WATERHAMMER ANALYSIS
IN CASE A RESERVOIR WATER LEVEL FLUCTUATES

BY

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I. SYNOPSIS:

This research paper represents a new situation where the water surface in a reservoir is not stable, but is fluctuating, i.e. the water pressure head in the reservoir is a function of time. The analysis in this case starts with the two fundamental waterhammer equations in terms of both the pressure head and velocity. These two equations can be derived by solving the dynamic equilibrium equation, in momentary fashion, with the continuity equation and then simplify and arrange the resulted equations in applicable form. These two equations are based on several basic assumptions. One of the most important assumption is that the water level in the reservoir keeps constant during the whole time of gate movements. For this reason, these equations are restricted to such basic assumption and should be modified to fit the new situation, where "H" represents any time variable function.

These two modified equations can be solved analytically by the method of characteristics using the computer facilities to speed up the calculations. As a result both the pressure and the velocity can be determed during any time interval at any of the selected locations along the pipe. Suitable incremental time intervals are carefully selected for each step of solution.

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Another way of using the same modified equations, providing availability of the gate movements equation, is the stepping wise graphical procedure. In this instance, although the curves (mostly parabolas) and lines will be more interfering than the case of constant "H", but it may be more understandable and easier to follow, besides its flexibility and controlable features. Eventhough, for complex situations, analytical procedure applying computer facilities becomes essential and more efficient, at any of the assigned locations for any selected number of time intervals.

II. INTRODUCTION:

Waterhammer has been always one of the serious problems in the engineering practical field. Lately, waterhammer problem occupied the interest of many research workers and anhanced great concern from variety of specialist engineers and planners along with the care of producers, because of its numerous applications, regardless of causes, the type of fluid or media experiencing the problem. Keeping in mind that waterhammer phenomenon can happen for water flow as well as for any other liquids or fluids including gases.

Generally speaking, in waterhammer analysis, one basic fact has to be recognised, that is: the flow is unsteady and consequently, the discharge at each section everywhere along the pipeline is varying rapidly from one instant to the next, i.e. $dQ/dt = 0$. So, rapid changes in pressure occur inside the pipe and Bernoulli's equation is no longer appliceable. The sudden change in pressure accompanies with change in the velocity too which are inversally proportional.

It was assumed in most of what has been covered in past literature in waterhammer analysis, so far, that the reservoir water level remains constant during the gate movements as a function of time. If the water surface of the reservoir is compartively large, such an assumption (H = constant) in this case can be provided with accepted accuracy. The new case where the pressure water head "H" is not constant can be found practically in surge-tanks, filling process of the lock-chamber creating navigation problems, the upstream surface of reservoirs during the flash flood period, where the turbines units of the hydropower plant will be experiencing flood waves action under fluctuating working heads. One may also face a similar problem which may lead to an instantanious failure in any of the pumps in e waterplant fed from such reservoirs or along a tide dam, where a similar situation may exist and a probable failure may take place. Also, a consequence of such a problem is profitable when an adopted solution for the new case would be applied to solve the case of two reservoirs, with their water fluctuating, due to any reasons, and these reservoirs are connected together with a pipe-line. Here one can see variety of cases, such as: suddenly movement in a valve lies somewhere along the connecting pipe, where the water surface in each reservoir fluctuates accoding to certain function. They may have the same function or with different periods, frequences and amplitudes or they may be matching in every thing.

One may also deal with the problem of not only two reservoirs but group of feeding or collecting reservoirs. Nevertheless, these kinds of problems, as they become more complicated, either by using the same procedure adding the new boundary conditions for each problem individually.

Moreover, pulsatile blood flow through distensible vessels, vena cava, aorta, etc., where $A = F(x, y, z; t)$, which can be treated in a similar way taking into consideration the variation of the size of each individual vessel with time, the branching problem, flexibility of vessels walls, the properties of blood as a viscous composite fluid, mechanism of the heart, etc. Analogous study can be carried out oorrelating heart stroke (heart attack) problem with the hydraulic transient phenomenon after indispensable modifications in the basic waterhammer equations take place.

Actually, there is a broad field of studies for the different phases in the various applications of waterhammer problems; some are solved or partly solved and many still not yet.

III. THE BASIC ASSUMPTIONS:

Before carrying out the analysis, the following basic assumptions have to be taken into consideration, any additional assumptions will be stated wherever they are stated.

1) The elasticity of the pipe walls and the compressibility of the fluid (water) under the action of pressure changes are also taken into consideration.
2) The pipe-line remains full of water at all times i.e.: the law of continuity holds.
3) The static pressure in the pipe is sufficiently high to sustain the minimum pressure inside the pipe is in excess of the vapor pressure of water.
4) The velocity of water in the axial direction of the pipe is uniform over any cross section of the pipe is uniform over any cross section of the pipe.
5) The pressure is uniform over any transverse cross section which is the same as that at the centerline of the pipe.
6) The water level at the reservoir remains contstant during each incremental period of investigation and during each individual time interval the gate movement process is taking place.
7) The pipe is of constant wall thickness.
8) The fluctuating function may take a sort of sinusiodal shape or any repeating pattern.

) The geometrical characteristics and the boundary conditions are introduced wherever they need to be implied.

)) The cases of sudden closure, gradual closure and so for opening cases are treated seperately.

IV. THE MODIFIED EQUATIONS FOR THE WATERHAMMER PROBLEMS, HAVING THE PRESSURE HEAD "H" VARIES WITH TIME:

In the schematic sketch of Fig. (1) for nonfluctuating condition and Fig. (2) for the fluctuating case, considering the value is located at the end which is partially closed suddenly or opened instantaneously. This simple case shown in figures are selected for just a matter of convenience. Now, a sudden change in both velocity and pressure create an "F" type pressure wave running in the opposite direction of the initial flow velocity "V_o" addvancing toward the rservoir in the positive "X" - direction " with a value equal to the velocity of pressure wave C, which is the velocity of sound in water or the " celerity".

Upon reaching the reservoir this "F" wave will be reflected back by the produced "f" type in the direction of negative "X - direction" (refer to Fig. (2)).

Taking into consideration the dynamic equilibrium of an element and solving the momentum equation with the continuity equation, in unsteady flow fashion, for an incremental time interval "Δt", one can get the fundemental waterhammer equations derived in case the water level in the reservoir is constant in their final form, after necessary simplifications, as follows (refer to Refs, 24 & 25, etc.).

$$H - H_o = F(t - \frac{X}{C}) + f(t + \frac{X}{C}), \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

and

$$V - V_o = -(\frac{g}{C}) \quad F(t - \frac{X}{C}) - f(t + \frac{X}{C}) \quad \ldots\ldots\ldots \quad (2)$$

in which:

H_o and V_o: are the pressure head and the velocity in the

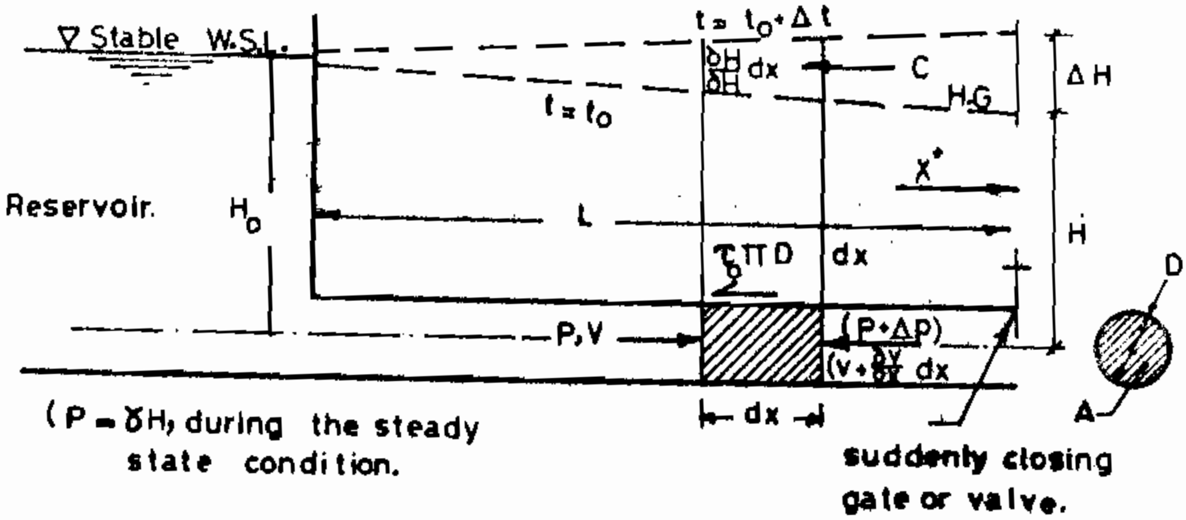
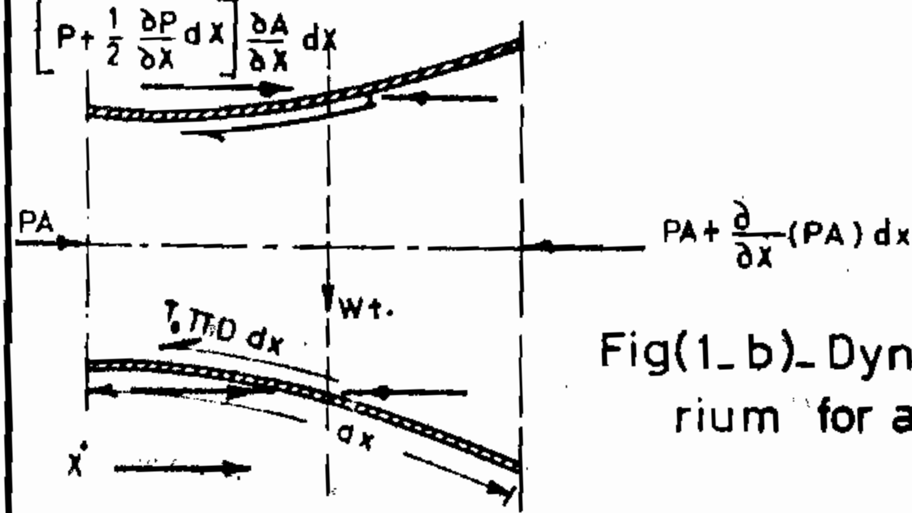
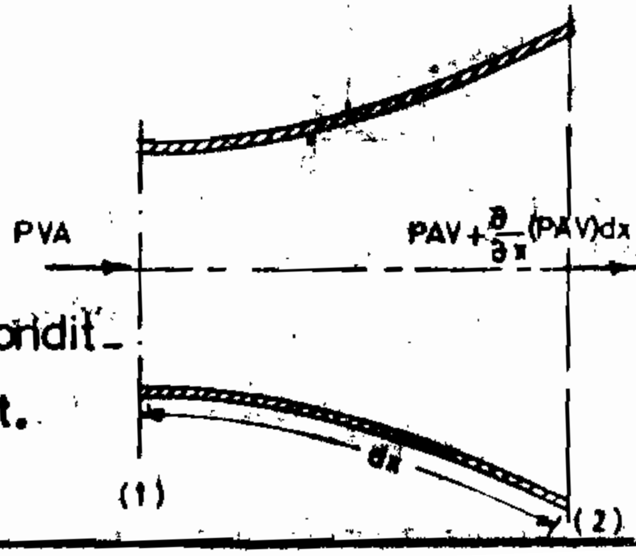


Fig. (1_a)- Definition sketch.



Fig(1_b)- Dynamic Equilibrium for an Element.



Fig(1_C)-Continuity Condition for an element.

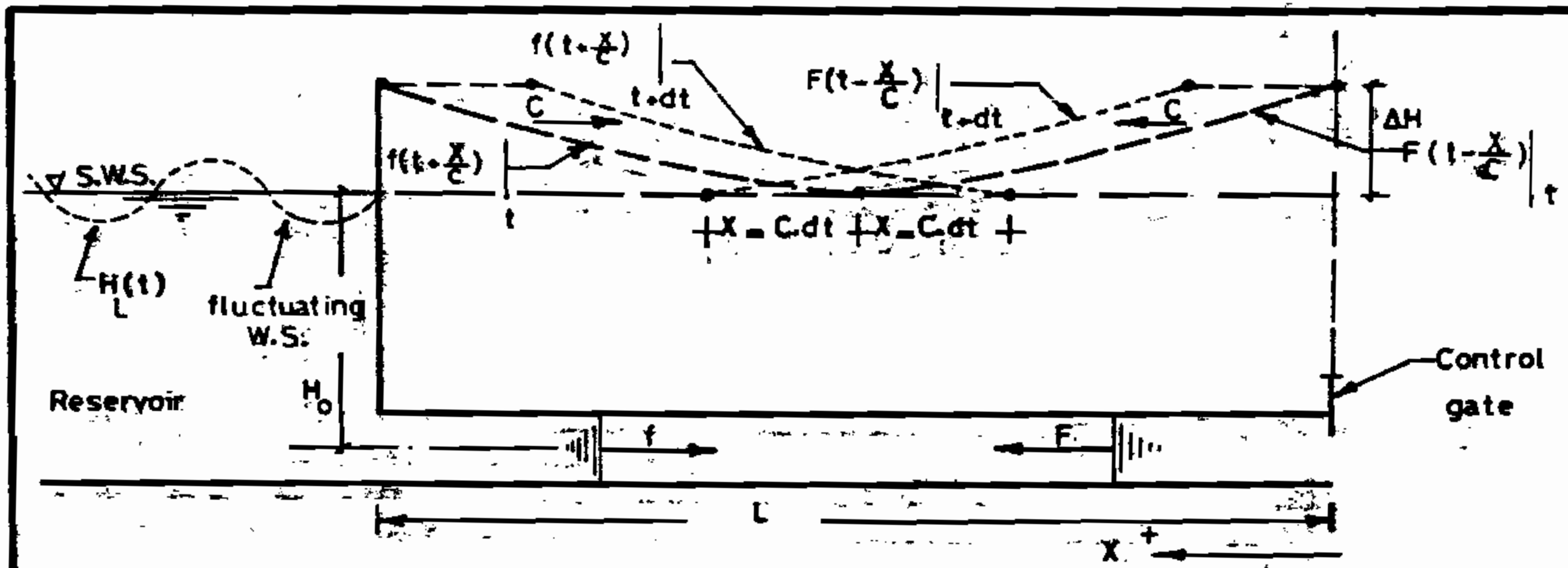


Fig.(2_a) Representation of "F" and "f" _type waves.

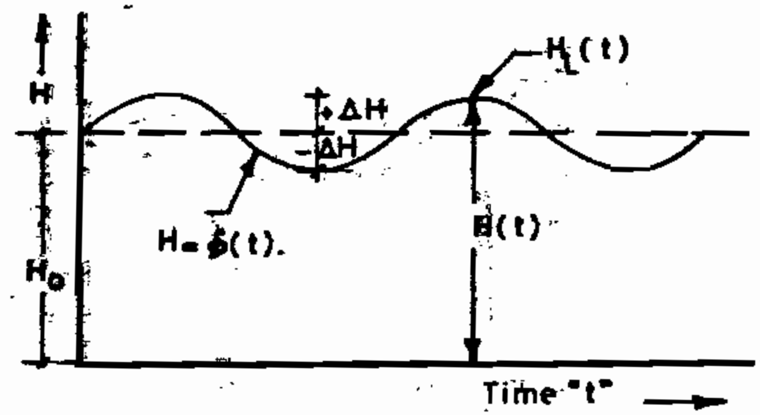


Fig. (2_b). Signal flow graph of a hypothetical fluctuating function.

pipe at the initial steady state condition,

H and V: are pressure head and velocity at transient condition,

x : the distance which is measured positive on the "X - direction", i.e. from the value along the pipe toward the reservoir,

t : the time meausred from the begining of value movement, and

C : the velocity of pressure wave

$$= \sqrt{(K/\rho) / (1 + \eta KD/Et')}, \text{ where}$$

K: the modulus of elasticity of water,

E: the modulus of elasticity of pipe walls,

ρ: the water density,

t': the pipe wall thickness, and

η: a coefficient (always less than unity) related to Poisson's ratio and the manner in which the pipe is fixed or held in place, considering both lateral and longitudinal deformations. "η" can be assumed unity on the safe side, other values are tabulated in references.

F : A Pressure wave travelling in the positive "X-direction", and

f : A Pressure wave travelling in the negative "X-direction".

Now, if the water level of the reservoir fluctuates; so, instead of having "H" in our first equations (1) and (2), $H_L(t)$ will replace H in which L is the total length of the pipe. "x" is an element of "L", and "H_L" for the new case becomes a function of time "t".

So, equations (1) and (2) will be as follows:

(i) <u>At x = L, i.e. at the reservoir:</u>

$$H_L(t) - H_o = F(t - \frac{L}{C}) + f(t + \frac{L}{C}), \text{ and } \ldots\ldots\ldots, \quad (3)$$

$$V - V_o = - \frac{g}{C} \; F(t - \frac{L}{C}) - f(t + \frac{L}{C}) \ldots\ldots\ldots \quad (4)$$

(1) At $x = 0$, i.e. at the gate :

$$H(t) - H_o = F(t) + f(t), \text{ and} \quad \ldots\ldots\ldots\ldots (5)$$

$$V - V_o = -\frac{g}{C}\left[F(t) - f(t) \right] \quad \ldots\ldots\ldots\ldots (6)$$

Putting (t - L) instead of (t) in equations (3) and (4) as f llows:

$$H_L(t - \frac{L}{C}) - H_o = F(t - \frac{2L}{C}) + f(t) \ \ldots\ldots \text{ or}$$

$$f(t) = H_L(t - \frac{L}{C}) - H_o - F(t - \frac{2L}{C}) \ldots\ldots\ldots\ldots (7)$$

Substituting from equation (7) into equations (5) and (6), hen:

$$H(t) - H_o = F(t) + H_L(t - \frac{L}{C}) - H_o - F(t - \frac{2L}{C}) .. \ (8)$$

$$V - V_o = -\frac{g}{C}\left[F(t) - H_L(t - \frac{L}{C}) + H_o + F(t - \frac{2L}{C}) \right] (9)$$

In general, at any point where x = x, equations (3) and (4) v ll be:

$$H(t) - H_o = F(t + \frac{x}{C}) + H_L(t - \frac{L}{C} + \frac{x}{C}) - H_o - F(t - \frac{2L}{C} + \frac{x}{C}) \ (10)$$

$$V - V_o = -\frac{g}{C}\left[F(t - \frac{x}{C}) - H_L(t - \frac{L}{C} + \frac{x}{C}) + H_o + F(t - \frac{2L}{C} + \frac{x}{C}) \right] (11)$$

According to the schematic sketch of Fig. (2) and assuming t at the relationship between the pressure head "H" and the time " " is represented in the following shifted sinusiodal equation:

$$H_L(t) = H_o + \Delta H. \ \sin(\pi t/2), \quad \text{then:}$$

t	secs. :	0	1	2	3	4	5 .., etc.	
H	m. :	H_o	$(H_o + \Delta H)$	H_o	$(H - \Delta H)$	H_o	$(H_o + \Delta H)$.., etc.	
H	m. :	100	110	100	90	100	110	.., etc.

.................., etc.

(f for Ex.: H_o = 100 and H = 10 m, say). (m:stands for equiva- l nt meters).

V. THE MODIFIED WATERHAMMER EQUATIONS FOR SUDDEN VALVE CLOSURE, ($t_c \leq 2L/C$), AT THE GATE.

(N.B.: t_c is the clusure time of valve or gate).

Equation (8) turns to:

$$H(t) - H_o = F(t) + H_L\left(t - \frac{L}{C}\right) - H_o \qquad \text{.........} (12)$$

Also, equation (9) turnsd to:

$$V - V_o = -\frac{g}{C}\left[F(t) - H_L\left(t - \frac{L}{C}\right) + H_o\right] \qquad \text{.........} (13)$$

Eliminating F(t), then;

$$H(t) - H_o = (C/g)(V_o - V) + 2\left[H_L\left(t - \frac{L}{C}\right) - H_o\right] \qquad ..(14)$$

Just for the sake of comparison, equations (1) and (2), where two equations at the gate and for $t_c \leq 2L/C$, and since there is no time to have the "f" reflected toward the value yet,

then:

$$f\left(t + \frac{x}{C}\right) = 0$$

Consequently, the sudden rise in pressure and corresponding velocity in the pipe adjacent to the gate at the instant of gate closure will have the following modified equations derived from equations (1) and (2):

$$H - H_o = F\left(t - \frac{x}{C}\right); \qquad \text{...........} (15)$$

$$V - V_o = -\frac{g}{C}\left[F\left(t - \frac{x}{C}\right)\right] \qquad \text{...........} (16)$$

Solving the above two equations (15) & (16) in $(H - H_o)$, we get:

$$H - H_o = -\frac{C}{g}(V - V_o) = \frac{C}{g}(V_o - V), \qquad \text{...........} (17)$$

$$\text{or} \quad \Delta H = \frac{C}{g}(\Delta V), \qquad \text{...........} (18)$$

In which " ΔV" is the change in velocity of water at the gate at the instant the gate movement is completed due to a change in pressure equivalent to " ΔH". Keeping in mind that they have positive sign for the closing case, as $V_o > V$, and negative sign for the suddenly opening case.

Then, comparing equations (17) or (18) with equation (14), we deduce that: because of the fluctuation of the water in the reservoir, the pressure change at x = o (at the gate), at any time "t" is larger by TWICE the change of pressure at time (L/C) before an elapsed time "t", i.e. at time $(t - \frac{L}{C})$. This is compared with the pressure change when the water level in the reservoir is always constant during the gate movement, i.e.:

$$\Delta H \Big|_{\substack{t=0 \rightarrow \\ t=t}} = \frac{C}{g} \cdot \Delta V \Big|_{\substack{t=0 \rightarrow \\ t=t}} + 2 \; \Delta H \Big|_{\substack{t=0 \rightarrow \\ t=t-\frac{L}{C}}} \quad \ldots\ldots\ldots (19)$$

For complete closure of the valve and if $V = o$ at $t = t_c$, equation (14) will be:

$$H(t_c) - H_o = (C\,V_o/g) + 2\left[H_L(t_c - \frac{L}{C}) - H_o\right] \quad \ldots\ldots\ldots (20)$$

$$\text{or:}\;\Delta H \Big|_{\substack{t=0 \rightarrow \\ t=t_c}} = (C.V_o/g) + 2\,\Delta H \Big|_{\substack{t=0 \rightarrow \\ t=t_c - \frac{L}{C}}} \quad \ldots\ldots\ldots (21)$$

One can notice that equations (14) and (20) are for the limiting conditions, and at x = o, while during the operating time of the gate, i.e. when $0 < t < t_c$, equations (14) and (20) can be arranged as follows:

Let "A_g" be the gate opening at any instant, and "A" be the full sectional area of the pipe. "A" is assumed constant for convenience. Now, if "C_d" is the coefficient of discharge through the gate for any optional opening; then, the orifice equation becomes in its general form as follows:

$$V = C_d . (\frac{A_k}{A}) . \sqrt{2 g H} = C_d . \lambda \sqrt{2g H} \qquad \ldots\ldots\ldots\ldots (22)$$

Then, substituting by the value of "V" in equations (14) and (20) from equation (22), one can get the following expression:

$$H (t) - H_o = (\frac{C}{g})(V_o - C_d . \lambda . \sqrt{2g H}) + 2 \left[H_L(t - \frac{L}{C}) - H_o \right] \quad (23)$$

The above equation can be simplified and rearranged such that we can put "H" in terms of the other terms to become:

$$H^2(t) - \left[H_o + (\frac{CV_o}{g}) + (C^2 . C_d^2 . \lambda^2/g) + 2 \left\{ H_L(t - \frac{L}{C}) - H_o \right\} \right] . 2H(t)$$
$$+ \left[H_o + (C.V_o/g) + 2 \left\{ H_L(t - \frac{L}{C}) - H_o \right\} \right]^2 = 0$$

Solving for H at time t, (H(t)), one can get:

$$H(t) = \left[H_o + (C.V_o/g) + (C^2.C_d^2 . \lambda /g) + 2 \left\{ H_L(t - \frac{L}{C}) - H_o \right\} \right]$$
$$\pm ½ \left[\left[H_o + (C.V_o/g) + C^2.C_d^2 . \lambda/g) + 2 \left\{ H_L(t - \frac{L}{C}) - H_o \right\} \right]^2 \right.$$
$$\left. -4 \left[H_o + (C.V_o/g) + 2 \left\{ H_L(t - \frac{L}{C}) - H_o \right\} \right]^2 \right]^{½} \qquad \ldots\ldots (24)$$

But from equations (14) and (20), we found that:

$$H(t) \text{ is } \not> \left[H_o + (C.V/g) + 2 \left\{ H_L(t - \frac{L}{C}) - H_o \right\} \right],$$

then:

$$H(t) = \left[H_o + (C.V_o/g) + (C^2.C_d^2 . \lambda/g) + 2 \left\{ H_L(t - \frac{L}{C}) - H_o \right\} \right]$$
$$- ½ \left[\left[H_o + (C.V_o/g) + (C^2.C_d^2 . \lambda /g) + 2 \left\{ H_L(t - \frac{L}{C}) - H_o \right\} \right]^2 \right.$$
$$\left. - 4 \left[H_o + (C.V_o/g) + 2 \left\{ H_o(t - \frac{L}{C}) - H_o \right\} \right]^2 \right]^{½} \qquad \ldots\ldots (25)$$

By using the above equation, (25), we can solve the pressure head "H" at the gate at any location at any time interval, in terms of:

$$H_o,\ H(t - \frac{L}{C}),\ V_o \text{ for given } C,\ C_d,\ A_g,\ A \text{ and } g.$$

I. WATERHAMMER EQUATIONS FOR GRADUAL OR THE SO CALLED SLOW GATE MOVEMENTS ($t > 2L/C$):

Such a problem can be treated as follows:

Case A: During the time "t" where ($0 < t \leq 2L/C$):

The procedure will be just similar to the previous case, where both the pressure and the velocity can be obtained at any time $t \leq 2L/C$. For instance, substituting for t=1.0 sec. (assuming 1.0 sec. is less than 2L/C), the pressure at the valve will be:

$$H(1) = \left[H_o + (C.V_o/g) + (C^2.C_d^2.\ \lambda^2/g) + 2\left\{ H(t_1 - \frac{L}{C}) - H_o \right\} \right] - \tfrac{1}{2} \left[\left[\left\{ H_o + (C.V_o/g) + C^2 C_d^2.\ \lambda^2 + 2\ \ H(t_1 - \frac{L}{C}) - H_o \right\} \right]^2 - 4 \left[H_o + (C.V_o/g) + 2\left\{ H_o(t_1 - \frac{L}{C}) - H_o \right\} \right]^2 \right]\right]^{\frac{1}{2}},$$

$$\text{........}(t_1 = 1.0 \text{ sec.})$$

In case if (L/C = 1.0 Sec.), then:

$$H(1) = \left[H_o + (C.V_o/g) + (C^2.C_d^2.\ \lambda/g \right] - \tfrac{1}{2} \left[\left[H_o + (C.V_o/g) + C^2.C_d^2.\ \lambda/g \right\}^2 - 4\left\{ H_o + (C.V_o/g) \right\}^2 \right]\right]^{\frac{1}{2}}$$

$$\text{............}(26)$$

Case (B): During the period ($0 < t > L/C$)

The procedure for such a case can be accomplished by putting case (A), discussed previously, in the form:

$(i-1)(2L/C) < t < i(2L/C)$, in which "i" can be any integer number equivalent to the number of turns, say, taking each turn = 2L/C.

Now, let "t" be expressed as:

$t = t_{i-1} + (2L/C)$.

Then introducing "i" in equation (8), then:

$$H_i - H_o = F(t_i) - F(t_i - 2\frac{L}{C}) + H_L(t_i - \frac{L}{C}) - H_o \quad \ldots\ldots (27)$$

(noticing that "i" will be = 1.0 if t = 2L/C, this can be obviously verified).

Again, applying equation (27) for sucessive "i" s, we get the following:

<u>For "i" = 1</u>: $H_1 - H_o = F(t_1) - F_1(t_1 - 2\frac{L}{C}) + H_L(t_1 - \frac{L}{C}) - H_o$

$= F(t_1) - F(0) + H_L(t_1 - \frac{L}{C}) - H_o$

Then: $H_1 - H_o = F(t_1) + H_L(t_1 - \frac{L}{C}) - H_o$

<u>For "i" = 2</u>: $H_2 - H_o = F(t_2) - F(t_2 - 2\frac{L}{C}) + H_L(t_2 - \frac{L}{C}) - H_o$

<u>For "i" = 3</u>: $H_3 - H_o = F(t_3) - F(t_3 - 2\frac{L}{C}) + H_L(t_3 - \frac{L}{C}) - H_o$

................, etc.

$$H_{(i-1)} - H_o = F(T_{(i-1)}) - F(t_{(i-1)} - 2\frac{L}{C}) + H_L(t_{(i-1)} - \frac{L}{C}) - H_o$$

$$H_i - H_o = F(t_i) - F(t_i - 2\frac{L}{C}) + H_L(t_i - \frac{L}{C}) - H_o$$

(N.B.: $t_1 - 2\frac{L}{C} = t_o = 0$, $t_2 - 2\frac{L}{C} = t_1$, $t_3 - 2\frac{L}{C} = t_2$, ..., etc)

In addition to the above, we deduce that:

$$H_1 + H_2 + H_3 + \ldots\ldots\ldots + H_i = F(t_i) + \sum_{i=1}^{i=i} H_L(t_i - \frac{L}{C})$$

or $$\sum_{i=1}^{i=i} H_i = F(t_i) + \sum_{i=1}^{i=i} H_L(t_i - \frac{L}{C}) \quad \ldots\ldots\ldots (28)$$

Similarly, for the velocity, using equation (9), one can get:

$$V_i - V_o = -\frac{g}{C}\left[F(t_i) - H_L(t_i - \frac{L}{C}) + H_o + F(t_i - 2\frac{L}{C})\right] \quad \ldots.(29)$$

or $$F(t_i) = -\frac{C}{g}(V_i - V_o) - F(t_i - 2\frac{L}{C}) + H_L(t_i - \frac{L}{C}) - H_o \quad \ldots.(30)$$

Then substituting for $F(t_i)$ of equation (30) into equation (27), one can get:

$$H_i - H_o = +\frac{C}{g}(V_o - V_i) - 2F(t_i - 2\frac{L}{C}) + 2\left[H_L(t_i - \frac{L}{C}) - H_o\right] \ldots.(31)$$

Equation (31) can be simplified by solving with equation (28) to get:

$$F(t_i - 2\frac{L}{C}) = H_1 + H_2 + H_3 + \ldots\ldots\ldots + H(t_i - 2\frac{L}{C}) - \sum_{i=1}^{i=i} H_L(t_i - \frac{L}{C}) - \ldots\ldots\ldots\ldots (32)$$

Thus, using equation (31) and in a similar manner, one can get:

$$H_i - H_o = +\frac{C}{g}(V_o - V_i) - 2\left[H_1 + H_2 + H_3 + \ldots\ldots\ldots + H(t - 2\frac{L}{C}) - \sum_{i=1}^{i=i} H_L(t_i - \frac{L}{C}) + H_L(t_i - \frac{L}{C}) - H_o\right] \ldots\ldots\ldots\ldots (33)$$

or, finally,

$$H_i - H_o = +\frac{C}{g}(V_o - V_i) - 2\sum_{i=1}^{i=i}(H_i - H_o) + 2\sum_{i=1}^{i=i}\left[H_L(t - \frac{L}{C}) - H_o\right] \ldots\ldots\ldots\ldots (34)$$

From all the above expressions, equation (29) presents a solution for the velocity, and equation (31) present a solution for the pressure. Also, equation (34) gives a solution for both the pressure and the velocity at any of the time intervals "t_i". The solutions of these equations and the analytical evaluation of the variables involved can be readily carried out by using computer operational system.

VII. CONCLUSIONS:

Solution of vast variety of waterhammer problems becomes vitally important covering the fluctuating cases which showed great extent of applications. The presented research paper showed definite solutions for the waterhammer analysis in both the sudden closure and slower gate movement while water in the supplying reservoir is fluctuating matching any sort of sinusoidal function according to any cause.

In order to solve for both the pressure and the velocity at any location for any selected time interval, the presented equations are capable to do the job taking into consideration the boundary conditions for the identified case.

Moreover, the necessity of using computer facilities becomes essential to easy up the solution. Either the method of characteristics or the impedance method is suggested as an analytical procedure in this regard. Computer techniques become very handy and greatly needed especially when the situation gets complicated or in cases of having an existing complex waterhammer problem.

Rearrranging the above presented equations in terms of the variation in both pressure and velocity at definite time intervals, graphical analysis can be done too, taking into consideration the gate's movement equation. Eventhough, combining both procedures will be profitable and very fruitful.

In addition, the presented analysis showed that pipes experiencing ring tension stresses due to the sudden rise of positive pressure during the suddenlygate closure movement. While on the other hand, pipe wall are experiencing sudden ring compression due to rapid opening case.

The worst case for pipe wall stresses is that if closing and opening operations happen in series. As a result, the pipe

... in this case will be subjected to a severe fatigue stresses.

It is recommended to construct all pipes expected to experience waterhammer failure of material that withstand such internal dynamic stresses, besides providing all sort of precautions to lessen the effect of extra pressure and absorb excess strains or any means of releasing surplus pressures.

VIII. BIBLIOGRAPHY:

1. Alleivi, L.: "Theory of Water-Hammer", translated by E.F Hamos, published by Richardo Gaoni, Rome, Italy, 1925.
2. Allievi, L.: "Air Chambers for Discharge Pipes", Trans. A.S. M.E., Vol. 59, paper: Hyd. 59-7, Nov. 1937(P. 651-659).
3. Angus, R.W.: "Water-Hammer in pipes, Including Those Supplied by Centrifugal Pumps; Graphical Treatment", Proc. Institute of Mechanical Engineers, Vol. 136, 1937 (P. 245).
4. Angus, R.W.: "Water-Hammer Pressures in compound and Branched Pipes", Proc. A.S.C.E., January 1938 (P.133-169) or Trans., A.S.C.E., Vol. 104, 1939 (P. 340).
5. Bergeron, L.: "Waterhammer in Hydraulics and Wave Surges In Electricity", John Wiley and Sons, N.Y. & London, 1961.
6. Binnie, A.M.: "The Effect of Friction on Surges in Long Pipelines", Quarterly Journal of Mechanics and Applied Mathematics, Vol. IV., Pt. 3, 1951(P. 330-343).
7. Cazard, R.: "Fatigue of Materials", translated by Fenner, A.J., Philosophical Library, Inc., 1953.
8. Crawford, C.C.: "Cuives for the Quick Estimation of Transient Hydraulic Conditions Following Failure of Electric Power to a Pumping plant", Thesis for M.S. Degree, Univ. of Colorado, 1948.
9. "Damped Vibrations", University of Oregon Publication, Vol. 2., No.2, Aug. 1923.

10. Dawson, F.M. and A.A. Kalinske: "Methods of calculating Water-Hammer Pressures", Journal of American Water Works Assoc., Vol. 31, No.11, Nov. 1939(P. 1835).

11. Durand, W.F.: "Hydraulios of Pipe Lines", D.Van Nostrand Co., Inc., N.Y., U.S.A., 1921.

12. Freerman, John R.: "Flow of Water in Pipes and pipe Fittings", published by A.S.M.E., 1941.

13. Jacobson, R.S.: "Charts for Analysis of Surge Tanks in Turbine or pump installations", Sepecial Report 10[illegible], Bureau of Reclamation, Denver, Colorado, Feb., 1952.

14. Jaeger, C.: "Theory of Resonance in Pressure Conduits", Trans., Vol. 61, Feb. 1939 (P. 109 - 115).

15. Jaeger, C.: "Waterhammer Effects in Power Conduits", Civil Engineering and public Works Review, 1948.

16. Joukowsky, N.: "Water-Hammer", translated by Miss. O.Simin, Proc. American Water Works Assoc., Vol. 24, 1904.

17. Kessler, L.H.: "Speed of Waterhammer Pressure Waves in Transite Pipe", Trans. A.S.M.E., Vol. 61 Jan. 1939 (P. 11-15).

18. King, H.W. and E.F. Brater: "Handbook of Hydraulics", Fifth edition, McGraw-Hill Book Co., U.S.A., (P. 11-13 to 11-24), 1963.

19. Le Conte, J.N.: "Experiments and Calculations on the Resurge Phase of Waterhammer", Trans. A.S.M.E., Vol. 59 paper: Hyd. 59-12, Nov. 1937(P. 691-694.)

20. Lister, M. and L. Roberts: "On the Numerical Solutions of Spherical Waves of Finite Amplitude", Technical Report on the Project of Machine Method of Compulation, M.I.T. Proj. Dio. 6915, June 1956.

21. McNown, J.S.: "Surges and Waterhammer," in Engineering Hydraulics", edited by H. Rouse, Hohn Wiley and Sons, Inc., New York, U.S.A., 1950.

22. Merritt, H.E.: "Hydraulic Control Systems", John Wiley & Sons Inc., N.Y., U.S.A., 1967.

23. Moody, Lewis F.: "Simplified Deriviation of Water-Hammer Formula", Symposium on Water-Hammer, A.S.M.E., U.S.A., 1933 (P. 25-28).

24. Owais, Talaat M.: "Studies in Waterhammer Analysis", Tech. Rep., J. 64, C.E. Dept., Univ. of N. Mex., U.S.A.,1964.

25. Owais, Talaat M.: "Annotated Bibliography on Hydraulic Transient", SP. Conf. Rep., F. 66, C.E. Dept. and Utah Water Resource Research Lab., U.S.U., Logan, Utah, U.S.A., 1965.

26. Parmakian, John: "Waterhammer Analysis", Prentice Hall, New York, 1955.

27. Rich, George R.: "Water-Hammer Analysis by Laplace-Mellin Transformation", Trans. A.S.M.E., 1945.

28. Rich, George R.: "Hydraulic Transients", McGraw Book Co., Inc., 1951.

29. Rouleau, W.T.: "Pressure Surges in Pipelines Carrying Viscous Liquids", Journal of Basic Engineering A.S.M.E., December, 1960.

30. Rouse, Hunter: "Elementary Mechanics of Fluids", John Wiley and Sons, Inc., 1953.

31. Streeter, Victor L.: "Friction Resistance in Artifitially Roughened Pipes", Trans. A.S.C.E., Vol. 101, 1936 (P. 681-713).

32. Streeter, V.L.: "Fluid Mechanics", McGraw-Hill Book Co., Inc., 1963 (P. 352-374).

33. Streeter, V.L. and E.B. Wylie: "Hydraulic Transients", McGraw-Hill Book Co., Inc., N.Y. U.S.A., 1967.

34. "Symposium on Waterhammer," A.S.M.E. and A.S.C.E., 1933.

35. Wood, F.M.: "The Application of Heavisides Operational Calculus to the Solutions of Problems in Water-Hammer", Trans. A.S.M.E., Vol. 59, paper: Hyd. 59-15, Nov. 1937, (P. 707-713).