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Concrete Face Rockfill Dam Failure Process

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Abstract

The dams are used for various purpose such as reservoir impoundment for generating hydroelectricity, fulfilling the demand of water supply for the hugely populated inhabitances of urban cities and supplying the demand of irrigation, for the navigation purpose and also for the flood control to protect the cultivated land of the communities. A full non-risk guarantee is not possible for such dams which are built for such purposes and accidents may occur owing to natural hazards or human actions, also can fail due to structural deficiencies in the original design or by external events like in the events of earthquake ground motion which triggers the conditions where it exceeds the dam capabilities.

The failure of the dam due to the poor geological condition can cause a catastrophic failure on dams which hugely damages to the life & property of the downstream communities. Also, heavy thunderstorms such as PMF (Probable Maximum Flood) can cause to overtop the dam and the reservoir can empty within few hours of time which led to a devastating damages of the flood vulnerable inundation to the downstream communities of the dam.

The failure mechanism of concrete face rockfill dam (CFRD) is predicted due to overtopping by the flood hazard and eroded its downstream face due to the head cut process. After certain interval of time of breach initiation, the rockfill material behind upstream face of CFRD will wash away. Thus created a cantilever projection of CFRD will break away ultimately and more and more opening will be created in the same process then a huge amount of discharge tends to spill from the reservoir from its bigger opening in dam until the entire flow drawdown from the reservoir.

Keywords: *Concrete Face Dam Breaching, Breaching Process, Breach Development Time*

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I. Introduction

The first dams known date back to 3000 BC in Mesopotamia. In recent times, as early as 1800 AD, technological progress has allowed the construction of large dams. The most impressive ones have been built within the last century, moreover, the number of dams has significantly increased according to water demand. In addition to supplying water and controlling floods, modern dams are often designed for power production.

However, despite its great benefits, the storage of large volumes of water poses serious risks for the downstream areas. Unfortunately, over the centuries, the history of retaining dams has been studded with disasters of various types, sometimes of great magnitude, with loss of human lives and destruction of downstream properties, agricultural lands, historical sites, industrial and productive settlements, and urban areas. Even though a time-related analysis shows that the frequency of failure of large dams has been reduced by a factor of four or more over the last forty years worldwide ICOLD Dam Safety 24th April 2021, dam incidents still occur at present with a non-negligible frequency. In the current year, the failure of the Rishiganga dam (India), recent incident of 60metre high concrete faced rock-fill dam of the 1,200 MW Teesta Stage III hydropower project in Chungthang, North Sikkim, was breached; the power house was submerged and the bridge connecting the power house washed away by a glacial lake outburst flood (GLOF) around midnight on 4th October 2023. Rockfill dam of Sikkim as mentioned induced by a glacier avalanche, caused a catastrophic flood in the downstream valley with many casualties and huge damages to four hydropower plants.

Moreover, the state of emergency was declared over toxic wastewater leaks in Florida due to the dreaded breach of the Piney Point reservoir. In this case a potential disaster was ultimately fortunately averted.

St Francis Concrete Gravity Dam was failed on 12th March 1928 due to the unanticipated adding of the dam height and the pressure behind the dam so its foundation could not sustain the addition stresses. As a consequences of its failure 400 people lost their lives in the casualties.

The Malpasset double curvature concrete arch dam was failed due to heavy thunderstorm. The reservoir level was drastically raised and within hours the bottom outlet gate being opened on 2 December 1959, the dam was failed without warning, almost 300 people died in the disaster.

On 9 October 1963, Vajont double curvature concrete arch dam, suffered a failure of its southern rock slope over an approximate length of 2 km. As a result of the devastating dam breaching; five village communities with 2,040 lives were lost due to the failure of the dam.

On February 9, 1971, the San Fernando earthquake with an estimated magnitude of 6.6 Richter scale occurred and the San Fernando earthen dam was breached catastrophically. To avoid the further damage of the life and the property during the presence of after-shocks, 80,000 people living downstream of the dam were evacuated over a single day and over 340 people were died.

In June 1976; 90 m high Teton rock-filled earth dam was constructed in a steep-walled canyon eroded by the Teton River in Idaho. It had a wide silt core, with upstream and downstream shells consisting mainly of sand, gravel, and cobbles. The dam failed due to excessive seepage and incompetence in resisting uplift pressure in the dam body. The flooding of the downstream regions after the failure of the dam resulted in the loss of 14 lives and caused an estimated loss property of the cost of $400 million.

Consequently, the development of CFRD construction has accelerated globally during the recent decades. Once the flood level surpasses the designed one and additional subjective or objective factors cause the water to overflow at the dam’s crest, an overtopping induced dam breach is prone to occur. For instance, on August 27, 1993, Gouhou CFRD, located in Gonghe County, Qinghai Province, China, with a maximum height of 71.0 m, was breached, causing 320 fatalities and a massive loss of properties. It is also the first documented dam failure case of CFRD built by modern construction technology. On December 14, 2005, the Upper Taum Sauk dam, situated in Reynold County, Missouri State, United States, was breached by overtopping flow due to the failure of reservoir stage sensors, resulting in nine casualties and significant property damage. As climate change intensifies, there is an increasing trend of extreme flood disasters worldwide, which may bring a higher risk of dam failure. Therefore, it is essential to deepen the understanding of the breach process of CFRD and develop suitable numerical methods to predict it.

On July 2018, sudden breaching occurred to a 60m high concrete gravity Saddle Dam in Mekong Basin. The Dam was constructed for hydroelectric-power reservoir of southern Laos, caused catastrophic flooding after the breaching that resulted as a report indicated by the United Nations that 13,100 people were affected, 6000 evacuated, 13 died and 120 remain missing.

Hence it has reported that Overtopping flow is a prominent event of many or even most potential failure modes resulting from floods. Dams could have overtopped by a few millimetres to more than a meter without breaching, but other structures could fail quickly. Overtopping is a failure mode of concern since Costa (1985) reported that of all dam failures as of 1985, 34% were caused by overtopping, 30% due to foundation defects, 28% from piping due to seepage, and 8% from other modes of failure. Costa (1985) also reports that for earth/embankment dams only, 35% have failed due to overtopping, 38% from piping and seepage, 21% from foundation defects; and 6% from other failure modes.

II. Materials And Methods

Brief background of CFRD breaching process prediction methods

In recent years, numerous physical model tests with different scales have been performed to reveal the breach mechanism for homogeneous earth fill dams, M.W. Morris,G.J. Hanson2013. The surface erosion and intermittent mass failure in the cross section and the head cut formation and migration in the longitudinal section were determined as the critical breach mechanism for a homogeneous earth fill dam due to overtopping. The breach process of the CFRD is more complicated than that of a homogeneous earth fill dam, owing to its composite structure. Few studies have been conducted to analyze the dam breach mechanism of CFRD. Chen, 2012 reproduced the overtopping induced failure process of the CFRD by using the centrifugal model. The test results showed that the overtopping flow first eroded the downstream rockfill, while the concrete face slab still played a role in retaining water. With the intensification of soil erosion, the suspended face slab would break several times under the combined action of water load and self-weight, with the continuous development of the breach. Li et al. 2021, also obtained similar conclusions by observing the overtopping breach process through the flume model tests. Due to the imperious need for the accurate prediction of CFRD breach flood hydrograph, numerical simulation methods have gradually become an effective tool. In general, numerical models for the CFRD breach process can be divided into three categories: empirical, simplified physically based, and detailed physically based models.

Based on the measured data of historical dam failure cases, empirical formulas for predicting the critical breaching parameters, such as peak breach flow, final breach size, and failure time, can be proposed for CFRD by regression analysis, Y, Xu, D.Y. Sen 2020. However, this model cannot provide a breach hydrograph or a breach development process, nor can it accurately represent the dam breach mechanisms.

The CFRD breach model tests showed that S.S. Chen, Y. L. Lee, 2021, the water retaining effect of the concrete face slabs is the feature of CFRD breaching and should be considered in the numerical modelling to obtain reasonable breach hydrograph and breach morphology evolution processes in rockfill materials and concrete face slabs. Hence, the numerical methods for the homogeneous earth fill dam cannot be directly applied to simulate the breach process for CFRD. Recently, the simplified models developed by approximating the hydrodynamic and morphodynamic processes with certain simplifications and assumptions have become increasingly desirable for engineering applications. Chiganne et al. 2014 proposed a simplified numerical approach for evaluating an embankment dam's flood overtopping failure scenario with concrete upstream slope protection. Wang et al.2015 established a dynamic bed coupling analysis model considering the influence of sediment concentration change on the CFRD breach process. However, the analysis of the concrete face slabs' failure process is oversimplified and generally uses the analysis of the force conditions of a unit width slab to emulate the slab damage without taking the three-dimensional characteristics of the slabs into account. Zhong et al.2019 studied the coupling relationship between the transport of sand gravel materials and the failure of concrete face slabs and proposed a simplified physically based numerical model for the overtopping induced breaching of CFRD. Although this model can consider the necessary physical processes, it introduced many assumptions related to the dam shape, the breach morphology, and the physical and mechanical properties of the dam materials, which cannot reflect the complex hydrodynamic characteristics of turbulent flow during the CFRD breach process with actual topography.

With the development of sediment dynamics and computational fluid dynamics, the detailed physically based models that resolve the breach flow and sediment transport throughout the entire computational domain have gradually become a research hotspot. Such numerical models usually use the mass and momentum conservation equations of clear or muddy water to calculate the hydrodynamic conditions, the equilibrium or non-equilibrium sediment transport equations to determine the erosion of the dam material, and the sediment mass conservation and slope stability conditions to compute the morphological evolution of the breach. The detailed physically based models can be classified as equilibrium, non-equilibrium, two-phase flow, and two-layer transport models based on various sediment transport equations. These four detailed models can simulate the breach hydrograph and the morphological evolution of dam breach under their respective assumptions and theoretical frameworks, thereby effectively improving the accuracy of numerical simulation. However, the detailed physically based dam breach models have been used in the numerical modelling of homogeneous earth fill dams and landslide dams but not in the CFRDs with composite structures of concrete face slabs and rockfill materials.

In the study, the Upper Taum Sauk dam catastrophe is chosen as a sample instance for this research as one of the few CFRD failure cases that have detailed measurements and survey records worldwide. This study aims to reproduce the breach process of the Upper Taum Sauk dam and evaluate the performance of the numerical method on the erosion of rockfill and the fracture of concrete face slabs. A detailed physically based numerical model was developed to depict the characteristics of the overtopping induced breach process of the Upper Taum Sauk dam. The numerical model will have three main features include: (1) simulation of breach flow discharge by considering the water retaining characteristics of concrete face slabs, (2) adoption of the bedload and suspended sediment transport equations to calculate the erosion rate of the rockfill materials, and (3) the moment balance method to imitate the times and lengths of failure for each concrete face slab under variable loads.

Failure of the Upper Taum Sauk dam case history

Characteristics of the dam

In the following paragraphs the Taum Sauk Pumped Storage Power Station in Reynolds County, Missouri State, United States is described. The project was completed in 1962 and put into operation in 1963. It was the first reversible pumped storage power station in the United States and was utilized to supplement the generation and transmission facilities of Ameren Union Electric. The main constituent parts of the project include an upper reservoir, a shaft, tunnel conduit, a 450 MW, two-unit pump turbine, generator motor plant, and a lower reservoir. The lower reservoir was formed by constructing a concrete gravity dam of 18.29 m height along the East Fork Black River about 3 miles upstream of Lesterville, Missouri (Fig. 1). It is focused on the overtopping failure process of the upper reservoir dam, which is situated on top Proffit Mountain, 243.84 m above the lower reservoir, and connected by a 2133.6 m long tunnel.

It has a temperate climate with an average annual precipitation of approximately 1016 mm and a mean annual air temperature of 15.6 degrees Celsius, N. Ocenie, 2006. The northern part of the area is located in the St. Francois Mountains, composed of exposed Precambrian igneous knobs and valleys underlain by Paleozoic sedimentary rocks, such as dolomite and sandstone, N.M. Penneman,1938, and cover about 2600 km^2. This region preserves many ancient, deeply weathered bedrock zones. During the construction of the Upper Taum Sauk dam, much of the Proffit Mountain top was blasted off, with the material, mainly broken Taum Sauk Rhyolite, being utilized to construct a kidney shaped CFRD with the dam crest elevation of 484.33 m. A reinforced concrete parapet wall with a height of 3.05 m and a thickness of 0.30 m is built on the dam crest. The design elevation of the parapet wall crest is 487.38 m, whereas the maximum operating water level of the upper reservoir is 486.77 m. The water side of the dam is lined with concrete and consisting of 111 concrete face slabs, each measuring roughly 18.29 m in length. The width of the dam crest is about 3.7 m, and the designed thickness of each upstream slab is 0.25 m. Due to the unevenness of the rockfill during the actual concrete pouring process, the slab's thickness is close to 0.46 m on average, J.D. Rogers, 2005. At an elevation of about 455.37 m, the entire reservoir bottom is sealed with two layers of hot-mix asphalt concrete placed over-leveled and compacted quarry muck. The upper reservoir holds about 5.37 million m^3 of water, and the upstream and downstream slopes of the dam are 1:1.4 and 1:1.3 (Vertical/Horizontal), respectively.

In many cases, the upper reservoir in the pumped storage projects is not connected to a river, and the reservoir levels are determined solely by controlled pumping and power generation activities. Because the only inflow water is from pumping and precipitation, this project was constructed without a spillway and required constant monitoring to prevent overtopping, C.M. Watkins, J.W. Chung, 2005.

Based on the dam failure analysis report conducted by the Federal Energy Regulatory Commission of the United States, FERC (Federal Energy Regulatory Commission), 2006, most of the rockfill materials for the Upper Taum Sauk dam were built by simple end dumping. The dam fillings were let to tumble down the side of the dam, lying near their natural repose angle. The boundaries between the different filling layers were visible in the final breach side slope of the dam (Fig2).

Dam breach process

On December 14, 2005, the stage sensors of the upper reservoir failed to turn off the pumps employed to convey water from the lower reservoir during the overnight filling, resulting in the water overflowing the wall top of Upper Taum Sauk dam. When the dam breached, 5.30 million m^3 of water was released within 25 min and flowed into the Black River. According to the site investigation, FERC (Federal Energy Regulatory Commission), 2006, the circle parapet wall was not horizontal due to differential settlement of dam materials. Some parapet wall does not fulfill the requirements compared to the designed value of 487.38 m, and the slab labeled 92 had the most differential settlement. According to the surveyed data, the slab 92 crest elevation was 486.76 m below the design elevation of
0.62 m, A. J. Hendron,2005.

According to the accident investigation report, FERC (Federal Energy Regulatory Commission), 2006, due to the lack of timely monitoring information on the settlement of the dam crest, the stage sensors installed in the upper reservoir set a higher water level than the dam crest in some parts of the parapet wall, resulted in the overtopping failure of the Upper Taum Sauk dam. Data recovered from the control system of the upper reservoir and back calculations indicated that the water initially overtopped the crest of the parapet wall at about 4:55 a.m., December 14. Then, around 20 min later, the water overflowed, and the Upper Taum Sauk dam began to breach, J. L Ehasz, P.H. Rydlund,2006. One of the turbine pump units had stopped before the overtopping (this unit was programmed to automatically shut down when the water level of the upper reservoir reached 1.50 m below the crest of the parapet wall), but the second unit continued to run until the overflow height attained 0.11 m. This pump unit was intended to shut down automatically when the reservoir water level reached 0.61 m below the specified parapet

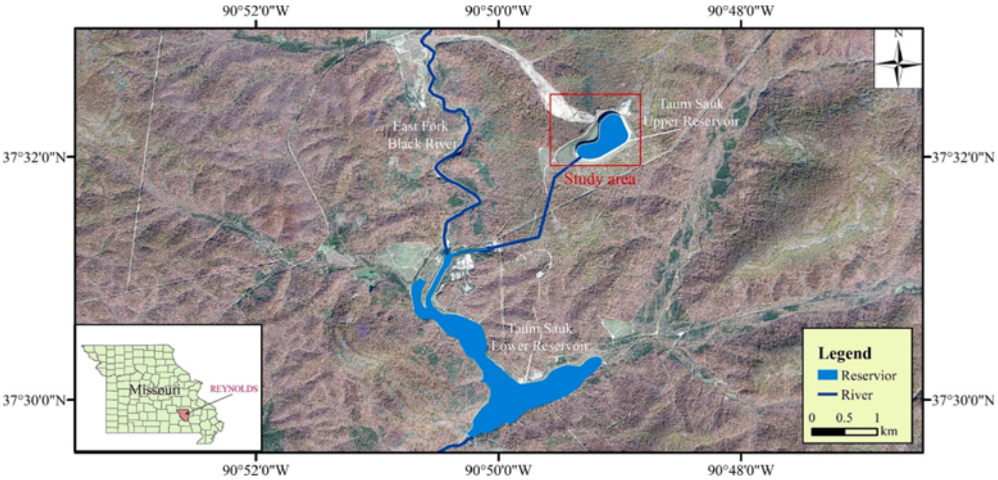

Figure 1 Location of the Taum Sauk Pumped Storage Power Station.

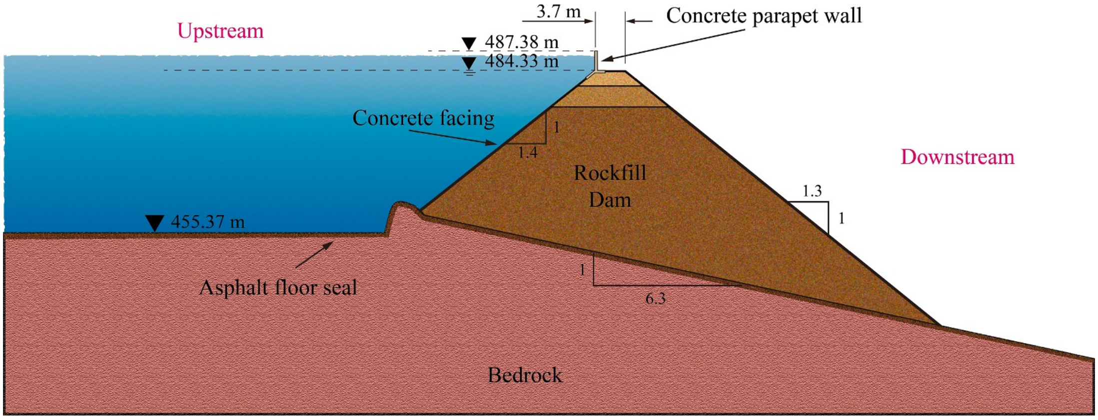

Figure 1 Schematic diagram of the typical longitudinal section of the Upper Taum Sauk dam.

Figure 3Photo of dam materials in the breach side slope, W. M. Wu.

wall peak, where the maximum operating water level was 486.77 m. Hence, the water level continued to rise in the upper reservoir until the second unit was turned off. The total pumping volume of the upper reservoir was about 86000 m^3, and the overtopped water volume before the dam breaching should have been 38237.88 m^3, relying on the overall water pumped into the reservoir minus the volume of water stored. Based on back calculations, FERC (Federal Energy Regulatory Commission), 2006, K. Paul, 2005, the reservoir was anticipated to breach within seconds of the second pump unit being stopped down, and the peak breach flow was estimated to be 8183.6 m^3/s, A. J. Hendron, 2005.

Cause of dam failure

Since the Upper Taum Sauk dam was built in 1963, leakage from the dam has been a re occurring problem and concern. During the 40 years of operation, several repairs were performed on the joints between the concrete liner and the bedrock, the concrete liner and the plinth, and the upstream toe of the parapet wall, FERC (Federal Energy Regulatory Commission), 2006, Subsequent investigation of the geological conditions showed that the plinth was not extended to bedrock, at least in the breach area. The drilling work has also indicated that the dam materials contain more fines than expected for a rockfill dam, which can lead to a fine particle loss under the leakage flow.

As undermining, scouring, and erosion progressed, enough rockfill material could have been removed directly below the base of the parapet wall, resulting in a localized soil shear failure. This effect is similar to the sliding or overturning instability of the wall, and both

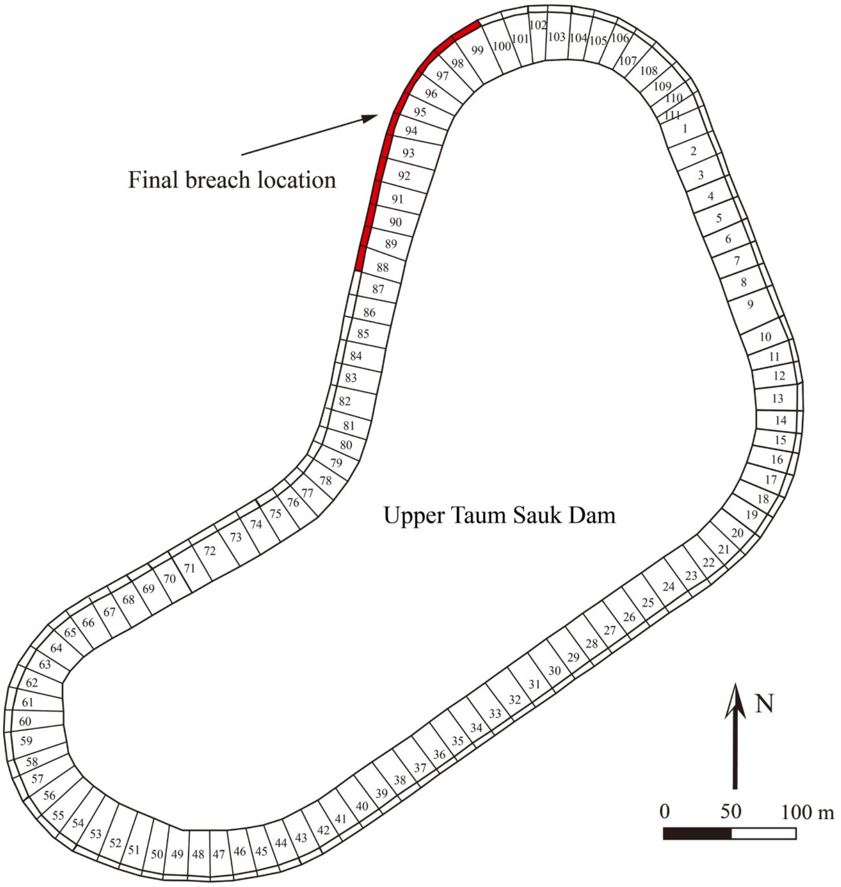

Figure 2The schematic diagram of the distribution of the concrete face slabs and the location of the final breach.

proposed circumstances could have led to wall failure. By observing the overflow section after the dam breaching, it can be seen that the overflow resembles a broad crest weir, with a broad "V-shaped" in the beginning of the breach in later stages the breach shape followed the trapezoidal shape of nearly 274 m. This condition would result in greater discharge towards the center of the settled section. Moreover, the steep face of the rockfill dam (1:1.3, Vertical/Horizontal) can exacerbate this situation, allowing a deeper plunge pool to develop, as depicted in Fig.4.

Figure 5 Breaching Photos

Based on the characteristics of the Upper Taum Sauk dam and the post failure investigation reports, the most likely precipitating factor for dam failure was the collapse of the concrete parapet wall and subsequent overflow erosion of rockfill materials. The primary cause for dam failure can be summarized as follows: As the overtopping of the Upper Taum Sauk dam was initiated, water overflowed from the concrete parapet wall, causing erosion and scouring at the dam's downstream crest. This process began to undermine the foundation of the parapet wall. The rockfill materials on the downstream slope were washed away as undermining and scouring progressed. Once enough rockfill materials were lost, the stability of the concrete parapet wall and the rockfill's shear capacity were severely compromised to the point of wall or shear failure. As a result of the collapse of the parapet wall, more water and consequently more flow was released in the area of the initial breach. The additional flow accelerated the erosion process down to the toe of the dam, yielding catastrophic failure. Fig.5 displays photos of the final breach morphology of the Upper Taum Sauk dam from various angles.

Failure of concrete face slabs

In general, vertical and peripheral joints are embedded in the concrete face slabs of CFRD and are connected to the adjacent slab and toe slab through the waterproof structures. However, the waterproof structures cannot withstand the bending moment when the rockfill materials beneath the concrete face slab are washed away. Based on the failure mechanism of CFRD revealed by the model tests, S.S Chen, Y.L. Lee, Z. Chen 2021, when the suspended length of a single concrete face slab increases, it breaks due to the combined impact of upstream water load and the self-weight of the suspended part (Fig. 6below).

It is considered that a single face slab is a cantilever panel, and the following conditions must be satisfied for its failure: the bending moment caused by upstream water load and self-weight is greater than the slab's ultimate bending moment. When the first slab breaks, the breach flow through the concrete face slab increases abruptly, and then the analytical process is applied to the next slab. It is worth noting that each slab may be failed several times as the erosion process progresses.

The bending moment of a single face slab, as an example, generated by self-weight can be represented as follows (Fig. 7below):

Were,
is the effective span of cantilever concrete face rockfill slab during its failure time.
is the density of the slab;
is the slope ratio of the dam's upstream;
is the thickness of the slab;
is the width of the slab
is the bending moment generated by the slab's self-weight;

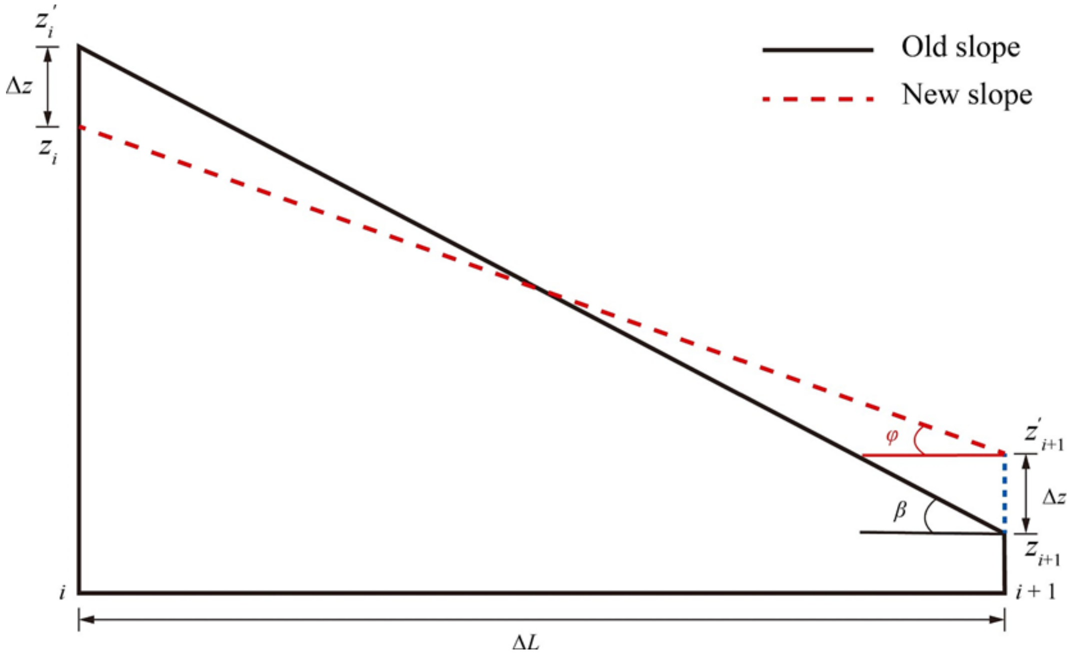

Figure 6Schematic diagram of proposed bed level updating of two adjacent computational cells.

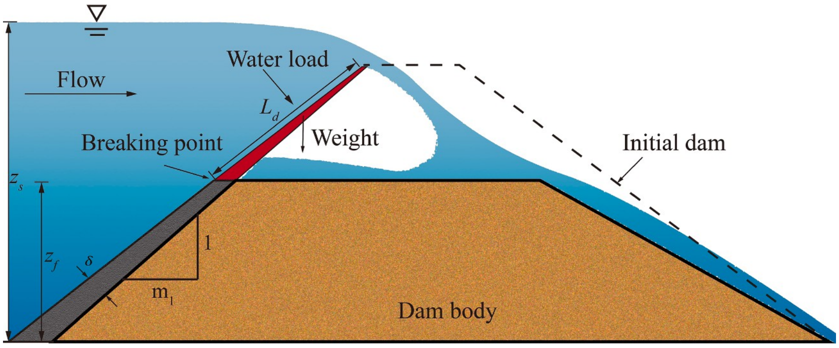

Figure 3Schematic diagram of the failure of the concrete face slab.

Additionally, the bending moment caused by water load can be described as follows:

where M_2 is the bending moment caused by water load; z_s is the water level; z_f is the crest elevation of the slab. The total bending moment generated by self-weight and water load may thus be depicted as:

$M = M_1 + M_2$

where M = total bending moment.

The ultimate bending moment of the concrete face slab can be calculated as:

where is the ultimate bending moment;
 is the tensile strength of slab steel;
 is the section area of slab steel;
 is the distance from slab steel to the edge of the slab;
 is the axial compressive strength of concrete.

The following conditions should be met for the failure of a concrete face slab:

$M > M_u$

When a concrete face slab fails, the adjacent slabs will break one after another as the breach widens. A slab may fracture several times when the breach develops in the rockfill material. According to above statement when the concrete face slab stops failing, the dam breach process will gradually end with the continuous decline of the water level in the reservoir.

III. Conclusion

The failure mechanism of concrete face rockfill dam (CFRD) is predicted due to overtopping by the flood hazard and eroded its downstream face due to the head cut process. After certain interval of time of breach initiation, the rockfill material behind upstream face of CFRD will wash away. Thus created a cantilever projection of CFRD will break away ultimately and more and more opening will be created in the same process then a huge amount of discharge tends to spill from the reservoir from its bigger opening in dam until the entire flow drawdown from the reservoir.

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