Concrete Erosion Modelling by Water Jet using Discrete Phase Method

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Abstract. To a great extent, for hydraulic structures, the durability relies upon the resistance that the concrete surface offers to mechanical wear. The surface damage caused by the process of uninterrupted material removal, induced by the impact of the water-borne solid particles, is termed hydro-abrasion. In nearly all hydraulic structures, this kind of progressive deterioration of the concrete surfaces is observed, in different intensities. Obviously, such hydro-abrasive concrete wearing normally results in a reduction in the service life of the hydro-technical facility, and consequently because of the repairs required, thenon-functioning of the facility during the repair period results in an expenditure spike. The influence exerted by the flow inclination angle was determined in this study. Numerical estimations were made of the four different angles (30°, 45°, 60° and 90°) employing the ANSYS software and discrete phase model (DPM) to simulate the fluid particles. From the findings of numerical investigations, it was clear that the maximum erosion rate can be reached when the flow inclination angle is 45° while the lowest rate can be achieved at a flow inclination angle of 30°.

Key words: concrete erosion, inclination angle, ANSYS

1. Introduction.
Generally, hydraulic structures are constructed using concrete. Therefore, during their operation, abrasion-induced erosion has been found to rank high among the main problems faced. Decomposition takes place due to the loads caused by the water flow of the sediment being transported. This becomes a serious issue when high velocities of water flow are encountered [1]. The water jet flow, was used to identify the relative abrasion resistance of the concrete surface caused by the impact of the flow inclination angles and the water-borne particles (sand, gravel and other such debris). It was Liu et al., who first proposed this method, in Taiwan [2]. The following characteristics of the sediment particles, namely size, shape, roughness, concentration, hardness, and angle of impact, all exert significant effects on the abrasion erosion which occurs on the surface of the concrete, an increase in the particle size would cause a rise in the abrasion rate[3]. This occurs due to the inability of the small particles to initiate cracks on the concrete surface. In addition, any increase in the
concentration of these particles induced a rise in the rate of abrasion. In reality, many factors strongly affect the abrasion resistance of the concrete[4], These factors can be classed under two categories, namely, the factors that relate only to the properties of the concrete, and the ones that depend upon the environment surrounding the hydraulic structures, which would include the specific aspects of the abrasive particles, angle of the fluid flow. Composites caused by waterborne materials in hydraulic structures, was determined. From the results it was evident that the abrasion resistance increased with a corresponding addition of the fibre content [5]. Based on the properties of the concrete, the abrasion resistance was noted to escalate[7,8]. In another study it was evident that abrasion erosion decreased when the quantity of cement was replaced with silica fume [9]. However, only a slight improvement was seen in the abrasion when small amounts of cement were replaced [10]. The erosion of pre-cracked cementitious composites by high-velocity hydro-abrasive flow can be described with a modified probabilistic comminution model [11]. A series of papers has been presented on concrete abrasion in hydraulic structure. Utilising the ASTM C1138 (underwater) test method appears to simulate all the critical processes of sediment induced abrasion expected in field conditions [12]. In this paper, we performed a CFD simulation as a numerical study by employing the ANSYS Fluent 19.0 to examine the manner in which the rate of erosion affected the concrete specimens, at different angles of impact and mass flows of the abrasive articles. To solve the flow of the water and abrasive sand particles, we used the two-phase Discrete Phase Method (DPM).

2. Numerical Methodology
Employing the ANSYS Fluent 19.0, a commercial CFD software, we simulated the abrasion erosion on the concrete samples used in this study. Applying the κ-epsilon equations and scalable wall function model, the high-quality meshes were generated. Applying the Discrete Phase Model (DPM) we calculated the particle sand erosion rates.

3. Numerical Modelling
3.1 Governing Equations
In this study, we used ANSYS Fluent 19.0 for the steady simulation of water, incorporating the effect of gravity, whereas the solid (sand particles) phase was modelled using the Discrete Phase Model (DPM). We employed the erosion model to find the final erosion rate on the concrete sample. In this program, the equations of continuity and momentum[13] (Eqs. 1 and 2, respectively) were applied to show the water flow.

\[
\frac{\partial u_i}{\partial x_i} = 0 \tag{1}
\]

\[
\frac{\partial}{\partial x_j} (\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ (\mu + \mu_t) \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] + \rho g_i \tag{2}
\]

Where \( \rho = \) density; \( \mu = \) dynamic viscosity; \( u = \) velocity, \( \rho g = \) gravitational body force, \( \mu_t = \) turbulent viscosity of liquid phase

3.2 Geometry Creation
Using the popular CFD Tool - ANSYS Fluent19.0, the geometry for the concrete plate is sketched in 3D with the dimensions of 20*20*5 cm, and jet dimensions of 1*20 cm. The concrete plates were positioned at the angles of 30°, 45°, 60° and 90° which represents the angle \( \theta \) revealed in Figure 1, measured from the y-axis.
3.3 Meshing Process

The four models were created using a tetrahedron mesh to mesh them, as depicted in figure 2. The features of the elements and nodes are given in table 1.

| Geometry | Number of Elements | Number of Nodes |
|----------|--------------------|-----------------|
| Angle 30 | 855066             | 161451          |
| Angle 45 | 855375             | 161529          |
| Angle 60 | 856228             | 161646          |
| Angle 90 | 843934             | 159587          |

4. Discrete Phase Method (DPM)

We used the Discrete Phase method (DPM) technique in Fluent to simulate the fluid particles as the second phase, to simulate the trajectories and interactions of the particles. The DPM is accurate in handling the particle movement associated with the fluid.
When momentum between the fluid and particles takes place, Fluent offers the option of including or excluding these effects by the use of Coupled or Uncoupled DPM. If the particles affect the flow solution, then the Coupled DPM will be utilised. If this is not the case, the uncoupled DPM is the preferred choice.

To solve the particle force balance equation, the local continuous phase conditions are applied, as given [13].

\[ \frac{d\mathbf{u}_p}{dt} = F_D (\mathbf{u} - \mathbf{u}_p) + g_x (\frac{\rho_p - \rho}{\rho_p}) + F_x \]  

(3)

Where \((\mathbf{v}_p \text{ and } \mathbf{v}_f)\) are, respectively, the particle and fluid velocities, \(\rho_p\) and \(\rho_f\) are the particle and fluid densities, respectively, \(g\) is the gravitational acceleration, where \((F_x)\) is used to account for additional forces, \(F_D (\mathbf{v}_f - \mathbf{v}_p)\) is the drag force per unit particle mass.

5. Erosion model

It is important to indicate in ANSYS Fluent has an inbuilt erosion model. [14], The erosion rate is defined by ANSYS FLUENT’s (standard model of erosion) a product of the mass flux, and specified functions diameter of particle, impact angle, and the velocity, as given below[13].

\[ R_{erosion} = \sum_{p=1}^{N} \frac{m_p C(d_p) f(\alpha) v^{b(\nu)}}{A_{face}} \]  

(4)

Where \(C(d_p)\) is a function of a particle, \(\alpha\) indicates the angle of impact of the path of the particle with the wall face, \(f(\alpha)\) refers to a function of the angle of the impact, \(v\) is the relative velocity of the particle, \(b(\nu)\) is a function of relative velocity of the particle, and \(A_{face}\) implies the cell face area at the wall.

6. Boundary conditions

1. The concrete specimens are held at four angles (30°, 45°, 60°, and 90°).
2. The jet velocity is set at 10 m/s.
3. The solid particles (sand), 0.6 mm in diameter, are injected into the domain, at a total mass flow rate of 0.00277 (kg \(\cdot\) s\(^{-1}\)).
4. The density of the concrete specimens used is 2300 kg/m\(^3\), ordinary Portland cement type R42.5.
5. A distance between concrete specimen and jet is 20 cm.

7. Results and Discussion

7.1 Velocity distribution on the concrete specimen

In figure 3, the results of the velocity distribution for the different angles of flow are depicted. The colour is indicative of the magnitude of the velocity on the surface of the concrete. It is evident that the maximum velocity zone is at the lower region of the specimens, while the lower velocity zone is at the upper region of the concrete specimens, which implies that the maximum velocity is seen under the effect of the streamline on the concrete specimens. The maximum velocities observed at the different angles are, respectively, (33.6, 39.1, 39.6, and 39.5) m/s.
Figure 3. Changes in distribution of velocity and location at different angles of impact; (a) angle 30°; (b) angle 45°; (c) angle 60°; (d) angle 90°.
7.2 Effect of angle of inclination on velocity
In figure 3, the effects of the angles of impact on the maximum velocity for the 30°, 45°, 60°, and 90° test geometries are (33.6, 39.1, 39.6, and 39.5) m/s, respectively, as shown. As evident, the surface area affected by velocity escalates as the angle of impact increases with the vertical, but it is also clear that when the angle of impact is 90°, the velocity is lower than that when the angle of impact is 60°.

In figure 4, the velocity distributions on the concrete sample on the z-axis are revealed. When the velocity of the concrete samples are seen, at the 45° angle of impact the vertical starts from 32 m/s velocity; at the 60° angle of impact the start is from 28 m/s; then, at the 30° angle of impact, it starts from 26 m/s; and at the 90° angle of impact, it starts from 21 m/s and then begins to decrease.

![Figure 4. Velocity distribution in the z direction.](image)

In Figure 5, the velocity distributions on the concrete sample on the line in the x-direction are shown, with all four angles of impact (30°, 45°, 60°, and 90°).

![Figure 5. Velocity distribution in the x direction.](image)

In figures 6 and 7, the maximum velocity for the four different angles, in the z and x directions, are shown.
7.3 Effect of the angle of inclination on erosion rate

The effects exerted by the different angles of inclination on the rates of erosion were examined using the concrete samples and sand particles, 0.6 mm in diameter, employing the Discrete Phase Model (DPM). In this study, four angles of inclination were investigated, with the verticals 30°, 45°, 60°, and 90°. In figure 8, the effects of the angles of inclination on the erosion rates are shown.
In figure 8, the inclination flow angle 45 has maximum erosion rate. This result since of within the case of the samples where the water jet is perpendicular on the concrete abraded surfaces (zero degree), the entire water affect strikes the concrete surface whereas For the case of the inclined surfaces, the pressure is analyzed into two components, with critical impact on the surface and led to serious abrasion.
As depicted in figure 9. The erosion rate on the concrete surface on the line in z direction explain that the erosion rate when concrete specimen hold on angle 90 is focused on the centre of the specimen while on angle 45 the erosion rate distribution to the all the surface.

![Figure 9. Erosion rate in the x direction.](image)

In Figure 10, the rates of erosion for the four different angles in the x-direction, are shown. It is evident that for the angle of impact of 45°, the erosion rate distribution on the lower and upper regions of the specimen occurs over the entire surface of the specimen in comparison with the other angles (30°, 60°, and 90°).

On the other hand the erosion rate in angle 30 is the minimum erosion comparing with other angles (45,60,90) because a small portion of the concrete surface angle is exposed to erosion by the influence of inclination flow angle.

![Figure 10. Erosion rate in the x direction.](image)
In figures 11 and 12, the maximum erosion rates for the four different angles, in the z and x directions, are shown. These two charts confirm that the erosion rate has the maximum value when the angle of impact is 45°.

8. Conclusions
1- In this study, the combination of the CFD model and DPM was used as the method of measuring and predicting the flow erosion of the particle-laden water. Many factors were taken into consideration such as, angle of impact, size of particle, velocity of flow, and total flow rate of the discrete phase model. From the simulation findings, the maximum erosion rate was observed for the 45° angle of impact.
2- The maximum rate of erosion of the concrete specimen was observed at the 45° angle of impact. This rate was seen to rise as the angle of impact increased from 30° to 45°; however, the rate was observed to drop above 45° and up to 60°; and then, for the 90° angle of impact, the erosion rate was seen to increase once again.
3- The high velocity noted in the lower regions of the specimens is initially explained as being caused by the sudden alteration in the direction of the flow. This occurs because the angle and flow induce more turbulence in the lower zones of the specimens.

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