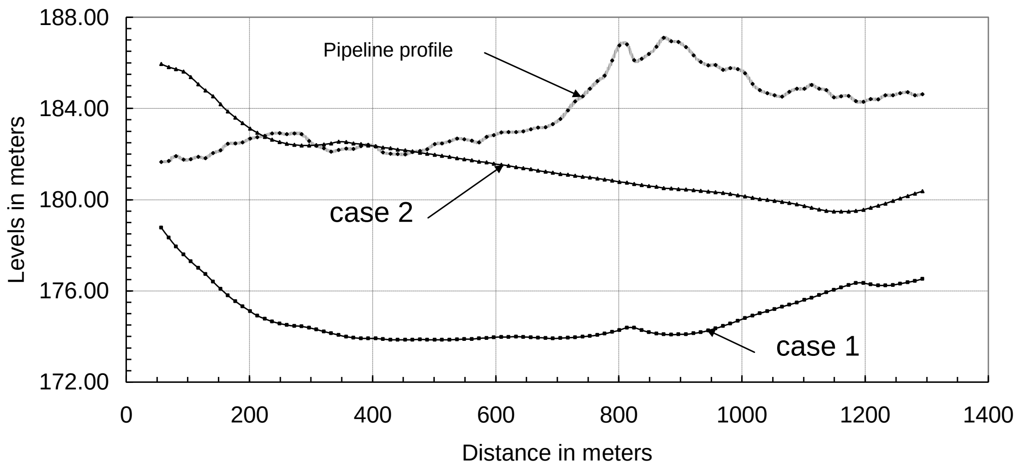

Fig.7. Distance versus levels.

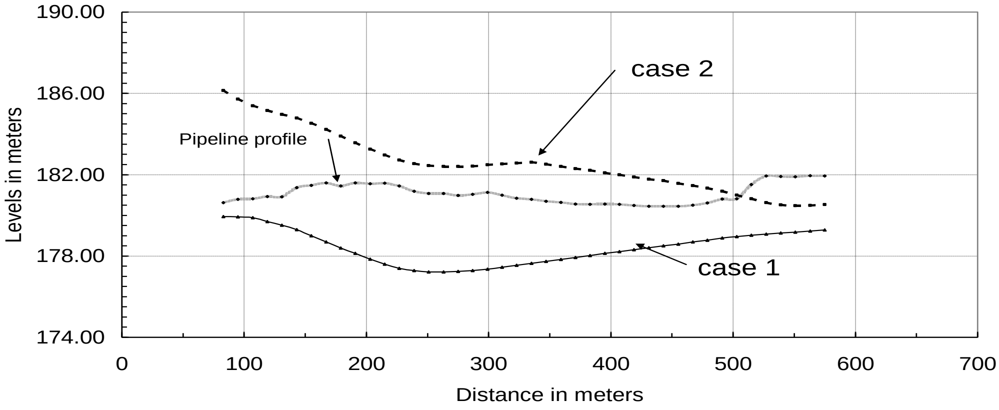

Fig. 8. Distance versus levels.

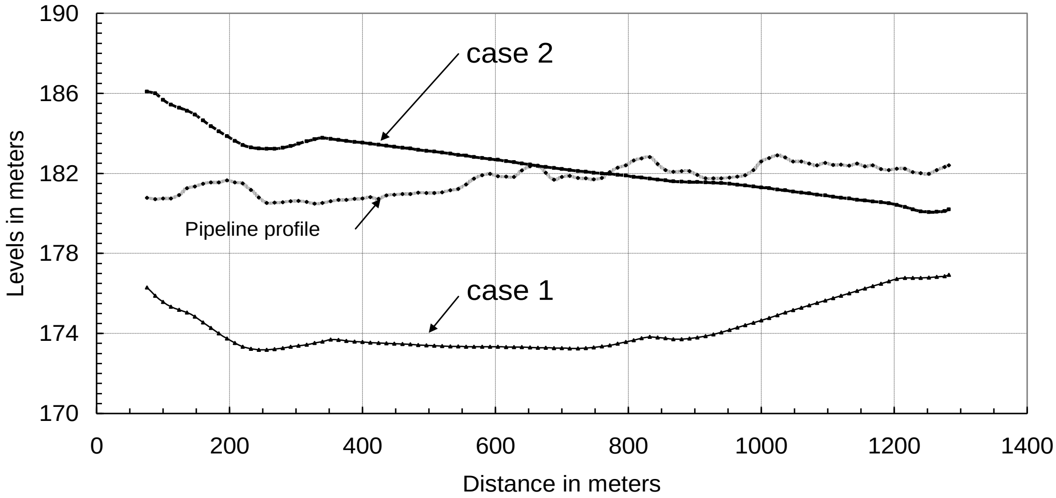

Fig. 9. Distance versus levels.

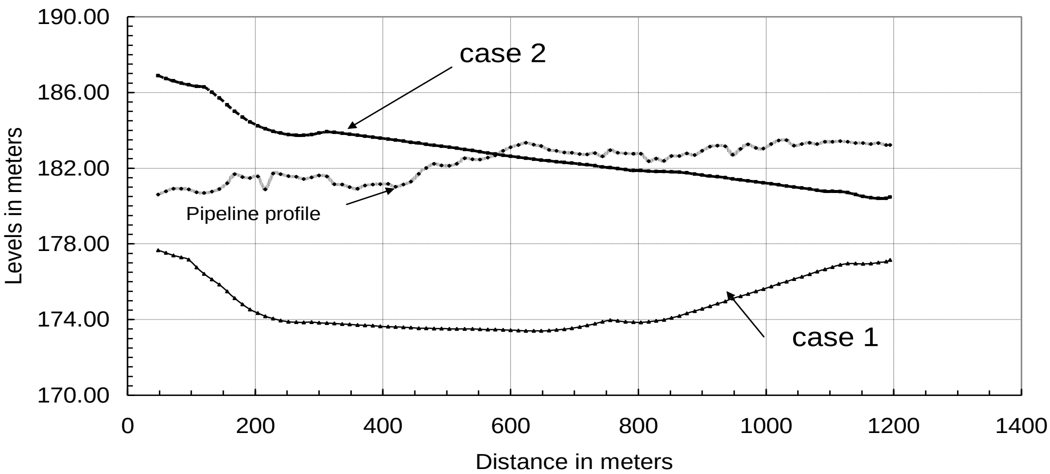

Fig. 10. Distance versus levels.

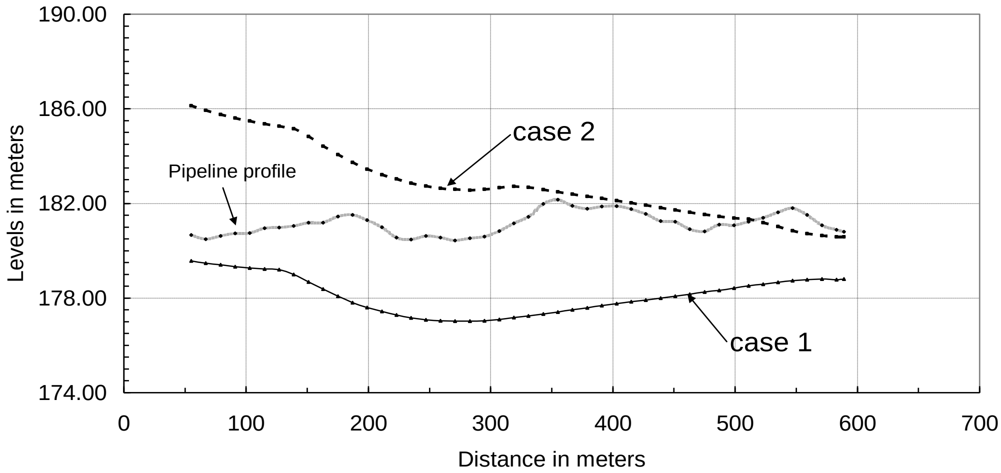

Fig.11. Distance versus levels.

5. Results

The above analysis performed for different case studies shows that the one-way-surge tank is effective in reducing the minimum heads values along the pipelines of the shown pivot irrigation network.

Table 2 shows the head values in meters for the two cases considered, where:

- case 1:- without protection
- case 2:- with one-way-surge tank protection:

Table 2
Head values for considered cases

Booster station	Branch	Case 1	Case 2
(B2)	(B21)	-4.64	-3.05
	(B22)	-9.84	-3.84
(B3)	(B31)	-3.69	-2.13
	(B32)	-5.14	-2.38
	(B33)	-13.0	-6.58
(B4)	(B41)	-4.04	-1.46
	(B42)	-9.09	-2.21
	(B43)	-9.93	-2.93
	(B44)	-4.75	-0.95

6. Conclusions

a. Due to pump power failure, the maximum head values during the transient state along a pipeline feeding a pivot do not exceed the initial steady state head.

b. The first network, (B2), consists of two branches fed by one pump. A proposed one-way surge tank as a protection device leads to the reduction in the minimum head value from (-9.84 m to -3.85 m).

c. The second network, (B3), consists of three branches fed by two pumps. A proposed one-way surge tank as a protection device leads to the reduction in the minimum head value from (-13.00 m to -6.58 m).

d. The third network, (B4), consists of four branches fed by two pumps. A proposed one-way surge tank as a protection device leads to the reduction in the minimum head value from (-9.93 m to -2.93 m).

e. The proposed one-way surge tank implemented at the above three sites leads to satisfactory results.

Notations

a	is the wave speed,
A_{pi}	is the cross-sectional area of the connecting pipe,
C_s	is the loss constant for the connecting pipe between the surge tank and the pipe,
C_{spr}	is the sprinkler discharge coefficient,
D	is the inside pipe diameter,
f	is the darcy Weisbach friction factor,
g	is the acceleration due to gravity,
h	is the piezometric head,
H_s	is the height of water in the tank,
H_{spr}	is the pressure head at the sprinkler inlet,

I is the total rotational moment of inertia of the rotating parts of the pump,
N is the rotational speed of the pump,
P is the pressure,
Q_s is the discharge from the tank,
Q_{spr} is the sprinkler discharge,
T is the decelerating torque of the pump,
t is the time,
v is the fluid velocity,
x is the distance,
z_s is the elevation of the junction of the tank, and
θ is the slope angle of the pipe.

References

[1] M.H. Chaudhry, and E.A. Portfors. "A Mathematical Model for Analyzing Hydraulic Transients in a Hydroelectric Power Plant", Proc., 1st can. Hydr. Conf., univ. of Alberta, Edmonton, Canada (1973).

[2] M.H. Chaudhry, "Applied Hydraulic Transients", Van Nostrand Reinhold, New York, pp. 89-125 (1987).

[3] M.H. Chaudhry, D.E. Cass and W.W. Bell, "Hat Creek Project: Hydraulic Transient Analysis of Makeup Cooling Water Supply System", Rep. No. DD 108, Hydroelectric Des. Div., British Columbia Hydro and Power Authority, Vancouver, Canada, (1978).

[4] A.R. Simpson, and E.B. Wylie, "Large Water-Hammer Pressures for Column Separation in Pipelines", J. Hydr. Engrg., ASCE, Vol. 117 (10), pp. 1310-1316 (1991).

[5] W.T. Hancox, and S. Banerjee. "Numerical Standards for Flow-Boiling Analysis", Nuclear Sci. and Eng., Vol. 64 (1), pp. 106-123, (1978).

[6] E.B. Wylie, and V. L. Streeter, Fluid Transients, McGraw-Hill Book Co., New York, pp. 31-65 (1978).

[7] G. Watters, B. Larock, and R. Jeppson, "Hydraulics of Pipeline Systems", by CRC Press LLc, pp. 469-473 (2000).

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