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# Maximum Water Hammer Sensitivity Analysis

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***Abstract*****—**Pressure waves and Water Hammer occur in a pumping system when valves are closed or opened suddenly or in the case of sudden failure of pumps. Determination of maximum water hammer is considered one of the most important technical and economical items of which engineers and designers of pumping stations and conveyance pipelines should take care. Hammer Software is a recent application used to simulate water hammer. The present study focuses on determining significance of each input parameter of the application relative to the maximum amount of water hammer estimated by the software. The study determines estimated maximum water hammer variations due to variations of input parameters including water temperature, pipe type, thickness and diameter, electromotor rpm and power, and moment of inertia of electromotor and pump. In our study, Kuhrang Pumping Station was modeled using WaterGEMS Software. The pumping station is characterized by total discharge of 200 liters per second, dynamic height of 194 meters and 1.5 kilometers of steel conveyance pipeline and transports water to Cheshme Morvarid for farmland irrigation. The model was run in steady hydraulic condition and transferred to Hammer Software. Then, the model was run in several unsteady hydraulic conditions and sensitivity of maximum water hammer to each input parameter was calculated. It is shown that parameters to which maximum water hammer is most sensitive are moment of inertia of pump and electromotor, diameter, type and thickness of pipe and water temperature, respectively.

***Keywords*****—**Pressure Wave, Water Hammer, Sensitivity Analysis, Hammer Software, Kuhrang, Cheshme Morvarid

## I. Introduction

PIPES installed in water distribution and conveyance networks, irrigation systems, hydroelectric power plants, nuclear power plants and industrial facilities are required for reliable, safe and economic conveyance. Fluid velocity variations cause pressure variations. Sudden failure of a pump or closing a valve causes fluid waves of translation which in turn may cause significant pressure variations, creation of local gaps, extensive cavitation, structural shakes and mass vibrations [1].

Cukier studies nonlinear sensitivity analysis of multivariate models [2]. Saltelli et al. (1999) proposed model-based quantification of output sensitivity analysis [3]. an International Meeting in the U.S. (2000), Glaeser offered uncertainty evaluation results of a hydraulic system [4]. Saltelli et al. (2002) studied the best possible application of model evaluations for estimation of sensitivity levels and proposed an approach to do so [5]. Using UMSICHT model, Kaliatka et al. applied uncertainty and sensitivity analysis to water hammer phenomenon [6] and calculated uncertainty and sensitivity level of parameters affecting pressure waves [7]. Kaliatka et al. (2009) studied water hammer model's sensitivity using a new approach called FAST and offered the results of their study [8].

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Many various codes and applications are developed to calculate or simulate water hammer, including but not limited to: TREMOLO, HiTran, AFT Impulse, Surge, TRACE,CATHARE,ATHLET,TRAC, FLOWMASTER, RELAP5 and Hammer.

In the present study, we take advantage of Hammer7. Hammer is a powerful application which helps designers analyze waves of translation in the pipeline and complicated pumping systems. It is developed by Environmental Hydraulic Group Inc. (EHG) in cooperation with water hammer experts and followed a long term cooperation of EHG with Bentley Company. Hydraulic translations in a period ranging from a few seconds to a few minutes may damage the system or cause application failures. The name Hammer is taken from loud noise of impact which may be heard when waves of translation occur. The software helps engineers achieve appropriate designs and develop economic surge control systems for pipeline and pumping systems [9].

## II. Capabilities of Hammer Software

The software uses an advanced graphic interface through which a pipeline system, storage facilities, pumps and wave control facilities may be easily and rapidly designed. The software is equipped with flexible tables and predefined libraries which allow for quick copy of model's parameters. The user may import data and results associated with other models to the application. This method not only saves times but also reduces likelihood of mistakes which may occur while copying date to the software. Using Hammer software, the user may analyze waves of translation and:

- Reduce the risk of damages associated with water hammer, and consequently increase safety and reduce failure rate.
- Reduce wearing and tearing effects of water hammer in pumping and pipeline systems, and increase lifetime of the infrastructure.
- Reduce the risk of water pollution in the case of pressures less than an atmosphere where there is the risk of underground water suction and transfer of pollution to pipeline system.
- Reduce the frequency and severity of translational pressure shocks (translational pressures and forces may cause loose junctions, growth of cracks, increasing leakage).

Therefore, water industry's risk management plan should address hydraulic translations and wave protections needs [9].

## III. Investigation Questions

In order to analyze unsteady waves in water conveyance systems, we use elastic properties of pipelines and the fluid in our calculations. Such features are closely associated with pressure variations and pressure waves' propagation velocity. Hammer Software used the Method of Characteristic to solve nonlinear differential equations. Then, boundary conditions should be specified.

In order to solve momentum and continuity equations, the software presumes a combination of following conditions:

- The fluid is homogeneous.
- Elasticity of pipeline and fluid follows a linear pattern.
- The flow is unidimensional and fluid is incompressible.

Moreover, the software uses average velocity [9].

## IV. Method of Experiment

In present paper, using Hammer Software, we examine significance of each parameter affecting maximum water hammer in the context of the project. Once significance of each input parameter is determined, in the course of pumping station and pipeline system development, engineers and designers may devote a better part of their time to more important parameters. Water hammer varies with various factors. Altitude difference between pumping station and delivery point, as well as the path and the length of conveyance pipeline are among the factors which affect water hammer. Of course, abovementioned factors follow topographic features of the location and consequently the designer may have no control over them. However, some factors such as diameter, thickness and type of the pipe as well as pump and electromotor features may be appropriately tailored by the designer so as to shrink maximum water hammer to its lowest possible level. In the present paper, we try to establish significance of each factor relative to maximum water hammer in order to enable designers to lower risk in pumping stations and pipeline systems. Our study examines maximum water hammer in the context of Kuhrang Pumping Station which supplies water to Cheshme Morvarid. Length of pipeline system is 1,517 meters. Starting point of pipeline system is Kuhrang River with an altitude of 2,334 meters. Altitude of delivery storage tank is 2,502 meters. The pumping station takes advantage of two pumps. Diameter, type and thickness of pipeline as well as discharge rate follow a uniform pattern throughout the pipeline system.

The plan of conveyance pipeline is shown in Figure 1. Technical details and working point of the system are provided in Table 1 and Table 2, respectively.

TABLE I
TECHNICAL DETAILS OF CONVEYANCE PIPELINE

| Pipe | Length (m) | Diameter (mm) | Junction | Elevation (m) | pressure (m H2O) |
|---|---|---|---|---|---|
| P-1 | 81.5 | 400 | J1 | 2335.0 | 194 |
| P-2 | 103.8 | 400 | J2 | 2353.0 | 175.3 |
| P-3 | 143.0 | 400 | J3 | 2370.8 | 156.7 |
| P-4 | 331.0 | 400 | J4 | 2389.0 | 137.2 |
| P-5 | 315.0 | 400 | J5 | 2401.8 | 121.7 |
| P-6 | 308.3 | 400 | J6 | 2442.2 | 78.6 |
| P-7 | 241.4 | 400 | J7 | 2487.0 | 31.3 |
| | | | Tank | 2502.0 | 13 |

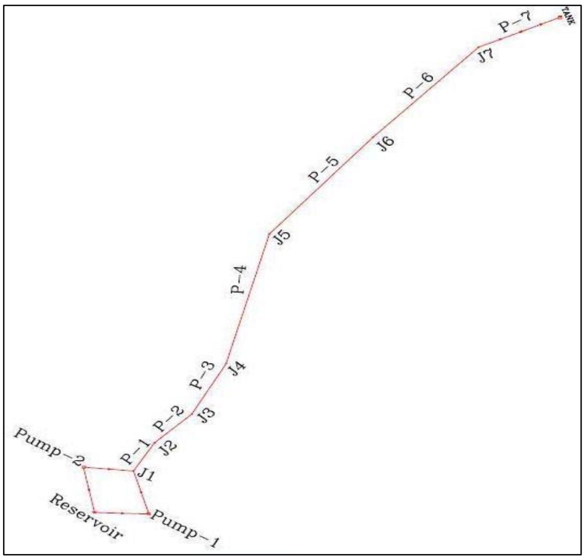


Fig. 1 Pumping Station Plan and Conveyance Pipeline Path in WaterGEMS Software

TABLE II
WORKING POINT OF THE SYSTEM WITH TWO PUMPS WORKING.

| Description | |
|---|---|
| Discharge (lit/s) | 208 |
| Pressure (Meters of Water Column) | 194 |
| Power (kw) | 350 |
| Moment of Inertia of the Pump and Electromotor (Newton/sq meters) | 100 |
| Efficiency (percent) | 78 |

Given conveyance pipeline's features including diameter, thickness and type of the pipe, altitude difference, pump type and its characteristic curve, we used Water GEMS Software for hydraulic simulation of the pipeline in steady state. Then, we ensured that simulation results were consistent with relevant standards in terms of velocity and pressure. For hydraulic simulation of conveyance pipeline in unsteady condition and examination of maximum water hammer due to switching off the pumps, we modeled pumping station and conveyance pipeline in Hammer Software. Results of running the model for various conditions of interest (i.e. by varying input parameters such as diameter of the pipe or moment of inertia) are provided in the form of tables and graphs. We analyze the results through comparing graphs.

Input parameters of the software are: diameter, thickness and elastic modulus of the pipe, moment of inertia of pump and electromotor, running time, temperature, density and elastic modulus of water and wave velocity.

Pipe diameter, temperature, water density, moment of inertia and running time are directly inserted in the application. With power and rpm being 350 kw and 1,450 rpm, respectively, moment of inertia of pump and electromotor are calculated through experimental expressions. Running time was equal for all various conditions. Wave velocity is calculated through following equation [9]:

$$a = \sqrt{\frac{(k/\rho)}{\frac{k}{E}\frac{D}{e}(1-\mu^2)}} \qquad (1)$$

where $D$ is pipe diameter, $e$ is pipe thickness, $\rho$ is density of water, $E$ is elastic modulus of the pipe, $k$ is the elastic modulus of the water, $\mu$ is Poisson ratio and $a$ is wave velocity in m/s.

Typical technical details of the project are as follows:

- Steel pipe thickness: 7 mm
- Pipe diameter: 400 mm
- Temperature: 15 degrees Celsius
- Moment of Inertia of pump and electromotor: 110 $N.m^2$

In above context, maximum water hammer is equal to 214 meters of water column (equal to an elevation of 2,729 meters). The experiments were carried out in 5 parts as follows.

*1. Examining variation of maximum water hammer due to pipe diameter*

Pipe diameter is amongst parameters which affect velocity and pressure caused by water hammer event. In fact, pipe diameter affects flow velocity as well as direct and reflection pressure wave velocities, especially in pump-pipeline junction which is considered most critical point of conveyance pipeline system [10].

To investigate the effect of pipe diameter on maximum water hammer, we chose 4 different diameter values (300, 400, 500 and 600 mm). With other parameters kept constant, results are shown in Figure 2. It's seen that maximum water hammer linearly decreases with increasing diameter. In the context of the project, 100 mm increase in pipe diameter causes a decrease of about 74 meters of water column in maximum water hammer. Therefore, it is recommended to increase pipe diameter in order to reduce maximum water hammer. Even though this may increase initial costs of the project, it not only eliminates the need for Water Hammer Arrestors in pumping stations but also reduces future maintenance risks and costs.

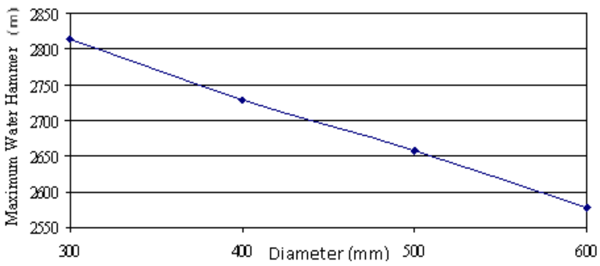


Fig. 2 Variation of Maximum Water Hammer with Pipe Diameter

*2. Examining variation of maximum water hammer due to pipe thickness*

According to Equation (1), wave velocity increases with pipe thickness. To investigate the effect of pipe thickness on maximum water hammer, we chose 5 different thickness values (6, 7, 8, 9 and 10 mm). With other parameters kept constant, results are shown in Figure 3. It's seen that in average, for one millimeter increase in pipe thickness, maximum water hammer increases by 3 meter of water column.

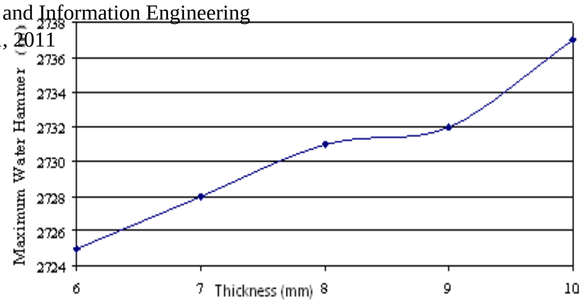


Fig. 3 Variation of Maximum Water Hammer with Pipe Thickness

*3. Examining variation of maximum water hammer due to moment of inertia*

To investigate the effect of moment of inertia on maximum water hammer, we chose 7 different levels of moment of inertia (100, 150, 200, 250, 300, 350 and 400 N.m2). Results are shown in Figure 4.

According to Figure 4, when the initial moment of inertia is doubled to 200 N.m2, maximum water hammer decreases by 100 meters of water column. After that point, maximum water hammer doesn't decrease significantly.

Therefore, increasing the moment of inertia may decrease maximum water hammer. It's most significant effect is on first negative wave and then on the positive wave. Various authors recommend using flywheel for pipelines less than 3 kms, which is justified for our project. Compared to other water hammer Protective Equipments, flywheel is less costly and occupies much less space in pumping stations [11].

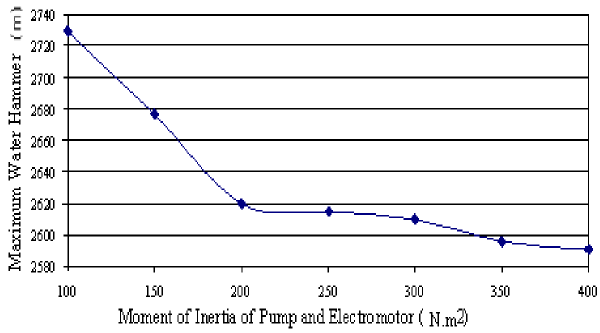


Fig. 4 Variation of Maximum Water Hammer with Moment of Inertia of Pump and Electromotor

*4. Examining variation of maximum water hammer due to temperature*

To investigate the effect of temperature on maximum water hammer, we chose 5 different temperatures (4, 10, 15, 20 and 25 degrees Celsius). Temperature affects water density and pressure of water steam. Hence, once the temperature is set in the software, water density and pressure of water steam are calculated [9].

According to fluid mechanics, elastic modulus of water ($k$) increases with temperature and water density ($\rho$) decreases with increasing temperature. These parameters in turn affect wave velocity an increase it. For 5 degrees Celsius increase in temperature, wave velocity increases by about 8 m/s. By applying this estimation to the model, it's seen that maximum water hammer increases by about 2 meters of water column. Results are shown in Figure 5.

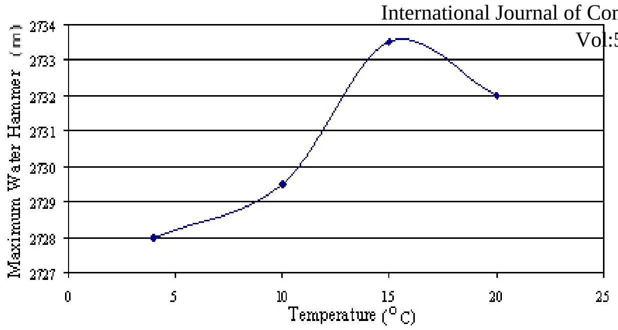

Fig. 5 Variation of Maximum Water Hammer with Temperature

*5. Examining variation of maximum water hammer due to pipe type*

Given above 20 atmosphere pressure of the pumping system, two pipe types, namely steel and GRP (Glass Reinforces Pipe) were compared in terms of their respective effects on maximum water hammer. In Equation (1), elastic modulus of the pipe ($E$) and Poisson ratio ($\mu$) depend on pipe type. As for the steel pipe, elastic modulus and Poisson ratio are $2.07\times10^{11}\ Pa$ and $0.3$, respectively. As for the GRP, elastic modulus and Poisson ratio are $5\times10^{10}\ Pa$ and $0.25$, respectively [2]. With similar conditions for pumping station and conveyance pipeline, wave velocity in steel and GRP pipes is 1,167 and 620 m/s, respectively. Importing these parameters in Hammer Software, maximum water hammer for steel and GRP pipes is calculated at 2,725 and 2,650 meters of column water, respectively. Therefore, given economical considerations of the project, GRP pipe is more effective in reducing maximum water hammer.

## V. Conclusions and Suggestions

According to present study which was aimed at investigation the effect of parameters such as pipe diameter, thickness and type, moment of inertia and temperature on maximum water hammer in the context of Kuhrang Pumping Station, we conclude that:

1. With each 100 mm increase in pipe diameter, maximum water hammer is reduced by 74 meters of water column.
2. Given similar circumstances, maximum water hammer reduction due to use of GRP pipe is 74 meters of water column more than that of steel pipe.
3. With each 1 mm increase in pipe thickness, maximum water hammer is reduced by 3 meters of water column.
4. Doubling moment of inertia to 200 N.m2 will reduce maximum water hammer by about 100 meters of water column (note that total water hammer is about 214 meters of water column). This is carried out through using flywheel. If the moment of inertia is doubled again to 400 N.m2, maximum water hammer reduction will be about 15 meter of water column.
5. With each 5 degrees Celsius increase in temperature, maximum water hammer is reduced by about 2 meters of water column.

In conclusion, given economical considerations of the project, parameters which are most effective in terms of maximum water hammer reduction are moment of inertia of pump and electromotor, diameter, type and thickness of pipe and water temperature, respectively.

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