Study of distribution and characteristics of the time average of pressure of a water cushion pool

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Abstract. When a dam discharges flood water, the plunging flow with greater kinetic energy, will scour the riverbed, resulting in erosion damage. In order to improve the anti-erosion capacity of a riverbed, the cushion pool created. This paper is based on turbulent jet theory to deduce the semi-empirical formula of the time average of pressure in the impinging portion of the cushion pool. Additionally, MATLAB numerical is used to conduct a simulation analysis according to turbulent jet energy and watercushion depth when water floods into the water cushion pool, to determine the regularities of distribution and related characteristics.

1. Introduction
A stilling basin is a traditional method of underflow energy dissipation. When jet freefalls into a stilling basin where hydraulic jump takes place, turbulent fluctuation action transforms, kinetic energy into heat energy and potential energy. The effect of a stilling basin is advantageous for its dissipation effect, because it is adaptable to the geological conditions and the amplitude of tailwater variation. However, it is also widely used for moderate-lower head projects. However, the water cushion pool is usually formed by downstream barrages or check dams, which belongs to a new type of energy dissipater [1]. The mainstream of kinetic energy passes down a turbulent fluctuation (for turbulence generation and turbulent dissipation) and a large-scale water vortex in the pool is continually exposed to the turbulent shearing and diffusion effect. Accompanied by these processes, energy is consumed by the viscous dissipation. This is a better method of energy dissipation, mainly used in high arch dam spillways and energy dissipation. For example, this method is already used in the Ertan and Xiluodu projects, etc., as shown in figure 1.

In cushion pool energy dissipation, energy is dissipated by turbulent fluctuation, collision and hydraulic jumps in the water cushion pool [2]. Therefore, compared to traditional methods of energy dissipation, the reduction of the huge impact and severe fluctuating pressure is necessary, as well as the reduction
of erosion damage on the bottom of the water cushion pool. At present, water cushion pool impact resistance design is only measured by the maximum allowable impact pressure difference at the bottom of the water cushion pool; in a sense, this method is not very rigorous [3]. Therefore, the analysis of time-continuous pressure spatial distribution in the cushion pool is necessary. Meanwhile, different hydraulic factors might affect the time average of pressure, requiring appropriate adjustment for corresponding hydraulic factors in order to reduce the pressure threshold and reduce the probability of erosion damage to the cushion pool to ensure the safety of the downstream riverbed.

![Figure 1. The flat and counter-arch water cushion pool profile.](image)

**Figure 1.** The flat and counter-arch water cushion pool profile.

1.1. The significance of study on time-average pressure of the cushion pool impinging portion

When the main stream of a submerged jet reaches the bottom of the water cushion pool, part of its kinetic energy is converted to pressure energy, and a huge impinging pressure is generated. Meanwhile, sand carried in the water jet impacts the bottom directly. Therefore, the impinging portion is the greatest area of cavitation erosion and scour damage. Similarly, the impinging is the main energy dissipation area [4], which plays an important role in the improving of the energy dissipation effect. This paper analyses the time average of pressure distribution of the impinging portion of a water cushion pool, and estimates corresponding hydraulic factors that might affect the time average of pressure. This is significant to the design of a water cushion pool, by analyzing the compressive strength of bottom concrete which must be more stronger than the maximum time average of hydrodynamic pressure [5]. On one hand, the water cushion pool must be subjected to erosion damage and maintain the safety of the downstream slope; alternatively, this can effectively improve energy dissipation of the water cushion pool. The present research conducts simulation analysis to study the time average of pressuredistribution of the impinging portion of a water cushion pool.

A large portion of energy dissipation is related to the aeration of the plunging jet so that the pressure on bottom decreases; however, under such conditions, the mainstream is refracted by the riverbed in an impinging area, the flow rate decreases rapidly, and pressure increases sharply. These water flow characteristics are similar to those around the flow stagnation point [6-7].

A numerical calculation model is as shown in figure 2, in which the flow direction is designated by the X axis, the cross initiative transversal section and the water inlet is set to the origin of coordinates,
and the vertical direction is designated by the Y axis. The water cushion pool length is set to 150cm, and the width is 100cm.

Generally, the mean pressure is described by $\Delta p_m = p_s - p_{\min}$, $p_s$ is the maximum time average of pressure at the stagnation point, $p_{\min}$ is the minimum bottom time average of pressure, and $\Delta p_m$, is typically described by equation (1).

$$\Delta p_m = f(u_0, h_0, H, \rho)$$  \hspace{1cm} (1)

Among these, $\rho$ is the water density, obtained by dimensional as equation (2):

$$\Delta p_m \left( \frac{1}{2} \rho u_0^2 \right)^{-1} = f(H, p_0^{-1})$$  \hspace{1cm} (2)

For a submerged impinging jet, the experimental result reported by Dr. Duoming Xu [8] is $\beta = 40^\circ - 50^\circ$, as equation (3):

$$\Delta p_m \left( \frac{1}{2} \rho u_0^2 \right)^{-1} = 0.475 \exp \left[ - 0.088 \left( H h_0^{-1} \right)^2 \right]$$  \hspace{1cm} (3)

In order to deduce the formula of time average of pressure distribution under experimental conditions, and to investigate whether the impinging portion is corresponds to a normal distribution [9-11] of the time average of pressure, the maximum flow velocity at the centeral axis of the cushion pool is set as follows:

$$u_0 u_0^{-1} = k x h_0 + A$$  \hspace{1cm} (4)

In equation (4), and as shown in figure 2 below, the jet direction is designated by the X axis, the vertical jet direction is designated by the Y axis, $u_{\max}$ is the maximum flow velocity of the impinging jet center, $h_0$ is the thickness of the incident flow, and $u_0$ is the flow rate into the pool. The measured data and simulation data are shown in figure 3.

**Figure 2.** Flow diffusion diagram of submerged jet area in water cushion pool.
Figure 3. Maximum velocity distribution of submerged jet axial line.

Using the planar diffusion equation [13], the formula of maximum flow velocity is obtained as follows:

\[ u_0 u_{max}^{-1} = 0.56 x h_0^{-1} + 0.31 \]  

(5)

According to the law of conservation of energy:

\[ \sin \theta_{max} = (2 p_{max} \rho^{-1})^{1/2} \]  

(6)

As deduce from equation (5) and equation (6):

\[ p_{max} = \frac{\rho \sin^2 \theta h_0}{2(0.56 \frac{x}{h_0} + 0.31)^2} \]  

(7)

The time average of pressure when a two-dimensionalsubmerged turbulent jet impacts the bottom of a water cushion pool, making the process dimensionless, there is a right similarity on test points near the normal distribution curve, expressed as follows:

\[ p_w p_{max}^{-1} = \exp[-0.625 \frac{k b_p^{-1} \hat{y}}{7}] \]  

(8)

In equation (8), \( p_w \) is the time average of dynamic pressure of each measuring point, \( p_{max} \) is the distance from the maximum measuring time average of the pressure point, and \( b_p \) is the jet flow half width at the \( p_w = p_s / 2 \) position.

Figure 4 and figure 5 respectively represent the dynamic pressure distribution at different turbulent energies and water cushion depths. According to the previous research results[14], the impinging area ranges from approximately \( \frac{x}{H} > 0.70 \) (the \( x \) axis is the mainstream distance measurement, and \( H \) presents water depth), to the downstream wall jet area \( \frac{x_f}{H} \approx 0.35 \) (\( x_f \)is the wall jet area). The diagrams
indicates that the experimental data not only corresponds to the pressure of the normal distribution at the impinging portion, but also indicates similar impinging portion ranges, verifying the rationality of equation (8). According to the article, the impinging portion range is selected along the center axis from 50cm-80cm.

**Figure 4.** The time average of dynamic pressure energies distribution diagram for different turbulent.

**Figure 5.** The time average of dynamic pressure distribution diagram for different water cushion.

### 2. Experimental model

#### 2.1. Measuring point setup.

On the basin floor of the water cushion pool, there are 6 rows of 84 pressure taps along the path of the layout; the specific setup is shown in figure 6. The floor length is 150cm, floor length is 100cm, the impact area measuring points are selected along the axis direction D5-D8, and the origin of coordinates are selected from the product of the length and width.

**Figure 6.** Arrangement diagram of pressure measuring points at the water cushion pool floor.
2.2. Experimental working conditions.
The working conditions in our experiments are as follows: the turbulent energy was set to $6.25 \times 10^{-3} \text{m}^3/\text{s}$, $8.25 \times 10^{-3} \text{m}^3/\text{s}$, $11.30 \times 10^{-3} \text{m}^3/\text{s}$, water cushion depth was 12cm, 14cm, and 16cm. By changing the 16 working conditions of turbulent energy and water cushion depth, the influence of the condition on the time average of pressure were investigated, while the different turbulent jet energy and water cushion depth impacted the cushion pool impinging portion. The specific working conditions are shown in table 1.

**Table 1. Different working conditions.**

| Working condition | Incident flow angle(°) | Depth of water cushion (cm) | Turbulent jet energy $(10^{-3} \text{m}^3/\text{s})$ | Time average of pressure(9.8kpa) |
|-------------------|------------------------|-----------------------------|------------------------------------------------|----------------------------------|
|                   |                        |                             | $D_5$ | $D_6$ | $D_7$ | $D_8$ |
| 1                 |                        |                             | 6.25  | 0.13  | 0.13  | 0.12  | 0.13  |
| 2                 | 0                      | 10                          | 8.25  | 0.15  | 0.13  | 0.13  | 0.13  |
| 3                 |                        |                             | 11.30 | 0.33  | 0.14  | 0.15  | 0.14  |
| 4                 |                        |                             |       |       |       |       |       |
| 5                 | 0                      | 14                          | 6.25  | 0.17  | 0.17  | 0.17  | 0.17  |
| 6                 |                        | 16                          |       | 0.20  | 0.19  | 0.19  | 0.20  |

2.3. The influence of different turbulent jet energy on time average of pressure at impinging portion.
Using MATLAB, a simulated analysis of the time average of pressure of the impinging portion in a water cushion pool was conducted, in order to demonstrate that under identical conditions, the time average of pressure at the impinging portion of the basin floor was much greater than that at other portions of the flow structure. Therefore, the impinging portion is more prone to suffer impact damage [15]. The experimental data consists of 16 numerical test values along the center axis of the basin floor, respectively drawing the nephogram and 3D space diagram distribution of time average of pressure under different working conditions with regard to the influence of different turbulent jet energies on the time-averaged pressure, set as from condition 1 to condition 9. By observing the pressure distribution, the pressure variation trend was analyzed as well as its influence on hydraulic factors under corresponding working conditions.
2.3.1. The influence of different turbulent jet energies on the time average of pressure at the impinging portion. See figure 7 to figure 12.

**Figure 7.** Working condition 1: $\theta=0^\circ$ d=10cm $Q=6.25\,m^3/s$.

**Figure 8.** Working condition 1: $\theta=0^\circ$ d=10cm $Q=6.25\,m^3/s$.

**Figure 9.** Working condition 2: $\theta=0^\circ$ d=10cm $Q=8.25\,m^3/s$.

**Figure 10.** Working condition 2: $\theta=0^\circ$ d=10cm $Q=8.25\,m^3/s$.

**Figure 11.** Working condition 3: $\theta=0^\circ$ d=10cm $Q=11.30\,m^3/s$.

**Figure 12.** Working condition 3: $\theta=0^\circ$ d=10cm $Q=11.30\,m^3/s$. 
2.3.2. The time average of pressure analysis.

- For any condition, under identical conditions, the time average of pressure at the impinging portion of the basin floor was much greater than that at other flow structure portions, and the maximum pressure appeared in the impinging portion, indicating that the impinging portion is more prone to suffer impact damage. In the design of a water cushion pool, the compressive strength of the bottom concrete slabs should be much greater than the time average of the dynamic pressure maximum.

- From condition 1 to condition 3, the incident angle was 0 degrees, the water cushion depth was 10cm, the turbulent jet energy increased in turn. From condition 4 to condition 6, the incident angle was 0 degree, the water cushion depth was 12cm, the turbulent jet energy increased in turn. From condition 7 to condition 9, the incident angle was 0 degree, the water cushion depth was 16cm, the turbulent jet energy increased in turn. The three conditions were compared and analysis was conducted. The average dynamic pressure at the impinging portion increased with turbulent jet energy, up to a peak value at the impingement point. The peak difference were large, but the corresponding impact on the upstream and downstream area and the time average of dynamic pressure tends to be approximately stable and equal.

- Once the incident angle and the depth of the water cushion are defined, the pressure is more concentrated and the peak value increases with turbulent jet energy. A great visible difference was observed on maximum impact pressure from the turbulent jet energy; for practical project applications, great attention must be paid to the control of turbulent jet energy.

2.4. The influence of different water cushion depths on time average of pressure at the bottom floor.

The influence of different depths of water cushion on the time average of pressure took into account nine working conditions for analysis. Two conditions were identical as conditions 1 and 4 mentioned above, and are there removed from the following analysis (See figure 13 to figure 18).

![Figure 13](image13.png)  
**Figure 13.** Working condition 4: \( \theta=0^\circ \) \( d=12\text{cm} \) \( Q=6.25\text{m}^3/\text{s} \).

![Figure 14](image14.png)  
**Figure 14.** Working condition 4: \( \theta=0^\circ \) \( d=12\text{cm} \) \( Q=6.25\text{m}^3/\text{s} \).
Figure 15. Working condition 5: $\theta=0^\circ$ d=14cm Q=$6.25m^3/s$.

Figure 16. Working condition 5: $\theta=0^\circ$ d=14cm Q=$6.25m^3/s$.

Figure 17. Working condition 6: $\theta=0^\circ$ d=16cm Q=$6.25m^3/s$.

Figure 18. Working condition 6: $\theta=0^\circ$ d=16cm Q=$6.25m^3/s$.

2.4.1. The time average of pressure analysis.

- Under changing depths of water cushion, the peak value of the time average of pressure still appears in the impinging portion, indicating that the impinging portion is most prone to suffer scour damage.
- Conditions 1, 4, 10 and 11, all included incident angles of 0 degrees, turbulent jet energy of $6.25 \times 10^{-3} m^3/s$, and increasing water cushion depth. From condition 12 to condition 16, the incident angle was 45 degrees, the turbulent jet energy was $6.25 \times 10^{-3} m^3/s$, depth of water cushion increased in turn. The two conditions were compared for analysis. Results clearly indicate that with different water cushion depths, when the time average of dynamic pressure reached the maximum value, the corresponding impact on the upstream and downstream area, and the time average of dynamic pressure tends to be approximately stable and equal. Additionally, the average dynamic pressure of the impinging portion increases with the depth of water cushion; however, under different working conditions, the pressure difference value near the maximum
pressure portion is more obvious than that of turbulent jet energy, and tends to increase with water cushion depth, though the peak value difference is not large.

- Once the incident angle and the turbulent jet energy are defined, as the depth of the water cushion increases, the pressure becomes more concentrated. There is little influence on the impingement portion time average of dynamic pressure exerted by the depth of the water cushion.

3. Conclusions

- Using MATLAB combined with numerical analysis and simulation, respectively for turbulent jet energy and the depth of water cushion, the distribution of time average of pressure on water cushion pool impinging portion was analyzed. Based on the corresponding pressure nephograms and 3D space diagrams, the water cushion impinging portion was verified as the most prone to suffer erosion damage. Therefore, subsequent recommendations can be made for water cushion pool anti-scouring design. The specific conclusions of this paper are as follows. Based on turbulent jet theory, dimensional analysis and the corresponding experimental data, semi-empirical formula for the impinging portion at any point pressure under the condition of this experiment can be determined and compared to the corresponding time average of pressure distribution curve, proving that the time average of pressure on the impingement area is in accordance with normal distribution characteristics. The present study demonstrated that the formula correctly, deduces the approximate range under experimental working conditions.

- In the experiment, incident angle and the depth of water cushion were defined, by adjusting the turbulent jet energy, and obvious wave change peaks were observed. Stronger turbulent jet energy resulted in greater peak values, and the time average of dynamic pressure tended to be stable and approximately equal.

- The incident angle and turbulent jet energy were defined by adjusting the depth of the water cushion. Results indicate that the time average of pressure on the impinging portion increases with the depth of the water cushion, but the peak of the wave change does not vary greatly. The time average of dynamic pressure distribution on the upstream and downstream areas indicate clear variation as compared to that observed under the turbulent jet energy working conditions. As the depth of water cushion increased, the time average of dynamic pressure tended to increase generally under each working condition in the upstream and downstream areas.

The calculated results of the semi-empirical formula are in good agreement with the experimental results, and confirm the relevance of parameters based on analysis of the time average of pressure on the impinging portion. Compared to other areas, the impinging portion is most prone to suffer erosion damage. According to the described experimental research, aeration decreases the dynamic pressure at the bottom of the water cushion pool, while the fluctuating pressure increases. Therefore, optimal design of water cushion pools should conduct self-aeration and artificial aeration appropriately, to reduce scour damage to the impinging area of the water cushion pool.

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Reference
[1] Lv Y Q, Li X Y and Dong J R 2001 Study on flow characteristics in water cushion pool and mechanism of energy dissipation Journal of Yangtze River Scientific Research Institute pp 10-12
[2] Liu P Q 2003 Probe into design criteria on energy dissipation and scour-prevention for plunge-pools Journal of Yangtze River Scientific Research Institute pp 3-6
[3] Rae P J 1994 Hydraulic design of spillway plunge pool linings Proceeding National Conference on Hydraulic Engineering pp 396–400
[4] Abramovich G and Schindel L 1963 The Theory of Turbulent Jets MIT Press
[5] Yang Y Q and Xu W L 1991 Numerical simulation of submerged jet within a water cushion pool Journal of Hydrodynamics pp 36–44
[6] Liu P Q, Dong R J and Yu C Z 1993 Investigation on rock bed scour by ski-jump water jets Journal of Yangtze River Scientific Research Institute pp 1–9
[7] Chen Y C, Dong J R and Wang Y M 1998 Study of the flow characteristics in the scour of downstream of Three Gorge spillway Journal of Tsinghua University(Sci& Tech) pp 115-18
[8] Xu D M and Yu C Z 1983 Surface water jet and its impact on the bottom of the channel pressure pulsation characteristics Shuili Xuebao pp 52–58
[9] Rajaratnam N 1967 Hydraulic jumps Advances in Hydroscience pp 197–280
[10] Rajaratnam N 1976 Turbulent jets Amsterdam: Elsevier Sc PublCo
[11] Frost W and Moulden T H 1977 Handbook of turbulence New York: Plenum Press
[12] Liu P Q 2008 The free turbulent jet theory Beihang University press
[13] Wang H Q and Zhang G B 2008 Hydraulic structures rushed abrasion and cavitation erosion failure mechanism and countermeasures Yunnan Hydroelectric Power Generation pp 89–92
[14] Dong Z Y, Yang Y Q and Wu C G 1994 Effect of aeration on dynamic water pressure at the bottom of the water cushion pool Science in China (Series A) pp 431-9
[15] Liu P Q, Li F T and Wang Y 2003 Experimental study on the change of flow pattern and pressure in the flow structure of the water cushion pool Shuili Xuebao pp 25-8