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Gravity dams under blast loading: A Review

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Abstract

Hi-tech wars, accidental explosions, and subversive bombing attacks have alarmingly increased throughout the globe in recent times. Destructive Beirut explosion that occurred recently is the witness of this fact. Thus, it is increasingly realized that blast loading is a potential threat to the structures of higher importance. With the rapid development of precision and transmission techniques, the accuracy to blast the target and destruction potential of guided or controlled blasts have increased the vulnerability of important structures from subversive attacks in strategic border areas. Consequently, important infrastructure has become susceptible to such harsh blast loadings. Notwithstanding this prevailing belief that risk to water facilities from blast loading is small, yet dam operators and engineers are aware of 9/11 kind of threat [6]. The failure of dams with large reservoirs as a result of blast loads will cause serious economic loss by damaging the structure, hit agricultural sector of the area and also inundate downstream populated area. Modern dams are designed considering conventional loads, including hydrostatic pressure, gravity, sediment pressure, uplift pressure and seismic loads. Seismic performance evaluation of dam-reservoir-foundation systems under strong earthquakes has been widely studied [1, 10, 17, 18, 28, 29]. The effects of explosions on dams are not very well understood because not many investigations have been done on blast performance of dams. This is why most dam engineers lack the understanding of response of dams under blast loading.

This review presents the studies conducted on gravity dams subjected to various kinds of impulsive loadings. Also, numerical investigations done on concrete gravity dams (CGD) subjected to blast loading have been comprehensively reviewed. Probable research gap on underwater explosive loading to dams is also presented.

Keywords: Blast, Gravity Dams, Underwater Explosion, Finite element (FE) simulations, Review

1. Historical review of attacks against dams

Dams are primarily designed for creating a water reservoir. Other benefits include power generation, flood and storm surge protection, recreation, and many other critical economic and social benefits. Being prominent source of economy, dams and reservoirs are targeted and attacked by blast loading during wars. There were several blast attacks on dams over the past century, as summarized in Table. 1. A brief historical review of some prominent attacks is presented as follows:

1) Concerned with leaving the Dnjeprostroj Dam, also known as Dnieper hydroelectric power station under German control during the Second World War (1941), the Soviet Army dynamited this dam using total 90,000 kg of explosives in the inspection gallery as a retreat [5]. The dam suffered extensive damage, as shown in Fig. 1(a). The breach of the upper part of the dam was approximately 200 m wide, and the resultant outflow of water through the breach reached a maximum rate of 34000 m^3/s making twenty thousand to one lakh people the victims of this incident.

2) During Operation Chastise, four dams came under attack by British Royal Air Force (RAF) in the Ruhr valley of Germany:
The first was earth fill embankment dam known as Sorpe Dam. This dam had suffered two direct hits on its crest by the Upkeep bomb (Bouncing bomb) filled with 3,600 kg of RDX in 1943, which resulted in craters of 12 m depth. However the dam was not compromised. Shortly after the Dambusters raid, the water level of the Sorpe reservoir was lowered as a precautionary measure. In 1944, the Sorpe Dam was again attacked several times by the Allied Forces. Attack on the Sorpe Dam resulted in a total of 11 direct hits. The craters caused by bombing could be seen on the downstream surface of the dam, as depicted in Fig. 1(b). Although this attack led to a depth of 12 m and 25 to 30 m diameter craters to the dam, the Sorpe dam did not breach. When the dam was repaired in 1958, an unexploded "Tallboy" bomb was found buried in the dam.
The second was the Möhne Dam, arched concrete gravity dam, which was also attacked by the Upkeep bombs in the same year. Although the Möhne Dam was attacked with five bombs, only two bombs struck dead-center of

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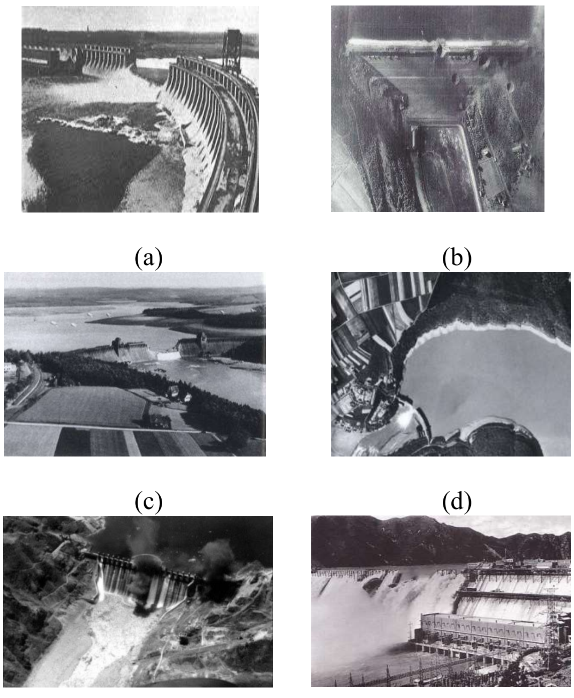
the upstream face of the dam.. The breach of the Möhne Dam was about 75 m wide at the top and 22 m at the center. After removing all loose material, the breach size was estimated to be approximately 105 m wide and 27 m high, as given by Fig. 1(c). The breach of the Möhne Dam resulted in a 10 m high wave through the narrow Möhne Valley, which caused huge destruction. The third was the Eder Dam, a rubble stone masonry dam which was attacked by three Upkeep bombs in 1943. Although one bomb overshot the dam, the other two Upkeep bombs hit just off-center and breached this arched stone masonry dam. The breach was approximately hemispherical with a radius of 25 m, as shown in Fig. 1(d).

3) In the Korean War (1952), many dams, such as the Hwachon dam, concrete gravity dam [41] (Fig. 1(e)) and Sui-Ho Dam concrete gravity dam [40] (Fig. 1(f)) on Han River in South Korea were attacked, causing serious damage to the country's economy. Sui-Ho Dam was attacked multiple times by aerial bombing by US forces. The attack resulted in permanent destruction of 90% of generating capacity of Sui-Ho dam. The Hwachon dam was initially attacked by the U.S. Navy using conventional bombs. Seven of the eight torpedoes used for attack struck the dam and six exploded on or near the floodgates. The dam got breached and one sluice gate was destroyed. This is the last time that aerial torpedo was used globally.

4)



(a) (b) (c) (d) (e) (f)

Fig. 1: Dam breach due to military attacks. (a) Dnjeprostroj Dam [4]; (b) Sorpe Dam [21]; (c) Möhne dam [9]; (d) Eder dam [9]; (e) Hwachon Dam [41]; (f) Sui-ho Dam [40].

5) Peruća Dam, located in Croatia is an earth fill embankment dam. During the Balkan war, Serbian forces installed approximately 20 to 30 tons of TNT at five locations in the wall of the spillway structure and the inspection gallery in 1992. On January 28, 1993, the Serbian forces again took control of the dam, and subsequently detonated the explosives pre-embedded in the spillway structure and inspection gallery of the Peruća Dam. Although this attack did not cause a failure of the dam body on account of lowering the water level however inspection gallery was heavily damaged. The explosions resulted in two large craters at the left and right abutments [16]

Besides the above large-scale military strikes on dams, attacks carried out by individuals, small or large militant groups may also cause damages to dams. According to statistics from the U.S. Department of Homeland Security (DHS), there were 25 attacks on dams worldwide between 2001 and 2011. These events include attacks on dam structures, power-generation equipments, control facilities etc. Explosive devices such as improvised explosive devices (IEDs) that functioned as a designed bomb, or a small number of explosives were the most common attack types; a small group of armed men and standoff weapons (mortars or artillery) were also common modes of attack [44]. Statistical results show that the blast performance under the blast attacks of dam structures (e.g. concrete gravity and embankment dams) is relatively higher due to the large volume. However, appurtenant facilities and equipment are easy to damage under blast attacks. All these attacks indicate that the dams too become targets of subversive attacks. Huge quantities of explosives can cause heavy damage to dams.

The safety of important infrastructure, such as dams, is facing an increasingly serious threat. High dams being built around the world poses a serious concern when it comes to their blast performance. Once the high dams with the large reservoir are destroyed, the consequences will be catastrophic. There was a huge statement of Bhakra dam builders about security of Bhakra dam. No terror attack can damage Bhakra dam, say dam builders. Los Angeles-based Awtar Singh told IANS on phone:"No possibility. Nothing short of atom bombs can damage this dam. It is so solidly built". Researchers need to study the design of Bhakra dam to better understand the blast resistant design of dam [45]. It is pertinent to mention that Bhakra Dam is a straight concrete gravity dam located in Himachal Pradesh in India. It is 226m high, 518m long and 9.1m wide and was described as new temple of Resurgent India by Pandit Jawaharlal Nehru, the first Prime Minister of free India.

Table. 1 Attacks against dams: a historical review

No.	Facility	Dam type	Country	Dimension	Event	Date	Results
1	Burguillo Dam	Concrete gravity dam	Spain	91 m height, 300 m crowning length 6.5m top width. No other data available	Spanish Civil War	1937	Inspection galleries were damaged, with no breach.
2	Ordunte Dam	Concrete gravity dam	Spain	56 m height, No data available on other dimensions.	Spanish Civil War	1937	Inspection galleries were damaged, with no breach.
3	Dnjeprostroj Dam	Concrete gravity dam	Soviet Union	700 m length, 60 m height No data available on other dimensions.	Second World War	1941	Breach with about 200m wide.
4	Möhne Dam	Arched Concrete gravity dam	Germany	650 m length, 40 m height,6.25 m crest width, 34 m base width	Second World War	1943	Breach with 75 m wide and 22 m height at the center.
5	Eder Dam	Rubble stone masonry dam	Germany	400 m length, 48 m height, 6 m crest width, 35 m base width	Second World War	1943	A hemispherical breach with a radius of about 25 m.
6	Ennepe Dam	Rubble stone Masonry gravity dam	Germany	320 m length, 51 m height, 4.5 m crest width	Second World War	1944	No breach.
7	Sui-ho Dam	Concrete gravity dam	Korean	853 m length, 160 m height, 18 m crest width, 97 m base width	Korean War	1952	90% of facilities were demolished.
8	Kajaki Dam	Concrete gravity dam	Afganistan	100m height, 270 m length	US bombing	2001	Facilities damaged
9	Kajaki Dam	Concrete gravity dam	Afganistan	100m height, 270 m length	Taliban Attack	2003	Missed the target
10	Tipaimukh Dam	Embankment dam	India	162.8 m height, 390m length	Assault team of Unknown agency	2008	Machinery destroyed
11	Myitsone Dam	Concrete faced rock-fill dam	Burma	139.6 m height, 1.310 km length	IED attack	2010	Damage to dam

2. Studies of blast effects on dams

Dams such as concrete gravity, concrete arch, and embankment dams subjected to underwater explosion, air blast, and internal explosion have been numerically studied in the past. Among them, the research on concrete gravity dams is the most comprehensive. This section presents the numerical and experimental studies performed on concrete gravity dams subjected to different blast loading patterns, which are as follows:

a) Underwater explosion

Among all kinds of blast scenarios, underwater explosions are the most common but complex. The dynamic behavior of dams subjected to underwater explosions has been widely investigated.

Chen J. et al. (2017) [8] performed a comparative study to assess the damage effect and anti-detonation property of the Huangdeng concrete gravity dam situated in the upstream areas of the Lancang River of China with spillway tunnel subjected to close-in underwater and air blast loadings of 2000 kg TNT by using software LS-DYNA. A typical non-overflow monolith of the concrete gravity dam is shown in Fig. 1. The width and height of the spillway tunnel located at 80 m above the bottom of dam were 5 m and 10 m respectively. Length of spillway tunnel was about 56 m. The standoff distance and detonation depth was taken as 10 m. RHT concrete model developed by Riedel, Hiemaier and Thoma was used to model concrete of average compressive strength of 35 MPa. The course of cumulative damage of the dam with and without spillway caused by 2,000 kg of TNT explosive can be seen from Fig. 2, 3. From the results, it was inferred that, it was necessary to consider the influence of the presence of spillway tunnel when numerical simulation of the dam under explosion was carried out. The blast pressure caused by the underwater explosion would result in serious local damage in the upper part of the dam. The damage area and crack depth of the dam expanded with time course. The main damage areas of the upstream moved down as the increase of the detonation depth, and the dam head was found to be the most seriously damaged part. As the standoff distance increased, the pressure acted on the dam weakened continuously, and the damage degree reduced accordingly.

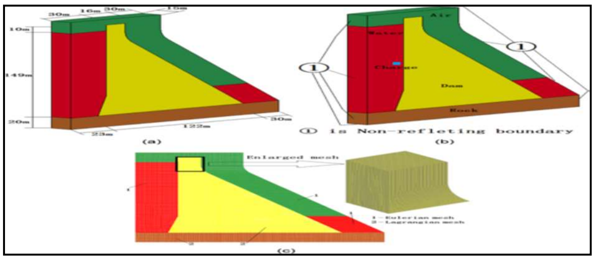
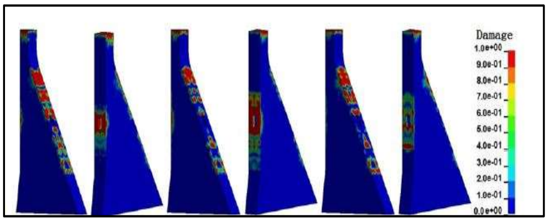
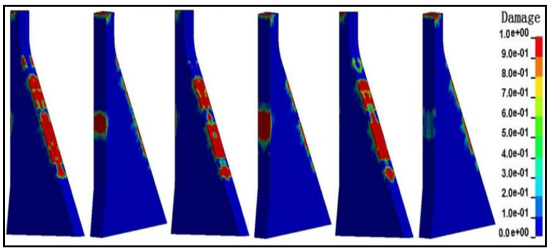


Fig.1: The Fully Coupled Numerical Model: (a) The Geometry Schematic, (b) The Boundary Conditions and the Dam, (c) The Fully Coupled Numerical Model



(a) (b) (c)

Fig.2:.Damage of the Dam with Spillway Tunnel: (a) D = 1 m, (b) D = 10 m, (c) D = 20 m



(a) (b) (c)

Fig.3: Damage of the Dam without Spillway Tunnel: (a) D = 1 m, (b) D = 10 m, (c) D = 20 m

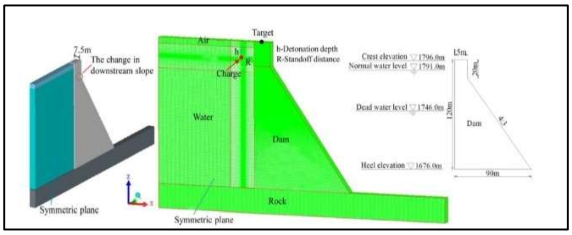


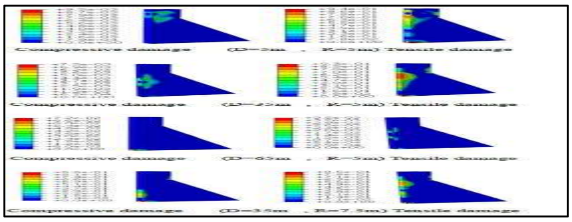
Fig.4:. Configuration of the fully coupled numerical model.

Li Q. et al. (2018)[15] employed ANSYS AUTODYN software to numerically investigate the effects of the reservoir water level on the performance of concrete gravity dam-reservoir-foundation system shown in Fig.4 under blast loading. For different standoff distances, a series of calculations with different charge weights, 100–1,000 kg were carried out to observe the dynamic response and damage state of concrete gravity dam. For every calculation case, the detonation depth was taken as 10 m. The mesh size was 100 mm for the explosive and water in the central part of the charge, in which the mesh size increased gradually away from the charge center, and 200 mm for the upper part of the dam. In this study, the Riedel-Hiermaier-Thoma (RHT) model was used for modeling the concrete having average strength of 35 MPa. The effect of reservoir water levels on the performance of dam was discussed. The main results and findings were summarized as follows:

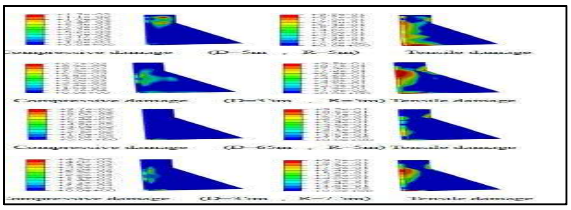
• Damage to the dam subjected to underwater explosion at the dead water level was significantly reduced when compared with the normal water level. At the normal water level, damage areas mainly concentrate in the upper zone and upstream surface of the dam. Although the damage to the dam heel was worse when subjected to underwater explosion at the dead water level, destructive damage is not observed at the dam heel.

• Reservoir water level had a significant influence on the protective performance of concrete gravity dams when subjected to underwater explosions. With the lowering of the reservoir water level, the maximum horizontal velocities of the dam crest were correspondingly reduced (25.0, 51.1, and 54.3% for water levels at the change in downstream slope, 10 m below the change, and 20 m below the change, respectively, compared with the normal water level), and the performance improves to a greater extent.

Saadatfar and Zahmatkesh (2018) [23] employed ABAQUS/CAE software to study the effects of bubble pulsation on concrete gravity dam with a height of 75 m, a thickness of 7.5 m, and a width of 15 m and 56.25 m. Concrete density, Young's modulus, and Poisson ratio taken used were 2750 kg/m^3, 27 GPa and 0.2 respectively and concrete damage plasticity (CDP) model was used to model concrete damage. The mesh size was 100 mm for the explosive and water in the central part of the charge, in which the mesh size increased gradually away from the charge center, and 200 mm for the upper part of the dam. A 300 kg TNT charge exploded in 5 m, 35 m, and 65 m depths at 5 m stand-off distance to understand the effect of explosion depth and compared the results of the explosion



(a) (b)

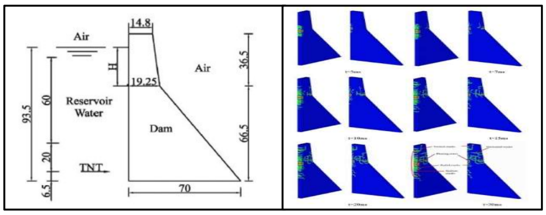


(a) (b)

Fig.5:. Compressive and tensile damage of dam (a) both explosion shock wave only (b) both explosion shock wave and bubble impulse D is charge depth, R is standoff distance

modeled by blast shockwave only with the explosion modeled by considering both the explosion shockwave and bubble pulsation. In order to find the influence of standoff distance, one other explosion was assumed at a 35 m depth by a 7.5 m stand-off distance. In high-depth detonation, because of reduced cavitation effect and growth in the dam structure thickness, damage was found to be reduced. The upstream side of the dam was severely damaged for detonation at a depth of 35 m and a stand-off distance of 5 m when the bubble impulse was considered. Damage occurred mostly in the dam's upstream face while tensile damages could be found at the downstream face near the change in the downstream slope. Horizontal displacement results illustrate that the maximum positive displacement of crest was 0.07 m for taking bubble impulse into account however reduced displacement of 0.04 m was observed in absence of bubble impulse. Paper recommended that the existence of sediments and surface waves could be considered in further studies.

Xu et al. (2018) [32] numerically investigated the dynamic response and damage crack distribution of a concrete gravity dam (CGD) i.e. Konya dam as shown in Fig 6(a) when subjected to underwater contact blast loading of 203.75kg mass using software ANSYS AUTODYN. In this study, the Riedel-Hiermaier-Thoma (RHT) model developed on the basis of the Holmquist-Johnson-Cook (HJC) model was used for modeling the concrete having average strength of 35MPa. Air, explosive, and water were simulated using an Euler method, while as, Lagrange method was used to simulate the dam. The damage patterns included blasting crater in the center of the explosive position, shallow and radial cracks on the upstream face, and vertical cracks near the downstream region as shown in Fig 6(b.) Moreover, effectiveness of aluminum foam as a protective anti-knock measure was assessed. It was found that the aluminum foam as an antiknock material can effectively reduce the tensile, shear, and compressive stress of CGD and weaken the water cut effect, especially for upstream and downstream faces of CGD as shown in Fig.7. With the increase in the detonation



(a) (b)

Fig.6. (a) Geometry of the Koyna gravity dam (m). (b) Propagation of cracks

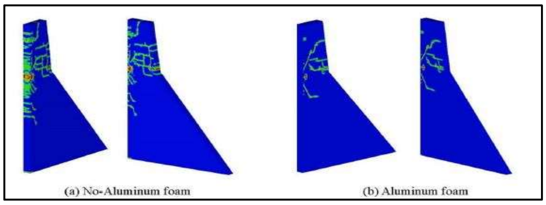


Fig. 7. Crack distribution comparison of no-aluminum foam and aluminum foam.

depth, the water cut effect was found to reduce and the regions of damage cracks of CGD first became larger and then became smaller. Meanwhile, the aluminum foam as an antiknock material had a better anti-knock effect with the increase in the detonation depth.

Wang X. et al. (2019) [31] numerically studied blast-induced damage to concrete gravity dams subjected to near-field underwater explosions using software LS-DYNA. Fully coupled model simulated is shown in Fig.8. Smooth Cap model (CSC model) was used to model concrete having compressive strength of 20 MPa. The Holmquist-Johnson-Cook (HJC) constitutive model available in LS-DYNA Version 971 was used to model bed rock. Comprehensive numerical simulations with different explosion parameters were carried out, in terms of the charge weight (100 kg–1000 kg TNT equivalent), the standoff distance (5 m–45 m) and the detonation depth under the water level (5 m–50 m). A total of 120 scenarios were observed in this study. To investigate the structural dynamic responses of a dam subjected to an underwater explosion, two target points were arranged on the upstream surface and the back-face (not the symmetry plane) of the dam model, as shown in Fig. 10(a), i.e., at the dam crest and at the downstream slope change respectively, since the upper body of dam is more likely to be fractured under the explosion, finally slipping or collapsing away from the dam section. Fig. 10 (b) and (c) showed that for both targets, the magnitude of the transverse velocity was extremely lower than the magnitudes of the horizontal velocity and vertical velocity.

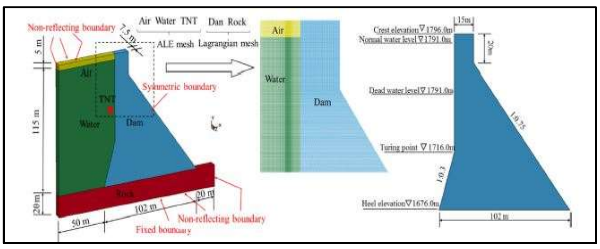


Fig.8: Fully coupled numerical model.

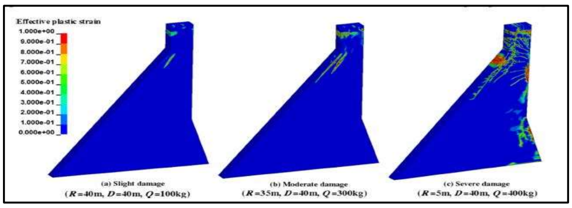


Fig. 9: Typical damage categories for concrete gravity dam under different blasting schemes: (a) slight damage; (b) moderate damage; (c) severe damage.

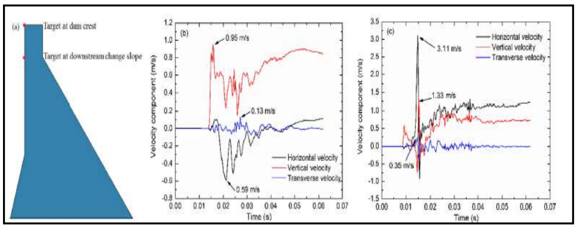


Fig. 10: Vibration velocity histories of different targets on the upstream surface of the gravity dam: (a) arrangement of targets on upstream surface; (b) at the dam crest; (c) at the slope change.for 500kg TNT at 35m depth and 5m standoff distance

b) Air blast

For air blast, many researchers compared the air blast effects with the underwater explosion.

Xue X. et al. (2012) [34] numerically studied Dagangshan arch dam (Figure 11) to develop three dimensional anisotropic dynamic damage model when subjected to blast loading using a finite element modeling software, the name of which was not clearly mentioned.. Results showed that when the structure was under impact loading the damage grew and extended significantly during a very short period. The most dynamic responses increased considerably after damage developed, and consequently the increased responses also affected the damage growth and propagation. When the dynamic stress due to the impact load exceeded the threshold value of the material, the damage in the material increased sharply, and considered to be extremely dangerous to the safety of structure. This provided a reasonable theoretical support for the safety evaluation of the capability of concrete arch dams against blast loading and some useful information for further research in these areas.

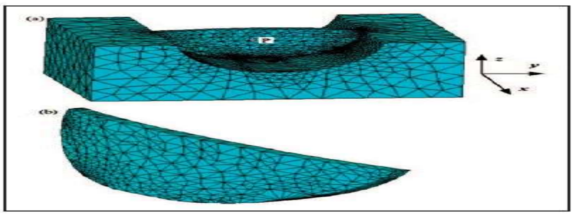


Fig.11: Finite element model of Dagangshan arch dam. (a) Finite element model of Dagangshan arch dam body and foundation; (b) Finite element model of Dagangshan arch dam body

Wang G. H. et al. (2015) [30] simulated the dynamic response of gravity dam shown in Fig. 12 and compared the damage distribution of the dam from explosions in water and air using AUTODYN software. Concrete having average compressive strength of 35 MPa used was modeled using RHT dynamic damage model, developed by Riedel, Hiermaier, and Thoma, which can reflect the characteristics of the concrete material behavior at a high strain rate efficiently. In this paper, a fully coupled numerical approach with combined Lagrangian and Eulerian methods was used to simulate the dynamic responses of a concrete gravity dam subjected to underwater and air explosions A cubical explosive charge of 1,000 kg of TNT, modeled using the standard Jones, Wilkins, and Lee (JWL) equation of state (EOS) was used at standoff distance and detonation depth of 10 m. The results showed that the submerged explosion caused significantly more damage to the dam than the same mass of explosives in the air. The damage distribution of the dam subjected to air blast and underwater explosion is given in Fig.13and Fig.14 respectively.

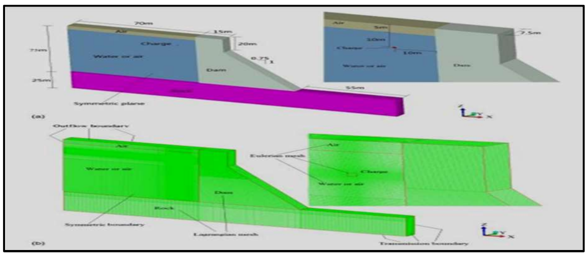


Fig. 12: Configuration of numerical model and coupled numerical model: (a) schematic description of model configurations; (b) coupled model for numerical simulation

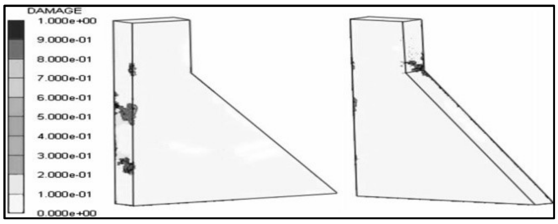


Fig. 13. Damage distributions of concrete gravity dams subjected to air blast.

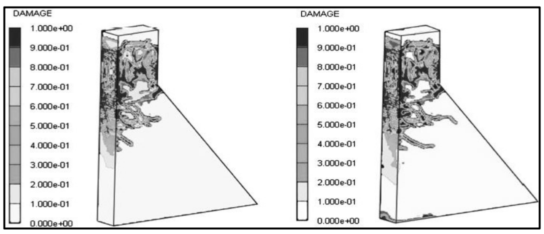
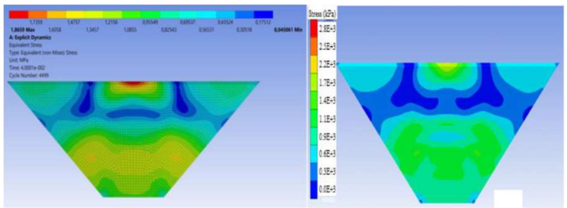
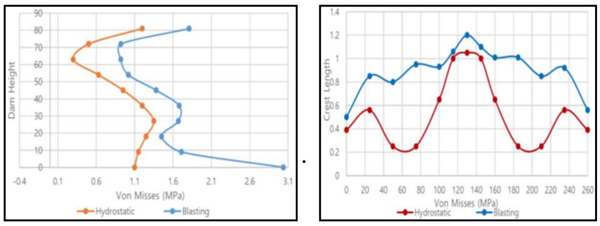


Fig. 14. Damage distributions of concrete gravity dams subjected to underwater explosion.



(a) (b)

Fig. 15: (a) Stress contour diagram of the body under hydrostatic analysis (b) Stress contour diagram of the body under blasting analysis



(a) (b)

Fig. 16: (a) von Mises stresschanges though dam height (b) von Mises stress changes though dam crest length

Sevim B. and Toy A. T. (2020) [24] performed numerical simulation of Sarıyar Concrete Gravity Dam (Turkey) having dimensions of 85 m of height (H), 255 m of length (3H), 72 m of bottom and 7 m of top width using software AUTODYN. The compressive strength of the concrete material was taken as 20 MPa referring to the technical report presented by the Chamber of Civil Engineers (CCE 1955). In the study, firstly 3D finite element model of the dam was constituted considering dam reservoir foundation interaction and a hydrostatic analysis was performed without blast loads. Thirteen tons of TNT explosive was considered 20 m away from downstream of the dam in addition to hydrostatic pressure. Two analyses were performed, one of which considers only hydrostatic loading and the other one consists of blasting loads as an addition. Results showed that all section responses such as displacement, stresses and strains obtained from blasting analysis were on higher side than those of hydrostatic analysis.. It was highlighted from the study that blasting analysis model was more effective than the hydrostatic analysis model.

C) Penetration and explosion

Research on penetration explosion is extremely scarce. The dynamic response of dams subjected to the combined effects of the penetration and explosion is a complex process. The penetration processes involve the interaction between the penetrator and solid medium, shock wave propagation, and penetration damage evolution.

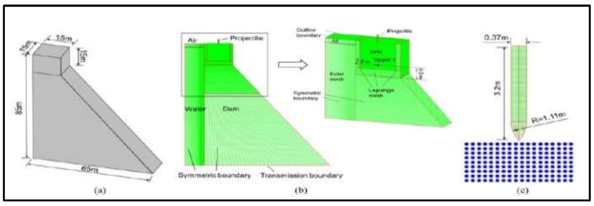
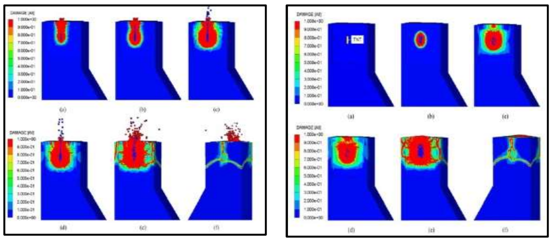


Fig. 17: Concrete Gravity Dam: (a) Dimensions of the Concrete Gravity Dam, (b) Configuration of the Coupled Numerical Model, (c) FiniteElement of the Projectile



(a) (b)

Fig. 18. Damage distribution of concrete gravity dams subjected to combined effect of penetration and explosion.(b)Penetration only

Yang et al.(2018) [35] employed the Lagrangian-Eulerian coupled method to simulate the penetration and explosion process of a concrete gravity dam under a high-velocity projectile, as shown in Fig. 17. using explicit hydrocode AUTODYN. The Lagrangian-Eulerian coupled method was used to model the concrete material with the large deformation near the penetration and explosion regions.

The initial penetration damage from the high-velocity projectile has a significant influence on the damage processes of the concrete gravity dam subjected to internal blasting loads. The results showed that the penetration of the high-velocity projectile only caused a local damage to the concrete gravity dam. The combined effects of the penetration and explosion caused significantly more damage to the upper regions of the dam. The final damage distribution of the dam is shown in Fig. 18.

Although the numerical simulation of blast effects on concrete gravity dams have been performed, there are still some problems: (1) lack of experimental data to verify the reliability of the numerical method. (2) The underwater explosion will damage the dam structure by both the shock waves and bubble pulsations. However, most of the aforementioned research did not consider the effects of bubble pulsations. (3) Most of the literature used the Lagrangian method to simulate the dam material. However, a large deformation may occur under near-field or contact explosions, which may cause calculation interruptions. (4) The hydrostatic pressure and gravity are usually neglected, and this may affect the dynamic response of the dams under blast loads. (5) Most of the research done is mainly concentrated in the non-overflow monolith; little attention has been paid to the monoliths with orifices.

IV. FUTURE PERSPECTIVES AND CONCLUSION

This review presents the studies conducted on gravity dams subjected to various kinds of impulsive loadings. Also numerical investigations done on concrete gravity dams (CGD) subjected to blast loading have been comprehensively reviewed.

The relevant investigations available in the literature are collected and discussed. The future research directions and some concluding remarks are summarized as follows:

(1) As the situation at international level becomes increasingly tense, subversive bombing attacks and local wars are becoming a potential threat to dams with large reservoirs because of their prominent social impact and military value. Thus, researchers and structural engineers have to gain a comprehensive understanding of dams' response to blast loadings.

(2) It is learnt that explosive attacks to dams can be of the form of air blasts, underwater explosions and penetration type.

(3) Underwater explosion can cause most severe damage to dams than by the air blasts. Problem of underwater explosions on dams provides lot of scope of further research.

(4) Response of concrete gravity dams is required to be investigated with different dimensions of dam and varying parameters such as detonation depth of blast, upstream water levels and boundary conditions.

(5) There is a huge deficit of experimental data on gravity dams subjected to blast loading to validate damage mechanisms and finite element simulation results. This necessitates conducting the experimental studies on scaled prototype models of concrete gravity dams subjected to blast loading.

(6) Available hydrocodes such as LS-DYNA and AUTODYN which use dynamic damage model developed by Riedel, Hiemaier and Thoma to model concrete behavior at high strain rate are useful to investigate the response of concrete gravity dams subjected to blast loading.

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