# CAVITATION DESTRUCTION OF CONCRETE AND PROTECTIVE FACINGS UNDER NATURAL CONDITIONS

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The first cases of cavitation erosion of concrete of hydraulic structures were noted at the end of the 1930's (Bonneville Dam, USA), but reports about this appeared much later in the literature [1, 2].

Cavitation erosion of concrete of hydraulic structures after 1-2 years service has been described and partially analyzed in domestic literature. Such destruction has been noted at the V. I. Lenin Volga [3-5], Bukhtarma [6], and Bratsk hydroelectric stations [7], and Suphung station in the Chinese People's Republic [8].

In 1963 a field inspection was made of the condition of the concrete in the lower pool of the dam of the V. I. Lenin Volga hydroelectric station.* Unlike previous years, besides the energy dispersion baffles an investigation was the made of condition of the concrete of the spillway face, piers, bottom of the stilling pool, and first subsidiary dam of the third section, which was dewatered for repair for the first time after 7 years of service.

The concrete dam is divided by two massive abutment piers reaching to the first subsidiary dam, into three sections (the sections are numbered from the left bank to the right). The stilling device consists of two rows of energy dissipation baffles in the form of truncated pyramids located on the bottom of the stilling pool in staggered order and two subsidiary dams. Twelve deflecting baffles are located in each extreme section to eliminate convergence of the current near the bank abutments.

The presence of destruction on such elements as the side faces of the baffles and bottom of the stilling pool in the wake of the piers precluded the assumption that destruction was caused by the impact of floating bodies or the dynamic action of the water flow. An analysis of the possible causes of destruction led to the conclusion that erosion in the examined cases was the result of cavitation. It was found in the inspection that the concrete of the energy dissipation baffles and the deflecting baffles had experienced maximum cavitation destruction. Out of 82 dissipating and deflecting baffles 57 were eroded to a depth of 10-60 cm. Destruction occurred mainly on the dissipation baffles located in the middle of the span (Fig. 1). One deflecting baffle and 13 dissipation baffles of the first row were severely erorded. For some, up to 60% of the side surfaces were eroded and the exposed 25-cm-diam. reinforcement was deformed (Fig. 2). The presence of a large quantitity of gravel protruding from the concrete was characteristic for the cavitation zone on the inside faces (Fig. 3). This fact, and the results of laboratory tests [9] proved the assumption that cavitation erosion of concrete begins in the "binder-aggregate" contact zone and consists in destruction of the hardened binder, weakening of the bond of sand grains in the conglomerate, and washing out of the mortar component and then of the coarse aggregate particles.

Destruction of the upper and front faces of the deflecting baffles and dissipation baffles of the first row was quite insignificant (Figs. 1, 2, and 4). The dissipation baffles of the second row were in much better shape; erosion of the side faces was rare and small in area, but in the overwhelming majority (about 80%) the front face was eroded. The erosion zone extended over the entire width of the face; it began at a height of 0.5-1 m from the base of the disspation baffle and had a height of 0.3-0.4 m, with uniform wear to a depth of 2-5 cm. The character of destruction differed from the cavitation destruction on the side faces of the dissipation baffles: the aggregate was exposed but not torn out, roughnesses were smoothed out, and there were no cavities, which were characteristic for the cavitation zone on the side faces.

Figure 4 shows cavitation destruction of the concrete on the side face of the deflecting baffle. Cavitation occurred when the current flowed from right to left past the edge between the front (inclined) face and the destroyed face of the deflecting baffle. The erosion zone extended up 2/3 of the side face. The depth of erosion was not constant over the entire zone. Erosion of maximum depth occurred at the site of a poorly made (as a consequence

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*The inspection was performed by G. A. Vorob'ev and the author.

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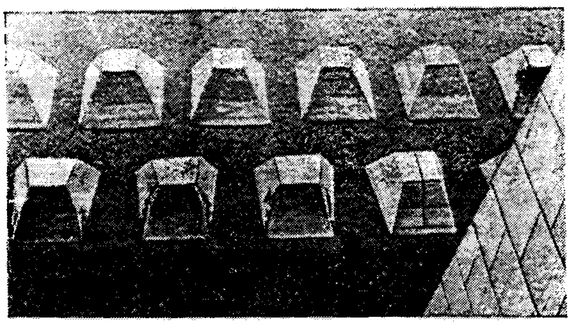

Fig. 1. Caviation destruction of energy dissipation baffles. View from the dam crest (the baffles of the first row located in the middle of the span were subjected to greates damage).

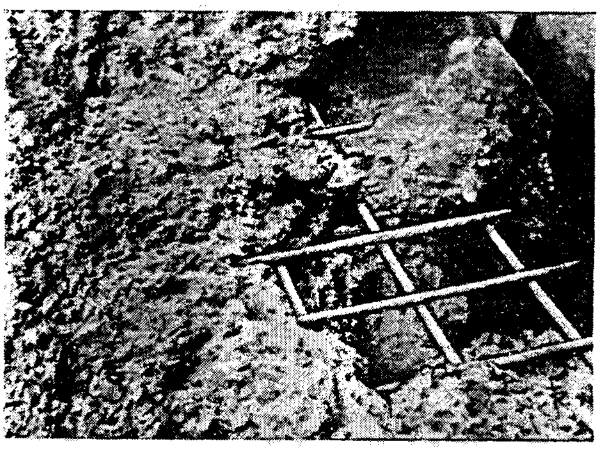

Fig. 2. General view of destruction on side face of energy dissipation baffle of first row.

of interruption during concreting) joint, which was indicated by a horizontal crack clearly seen on both sides of the eroded surface and outcropping on the front and second side face. This joint proved to be the weakest section on the side face of the dissipation baffle due to weak adherence of the new concrete to the old. Here the deepest erosion occurred. The same photograph demonstrates the decrease in resistability of the concrete to cavitation where the reinforcement rods are placed. This example shows that in those places of concrete structures where cavitation is expected to take place it is necessary to pay particular attention to the placement of high-quality concrete and appropriate control of the concrete hardening conditions, and the thickness of the protective layer should be increased as opposed to the standard 3-5 cm.

A few cases of cavitation destruction of the shell slabs on the walls of the piers and abutments were noted. The sources of cavitation here were the roughnesses in the vertical joints between the shell slabs or curvature of the surface at their junction, and also the energy dissipation baffle concreted to the wall of the abutment piers. Slight erosion occurred also on the floor of the stilling pool in certain places. Cavitation in this case occurred in the wake of the piers or dissipation baffles; destruction of the concrete also occurred here. Cavitation of the concrete was not noted on the spillway face and first subsidiary dam.

The energy dissipation baffles of the first section, which had been repaired in 1961, and the middle (second) section, which had not been repaired (both section had been filled with water), were inspected from the bridge crossing and first subsidiary dam. In both cases many baffles had caviation destruction. Of the baffles repaired in 1961, 15% were again eroded.

In 1961 energy dissipation baffle No. 243 (first section, second row) was repaired by means of plastic-concrete on a base of furfural acetone (FA) monomer [10]. The 1968 inspection revealed that the plastic-concrete filling (Fig. 5) on this baffle was in satisfactory condition: there were no appreciable traces of erosion, but large cavitation erosion had again appeared on some baffles repaired with cement concrete. However, it is necessary to point out that the joint between the cement concrete and the plastic-concrete was loose. This is explained by the difference of the materials being joined: cement concrete has an alkaline base whereas the FA-plastic-concrete has an acid base. Therefore, the joint between them is always a weak place, although the plastic-concrete itself has a high erosion resistance.

An analysis of the results of the described inspections and the data of domestic and foreign practice shows that cavitation arises at flow velocities of 12-15 m/sec on those elements of structures where smooth flow-around is not always possible: in gate guides, inlet heads and outlet portals of conduits, energy dissipation baffles, and on rough surfaces. Cavitation generally causes erosion of the concrete, which develops not only on the elements themselves, the cavitation sources, but also in their immediate vicinity: on the walls of piers behind the gate guides, on the floor of the apron beyond the baffles, on spillways near the discharge portals of conduits, and, finally, at any place of the structure beyond roughnesses or other sections of the surface with poor flow characteristics. Intense erosion of concrete develops at flow velocities greater than 18 m/sec.

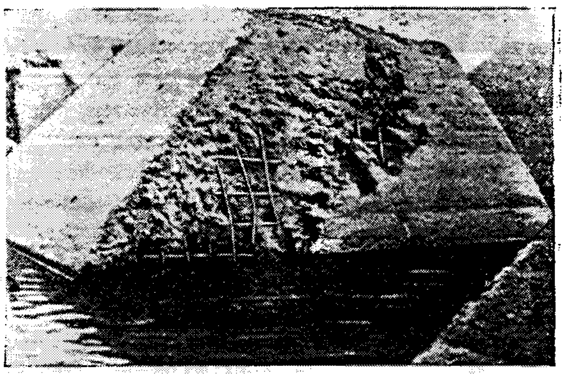

Fig. 3. Fragment of cavitation zone of concrete on side face of energy dissipation baffle.

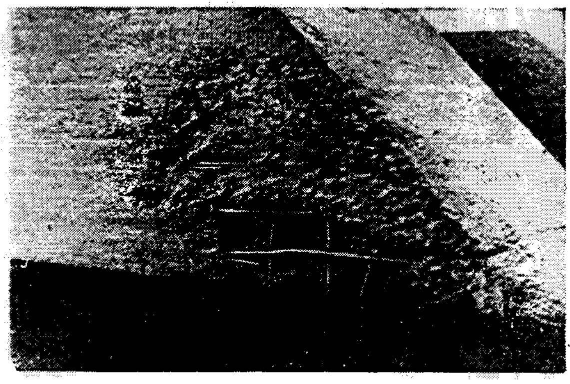

Fig. 4. Cavitation erosion on side face of deflecting baffle.

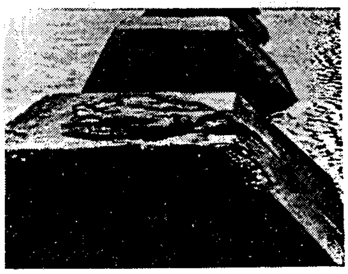

Fig. 5. Conditions of plastic-concrete filling on energy dissipation baffle after two years' service.

In this article an attempt is made to systematize data on the composition and strength of concrete subjected to cavitation and protection of concrete against cavitation by means of facings and coatings. Information on the composition and properties of facings and coatings of cavitation-damaged concrete is given in Table 1 compiled from data from domestic and foreign literature and from the results of the field inspections described above.

In most cases the slump of the concrete mix was less than 7-8 cm, the water-cement ratio (w/c) was 0.5. The consumption of pure clinker cement did not exceed 240 kg/m$^3$ mix. The type of material and particle shape of the aggregate were not of particular significance: gravel with a maximum size (MS) of less than 7.6 cm was used in most instances as the coarse aggregate. In this case the strength of the concrete did not generally exceed 200-220 kg/cm$^2$ and only in certain cases approached 300 kg/cm$^2$.

Appreciable erosion of the concrete developed at the flow velocities indicated in Table 1 and after the passage of one or two floods repairs were required. A concrete mix with a higher consumption of cement and smaller w/c prepared on aggregate with a smaller MS (Bull Shoals Dam, Table 1) were used for repair. At the Lucky Peak Dam a concrete mix with a cement consumption of 382 kg/m$^3$ prepared on aggregate with MS = 1.9 cm was placed at sites where cavitation was assumed to have occurred. It was found upon inspection after dewatering that there were practically no traces of erosion. At other places on this structure cavitation erosion of the concrete to a depth of 1 m with an area of individual eroded sections to 5 m$^2$ occurred within 15 days of service. The concrete of the eroded zone was prepared on an aggregate with MS = 7.6 cm and cement consumption of 245 kg/m$^3$.

These data show the importance of the cavitation-resistance factor of concrete, which was pointed out earlier [11]. Along with a more careful approach to the selection of concrete composition, it has become necessary to protect concrete surfaces by facings and coatings of more cavitation-resistant materials, since concrete of ordinary composition and strength is rapidly, and sometimes even catastrophically rapidly, eroded due to cavitation. Laboratory investigations [12, 13] showed that certain metals and alloys and polymer-base materials are cavitation-resistant materials.

The first experiment in the protection of concrete against cavitation by means of metal facings was made in 1947 on the Bonneville Dam (USA); the energy dissipation baffle was faced with steel sheets 9 mm thick [2]. The facing was fastened to the reinforcement frame by 30-mm-diam. bolts set every 30 cm in plan. Traces of erosion were recorded on the facing after a year's service by a water-diving inspection. After 7 years it was established that the facing on the front was intact, but on the sides was largely torn loose and the concrete eroded [14].

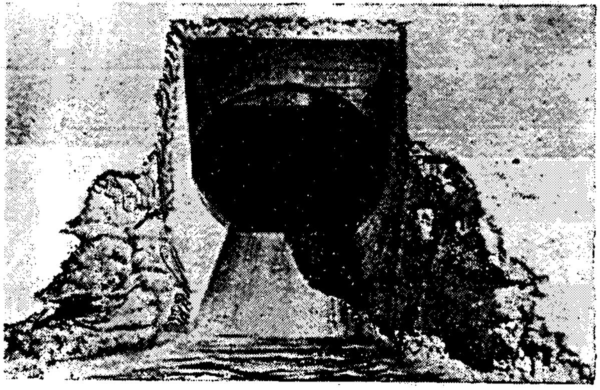

Fig. 6. Cavitation destruction of concrete of the junction between the outlet portal of the deep conduit and spillway face.

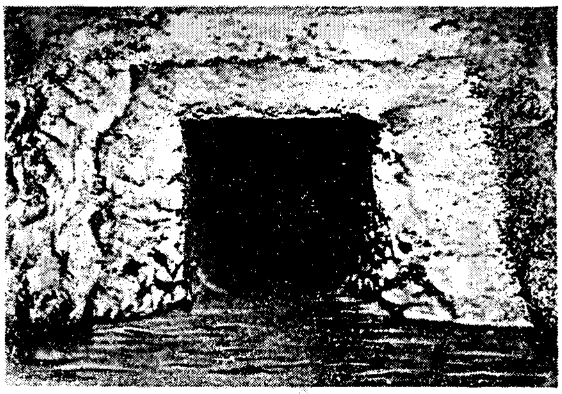

Fig. 7. Cavitation erosion of concrete of a model of the junction.

Later the inlet works of the deep conduits at the V. I. Lenin Volga station (front part) [4, 5] and at the Bratsk station (section beyond the gate guides) [7], the spillway piers behind the gate guides on the Bonneville Dam (USA) [14], and the energy dissipation baffle on the Gatun dam (Panama), etc., were faced with metal sheets 10-50 mm thick fastened by steel anchors up to 25 mm in diameter welded to the reinforcement.

The experiment of using steel facing to prevent cavitation erosion of concrete on the Miranda Dam (Portugal) is interesting and instructive [15]. At this 80-m-high dam considerable cavitation of the concrete occurred of the junction between the outlet portal of the deep conduit and spillway face during eight months of service (Fig. 6), when only the crest spillway was operating. Cavitation was an unexpected event for the designers and builders. Control model investigations of this component in the laboratory confirmed the occurrence of cavitation and development of erosion of the concrete (Fig. 7). On the basis of this it was decided to change the geometry of the junction component and use a metal facing of 10-20 mm steel sheet. The facing and the general view of the junction after repair are shown in Fig. 8. Such repair was done twice, but each time the facing was ripped away and the concrete severely eroded (Fig. 9).

Polymeric materials have also been used to protect concrete against cavitation [16]. A Neoprene coating was applied to the concrete baffles in the spillway channel on the Lower Durance River (France). Within a year's service it was completely destroyed in many places, after which erosion of the concrete began.

Information on the caviation erosion of protective facings of steel and polymeric materials are given in Table 2. Polymer coatings, mainly on an epoxy base, for protection of concrete against various actions, including cavitation, have recently been used in the construction and repair of hydraulic structures in our country (Charvak hydroelectric station) [17] and abroad (Milford, Priest Rapids, Rocky Ridge dams in the USA, and others). However, reliable and comparatively long experience has not been accumulated in the use of these coatings. Here it is necessary to take into account that preliminary experiments to check the caviation resistance of various polymer coatings on concrete, carried out at the V. V. Kuibyshev Moscow Civil Engineering Institute and the Research Department of Gidroproekt, did not give very encouraging results: most of the tested coatings were quickly separated from the concrete surface when affected by cavitation [18]. These results agree with the conclusions of other investigators [19].

## CONCLUSIONS

1. At flow velocities greater than 15-18 m/sec cavitation occurs at a number of places on hydraulic structures, which causes intense erosion of concrete. Therefore, when designing structures it is desirable to eliminate conditions giving rise to cavitation.

2. Experience gained in the use of protective steel facings and polymer coatings shows that under cavitation conditions the anchors are quickly torn away and the adherence of the facing (coating) to the concrete is disrupted, which leads to partial or complete separation of the facing (coating) and development of cavitation erosion of the concrete.

TABLE 1. Data on the Composition and Properties of Concrete Destroyed by Cavitation

| Structure (dam) | Country | Site of destruction | Flow velocity, m/sec | Concrete* | | | Data on composition, and properties |
|---|---|---|---|---|---|---|---|
| | | | | grade | actual strength, kg/cm$^2$ | age, days | |
| V. I. Lenin Volga station | USSR | Energy dissipation baffles | 18-21 | 250 | 160-170 | 60 | 7 of the 38 samples had the actual strength at the indicated age |
| | | Input heads of deep spillways | 18 | 250 V4 | – | – | – |
| Bratsk station | " | Deep conduits | 30 | 200 V8<br>Mrz 100 | 300 | 180 | – |
| Bukhtarma station | " | Gate units | 25-30 | 150 V8 | 172-184<br>222 | 28<br>18 months | – |
| Bonneville | USA | Spillway piers, apron, baffles | 18-21 | – | 130<br>185<br>260 | 3<br>7<br>28 | Maximum size (MS) of gravel 7.6 cm; w/c = 0.52; r = 0.35; slump 7 cm; cement consumption (25% additive) 324 kg/m$^3$ |
| Suphung | China | Spillway face | 30-40 | – | 51-192 | 12 years | Waterproofness below V4, unsatisfactory frost resistance at 75, 100, and 150 cycles |
| Lucky Peak | USA | Gate units | 37 | – | – | – | MS 7.6 cm; cement consumption 245 kg/m$^3$ and MS = 1.9 cm; cement consumption 382 kg/m$^3$ |
| Bull Shoals (repair) | " | Apron steps | 25 | – | – | – | MS = 3.8 cm; w/c = 0.41-0.45; cement consumption 335 kg/m$^3$ |

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*The actual strength of the concrete of the Suphung dam was determined by core samples, and in other cases by control cubes.

†The occurrence of cavitation was assumed in the second case. There was practically no erosion after discharge of water.

TABLE 2. Cavitation Erosion of Protective Facings (based on literature data)

| Structure (dam) | Country | Erosion site | Flow velocity, m/sec | Facing | | Character of destruction | Service time, floods |
|---|---|---|---|---|---|---|---|
| | | | | material | thickness, mm | | |
| V. I. Lenin Volga station | USSR | Inlet works of deep conduits | 18 | Steel | 16 | Partial or complete separation | 1 |
| Bratsk station | " | Deep conduits beyond gate guides | | | 10 | Complete separation | 1 |
| | | | 30 | Steel | 16* | Partial separation | 1 |
| Bonneville | USA | Baffle** | 18-21 | " | 9 | Partial separation on side faces | 7 |
| | | Spillway piers beyond gate guides | 15 | " | 12 | Part of the plate was torn away | 1-4 |
| | | | | | 25* | Erosion to depth of 12 mm | 6 |
| Gatun | Panama | Baffle | – | " | 50 | Partial separation on side faces | – |
| | | | | | 75** | – | – |
| Ross | USA | Bypass tunnel | 15 | " | 16 | Through-erosion beyond local roughnesses | – |
| Miranda | Portugal | Outlet portal of deep conduit | – | " | 10-20 | Complete separation | 1 |
| | | | | | | | 1 |
| Series of stations | France | Baffles in spillway channel | – | Neoprene | 5 layers | Erosion was through the Neoprene and concrete partially under it | |

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*Installed in place of destroyed facing

†Facing of front was not eroded

Fig. 8. General view of faced junction between outlet portal of deep conduit and spillway face.

Fig. 9. Erosion of faced junction after passage of one flood.

3. To increase the cavitation resistance of hydraulic concrete it is necessary not only to search for effective methods of protecting it by means of facings (coatings) and to perfect methods of their attachment on the concrete base, but also to study the possibility of increasing the resistance of the concrete itself under cavitation conditions. These investigations should determine under what conditions and in what elements of the structure the concrete can successfully and for a long time withstand cavitation and what requirements should be taken into account for increasing its cavitation resistance.

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