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STATE-OF-THE-ART PAPER

Hydraulic failures of earthen dams and embankments

Priyanka Talukdar[1] · **Arindam Dey**[1]

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Abstract
The problem of dam failures is of great importance as it has devastating impact upon humankind and the environment. This review highlights the hydraulic failure of earthen dams and embankments, emphasizing on the piping and overtopping phenomena. Piping failures are mostly attributed to the uncontrolled seepage or the absence of suitable zonation of materials and filters in earthen dams. The overtopping process is a complex unsteady, nonhomogeneous, nonlinear three-dimensional problem, which has not yet been methodically studied from a theoretical perspective. With the advancement of time and technology, different mathematical, analytical and numerical models, aptly supported by physical modeling, has led to the better understanding of these phenomena. Although these approaches have facilitated the evaluation of seepage and deformation in the earthen dams and embankments, still several critical issues need to be addressed. This review highlights the gap areas and possible future scopes related to the hydraulic failures of dams.

Keywords Earthen dams and embankments · Hydraulic failure · Piping · Overtopping · Seepage · Filters

Introduction

Dams are structural barriers constructed to block or control the water flow in rivers and streams. The dams are built to render two primary functions: (a) water storage to compensate the variations in river discharge (flow) and (b) increasing the hydraulic head (difference in height between upstream reservoir and downstream water levels), thereby creating additional head of water facilitating generation of electricity, providing water for agricultural, industrial or household needs and controlling river navigation. The type and size of a dam exhibit a complex dependency on the amount of water available, requirement for water storage or diversion, topography, geology and the characteristics and feasibility of local materials available for construction. Embankment dams are built of various types of geologic materials, with an exclusion of peats and organic soils. Most embankments are designed to utilize the economically available on-site materials for the bulk of construction. Considering the volumes of materials used in construction, embankment dams comprise the world's largest dams. The Fort Peck dam on River Missouri in Montana is one of the largest embankment dams, utilizing 125 million cubic yards (92 million m^3) of earth materials for its construction [1]. The large embankment dams require an extraordinarily critical engineering skill for conception, planning, design and construction.

Critical issues with embankment dams

The construction of embankment dams is most common and popular due to the easy availability and easy handling of the construction materials, lesser cost of construction and lesser restrictions in selection of sites. The chief drawback of earthen dams is that they are prone to be overtopped, subjected to seepage, internal erosion, piping and heaving. Apart from being subjected to transverse and longitudinal cracking, desiccation cracking also leads to sufficient malfunctioning. Embankment instability is another serious problem that comprises slides, displacements, slumps, slips and sloughs of the earthen structure. Depressions, sinkholes and settlement are some common early indicators of serious problems that are also noticeable in such dams. Intense rainfall, rapid drawdown and seismic excitations, leading to internal and local liquefaction, are also cited to be the

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✉ Arindam Dey
arindamdeyiitg16@gmail.com

Priyanka Talukdar
priyanka.talukdar1990@gmail.com

[1] Department of Civil Engineering, Indian Institute of Technology Guwahati, Guwahati, Assam, India

primary triggers for such failure and mishaps. Embankment dams should be assessed for various loading conditions. The range of loading conditions at various stages, from construction through the operational stage of the completed embankment, encompasses different cases such as the end of construction, rapid drawdown, steady seepage and partial pool of steady seepage condition. Thus, critical assessment of the failure of the earthen dams and embankments needs to be reviewed in order to find out the gap areas where further research should be conducted.

Failure of earthen dams and embankments

Fig. 2 Failure of Campos's dos Goytacazes dam [6]

Failure of earthen dams occurs when the structure is breached or significantly damaged, leading to catastrophic effects. Routine monitoring of deformation and discharge from drains in and around dams is extremely helpful to predict the problems and allow remedial measures to be taken before the occurrence of failure. According to the international humanitarian law [2], dams are considered "installations containing dangerous forces," since these structures have huge influence of an impending catastrophe on lives and property. The failure of the Banqiao Reservoir dam is shown in Fig. 1, which occurred in 1975, and other dams like the Upper and Lower Baoquan dams, Guxian dam, Nanwan dam and Xiaolangdi dam in Henan Province, China, are few such examples that resulted in more fatalities than any other dam failure in the history. The catastrophes resulted in the loss of lives of approximately 171,000 people and left nearly 11 million people homeless [3]. Thousands of people were left homeless in 2012, during the failure of Campos's dos Goytacazes dam, located in Brazil toward the northern state of Rio de Janeiro [4] as shown in Fig. 2. In India, major dam failures include the failure of Kaddam Project dam (Andhra Pradesh), Machhu (irrigation scheme) dam (Gujarat) shown in Fig. 3, Kaila dam (Gujarat), Kodaganar dam (Tamil Nadu), Nanak Sagar dam (Punjab), Panshet dam (Maharashtra) shown in Fig. 4 and the Jaswant Sagar dam (118-year-old, situated in Luni River basin, Jodhpur, Rajasthan). Such dam failures remind that non-scientific design may lead to catastrophic situation on the lives and environment [5].

Generally, failure of dams occurs quite rapidly and without sufficient warning, thereby representing a potential to an extensive calamity. Some of the typical dam failure incidents that resulted in such catastrophe are shown in Figs. 5, 6, 7 and 8. Therefore, the design of dams should be carried out scientifically to avoid such situations as much as possible.

The probability of failure of dams due to several reasons and the high risk involved during the construction of dams has not suppressed the worldwide construction of dams. To meet the ever-growing global demand of water, the intensity

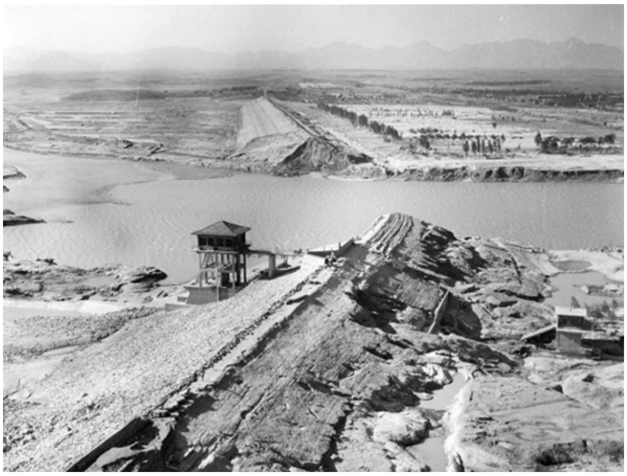

Fig. 1 Failure of Banqiao reservoir dam [3]

Fig. 3 Machhu dam diaster [7]

Fig. 4 Panshet dam disaster [8]

Fig. 6 Tous dam after failure [10]

of dam construction has been immense in the recent years [13]. This increasing demand for water would lead to an eventual steady depletion of the unevenly distributed freshwater resources around the world. During the past three centuries, the freshwater resources are depleted and the amount of water consumption has increased by a factor of 35. With the existing total storage capacity of about 6000 km^3, dam constructions definitely mark a vital contribution to the systematic management of limited resources of freshwater that are unevenly distributed and are prone to tremendous seasonal variations. Hence, with over lakhs of dams already in operation around the world and many upcoming ones, proper scrutiny and analysis of complicacies of the dams and their safety become one of the major concerns [14]. Until date, in India, approximately 4862 numbers of large dams were constructed, while another 812 are under construction [15], out of which the major share is in the states of Maharashtra, Madhya Pradesh, Gujarat, followed by the other states and

Fig. 7 Aerial view of Merriespruit dam failure [11]

Fig. 5 Birds-eye view of the third largest coal ash disaster in the history of the USA (the Duke Energy Company's Dan River (North Carolina) Coal Ash Earthen Dam Breach (February 2, 2014) [9]

Fig. 8 Brumadinho dam disaster [12]

union territories not lacking behind in dam construction and water management.

With such a huge number of dams located across the nation, all necessary measures to assure its safety become extremely necessary and mandatory. To understand all the intricate issues, an intricate and thorough research on the functionality and failure analysis of dams is the foremost need of the hour. In the recent past, it is seen that an interest in studying the static and dynamic behavior of earthen and rockfill dams is revived. Various new analytical and numerical formulations, as well as laboratory-based procedures, are developed for estimating the behavior and assessment of the complete safety of such dams against worst scenarios. At the same time, the number of case histories and outputs from full-scale vibration tests is continually increasing, which would eventually make it feasible to calibrate the developed procedures utilizing real field measurements. Based on such studies, it is observed that the two main causes for the hydraulic failure of earthen dams and embankments are piping and overtopping. The following sections present a detailed review on these issues.

Piping failures in dams

General perspective

A critical appraisal of the published literature on seepage failures of dams reveals that since the construction of the earliest dams around 2900 BC, piping failures in dams are quite common. In the earlier days, the construction methods did not cater the benefit of proper material zonation and filters in earthen dams, thereby leading to noticeable seepage effects. The successful dam designs evolved empirically by the first millennium AD, with the growing experience of construction of dams on a variety of foundation materials. A glaring example of a successful dam design is manifested by the 2000-year service life of the Proserpina dam constructed by the Romans [16]. Since then, a huge volume of research materials is developed to address the phenomenon on piping. Since the work is an outcome of global and interdisciplinary study, there exist numerous definitions of piping phenomenon in the literature. It is a usual practice to coalesce various phenomena and their consequences under the common term ‘‘piping.’’ For clarity, proper understanding of definitions is important [17] before advancing with the review, and the same given in Table 1. Although all the coined terms indicate piping as a final manifestation, it is very important to know the intricate mechanism that results in piping, as the same would guide for the remedial measures that can be adopted in practice.

Statistics of piping failures

The historic record of dam failures due to piping indicates the involvement of many factors resulting in this phenomenon. The progressive backward erosion of concentrated leaks evolves as the most serious problem from piping [22]. It is found that repeated cycles of swelling and shrinkage in soils also result in piping [27]. Numerous cases of piping were reported to occur due to internal erosion, incorrect design of the filter or poor maintenance. As per the assessment of the statistics of dam failures, proper design of conduits, or avoiding them altogether, would have significantly dropped the number of piping failures. Based on various sources [16, 17, 28–33], Table 2 compiles the piping failures experienced in earthen dams and embankments from 1950 onwards.

Early researches on piping phenomenon through embankments and dams

The process of piping was first referred in the context of landforms in loess by von Richthofen in 1886 [16]. Bligh

Table 1 Different definitions of piping existing in the literature

Researchers	Definitions
Terzaghi [18, 19]	The mechanism of ''piping associated with heaving'' was introduced. It was stated that heave takes place when a pervious zone is overlain by a semipermeable barrier under comparatively high pressure of fluid. In case of heaving, an increase in fluid pressure in the permeable zone (e.g., during flood event) may lead to a situation in which the uplift at the bottom of the semipermeable barrier surpasses the upward effective stress provided by the overlying barrier. This type of failure takes place at a hydraulic boundary in which the water migration through the barrier is at a lower rate than the pressure-increment rate
Terzaghi [20], Lane [21], Sherard et al. [22]	Piping was defined as a process in which particles are gradually removed from the matrix of the soil by the tractive forces generated by water seeping through the soil. The shear resistance of the grains balances the tractive forces that mobilize the weight of soil particle and toe filter. The greatest erosive forces are experienced at an exit point where there is concentration of the water flow, and as the removal of soil particles takes place due to erosion, the erosive forces increase due to the increased flow concentration. This type of piping is termed as "classic backwards-erosion type of piping"
Jones [16], McCook [23], Richards and Reddy [17]	Coined the term "suffusion" to define the gentle migration of fine-grained materials through a coarser matrix, resulting into failure. This phenomenon can lead into the formation of a loose cohesionless matrix permitting comparatively high flow of water that results into disintegration of the soil skeleton. Suffusion results into high water transmissivity with the formation of high permeable zones in non-cohesive soils. It also results in increased seepage through possible outbreaks, increase in the erosive forces and probable disintegration of the soil structure skeleton
Jones [16]	"Tunneling" or "jugging" is commonly seen in dispersive soils, mainly caused by erosion due to rainfall. Tunneling primarily takes place within the vadose zone and it occurs due to the chemical dispersion of clayey soils from rainfall water flowing between the open cracks or natural conduits. The occurrence of tunneling in the phreatic zone is rare, but in adverse situations, tunneling may result in the failure of dams
Franco and Bagtzoglou [24], Louis [25], Worman and Olafsdottir [26]	"Internal erosion" was defined as the flow of water through the already existing openings, e.g., cracks in cohesive material or voids along a soil–structure interface. The inter-granular flow does not have much role to play in internal erosion. The hydraulics of the problem is very different as compared with backwards erosion. Internal erosion is initiated by erosive forces of water flowing through planar openings, instead of being initiated by Darcian flow at an exit point. Thus, for planar openings, it is assumed that internal erosion would start according to the cubic law of flow

[34] described piping in the purview of the dismissal of soil along the foundation of masonry dams. Such form of piping was studied, as early as in 1895, in Indian geotechnical laboratories through mechanical models and laboratory prototypes [34, 35]. In 1898, the demolition of the Narora dam on the Ganges River, India, was the maiden incident where piping became a concern to the engineers [16]. Following the incident, Bligh [34, 36–38] proposed "line of creep" theory to calculate the piping potential along the soil–structure interface, thereby correlating the flow path and the length of seeping water to the tractive forces responsible for the soil particle movement. The proposed theory was based on the consideration that the flow along the most likely path is not Darcian, and the flow path is defined as the summation of the vertical and horizontal distances estimated along the soil–structure interface.

Based on the same context of piping as described by Bligh [34], with the aid of extensive case histories, Richards and Reddy [17] elucidated a clear distinction between the flow along structural interfaces and the diffused flow through granular media. The anisotropic conditions that govern fluid flow through stratified materials were taken into account by making suitable adjustments to the existing "line of creep" theory, and accordingly the "weighted creep method" was proposed by Griffith [39]. The "weighted creep method" considers a modified length of flow path, which is arbitrarily chosen to be 1/3rd the length of flow path used by Bligh [34]. The foremost application of the modified creep method was made to investigate the failure of the Prairie du Sac dam in Wisconsin, USA [34].

Terzaghi [19, 40] described piping as the progressive backward erosion of particles from the exit point of the soil–structure interface. Terzaghi [20] presented the estimation of piping potential for the case of boils and heaving in a cofferdam cell due to the vertical upward flow of groundwater into the excavated and dewatered floor of a cofferdam. Based on laboratory model tests, it was deciphered that as the critical value of hydraulic head is exceeded at the exit point, the rate of discharge increases, thereby manifesting a rise of the average permeability of the sand. A safety factor against such piping is defined by the ratio of the effective weight of a soil prism (in expected

Table 2 Piping failures of earthen dams and embankments

Sl. no.	Name of the dam	Year of failure	Height (m)	Type	Cause
1950–1960					
1	Stockton Creek dam, California, USA	1950	24.4	Rolled earth	Abutment piping
2	Masterson dam, Oregon, USA	1951	18.3	Rolled earth	Piping through dry fill
3	Owl Creek dam, Oklahoma, USA	1957	8.5	Earthen	Conduit piping
4	Penn Forest dam, Pennsylvania, USA	1960	46	Rolled earth	Piping-sinkhole developed on upstream
1961–1970					
5	Panshet dam, Maharashtra, India	1961	53.8	Earthen	Piping failure
6	Baldwin Hills Reservoir dam, California, USA	1963	48.8	Rolled earth	Piping toward foundation resulting from fault movement
7	Jennings Creek dam, Tennessee, USA	1963	61	Earthen	Foundation piping
8	Upper Red Rock Creek dam, Oklahoma, USA	1964	7	Rockfill	Erosion tunnel piping
9	Nanak Sagar dam, Uttarakhand, India	1967	16	Earthen	Breached due to foundation piping
1971–1980					
10	D.T. Anderson dam, Colorado, USA	1974	72	Earthen	Piping through foundation
11	Walter Bouldin dam, Alabama, USA	1975	51.8	Earthen and rockfill	Piping toward the downstream side next to intake structure
12	Dresser dam, Missouri, USA	1975	32	Earthfill	Piping
13	Teton dam, Idaho, USA	1976	93	Rolled earth	Piping through abutment
14	Bad Axe Structure dam, Wisconsin, USA	1978	22.2	Earthen	Piping toward abutment foundation joints
15	Upper Lebanon Reservoir dam, Arizona, USA	1978	13.7	Earthen	Piping into embankment (tree roots)
16	Fertile Mill dam, Iowa, USA	1979	3.4	Earthen	Piping or seepage initiated failure of slope
17	Morbi dam, Gujarat, India	1979	59.1	Earthen and masonry	Heavy rainfall resulting in piping and breaching
18	Saint John dam, Idaho, USA	1980	11.9	Rolled earth	Piping, sinkholes toward upstream side
1981–1990					
19	Johnston City Lake dam, Illinois, USA	1981	4.3	Earthen	Piping in badly conserved embankment
20	Roxboro Municipal Lake dam, North Carolina, USA	1984	10	Earthen	Piping beneath paved spillway
21	Upper Red Rock Creek dam, Oklahoma, USA	1986	9.4	Earthen	Piping into embankment
22	Little Washita River dam, Oklahoma, USA	1987	10.7	Earthen	Piping into soils, failed after 10 years of construction
23	Quail Creek dam, Utah, USA	1988	63.7	Earthen dike	Piping into foundation
1991–2000					
24	Boyd Reservoir dam, Nevada, USA	1995	9.8	Earthen	Piping into embankment after rainfall and snowfall
25	Eureka Holding dam, Montana, USA	1995	12.2	Earthen	Piping into dike after heavy downpour
26	Bergeron dam, New Hampshire, USA	1996	11	Earthen	Piping under spillway slab
27	Holland dam, Texas, USA	1997	4	Earthen	Piping failure
28	Hematite dam, Kentucky, USA	1998	4	Earthen	Piping between embankment and concrete sluice contact
29	Vertrees dam, Colorado, USA	1998	8.2	Earthen and rockfill	Piping, outlet damaged
30	Pittsfield Dredge Disposal Pond dam, Illinois, USA	1999	10.7	Earthen	Piping after 2 h of observed seepage
2001–2010					
31	Lake Flamingo dam, New Jersey, USA	2001	8.2	Earthen	Piping through conduit
32	Bridgefield Lake dam, Mississippi, USA	2001	7.6	Earthen	Piping initiated failure of slope

Table 2 (continued)

Sl. no.	Name of the dam	Year of failure	Height (m)	Type	Cause
33	Sauk River Melrose dam, Minnesota, USA	2001	8.2	Earthen	Piping failure of slope at the time of high water
34	Jamunia dam, Madhya Pradesh, India	2001	15.4	Earthen	Piping failure
35	Swift dam, Washington, USA	2002	25.3	Earthen	Piping through rock foundation
36	Beech Lake dam, North Carolina, USA	2002	6.7	Earthen	Piping rupture of conduit under high pressure
37	Big Bay Lake dam, Mississippi, USA	2004	17.4	Earthen	Piping into French drains
38	Jaswant Sagar dam, Rajasthan, India	2007	43.38	Earthen	Piping leading to breaching
39	Sardar Sarovar dam, Gujarat, India	2008	7.6	Earthen canal	Piping leading to breaching
40	Gararda dam, Rajasthan, India	2010	31.7	Earthen	Piping leading to breaching
2011–2019					
41	Bloom Lake mine, Fermont, Québec, Canada	2011	–	Tailing dam	Breach in the tailing pond resulted in a release of 20,000 m^{3}of harmful materials
42	Campos dos Goytacazes dam, Brazil	2012	14	Earthen	Piping initiated due to excessive rainfall causing flooding and leaving 4000 people homeless
43	Zangezur Copper Molybdenum Combine, Kajaran, Syunik province, Armenia	2013	60	Tailing dam	Piping initiated after the damage of the tailing pipeline
44	Dan River Steam Station, Eden, North Carolina, USA	2014	18	Tailing dam	Drainage pipe collapsed resulting in dam breach and releasing toxic coal ash
45	Mariana dam disaster, Mariana, Minas Gerais, Brazil	2015	90	Earthen	The damage of the dam resulting in piping followed by a breach resulted in the destruction of one entire village evacuating 600 people
46	New Wales plant, Mulberry, Polk County, Florida, USA	2016	18	Tailing dam	Internal erosion resulting in a 14-m-wide sinkhole finally opening pathway for contaminated liquids
47	Maple Lake, Paw, Michigan	2017	5	Earthen	The dam crumbled because of the heavy weight of the pond above it and resulted in its failure
48	Panjshir Valley dam, Afghanistan	2018	104	Earthen and rockfill type	Piping resulted in crumbling of the dam which further deteriorated during heavy summer rains leaving 300 homeless and 13 people missing
49	Brumadinho dam disaster, Brazil	2019	87	Tailing dam	Suffered a catastrophic failure releasing 12 million cubic meters of tailings slurry. 87 people missing

area of heave) to the excessive upward hydrostatic pressure [41]. A critical safety factor was determined by “trial and error method” conducted over numerous depths. According to Terzaghi et al. [42, 43], almost all piping failure results in a gradual reduction in the safety factor until attaining the failure point. The prevailing misperception about the non-occurrence of piping in homogeneous cohesionless was pointed. It was highlighted that in embankments comprising homogeneous cohesionless material, development of sinkholes is commonly witnessed due to piping phenomenon through the body of the embankment or through the heterogeneous foundation. It was recommended that piping potentiality in cohesionless embankments should never be completely neglected and should be checked with other possible failure modes.

Aitchison [44] and Aitchison et al. [45] stated that piping processes involved dispersion of clayey soils. Since then, a number of tests are developed to determine the dispersivity of soil. Dispersion Index method, developed by Ritchie [46], aids in the indication of probable tunneling failure of earthen dams comprising 33% of the soil lesser than 0.004 mm, which disperses after 10 min of shaking in water. The pinhole test was found to be the most suitable method for the classification of dispersive soils [47]. On the other hand, Decker and Dunnigan [48] concluded that the dispersivity of soils, maintained in their natural moisture content, could be better predicted by the "soil conservation services (SCS)" dispersion test. The review of the literature indicates that there is obvious that no single diagnostic test for the assessment of the quality of dispersive soils. It is a proposed practice to carry out numerous tests and utilize reasonable engineering judgment when dealing with dispersive soils [49].

Recent developments on piping phenomenon through embankments and dams

Recently, researchers have stressed on Lane's [21] differentiation between piping and internal erosion to distinguish between the processes of seepage through coarser medium compared to the seepage through openings like cracks [50]. Recent works related to piping have emphasized on the formulation of mathematical models that can predict particle transport and clogging of filter [50–54]. The studies on unstable dispersive soils and their effect on natural soils also form a prime crux of the continuing research. Data collection to create an inventory of earlier incidents and statistically characterizing them against the various piping failure modes of earthen dams is another attractive domain of research, thereby investigating the reasons, mechanisms and generic characteristics of piping [22, 28, 29]. The researches related to the prediction of the development time of piping are already attempted by few researchers [55, 56]. With the advent of superior computational and constitutive modeling, the developments in numerical and laboratory studies are currently being widely attempted [57].

Development of different physical models has gained popularity, which aids in evaluating the important parameters responsible for breaching of earthen dams due to overtopping. However, these models do not give considerable importance to dam failures due to piping [58]. A new mathematical model was introduced to give a detailed and proper insight about the evolution process of piping mechanism in earthen dams [59]. In the novel model, two vital mechanisms were highlighted to have a better understanding of the piping process. The two mechanisms that were included in the model comprise (a) the surface erosion on the wall of the pipe and (b) global collapse of the soil mass above the pipe. The study presented the principles of the mathematical modeling along with the simulation of the historic Teton dam failure (Fig. 9) [60] with the help of proposed model.

Both pipe flow and weir flow equations were used to describe the flow of the fluid in the model. The results from the simulations showed that the height and width of the pipe gradually increased and the process of evolution of the pipe geometry was different for different materials having varying erodibility characteristics. Eventually, the process of piping was converted into overtopping after the soil mass above the pipe collapsed. A number of attempts were made by different researchers to predict the time for piping failure. Different numerical approaches were attempted in this regard [61]. Bonelli [62] attempted to predict the erosion rate from hole erosion test (HET). It was attempted to quantify the time required for piping in the embankments, by correlating the critical stress and coefficient of erosion to common geotechnical soil properties. However, no prediction expression was provided for estimating the time of piping failure. Chang and Zhang [63] described that the mechanical behavior of the soil gets affected by the internal erosion of the soil. Backward erosion (a form of internal erosion in which the soil particles are removed gradually by the erosive action of water) results in the formation of shallow pipes in a direction opposite to the flow of the water. This kind of failure occurs mostly in dams and dikes where sandy layers are covered by a cohesive layer. An indication of backward erosion is given by the occurrence of sand boils at the ground surface downstream of the structure. Figure 10 shows the typical occurrence of sand boils along the Mississippi and Waal rivers. In this regard, the validation of Sellmeijer model was carried out by conducting small (1-g and n-g), medium and

Fig. 9 Historic Teton dam failure [60]

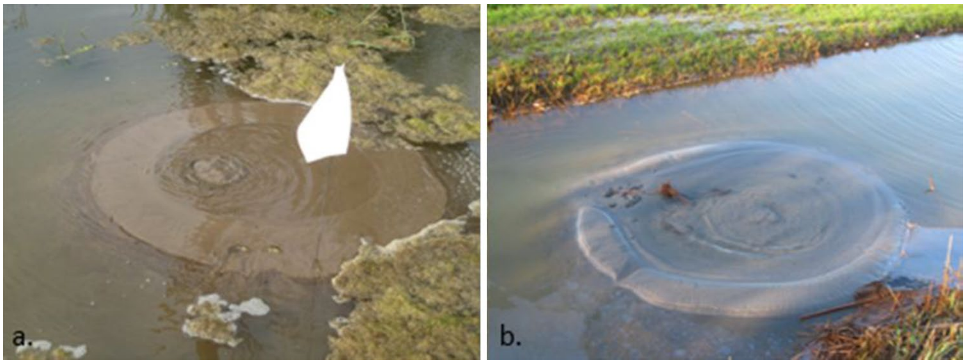

Fig. 10 Typical sand boils along **a** the Mississippi River in the USA and **b** the Waal River in the Netherlands [64]

large-scale experiments [64]. The model was later readjusted such that it can take into account the effect of pipe-forming erosion processes in uniform sands.

Modeling of piping through earthen embankments and dams

The available literature provides a number of mathematical, physical and numerical models in the context of piping phenomenon and associated mechanisms in the purview of failure of earthen dams and embankments. This section illustrates a few of the important studies. The number of fatalities arising from a dam failure event is largely dependent on the obtained early warning-based evacuation time to shift the population at risk on the downstream part of the dam. The United States Bureau of Reclamation [65] proposes that an early warning of failure time of as little as 60 min can sufficiently reduce the number of fatalities. Thus, attempts were made to define a reasonable prediction time, which is related to the development of breach in the dam owing to the progression of the pipe through the dam and its foundation [56]. In this regard, the process of internal erosion and piping is divided into four phases: (a) the initiation stage, (b) the continuation stage leading to erosion, (c) formation of a pipe with due course of time and (d) development of a breach. The initiation of piping may be generated by different processes like backward erosion, suffusion or concentrated leaks. The process of continuation may be controlled by filters and transition zones. The phenomena leading to piping in an embankment or its foundation include the capacity of the soil to prevent the collapse of the roof of the pipe, increment and rate of increment of the pipe diameter and the influence of migration of filter particle from the upstream in limiting the flow through the channels through a process called "crack filling." Considering all the above conditions, a generalized method was proposed by Fell et al. [56] to assess the likely time for the development of internal erosion and piping. For successful implementation of the proposed method, proper characterization of the embankment material, its degree of saturation, the hydraulic gradient across the core, soil type, clay fraction, dry density and the factors likely to limit the seepage flow from the upstream are to be thoroughly investigated to decipher their influence on the formation and progression of piping.

Erosion through concentrated leaks has resulted in a number of piping failures of dam. As the cracking of core cannot be totally avoided, the geotechnical engineers aim to construct earthen dams with such characteristics so that the closure of these core cracks takes places at the earliest, resulting in the blockage of concentrated leakage and soil erosion. The favorable condition of blockage of concentrated leakage and soil erosion is widely known as self-healing. Reddi and Kakuturu [52, 53] conducted laboratory experimental investigations to have a mechanistic understanding of the progressive erosion of core cracks in earthen dams and their self-healing characteristics. It was understood that the phenomenon of self-healing is affected by the characteristics of base soils and filters and the prevailing hydraulic, geometric and physicochemical conditions. The influence of partially cracked core (resulting in lesser leakage) and fully cracked core (resulting in substantial leakage) was investigated. A consistent hydraulic head was used to generate the horizontal flow through this crack. During the test, continuous monitoring of the effluent was carried out to figure out the characteristics of the progressive erosion and subsequent self-healing. Based on the experimental outcomes from various flow rates and effluent concentration with respect to time, the influence of critical seepage velocity through the filter, the surface erodibility characteristics of the base soil and the plug characteristics on self-healing are elucidated. Based on the experimental outcomes, a mechanistic 1D continuum model for predicting self-healing characteristics was developed [52, 53]. The numerical model represented the actual core cracks as irregular cross sections in a cylinder that represented the idealized domain. 1D flow through the domain under constant head condition was considered. At the exit point, the quantity of flow $Q(t)$ and the effluent concentration $C_e(t)$ were monitored which acted as indicators of self-healing or progressive erosion. Reduction in magnitude of the two indicators represents self-healing, while an increase in any one of the indicators illustrates progressive erosion. Based on the monitored results, the temporal variation in the two indicators was estimated.

Cividini and Gioda [66] presented a numerical model in which finite-element (FE) approach was used for the analysis of the erosion and transport of fine particles within a granular soil subjected to a seepage flow. The continuity equation for the mass of transported particles was derived considering a scheme conceptually similar to that applicable to the analysis of advective flow problems, followed by a finite-element formulation derived through a ‘‘two-step’’ time integration procedure. A mathematical model to describe the phenomenon of piping under a dam was presented by Sellmeijer and Koenders [67]. The model analyzed the groundwater flow problem with the presence of narrow channel under the dam, with an objective to identify any possibility of attaining equilibrium situation to inhibit further washing away of foundation material through the piping channel. A boundary value problem for the seepage flow following Darcy’s law was formulated to evaluate the particle forces on the lower periphery of the piping channel. The complexity of the solution was influenced by the sudden geometrical deviations at the ends of the piping channel. A design rule was formulated for the engineers to tackle all the possible realistic variations of the governing parameters.

A numerical modeling to investigate the process of erosion due to piping was developed by Alamdari et al. [68]. The piping was considered to originate from the upstream and progressively travel toward the downstream through the dam body, attributed to the enlargement of the pipe due to the axial flow of water. The numerical procedure was described by a two-phase 1D model, considering the soil as homogeneous and water-saturated. The mass and momentum conservation equations were used for the mixture of water/particle and the eroded particle phase in an Eulerian framework. In the framework of continuum mixture theory, based on solute transport, a new continuum fluid–particle coupled piping model was proposed by Luo [69]. It was assumed that the porous media comprises three phases, namely the solid skeleton phase, the fluid phase and the fluidized fine particles phase, in which the last phase is considered as a special solute migrating within the fluid matrix. The three phases interact while maintaining the mass conservation. Accordingly, a new continuum fluid–particle coupled piping model was established by introducing a sink term into the mass conservation equation, which is used to elucidate the erosion of fluidized fine particles. The proposed model considers the fluid particle interaction in the evolution of piping. The model is capable of predicting the piping development in complicated structures subjected to complex boundary and flow conditions. It can also highlight the temporal changes in porosity, permeability and pore pressure induced by eroded fine particles and can depict the unsteady, progressive failure characteristics of piping.

Laboratory experimental tests were carried out in the Hydraulic Laboratory, University of South Carolina, on piping erosion process in earthen embankment [70]. The experimental setup comprised a wooden flume of 6.1 m long, 0.46 m wide and 0.25 m deep. The soil compaction was made possible with 40-mm-thick flume walls. The disturbances and turbulence at the water surface were reduced by the straightener and wave suppressor on the upstream side of the flume. A constant upstream water level was maintained with a 0.30-m-wide side weir having a crest elevation of 0.13 m from the bed level of the flume. Visualization of the erosion process was made possible by using a plexiglass sidewall and flume bottom. A continuous flow to the flume was supplied with the help of an 8.5 l/s pump, and a control valve was used to regulate the flow of water. The embankment consisted of a mixture of sand, silt and clay, which was constructed with different construction rates. It was observed that increasing the compaction of the construction layers highly increased the erosion time. However, the final average depth of erosion remained the same in all the cases. The experimental results were used to produce exponential equations to calculate the erosion depth, the side area of the piping zone and the volume of eroded material. The effect of cement–bentonite treatments on erosion characteristics was studied by Wang et al. [71] with an aim to estimate the erosion percentage. This was further used to develop mathematical relationships between the percentage of erosion and different regimes (like curing period, erosion time, different cementitious replacement and sizes of initial holes), such that these relationships can be used in calculating the propagation of internal erosion originating from cracks in cement–bentonite seepage barriers. Hoffman and van Rijn [72] developed a piping model based on Darcy’s Law and incorporating Hagen–Poiseuille equation, Darcy–Weisbach equations and Shields’ equations, which can be used to describe the laminar pipe flow and incipient motion of the particles. The influence of non-uniformity of the sand mixture on pipe erosion was included in the model using the shear stress concept developed by Grass [73]. A comparison of the developed model was made with the Sellmeijer’s piping equations by using nearly 100 laboratory experiments along with some field observations. The basic difference between the two models was in the expression used in the calculation of critical hydraulic gradient that resulted in the backward erosion-induced dam failures.

Application of filters and drains in association with piping phenomenon

Piping can be controlled by the use of correctly designed granular filters that will retain any eroded soil particles while allowing the seepage water to flow. Empirical methods for filter design are formulated by rigorously testing different combinations of base soil–filter under various hydraulic gradients for its stability [74]. However, while these soil filters and drainage layers are expected to serve the purpose of protecting the earthen dams, the changes in the permeability of the material over the time become a critical issue. There is well-documented literature where many studies associated with inadequate filter design were reported [75, 76]. Studies have shown that poor drainage caused by particulate clogging can result in drastic variation in the pore water pressures within the embankment and can lead to substantial changes in the phreatic level with time, even reaching the higher limits of the downstream face.

The migration of particles in porous media is a subject of importance in several disciplines of geotechnical and geo-environmental engineering. With the aid of probabilistic methods, Silveira [77] examined the particle migration of base soil into filters and proposed the concept of pore constriction, which states that the movement of a particle from one pore to the next is facilitated if the particle size is smaller than the pore spaces. Based on the probabilistic comparison of the distribution of size of base soil particle and filter constriction size, a prediction model of the infiltration depth into clean filters was developed. Witt [78] developed a 3D pore network model comprising spheres (pores) interlinked by pipes (pore constrictions), which considers that the pore constrictions provide sufficient exits for each pore, and the movement from any pore is controlled by the largest size of adjacent pore constriction. Schuler [50] had chosen an identical 3D void network model, wherein Monte Carlo simulations were used to assess the extent of infiltration of the base soil particles into the filter. Indraratna and Vafai [79] suggested a finite-difference (FD)-based particle transport model, governed by mass and momentum conservation. The analysis aided in assessing the temporal change in the distribution of particle size, permeability and porosity of the materials at the interface of base–filter. Locke et al. [55] developed a revised analytical model capable of capturing the movement and temporal transport of non-cohesive base soil particles into granular filters, which can be suitably used in the design of non-cohesive, uniform and well-graded base and filter materials. The proposed model can capture the changes in rate of flow, porosity and permeability of non-cohesive, uniform and well-graded base and filter materials. Additionally, based on the washout of fine filter particle, the revised model is capable of estimating internal stability, although to a limited extent.

Laboratory experiments to model pipe flow and associated particle migration were conducted to understand the clogging process [80]. The corresponding numerical model was developed using Richards' equation to model the pipe flow. The modeling used two contrasting boundary conditions, constant flux (CF) and constant head (CH), to quantify pressure buildups due to pipe clogging. Wersocki [81] reported the clogging of drain around the drainage system of the hydropower plant Podgaje (located in the northern part of the Wielkopolska), owing to the precipitation of oxidized iron which subsequently reduced the soil porosity and hydraulic conductivity. Studies are available highlighting the most common forms of drain clogging and its influence on seepage under concrete dams built on permeable rock foundations [82].

Overtopping failures in dams

General perspective

Overtopping is usually caused due to the increase in the level of water or, many a times, due to the failure, insufficient size or elimination of the outlet works and the emergency spillway. Linsley and Franzini [83] have shown that 40 percent of the earthen dam failures take place due to overtopping. Therefore, it becomes imperative to pay proper attention to lessen the damage and reduce the risk of the life and property at the downstream side of the dam. This can be achieved by the construction of sustainable earthen dams that can overcome erosion for a greater duration of overtopping. As stated by Gilbert and Miller [84], overtopping for comparatively longer duration without catastrophic failure was seen in some earthen structures. Overtopping, during the outflows from a dam, is generally associated with complex temporal interaction of different entities, some of which are difficult to quantify, such as the variation in breach dimensions with time, reservoir size and volume, tail water and soil conditions and reservoir inflow.

Mechanism of overtopping of earthen dams and embankments

Embankment dam failure resulting from overtopping is a combination of hydrology, hydrodynamic, sediment transport and geotechnical events. Mathematically, overtopping is an unsteady, nonhomogeneous, nonlinear three-dimensional problem and involves a double-phase soil–water interaction system [85]. In this process of progressive overtopping, reservoir water starts flowing over the embankment crest, until a notch is created. Further, the notch gains in size with time due to progressive removal of soil. The process continues until the complete removal of reservoir water or the process of erosion attains a declining equilibrium. The parameters that substantially influence the dam breach event are size and geometry of the reservoir, size and geometry of the embankment, material and homogeneity of the embankment, texture and smoothness of the slope, overtopping depth and the existence or absence of tail water.

The sequential development of the overtopping process includes three distinct stages [85]. The first stage is the "onset of overtopping," which is governed by the temporal rise of reservoir level, whether rapid or slow. Overtopping is most commonly observed during flood events or incessant rainfall resulting in substantial runoff. Even before actual overtopping occurs, the rise in the reservoir level either leads to internal erosion occurring from piping process or erosion of the downstream due to excessive seepage, both processes endangering the stability of an embankment dam. The second stage comprises the actual "overtopping and development of the notch." At the beginning of overtopping, owing to the small overtopping height, water flows over the downstream face of the dam with a low velocity. With the increase in overtopping height, the velocity of flow increases to reach higher energy levels leading to unsteady flows. Under such conditions, the shear stress gradually builds up on the channel walls and leads to the development of notch as developed shear stress surpasses the threshold value to initiate the process of erosion. The rate with which erosion and notch development takes place after overtopping depends on the material characteristics, the velocity and depth of flow and the sediment load carried by the flowing water. The third and final stage is the "breach development" which is aggravated by the gain in energy and momentum as flowing water dips to the steeper slopes of the embankment, leading to a hydraulic jump. In this process, the severe turbulence and rapid energy dissipation leads to aggressive erosion of materials from the downstream, causing severe damage to the embankment toe and resulting in a local slope failure [85].

It is not necessary that the breach development has to initiate at the embankment toe. It may begin at any point along the downstream face of a dam where there is a geometrical discontinuity or a sudden change in the slope. As the initiated breach advances across the embankment crest, the notch deepens resulting in an increment of the flow area. The consequent increase in water flow will lead to increased erosion, which can progressively affect more area of the embankment before attaining equilibrium, thus leading to the possibility of a demolition of the embankment.

Statistics of overtopping failures

A thorough review of the trend and number of dam failures [30–33, 86, 87] has indicated that a large percentage of dam failure cases are due to overtopping. Table 3 presents a compilation of the overtopping-based dam failures.

Researches related to overtopping of dams and embankments

Several researchers have attempted to understand the behavior and mechanism of overtopping of dams and embankments through experimental, physical, numerical and mathematical modeling approaches [86, 87]. It is stated that the complex problem of overtopping may not necessarily be compliant to accurate mathematical solution, and hence, physical modeling should be resorted. The problem of overtopping encompasses difficult boundary conditions and nonlinear material properties, which makes the problem quite challenging. With the occurrence of overtopping, an unsteady nonlinear hydrodynamic process sets in, which includes flow conditions and temporally changeable boundary conditions [86, 87]. Although small-scale models are easy to fabricate and test until collapse in laboratory conditions, such models fail to replicate the exact behavior of full-size structures mainly due to the difference in stress state under gravity loading. In order to generate the stress conditions of full-size prototype model in a small-scale model, 1 g gravity force needs to be implemented, which can be achieved through centrifuge testing. It is also necessary that for the design of a good model experiment, a good similarity should exist between geometric and dynamic nature of the model and prototype, referred as similitude [88, 89]. This can be fulfilled by grouping important parameters in their non-dimensionless form to achieve equivalence between the model and prototype. However, strict fulfillment of all the criteria is impossible and there would always exist some difficulties in modeling the real field conditions. Ko et al. [90] conducted centrifuge modeling study to simulate the behavior of two prototype embankments that failed as the result of overtopping. The scenario of sustained overtopping of erodible dams made of silty and clayey soils was studied.

In the last few decades, the study of failures due to overtopping has gained popularity among the researchers due to the catastrophic disaster it causes to life and property. However, the cost and time involved in the actual measurements of overtopping erosion are immense, and thus the studies conducted are generally limited to small-scale experimental tests. Researchers have developed empirical relationships to calculate the peak outflow discharge at the time of dam breaching due to overtopping [91, 92].

Soil erosion is the primary outcome of overtopping of dams, and therefore, many researchers, in the recent years, have specifically focused on the topic of soil erosion. Bed deformation and bank erosion simulation were conducted by a coupled model that was developed by Deng et al. [93], which primarily highlighted the bank erosion in the composite riverbank of Lower Jingjiang Reach. The particle size distribution of the eroded soil was utilized to arrest the progressive nature of the fluvial erosion in a dam-breach erosion model proposed by Choi et al. [94]. The researchers carried out field investigation to have a better insight about the danger posed to the riverbank along the Parlung Tsangpo River, China, due to the formation of partial debris dams as shown in Fig. 11. By using the results from the field investigations,

Table 3 Overtopping failures of earthen dams and embankments

Serial no.	Dam	Year of failure	Height (m)	Type	Cause of overtopping failure
1950–1960					
1	Frenchman dam, California	1952	12.2	Rockfill and earthen	Overtopping
2	Palakmati dam, Madhya Pradesh, India	1953	14.6	Earthen	Overtopping followed by sliding
3	Ahrura dam, Uttar Pradesh, India	1953	22.8	Earthen	Breaching followed by overtopping
4	Girinanda dam, Rajasthan, India	1954	12.2	Earthen	Overtopping followed by breaching
5	Anwar dam, Rajasthan, India	1957	12.5	Earthen	Breaching
6	Gudah dam, Rajasthan, India	1957	28.3	Earthen	Breaching
7	Nawagaon dam, Madhya Pradesh, India	1959	16	Earthen	Overtopping leading to breach
1961–1970					
8	Oros dam, Brazil	1960	35.6	Earth fill	Overtopped
9	Khadakwasla dam, Maharashtra, India	1961	60	Masonry	Overtopping
10	Kedarnala dam, Madhya Pradesh, India	1964	20	Earthen	Breaching
11	Hell Hole dam, California, USA	1964	67	Rockfill	Overtopped
12	Swift dam, Montana, USA	1964	57.6	Rock with concrete facing	Overtopped
13	Lower Two Medicine dam, Montana, USA	1964	11.3	Earth fill	Overtopped
14	Cheaha Creek dam, Alabama, USA	1970	4.3	Zoned earth fill	Overtopped
1971–1980					
15	Knife Lake dam, Minnesota, USA	1972	6	Earthen	Torrential rains resulting in overtopping
16	Dantiwada dam, Gujarat, India	1973	60.96	Earthen	Overtopped on account of floods
17	B. Everett Jordan cofferdam, North Carolina, USA	1973	9.2	Earth fill	Overtopped
18	R.D, Bailey cofferdam, West Virginia, USA	1975	18.3	Earth fill	Overtopped
19	Upper Elk River and Big Caney watershed embankments, Colorado, USA	1976	12.2	Earth fill	Overtopped
20	Armando de Salles Oliveira dam, Brazil	1977	35	Earthen	Severe rains resulting in overtopping
21	Euclides da Cumha dam, Brazil	1977	53	Earth fill	Overtopped
22	Laurel Run dam, Pennsylvania, USA	1977	12.8	Earth fill	Overtopped
23	Kodaganar dam, Tamil Nadu, India	1977	12.75	Earthen	Overtopped on account of floods
24	Salles Oliveira dam, Brazil	1977	35.0	Earth fill	Overtopped
25	Sandy Run dam, Cambri	1977	8.5	Earth fill	Overtopped
26	McCarty dam, Texas, USA	1978	16.5	Earth fill	Overtopping leading to breach
27	Bloomington cofferdam, Maryland-Virginia, USA	1978	9.2	Earth fill	Overtopping leading to breach
1981–1990					
28	Clarence Cannon cofferdam, Missouri, USA	1981	13.7	Earth fill	Overtopping leading to breach
29	Little Blue River levees, Missouri, USA	1982	4.6	Earth fill	Overtopping leading to breach
30	Little Blue River levees, Missouri, USA	1982	4.6	Earth fill	Overtopping leading to breach
31	Jackson Port levee, Arkansas, USA	1982	4.6	Earth fill	Overtopping leading to breach
32	Elm Fork Structure, Texas, USA	1981	10.7	Earth fill	Overtopping leading to breach
33	Hart Hydro dam, Michigan, USA	1986	11.9	Earth fill	Overtopping leading to breach

Table 3 (continued)

Serial no.	Dam	Year of failure	Height (m)	Type	Cause of overtopping failure
34	Rainbow Lake dam, Arizona, USA	1986	14	Rockfill and earthen	Severe rainstorms resulting in overtopping
35	Mitti dam, Gujarat, India	1988	16.2	Earthen	Overtopping leading to breach
1991–2000					
36	Chandora dam, MP, India	1991	27.3	Earthen	Breach
37	Kaddam dam, Andhra Pradesh, India	1995	22.5	Composite	Overtopping leading to breach
2000–2010					
38	Pratappur dam, Gujarat, India	2001	10.67	Earthen	Breach on account of floods
39	Polecat Lake dam, Lawrence, Ohio, USA	2001	42.6	Earthen	Extreme seepage leading to breaching and overtopping
40	Rustic Hills Lake dam, Medina, Ohio, USA	2003	28	Earthen	Excessive rain leading to overtopping
41	Nandgavan dam, Maharashtra, India	2005	22.51	Earthen	Excessive rain leading to overtopping
42	Palemgavu dam, Andhra Pradesh, India	2008	13	Earthen	Overtopping on account of flash floods
43	Chandiya dam, Madhya Pradesh, India	2008	22.5	Earthen	Breach
2011–2019					
44	Sichuan Province tailings dam, China	2011	45	Tailing dam	Heavy rains caused damage to the dam
45	Gull bridge tailing dam, Newfoundland, Canada	2012	7	Tailing dam	Breaching took place while work was going on to stabilize it
46	Obed Mountain Coal Mine, northeast of Hinton, Alberta, Canada	2013	–	Tailing dam	Breach of wall in containment pond
47	Mount Polley tailings dam failure, British Columbia, Canada	2014	40	Tailing dam	Dam collapsed due to overtopping. The water flowed beyond the designed parameters
48	Mariana dam disaster, Mariana, Minas Gerais, Brazil	2015	90	Earthen	The damage of the dam resulting in piping followed by a breach resulted in the destruction of one entire village evacuating 600 people
49	Antamok mine Itogon, Benguet province, Philippines	2016	–	Tailing dam	Breaching followed by heavy rains
50	Kokoya tailing dam,Gold, Bong County, Liberia	2017	–	Tailing dam	Overflow of water after heavy rain caused rupture of a section of the geo-membrane layer
51	Xe-Pian Xe-Namnoy dam, Attapeu Province, Laos	2018	73	Earth filled	Saddle dam under construction collapsed during rainstorms. 6600 people homeless, 98 missing
52	Hpakant dyke, Kachin state, Myanmar	2019	6.09	Earthen	Waste heap failure killing three workers and resulting in missing of 54 others

the proposed erosion model was adopted to back-analyze the fluvial erosion along the riverbank.

Researchers have investigated the risk and uncertainty analysis of dam overtopping phenomenon, involving different types of statistical distribution of parameters and varying inflows in the reservoir. Chigare and Wayal [95] presented the risk and uncertainty analysis to evaluate the overtopping of the Bhatsa dam in Thane, India. In order to calculate the maximum reservoir water elevation, univariate analysis of flood frequency and reservoir routing was used. Evaluation of proper possibility of the risk of dam overtopping was done by choosing the probability distributions of multiple independent and random variables, namely the peak discharge of flood, initial water depth in the reservoir and discharge coefficient of the spillway. The possibility of overtopping was calculated by Monte Carlo simulation and goodness-of-fit test or by uncertainty analysis method. It was reported that the rise

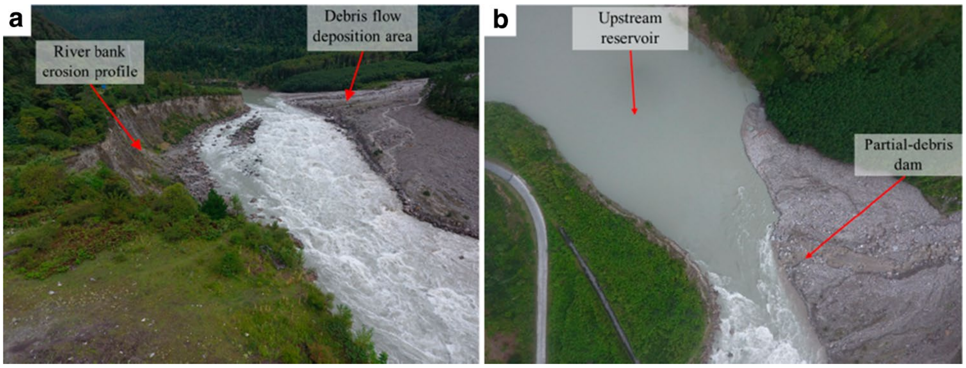

Fig. 11 Field investigation **a** river bank erosion profile, **b** upstream reservoir (unmanned aerial vehicle UAV photo taken on September 12 2017) [94]

of water level in the reservoir is the most important factor in overtopping risk analysis.

Field and laboratory tests of embankment breaches, created through overtopping, were also carried out to support numerical model development. Controlled field tests of rockfill, clay and glacial moraine embankments, 5–6 m high, were conducted on Rossvatn dam in northern Norway [96]. For the field tests, the test site and dams were instrumented and monitored to collect data on inflow and outflow volumes, pore water pressures in the dam body, and detailed information on breach initiation, formation and progression. Inflow to the test reservoir was determined by the positioning of the spillway gates. Water level in the reservoir upstream of the test embankment was monitored by two calibrated water level gauges. Two other gauges were placed along the downstream side of the embankment to calculate the discharges from the test site. Discharges that were less than 100 l/s were measured with the help of V-notch weir. In addition, discharges greater than 10 m^3/s were measured by a tail water level gauge. Monitoring of pore water pressures was done by placing eight number of piezometers inside the body of the dam. The test dams were furnished with breach sensors (combination of a tilt sensor and a time recorder), for monitoring of the breach development rate. In order to map the development of breach in time and space, nearly 100 sensors were installed in each test dam. Continuous recording of the tests was carried out with the help of many digital video cameras. In the failure tests, a shallow channel or notch was used as a controlled trigger to overtopping through the middle of the dam. Notches near the abutments led to the obstruction of free formation of the breach opening and its development in the vertical and lateral directions. These field tests were conducted with the aim of collecting authentic data sets for a broad range of embankment geometries and material types that would help in understanding and validating the predictive models [96]. Attempts were also made by different researchers to collect and analyze data from historical dam failures, so that graphical relationships can be developed to predict the characteristics of the breach, encompassing the shape and size of the breach or the time required for the formation of the breach [97].

Researchers have also attempted numerical modeling for accurate estimation of the breach rate of an embankment at the time of overtopping. Usually, the numerical models are based on sediment transport equations amalgamated with the assumption of homogeneity of embankment materials. Based on the transmissibility tests conducted on crushed dolerite samples using an upward water flow, researchers concluded that the stability of rockfill dam depends on overtopping and seepage [98, 99]. It was reported that unreinforced rockfill dams, built at the angle of repose, are not stable at the time of overtopping. Such dams undergo deep-seated sliding failure as the saturation level rises due to seepage. Wiggert and Contractor [100] presented a generalized theory to highlight the consequence of erosion on stability of embankment. Although the sediment transport theory can define the embankment notch erosion, it does not incorporate catastrophic predictions that can occur due to erosion in the downstream face of the embankment owing to the decrease in the soil strength or gully formation due to changes in the downstream slope geometry. To cater the latter conditions, Manning's equation was used to calculate depth and velocity of flow at every location of the downstream face, which is further used to evaluate the shear stress and rate of erosion. The difference in the rate of erosion at different locations in the downstream face would influence the stability of the slope, which was analyzed at specified time interval during overtopping.

A numerical model was developed by Fread [101] for investigating breaching of dam and flood routing, in which a V-notch was chosen with an arbitrary constant angle and subjected to a chosen rate of movement to study the mechanism of progression. Later, DAMBRK, a computer program developed used by Fread [102, 103], was used to perform rigorous research on flood wave propagation created due to dam breach. The developed program could accommodate different types of breach shapes, namely rectangular, triangular or trapezoidal. The program included flow through broad-crested weirs and spillway outlets. However, the program failed to incorporate the consequence of sloughing. Further, the program is not equipped to identify the single triggering flood event; rather it can provide a set of probable flood events depending on the time of failure and the terminal breach sizes and shapes. Based on flow through broad-crested weir across the breach and uniform quasi-steady-state flow along the downstream face of the embankment, Fread [104] developed an iterative numerical model, named BREACH, with the capabilities to arrest tail water effects. The model is equipped to incorporate the consequence of tail water buildup and stability of slope. The major limitation of the model is that the end-stage breach width and the critical shear stress need to be specified as input parameters, while they are expected to be the outcome of an analysis.

Based on sediment transport for modeling the progressive breaching of dam, a numerical scheme was introduced by Ponce and Tsivoglou [105] to calculate the flow along the breach using the St. Venant system of equations, while solving the same using finite difference (FD) method. The model considers the process of breaching to be initiated through an assumed notch, which increases in size in the increasing flow of water. No details regarding the mathematical relation between the breach width and flow rate were provided. A 1D numerical model for overtopping dam failure was proposed by Tingsanchali and Chinnarasri [106]. MacCormack's explicit finite difference method [107] was utilized to evaluate the 1D continuity and momentum equations for unsteady flow over steep bed slopes. In the solution of erosion process, sediment transport equations were chosen along with the modified Smart's expression [108] developed for steep bed slope. Modified "ordinary method of slices" were used to check the sliding stability of the overtopped dam. It was reported that the accuracy of the model greatly depends on the sediment transport formula and pore water pressure coefficient estimated with the experimental results.

By integrating the theory and a conceptual model describing non-equilibrium sediment transposition and the process of lateral erosion, a new physical-based model was described by Liu et al. [109] to describe the process of flooding. This study made significant contribution to the detailed understanding about the evolution of the overtopping phenomenon in tailings dam. Application of geosynthetics to strengthen or increase the height tailings dam, constructed with low shear strength tailings, was adopted for decades. Investigations to understand the parameters that influenced the strength and durability of fiber-reinforced compacted gold tailings were studied by Consoli et al. [110]. The overtopping failure evolution pattern of tailings dam was analyzed by Zhang et al. [111] based on experiments on physical models. It was found that tailings dam posed a breaching risk ten times more than that expected by an earthen rockfill dam [112, 113]. This observation was made by the statistical analysis of 3500 tailings dam worldwide. Breaching caused by the 2011 Japan earthquake of the Kayakari tailings dam resulted in liquefaction of the tailings, destroying many houses at the down reach of the Kayakari stream, as shown in Fig. 12 [114, 115]. Dam foundation instability leading to breaching in the Mount Polley mine tailings, releasing 4.5 million cubic meters of tailings posed serious pollution to the environment in the year 2014 [116]. The scenario of the Mount Polley mine tailing dam after failure was shown in Fig. 13 [117].

Fig. 12 Affected house inundated by liquefied tailings over the down reach of the Kayakari Stream [114]

Fig. 13 Mount Polley dam disaster [117]

The devastating breaching mechanism of tailings dams is presented using a few small-scale model tests [118]. However, a large difference in the stress levels was observed between these test models and actual tailings dams, making it doubtful whether the small-model tests can effectively capture the breaching process occurring in the field. Thus, centrifuge model tests gained popularity in due course of time where the stress level of the tailings dam can be improved by changing the centrifuge acceleration [119, 120]. Based on the results of centrifuge tests, mathematical models were developed to simulate the breaching of tailings dam due to overtopping. The formula for erosion rate, based on shear stress principle of water flow, was used to simulate the vertical undercutting and the horizontal expansion. The slope stability of the breach was simulated using limit equilibrium method [121].

Critical appraisal of literature, gap areas and scope of future research

The study gives a detailed review of the literature concerned to the hydraulic causes of earthen embankment and dam failures. It can be noted that the study of piping and overtopping mechanism was attempted by numerous researchers. However, to consider the range of processes that falls within the category of hydraulic failures, a lot of research is still required in order to reinforce the concepts on the evolution and progression of piping and overtopping. Individual occurrence of these phenomena, in real field conditions, is difficult to witness; in reality, mutual influences or complex combinations of different processes are the most common causes of dam failures. Therefore, development of holistic methods to study the dam failure mechanisms, incorporating the real field condition to their closest approximation, is the need of the hour. Development of rigorous numerical models to provide precise predictions of the stated processes and elucidating the mechanisms of dam breaching from a theoretical framework is also extremely necessary. The influence of hydrodynamic pressure requires a scrutiny on the piping and overtopping phenomenon. While piping was defined in the previous studies as a strict phreatic condition due to unfavorable hydraulic gradients, the recent instances of piping occurring at gradients as little as 0.17 have given the indication that piping can also occur in areas where the hydraulic gradients are not that dominant [122]. In this regard, the effect of confining pressure and seepage forces on piping should be studied, as only limited work is attempted in this aspect [123]. Other than the advances in filter designs and analyses, very few works with respect to piping in non-cohesive soils were made in the recent past [124, 125]. Minimal studies were attempted regarding piping in cohesionless soils [126, 127]. Development of a constitutive model related to piping that could be utilized in a continuum model to identify the mechanism and progressive development of piping in dams should be attempted. On the other hand, significant studies, utilizing intricate modeling aspects, related to the overtopping phenomenon should be carried out as breach models simulating all the features such as cracking, pipe formation, head cut formation and progression are yet to be developed. Despite many developments, the formation of breach with time yet remains a gray area for a detailed future study. With the gradual change in the climatic conditions, from normal to severe and harsh, there is an urgent necessity to include the impact of the material condition and method of construction on the breach formation and their response to harsh climatic scenarios. The problem of piping and overtopping is very complex, and any predictive models describing its onset and progression to collapse will be very useful.

The following are a list of areas where further studies can be attempted to enrich and discover the intricate mechanisms of piping and overtopping related to the hydraulic failure of the earthen dams and embankments.

- Most of piping works were carried out for cohesive soils. However, since the earthen dams and embankments are mostly constructed with the locally available soils having significant cohesionless content, it is imperative to study the effect of piping in cohesionless soils as well.
- Lesser number of studies is available with respect to constitutive models of piping. A constitutive behavior of piping that could be utilized in a continuum model to illustrate the complex piping phenomenon in dams is yet to be developed. Such a model should incorporate flow through porous media, appended by particle migration through very narrow and tortuous channels guided by gravity and pressure gradients.
- Researches were conducted to estimate the time of development of piping in terms of observational instances. However, numerical and laboratory investigations can be carried out to come up with processes that can explain the time required for pipe development with higher precision and confidence.
- Evaluation of the piping mechanism through unstable dispersive soils should be carried out.
- The mechanisms that take place at the instant of dam overtopping and finally dam breaching depend on many factors. Some of them are hydrodynamic surges, open channel flow, seepage, sediment transport and creep flow. It is not utterly difficult to attain similitude between models and prototypes with respect to any one of factors acting singly. However, in most of the cases of dam breaching, the above factors occur in unison, and it is ardently important to investigate their combined influences on the response of the dam.
- The problem in numerical modeling of embankment overtopping is sufficiently complicated and comprises a number of individual processes acting and interacting together. Steady uniform flow with fixed boundary conditions is the basis of many studies found in the literature; these assumptions are required to expedite mathematical understanding, although the results differ significantly from the real scenarios. A proper theoretical basis for transport of sediment during unsteady process is not yet devised and is the need of the current research trend.

- The drains and filters play an important role in preventing migration of particles that, otherwise, can initiate piping and overtopping. The processes of filtration, interface behavior and time-dependent changes that take place within the filter medium in a dam should be studied in further details.

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