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Failure Investigation of Tawila Dam in North Darfur, Sudan

Magdi M.E. Zumrawi[1]

[1]University of Khartoum, Civil Engineering Department, Khartoum, Sudan

Abstract: ***This paper will visually and experimentally assess the failure of recently constructed dam at Tawila in North Darfur as well as examine and identify the causes of the failure. Intensive literature of historical cases of dam failure events throughout the world is reviewed. The investigation is conducted to provide an extensive diagnosis study to point out the structural and geotechnical defects of the Dam. The investigation results showed that the sediment deposition lead to reduction in reservoir capacity and the collapse of the spillway occurred due to erosion and excessive deformation of the foundation. The high silting rate and seepage of water lead to piping through the foundation soil of loose sand were detected as the main causes of the dam failure. It was recommended that necessary and urgent technical solutions such as desilting and seepage control to be considered in the new rehabilitation of the dam.***

Keywords: Failure, diagnosis, spillway, seepage, erosion

1. Introduction

Dams are water storage, control or diversion structures that impound water upstream in reservoirs. Their role is not limited to the storage of water but the management, interms of managing the time and quantity of the releases, plays a vital role as well [1]. The dams must be designed, built, and operated so that they make a positive contribution to socio–economic development, while having minimal impact on the environment. The acceleration of economic growth is not possible without the generation of power and availability of water for agriculture as well as for domestic consumption. Current estimates suggest that nearly 30 – 40% of irrigated land worldwide now relies on dams and that dams generate 19% of the world's electricity [2].

Dam design criteria require the dam to withstand different loads, namely construction and reservoir water loads. Dams are designed to have a low probability of failure during their construction and operation life span. Dam failure may occur due to a variety of causes. The most common causes of dam failure are leakage and piping (35%), overturning (25%), spillway erosion (14%), excessive deformation (11%), sliding (10%), gate failure (2%), faulty construction (2%) and earthquake instability (1%), Arizona Division of Emergency Management (2007). Clearly, dam failure events pose a significant threat not only to human life but also to the environment and in general to economic development. Thus, it is essential to investigate properly these failures and to find out technical solutions to reduce their risk of occurrence. Recently, dam safety draws increasing attention from the public authorities. This is because floods resulting from dam failure can lead to terrible disasters with tremendous loss of life and properties, especially in densely populated areas.

2. Literature Review

Many studies have been conducted to investigate dams failures. The International Commission on Large Dams (ICOLD) has reported statistics of dams failures [3]. The United States Committee on Large Dams (USCOLD) has made a survey of incidents including failures and accidents to dams in the United States [4]. Many researchers investigated dams failures using statistical methods [5]–[9].

The world’s worst dam disaster occurred in Henan province in China, in August 1975, when the Banqiao Dam and the Shimantan Dam failed catastrophically due to the overtopping caused by torrential rains. Approximately 85,000 people died from flooding and many more died during subsequent epidemics and starvation; millions of residents lost their homes [10]. Costa [11] compared the loss of life during two dam failure events: the Teton Dam in Idaho (93m high) that failed at midday on 5 June 1976 and Laurel Run Dam in Pennsylvania (12.8m high) that failed on 20 July 1977. The latter event claimed the lives of 1 out of every 4 people exposed to floodwaters, while only one out of 3,000 people exposed to floodwaters suffered from casualties in the case of the Teton Dam failure. When the failure of a dam happens, the socio–environmental implications might affect the flooded region for a long period of time. The dam failure at the Los Frailes mine in Spain, in April 1998, released between 5 to 7 million tons of toxic mud carrying heavy metals and highly acid compounds in the Guadiamar River spreading in large areas of the floodplains. However, the environmental disaster was immense and its long–term consequences are feared to affect the region for many years to come [12].

A dam failure is an uncontrolled release of water impounded behind the dam. Failure of a dam can be sudden or gradual. A sudden failure is associated with concrete dams. Rockfill and earthfill dams, termed embankment dams, their failures are mostly a gradual process rather than a sudden one. Failure of an embankment dam can be triggered by different factors such as overtopping, piping, seepage and earthquakes failure. Overtopping is one of the most common failure modes for earthfill dams. It can be triggered by inflows higher than the design inflow, malfunctioning or a mistake in the operation of the spillway or outlet structure, inadequate carrying capacity of spillways, settlement of the dam or as a result of landslides into the reservoir. According to National Performance of Dams Program in USA [13], 245 of 256 dam failure events recorded in the USA during the year 1994 happened due to high inflow discharges. Any embankment dam will fail if the spillway capacity is too small and flood waters raise high enough to flow over the top of the dam for a considerable amount of time. In August 1979, a flood two to three times larger than the design flood triggered the failure of the Machhu II dam in India, causing more than 2,000 casualties [14]. Once an initial breach channel is created, and the high reservoir water levels persist, the breaching will continue to develop and any effort made to stop it will be unsuccessful. Overtopping may not result in structural failure, but still presents a major flood hazard as happened during the overtopping of the Vaiont Dam in Italy [15]. Similarly, rapid release of reservoir water in order to lower the water level within safe limits can be a big concern in downstream areas.

Water penetrating through the dam's interior body or its foundation might progressively erode soil from the embankment or its foundation leading to the failure of the dam. Piping failure is defined as a failure mode caused by water penetrating through the dam's body, carrying with it small particles of dam material, continuously widening the gap. If the initial piping can be detected before it reaches the critical condition, remedy might be possible. Penetration of water in the dam body can cause slope failure. To prevent this type of failure, appropriate instrumentation is needed to estimate the rate of infiltration within an embankment.

Seepage failure (Figure 1) or foundation failure occurs due to the saturation of the foundation material leading to either washout of the material or a weakening of the rock towards a sliding failure. The flow of water through a pervious foundation produces seepage forces as a result of the friction between the percolating water and the walls of the pores of the soil through which it flows. Figure 1 shows how water flows through the pervious foundation of a dam.

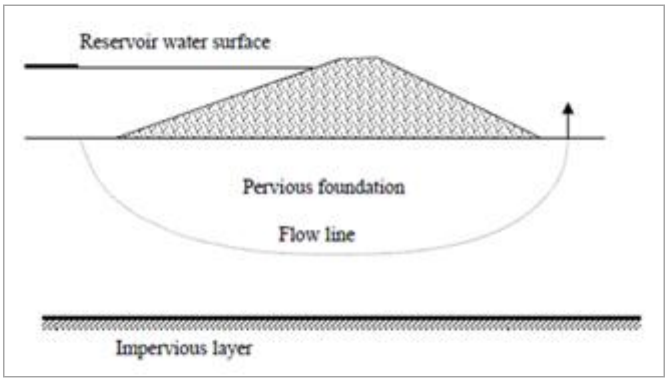

Figure 1: Seepage on the foundation of a dam

Earthquakes that have stimulated immediate failure of a dam appear to be very rare. The upstream slope of the Lower San Fernando Dam in California (USA) failed due to liquefaction during the earthquake in 1971. The dam was constructed by fill soil mixed with a large amount of water, transported to the dam site by pipeline, deposited on the embankment in stages, allowing the excess water to drain away. The fill that remained was loose, and was subject to liquefaction as a result of the earthquake. Fortunately, the reservoir level was low at the time of the earthquake and no flooding occurred. Failure due to an earthquake might result in a higher threat to the population downstream rather than the overtopping failure.

3. Case Study

The objective of this investigation is to provide an extensive diagnosis to find out the structural and geotechnical weaknesses of the failed dam. The investigation based on an extensive visual inspection, experimental work and the design and construction data of the original dam. The diagnosis had to emphasize the spillway, embankment and foundation structural stability. The study was concentrated on Tawila dam in North Darfur.

3.1 Project description

Tawila dam is located about 70 km west of North Darfur capital El Fasher town; it was constructed in 1954 by the State Water Corporation. The dam is an earthen embankment (1.8 km long) across the wadi, with two spillway structures (primary and secondary). The project area is located in El ku basin of the North Darfur. The river is one of the main flow contributors to wadi El ku (Figure 2).

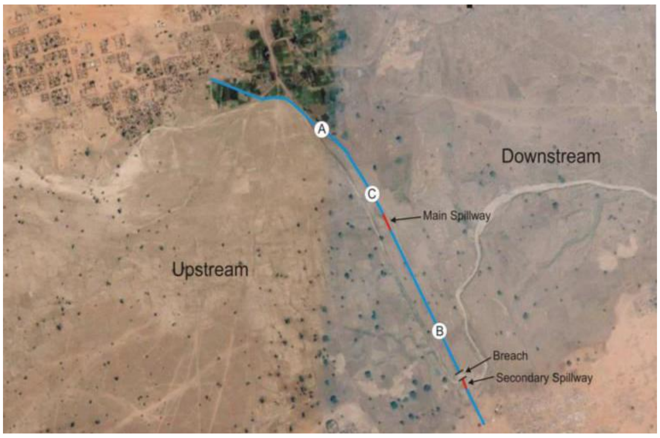

Figure 2: Location map of Tawila dam

This dam is one of the interventions of Drought Risk Reduction Project in North Darfur State. The project is to contribute in increasing the products of rain-fed agriculture schemes through reduction of water storage period and use of complementary irrigation. As per the State Water Corporation sources, the design capacity of the reservoir is 300,000 m^3, however it has lost storage volume due to silt accumulation.

The dam suffered from water erosion and sever damages occurred in the dam body in July 2014. It is required to investigate the prevailing situation and to suggest solutions for proper design and rehabilitation of the dam.

3.2 Field investigation

The field investigation was comprised of a site visit to the dam location at Twaila and collecting soil samples. The investigation started with the site reconnaissance in order to collect information about the dam construction and how the failure occurred from the local and the contractor to assess in investigating the source and reasons of failures.

A visual inspection was conducted for the dam in order to detect any obvious structural defects in the spillways and the dam embankment. It was observed that the secondary spillway structure and the adjacent embankment of the dam collapsed due to excessive seepage that caused voids creation underneath the structure. The new constructed section of the secondary spillway has severed failure due to shear stress and washed away during the first rainy season. The reservoir is no more holding water. As per the information for the locals, the dam failure has occurred same year where the nearby secondary spillway was constructed and this had subjected to seepage underneath the embankment close to the spillway as shown in Figure 3.

Figure 3: Damaged spillway with severe cracks

The partial breaching/weakening of embankment section is also observed at the far north part of the embankment which could lead to total collapse. This embankment weakening was happening mainly due to scouring effect of the incoming waddy which flows adjacent to the embankment section and parallel to the dam axis. This scouring has caused the embankment slope to get steeper and has increased the waddy depth which has increased the embankment height which can lead to failure (Figure 4). During rainy season, this steeper section was falling in to the waddy when it get saturated and washed downstream which further weakens the embankment section.

Figure 4: Weak and steep slope of the embankment

In general, the embankment has changed its original section dimension and shape throughout the entire length where the crest of the embankment is narrowed and the side slopes are flattened at some sections and steeped at others.

In addition to breaching and weakening of the embankment, the other concern observed in Tawila dam is sediment deposition in the reservoir area. The sediment deposition has reduced the storage capacity of the reservoir by significant volume. This is mainly due to huge sediment load form the catchment is caused by degradation and less vegetation cover. There is no any sediment releasing sluice gate provision to release flush floods carrying high sediment load are experienced in other dams in Darfur. As shown in Figure 5, the sediment deposition lead to reduction in reservoir capacity as well as reduction in aquifer recharging to augments the ground water.

Figure 5: Sediment deposition in the reservoir area

The current situation of Tawila dam is complete damage and washed away of the spillway and the reservoir is no more holding water. As a result, surrounding communities have hard living conditions due to shortage of water and absence of agricultural activities where farming was taking place in the reservoir area during recession period and downstream of the dam while the reservoir is full. Additionally, depletion of groundwater which resulted in drying up many of hand dug wells in the surrounding area.

3.3 Experimental work

The experimental work consists of two tasks; field work and laboratory testing. A borehole of 10m depth was drilled at the failed spillway location. A pithole of 2m depth was excavated in embankment adjacent to the damaged spillway. Three disturbed soil samples (S1 to S3) were taken from the borehole at an interval of 3m depth. The sample (S4) was taken from the embankment material at 1 to 2m depth of the pithole. The collected disturbed soil samples were kept in plastic bags, labeled and transported to the soil mechanics Laboratory in Khartoum University for testing.

The Laboratory testing program was conducted to determine the physical and mechanical properties of the soils encountered during the site exploration. The testing procedures followed were in general conformance with those recommended in the British Standard BS 1377 (1990) and the soils were classified according to the Unified System for Classifying Soils (USCS). The laboratory tests performed included Atterberg's Limits, grain size distribution, compaction, permeability and shear strength tests.

The tests results of the soils samples (S1 to S3) obtained from the foundation soil of the spillway and also the sample (S4) taken embankment material are summarized in Tables 1and 2.

Table 1: Classification tests results for the soil samples

Test	*Property*	*S1*	*S2*	*S3*	*S4*
Sieve Analysis	Gravel	0	3	8	0
	Sand	94	92	90	1
	Silt/Clay	6	5	2	99
Atterberg's Limits	LL	NP	NP	NP	57
	PL				27
	PI				30
Classification	USCS	SP	SP	SW	CH

Table 2: Physical and mechanical tests results

Property	*S1*	*S2*	*S3*	*S4*
Friction Angle (°)	40	39	42	12
Cohesion (KPa)	2.0	1.5	0	62
Permeability (mm/s)	$9.5\text{x}10^{-2}$	$1.5\text{x}10^{-1}$	$2.1\text{x}10^{-1}$	$3.8\text{x}10^{-6}$
Dry Density (KN/m^3)	15.0	16.1	16.5	14.2
Moisture Content (%)	3.4	2.7	3.1	16.4

The soil profile for the dam is determined based on the visual inspection at the site and the tests results of the samples as given in Tables 1 and 2. The profile generally reflected similar soil stratifications with slight variations. The soil profile at the location of the secondary spillway consists of a top thick layer of fine sand was encountered up to 6m depth. This is followed by fine to medium Sand was encountered below 6m depth and extended down to the end of the borehole at 10m depth. In general, the soil at the dam site is sand of non plasticity. This soil was encountered mostly mixed with silt. Thus, the permeability of this soil as given in Table 2 is high leading to water seepage below foundation of the spillway.
The embankment material was determined as clay soil of high plasticity and very low permeability.

3.4 Discussion

The main objective of this investigation is to explore the causes that led Tawila dam to collapse. On basis of the site observations and tests results, the main cause of Tawila dam failure may be due to seepage of water, design and construction mistakes.

The seepage of water through the body and foundation of the earth dam may lead to piping and excessive erosion from concentrated leaks, causing sever failures. Water seeping through the earth dam structure may have four bad effects as follows:

1. Seeping water generates erosive force which dislodges particles from the soil structure and cause rearrangement or migration of the fine to voids between larger grains.
2. Internal erosion of the soil mass finally progress backwards from the exit points to form open pipes.
3. The internal pressure in the soil water can reduced that part of the soil strength that is developed by internal friction thereby, lead to weakening of the soil mass and even failure by shear.

The most probable cause of spillway failure may be due to poor construction. The new constructed part of the spillway has no link with the old part of the spillway. As settlement occurred in the new one, the two parts were completely separated due to shear forces. Thus leading to collapse and wash away with water flow of the new constructed portion of the secondary spillway.

The embankment close to the spillway (right wing) of Tawila dam got saturated due to excessive seepage. It might have been eroded, producing small slumps/slides presenting relatively steep faces which once again became saturated by seepage from the reservoir and slumped again, forming slightly higher and unstable faces. This raveling process kept on going until the remaining portion of the embankment became too thin to withstand the water pressure, thus leading to the collapse of embankment and right wing-wall.

It is clear that the failure of the spillway structure and the embankment of the dam are mainly due to seepage of water. Thus, to avoid and prevent any seepage of water below the spillway structure that may occur, vertical moisture barriers can be used to a satisfactory depth at different locations below the concrete slab. Also in order to control the escaping of fine particles, a rock toe drain to be provided which consists of filter and rock. The purpose of the filter and drain is to provide a way for seepage to exit the dam without causing excessive erosion of the dam material.

For a proper design and construction of dam embankment, hand-placed riprap can be used to protect the slopes of the embankment against destructive wave action in the upstream and from weathering effects for downstream slopes.

4. Conclusion

This paper focused on failures of dams and properly described the modes and causes of failures. Based on the review of literature, previous experiences and the study testing results, the following conclusions are drawn.

- The most common causes of earth dam failures are overtopping and piping in the dam body or foundation.
- A good understanding of failure causes leads to prevent similar failures from occurring in the future and this is required for disasters prevention.
- Conveying dam failure information to the broad of dam safety and the community so that similar deficiencies can be corrected at existing dams and avoided at new dams.
- Proper geotechnical and hydrological investigations are essential prior to design or rehabilitation of dam.
- For homogeneous earthfill dams, spillways, foundations, and downstream slopes are believed to be potential locations at risk for overtopping failure; while any part of the dam body/foundation can be a potential location at risk for piping failure.

- Any dam that fails has a detrimental impact on the environment. This will vary depending on the size of the failure. Small dams will probably only impact a very small portion of the environment downstream.

References

[1] Z. Shah, M. Dinesh Kumar, “In the Midst of the Large Dam Controversy. Objectives and Criteria for Assessing Large Water Storages in the Developing World,” International Water Management Institute, India Project Office, VV Nagar, India, 2009.
[2] J. Bird, P. Wallace, “Dams and Development—An Insight to the Report of the World Commission on Dams, Irrigation and Drainage,” Wiley, New York, 2001.
[3] ICOLD, Dam failures statistical analysis, International Commission on Large Dams (ICOLD), Bulletin 99, 1995.
[4] USCOLD, Lessons from dam incidents, USA II, Committee on Dam Safety of the United States Committee on Large Dams (USCOLD). American Society of Civil Engineering, New York, 1988.
[5] T.R. Howard, “Statistical analysis of embankment dam failure,” Proc. 19th Annual Engineering Geology and Soils Engineering Symposium, Pocatello, ID, USA. pp. 1 – 17, 1982.
[6] H. Blind, “The safety of dams,” Water Power and Dam Construction, 35(5), pp. 17 – 21, 1983.
[7] A. Silveira, “Statistical analysis of deteriorations and failures of dams,” In Safety of dams. Edited by J.L. Serafim. A.A. Balkema, the Netherlands. pp. 55 – 60, 1984.
[8] O.G. Ingles, “A review of dam failure: past, present and future,” In Flood insurance and relief in Australia. Edited by D.I. Smith, H. Smith, and J.W. Smith. Australian National University, Canberra. pp. 159 – 167, 1988.
[9] M. Foster, R. Fell, M. Spannagle, “The statistics of embankment dam failures and accidents,” Canadian Geotechnical Journal, 37(5), pp.1000 – 1024, 2000.
[10] D. Qing, The River Dragon has come!: Three Gorges dam and the fate of China’s Yangtze River and its people, ME Sharpe, 1997.
[11] J.E. Costa, “Floods from dam failures,” Open-file report, U.S. Department of the Interior Geological Survey, Denver, USA, 1985.
[12] M. Olias, J. Ceron, I. Fernandez, F. Moral, A. Rodriguez-Ramirez, “State of contamination of the waters in the Guadiamar Valley five years after the Aznalcollar spill,” Water, Air, & Soil Pollution 166(1), pp. 103–119, 2005.
[13] NPDP, Dam incidents database, National Performance of Dams Program, Stanford University, California, USA. Available at npdp.stanford.edu, 2007.
[14] V.K. Hagen, “Re-evaluation of design floods and dam safety,” Vol. 1, Proc. of 14th Congress of International Commission on Large Dams, Rio de Janeiro, Brasil, pp. 475 – 491, 1982.
[15] C.A. Pugh, D.W. Harris, “Prediction of landslide generated water waves,” Vol. Q. 54, Proc. of the 14th International Congress on Large Dams (ICOLD), Rio de Janerio, Brazil, pp. 1056 – 1075, 1982.

Author Profile

Dr. Magdi Zumrawi was born in Omdurman, Sudan, 19 May 1963. He received the B.Sc. degree in Civil Engineering and M.Sc. degree in Road Technology from University of Khartoum in 1987 and 1991, respectively. He achieved Ph.D. in Highway and Railway Engineering, Chang'An University, Xi'an, in Sept. 2000. Now he is Associate Professor in Highway Engineering. His present occupation is Head, Civil Engineering Department, Faculty of Eng., Khartoum University, since Nov. 2014. He is a highway expert working with local and international consultant firms. He has published many articles in local and international journals and attended national and international conferences. He is a member of International Society for Soil Mechanics and Geotechnical Engineering. He is a senior member of the APCBEES.