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Pressure fluctuations and cavitation index in the slot of lift bottom outlet gate, by using a physical model and introduction of normal standard distribution formula

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Abstract

The high velocity flow of water along with the severe head loss causes several turbulences and may lead to occurrence of cavitation phenomenon in hydraulic structures and severe destruction in some parts of them. Flow separation within the slots make eddies and vortices, which can also create cavitation. This study deals with the pressure fluctuations which are product of current severe turbulence, their processes and cavitation phenomenon at the gate slot region (with length/wide ratios of 2 and a 45^{o} angle to the edge of the vertical-gate) of physical model of bottom outlet of Gotvand Olya storage dam. The study was conducted at the gate openings of 10, 30, 50, 70, and 100% and in different 2, 3 and 4 meter-heads and at0.1 %probability levels. Data collected using a transducer, were then transferred to an amplifier, and finally recorded in a computer. The results obtained indicated that at the gate openings of 30%, 50% and 70%, risk of cavitation occurrence is the maximum and at 10% and 100% it is the minimum. Also the piezometer, closest to the gate edge, is subjected to more fluctuations and critical point of pressure fluctuations are transferred to higher points upon with increase of gate opening. Coefficient of pressure fluctuations (C'p) is the maximum at10 % opening that indicates compaction and pressure beats to the structure in this opening. Therefore control hydraulic conditions and geometric changes of the gate slot decreasing cavitation occurrence to the minimum would be possible.

Keywords: Bottom outlet, Cavitation, Coefficient of pressure fluctuations, Gate slot.

Introduction

Gotvand Olya dam is located on Karoun river in 35th km of Shoushtar Town. In this paper, pressure fluctuations and cavitation phenomenon on the bottom outlet of this dam at the service gate slot have been investigated. Vertical-lift gates of the roller or slide type require recessed slots in abutments for the movement of the gate guide rollers or slides. The flow of water across the slots causes flow separation at the upstream edge of the slot and reattachment on the downstream side. Eddies are set up within the slots and vortices are formed. Under conditions of high velocity flow cavitation can occur within gate slots (Jack Lewin, 2001). Bottom outlets have major roles such as drain of reservoir in emergency, lowering water level in the reservoir and excess discharge diversion and flash -flood. Model 1:17 of the bottom outlet was made in laboratory. Pressure fluctuations were measured in each 20 seconds (200 Hz frequency) by 4,000 records in each experiment and by using transducer and were changed to real forms of dynamic pressures by using Data Logging software and were then stored and recorded in the computer. Then the coefficients of pressure fluctuations including C'p, C'p+, C'p- and Cp as well as cavitation index were calculated and investigated and analyzed. Afterwards the above parameters were plotted for openings of the gate and in different 2, 3, and 4 meter-heads of the reservoir in each chart. Investigation and necessity of conducting this research in this relation is so important because pressure fluctuations followed by cavitation phenomenon have so far led to serious damages in most parts of hydraulic structures including the tunnel of bottom outlets of dams and have caused serious complications to structure performance and have sometimes interrupted it. For example, after 2 years of operation of Glen Canyon dam, which was constructed on the Colorado River in the US, pressure fluctuations and occurrence of cavitation phenomenon led to serious damages in the ceiling of bottom tunnel of that dam. Moreover, a hole with a depth of 11 meters was created in the weir bottom of left tunnel of Glen Canyon dam due to occurrence of cavitation. Wagner (1967) and Falvey (1990) made researches in the field of occurrence of the destructions and specified conduit roughness and fluid turbulence as the main causes of damages occurred to channel gates and lined. In addition, Falvey (1990) recommended the probability pressure of 0.1% for cavitations index. Damages occurred to bottom tunnel No. 2 of Tarbela dam in Pakistan are as the result of cavitation of another type of destructions caused by this phenomenon on some parts of the structure. Kenn & Garrod (1981) investigated the damages caused by cavitation on the tunnel of that dam. Akbari (1982) made research in relation to the time of record fluctuations and showed that after 60 seconds, pressure fluctuations will be independent of time. Sagar (1979) during his studies at the high head - gates,

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emphasized on very little gate slots and the observed problems including cavitation, erosion and vibration which were the failure factor of the gate. To prevent vibration and the bottom forces, Sagar (1995) achieved the 45^o angle of the gate edge of the sluice-gates. Naudascher (1991) made extensive researches on the bottom outlets, especially with high-head gates and found that pressure decreased clearly in the gate slot which is the place where vortex is formed. He also published several papers in this regard. In addition, Claudio & Lopardo (2007) studied the cavitation status in pressure fluctuations with turbulent flows under hydraulic jump in stilling basins. In this study, they considered a destructive function of turbulent flows in the hydraulic jump focusing on the initiation of cavitation. In addition, to this work that was carried out in Arroyito dam, the observed destructions at relatively low velocity and under varied pressure fluctuations with probability level of 0.1%.

Materials and methods

The bottom outlet model of this dam was designed and constructed in the laboratory by considering hydraulic. Experiments were carried out at the Institute of water research. Experimental data was used based on measuring pressure fluctuations by pressure transducer. Data logging software - one of the data recording software packages of pressure fluctuations, have been used in these experiments. Sensors were installed on a level sheet and connected to the amplifier which is connected to a computer and the input data were recorded by the software installed on it. There are eight channels for data recording in this software and eight dynamic pressure numbers may be recorded simultaneously from eight different piezometers. Experiments were performed with 2, 3 and 4m heads of water column in the reservoir. Pressure fluctuations were measured in each 20 seconds (200 Hz frequency) by 4,000 records in each experiment. The results are also shown on the monitor and saved. Sensors are DRUCK type with a voltage of 10 volts. The sensors have an accuracy of ±1 mm water column. Discharge in each opening was measured by the weir located at the end of the model and by reading water height on the weir and refereeing to discharge-gauge calibration table. The limnimeter installed in the channel wall has a ruler that is equipped with a vernier with an accuracy of ±1 mm. Fig.1 shows the transducer used in the experiment. Fig.2 shows the weir and limnimeter mounted at the end of outlet for measuring fluid discharge.

The bottom outlet model of Gotvand Olya dam includes channel input pipe to a diameter of 9.5m, transition, contraction, slots and chambers of emergency and service gates, middle channel, aerators between the two gates and the whole downstream channel of service gate along with the end inverse slop. Details of the model geometry were shown in Fig. 3 & 4.

Fig. 5 shows the bottom modeled tunnel and gate slots of Gotvand Olya dam, model strengtheners mounted on the body and emergency and service gates made vertically. Fig. 6 shows vertical emergency and service gates installed following each other during the experiment.

In this study, the fluid in the inlet part of the model is considered which is pressurized in the upstream part of service gate and free fluid in the downstream part of it. In this experiment, Froude number analogue index will be used instead of Reynolds number (R_e) because considering the high velocity of fluid in the prototype 43.57 m/s in case of use of analogue index of Reynolds number in the model, velocity will increase to 740.74 m/s which will not be possible to supply. Therefore, based on experiences and available scientific resources, Froude analogue index (F_r) is used instead of Reynolds rule, if Reynolds number in model (R_{em}) is larger than a special limit (10^5) so that the viscosity effect may be neglected (Novak & Ceblcka, 1981). Cavitation index (σ), Cp, C'p, C'p+, C'p- and velocity under the gate and other parameters were extracted and calculated and the relevant analysis were performed on them.

Excess increase of fluid velocity in the fluid path causes intense loss of pressure. If the relative pressure of fluid in ambient conditions becomes less than the pressure of water vapor, cavitation occurs in the field fluid, which provides and accumulates bulbs in the fluid and will be transferred to sections with low velocity. As the result of decrease of fluid velocity and pressure increase, the bulbs will explode and will remove the walls in hydraulic structures by providing a strong negative suction. This phenomenon is called cavitation.

The Cavitation parameter σ_i of a slot is obtained from equation 1.

$$\sigma_i = \frac{p - p_v}{0.5\rho V^2} \quad (1)$$

Where, p is Fluid pressure in a reference point, Pv is vapor pressure; V is the fluid velocity and ρ is fluid density of water.

The important point in connection with cavitation index is calculated P._According to credible sources, the index is calculated by the pressure with probability level of %0.1 (P is equal to $P_{\%0.1}$) (Lopardo *et al*., 1982; Falvey, 1990). Thus the use of statistical distribution (normal distribution here), the first the variable (pressure) with the desired probability, obtained from the following equation:

$$X = \overline{X} + K.S \quad (2)$$

In this formula: $\overline{X}$ mean data, S standard deviation and K is abundance coefficient of data that are derived

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Fig.1. Transducer and its components

Fig. 2. The weir and limnimeter installed for measuring

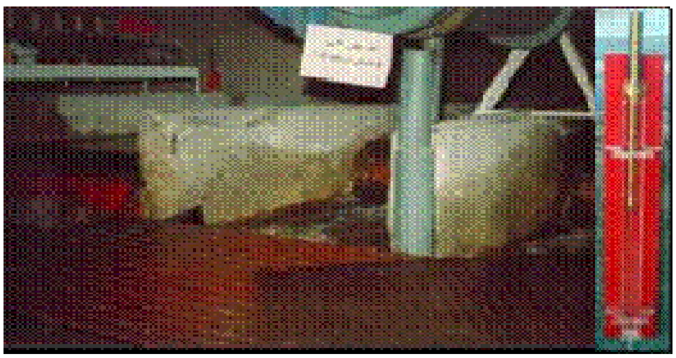


Fig.3. View of plan of gate slot (cm)

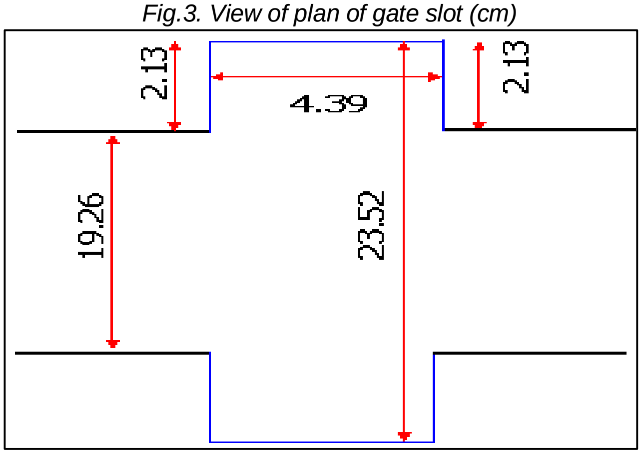


Fig. 4. A view of section of gate slot (cm)

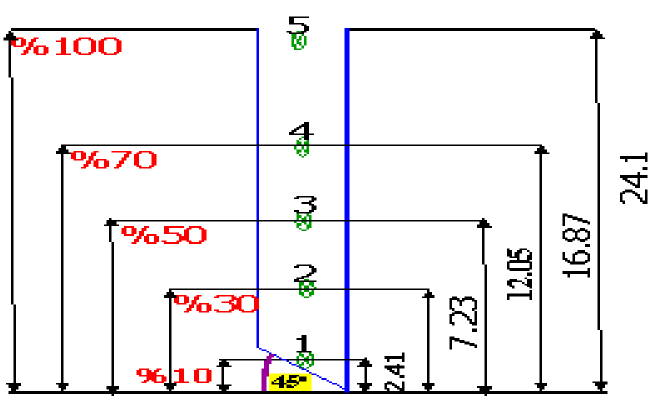


Fig.5. A view of bottom outlet laboratory model

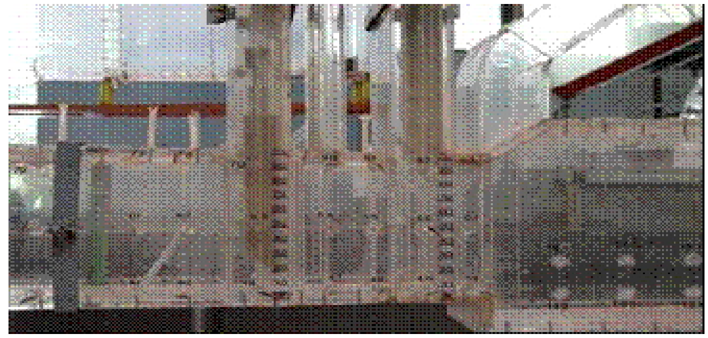


Fig.6. Gotvand Olya service gate model (During experiment, with a 3-m head and 100% opening)

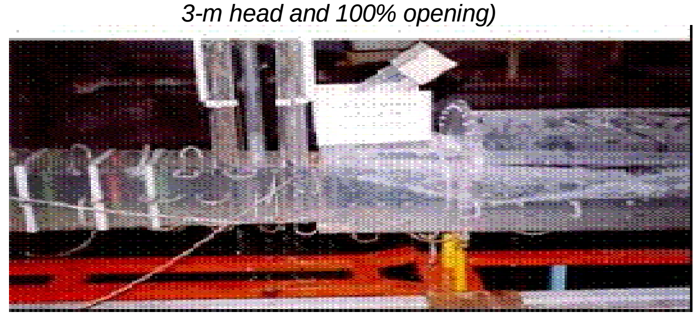


Fig. 7. Diagram of dynamic pressures for the percentage of different openings of the gate slot separated for head and number of piezometer

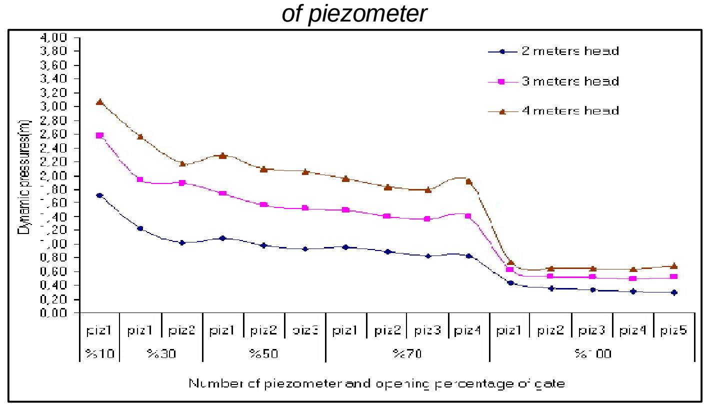
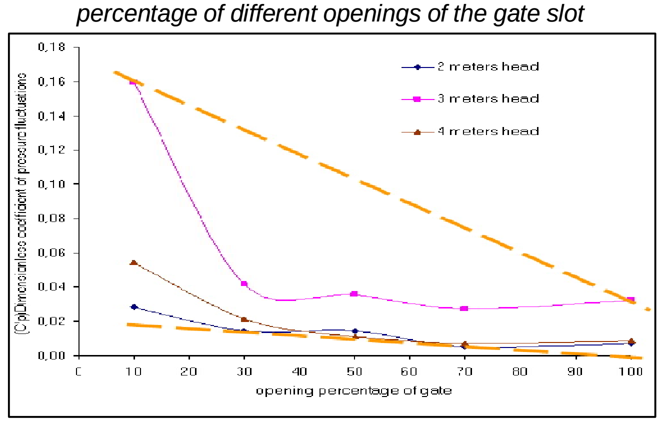


Fig. 8.Diagram of coefficient of pressure fluctuations C'p for the percentage of different openings of the gate slot



from statistical tables. So instead of setting the corresponding values in the above formula, we will have:

$$P'_{\%} = D_p(ave) + K.D_p(stdev) \quad (3)$$

Where: $P'_{\%}$ is pressure probability, $D_p(ave)$ is the mean dynamic pressure (4000 records) and $D_p(stdev)$ is standard deviation of the data. To obtain absolute pressure value should be P' computed addition with the atmospheric pressure (10. 13 m), that will have:

$$P = P'_{0.1\%} + 10.13 \quad (4)$$

Then $P - P_v$ calculated and put in the formula (1). If the cavitation index was in the range 0/2 - 0/25, a cavitation phenomenon will occur (Falvey, 1990).

The coefficients of pressure fluctuations that will indicate pressure changes are given by:

$$C'_P = \frac{RMS}{\frac{V_1^2}{2g}} \quad (5)$$

$$C'_{p+} = \frac{p_{\max} - p_{mean}}{\frac{V_1^2}{2g}} \quad (6)$$

$$C'_{p-} = \frac{p_{\min} - p_{mean}}{\frac{V_1^2}{2g}} \quad (7)$$

$$C_p = \frac{p_{mean} - p_0}{\frac{V_1^2}{2g}} \quad (8)$$

Where, RMS is standard deviation, $V_1^2/2g$ is velocity head of entrance, P_{mean} is the average of dynamic pressures; P_{max} and P_{min} are maximum and minimum dynamic pressures in each experiment, respectively. P_0 is the reference pressure in a point and here static pressure in each experiment is addressed. By considering dynamic pressures that may decrease the pressure below under vapor pressure, cavitation condition is caused. Determine the intensity of cavitation occurrence and the beats of pressure fluctuations on the region of gate slot will be investigated and analyzed by the above parameters. The critical number of cavitation index has been calculated 0.2-0.25 according to available authentic references (Falvey, 1990). Moreover, in order to investigate the treatment of fluctuations and to achieve a definite pattern to predict the treatment of pressure fluctuations in the future, we should calculated probability distribution of fluctuations and their comparison with normal standard distribution. The normal standard distribution is obtained from the following equation:

$$F_p = \frac{1}{\sqrt{2\pi}} e^{-\frac{z^2}{2}} \quad (9)$$

Where, Z is standard variable. By changing this equation to corresponding variables with pressure we will have:

$$F_p = \frac{1}{\sqrt{2\pi}} e^{-\frac{P'^2}{2}} \quad (10)$$

P' value is obtained from the following equation:

$$P' = \frac{P - P_{ave}}{S} \quad (11)$$

Where

P is the recorded pressures, P_{ave} is the average pressures and S is standard deviation.

Normal standard distribution has an average equal to zero and a standard deviation equal to one. By obtaining P' and drawing the data it was specified that normal standard distribution was a suitable standard. By applying a coefficient of 0.4 on the denominator of the fraction, we reached a total relation for distribution of obtained pressure fluctuations as follows:

$$F_p = \frac{1}{0.4\sqrt{2\pi}} e^{-\frac{P'^2}{2}} \quad (12)$$

Considering the obtained equation we can predict structure treatment in the gate slot in high probability levels to prevent from the effects of pressure beats and to provide destruction in the structure. In low probability levels we can predict structure treatment in order to prevent from the effects of cavitation and negative suctions.

Results and discussion

Dynamic pressure changes

Dynamic pressure for opening percentage of the gate shown in Fig.7. In the relevant graphs 2, 3, and 4-m heads are specified by blue, pink and brown colors, respectively. This chart shows that increase of opening of the gate has an inverse relation with values of dynamic pressures. This may be due to increase of discharge which will be followed by increased head loss. Moreover, increase of the head has a direct relation with pressure values in addition, the highest and lowest levels of pressure are seen in the lowest and highest piezometers in each opening, respectively.

Coefficient of pressure fluctuations (C'p)

Fig.8 shows 10% opening of the gate the coefficient of pressure fluctuations have been maximized in all the three heads which shows the effect of beat of flows in this gate opening. The range of C'p is between $0.032 < C'_p < 0.159$ in 3 meters head and $0.006 < C'_p < 0.029$ in 2 meters head (orange lines). According to Fig.7 and the maximum pressure at 10%

Fig. 9.Diagram of coefficient of pressure fluctuations

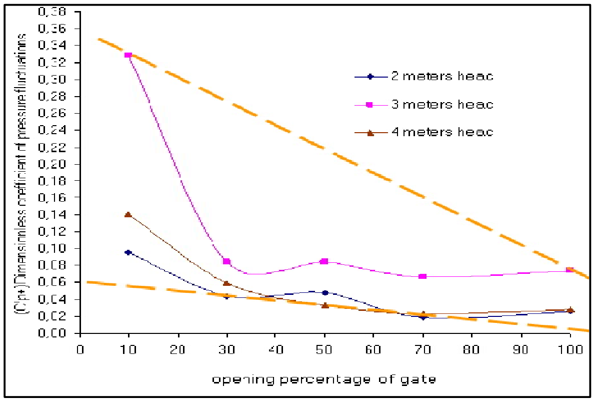


Fig. 10.Diagram of coefficient of pressure fluctuations

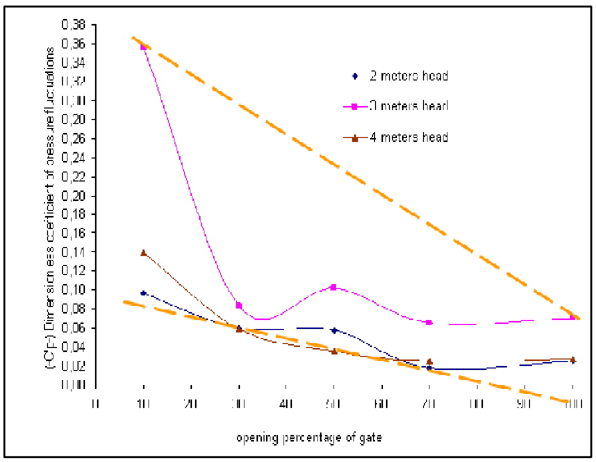


Fig.11. Diagram of coefficient of pressure fluctuations Cp for the percentage of different openings of the gate slot separated as head and number of piezometer

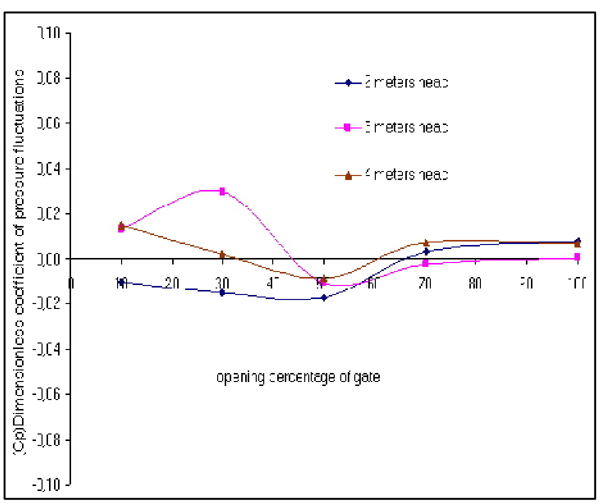


Fig.12.Diagram of dynamic pressure variance for percentage of different openings of the gate slot separated as head and number of piezometer

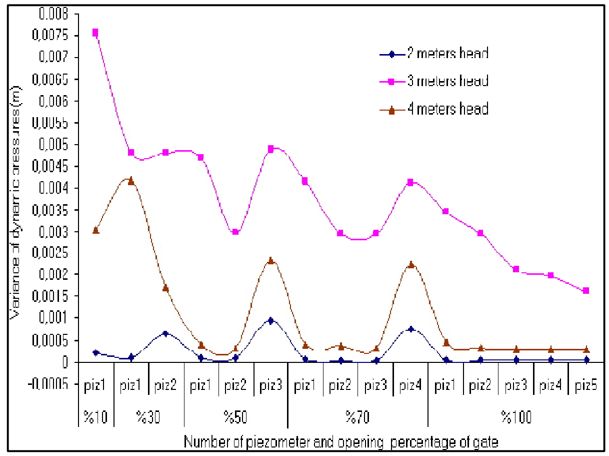


Fig.13. Cavitation index diagram for the percentage of different openings of the gate slot separated as head and number of piezometer

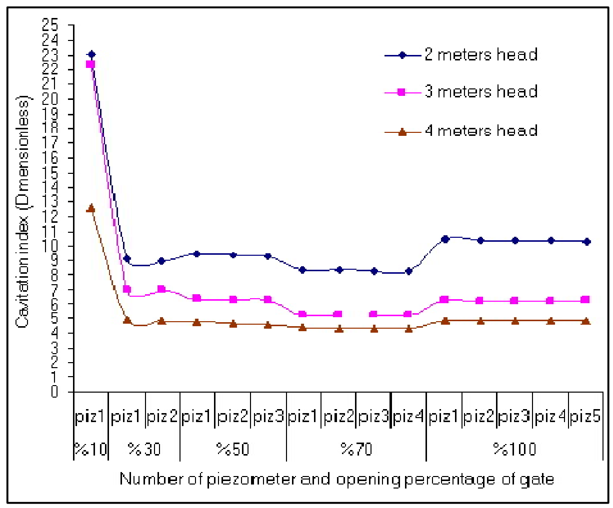
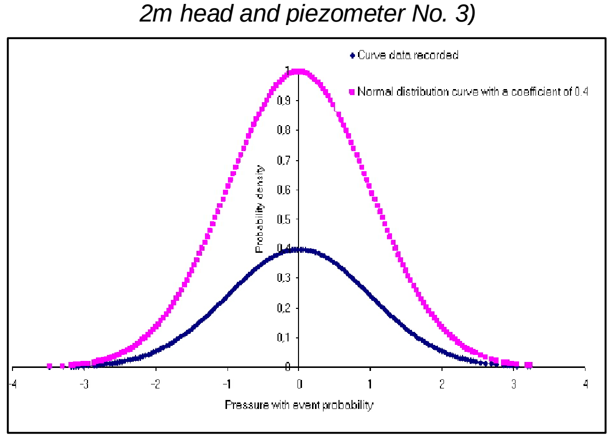


Fig.14. Diagram of normal distribution curve of dynamic pressures data probability (100% opening, 2m head and piezometer No. 3)



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opening, pressure fluctuations can make beats on the structure. Expectation in this opening beats of pressure, make crushing of concrete and damages on the structures.

Coefficients of pressure fluctuations (C'p+ & C'p-)

These diagrams show that the trend of coefficient of pressure fluctuations C'p+, C'p- conform to C'p. The range of C'p+ is between $0.074 < C'_p + < 0.330$ in 3 meters head and $0.02 < C'_p + < 0.1$ in 2 meters head. In addition, C'p- is between $0.071 < C'_p - < 0.355$ in 3 meters head and $0.018 < C'_p - < 0.097$ in 2 meters head (orange lines) (in here the absolute value of C'p- is used) (Fig. 9 &10).

C'p+ for the percentage of the gate openings -C'p- for the percentage of the gate openings

Coefficient of pressure fluctuations (Cp)

The diagram shows that the trend of pressure fluctuation Cp has almost become linear after 50% opening onward which shows the closeness of static and dynamic pressures (Fig.11).

Variance of dynamic pressures

The diagram shows that the level of fluid turbulences in 100% opening of the gate has decreased to a minimum level. Due to fully open gate and no obstacle against flows, the trend of the curve is reasonable (Fig.12).

Cavitation index

In this diagram, cavitation index at 10% and 100% openings of the gate show the highest level that indicates the minimum risk of cavitation phenomenon occurring. Cavitation index is the minimum level at 30, 50 and 70% openings of the gate, which shows the maximum risk of this phenomenon. Due to high velocity and the severe turbulences of flows and eddies within the gate slot and also sudden head loss in accordance with Fig. 7 in these openings, cavitation phenomenon can occur. At 10% opening due to low velocity of fluid and high positive pressure (Fig.7) occurrence of cavitation would be improbable. Also at 100% openings due to lack of any obstacle in the route of fluid and not produce vortices and reduce gradually of fluid velocity, the minimum risk of cavitation would be possible (Fig. 13).

Normal distribution curve of pressure fluctuations

The following formula was obtained by applying normal distribution on the data recorded of pressure fluctuations:

$$F_p = \frac{1}{0.4\sqrt{2\pi}} e^{-\frac{P'^2}{2}} \qquad (13)$$

By using this equation and probability tables we may predict the treatment of structure in high and low occurrence probabilities to investigate the effects of impacting on the structure and the effects of cavitation, respectively. These probability levels are usually considered in 0.1, 1, 5, 95 and 99.9%. The lower percentage (for lower pressures) is used in studying the cavitations and the higher percentage (for higher pressures) is used for impacting the flow on structures (Fig.14).

The results obtained is indicated in the gate slot at the 10% gate opening, due to high positive pressure, cavitation phenomenon probably is minimum, but this high pressure to apply impacts and beats of pressure on the structure. Also at 100% opening can be the safest condition for draining of dam. In 30, 50 and 70% openings of the gate the maximum risk of cavitation phenomenon would be possible. Therefore, it is essential, that the necessary safeguards to be done in this range.In addition, coefficients of pressure fluctuations including C'p, C'p+ and C'p- from 10% to 100% opening are convergent. If that can be geometric dimensions of the slots eliminated or minimized (a new type of gates that have no slots should be designed like radial gates) largely to prevent of cavitation phenomenon or will control. So, by suitable lining, control of hydraulic conditions and change of slot geometry decreasing cavitation occurrence to the minimum would be possible.

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