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MECHANISMS OF HYDRO-ABRASIVE DAMAGE IN HYDRAULIC STRUCTURES

Summary

Durability of hydraulic engineering structures in most part depends on the resistance of concrete surface to mechanical abrasion. Hydro-abrasion represents a surface damage caused by continuous removal of material due to impact of waterborne hard particles. This form of progressive deterioration of concrete surface occurs, to a varying extent, in almost all hydraulic engineering structures. Therefore, hydro-abrasion wear of concrete in general causes reduction of the service life of a hydraulic engineering structure, as well as an increase in operating costs due to the necessary maintenance, and the downtime of the structure during the repair period.

Key words

Hydro-abrasion erosion, concrete, hidraulic structures, mechanism of hydro-abrasion

MEHANIZMI NASTANKA HIDRO-ABRAZIVNOG OŠTEĆENJA KOD HIDROTEHNIČKIH OBJEKATA

Rezime

Trajnost hidrotehničkih objekata u najvećoj meri zavisi od otpornosti površine betona prema mehaničkom habanju. Hidro-abrazija predstavlja površinsko oštećenje nastalo kontinuiranim uklanjanjem materijala usled udara čvrstih čestica nošenih vodom. Ovaj vid progresivne deterioracije površina betona javlja se u različitoj meri kod gotovo svih hidrotehničkih objekata. Stoga, hidro-abrazivno habanje betona generalno uzrokuje smanjenje upotrebnog veka hidrotehničkog objekta, kao i povećanje troškova zbog neophodnih popravki i neaktivnosti objekta u periodu reparacije.

Ključne riječi

Hidro-abrazija, beton, hidrotehničke konstrukcije, mehanizmi nastanka hidro-abrazije

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1. INTRODUCTION

Hydraulic structures are permanently or occasionally exposed to action of stagnant or running waters, across at least one of its surfaces. Since they are usually made of concrete, the used concrete, also called „hydraulic concrete“, must possess special performances in order to satisfy specific quality requirements for such structures. Surfaces of hydraulic structures (e.g. spillways, open channels, water tunnels, outlets) loaded by running water are exposed to action of high forces which generate mechanical erosion of concrete surface. In more precise terms, this mechanical erosion of hydraulic structures surfaces consists of “cavitation” (extraction of concrete parts from it surface), „fluid erosion“ and hydro-abrasion [1]. Fluid erosion is a special case of hydro-abrasion where the content of suspended matter is 0%.

At standard conditions, the impact of fluid erosion can be neglected, since its effects are relatively small. Cavitation erosion can be avoided by special structural shaping of hydraulic structures. Hydro-abrasion cannot be completely eliminated, but it can be mitigated using good quality abrasion resistant material, by periodical maintenance, occasional repairs and proper management of hydraulic equipment.

According to ACI 210R-93(R2008) [2], concrete erosion of hydraulic structures comprises surface damage of concrete, caused by three phenomena: cavitation, abrasion and chemical aggression. Cavitation is suction of loosely bound concrete particles from the spots on the hydraulic structures where high rate water flow generates low pressure. Abrasion is the phenomenon of wear of a concrete surface, occurring when grains of sand, gravel, silt, ice or waterborne rubble scrape and impact a concrete surface. Concrete erosion caused by chemical aggression is the phenomenon occurring when concrete degrades under the action of chemicals diluted in water, while water is in permanent contact with concrete. This concrete erosion is correlated with the cavitation and abrasion: chemically degraded concrete is a potential spot where suction of particles and crumbling of concrete surface is likely to occur.

2. HYDRO-ABRASIVE EROSION

In contrast the process of hydro-abrasion can be considered as the normal erosion case of surfaces of flow stressed hydraulic structures in natural waters. Hydro-abrasion represents a surface damage caused by continuous removal of material due to impact of waterborne hard particles and effect hydraulic forces on concrete. Hydro-abrasion of concrete surfaces causes intense demolition and leads to an increase of the hydraulic roughness. This kind of demolition acts as a combination of blasting and sliding [1,3-5] and is the most important type of mechanical erosion, Figure 1.

Hydro-abrasive damage is cause both by bed and suspended load. Bed load damage are usually found on the bottom of a channel or bottom parts of walls and columns, while abrasion with suspended load can occur in almost any part of the channel cross-section. The value of abrasion by the load carried by a channel can be predicted and taken into account in designing. Contrary to this, the value of abrasion caused by the swirl of water and solid material in the apron is not predictable, so in this case protective prevention measures are undertaken.

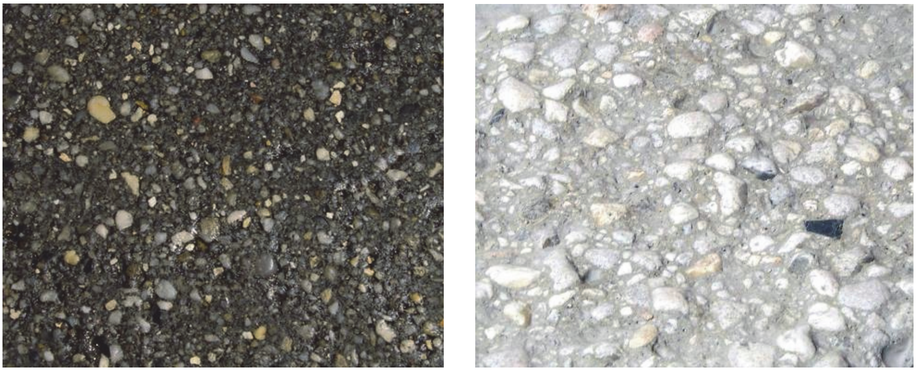

Figure 1. Hydro-abrasive stressed surfaces with visible scuffing damages left/right: grain diameter equal to or less than 8/16mm [6]

Damage which can be caused by hydro-abrasive wear ranges from surface wear of concrete directly exposed to water action to destruction of reinforcement and removal of a several decimeters thick layer of concrete [7]. Open channels, water tunnels, bottom outlets of dams, accumulation basins are particularly exposed to risk [1]. All these structures feature a combination of high velocity of water discharge and high amount of bed load.

In Europen and German Standards [8-10] the mechanical erosion is classified for practial use in three hierarchical „Exposition Classes“ (XM 1,2,3). It is treated as “Concrete Corrosion caused by Wear Stress“, Table 1. An classification shall be made by the dominant exposure during the whole anticipated average life of the hydraulic structure. A computation is also not intended in a practical appliance. The standards actually assume that a sufficient abrasive wear resistance of the exposition classes is given by the compliance with a minimium water/cement ratio, a minimum content of adhesive agent, the minimum compressive strength class as well as the kind and the consistence of the aggregate.

Table 1. Exposition classes for mechanical erosion (hydro-abrasion) on concrete surfaces on hydraulic structures [6]

Class	Desciption of the enviroment	Examples
XM 1	moderate wear stress	ship-induced rubbing (e.g. inside of lock chambers, above the tailwater – 1,0 m); surfaces stressed by moderate sediment transport and moderate flow velocities; grit chambers; river structures; ice rubbing
XM 2	strong wear stress	weirs and stilling basins stressed by moderate sediment transport and high flow velocities; torrent control
XM 3	very strong wear stress	stilling basins stressed by high sediment transport and high flow velocities; torrent structures; diversion tunnels

3. THE MECHANISM OF HYDRO-ABRASIVE DAMAGE

Hydro-abrasive damage of concrete surfaces of hydraulic structures develops in several phases. Lui et al. In their research [11] state that in chronological terms, abrasion advances in three phases, as displayed in figure 2. The first to occur is erosive peeling of a thin layer of concrete surface, by action of the water molecules, which is closely correlated to the flow velocity and corresponding hydraulic pressure, figure, Figure 2 (a). Afterwards, solid particles act on the concrete aggregate grains, creating surface cracks, figure 2 (b). Eventually, there occurs abrasive-erosive process related to the toughness of water-borne particles, flow velocity and bond strength of concrete component materials, figure 2 (c). Therefore, hydro-abrasive erosion was not caused only by the action of waterborne particles, but there are other factors as well.

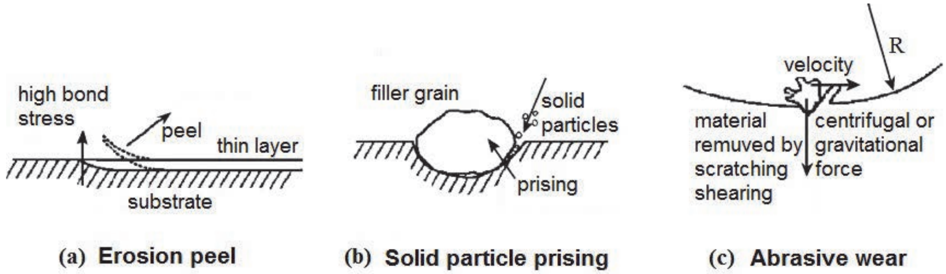

Figure 2. Applied stresses from water-borne sand on concrete surface [11-12]

Figure 3 illustrates a chronological abrasion of concrete surface exposed to hydraulic impacts of water borne particles over a long period of time. Initially, the surface layer of mortar is gradually worn, until the coarse grains of aggregate are directly exposed to the abrasive action. Further, the coarse grains are broken or prised out of the cement matrix. This results in formation of small cavities in the matrix, immediately next to the aggregate grains. Formation of cavities largely depends on the size of the coarse aggregate, type of used sand and rotation momentum of water jets which in time penetrate the interior of the concrete mass. Value of bonding force between the coarse aggregate and the matrix affects the hydro-abrasive resistance of hydraulic concrete.

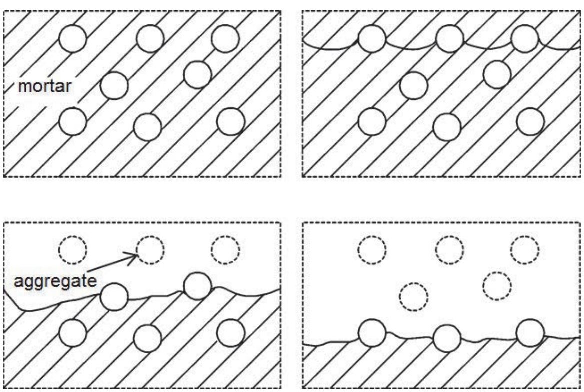

Figure 3. Abrasion erosion process of hydraulic concrete surface [11]

Jacobs et al. [13] also described the stress mechanism of concrete layer due to the action of abrasives from water. In figure 4 are displayed phases in the process of hydro-abrasive wear of a concrete surface. At the moment of impact, kinetic energy of a waterborne hard particle is expended on breaking the bond between the component materials in concrete. However, energy of the first impact is most frequently insufficient for breaking the bond (figure 4, phase 1), but accumulated effect of multiple particles will cause material fatigue and separation of parts of the concrete surface (figure 4, phase 2). Since the concrete surface grows increasingly rougher, the impact of the abrasive particle effect will be more intensive, and thus the damage propagation will progress (figure 4, phase 3).

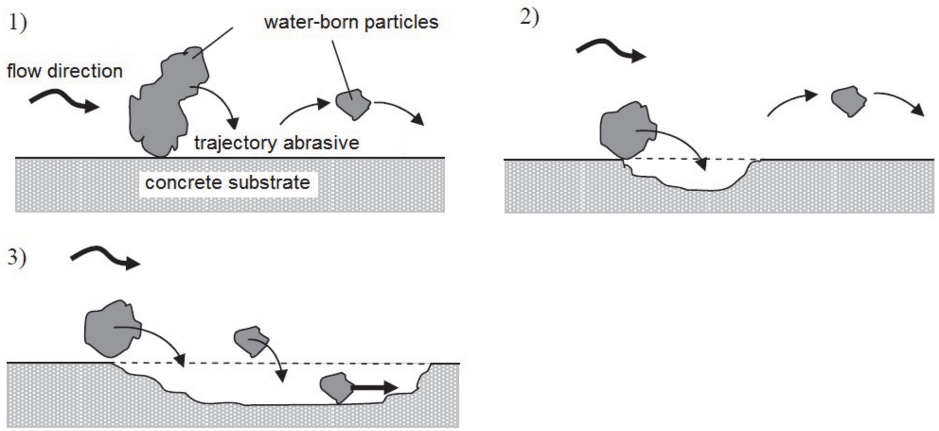

Figure 4. Initial and subsequent damage of a concrete surface due to the hydro-abrasive wear [13-14]

An accurate description of the particles in water, i.e. determination of its path and attack angle is not known in practice. For a better understanding of hydro-abrasive wear mechanism, in figure 5 was presented a simplified set of possible situations. A clear distinction was made between the impact and sliding of a hard particle. [13].

Huovinen [15] uses a different approach for explaining the mechanism of hydro-abrasive loading of a concrete surface, figure 6. The basis for this model are the loads acting on the maritime structures in the Arctic region. In this type of erosion, abrasion occurs due to the ice action on the concrete surface. As it can be seen, the process of hydro-abrasive wear occurs in three phases. In the first phase, the surface layer of mortar is abraded due to normal and tangential stresses, whereby the damage propagates until the first coarse grains of aggregate become visible. For this stress phase, the quality of cement stone is very important, i.e. its resistance to abrasion, because the higher the resistance the slower the damage propagation. In the second phase, the coarse aggregate grains take on the hydro-abrasive stress and prevent further propagation of erosion, until they fail or get prized out of the cement stone. The quality of the coarse aggregate is of great importance for this stress phase, as well as the quality of the bond between the cement stone and aggregate. In the third phase, there is an accelerated abrasion of concrete created due to the pitted concrete and increased wear surface area. The abrasion process will decelerate as the coarse grains of aggregate appear on the surface of concrete. Propagation of hydro abrasive wear is considerably faster if a concrete surface has some discontinuities or joints [13,16].

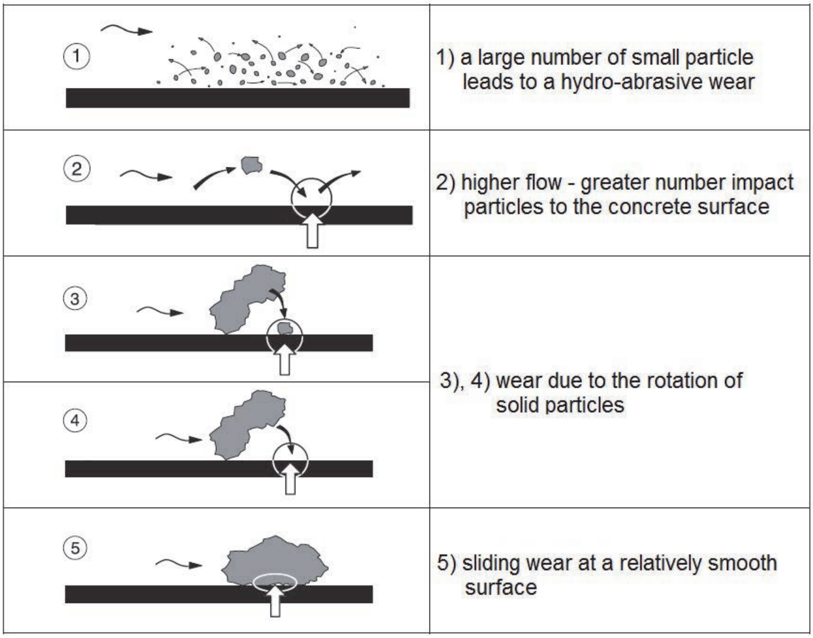

Figure 5. Classification of various stresses on the concrete surface due to the action of abrasive from water [13]

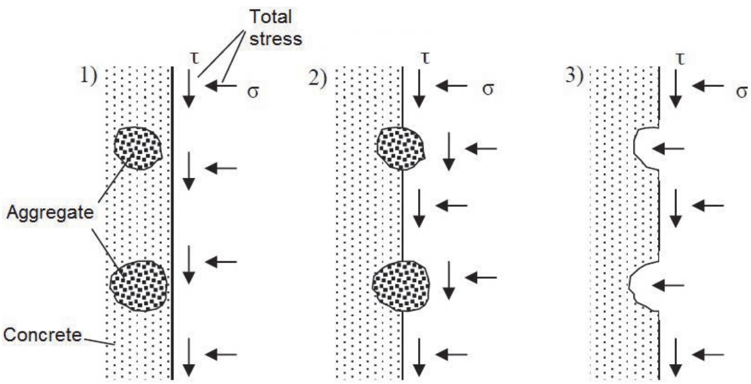

Figure 6. Stress and abrasion mechanism due to ice action [7,9]

Volkart in his research [17] discusses the effect of hard water-borne particle impact on the concrete surface. He states that the momentum of a hard particle is mostly defined by its mass, velocity and attack angle, whereby velocity and attack angle depend on the characteristics of the water flow, Figure 7. Particle strength and surface toughness of concrete, as well as the particle shape affect the abrasion degree of the concrete surface caused by the impact. When analyzing hydro-abrasive wear, one should take into consideration the total number of dynamic contacts in a unit of time, particle concentration and distribution of particle size and shape.

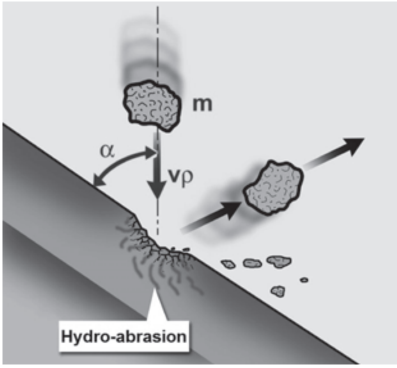

Figure 7. Effects of water-borne hard particle impact on the concrete surface [17]

4. CONCLUSION

Concrete abrasion is the main problem of hydraulic structures, through which or over which the water flow transports large quantities of sand and gravel. Due to the impact of solid particles on a hard obstacle, fine cracks develop on the contact surface with water; pulsating hydraulic forces then start to act inside the cracks. If in those conditions the compressive and tensile stresses are exceeded, the material will fail and its interior bonds will be destroyed, and the broken off particles, which became new causes of concrete wear, as they are carried downstream by the flow.

Abrasion intensity depends on the hydrodynamic characteristics of the water flow (water velocity, pressure pulsations, turbulence, presence of vortices, velocity of impact of solid particles on the hard surface, that is, energy imparted by the particle at impact, angle at which the particle impacts the hard surface), physical characteristics of sediment (shape, size, weight, mineralogical composition - toughness), quantity of transported sediment, duration of sediment transport and mechanical characteristics of concrete or concrete cladding (compressive and tensile strengths, resistance to fatigue, impact and abrasion). The higher the sediment concentration and the weaker the mechanical characterizes of concrete, the damage is greater.

Abrasive damage of concrete on hydraulic structures represent a continuing technical problem, so in order to increase durability of these structure, the concrete mix designs must be resistant to abrasion-erosion action. It is necessary to study in detail the damage mechanism, determine research methods, test various material for abrasive resistance, provide proposals of how to rehabilitate the existing damaged hydraulic structures and how to construct new ones. Abrasion process can be slowed down, but not eliminated using protective concrete mass cover, plan of hydro-mechanical equipment management, periodical maintenance and occasional repairs.

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