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Effectivity of Surge Tank Design to Control Water Hammer Effect in Hydro-Electric Power Plant

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***Abstract*—** *Water hammer is a phenomenon that happens in closed conduits when the water velocity and flow changes because of the sudden closed. This phenomenon can cause the bursting of pipe by the very high fluidal pressure. The cases of bursting pipe often happen on the long dimensional pipes such as penstock that distributes water from reservoir to the power house in hydroelectric power plants system. To reduce the water hammer effect in the penstock, surge tank is used as an energy reducer. Surge tank would be used as a physical model to simulate hydraulic condition. The observation comprises of water level and mass oscillation in surge tank after the valve is closed rapidly. Fluctuation of mass oscillation in surge tank is temporary until the water level reaches its steady state level. In this research, two variations of surge tank diameters and three different length of penstock pipes are being observed. The parameters of this research are water level in the surge tank and the wave travel time to reach steady state flow when water hammer phenomenon occurs. The rise of pressure head and oscillation time are computed using Minitab.*

***Keywords*—** *Hydro-electric power plant, mass oscillation, steady state flow, surge tank, water hammer.*

I. INTRODUCTION

System flow control is an integrated part of water pipeline system operation[1]. In a normal operation, the closing of the valve at the end of pipeline system is controlled slowly and gradually. However, a failure in power cable system, short circuit, and water flow demand can change the water velocity in the closed conduit. This condition alters to hydraulic transient or water hammer phenomenon. The water hammer phenomenon is the pressure waves that generate, propagate, and reflect in the penstock by the sudden changes or adjustments in the momentum of fluid condition[2].

When the water hammer phenomenon occurs, the energy of pressure wave will change from kinetic energy to the potential energy of the fluid and pipe material. Water hammer effect can destroy turbo machines and lead to pipes and penstocks failure[3]. Penstock and closed conduit in hydropower plant experience hydraulic transient and water hammer phenomenon regularly. Therefore, designing the length of penstock is considered effective and efficient.

The effects of water hammer can be avoided by designing and operating the system to minimize water velocity. There are some causes that can alter the water hammer phenomenon, such as pipeline profile, pipe's length, pipe's material and dimension, and the type of the fluid in the pipe.

Some methods are used to control the hydraulic transients in pipeline systems and to scale down the negative effects. Bleeding in air directly into the pipeline, air chambers, valve stoking, and surge tanks are considered to reduce the effect of water hammer in pipeline system. In the hydropower plant, the pressure of fluid in the pipe can be reduced by the surge tank.

Surge tank is an open standpipe connected to the conduits of the hydroelectric power plant[4]. The main functions of surge tank are to reduce the amplitude of pressure fluctuations by reflecting the pressure waves, mend the regulating characteristics of hydraulic turbine, and act as the second reservoir to store or provide water.

Experimental research is observed in the laboratory by using surge tank model. In this study, we evaluated the effects of varying surge tank diameter and length of penstock on the water oscillations. The varies of diameters are d1 = 5.73 cm and d2 = 7.64 cm, meanwhile the varies of penstock length are L1= 84cm, L2= 120 cm, L3=156 cm. The surge tank model in this research is designed as a hydropower plant with a surge tank with the general structure is shown in Fig. 1[5].

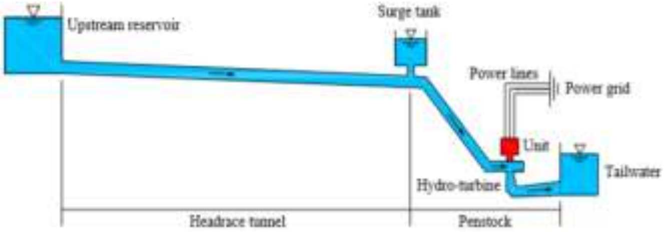

Fig. 1. Model of hydropower plant with a surge tank.

The surge tank model in this experimental research is a surge tank with open chamber, open standpipe connected to the conduit of a hydropower plant or to the pipeline of a piping system.

II. PROBLEM STATEMENT

Hydraulic transients or water hammer can result in large pressure forces and rapid fluid acceleration in the water pipeline system[6]. Those conditions can alter to pipe failure, pipe raptures, and the intrusion of unclean water.

Any disturbance in water caused during a change in flow conditions initiates a sequence of transient pressure or water hammer. Typical events that can cause water hammer phenomenon include:

1) Starting or shutting down of pump;
2) Opening or closing of the valve;
3) Pressure changes in pipe caused by the adjustments in the water level at reservoir;
4) Rapid changes in water flow demand;

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5) Changes in transmission condition (power break system);
6) Pipe filling or draining;
7) Dam failure or collapse[7].

Here are some methods to reduce the water hammer effects:

1) Designing of the pipes and fittings to anticipate the high pressure;
2) Locating the control devices in the proper area to adverse effects of transients;
3) Regulation of pump and valve operation for the pipeline system.

III. METHODOLOGY

Two variations of surge pipe diameter and three different length of penstock pipes are being used in this experimental research. Surge tank model in laboratory is equipped with reservoir, closed conduit that connects the reservoir to the surge tank, penstock, and adjustable valve at the end of the penstock. The Table I shows the model of surge tank design with variations respectively.

TABLE I. Surge tank model variations.

Surge Tank Diameter	Length of Penstock	Model's Name
d1 (7.64 cm)	L1 (156 cm)	1
		2
	L2 (120 cm)	3
		4
	L3 (84 cm)	5
		6
d2 (5.73 cm)	L1 (156 cm)	7
		8
	L2 (120 cm)	9
		10
	L3 (84 cm)	11
		12

Source: Experimental research design by author

A. Surge Pipe

The equipment is set up as shown in Fig. 1 where the water surface can be measured. The static head (h_0) is recorded through the level on the surge pipe when there is no flow, this condition will be the datum level throughout the experiment. Then adjusting the gate valve so that there is a steady of water flowing out from the penstock. After that, the gate valve is closed quickly, and the water level will drop and rise in surge pipe. More reading should be taken for better accuracy.

The maximum and minimum surge heights are measured by oscillations and the time when the gate valve is closed rapidly. The same procedure is repeated, and the time taken between the surges passing the datum point is observed.

The period of oscillation (T) of the water surface in surge tank for frictionless system relates to the length of surge tank (L), cross-section area of surge tank (A_s), and cross-section area of the penstock pipe (A_p) as shown below.

$$T = 2\pi \sqrt{\frac{L.A_s}{g.A_p}}$$

Then, the amplitude of oscillation in surge tank relates to initial discharge of flow in closed conduit (Q_0), as shown below.

$$Z = Q_0 \sqrt{\frac{L}{g.A_s.A_p}}$$

B. Water Hammer

The equipment is set up as the Table I. Water hammer flow control valve is fully opened. The measurement of the volumetric velocity can be measured by using the total flow comes out from the penstock pipe and the time of opened valve. Thus, calculate the flow velocity in the pipe. Then, the valve is closed rapidly, and the pressure waves travel up and down the pipe. This is categorized as instantaneous closures since the valve is closed before the reflected wave reaches the end of the pipe (2L/c). These conditions are recorded for the measurement of average amplitude, time base, and the oscillation time.

The pressure wave velocity (c) depends upon the characteristics of the liquid, such as the bulk modulus (K) and density (ρ); the characteristics of the pipe material, including the conduit size (D), wall thickness (e), and material of the pipe (E). The wave velocity in a thin-walled elastic conduit is given by the Korteweg's equation.

$$c = \sqrt{\frac{1}{\rho\left(\frac{1}{K}+\frac{D}{Ee}\right)}}$$

Then, the momentum equation to calculate the pressure when water hammer phenomenon occurs depends upon the density of fluid (ρ), pressure wave velocity (c), and initial flow velocity (v). The maximum pressure of the water hammer effect is determined by using Joukowsky equation.

$$P = \rho c v$$

C. Head Losses Due to Friction

The head loss is a measure in the total head of the fluid as it moves through the pipeline[8]. Head losses are caused by the friction of the fluid against the pipe walls, those conditions are called friction losses or head loss due to friction. The head loss due to friction (Hf) in the experimental closed conduit is determined by *Darcy-Weisbach* equation.

$$H_f = f \frac{L}{D}\frac{V^2}{2g}$$

The dimensionless (f) is friction factor, (L) is the length of pipe, (D) is the diameter of the pipe, and (v) is the velocity of the fluid. The evaluation of the friction factor is using the Reynolds number. The Reynolds criterion relates the inertial forces per unit of volume to the viscous forces per unit of volume (V). The Reynolds number (Re) for full flowing circular pipes is shown as below.

$$Re = \frac{VD}{v}$$

The friction factor (f) in a turbulent regime ($Re > 4000$) is calculated from the equation below.

$$f = 0{,}316 \times \mathrm{Re}^{-0{,}25}$$

D. Undedamping Oscillation

Oscillation in hydraulic transients refers to repetitive variation of fluid from the mean flow condition to amplitude of water surface when water hammer phenomenon occurs in time. The water hammer oscillations occur in the form of propagation wave. In this study, hydraulic transient is categorized as the underdamping oscillation, where the attenuation factor (γ) is smaller than oscillation frequency (ω). Oscillation function in water surface height ($h(t)$) is an exponential function with angular frequency and amplitude by time (t) as shown below[9].

$$h(t) = e^{-\gamma t}\,(Ae^{\psi t} + Be^{-\psi t})$$

It is shown that the bigger value of γ, then the oscillation frequency will decrease, and the amplitude will decrease faster.

IV. EXPERIMENT RESULT

A. Varying the Diameter of Surge Tank

The results for different models of surge tank are obtained by calculating the water surface oscillation in the surge tank and the oscillation time until the flow reaches the steady state flow condition.

Fig. 2, 3, and 4 are constructed to show the effect of varying diameter of a surge tank on oscillation amplitude. As the cross-sectional area of surge tank increases, the water level in surge tank decreases. The fluctuation of oscillation amplitude will take some time until the flow reaches the steady state condition. The length of the pipe and the cross-sectional area of the surge tank affect the height of upsurge and flow time to reach its steady state condition to the initial height in surge.

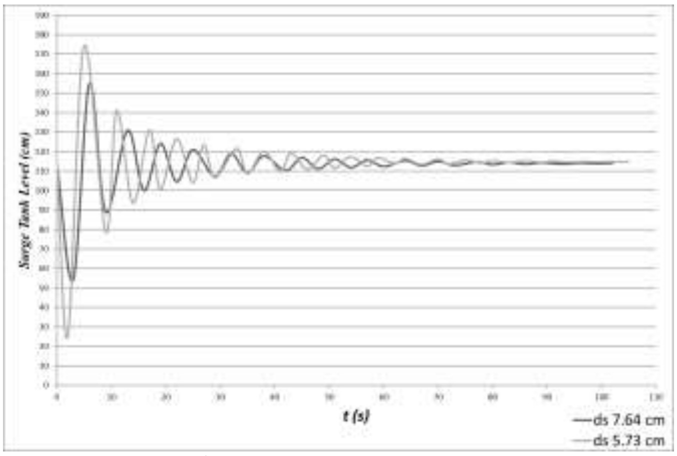

Fig. 2. The variation of surge tank level with time at (diameter = 7.64 cm and 5.73 cm), Length of Penstock 156 cm.

For the design in Fig. 2, the length of penstock pipe is 156 cm with the two diameter of surge pipes. The maximum amplitude is shown by the diameter 5.73 cm, meanwhile the diameter 7.64 cm decreases the first upsurge level to about 20 cm at 7th second. The time until the flow reaches its steady state condition is at the time 103 second for surge diameter of 7.64 cm, and 108 second for surge diameter of 5.64 cm.

For the design in Fig. 3 and Fig. 4, the length of penstock pipe is reduced to 120 cm and 84 cm, respectively. The larger diameter reduces the oscillation amplitudes in surge tank to the average height of 20 cm.

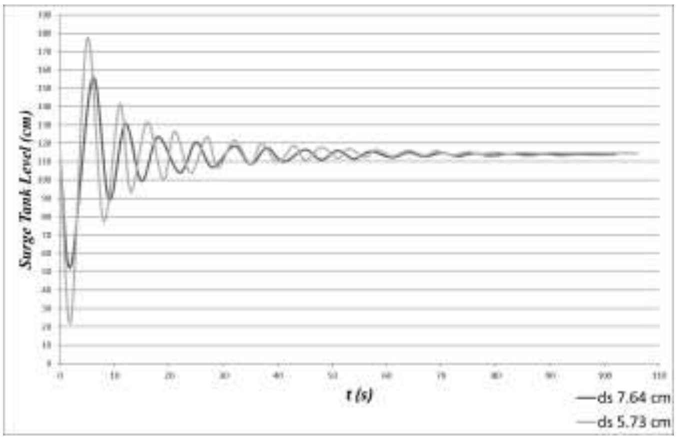

Fig. 3. The variation of surge tank level with time at (diameter = 7.64 cm and 5.73 cm), Length of Penstock 120 cm.

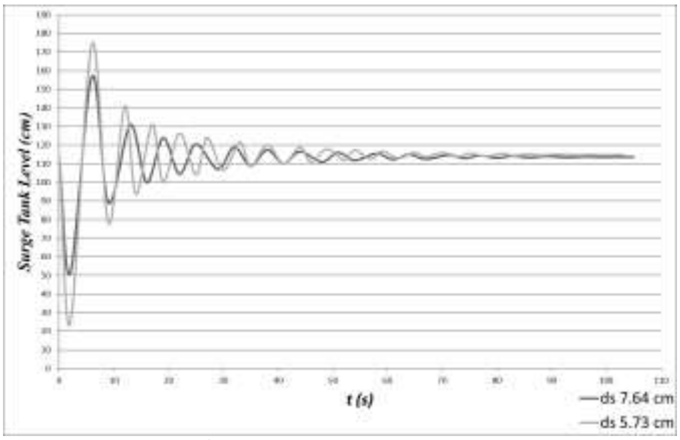

Fig. 4. The variation of surge tank level with time at (diameter = 7.64 cm and 5.73 cm), Length of Penstock 84 cm.

B. Varying the Length of Penstock

Fig. 5 and Fig. 6 are constructed to show the effect of varying the length of penstock pipe. As the length of the penstock increases, the surge tank level decreases and the oscillation time drops faster.

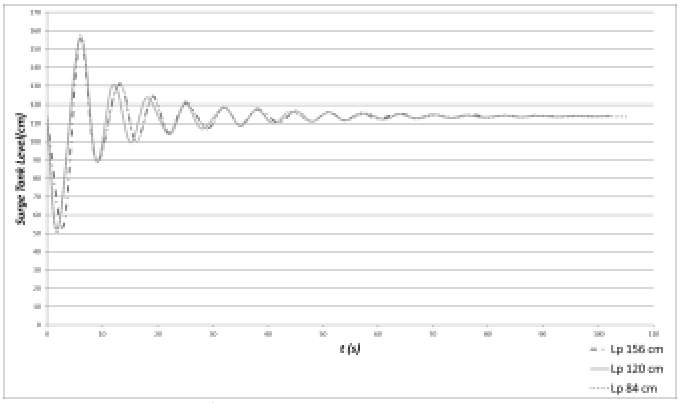

Fig. 5. The variation of surge tank level with time at (penstock length = 156 cm, 120 cm, and 84 cm), Diameter of Surge 7.64 cm.

In Fig. 5 with the diameter 7.64 cm, the first upsurge fluctuations range from 155 to 158 cm at corresponding length of penstock pipes. The oscillation time reaches the steady state flow the slowest with the length of the penstock 84 cm at the time 108 second.

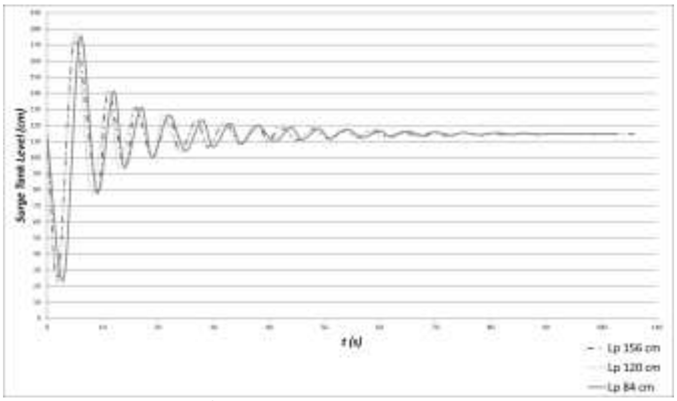

Fig. 6. The variation of surge tank level with time at (penstock length = 156 cm, 120 cm, and 84 cm), Diameter of Surge 5.73 cm.

In Fig. 6, with the surge diameter 5.73 cm and three variations of penstock length, the maximum oscillation amplitudes range from 172 to 178 cm. The penstock with the length of 84 cm shows the slowest oscillation frequency until the wave reaches the steady state flow at the second 108.

C. *Water Surface Level in Surge Tank and Steady State Flow*

Fig.7 shows the oscillation amplitude that decays against the time. As the attenuation factor increases, the oscillation frequency decreases and oscillation amplitudes drop faster.

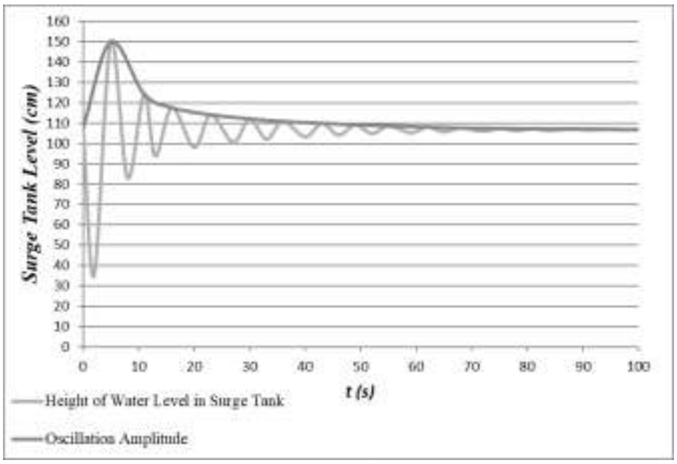

Fig. 7. Underdamping condition of surge tank level with time.

The first upsurge in the surge tank is 150 cm at time 8 second and gradually decreases because of the friction loss or attenuation factor between the fluid and the pipe. The flow reaches its steady state condition at the time 100 where the flow changes to its initial height at 108 cm.

The relation between surge tank level with oscillation time until the wave reaches the steady state flow is measured by using Minitab Programming as in Fig. 8 below.

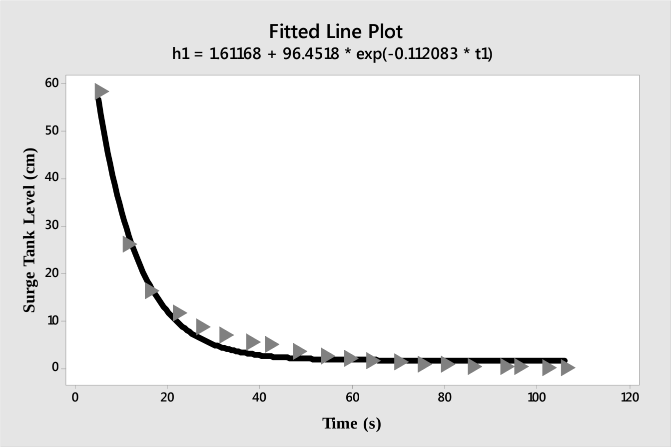

Fig. 8. Non-Linear regression of surge tank level with time.

The equation obtained the relation between surge tank level (H) and oscillation time (t) in the form of non-linear regression:

$$H = 1.2792 + (83.216 \times e^{(-0.116311 * t)})$$

The value of MSE (Mean Squared Error) from the equation by using Minitab Programming is 1.5 with the deviation of 1.2.

D. *Calculation of Water Hammer*

The pressure waves in the pipeline system are obtained by using Joukowsky's equation and to determine the safety factor of pipe material. As shown in Table II, the higher pressure in pipeline happens when surge tank diameter 5.73 cm is installed in the model. The lowest pressure in pipelines is 11.94 bar with the diameter of 5.73 and length of penstock of 120 cm. Safety factor is obtained by corresponding the pipe material. This experiment uses the PVC pipes, then the safety factor of load service should be more than 2.

TABLE II. Pressure in pipeline and safety factor material.

Variation No.	Diameter	Volume	Time	Discharge		Flow Velocity	Pressure in Pipe		*Safety Factor*
		(litre)	(s)	(litre/s)	(m3/s)	(m/s)	(N/m2)	bar	*(SF >2)*
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1	d1	6.9	3.1	2.23	0.0022	0.94	1,390,227	13.90	2.63
2		8.5	3.6	2.36	0.0024	0.99	1,474,737	14.75	2.61
3		8	3.2	2.50	0.0025	1.05	1,561,486	15.61	2.58
4		8.75	3.6	2.43	0.0024	1.02	1,518,112	15.18	2.59
5		7.3	3.2	2.28	0.0023	0.96	1,424,856	14.25	2.62
6		8	3.6	2.22	0.0022	0.94	1,387,988	13.88	2.63
A	d2	7	3	2.33	0.0023	0.98	1,457,387	14.57	2.61
B		9.05	3	3.02	0.0030	1.27	1,884,194	18.84	2.49
C		6.4	3	2.13	0.0021	0.90	1,332,468	13.32	2.65
D		6.5	3.4	1.91	0.0019	0.81	1,194,078	11.94	2.70
E		9	3.4	2.65	0.0026	1.11	1,653,338	16.53	2.55
F		8.35	3.4	2.46	0.0025	1.03	1,533,931	15.34	2.59

Table III presents that the decreasing of length of penstock results in the lowest head loss due to friction. In this experimental research, the friction losses take average of 10% of the total length of penstock pipe. Highest head loss due to friction is measured in surge tank variation number 8 with total $Hf = 0.26$ m. This variation model uses the surge diameter of 5.63 cm and penstock pipe 156 cm.

TABLE III. Head loss due to friction in penstock pipe.

Variation No.	L	Flow Velocity	Reynolds Number	*Hf*
	(m)	(m/s)		(m)
(1)	(2)	(3)	(4)	(5)
1	1.56	0.94	51450.231	0.14
2	1.56	0.99	54577.842	0.16
3	1.2	1.05	57788.303	0.14
4	1.2	1.02	56183.072	0.13
5	0.84	0.96	52731.826	0.08
6	0.84	0.94	51367.38	0.08
7	1.56	0.98	53935.749	0.16
8	1.56	1.27	69731.219	0.26
9	1.2	0.90	49312.685	0.10
10	1.2	0.81	44191.055	0.08
11	0.84	1.11	61187.615	0.11
12	0.84	1.03	56768.509	0.09

E. Calculation of Surge Tank

TABLE IV. Theoretical surge tank calculation.

Variation No.	Discharge	Surge Tank Diameter	Penstock Length	As	Z	T
	(m3/s)	(m)	(m)	(m2)	(m)	(s)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
1	3.1	0.076	1.56	0.004534	0.34	4
2	3.6	0.076	1.56	0.004534	0.36	4
3	3.2	0.076	1.2	0.004534	0.38	4
4	3.6	0.076	1.2	0.004534	0.37	4
5	3.2	0.076	0.84	0.004534	0.35	4
6	3.6	0.076	0.84	0.004534	0.34	4
7	3.0	0.057	1.56	0.00255	0.48	3
8	3.0	0.057	1.56	0.00255	0.62	3
9	3.0	0.057	1.2	0.00255	0.44	3
10	3.4	0.057	1.2	0.00255	0.39	3
11	3.4	0.057	0.84	0.00255	0.54	3
12	3.4	0.057	0.84	0.00255	0.50	3

The highest upsurge in surge tank is shown at the height of 0.62 cm by using the surge diameter of 5.73 cm and length of penstock is 156 cm. The surge diameter of 7.64 results better in reducing the oscillation amplitude. The higher oscillation amplitude is expressed by the surge tank diameter 5.73 cm by the average upsurge of 0.49 cm.

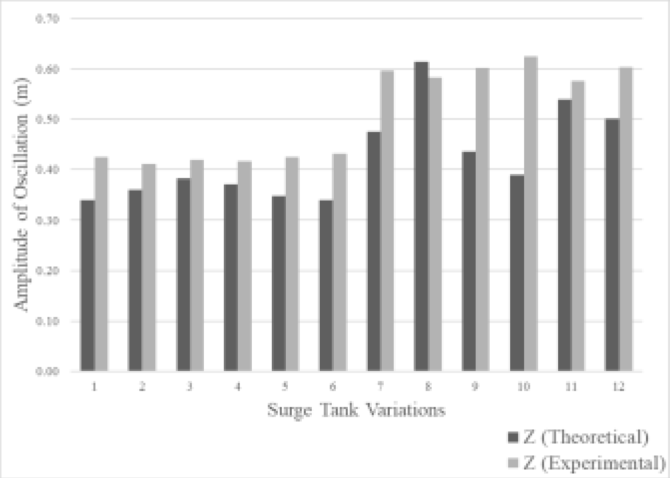

Fig. 9. The comparison of oscillation amplitude in theoretical and experimental on each variation.

By obtaining the theoretical oscillation amplitude and period, the comparison between theoretical and experimental amplitude is shown in Fig. 9. Experimental research of surge tank models by using different pipe diameters and length, result in observed calculations. These observed calculations then compared by the theoretical equation. The experimental oscillation amplitudes on each variation are moderately 0.08 m higher than the theoretical upsurge.

V. CONCLUSION

In this study, we observe effects of varying diameter of surge tank and length of penstock. Effectiveness of the surge tank is indicated by the lowest oscillation amplitude and time of oscillation. The final conclusions of the study are as follow:

1. The amplitude of water oscillation is affected by the area of the surge tank pipe. As cross sectional of the pipe increases, then the height of water in surge pipe decreases when oscillation occurs.
2. Velocity of propagation will be decreased by using the longer penstock because the head loss due to friction along the pipe. This condition makes the flow reaches the steady state flow faster.
3. Result obtained by Minitab programming is much closer from the results obtained by theoretical method.

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