

Review

Overflow-Induced Breaching in Heterogeneous Coarse-Grained Embankment Dams and Levees—A State of the Art Review

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Abstract

This review article synthesizes recent experimental research on the breaching of noncohesive embankment dams and levees caused by overflow, with a specific focus on coarse-grained soil materials. Despite the high incidence of embankment dam collapses leading to significant socio-economic and environmental impacts, comprehensive understanding of the underlying physical processes remains incomplete. Historically, studies have largely concentrated on embankments made from uniform materials ranging from fine cohesive soils to noncohesive clean rockfill. However, recent shifts in focus to well-graded heterogeneous coarse-grained soil materials underscore the complexity of predicting breach mechanics, given the absence of physically based models for these materials. This review aims to compile and elucidate the factors affecting breaching in an effort to inform future research and practical applications in dam safety assessments.

Keywords: dam breach; dam failure; overflow; overtopping; coarse-grained soil; physical modeling



Academic Editor: Nikolaos Koukoulas

Received: 20 June 2025

Revised: 24 July 2025

Accepted: 30 July 2025

Published: 9 August 2025

Citation: Monteiro-Alves, R.; Moran, R.; Toledo, M.Á.; Jimenez-Rodriguez, R.; Picault, C.; Courivaud, J.-R.

Overflow-Induced Breaching in Heterogeneous Coarse-Grained Embankment Dams and Levees—A State of the Art Review. *Appl. Sci.* **2025**, *15*, 8808. <https://doi.org/10.3390/app15168808>

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1. Introduction

Embankment dams can originate from both natural processes and deliberate human construction. Natural examples include landslide dams [1,2] and moraine dams [3]. Constructed examples encompass a wide range of dams and levees (both fluvial and maritime) built for purposes such as flood control, energy production, water supply, irrigation, and recreational activities. Embankment dam collapses are more common than typically presumed, a recurrent and serious issue often resulting in substantial economic and environmental damage, and in the worst cases, leading to loss of human lives. One of the most recent incident which led to at least 4000 confirmed deaths and to an additional 10,000 people missing was the collapse of two rockfill dams upstream of Derna, Libya, on 11 September 2023 [4]. The failure of the Brumadinho tailing dam in 2019 is also an example of the catastrophic consequences of a failure, which in this case altered the geomorphology

and geochemistry of the Ferro Carvão stream and the Paraopeba River [5]. Overtopping is the leading cause of failure of embankment dams, accounting for 48% of all cases, followed by internal erosion, which is responsible for 35% [6].

Given the potential impact of such hydraulic infrastructures, extensive research has been carried out to understand the physics of the breaching process and how the characteristics of the embankments and flood may affect the final breach outflow hydrograph, which is the foundation for the classification of dams in terms of their potential impact upon society and/or the environment, as well as the basis for the implementation of emergency plans. Historically, these studies have mainly focused on embankments constructed with uniform materials such as fine cohesive soils [7–19] and noncohesive materials from sands to rockfill [20–40], but recently, the scientific community has shifted its attention to those embankments constructed with well- or gap-graded soil materials, which are a mix of sand and gravel and which may also include a fraction of fines. Physically based models have not been specifically developed for these materials, highlighting the need for validation studies.

Headcut and surface erosion, two major macro erosion processes, are typically associated with cohesive and noncohesive embankments, respectively. However, there are cases in which noncohesive heavily compacted embankments may also erode in the form of a headcut [41] and cases in which cohesive embankments do not experience headcut formation as its occurrence can be influenced by other factors such as the presence of tailwater and the formation of recirculating flow against the downstream side of a potential headcut overfall [42]. The underlying physics driving the various macro erosion processes remains poorly understood, even in cases involving uniform soil materials. Therefore, when dealing with heterogeneous mixtures of fines, sands, and gravels, comprehending these processes becomes significantly more challenging.

In this context, the aim of this review is to gather and analyze the most relevant and recent experimental research on embankment breaching, with a particular focus on coarse-grained soil materials. The objective is to compile available information to improve understanding of the various factors influencing the breaching of noncohesive embankment dams and levees due to overflow. To achieve this, this review is organized into eight chapters in addition to the introduction. Section 2 discusses the physics of breaching in different types of embankment dams, ranging from clean rockfill to uniform clay. Section 3 introduces the various types of models used in embankment breach research, with emphasis on physically based models designed to simulate the breaching process in dams and levees. Sections 4–6 present the main results from physical models developed to assess the influence of specific variables—such as soil components (Section 4), hydraulic conditions (Section 5), and embankment geometry (Section 6)—on breaching characteristics, including macro erosion features, peak outflow, and soil or embankment erodibility. Section 7 has a similar purpose to Sections 4–6 but focuses on results from numerical models. Sections 4–7 conclude with a summary to help readers better understand and synthesize the main findings. Section 8 discusses the most relevant results of the studies presented in Sections 4–8, while Section 9 summarizes the key conclusions from these studies and pinpoints the current research gaps.

2. Physical Processes of Breaching

The breaching process changes significantly between types of embankment dams, mainly due to the interaction between the overflowing water and the soil material forming the embankment. The soil used in the construction of earthen embankments generally has low permeability in relation to the amount of water flowing over the embankment, and as a result, the majority of the overflowing water flows over the embankment. In contrast, in highly permeable clean rockfill embankments with an impervious core, the overflow

seeps near the crest through voids in the material, forming a flow profile at the base of the embankment [43–53], which emerges from the toe [52,54–59].

2.1. Rockfill Embankments

In clean rockfill embankments, the breach starts when a certain discharge threshold is reached. The unraveling process starts at the toe where the hydraulic gradients are at their maximum [58]. If the overflow discharge is constant and slightly higher than the threshold discharge, then the breach will migrate upstream up to a given point at which it will be maintained constant. From this point, the breaching process will keep migrating only if there is an increase in the overflow discharge that, if high enough, will force breach migration up to the crest of the embankment. At this moment, the impervious element is unprotected and close to a catastrophic failure.

Depending on the slope of the downstream rockfill shoulder, the unraveling process is controlled by two main failure mechanisms, slumping that occurs in dams with steep slopes and erosion or particle dragging in dams with gentle slopes. Experimental tests have shown that the critical slope which defines the occurrence of one or the other mechanism in clean rockfill is around 2H:1V [60]. Slumping is related to the problem of global instability of a certain mass of rockfill material, controlled mainly by the pore water pressures inside the embankment. In these cases, the unraveling process occurs for all unstable sections of the dam along its width. On the other hand, when particle dragging is the predominant failure mechanism, it means that we are dealing with slopes that are stable to slumping. In these cases, particle stability subjected to seepage forces and hydraulic gradients drives the breaching process, taking the form of an erosion channel where the flow concentrates, forcing the failure to evolve through it until the crest of the dam is reached. This erosion channel is generally narrower than the total width of the dam and will depend on the depth of the breach and rockfill repose angle.

2.2. Earthen Embankments

In embankments constructed with soil materials where permeability is low in relation to the amount water flowing over the embankment, breaching is controlled by erosion forces caused by the flow shear stresses acting on the embankment. Headcut and surface erosion are two macro erosion processes known to drive the failure of embankment dams and levees. Although headcut and surface erosion are both controlled by soil erosion on a micro-scale (for soils, these comprise the detachment and transport of soil particles by an internal or an external flow), they lead to different types of breach and breaching processes. When headcut erosion prevails, the eroded embankment profile presents a clear vertical or near-vertical step that cuts into the embankment, which tends to migrate upstream without significantly changing its slope [7,8,61,62]. On the contrary, when surface erosion is the main process, soil particles tend to be removed quite uniformly along the downstream slope, allowing the eroded profile to progress backwards as a slope through the embankment, which may flatten, steepen, and erode backwards parallelly, depending on the soil type and state [41] and possibly other parameters such as hydraulic conditions, etc. It must be noted that, in noncohesive mixed soil materials, it is not clear which processes dominate.

In cohesive embankments, typically associated with headcut erosion, headcut usually follows initial sheet and rill erosion on the downstream slope where several rills will develop and which will eventually merge into a single dominant propagating and widening the channel [7,8]. This process involves the development of a sequence of cascading steps which will eventually erode, forming a single dominant headcut face. The upstream progression of the headcut is primarily governed by block failure. This occurs as the overflow jet impinges on the base of the breach, generating shear stresses that undermine

the headcut face. All these physical processes fall within the same stage of breaching, which is known to be the ‘breach initiation’ stage. Once the reservoir is reached, the breaching process enters a new stage in which the embankment crest lowers, leading to an increase in the outflow discharge. Generally, the term ‘breach’ or ‘breach formation’ is used to describe this stage of the breaching process.

Breach widening can generally occur throughout all phases resulting from the erosion of the bed material, making the side walls become unstable and eventually resulting in block failures along the breach side walls [7,8]. However, the main widening stage and lateral expansion of the breach occurs once the headcut cuts into the reservoir, leading to its drawdown.

This failure process for cohesive embankments was simplified and summarized as follows [12,63]:

- Stage 1: Breach initiation, which contains several stages, such as surface failure leading to cascading steps and headcut formation on the downstream slope, and headcut migration through the embankment;
- Stage 2: Breach formation as the headcut enters the reservoir;
- Stage 3: Breach expansion/widening during the reservoir dropdown.

Headcut migration garners significant interest across various engineering disciplines, from landscape management and river geomorphology and restoration to embankment dam design and risk analysis. In embankment scenarios, determining the exact starting point of the headcut face remains a challenge, but nonetheless, it is important for drafting emergency plans. Typically, erosion begins at a soil discontinuity at which flow disruption and local turbulence can dislodge particles or even larger blocks [13]. However, there are studies suggesting that headcut erosion often starts at the toe of the downstream slope, where flow velocities are higher and the potential for erosion is greater [64]. On the other hand, in embankments constructed from very erodible soil materials, erosion tends to be triggered by the change in the slope when the overflow passes from flowing over the crest to flowing over the downstream slope. In these cases, erosion will start close to the crest of the embankment.

3. Breach Modeling

3.1. Objectives

Modeling aims to replicate real, natural, or artificial systems to enhance human understanding and predict future behavior. Models can be categorized into mental, semantic, physical, analog, or numerical models [65]. Concerning embankment breaching, the main objectives of research typically encompass (i) understanding the physics behind the breaching processes, (ii) quantifying the breach parameters, such as their geometry and dimensions, and (iii) determining the main characteristics of the outflow hydrographs. Breach parameters have been typically quantified through experimental laboratory tests [1,2,7,9,12–16,18–21,23,25–32,34–40,42,60,66–106], statistical analysis of past dam failures [103,107–114], or numerical modeling [24,33,82,93,115–135].

3.2. Types of Models

The different model types arising from these studies can basically be grouped into four categories [136]:

- Parametric Models: These use historical case studies to estimate geometric and temporal breach characteristics; then, they simulate breach growth as a time-dependent linear process and compute breach outflows using basic hydraulic principles.

- **Predictive Equations:** These estimate the peak outflow discharge from empirical equations based on case study data or synthetic data (obtained with physically based models) and assuming a reasonable shape for the outflow hydrograph.
- **Physically Based Models:** These use an erosion model based on principles of hydraulics, sediment transport, and soil mechanics to predict the development of a breach and the resulting breach outflows.
- **Comparative Analysis:** This is used when the dam under consideration is very similar in size and construction to a dam that has failed and if the failure is well documented.

Some articles and literature reviews present compilations of different physically based models, parametric models, and laboratory embankment breach tests [6,41,134,136–138].

3.3. Parametric Models

Although there is a great amount of uncertainty associated with parametric models based on the analysis of past dam failures, these are commonly used in the engineering practice to estimate basic geometric and temporal parameters. Predictions of breach width and failure time have uncertainties ranging in orders of magnitude from 1/3 to 1, respectively, and for peak outflow, uncertainties vary in order of magnitude within the range of 0.5 to 1 [137].

These uncertainties could well be the result of the very few variables used to describe a very complex engineering problem, including the height of the dam, the volume of the reservoir, and sometimes the failure mode. Occasionally, other parameters, such as, for example, shape factors for the storage function or the erodibility of materials, are also incorporated [42].

Finally, once the final breach parameters are estimated, they are used in emergency plans to describe the opening process, usually assuming a linear increase in the breach dimensions, starting from an initial condition until the final geometry and dimensions are reached. The outflows are then estimated using basic hydraulic formulations. Depending on the type of flow occurring during failure (overflow or pipping), weir or orifice equations are used to estimate the breach outflows.

3.4. Physically Based Models

Currently, there are several physically based models that can simulate the breaching process of embankment dams and levees, such as WinDAM C [139], DL Breach [140,141], EMBREA [13,142] (the HR BREACH successor), RoDaB [143], AREBA, BASEMENT, etc. WinDAM C and RoDaB were developed to model the failure of homogeneous dams, the first being specifically dedicated to fine materials and the second to clean rockfill dams. The remaining models were developed with the aim of also applying them in composite dams, but very few laboratory tests have been carried out to validate them [42].

The following bullet points summarize the main characteristics of some physically based models currently in use:

- **WinDAM C** allows for the modeling of both overtopping and piping failure modes. Although it was designed to model the failure of cohesive homogeneous embankments, nothing prevents it from being used on composite or zoned dams. In this case, a great deal of simplification must be applied to simulate the materials. The suggested approach is to consider the material and geometry that will dominate the process [144,145]. Another simplification of this model is that it only allows for headcut erosion, whether using the Temple/Hanson energy model or the Hanson/Robinson stress model [42,61,62]. These are used to model erosion, assuming that the headcut starts at the top of the downstream slope, deepening and advancing from that point, conservatively starting as close to the crest as possible.

- DL Breach is more flexible than WinDAM C, as it allows for the modeling of the same two failure modes, overtopping and piping, but permits surface erosion in addition to headcut erosion. The difference between these two types of erosion when caused by a surface or skimming flow is that headcut erosion forms a near-vertical face. This improvement is a great step forward when dealing with coarser heterogeneous noncohesive soil materials in which water is predominantly flowing over the downstream slope. The DL Breach headcut erosion mode assumes that the headcut begins at the toe of the downstream slope. On the other hand, surface erosion can be used in homogeneous and composite dams with a cohesive central core. When using the headcut mode, crest lowering is allowed due to surface erosion. DL Breach also assesses the stability of a portion of the core to sliding on the base of the dam through an equilibrium of forces. In composite dams, the stability of the core is assessed on the base of the unprotected section of the core. The same stability analysis is applied to the breach lateral walls or banks. Other works have focused on the failure of the cohesive core [106,146,147].
- EMBREA, developed by HR Wallingford, refines the HR Breach model to improve predictions and to include the ability to model zoned dams and levees. It simulates overtopping and internal erosion failures, accommodating cohesive and non-cohesive materials, and uniquely models mass and micro failure due to slope instability without predetermining the breach geometry.
- AREBA can model overtopping failures in homogeneous and composite embankments and internal erosion in homogeneous embankments. It includes features for modeling surface erosion or headcut erosion and simple slope stability equations. The major advantages of this model are its quick running times and computational efficiency as well as its simplicity; the fewer input parameters required also make it user-friendly.

Nowadays, typical computational fluid dynamics software for the two-dimensional modeling of river or coastal hydrodynamics and sediment transport, such as HEC-RAS, MIKE 21, Telemac-2D, SRH-2D, Nays2D, Iber, etc., tend to incorporate breach modules designed for assessing embankment dam and levee breaching. These result in a more comprehensive and global assessment of the consequences observed from an embankment dam or levee breakage.

4. The Effect of Soil Materials

This section summarizes studies that primarily focus on assessing how specific soil parameters influence the breaching process of overflowed embankment dams and fluvial levees. Some of the studies included here do not involve embankment physical models directly but instead investigate soil erodibility, an essential aspect of embankment breaching. The section is organized into five subsections: (i) Soil Gradation, (ii) Content of Fines, (iii) Cohesion and Soil Strength, (iv) Saturation Conditions, and (v) Compaction.

Given the complex and interdependent nature of soil properties, it was sometimes challenging to categorize studies into a single subsection. This occurred either because multiple parameters were assessed in a single study or because the main conclusions related more closely to a different aspect than the experimental setup suggested. In such cases, classification was based on the most relevant findings of each study. Within ‘Cohesion and Soil Strength’, we only included studies which quantified soil strength parameters through standardized tests, excluding those which used cohesive soils such as clays without any quantification.

4.1. Soil Gradation

4.1.1. Pickert and Colleagues (2011) [88]

In 2011, Pickert and colleagues examined the effects of overflow on embankments built with three distinct forms of uniform sand, each compacted to a similar moisture content of 5% [88]. These poorly graded sands differed in their median particle sizes (D50) which were 0.2, 0.35, and 0.6 mm, and in their content of fines: fine sand had 5% fines, intermediate sand about 1%, and coarse sand contained no fines. The Air Entry Value (AEV) for each sand type was determined: (i) 2.7 kPa for fine sand, (ii) 1.4 kPa for medium sand, and (iii) 0.8 kPa for coarse sand.

The researchers found that the mean negative pore water pressure at the point of failure for each sand type closely matched its respective AEV. This correlation suggests a critical role for negative pore water pressure in breach formation at the scale of the constructed models. Their findings included that breach side slopes, regardless of material, were near-vertical and sometimes inversely steepened by erosion at the base, challenging common assumptions about noncohesive materials and suggesting that numerical models using soil friction angles might inaccurately predict breach wall stability.

The study also noted differences in the breaching process when transitioning from finer to coarser materials, attributing the behavior of finer materials to capillary rise and apparent cohesion, and that of larger particles to flow shear stresses. Observations showed that coarser materials breached faster with consistent erosion rates, while finer materials displayed unsteady erosion. Therefore, two failure mechanisms were identified: constant erosion and sudden collapse, without a linear lateral widening of the breach.

Regarding the evolution of the longitudinal breach profile, initial erosion was nearly parallel to the embankment surface in finer sands, slightly flattening in coarser sands. Once erosion penetrated the reservoir, the breach profile steepened on the upper half and became gentler on the lower half of the breach. The finer and intermediate sand embankments developed a berm (plateau) halfway from bottom to crest, which evolved to a scour hole hitting the bottom of the flume. Graphical analysis indicated that finer materials result in steeper slope angles, with observations of 50° in finer sand embankments compared to 27° and 18° in intermediate and coarser sands, respectively. This contrasts the internal friction angles, which ranged from 32° to 37°, increasing with particle size. It is important to note that, based on the testing methodology, the embankments, especially in the upstream slope area, should be fully saturated, implying that apparent cohesion is unlikely to affect the soil strength in these tests.

The timing of erosion breakthrough and its relation to material erodibility suggested that particle size influenced soil erodibility to a degree, with finer materials showing less erodibility. This distinction points to a complex interplay between flow conditions, material properties, and erosion dynamics that influences embankment stability and breach evolution.

4.1.2. Ellithy and Colleagues (2017) [71]

In 2017, Ellithy and colleagues published the results of their research on the erosion behavior of small-scale embankments constructed from coarse-grained soils under overtopping conditions [71]. The study utilized four soil mixtures: two with a D50 of 2 mm (mixes 1 and 2) and two with a D50 of 0.5 mm (mixes 3 and 4). Mixes 1 and 3 lacked fines, while mixes 2 and 4 were devoid of gravels. Mixes 1 and 3 were identified as poorly graded sands (SPs), and mixes 2 and 4 as silty-clayey sands (SM-SCs) with slight cohesiveness, containing 17% to 20% fines including 3 to 5% clay. The fine-bearing soils exhibited a plasticity index (PI) of 7.7%, with a liquid limit (LL) of 29.6% and a plastic limit (PL) of 21.9%.

Jet Erosion Tests (JETs) yielded critical shear stress values of 1.85, 0.39, 1.79, and 0.29 Pa, and erodibility coefficients (k_d) of 119.3, 117.2, 507, and 248 cm³/N·s for mixes 1 through 4, respectively, classifying all as highly erodible per Hanson and Simon's criteria.

The tests showed that cohesive or fine-containing soils initiated erosion near the downstream toe of the embankment, progressing via headcutting, whereas noncohesive soils began eroding from the crest downwards. The presence of gravels was found to increase the critical shear stress, while the presence of fines tended to slow erosion in well-graded mixes. In poorly graded mixes, soil particles eroded individually, unaffected by cohesiveness.

4.1.3. Ellithy and Colleagues (2020) [148]

In 2020, Ellithy and colleagues presented [148] a new study using the same erosion box setup used in previous research. In this study, soil samples were compacted in two layers to achieve the maximum Proctor density and optimal moisture content, which varied between 6% and 8%, with maximum dry unit weights from 18.9 to 21.5 kN/m³. Four soil mixtures, all with a median particle size (D50) of approximately 5 mm, were tested under varying conditions. These mixtures included well-graded gravels (GWs), well-graded clayey gravels (GW-GCs), and clayey gravels (GCs), adjusted by adding silt, kaolin clay, and gravel particles measuring up to 25 mm to alter fine content and the distribution of coarser particles.

The tests, conducted with inflow rates of 57 L/s and 85 L/s and flume slopes of 2% and 6%, demonstrated that mixtures with a lower fine content (0% and 5%) developed deeper scour holes than those with a higher fine content (15%), even under conditions that produced lower estimated flow shear stresses (16 Pa compared to 37 Pa). The erosion rate decreased over time for all soil materials, highlighting the dynamic nature of erosion, which may be missed by studies only considering the initial and final states. This decline in erosion rate is attributed to changes in hydraulic loading as erosion progresses.

Further analysis showed that under identical hydraulic loading conditions, when soil samples with varying fine and coarser particle contents were compared, it was found that mixtures in which the soil contents larger than D50 had the smallest particles experienced higher initial erosion rates and therefore lower critical shear stress. This is attributed to the fact that smaller particles are more easily dislodged by the same bed shear stress. Notably, the difference in fine content—0% and 5%—did not significantly impact the erosion rate, as both mixes showed similar trends in the variation in erosion rate over time. The same conclusions were drawn when comparing samples with similar fines but varying larger particle sizes, i.e., mixtures with smaller particles above D50 eroded faster. Additionally, for mixtures with different fine contents but identical distributions of larger particles, those with fewer fines showed considerably higher initial erosion rates, even under less severe hydraulic loading.

In summary, soil mixtures in which the fine and clay content had been increased generally had reduced erosion rates compared to mixtures with less fines but similar coarser components. Likewise, soils with the same content of fines but larger coarser particle portions in the grain size distribution above D50 correlated with slower initial erosion rates under the same hydraulic conditions.

4.1.4. Rifai and Colleagues (2019) [39]

In 2019, Rifai and colleagues studied the breach dynamics of canal embankments [39]. This involved experiments with embankment sections that were 0.3 m high featuring 2:1 upstream and downstream slopes and a 0.1 m wide crest tested under different inflow discharge conditions. Two types of uniform coarse sands were tested with different median

grain sizes (D50), 1 mm and 1.7 mm. These soils were likely poorly graded sands given the absence of detailed granulometry information. Additionally, 1 mm uniform coarse sand was mixed with uniform fine sand with median grain size (D50) of 0.24 mm in three different proportions (10%, 20%, and 30%), though it is unclear whether these mixes resulted in poor or well-graded sands.

A drainage system was implemented at the base of the embankment to minimize seepage through the embankment. Constant-inflow discharge was maintained in the canal, and the water level within the canal was regulated using a perforated weir (sluice gate) at the end of the canal. This setup ensured that, for a given inflow, the water level would rise to match the crest of the embankment. The breach was initiated through a notch that was 0.1 m wide and 0.02 m deep.

The breaching process was categorized into three distinct stages: (i) 'Initiation', where erosion rates were initially low; (ii) 'Deepening and Widening', marked by an increase in breach size due to higher flow depths and velocities, with a gradual collapse of the breach sides leading to an asymmetrical shape influenced by the momentum of the flow in the canal parallel to the embankment; and (iii) 'Widening', occurring as the canal water level lowered and stabilized at a minimum, characterized by reduced erosion rates, stabilization of the breach crest, and further breach widening in the canal flow direction caused by the block failure of the breach sidewalls.

The investigation into soil gradation, achieved by varying sand particle sizes, revealed that while increased fine sand content did not notably affect breach development, it did lead to larger, less frequent side slope collapses.

4.1.5. Rifai and Colleagues (2021) [92]

The same authors in 2021, using the same setup and materials as in 2019, found no clear trend in breach widening with the same inflow discharge across different levee compositions, which occurred through successive slope collapses indicating a stair-like progression in breach width over time [92]. However, breach depth evolution moderately depended on the soil type, with finer materials leading to faster deepening, particularly at higher inflow rates. Finer sediment content correlated with quicker breach outflow increases and peak discharge development, suggesting a swift reservoir level decrease due to faster outflow rates.

Breach shapes exhibited milder slopes in the most uniform sand, whereas mixes with a higher fine sand content showed steeper slopes and a hydraulic jump at the breach toe. The erosion process varied with the sediment composition: coarser, more uniform sands saw downstream slope erosion pivoting near the original toe, with eroded material accumulating at the toe; in contrast, mixes with more fine sand saw the eroded material become washed away up to the base of the flume, leading to breach slopes eroding back parallel to the original embankment slope and an upstream migration of the toe of the breach.

This study did not detail the effective strength parameters of the soil but noted that friction angles in dry and wet conditions ranged from 28° to 30°, a gradient slightly steeper than the original downstream slope. Therefore, the question remains as to whether the breach slope tends toward the internal friction angle of the soil material or if it erodes back parallelly. The presence of fine sand increased soil and embankment erodibility, with the authors arguing that erodibility of this kind of soil may be influenced by hiding–exposure effects where larger particles can shelter smaller ones from flow or make larger particles more exposed to erosion by filling gaps with smaller particles.

4.1.6. Zhu and Colleagues (2020) [69]

In 2020, Zhu and colleagues published their findings from 11 experiments aimed at understanding the failure processes of 0.25 m high landslide dams under various grain size distributions and hydrodynamic conditions [69]. These tests utilized small inflow discharges to the flume (0.3 L/s) to explore the impact of seepage on the stability of these models. The researchers varied the flume gradient (bed slope) to simulate different hydrodynamic conditions while keeping the grain composition constant, and alternately, they varied the soil compositions while maintaining consistent hydrodynamic conditions.

These experiments showcased distinct failure modes of landslide dams, specifically identifying scenarios where only overtopping occurred and others where both piping and overtopping were observed. The soil materials that experienced only overtopping included poorly graded gravels with different proportions of sand and about 1% fines, as well as well-graded sand containing 43% gravels and roughly 4% fines. A key distinction noted was that the well-graded sand saw a significant collapse of the downstream slope, in contrast to the poorly graded gravels, which maintained slope stability. However, the poorly graded gravels failed due to erosion that led to a central breach, accompanied by side slope structural instabilities that caused sliding and temporarily blocked the breach—though this material was rapidly cleared by the outflow. Figure 1 presents images of one of the tests performed with a poorly graded gravel with a sand content of 31% and approximately 1% fines passing the ASTM #200 sieve (0.075 mm), while Figure 2 presents images of the test performed with well-graded sand.

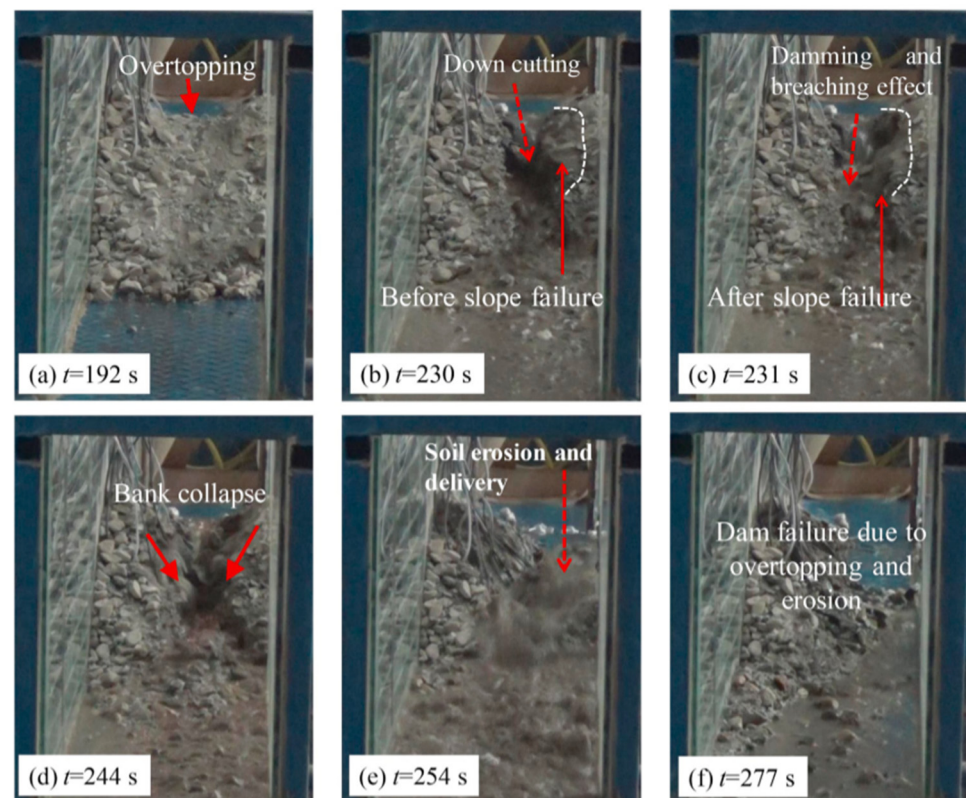


Figure 1. Images of one of the tests performed by Zhu and colleagues constructed with poorly graded gravel with a sand content of 31% and approximately 1% fines passing the ASTM #200 sieve (0.075 mm) [69].

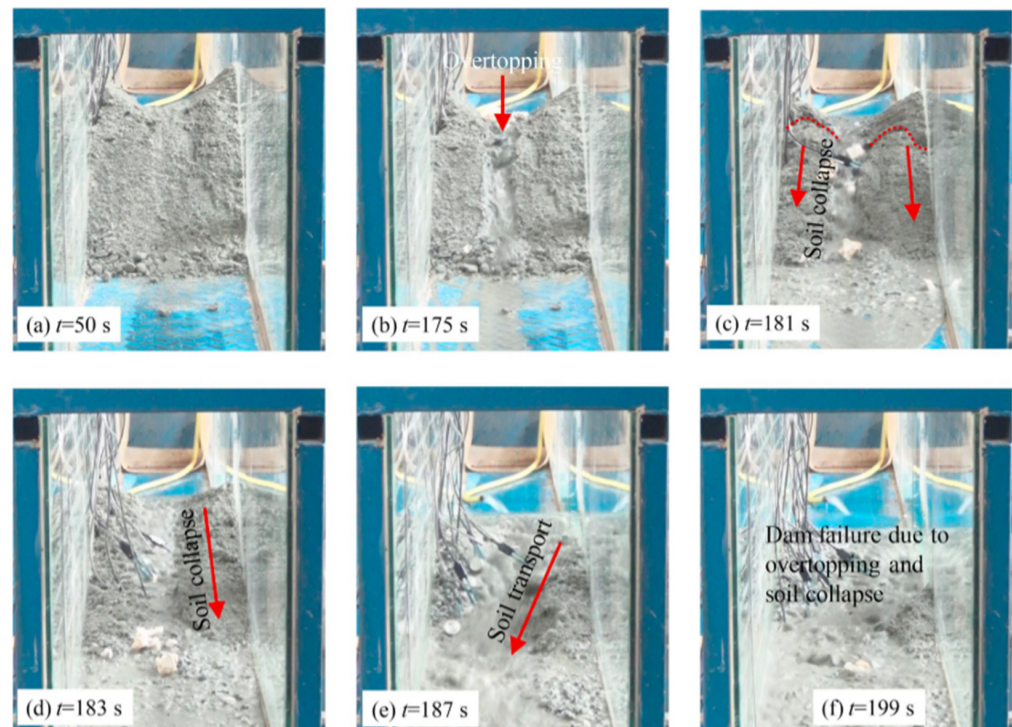


Figure 2. Images of the test performed by Zhu and colleagues constructed with well-graded sand with 43% gravels and roughly 4% fines (the clay content is unknown for all materials) [69].

The authors discovered that variations in grain size distribution and flume gradient significantly impacted the outcomes of their experiments, leading to the conclusion that the textural properties of landslide dams—defined by particle size distribution and the hydrodynamic conditions of the inflow discharge—play a crucial role in determining the failure modes and processes of these dams. They observed that traditional metrics like grading dimensions, uniformity, and curvature coefficients are inadequate for predicting the failure mode of a specific embankment. Consequently, they propose a novel classification system for embankment materials based on two distinct grading dimensions, identifying four soil types, fine-matrix-controlled, medium-particle-controlled, coarse-matrix-controlled, and balanced-composition soils, as illustrated in (Figure 3).

In this classification, particles up to 2 mm were considered the upper size limit for fine-grained particles. Furthermore, they introduced an additional particle size threshold greater than 2 mm to differentiate particles that can be transported by flow from those that cannot. This distinction was based on a state-of-the-art formulation that considers variables such as flow velocity, flow depth, and the bulk densities of the sediment and flow. This approach aimed to provide a more nuanced understanding of how different soil compositions affect the stability and erosion dynamics of landslide dams.

The experimental findings effectively correlated specific failure modes with the textural characteristics of the soils, summarized as follows: (i) embankments classified as coarse-matrix-controlled remained stable, though they exhibited a seepage path allowing for the migration of finer grains; (ii) embankments identified as medium-particle-controlled struggled to form a seepage profile before overtopping occurred, ultimately failing due to the mass sliding of the downstream slope post-over topping; (iii) embankments with a balanced composition successfully formed a seepage profile, which made piping possible, and the subsequent overtopping then resulted in failure, predominantly through erosion. These observations highlight how the structural integrity and failure dynamics of embankments are intricately linked to their soil composition and textural properties.

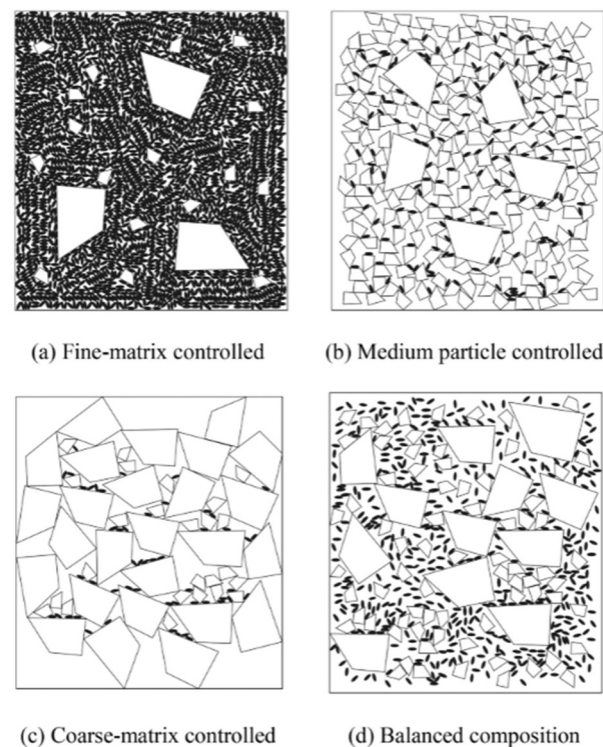


Figure 3. Types of textural properties of coarse-grained soils [69].

4.1.7. Kouzehgar and Colleagues (2021) [103]

In 2021, Kouzehgar and colleagues published an article which contributed to the body of research focusing on the definition of parametric models derived from historical data for estimating the geometric and temporal characteristics of embankment breaches [103]. Despite the inherent uncertainties associated with these models, the authors posit an improvement in accuracy over previous studies by separately considering the effects of overtopping and non-overtopping failures.

In addition, they conducted experimental tests on overtopped sand embankments at varying heights ranging from 0.3 m to 0.5 m and with five different soil gradings ranging from sands to gravels up to approximately 6 mm in diameter under identical hydraulic conditions (a constant inflow discharge of 6 L/s). Notably, none of the tested materials contained fines.

The experiments revealed seepage-induced failures, with erosion initially vertical and then predominantly lateral as the breach depth neared the flume bed. Interestingly, the final breach height remained roughly constant across different soil gradations and embankment heights. Analysis of the outflow hydrographs did not showcase a clear trend between soil gradation and peak outflow, though the finer materials generally led to higher peak outflows. The paper mentions that soil gradation influenced the breach widening rate but lacked a detailed explanation of this relationship. A particular figure in the paper illustrates the evolution of the breach, displaying a step or headcut face in the upper half of the embankment.

A key finding from the study is that soil gradation impacts the erosion rate, with embankments made of coarser soils eroding more quickly. This observation aligns with that of previous works [88] which found that the coarser the materials, the faster is the breaching processes and the smoother is the erosion rate. However, it appears to contradict other studies on soil erodibility (not embankment physical tests) [71,148,149], as Kouzehgar and colleagues state that coarser sands erode faster due to lower shear stresses, suggesting a clerical error. These other works report an inverse relationship between D50 size and

erodibility, aligning with the Shields equation, which implies that larger D50 values should correspond to higher critical shear stresses, not lower. If their results are correct and they are not a clerical error, then they suggest that soil erodibility's influence on embankment erodibility is not straightforward. While both may be affected by similar factors, their responses may differ. For example, apparent cohesion in embankments is known to be a key factor in block failure occurrence [88], a process not captured in standardized or non-standardized soil erosion tests.

4.1.8. Ellithy and Parida (2022) [149]

The article by Ellithy and Parida published in 2022 reports on flume soil erosion tests performed on three different sand and gravel mixtures, each defined by a specific median particle size (D50) of 2, 5, and 20 mm, and characterized by an absence of fines [149]. The tested materials were a well-graded sand (2 mm), well-graded gravel (5 mm), and poorly graded gravel (20 mm). The study focused specifically on the influence of D50 on erosion without delving into the effects of fine content.

All tests maintained nearly identical conditions to highlight the impact of particle size on erodibility, which was assessed under near-optimum-density conditions determined by the standard Proctor test, with moisture contents ranging from 3% to 6% and dry unit weights between 19 and 20 kN/m³. Erosion measurements were captured using a shallow water lidar (SWL) from ASTRALiTE Inc., allowing for the precise monitoring of soil and water surfaces during the tests.

The results indicated that the erosion rate decreased significantly by increasing D50, dropping approximately fourfold from 0.13 cm/s at a D50 of 2 mm to 0.03 cm/s at a D50 of 20 mm. Erosion rates also decreased over time for all soil materials but were more pronounced in the soil with the largest D50.

4.1.9. Summary

In summary, the main conclusions drawn from the research studies reviewed in this section are as follows:

- Embankment physical tests, the majority dealing with sand or gravel soil materials, have shown that soil gradation affects the breaching process in different ways:
 1. Failure occurs when negative pore water pressure approaches the Air Entry Value (AEV), which will depend on the particle size [88].
 2. Finer sands present slower and more irregular breaching processes [88], while coarser sands breach faster and more consistently [88,103]. A different study [92] presents contradictory results, with quicker breaching processes correlating with finer sand embankments. With silty–clayey soils, the coarser granular content will affect the ‘moment’ at which erosion is initiated, as larger particle sizes correlate with higher critical shear stress, i.e., they need higher overflow rates to initiate erosion [71].
 3. Longitudinal profile slopes are steeper for finer sand embankments than coarser sands, contradicting expected trends based on internal friction angles [88]. On the other hand, uniform soils lead to gentler slopes, while well-graded soils lead to steeper ones [92].
 4. Breach side slopes are not clearly affected by soil gradation. However, near-vertical or inversely steepened slopes caused by basal erosion challenge assumptions about noncohesive behavior and suggest that friction angle-based models may mispredict breach stability [88].

- Non-standardized soil erosion tests (not based on embankment physical models) have shown that the size of the coarser particles affect the rate at which the soil is eroded, with increasing particle size correlating with slower initial erosion rates [148].

Contradictory findings on the influence of coarser particle size in embankment erosion suggest that embankment erodibility is more complex than soil erodibility. While both may be affected by similar factors, their responses may differ. For example, apparent cohesion in embankments is known to be a key factor in block failure occurrence, a process not captured in standardized or non-standardized soil erosion tests.

4.2. Content of Fines

4.2.1. Zhu and Colleagues (2011) [74]

In 2011, Zhu and colleagues investigated the breaching of embankments dams, focusing on silty sand with 15% fines (SP-SM, $D_{50} = 0.09$ mm, $C_u = 1.4$, $C_c = 0.96$) and two cohesive soil mixtures containing fines ranging from 50% to 55%, with contents of clay ranging from 10% to 12% [74]. The embankment models used were 0.75 m high with 0.6 m long crests and 2:1 slopes. The reservoir was filled until the water level was 5 cm above the crest, controlled initially by a wooden board to prevent overflow, which was removed once the desired water level was reached.

For the poorly graded silty sand embankment, initial erosion was noted on the upper half of the downstream slope, progressively steepening and forming a headcut. This breach behaved similarly to those in cohesive embankments, i.e., with flow escaping from the brink of the headcut, but without significant mass slope failures. The headcut backward migration was also different from headcut migration in cohesive embankments, being primarily driven by surface erosion and not by block failure. Once it reached the upstream slope, the breach bed slope gradient mellowed and stabilized, indicating a more uniform erosion pattern across the slope.

In cohesive soil embankments, erosion typically started near the downstream toe and spread along the slope, with higher erosion rates observed at the lower sections causing the slope to steepen. The crest erosion proceeded more slowly, reducing its height and increasing overflow discharges. This resulted in the formation of a near-vertical headcut face. The overflowing water created an impinging jet at the headcut, undermining it and occasionally causing discrete headcut mass failures, although these were infrequent. Notably, a rounded crest was sometimes observed, altering the flow dynamics to run along the headcut rather than jumping over it.

Comparative analysis revealed that the presence of cohesion in the embankments markedly decelerated the erosion process, with a higher clay content correlating with reduced erosion rates. This highlights the significant role of cohesive properties in influencing the dynamics and stability of embankment breaching.

4.2.2. Tobita and Colleagues (2014) [99]

In 2014, Tobita and colleagues performed field experiments conducted to explore the erosion processes of coarse-grained canal embankments under overtopping conditions [99]. Four 3 m high embankments were tested, varying in parameters such as the soil type and crest length. The discharge in the canal was regulated to maintain a 0.3 m flow depth at the notch. The soils used were poorly graded gravels (GP) and two silty sands (SM), one with 20% and another with 30% of fines, both with similar clay contents of around 4%.

The terms “inner” and “outer” slopes typically used to describe maritime dikes were used in the study, likely corresponding to the downstream and upstream slopes, respectively, of traditional dam or levee terminology. In these experiments, erosion initiated on the inner (downstream) slope, progressing up to the crest and across to the outer (upstream)

slope. Once erosion reached the top of the upstream slope, the breach expanded parallel to the canal flow direction both upstream and downstream.

The built-in acceleration sensors in the embankments allowed for the monitoring of the progression of the breach. However, only two-time steps per case were presented, limiting the detailed assessment of early-stage erosion processes. Erosion first appeared centrally on the downstream slopes in both poorly graded gravel embankments and in the silty sand embankment with a higher fine content. In the other silty sand embankment, with a lower content of fines (10% less fines), erosion presumably initially appeared near the downstream side of the notch, likely because in that location, the scour hole was deeper. Further interpretation of the macro erosion process based on the acceleration sensors data presented is not possible.

4.2.3. Kakinuma and Shimizu (2014) [72]

The primary goal of Kakinuma and Shimizu's study in 2014 was to elucidate the mechanisms behind riverine levee breaches and introduce a novel numerical model for this phenomenon [72]. The study involved conducting four large-scale physical tests on 3 m high levees with 2:1 slopes, varying the inflow rate, levee material, and crest length, while monitoring the breaching process via acceleration sensors installed within the levee. A 0.5 m deep and 3 m wide notch was used to initiate the breaches. Four distinct tests were carried out, each utilizing different soil materials. Two tests used very similar poorly graded silty gravels (GP-GM) with 5.6% fines (unknown clay content) and 44% sand. Another test involved silty sand (SM) with 12% gravels and 20% fines, from which 3% were clays. The final test likely used silty-clayey gravel (GC-GM) containing 32% sand and 30% fines with about 4% clays. These materials had median particle diameters (D_{50}) of 5 mm, 0.7 mm, and 0.2 mm, respectively.

The description of the initial erosion stage is notably brief and does not specify whether a headcut step forms. It mentions that erosion commenced on the downstream slope and migrated upstream from the top of this slope to the top of the upstream slope. Once the breach penetrated the upstream slope, it gradually widened both upstream and downstream, terms which refer to the flow direction in the canal, not through the breach. The duration of this initial stage was longer in tests using soils with 20% and 30% fines. The authors suggest that the completion time of this stage depends on the soil's cohesion—higher cohesion makes the material less erodible, thus extending the duration—and the width of the crest, with wider crests taking longer to breach. Additionally, the inflow discharge into the canal also influenced the duration of this stage, with higher inflows shortening the time required for the initial stage of breaching.

4.2.4. Tabrizi (2016) [82]

Tabrizi's Ph.D. thesis from 2016 details a range of experimental tests conducted to assess the impact of cohesion on the erodibility and failure mechanisms of silty-clayey sand canal embankments due to overtopping, performing four tests in which the content of clay and silt varied and compaction was maintained throughout [82]. Three of these tests included embankments with 6% clay and silt contents ranging from 20 to 40%, while the fourth test involved a soil mixture of 12% clay and 20% silt.

The erosion process was characterized by initial headcut progression starting from the downstream toe and moving towards the crest, with the breach width staying consistent in this phase. Upon the headcut reaching the crest, the breach then deepened towards the base before beginning to widen. All experiments showcased non-symmetric breach development, with the downstream breach bank experiencing higher shear stresses and, thus, more rapid erosion compared to the upstream side. The study found that increasing

clay content substantially enhanced the resistance to erosion of the embankment, much more so than variations in silt content. Thus, cohesion, and particularly clay content, was identified as the primary factor influencing the breaching process.

4.2.5. Ellithy and Colleagues (2018) [150]

In 2018, Ellithy and colleagues investigated the erosion rates of coarse-grained soil materials through tests in a 1.2 m long, 0.5 m wide, and 0.2 m deep testing box filled with soil samples compacted to the optimum moisture content, as defined by the Standard Proctor test, with overflow parallel to the box [150]. The soils, despite sharing a common particle size (D_{50}) of approximately 2 mm, varied in fine content, ranging from 0% to 20%, as well as clay content, ranging from 0% to 10%, and had a gravel content of roughly 30%. All grading curves differed primarily below the D_{50} size. The soils were classified as well-graded sand (SW) with 0% fines, well-graded silty sand (SW-SM) with 5% fines of which 2% were clays, and clayey sand (SC) with 20% fines of which 10% were clays.

Erosion rates were determined by the erosion depth over time, and flow shear stresses were calculated using a discrete form of the momentum equation. The study introduced a dimensionless form of the excess stress equation, incorporating D_{50} , gravitational acceleration, and the specific and submerged unit weights of the soils, to express erosion rates and shear stresses as dimensionless variables. This formula, following a power law, allows for flexibility in correlating erosion rates with shear stresses without incorporating the critical shear stress directly, suggesting that its influence might be reflected in the calibration of its constants.

Linear models relating shear stresses to erosion rates identified critical shear stresses of 1.5, 3.5, and 20 Pa for the respective soil samples, with the erodibility coefficient halving for the sample with the highest clay content, which is nevertheless indicative of very erodible soils. The presence of fines and clay was observed to increase critical shear stress and decrease erodibility (k_d), suggesting that fine content makes soils less erodible. However, the presence of fines at concentrations of 0% and 5% (with clay contents of 0 and 2%, respectively) yielded identical erodibility coefficients, indicating that erosion rates only begin to be significantly affected when the fine content exceeds 5%. This suggests the need for further research to determine which component of the fines—silt or clay—exerts greater control over soil erodibility. In addition, the study notes that a bilinear model could more accurately depict the erosion behavior of the soils, proposing that a linear model oversimplifies the relationship (Figure 4).

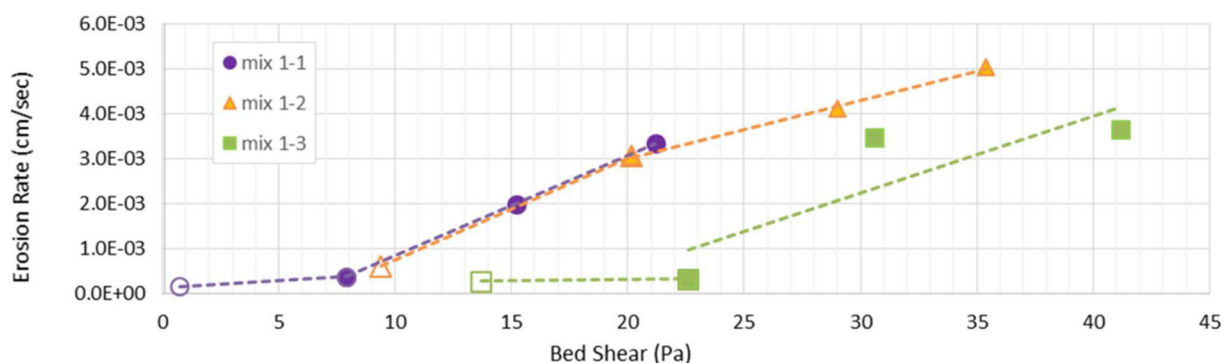


Figure 4. Relationship between erosion rate and bed shear stress fitting bilinear models [150]. Scour and Erosion IX, Proceedings of the 9th International Conference on Scour and Erosion (ICSE 2018), Edition by Yeh Keh-Chia, Copyright © 2019 by CRC Press. Reproduced by permission of Taylor & Francis Group.

Ultimately, the study concludes that fines and clay make soil materials less erodible by raising the critical shear stress and lowering the erosion rate. The dimensionless “excess stress equation” offers a simpler and more effective model for estimating the erosion rates of coarse-grained soils over a broad range of shear stresses, effectively accounting for the influence of fines content.

4.2.6. Ashraf and Colleagues (2018) [19]

In 2018, Ashraf and colleagues aimed to develop a new set of statistical equations to predict the key parameters of embankment breaches [19]. The authors analyzed 126 historical embankment failures, which served as the basis for calibrating these statistical formulations. To validate their equations, the authors conducted experimental tests with both cohesive and noncohesive soil materials. Specifically, they utilized poorly graded sand (SP) without fines and two different cohesive soil mixtures, one consisting of 41% sand, 44% silt, and 15% clay and another comprising 45% sand, 33% silt, and 22% clay. The inflow to the flume was adjusted as necessary to balance the breach outflow and maintain a constant reservoir level.

The findings indicated a good correlation between the new formulations and the test results for embankments made of noncohesive soils. However, for embankments constructed with cohesive soils, the results were more varied, largely due to the significant impact of the specific soil properties on the breaching process. These new formulations, which fall within the category of parametric models, were not included in one of latest reviews of the state of the art published in 2021 [6].

For the embankments comprising pure sand, erosion occurred uniformly along the downstream face, with a gradual flattening of the breach bed gradient until it reached the embankment toe. This study highlights the complex interplay between soil composition and the breaching process, underscoring the need for tailored prediction equations that account for the variability in soil properties, particularly when dealing with cohesive soils. In contrast, the embankments made with cohesive soil, particularly those with a 15% clay fraction, exhibited erosion initiating at the toe and forming a headcut step. This erosion then migrated upstream, creating additional headcut steps toward the embankment crest. The embankment with a 22% clay fraction underwent a similar headcut migration process. However, in this case, the breaching process did not complete within 30 h of overflow, as the breach failed to reach the upstream reservoir.

4.2.7. Summary

In summary, the main conclusions drawn from the research studies reviewed in this section are as follows:

- In silty sand embankments, erosion begins at the upper sections, forming a near-vertical face that progresses through surface erosion rather than block failure [74].
- The presence of fines, whether cohesive or non-cohesive, has been shown in embankment physical tests to affect breach dynamics in several ways:
 1. It influences breach evolution rates [71,72], with clay content offering more resistance to erosion than silt [74,82].
 2. It significantly affects erosion rates only when the fine content exceeds 5% [150].
 3. It delays erosion initiation by increasing the soil's critical shear stress [150].
- Non-standardized soil erosion tests (not using embankment physical models) corroborate that increasing the fine and clay content reduces erosion rates [148].

4.3. Cohesion and Soil Strength

4.3.1. Zhang and Colleagues (2009) [9]

In 2009, Zhang and colleagues published the results of a study focusing on the impact of cohesion on large-scale homogeneous embankment dams subjected to overtopping [9]. Conducted in China, the research involved four large-scale tests on 10 m high embankments made from homogeneous cohesive soil materials with varying clay contents ranging from 12% to 33%, corresponding to cohesion values ranging from 8 to 40 kPa.

The authors explore the theory that different compaction levels within soil layers lead to varying erodibility and erosion rates, which contribute to the formation of headcut steps. They note that the appearance of a scour hole can decrease flow velocity and subsequently reduce shear stresses.

Observations from the tests indicated that higher cohesion in the soil materials correlates with slower rates of headcut erosion and breach widening, smaller final breaches, and reduced peak outflow discharges. Embankments with higher cohesion tended to exhibit multi-step headcuts and block dumping (block detachment) of the breach sidewalls. In contrast, lower cohesion typically resulted in rapid scouring of the downstream slope, with the failure process characterized by a single-level headcut and shearing collapse.

4.3.2. Feliciano and Colleagues (2015) [16]

In 2015, Feliciano and colleagues delved into the impact of varying proportions of cohesive and noncohesive fine sediment on the breaching process of overflowed embankments [16]. With embankments standing at 0.25 m in height with 3:1 slopes and featuring crests 0.1 m long, the authors conducted tests using six different soil types to understand these effects under a constant inflow to the flume of 5.4 L/s. The soils tested were poorly graded sand (SP) without fines, and different mixtures of sands with approximately the same content of fines of about 40% and varying contents of clays ranging from 4% to 20%, assuming low plasticity for these soils due to the type of clay used (kaolin).

The study found distinct behaviors between pure sand embankments and those with cohesive materials or fines. Pure sand embankments exhibited nearly vertical breach walls, attributed to apparent cohesion, likely resulting from negative pore pressure. The breach development appeared to be primarily driven by surface erosion. In contrast, embankments with fines underwent headcut-like erosion. This process involved the formation of gullies and rills that evolved into small headcuts, later converging into a single large headcut face, which migrated upstream at a rate dependent on soil properties, including unconfined compressive strength. The headcut migration led to the undermining of breach side walls, resulting in block failures that widened the breach. However, the description of the timing and mechanisms of embankment crest lowering and pilot channel erosion is vague, making it difficult to ascertain the exact process of overflow control and headcut migration.

The study also noted the impact of noncohesive fines, like silt, significantly affecting the breach process by reducing soil and embankment erodibility. This resulted in a 50% reduction in peak outflow magnitude and a 7.5-fold increase in the time to reach peak outflow compared to pure sand embankments.

Regarding clay content, while increasing clay content (thus reducing sand and silt content) led to decreased soil and embankment erodibility, as well as slower headcut migration, the relationship between clay content and soil strength was complex. Interestingly, comparing soils with identical silt content but different clay contents (0% and 5%) revealed that soil strength, rather than clay content per se, played a more significant role in determining breach dynamics. The soil without clay presented a higher unconfined compression strength, a lower breach peak outflow and a longer time to peak, suggesting

that the unconfined compressive strength of the soil is a more critical factor in embankment erodibility and breach development than the presence of clay alone.

4.3.3. Summary

In summary, the main conclusions drawn from the research studies reviewed in this section are as follows:

- Cohesion influences breach dynamics; higher cohesion correlates with slower erosion rates, smaller breaches, and lower peak outflows. It also affects breach patterns, with greater cohesion leading to multistep headcut erosion, while lower cohesion results in single-level headcuts and shearing collapses [9].
- Soil strength may play a more significant role in determining breach dynamics rather than clay content alone [16].

4.4. Saturation Conditions

4.4.1. Al-Riffai and Nistor (2010) [70]

In 2010, Al-Riffai and Nistor investigated the effect of unsaturated conditions on the homogeneous noncohesive embankment dam breaching process [70]. This work also aimed to explore the effect of other variables such as the dry unit weight of the soils and the compaction effort which, will be presented in a different section. The experimental models were scaled representations of a 30 m high homogeneous noncohesive embankment dam, built to heights of 0.30 and 0.25 m, and featured upstream and downstream slopes of 2.5 and 3.0, respectively. To mimic the prototype's median grain size of $D_{50} = 0.5$ mm in the models, cohesive or liquefiable soils like clay or silt would have been necessary. However, the researchers chose a poorly graded sand with approximately 3% fines and a $D_{50} = 0.225$ mm, ($C_u = 3$, $C_c = 0.4$).

The small-scale experiments conducted were limited by the narrowness of the flume relative to the tested soil erodibilities, leading to breaches expanding to the flume walls before peak outflow was reached. Despite these constraints, the experiments provided significant insights, including the observation that increasing the soil's dry unit weight decreased the embankments' erosion rates, the effect of compaction being reduced when toe drains were installed. In physical models lacking a toe drain, the downstream slope remained nearly fully saturated, greatly enhancing soil erodibility. These saturation conditions also resulted in more frequent side-slope failures, often manifesting as slides rather than slumps, contrasting conditions with a drain. The study concluded that unsaturated soil conditions significantly postponed the breaching process. Scaling the delay to the original 30 m high prototype dam resulted in an 25 min real delay.

The researchers utilized SEEP/W software to assess pore water pressure distribution within the models, finding that the presence of a toe drain slightly increased the shear strength of materials by 1 to 2 kPa due to maximum negative pressures of around 1.5 kPa. Despite the minimal role of suction forces in enhancing shear strength, they noted an increased stability of the lateral walls of the breach, attributed to the reduced material density in semi-saturated states.

4.4.2. Al-Riffai and Nistor (2013a) [78]

In 2013, the same authors focused on the effects of seepage through the downstream slope of noncohesive embankments during overtopping events, particularly on the shear stresses acting on the embankment and the erosion rates, tackling this issue by modifying classical sediment transport formulations to incorporate seepage through this porous boundary [78]. Previous research has demonstrated that seepage can significantly affect flow parameters such as pressure distributions, velocity profiles, turbulent intensity, and

flow shear stresses, which in turn influence erosion rates [151–154]. Concerning bed shear stresses (flow shear stresses), these tend to decrease with increasing upward seepage velocity [152].

The authors propose a theoretical framework for analyzing overflowed noncohesive embankments, introducing the concept of a recirculating zone on the upper half of the downstream slope and distinguishing areas of downward and upward seepage, i.e., flowing in and out of the slope. They note that vertical erosion on the downstream slope starts immediately downstream of the crest, where the bed slope increases abruptly. This area experiences negative pressures due to flow separation from the boundary, resulting in a subhydrostatic pressure distribution and a recirculating flow in the transition zone (Figure 5). The authors discuss how energy dissipation in this zone, and within the recirculation zone itself, may lead to reduced flow shear stresses along the slope, particularly under supercritical flow conditions where seepage becomes critically important near incipient fluidization conditions.

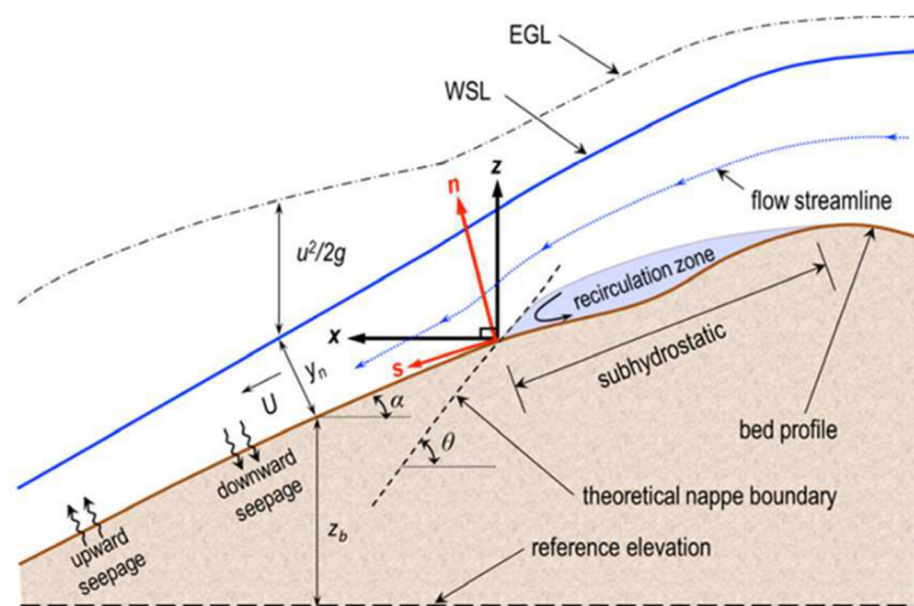


Figure 5. Hypothetical flow overtopping a steep non-cohesive bed showing the recirculation zone, water surface levels, bed elevations, flow parameters, the energy grade line and upward/downward seepage [78].

To investigate these phenomena, the authors employed micro tensiometer–transducer probes to measure pore water pressures within the downstream shoulder of the embankment. They constructed 0.30 m high physical models using uncompacted poorly graded sand (SP) with 3% fines, for which the soil water characteristic curve was characterized using the Tempe Cell apparatus to obtain the Air Entry Value (AEV) and residual suction value (RSV).

The study explored three embankment configurations: one without seepage control, one with seepage control, and one with seepage control under dry conditions. By performing a transient flownet analysis and applying modified dimensionless bed shear stress and sediment transport rate parameters to account for the seepage, the study particularly focused on the conditions of embankments without seepage control. The authors suggested that erosion in these scenarios is predominantly influenced by the modified bed’s mobility due to the seepage mechanism, with hydraulic gradients at both ends of the slope moving in opposite directions and near-fluidization conditions occurring at the downstream end.

The findings indicate that in laboratory settings, embankments without an impervious element or toe drain are susceptible to seepage-induced failure, highlighting the role of

seepage in determining the failure mechanisms of noncohesive materials. This contrasts less permeable materials or tests incorporating an impervious element, where the flow patterns and failure modes are primarily dictated by the overtopping flow, leading to different erosion and failure characteristics.

4.4.3. Al-Riffai and Nistor (2013b) [68]

Also in 2013, the same authors presented a conference paper [68] expanding upon their previous research [78], delving into how soil saturation levels impact the erosion of embankments, revealing that higher saturation degrees correlate with increased breach peak outflows, unlike drier embankment conditions which show better resistance to erosion. This observation was supported by the measurement of increasing pore water pressures near the flume's bottom.

The study notes the relationship between Froude numbers and the seepage direction, where low Froude numbers near the embankment crest lead to downward seepage, and high Froude numbers near the toe result in upward seepage. Interestingly, the calculation of flow shear stresses, whether performed using the traditional method or a corrected version accounting for seepage through the downstream slope, yielded similar outcomes, which contradicts previous studies [152]. They highlight the need for further research to quantify the influence of both erosion and the fluctuating pressure field near an eroding bed under accelerating flow on the seepage forces.

4.4.4. Al-Riffai and Nistor (2015) [67]

In 2015 [67], the same authors presented updated results and expanded on the findings from their previous work regarding the erodibility of overtopped embankments [78], focusing on experiments with 0.28 m high embankments under 0.12 m overtopping heads. The embankments, constructed from poorly graded sand with 3% fines, were tested under the same three conditions as in their previous studies: without seepage control, with a toe drain, and with a toe drain in dry conditions.

The study reinforced previous observations, noting that embankments without a drain exhibited higher peak outflows and shorter hydrograph durations, while those with a toe drain and in dry conditions showed the lowest peak outflows and the longest durations.

Initial soil moisture was found to affect erosion rates, with dryer soils eroding more slowly. Breach profiles were smooth, slightly steepening as they migrated upstream but not exceeding the internal friction angle of the soil. The original downstream slope was 3H:1V (18°) and the steepest breach profile presented had a slope of approximately 30°, therefore tending to the internal friction angle of the soil material (36°).

Using tensiometer–transducer probe assemblies and ArcGIS, the authors mapped pore water pressures and constructed flow nets to estimate hydraulic gradients, seepage angles, and flow velocities. These measurements informed calculations of bed shear stresses (flow shear stresses) in the presence of a seeping boundary, comparing them with conventional formulations like Manning's equation. Results showed minor differences in shear stress calculations between both approaches (2 Pa in difference), although these were higher in calculations with a seepage boundary.

4.4.5. Orendorff and Colleagues (2013) [73]

In 2013, Orendorff and colleagues explored how different initial conditions of overflow influence the breaching process of poorly graded sand embankments containing 3.4% fines with a median particle size (D50) of 0.22 mm [73]. Within this broader research, they assessed the effect of the embankment's initial conditions by using a toe drain. For this purpose, the experimental setup included two V-notch tests, one with a toe drain and the other without, using different uniform sands (the no-drain test utilized finer sand with

a D50 of 0.140 mm). The internal friction angle of the coarser sand was measured at 36° , with a specific gravity of 2.75, attributed to high iron content. This sand was prepared with a 16% moisture content, based on a standard Proctor test, achieving a dry density of 1530 kg/m^3 . Tests were conducted with a constant inflow rate of 0.45 L/s.

Both V-notch tests resulted in similar failure hydrographs, with peak outflows around 80 L/s, albeit at slightly different times. Breach development progressed more rapidly in the V-notch without a toe drain. This sequence is consistent with previous findings indicating that the absence of a toe drain leads to nearly saturated conditions on the downstream slope, thereby increasing soil erodibility—a conclusion drawn without explicit mention by the authors but supported by the work of Al-Riffai and Nistor (2010) [70].

However, comparing these tests might be misleading due to the use of finer sand in the no-drain test, which is more erodible in saturated conditions [92,149] but will certainly show higher apparent cohesion in semi-saturated states, which will decrease erodibility and affect other properties of breaching [88].

4.4.6. Lin and Colleagues (2016) [155]

In their 2016 study, Lin and colleagues aimed to determine the feasibility of using unconfined compression test results to assess the apparent cohesion of unsaturated lateritic soil, which is traditionally measured using more complex unsaturated triaxial tests [155]. The research involved laboratory tests on unsaturated compacted lateritic soil samples from northern Taiwan. The unconfined compression strength and matric suction were measured using unconfined compression tests combined with filter paper tests.

During unsaturated triaxial tests, they noted that pore water pressures showed little change with axial loading, allowing for the assumption of constant water pressure throughout the tests. The authors found that the unconfined compressive strength of specimens compacted at the optimal moisture content (OMC), OMC minus 3%, and OMC plus 3%, increases with matric suction. Notably, specimens at the OMC show a greater increase in strength compared to those on the drier or wetter sides, likely due to the presence of a compact soil structure with high water retention. Additionally, the strength change is more pronounced on the drying path than on the wetting path, as the specimen becomes gradually saturated along the wetting path, limiting changes in matric suction and strength.

The unconfined compression test, combined with the filter paper test, revealed a strong positive correlation between the calculated apparent cohesion and the actual apparent cohesion of unsaturated compacted lateritic soil. Matric suction emerged as a crucial factor linking these two forms of apparent cohesion. From unsaturated triaxial test data with matric suctions below 200 kPa, the ratio of actual to calculated apparent cohesion varied between 0.65 and 1.04. Based on these observations, they introduced an equation to calculate apparent cohesion from unconfined compression tests, using the effective friction angle obtained from saturated triaxial CU tests conducted under zero-matric suction conditions. Additionally, they proposed another equation to determine apparent cohesion under variable matric suction, incorporating effective cohesion, matric suction, and the friction angle.

4.4.7. Ravindran and Gratchev (2022) [156]

In their 2022 study, Ravindran and Gratchev sought to explore the effect of water content on apparent cohesion and into developing a model to predict apparent cohesion in coarse-grained soils ranging from 0 kPa to 100 kPa [156]. They conducted shear-box and suction tests on a variety of coarse-grained soils, including gravels and sand with the content of fines measuring below 0.075 mm ranging from 1% to 12%. Based on the ASTM Unified classification, the soils were categorized as sands (three soils with less than 5%

fines) and silty or clayey sands (one soil with 12% fines). Information on the coefficients of uniformity and curvature was not provided, leaving the exact classification of their gradation (poorly or well-graded) open to interpretation. They also tested gravels with less than 5% fines (three soils with the same problem concerning gradation).

This study highlighted significant differences between unsaturated and saturated shear strengths, illustrating the role of apparent cohesion, which they found to vary with water content. Results showed an average 89% decrease in apparent cohesion as water content increased from 0% to 30%. To predict apparent cohesion, the authors introduced a new model for unsaturated coarse-grained soils based on low-range matric suction, with an equation expressing apparent cohesion as a function of water content, $(c/c_0 = 1.1 - 4.7w + 5.9w^2)$, where c_0 is the apparent cohesion at zero water content and w is the water content. They also proposed a new relationship between apparent cohesion and matric suction, aimed at estimating the apparent cohesion for coarse-grained soils when matric suction ranges from 0 kPa to 100 kPa. They argue that this new relationship provides better predictions than existing models, enhancing the accuracy of assessments in geotechnical engineering applications involving coarse-grained soils.

4.4.8. Rivera-Henandez and Colleagues (2021) [157]

In 2021, Rivera-Henandez and colleagues addressed the scarcity of experimental investigations on the unsaturated soil mechanics of highly compacted silty sands, characterized by complex shear strength and dilatancy behaviors [157]. One of the objectives of this work was to examine the impact of suction and confining pressure on the shear strength of highly compacted silty sands, employing both multistage and single-stage triaxial testing. Multistage triaxial testing represents field conditions with fluctuating external loading. Soil samples were tested under various matric suctions (0, 20, 50, and 95 kPa) and net confining pressures (50, 100, and 200 kPa). The silty sand consisted of 14% gravel, 44% sand, and 42% nonplastic fines, with a maximum dry unit weight of 21 kN/m³ at an optimum moisture content of 7.2%.

Both multistage and single-stage triaxial tests under unsaturated conditions indicated that increasing matric suction and net confining pressure enhances shear strength. Unsaturated samples consistently showed higher shear strength than saturated ones, with their Peak State Lines being parallel but having a higher intercept as matric suction increased. Multistage testing generally resulted in higher shear strength due to cumulative volume changes in the specimens. The findings suggest the potential value of incorporating the void ratio as an independent variable in shear strength analysis. Additionally, dilatancy during shearing in both test types decreased with rising confining pressures, for both saturated and unsaturated specimens.

4.4.9. Summary

In summary, the main conclusions drawn from the research studies reviewed in this section are as follows:

- Saturated soil enhances soil and embankment erodibility, resulting in more frequent side-slope failures, often manifesting as slides rather than slumps [67,68,70,73].
- In very permeable soils, the lack of an impervious element may lead to seepage-induced failure, which is very different from overflow failure modes [78].
- Unconfined compressive strength and shear strength both increase with matric suction [155,157].
- Apparent cohesion was found to vary with water content, with data showing a decrease in apparent cohesion as water content increased. This observation is valid for water contents ranging from 0% to 30% [156].

4.5. Compaction

This section will include all studies which have investigated the effect of some soil parameter which may be related to compaction, such as, for example, the dry unit weight, soil moisture during compaction, the compaction energy, and others.

4.5.1. Al-Riffai and Nistor (2010) [70]

In 2010, Al-Riffai and Nistor, in addition to their investigation on the effect of saturation conditions on embankment dam breaching, which is presented in a different section of this document, also assessed the effect of the soil dry unit weight [70]. For that purpose, they tested 0.25 m to 0.3 m high embankment dam physical models constructed using a poorly graded sand with approximately 3% fines and a median grain size of $D_{50} = 0.225$ mm, adjusting compaction efforts to study a scaling approach based on soil erodibility rather than purely physical characteristics.

The small-scale experiments conducted were limited by the narrowness of the flume relative to the tested soil erodibilities, leading to breaches expanding to the flume walls before peak outflow was reached. Despite these constraints, the experiments provided significant insights, including the observation that the increased dry unit weight of soil extended the lag time of the outflow hydrograph, though the effect of compaction lessened with the installation of toe drains. Additionally, models constructed with higher unit weights saw fewer side-slope collapses, while those with lower unit weights were more prone to slumps over slides. As referred to in a different section, SEEP/W software calculations showed that the presence of a toe drain slightly increased the shear strength of materials by 1 to 2 kPa due to maximum negative pressures of around 1.5 kPa, suggesting that the increased stability of the lateral walls of the breach is attributed to the reduced material density in semi-saturated states rather than to increased apparent cohesion and soil shear strength.

4.5.2. Tabrizi (2016) [82]

Tabrizi's Ph.D. thesis from 2016 details a range of experimental tests on the impact of compaction on embankment dam breach processes using 0.55 mm noncohesive uniform sand (probably a poorly graded sand), compacted at four different levels, under a constant inflow rate of 0.5 L/s to the flume. Different degrees of compaction were achieved by varying the number of compaction blows on soil moistened to its optimum water content. The study found that while compaction did not alter the fundamental surface erosion mechanisms—surface erosion driven initially with a pivoting point around the downstream toe which subsequently progressed downstream to establish a stable slope—it influenced the final breach crest elevation, which tended to be higher with increased compaction efforts. Furthermore, compaction impacted the outflow hydrograph; the study notes that *“the peak discharge decreased with the compaction level”*, suggesting that greater compaction levels result in lower peak outflows, aligning with the expectation that more compacted embankments erode more slowly and therefore exhibit reduced peak discharges. This inference is further supported by the observation that the time to reach peak discharge increased with higher compaction, consistent with the notion that increased compaction slows erosion rates.

Jet Erosion Tests (JETs) conducted on silty–clayey cohesive soils revealed that compaction significantly affects soil erodibility, with varying compaction resulting in a spectrum from highly erodible to very resistant soils. The study observed that the coefficient of erodibility (k_d) generally reaches its lowest value near the optimum moisture content for any given compaction energy, suggesting that soils are the least erodible when moisture is close to optimum, independent of the compaction effort. Additionally, soils compacted on the

wet side of their optimum moisture content were less erodible compared to those compacted on the dry side. It was also noted that, for a specific moisture level, the resistance of soil to erosion improves with increased compaction effort, and for a set compaction effort, the critical shear stress required to initiate erosion rises with moisture content, particularly for soils compacted to the optimum moisture content. Ultimately, the study concluded that moisture content at the time of compaction has a more pronounced impact on soil erodibility than the level of compaction effort itself.

4.5.3. Jiang and Wei (2019) [40]

In 2019, Jiang and Wei explored the influence of the initial moisture content of soils on the outflow hydrographs, peak discharge, and the dimensions of breach (depth and width) in overflowed natural landslide dams composed of sandy gravels [40]. They base their model on the Zongqu natural dam, which formed from block rocks, gravels, sand, silt, and clay following the Wenchuan earthquake and was subsequently overtopped in 2009. The natural dam had a crest width approximately equal to its height of 30 m, was situated on a stream with a bed slope of approximately 4 degrees, and had upstream and downstream slopes of about 34 degrees (1.5H:1V) and 17 degrees (3.3H:1V), respectively.

To conduct their experiments, the authors created a scaled-down version of this dam using a length scale of 1:100. The experimental soil mixture consisted of 5% particles measuring 10–30 mm, 60% particles measuring 3–10 mm, 35% particles smaller than 3 mm, and 2% fines. This composition resulted in well-graded gravel with a median particle diameter (D₅₀) of 4.8 mm. All embankments were compacted to a uniform dry density of 1.72 g/cm³, using 10 cm layers, regardless of initial moisture content. The coefficient of permeability was 0.418 cm/s. All tests were conducted with an inflow discharge to the flume of 1 L/s, simulating the hydraulic conditions that would challenge the structural integrity of the dam and evaluate the impact of soil moisture on erosion dynamics and dam failure processes.

Although seepage was noted through the physical models, they did not experience seepage-induced failure. The experiments produced single peak outflow hydrographs, showing that higher initial soil moisture led to faster and more catastrophic failure: higher peak outflows occurred earlier as moisture increased. The authors explain that wetter soil allows seepage to develop more readily, saturating the embankment sooner and reducing apparent cohesion, thus facilitating the erosion of soil particles. Additionally, seepage erodes finer particles, enlarging pore spaces and increasing seepage discharge, which enhances the erodibility of the soil. Regarding the breach width-to-depth ratio, it was found to decrease as initial soil moisture increased, indicating deeper and narrower breaches at higher moisture levels.

The failure process of the natural dams studied began with tractive erosion (surface erosion), transitioned toward backward erosion (headcut erosion), and concluded with a return to tractive erosion (surface erosion). These observations suggest that different erosion models are necessary for various stages of dam failure, rather than applying a single mathematical model throughout.

The study also found that initial soil moisture did not alter the general characteristics of the failure processes, which consistently involved both tractive and backward erosion. However, the impact of these processes varied with moisture content. Analysis of the longitudinal profiles revealed that breach bed slopes were steep at lower initial soil moistures (e.g., 0.3%) but became less intense and gentler at higher moistures (10.3%). This indicates that increased initial soil moisture diminishes the impact of backward erosion while enhancing tractive erosion.

At the conclusion of the breach, the residual dam heights were typically higher upstream than downstream, and the gradients were steeper compared to the original riverbeds. Additionally, the data showed that higher initial soil moisture resulted in a lower residual dam height, suggesting that moisture content influences the final structure and stability of the dam post-failure.

4.5.4. Amaral and Colleagues (2020) [34]

The effectiveness of experimental studies aimed at investigating the hydraulics of dam breaching heavily depends on the proper specification of geotechnical parameters and precise control over their implementation, whether in field or laboratory settings. Despite the recognition of this necessity, there exists a limited number of studies that specifically focus on formulating and discussing the criteria for comparable laboratory hydraulic tests designed to study embankment failure caused by overtopping. In this context, in 2020, Amaral and colleagues presented their work seeking to fill this research gap by specifically addressing the requirements for conducting such tests on homogeneous earthfill dams mainly through testing different compaction methodologies [34].

Their experimental research used 0.45 m high and 1.5 m wide embankments constructed with two types of soil materials: clayey sand with a median particle size (D₅₀) of 0.23 mm with 42% fines, of which 37% were clays, and silty sand with a D₅₀ of 0.31 mm, including 7% gravels and 27% fines, of which 11% were clays. The silty sand had no plasticity while the clayey sand had a plasticity index of 18. HET tests were performed to obtain the coefficient of erodibility and the critical shear stress of the silty sand, which qualitatively corresponded to a soil with a moderately rapid rate of progression of internal erosion. Embankments were compacted using three distinct methods (i) using a lawn roller filled with water, without any vibration, (ii) by percussion, utilizing a metallic hand tamper, and (iii) by vibration, employing a low weight vibratory plate.

To assess the impact of relative compaction, two embankments constructed with the silty sand were compacted by percussion, maintaining a moisture level of 1.2%, i.e., the optimum wetness, and within $\pm 2\%$ of the optimum, adhering to standard dam engineering practices, obtaining bulk densities of 81% and 87% of the maximum standard Proctor dry density. The results indicated that lower relative compaction led to the faster erosion of the embankment and higher peak outflows.

To assess the impact of moisture content on embankment stability, two additional embankments were constructed again with the silty sand and compacted by vibration with moisture content set at -2% below the optimum. These were compacted to approximately the same relative compaction levels of 87% and 88%. A comparison of these tests with another test, compacted to a similar degree but on the wet side, as described previously, revealed that the drier the embankment, the more susceptible it is to erosion, leading to faster erosion and more severe peak breach outflows.

Regarding macro erosion processes, all the tests exhibited both hydraulic erosion and headcut erosion. Collapses of the side walls were also noted in the silty sand embankments.

4.5.5. Summary

In summary, the main conclusions drawn from the research studies reviewed in this section are as follows:

- The effect of compaction is reduced in non-saturation conditions [70].
- Higher unit weights of soil materials improve embankment stability, correlating with fewer side-slope collapses. Although numerical models show only slight shear strength increases between saturated and unsaturated conditions, observed stability appears to be more related to reduced soil density than to shear strength changes [70].

- The embankment compaction degree affects the beaching dynamics, with higher degrees correlating with slower erosion processes and exhibiting reduced peak discharges. Standard erosion tests also align with this observation [34,82].
- The coefficient of erodibility generally reaches its lowest value near the optimum moisture content for any given compaction energy [82].
- Initial soil moisture influences breach dynamics: higher moisture leads to faster and more severe failures, while lower moisture results in steeper breach profiles [40]. Contradictory findings show that embankments compacted to the same degree but on the dry side erode more quickly and produce higher peak outflows than those compacted on the wet side, indicating greater erosion susceptibility in drier conditions [34].

5. The Effect of Hydraulics

5.1. Wang and Colleagues (2011) [158]

In 2011, Wang and colleagues investigated how bed shear stress and suspended sediment concentration are interrelated through experiments in an annular flume, using sediment from the Jiangsu coast, China, which has silty sand comprising 78% sand, 21% silt, and 1.3% clay with median grain size (D50) of 0.1 mm [158]. These tests consisted of two distinct methodological phases. The initial phase involved determining the flow velocity profile along the depth of the flow at various angular velocities. This was achieved using a propeller current meter to measure the velocity at different depths. The objective was also to establish the time required for the flow to stabilize, from which point it was assumed that if the bed material remained unchanged, then the velocity profile, vertical distribution of suspended sediment, grain size, and bed morphology would also remain constant. The second phase was the actual testing phase. Here, for a specific flow velocity maintained over a 10 min period, water samples were collected at various depths. This sampling procedure was repeated multiple times, progressively increasing to the maximum flow velocity. It must be noted that both steps were initiated with clear water, and the water depth was consistently maintained at 0.235 m throughout the experiments.

The Ariathurai–Partheniades equation was used to estimate bed shear stresses (flow shear stresses) based on changes in suspended sediment concentration. This equation assumes that these stresses are proportional to the square of the flow velocity in the boundary layer, multiplied by a drag coefficient. The authors assumed this coefficient to be the product of the water density and the suspended sediment concentration measured at the lowest depth (75 mm above the sediment bed). For the critical shear stress of the bed material, they used the Soulsby method. Finally, the relationship between flow shear stresses and the suspended sediment concentration was established from a series of derived flow shear stresses and corresponding values of depth-averaged suspended sediment concentrations. On this basis, the influence of the suspended sediment concentration on the velocity profile was evaluated.

The findings suggest that while the suspended sediment concentration increases sharply with flow velocity during seabed erosion, the corresponding change in bed shear stress is not linear. Initially, as flow velocity increases, bed shear stress increases significantly. However, upon reaching a critical sediment concentration of approximately 0.55 kg/m^3 , further increases in flow velocity do not significantly alter the bed shear stress, which tends to stabilize or grow at a much slower rate. This indicates that beyond a certain point, suspended sediment concentration heavily influences bed shear stress, highlighting a complex interplay between the two factors under varying hydrodynamic conditions. This relationship can be observed in Figure 6.

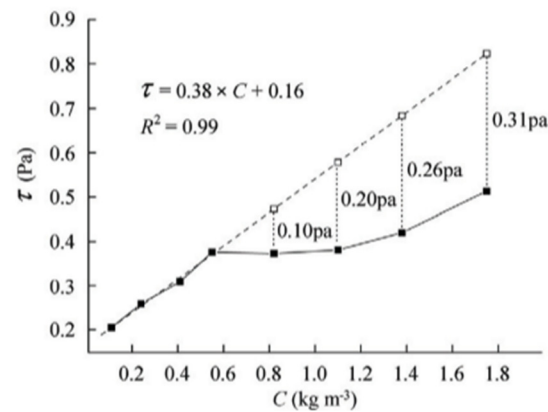


Figure 6. The relationship between bed shear stress and depth-averaged suspended sediment concentration. The equation represents the linear regression fitted to the first four solid data points on the left [158].

In analyzing the results, it is important to mention that the methodology employed did not allow for independent variation in suspended sediment concentrations and flow velocities. These two variables are intrinsically linked, with higher velocities leading to increased suspended sediment concentrations. This interdependence complicates the ability to distinctly isolate and assess the impact of each variable on the flow shear stresses.

5.2. Zhou and Colleagues (2019) [81]

In 2019, Zhou and colleagues presented findings from experimental tests designed to understand the effect of the inflow discharge on the evolution of the longitudinal breach profile in overflowed landslide dams [81]. The researchers utilized a soil material characterized by a median particle size (D_{50}) of 0.85 mm ($C_u = 167$ and $C_c = 1.1$), comprising approximately 20% fines with about 2% clay and 16% gravel. No information is provided on the nature and plasticity of fines, so given that most of the fines are silt, it is assumed that the result is soil classified as a silty sand under the Unified ASTM classification. The physical models, tested under four different inflow discharges ranging from 2 to 7 L/s, were compacted manually to achieve a consistent void ratio between 0.78 and 0.80, similar to field conditions.

The authors describe the initiation of erosion at the transition between the crest and the downstream slope of the dam, and they detail the progression of breaching in a manner that is challenging to reconcile with traditional macro erosion processes such as surface erosion and headcut erosion. The evolution of the longitudinal profile during the tests appears highly irregular, and it is not clear from the test images whether this irregularity might be due to block failures, for example. The described breaching process involves two key erosion points: one that advances upstream along the crest and another that moves downstream along the downstream slope. Three stages of breaching are defined: (i) the headcut erosion process, which is the initial stage involving the retreat of both erosion points as they migrate upstream along the crest; (ii) the accelerated erosional process, the stage that begins when the erosion point along the crest reaches the upstream edge, significantly increasing the breach outflow discharge, and that continues until the peak of the breach outflow; (iii) the attenuating erosional process, which is characterized by a decline in breach outflow discharges, and marks the slowing of erosional activity.

From the observations and descriptions provided, the breaching process in this study primarily exhibits characteristics of surface erosion. The typical headcut erosion observed in cohesive embankments, featuring a distinct and steadily migrating step, does not manifest in this case. The absence of a clear, consistently sloping step moving upstream complicates

the classification of the erosion process, though the overall dynamics suggest a dominance of surface erosion mechanisms. For modeling purposes, the researchers note that the erosion rotation point is not statically positioned at the toe of the embankment but instead moves along the downstream slope.

The authors analyzed erosion rates by observing changes in elevation across consecutive profiles, taken every 10 cm from the crest to the toe of the embankment. The erosion rates varied with the breach outflow, increasing significantly during Stage 2, where the highest erosion rates were recorded. Notably, the maximum erosion rates typically occurred near the central area of the downstream slope.

The study further explored the relationship between erosion rates and flow shear stresses, which were calculated using the hydraulic radius and flow velocity estimates based on Manning's equation. This relationship was examined across three vertical sections along the downstream slope, and linear regression analysis provided a relatively consistent value for the coefficient of erodibility, k_d , ranging from 0.19 to $0.26 \times 10^{-3} \text{ m/s/Pa}$ (the same dimensions as the JET test, typically presented as $\text{m}^3/\text{N}\cdot\text{s}$). Interestingly, the critical shear stress was found to vary with the vertical section analyzed, increasing in magnitude along the flow direction.

This increase in critical shear stress correlated with the concentration of suspended sediment in the flow. The analysis suggested that as flow moved downhill, the increasing sediment concentration reduced its capacity to erode the embankment, despite an increase in flow velocity which theoretically should have enhanced the erosive power. This finding suggests a more complex interaction between flow properties and erosion rates than traditionally understood. It indicates that critical shear stress, typically considered a function solely of soil material and embankment geometry, also depends on the properties of the overflowing water, particularly sediment concentration. We should note that for the type of soil material used in experiments, the amount of overflowing water seeping through the downstream slope is not negligible and could also contribute to decreasing the flow shear stresses along the slope of the embankment. Such results challenge the conventional belief that higher sediment content, which increases the density of the fluid, should inherently enhance its erosive capability. This aligns with the observations extracted from the work of Wang and colleagues described in the previous section [158].

The researchers observed that the greater the inflow discharge into the reservoir, the shorter the time required to reach the peak discharge. Additionally, the magnitude of the peak discharge itself was larger with increased inflow rates. This correlation highlights the significant impact of inflow discharge on the dynamics and severity of embankment breaching events.

5.3. Rifai and Colleagues (2019) [39]

The study performed by Rifai and colleagues in 2019, already described in previous sections, also assessed the effect of inflow discharge on the breach dynamics of canal embankments [39], identifying that inflow discharge significantly impacts breach expansion, with higher discharges leading to increased erosion rates and more pronounced downstream (canal direction) widening of the breach, driven by greater flow momentum in the canal. Floodplain confinement, defined as the water level downstream of the embankment, moderates the energy gradient of the outflow through the breach, resulting in shallower breaches.

5.4. Wahl (2019) [42]

In 2019, Wahl tested two zoned embankment dam models in the hydraulics laboratory of the Bureau of Reclamation to investigate erosion and breaching dynamics due to overtop-

ping and internal erosion [42]. These embankments featured a low-permeability cohesive silty clay core (CL-ML) and upstream and downstream shells composed of well-graded gravel with clay and sand (GW-GC). The material composition included 54% gravel with a maximum size of 19 mm, 34% sand, and 12% fines, of which 3% were clay particles. To evaluate overtopping resistance, the embankment was subjected to inflows of 17 L/s (131 L/s/m with a 10 cm overtopping head) on the first day and 140 L/s (1077 L/s/m) on the second day, testing the embankment's structural integrity under these conditions.

The author discusses the position of this soil within the ASTM Unified Soil Classification, saying that the dual-symbol classification, GW-GC, indicates that the soil contains fines with variable behavior, sometimes acting like coarse-grained soils and other times like fine-grained soils. With a fine content of 12%, this soil is on the borderline of being classified differently. Just an additional percent of fines would shift this classification to silty, clayey gravel with sand (GC-GM), reflecting the CL-ML (silty clay) classification of the fines. This classification could lead the material to behave as either silty or clayey material, depending on its plasticity, potentially being classified as clayey gravel with sand (GC) or silty gravel with sand (GM). In soil materials where fines make up 13% or more of the material, the behavior of the soil is more influenced by the content of fines than by the gradation characteristics of the coarser particles, regardless of whether they are well or poorly graded. Consequently, the gradation characteristic is omitted from the soil name in such classifications.

Focusing on the test with overflow, a 17 L/s inflow (131 L/s/m with a 10 cm overtopping head) was maintained for about half an hour, resulting in significant erosion both on the downstream slope and the top surface of the central core (crest). Notably, the erosion rate of the crest was similar to, or even exceeded, that of the downstream slope, indicating that the material in the central core was more erodible than that of the downstream slope. This is significant given that (i) the shear stresses exerted by the flow over the crest were considerably lower than those on the downstream slope, and (ii) the soil material of the central core was a cohesive silty clay.

During the test, small overfalls—or steps with vertical or near-vertical faces—formed on the downstream slope. However, these crests were eroded away before the overfalls could reach significant heights. In cohesive fine-grained materials, such small overfalls typically evolve into vertical headcuts, advancing upstream and eventually merging into larger headcuts. Nonetheless, in this test, a classic vertical headcut did not develop, and the erosion process was characterized predominantly by surface erosion. Post-analysis indicated that the downstream slope gradually steepened, rotating about 5 degrees from the initial slope of 2H:1V to a steeper final slope of approximately 1.6H:1V. The peak breach outflow recorded during the test was 54 L/s, reflecting the progressive erosion and geomorphic changes in the embankment structure during the overtopping event.

On the second day of testing, the experiment resumed with an inflow of 140 L/s while maintaining the same fixed reservoir level. This testing phase lasted about four hours. In the final 40 min, the inflow was incrementally increased several times to sustain the reservoir level, reaching a maximum breach outflow discharge of 300 L/s. During this period, the breach continued to widen. Contrary to the previous observation of the downstream slope gradually steepening from an inflow of 17 L/s, this trend reversed on the second day. The breach slope eventually flattened back to approximately 3H:1V.

The authors discuss several possible factors that might explain the absence of more pronounced headcut development:

- The lack of a significant tailwater pool: The absence of a significant tailwater pool downstream prevented the formation of a recirculation eddy at the toe. Such recircu-

lation could have accelerated erosion at the toe and promoted the steepening of the downstream slope toward a headcut configuration.

- Increased breach outflow due to crest erosion: The erosion of the crest might have increased the breach outflow to levels that significantly exceeded the critical shear stress of the gravel soil, thereby altering the erosion dynamics.

Commonly, the absence of headcuts in noncohesive soils is attributed to a lack of soil cohesion, which prevents the soil from maintaining nearly vertical slopes. However, observations that the breach side walls could support near-vertical slopes challenge this explanation, indicating that the soil's cohesive properties played a role in supporting steeper slopes without leading to headcut formation. These insights suggest a complex interaction between hydraulic conditions, soil properties, and erosion mechanisms, which collectively influenced the observed patterns of embankment erosion during the test.

5.5. Summary

In summary, the main conclusions drawn from the research studies reviewed in this section are as follows:

- Hydraulics obviously impacts breach dynamics, with higher inflows correlating to higher erosion rates [39,81] and wider breaches [39].
- The tail water level at the downstream toe moderates the energy gradient of the outflow through the breach, resulting in shallower breaches [39].
- One study suggests that the erosive capacity of skimming flow may be capped beyond a certain suspended sediment concentration, limiting further increases in erosion [158]. These observations seem to align with tests performed on embankments.
- Under high overflow, a well-graded gravel embankment near the silty gravel classification eroded mainly by surface erosion, rotating the breach profile about 5°, without forming a vertical headcut [42]. In contrast, a silty sand embankment under half the hydraulic head developed a near-vertical face [74]. This may suggest that overflow discharge influences the development of the breach profile.

6. The Effect of Geometry and Type of Infrastructure

6.1. Orendorff and Colleagues (2013) [73]

In 2013, Orendorff and colleagues explored how different initial conditions of overflow influence the breaching process of embankment dams [73]. They conducted experiments on overflows through various breach initiators: V-notch cuts, flat crests, and craters mimicking the impact of a blast. The embankment utilized poorly graded sand containing 3.4% fines and a median particle size (D50) of 0.22 mm. The internal friction angle was measured at 36°, with a specific gravity of 2.75, attributed to high iron content. This sand was prepared with a 16% moisture content, based on a standard Proctor test, achieving a dry density of 1530 kg/m³.

The experimental setup included two V-notch tests, one with the 0.22 mm poorly graded sand and another with finer 0.140 mm uniform sand. The crater, designed to simulate the effects of an 8000 kg TNT explosion, measured 120 mm in width and 30 mm in depth, whereas the V-notch dimensions were 40 mm wide by 20 mm deep. A flat crest with a slight center taper was also tested. All tests were conducted with a constant inflow rate of 0.45 L/s, though the reservoir volumes varied due to the differences in notch heights.

The study revealed negligible differences in the maximum outflow discharge among the tests, suggesting that the impact of initial breach geometry on peak outflow rates was not significant. Both the crater and V-notch tests resulted in similar failure hydrographs, with peak outflows around 80 L/s, albeit at different times. Breach development progressed

more rapidly in the crater test, followed by the V-notch tests. The flat crest test, having the largest reservoir, produced the highest peak outflow, approximately 90 L/s.

In summary, the study concludes that while the initial breach geometry influences the timing of peak outflow, the overall shape of the outflow hydrograph and the peak discharge rates remain relatively unaffected across different initial conditions.

6.2. Walder and Colleagues (2015) [25]

In 2015, Walder and colleagues published the results of 13 experiments on the breach processes of noncohesive earthen embankments, ranging in height from 0.6 to 1 m, using poorly graded beach sand with a median particle size (D50) of 0.21 mm and a very small content of fines of about 0.2% [25]. To minimize the risk of seepage failure, a horizontal perforated toe pipe drain was placed from the wall to wall area of the flume. All embankments were constructed with a uniform toe-to-toe distance of 3.5 m and identical upstream and downstream slopes of 1.7H:1V. Consequently, lower embankments resulted in wider crest widths. This study provides limited details on the inflow discharge into the flume. The authors mention using V-notches 0.025 m deep and 0.035 m wide to channel the overflow, which seems to have been kept at a constant elevation matching that of the crest. In certain tests, it was necessary to increase the inflow by 0.25 L/s to offset infiltration losses.

This study noted that sediment deposition creates an “alluvial fan” on the downstream face of the embankment, advancing towards the toe. This occurs as a result of the initial overflowing water being lost through infiltration. Alternating steep and gentle slopes create migrating steps that eventually form a broad sediment berm. The step starting from the crest is referred to as a “headcut”. Slumping from nearly vertical breach sidewalls interrupts these steps. As erosion reaches the upstream slope, the breach crest moves upstream and downwards, quickly releasing stored water. The breach crest evolving along the upstream slope takes on an arcuate shape.

The authors note that the “headcut” slope in their experiments, around 33.5° in the horizontal direction, matched the static friction angle and closely resembled the original 30° slope of the embankment, suggesting that erosion maintains the initial slope. Is the “headcut” slope shaped by the original embankment slope or the characteristics of the sand? The authors suggest that with noncohesive sand, the erosion slope aligns with the static friction angle. They propose that increasing flow shear stresses enhance erosion rates, steepening the slope up to the friction limit. Exceeding this steepness triggers mass failures, adjusting the slope back towards the friction angle. Higher outflows prevent achieving such steep slopes, although a plunge pool could potentially maintain or increase this steepness.

This paper discusses the notable link between breach peak outflow and initial reservoir level (reservoir depth which depends on the embankment height), aligning with other research showing that higher reservoir levels lead to increased peak outflows [26]. Their results show that the breach peak outflow tends to increase with the increase in the reservoir level. This connection is intriguing because the crest of the breach, as it migrates upstream and downwards along the upstream slope contour, is not aware of the depth of the reservoir upon reaching the upstream slope. They argue that if the flow depths at the crest are small compared to the reservoir, then the local shear stresses should not be influenced by it (depth of the reservoir). However, this assumption holds only if the water volume above the breach is consistent across tests. Their experimental setup, with embankments built to the same locations, suggests that higher embankments, having their crests more downstream, also have more water volume above the breach, affecting outflow.

Given these observations, the authors suggest that erosion at the breach crest may not directly relate to local shear stresses, proposing instead that erosion rates are limited by the maintenance of the “headcut” at the static friction angle. This argument implies that the

rate of vertical erosion of the breach crest along the upstream slope contour depends on various factors including reservoir level, breach crest and toe elevations, soil friction angle, and time. They believe that these geometric factors scale with the initial elevation of the reservoir, leading to a higher peak outflow with increased reservoir levels.

6.3. Rahman and Colleagues (2019) [28]

In 2019, Rahman and colleagues investigate how the downstream slope angle of noncohesive soil embankments affects the breaching process and the resulting outflow hydrograph [28]. To investigate this, the authors conducted experimental tests on physical models with varying downstream slopes ranging from 2H:1V to 4H:1V under two different overtopping head conditions (0.05 m and 0.10 m) while recording pore water pressures (PWP) during these experiments. The experimental setup included six physical models, each 0.3 m in height with a crest width of 0.10 m, as well as the use of poorly graded sand (SP) with a median particle size (D_{50}) of 0.5 mm without specific information on the content of fines.

The evolution of the breach profile indicated patterns of surface erosion, with the upper section of the breach progressing backwards parallelly as originally constructed, which can be deduced from assessing the breach profiles presented by the authors (downstream slope of 3H:1V). At the toe, the breach tended to become flattened due to soil deposition, so the breach tended to evolve with a concave shape.

The findings of this study, depicted in the hydrographs for different embankment configurations, show that, with a high initial overtopping head (0.10 m), steeper slopes experience faster erosion due to increased flow acceleration and shear stress, as well as higher breach outflow discharges. In contrast, with a lower initial overtopping head (0.05 m), the slope primarily affects erosion duration rather than affecting the peak flow rate, without a specific trend though. This indicates that while steep slopes amplify erosion under high overtopping conditions, their influence is less pronounced under lower overtopping heads, mainly affecting erosion timing.

6.4. Zhu and Colleagues (2021) [26]

Zhu and colleagues' investigation, conducted in 2021, delved into how the slope of the flume, embankment height, and downstream slope steepness influence the longitudinal breach profile evolution of overflowed landslide dams. For this purpose, they tested 0.15 m to 0.3 m high embankments constructed from poorly graded sand with 35% gravel-size particles ($C_u = 23$ and $C_c = 0.7$) with 6% fines, of which 2% were clays [26]. The inflow discharge to the flume was set to 1.5 L/s.

The authors identified four distinct stages of erosion: initiation, head cutting (backward erosion), acceleration, and riverbed rebalancing. During the initiation stage, low transport capacity led to soil deposition along the middle and lower slope. Head cutting progresses until it reaches the upstream slope, with little change in embankment height. Our understanding from the authors' description is that the authors see head cutting as a macro erosion process in which there backward erosion without downward erosion of the crest invert, without taking into account the value of the breach longitudinal slope. The acceleration stage is initiated when erosion reaches the upstream slope, leading to the release of the reservoir stored volumes. During this stage, the breach invert holding flow control cuts down rapidly along the upstream slope. The final stage, riverbed rebalancing, indicates that the breaching process has ended.

They found a critical embankment height which separates cases in which the eroded soil becomes deposited on the downstream slope from those which do not. Heights over

0.15 m lead to soil deposition and lower embankments result in reduced peak discharges, which are reached sooner.

The flume bed slope impacts the steepness of the longitudinal profile of the breach during backward erosion, with gentler slopes leading to steeper breach profiles. Flume slopes of 7° and 8° produced breach slopes exceeding 60° , steeper than those from flume slopes of 9° to 13° . Gentle flume slopes resulted in scour holes and vortex flow at the breach toe, explaining the steep breach profiles observed. Conversely, steeper flumes increased erosion capacity, moving scour holes downstream and reducing peak outflow discharges.

The downstream slope affects the erosion stages, with gentler slopes adding two extra headcut and acceleration phases. Steeper downstream slopes lead to earlier peak discharges given the higher flow shear stresses and faster erosion. The peak decreases as the slope steepens as a result of the smaller reservoir.

The combined effect of flume bed and downstream slope angles determines erosion patterns, with two critical angles identified that dictate erosion behavior across different slope conditions. The study summarizes the breaching process into four modes based on embankment height and downstream slope. Mode 1 applies when the embankment height is below the critical level, leading to a constant backward erosion profile. Modes 2, 3, and 4 occur for embankments higher than the critical height, with each mode corresponding to different slope conditions and resulting in distinct erosion and breach development patterns, from faster backward erosion on the upper half of gentle slopes to maintaining a nearly constant and slightly flattened slope profile on steep slopes.

6.5. Schmitz and Colleagues (2021) [31]

In their research, conducted in 2021, Schmitz and colleagues examined how embankment geometry affects the breaching of noncohesive homogeneous canal embankments, through systematic variations in upstream and downstream slopes, crest width, and inflow discharges [31]. Utilizing uniform sand with a median size (D50) of 1 mm for embankment sections 0.3 m high, the study aligns with Rifai and colleagues [39] in that it divided breach evolution into three stages: a gradual onset of overtopping at the initial notch leading to the slow start of dike erosion (Stage 0), followed by rapid erosion that significantly increases breach size (width and depth) and discharge (Stage 1), and culminating in a quasi-stabilization phase with reduced flow depth in the main channel and generally slow, continued breach expansion downstream (Stage 2). This investigation specifically omitted Stage 0, as it is primarily influenced by the characteristics of the initial notch and the method used to fill the canal. The authors used the concept of dike strongness (μ) as a metric to assess embankment resilience, with low μ values indicating weak embankments and high μ values denoting strong embankments.

The authors identified three patterns in breach outflow hydrographs: (i) those peaking at an absolute maximum, (ii) those reaching a relative maximum, and (iii) those showing a continuous increase. They noted that weaker embankments, indicated by lower μ values, exhibited more pronounced peak outflows. Strong embankments with $\mu \geq 1$, or under the highest inflow tested (55 L/s in the canal), did not display a maximum peak outflow. This suggests that strong embankments experience slower outflow increases, potentially due to slower breach widening, a trend also noted during their experiments. During Stage 1 of breaching, the upstream embankment slope seemed to minimally impact breach development, a finding attributed to the limited range of slope values tested (1.5 to 2.0). In the final stage, Stage 2, embankment geometry had less of an effect on breach evolution than in Stage 1, except for the upstream slope value, which significantly influenced breach widening. The authors argue that this impact stemmed from gentler slopes reducing the main canal reservoir volume, consequently affecting flow velocity and the Froude number.

6.6. Islam and Tsujimoto (2015) [89]

In 2015, Islam and Tsujimoto investigated the failure of riverine levees, focusing on the effect of different relative heights between the canal bed and the floodplain elevation and different soil materials [89]. The experiments used embankments constructed from coarse and fine sands, each 0.15 m in height with 2:1 slopes on both upstream and downstream sides. The inflow discharge in the canal was kept nearly constant across tests (31 to 32 m³/h), leading to varying overflow depths given the varying depth of the canal. Therefore, in fact, the authors varied two variables, the overflow depth and the difference in elevation between the canal bed and the floodplain.

The authors observed that the shallower the canal, and, therefore, the higher the difference in elevation between the canal bed and the floodplain, the faster the breach erosion, both vertically and laterally. To this observation, it must be added that the higher overflow depth observed in the shallower canals (the same constant inflow was used throughout the tests) may also have contributed to the faster erosion of the embankment.

Concerning the effect of the soil material, the coarser sand seemed to result in the smoother deepening and widening of the breach. The fine sand resulted in irregular breach deepening, probably due to mass failures of the side.

6.7. Summary

In summary, the main conclusions drawn from the research studies reviewed in this section are as follows:

- The overall shape of the outflow hydrograph and the peak discharge rates remain relatively unaffected across different breach initial conditions [73].
- A notable link between the depth of the reservoir and breach dynamics was identified, with deeper reservoirs leading to increasing peak outflow discharges [25], which is intriguing because outflow discharges are mainly a function of the breach dimensions, the head and the volume of water above the notch invert. This methodological approach may have led this volume to be different across different embankment heights, which could explain the trend observed.
- The downstream slope of the embankments was identified as a factor impacting breach dynamics as steep slopes tend to amplify erosion [26,28].
- The height of the embankment was observed to define whether the eroded soil becomes deposited or not at the toe of the embankments [26].
- The flume bed slope impacts the steepness of the longitudinal profile of the breach during backward erosion, with gentler slopes leading to steeper breach profiles [26].
- The type of infrastructure influences breach shape: canal embankments, where flow runs parallel to the canal, tend to develop asymmetrical breaches [82,89], while dam breaches are generally symmetrical.
- Embankment geometry, defined by combinations of upstream/downstream slopes, and crest width can influence embankment resilience [31].

7. Numerical Modeling

7.1. Kakinuma and Shimizu (2014) [72]

In 2014, Kakinuma and Shimizu performed numerical modeling to replicate one of their experimental tests, described previously [72], on 3 m high canal embankments. In their study, the researchers employed the Nays 2D numerical model, which is based on shallow-water flow and bed load transport, to simulate the breaching process of an embankment containing 20% fines. They justified the use of this model by arguing that the material, predominantly consisting of sand (42%) and gravel (38%), leads to the neglect of

suspended load due to its sandy nature. However, the significant content of fine particles makes this assumption debatable.

The model runs were unable to replicate the initial stage of breaching, leading to comparisons between numerical and physical results from Stage 2 onwards—when widening of the breach began. The Nays 2D model does not incorporate a mechanism for lateral erosion, nor does the input parameter for the repose angle reflect the observed mechanisms accurately. Consequently, the authors suggest that enhancements are needed in the model's ability to simulate lateral erosion processes. In response to these limitations, they modified the morphodynamic formulas of Nays 2D by integrating empirical formulations derived from their experimental findings instead of using standard sediment transport and slope stability models.

The numerical modeling primarily addressed the widening stage of breaching, though the authors acknowledge the necessity of accurately simulating the earlier stages of the process. They suggest that dam breach models, which account for the interaction between flow and sediment, much like what occurs during early breaching stages, might be appropriate.

7.2. *Lorenzo and Macchione (2014) [134]*

The objective of the study performed by de Lorenzo and Macchione, which was presented in 2014, was to calibrate new empirical formulations for calculating breach peak outflow discharges, considering factors like dam erosion susceptibility, reservoir shape, and reservoir filling ratio. Using regression analysis with data from a physically based numerical model [134], the authors differentiated between overtopping and piping failures.

Their new equations, tested against 14 historical dam failures, showed better accuracy compared to existing models like the Froehlich, MacDonald and Langridge–Monopolis, Evans, and Costa equations. The $\log_{10}(Q_{\text{calc}}/Q)$ error rates from Macchione's model and the newly derived equations were notably lower, at 0.067 and 0.084, respectively, than those from other referenced equations, which ranged from 0.138 to 0.375. Additionally, a sensitivity analysis of the numerical model indicated minimal impacts from the crest width but significant effects from the slopes of the dam on the peak outflow. The proposed formulas are most applicable when inflow to the reservoir is negligible compared to the breach outflow.

7.3. *Tabrizi (2016) [82]*

Tabrizi's Ph.D. thesis from 2016 details a range of numerical modeling runs using the iRIC-Nays2D software, developed by the Foundation of Hokkaido River Disaster Prevention Research Center, utilized to analyze the impact of various model parameters on the prediction of breaching processes, focusing on turbulence models, finite-difference approximations of the advection term, sediment transport types, and bedload transport formulas [82].

It was found that the bedload transport formula significantly influenced breach prediction accuracy. Experimental tests conducted with 0.55 mm uniform sand helped validate the numerical simulations. Calibration runs adjusted basic variables like Manning's roughness coefficient and soil void ratio, based on comparing simulated and observed breach profiles and outflow hydrographs.

The effect of suspended load was assessed by comparing simulations with only bedload to those including both bedload and suspended load, under identical simulation conditions. No notable differences were found, aligning closely with experimental observations, which suggested that the suspended load contribution was minimal due to the larger grain size. However, Tabrizi conducted further simulations with smaller grain sizes (0.2 and 0.125 mm) and observed that the significance of considering suspended load

increases as grain size decreases. Simulations including both loads indicated increased erosion, highlighting the greater erosivity of the overflow with the inclusion of suspended load, particularly as finer particles with slower settling velocities tended to enhance the suspended load's impact.

7.4. Wu and Colleagues (2018) [102]

In 2018, Wu and colleagues published the results of an experimental study which examined the overtopping breaching process of canal embankments, using a nonconventional curved flume that was U-bend-shaped [102]. The materials tested included fine and coarse sands (both poorly graded and without fines smaller than 0.063 mm) and a silt loam consisting of approximately 80% fines, with 20% being clay. The median sizes (D50) for the coarse sand, fine sand, and silt loam were 0.6 mm, 0.4 mm, and 0.03 mm, respectively. The sands had no cohesion and a friction angle of about 32°, while the silt loam had a cohesion of 21 kPa and an internal friction angle of 26°.

Regardless of the soil type, the breaching process was categorized by the authors into four stages: slope erosion, longitudinal headward gully cutting, lateral erosion, and relative stabilization. Unlike typical observations of sand embankments erosion starting at the crest, this study observed initial erosion at the toe, suggesting a possible seepage-induced failure due to the absence of an impervious element on the upstream slope.

For cohesive embankments, initial toe erosion creates scour holes, evolving into a stepped profile and eventually a near-vertical headcut, influenced by soil cohesion. Numerical modeling using the 3D k-epsilon turbulence model estimated flow shear stresses across all breaching stages, identifying maximum stresses at the breach toe in the initial stages, which decreased while migrating upstream as the breach widens. These observations are in line with previous studies [64].

Critical shear stresses for noncohesive soils were determined using the Shields curve based on D50 sizes, while a different approach, based on Brooks' work [159], assessed critical shear stresses for the breach side walls, accounting for slope angles and flow direction relative to each wall. The authors identified a nonlinear relationship (power function) between erosion rates and excess shear stresses. For noncohesive embankments, coarser sands tend to accelerate the breaching process initially but depress the process at the end. This observation aligns with previous works [88,103].

The inertia of the flow in the canal led to more severe erosion on the downstream side of the breach in both cohesive and non-cohesive embankments, obtaining non-symmetrical coefficients (the ratio of the downstream side width to the upstream side of the breach) of about 2.2–2.6 for non-cohesive levees and 2.7–3.3 for cohesive levees. These observations show that the breach tends to be more asymmetrical in the cohesive embankments.

7.5. Zhong and Colleagues (2019) [18]

In 2019, Zhong and colleagues published a comprehensive study on the breach mechanisms of cohesive dams resulting from overtopping [18]. The research conducted at Nanjing Hydraulic Research Institute (China) included detailed large-scale field tests of cohesive embankment dams, the height of which was not detailed. The dams tested had a crest width of 3 m and a length of 120 m, featuring 2H:1V and 2.5H:1V upstream and downstream slopes, respectively. To simulate overtopping events, a rectangular flow conveyance notch was cut into each test dam. The notch was 1.3 m deep and 1.5 m wide. This empirical data supported the development of a physically based numerical model aiming to enhance breach predictions. They conducted tests on soils with fine contents ranging from 80% to 95%, of which the content of particles finer than 0.005 mm ranged from 7 to 33%, exhibiting increasing cohesion levels from 6.5 kPa to 40 kPa.

The breach process was categorized into four distinct stages to provide a structured approach for future numerical modeling efforts. Initiation of breach erosion occurs as water flows through and erodes the dam crest and downstream slope, gradually steepening the breach channel towards a 90° angle, significantly altering the downstream slope profile (Stage I). The steepened downstream slope maintains a vertical 90° angle, functioning similarly to a headcut during backward erosion. This stage concludes when the dam crest is fully eroded, creating a transition in the erosion mechanism from headcut to surface erosion (Stage II). Erosion continues both vertically and laterally, with the stability of the breach side slopes at the dam crest and downstream slope varying based on the soil properties of the dam fill, affecting the breach side-slope angles (Stage III). The final stage of breach erosion mimics the characteristics of Stage III where erosion ceases when the flow shear stress within the breach falls below the critical shear stress of the soil, stabilizing the breach (Stage III). These stages, while generalized, accommodate exceptions based on specific conditions inherent in such dynamic geological processes.

This empirical data supported the development of a physically based numerical model aiming to enhance breach predictions. The model integrates various factors like dam configuration, soil properties, dimensions of the initial breach, and inflow conditions to simulate the overtopping-induced breach process. It specifically addresses the critical phases of erosion and mass failure, providing a step-by-step breakdown of the breach mechanics and the associated erosion parameters. It uses state-of-the-art equations for the breach flow discharges, soil erodibility, the location of the initial scour hole and headcut migration, proposing that the cohesiveness of the soil influences the breach's shape. Soils with low cohesiveness lead to a trapezoidal evolution of the breach, while highly cohesive soils result in a breach that develops a rectangular shape.

Comparative analysis with other established models (like WinDAM B and NWS BREACH) showed that the newly proposed model offers superior performance in breach prediction accuracy. Soil erodibility was identified as a critical parameter influencing dam breaching processes, so they performed a sensitivity analysis, each model representing soil erodibility differently: NWS BREACH uses the sediment transport rate as defined by Freda in 1988, while WinDAM B and the new model utilize the erodibility coefficient (k_d). The analysis involved recalculating results by adjusting the erodibility values to 0.5 and 2.0 times the original. The findings indicate that peak discharge sensitivity to soil erodibility is higher in the new model and WinDAM B compared to NWS BREACH. Moreover, the new model shows greater sensitivity to changes in erodibility in terms of final average breach width. While all three models are sensitive to soil erodibility in terms of time to peak discharge, the data does not conclusively determine which model is most sensitive.

7.6. Rifai and Colleagues (2019) [39]

The study performed by Rifai and colleagues in 2019, already described in previous sections, also conducted numerical modeling of the breaching process of canal embankments with TELEMAC-2D [39], accurately capturing the breach outflow and water level dynamics in the canal, especially during the deepening and widening stage and the onset of the widening stage. The coupled hydro-morphodynamic model TELEMAC-2D/SISYHE effectively replicated the eroded surface of the breach in the initial stages, identifying that inflow discharge significantly impacts breach expansion, with higher discharges leading to increased erosion rates and more pronounced downstream (canal direction) widening of the breach, driven by greater flow momentum in the canal. Floodplain confinement, defined as the water level downstream of the embankment, moderates the energy gradient of the outflow through the breach, resulting in shallower breaches.

7.7. Summary

In summary, the main conclusions drawn from the research studies reviewed in this section are as follows:

- A parametric analysis performed with iRIC-Nays2D software found that the bedload transport formula significantly influenced breach prediction accuracy and highlighted the greater erosivity of the overflow with the inclusion of suspended load [82].

8. Discussion

8.1. Macro Erosion Processes

One of the main objectives of this review was to explore the factors influencing breach dynamics and patterns. As previously noted, headcut and surface erosion are typically associated with cohesive and noncohesive soils, respectively—headcut characterized by near-vertical faces retreating upstream through block failures, and surface erosion by gradual upstream progression of sloped breaches through the detachment of individual soil particles. However, this review has shown that when embankments are built with heterogeneous soils, breach dynamics become more complex, and both mechanisms often occur in combination rather than in isolation. The following paragraphs summarize and discuss these processes.

Experimental research has demonstrated that both soil gradation and particle size influence both the breach slope and erosion process [88,92]. Uniform sands tended to produce milder breach slopes while less uniform sands were associated with steeper breach slopes [92]. Regarding particle size, experiments using fine uniform sands resulted in breach slope angles steeper than the material friction angle while coarser sands—ranging from fine to medium size uniform sands—presented gentler slopes [88]. These observations suggest that there may not be a direct relationship between breach profile slope and intrinsic soil strength parameters, as the coarser the soil, the higher the friction angles, but rather with negative pore pressures (suction forces) affecting apparent cohesion. Some studies suggest, however, that the breach slope in uniform fine sand embankments is limited by the static friction [25].

As a remark, it must be noted that the depth of the breach in small-scale experiments can influence our perception of the macro erosion processes that drive embankment breaching. Experiments have shown that the breach depth depends on the soil gradation [92], with uniform medium sand embankments showing erosion to pivot near the original toe of the downstream slope, with eroded materials accumulating at the toe. Other experiments have reported the same erosion pattern [19]. Conversely, less uniform sands with higher contents of medium sand tended to see eroded materials washed away to the base of the flume, resulting in breach slopes that migrated back parallel to the original slope of the embankment, accompanied by an upstream migration of the breach toe. It is important to note that these specific observations are tied to particular hydraulic loading conditions, meaning that changes in overflow rates could significantly alter these findings. Therefore, for specific hydraulic loading conditions, differences in the breaching process are observed when transitioning from finer to coarser poorly graded sands, typically attributing the behavior of finer materials to capillary rise and apparent cohesion, and that of larger particles to flow shear stresses.

Macro erosion patterns shift when fines are present, even if they are noncohesive, such as silts. Experiments have shown that embankments constructed from noncohesive clayless silty sands with a content of fines close to its lower bound, which is set at 12%, present the formation of a near-vertical headcut face [74]. In contrast to typical headcut erosion processes where erosion often begins near the downstream toe where flow shear stresses are highest or along the slope where a flaw initiates a scour hole, in noncohesive

heterogeneous soils, erosion is noted on the upper half of the embankment at the transition between the crest and the downstream slope of the dam [81], progressively steepening and forming a steep headcut face [73]. Another major difference involves headcut migration, which in silty sand embankments is driven by the detachment of individual soil particles. These same processes are observed even in soils with slightly higher fine contents around 17%, and clay contents below 6% [71,82].

Increasing the content of fines so that it is close to the upper bound of coarse-grained soils (<50%) and increasing the clay portion to roughly 5% lead to more typical headcut erosion processes involving the formation of gullies and rills that evolve into small headcuts which later converge into a single large headcut face [16].

Initial moisture does not change the fundamental characteristics of the macro erosion processes on sandy gravel embankments, but nonetheless, it tends to influence the slope of the breach longitudinal profile. A study showed that the longitudinal breach profile tends to become steeper as initial moisture decreases [40], suggesting that apparent cohesion resulting from suction forces within the soil may control the breach slope. These observations contrast those of a different study which showed that dryer soils correlate with smoother breach profiles never exceeding the internal friction angle of the soil [67].

As for initial moisture, hydraulic loading has been shown to affect the longitudinal slope of the breach, with steepness increasing with increasing overflow discharges. These observations were obtained for embankments constructed from well-graded gravel with 12% fines, the slopes of which were not as pronounced as those in cohesive embankments [42]. These insights suggest a complex interaction between hydraulic conditions, soil properties, and erosion mechanisms, which collectively influence embankment erosion.

Concerning breach side slopes, experimental research has shown near-vertical breach side walls even in sand embankments, sometimes inversely steepened by erosion at the base, challenging common assumptions about noncohesive materials and suggesting that numerical models using soil friction angles might inaccurately predict breach wall stability [16,88]. The compaction degree and dry unit weight are nonetheless important factors acting in favor of the stability of the breach side-walls, as experimental research has found that higher unit weights tend to lead to fewer side-slope collapses and are associated with longer breach outflow hydrographs and lower peaks [70,82], suggesting a decrease in soil erodibility. Compaction seems to not affect the macro erosion processes but does seem to influence the final breach crest elevation, which tends to be higher with increasing compaction efforts [82]. Experiments on the effect of the soil state have shown that nearly fully saturated soils result in more frequent side-slope failures, often manifesting as slides rather than slumps [70].

Numerical modeling of different saturation states within an uniform sand embankment has revealed the minimal role of suction forces in enhancing the shear strength's absolute value, suggesting that increased stability of the breach side walls is attributed to the reduced material density in semi-saturated states [70]. While the absolute shear strength increase may be small when comparing fully and partly saturated states, it is significant in relative terms, consistent with geotechnical laboratory experiments which have shown that increasing matric suction enhances shear strength [155,157], with some studies reporting that unconfined compressive strength increased by 64% as matric suction varied from 0 kPa to 40 kPa and by 150% as matric suction varied from 0 kPa to 200 kPa. In the same vein, the initial moisture content was also identified as another factor influencing apparent cohesion, with a new set of geotechnical laboratory tests denoting an average 89% decrease in apparent cohesion as water content increased from 0% to 30% in heterogeneous coarse-grained soils [156].

8.2. Erosion Rates

Surface erosion and headcut migration rates are influenced by soil properties as well as by hydraulic loading. For instance, the presence of fines, even noncohesive fines such as silt, significantly reduce both soil and embankment erodibility [16,148]; however, significant effects on erosion rates are observed only when the fine content exceeds 5% [150]. Clay content is more effective than silt in reducing soil erodibility and slow down headcut migration [71,82], yet the interplay between clay content and soil strength is intricate and varies based on other factors. Interestingly, experiments have shown that when comparing two soil samples with identical silt content, one containing 5% clay and the other containing none, soil strength and cohesion have a more significant impact on erodibility than clay content alone, as soils without clay can exhibit greater cohesion and lower erodibility compared to those containing clay [16]. Several other studies indicate that increasing cohesion correlates with slower rates of headcut erosion and breach widening, hence affecting breach dynamics [9,72,74,150]. The presence of fines and clay not only reduces soil erodibility but also increases the critical shear stresses of the soil, requiring embankments higher overflow rates for erosion to progress [150].

Besides the presence of fines and cohesiveness, there are other factors affecting soil erodibility such as soil gradation and particle size, as well as compaction and moisture content. Increasing particle size decreases the erosion rates [149] and increases the critical shear stresses of the soil [71,148], meaning that embankments made with coarser particles require higher overflow rates for breach initiation. Experimental observations have shown that coarser materials tend to breach faster with more consistent erosion rates, while finer materials display unsteady erosion and less erodibility [88,89,103]. Other contradicting findings suggest that the presence of fine sand can increase the erodibility of soil and embankments, correlating with quicker breach outflow increases and peak discharge development [92]. This last observation aligns with trends noted in more heterogeneous soil materials, which have shown that finer textures tend to enhance erodibility [149]. It seems clear that the erodibility of coarse-grained soil materials can be impacted by apparent cohesion or/and hiding–exposure effects, where larger particles shield smaller ones from erosive flows or become more exposed due to the smaller particles filling gaps. These contradictory observations highlight that evaluating soil erodibility based solely on particle size dimensions is overly simplistic. Concerning breach widening, it has been shown that the finer the sand, the larger but less frequent the side-slope collapses [39].

Compaction and its different sub-variables such as compaction moisture and energy of compaction have been found to affect soil erodibility [34,82]. In general, for cohesive sand embankments containing approximately 25% fines and 10% clay, the lower the compaction degree—and so the less dense the soil material—the more prone is an embankment to erosion, which will end in faster erosion processes and higher breach peak outflows [34]. The lowest erodibilities have been consistently correlated with the optimum moisture content regardless of the compaction energy applied, with soils compacted on the wetter range of their optimum moisture content tending to be less erodible compared to those compacted on the drier range. For a given moisture content, increased compaction effort enhances soil erosion resistance, raising critical shear stresses, but nonetheless, moisture content at compaction has been found to influence soil erodibility more than the degree of compaction [82]. For these type of materials, i.e., cohesive sands, the drier the embankment, the more susceptible it is to erosion, leading to faster erosion and more severe peak breach outflows [34].

These observations contrast those of other studies performed to understand the influence of the initial moisture content on the breaching of embankments made from sandy gravels containing 2% fines, reporting that higher initial soil moisture leads to faster and

more catastrophic failure, i.e., higher peak outflows tend to occur earlier as moisture increases. This can be explained by the fact that wet soil facilitates saturation, eliminating suction forces—and hence apparent cohesion—and facilitating particle erosion, which will end in deeper breaches [40]. This shows how cohesiveness affects soil erodibility. Low contents of fines lead to a low “gluing” effect, so particles tend to be eroded individually unaffected by cohesiveness [149]. In soil materials where fines make up 13% or more of the material, the behavior of the soil is more strongly influenced by the content of fines than by the gradation characteristics of the coarser particles, regardless of whether they are well or poorly graded [42].

Soil state, which is associated with pore water pressure, suction forces and apparent cohesion, has been identified as one important factor affecting the breaching process. Experimental results have shown that nearly fully saturated states greatly enhance soil erodibility [70]. More erodible soil in saturation conditions correlate with increased breach peak outflows and shorter hydrograph durations [68,78]. In addition to saturation conditions, initial soil moisture was also found to affect erosion rates, with dryer soils eroding more slowly [67], suggesting that capillary rising and saturation of the embankment are more difficult in dryer states.

Another factor to consider is the suspended sediment concentration, which could cap the flow shear stresses at the maximum value [158], implying that water flowing over a highly erodible coarse-grained soil embankment with a continuous inflow of sediment could alter shear stresses in unexpected ways. It is important to approach these observations with caution, as the experiments did not vary suspended sediment concentrations and flow velocities independently. This limitation complicates the ability to distinctly isolate and assess the impact of each variable on the flow shear stresses. Nonetheless, this could explain why erosion rates tend to be higher in the central area of the downstream slope in embankments constructed from non-cohesive granular soils [81], promoting erosion to form a headcut face in the upper sections of the embankments. Additionally, seepage through the downstream slope might also contribute to reducing the flow shear stresses along the slope.

Regardless of the soil material forming the embankment and its state during construction and an overflow event, the breaching processes and total duration of erosion will also depend on several other factors related to hydraulic loading and embankment geometry and dimensions, with embankments with wider crests taking longer to breach, and higher overflows increasing erosion rates and shortening the breaching time [39,72,81,89]. Higher embankments have also been correlated with higher breach peak outflows [25], which is intriguing because the crest of the breach, as it migrates upstream and downwards along the upstream slope contour, is not “aware” of the depth of the reservoir upon reaching the upstream slope. While these observations could be influenced by methodological errors, as described in the main text of this document, they might also be attributed to scale effects. The height of the embankment could determine whether sediment is deposited at the toe of the embankment, thereby limiting the depth of the breach [26]. Concerning embankment geometry, steep slopes tend to experience faster erosion due to increased flow acceleration and shear stress, as well as higher breach outflow discharges [26,28].

9. Conclusions and Research Gaps

Concerning macro erosion processes, the main and most relevant conclusions that can be drawn from this review are as follows:

- In sand embankments, the breach tends to progress as a slope. However, there is no evidence suggesting a correlation between the slope of the breach profile and the intrinsic strength parameters of the soil. On the other hand, factors such as gradation,

particle size, and initial moisture appear to influence the slope of the longitudinal profile of the breach. Studies in this area often suggest, though without concrete evidence, that these correlations are indirect, with the primary factor affecting the slope likely being negative pore pressures (suction forces) contributing to apparent cohesion.

- Macro erosion patterns shift when fines such as silts are present, even if they are noncohesive, leading the breach longitudinal profile to develop a near-vertical headcut face. Unlike typical headcut erosion processes, erosion occurs in the upper half of the embankment, at the transition between the crest and the downstream slope, progressively steepening and forming a steep headcut face. In this case, the upstream progression also differs from typical headcut erosion as it is driven by the detachment of individual soil particles and not by consecutive block failures.

In terms of erodibility/erosion rates, the main and most relevant conclusions that can be extracted from this review are as follows:

- The presence of fines, even noncohesive ones such as silt, significantly reduces both soil and embankment erodibility, though notable effects on erosion rates are observed only when the fine content exceeds 5%. While some studies suggest that clay content is more effective than silt content at reducing soil erodibility and slowing down erosion rates and headcut migration, it has been identified that soil strength and cohesion have a more substantial impact on erodibility than clay content alone. Moreover, the presence of fines and clay not only reduces soil erodibility but also increases the critical shear stresses of the soil, necessitating higher overflow rates for erosion to progress.
- Other soil parameters such as soil gradation and particle size have been studied, but contradictory observations highlight that evaluating soil erodibility and erosion rates based solely on particle size dimensions is overly simplistic.
- Compaction and its related factors, such as moisture content and compaction energy, have been found to influence soil erodibility. Increasing compaction effort or compacting soil at its optimum moisture content generally reduces erodibility. In silty sands within the wet range, compaction results in less erodible soils, whereas in sands without fines, it tends to make them more erodible.

From this state-of-the-art review, we identify several research gaps that should be tackled in the future. The identified research gaps are as follows:

- A unification of criteria is needed to facilitate the interpretation of results, requiring clear definitions of the different macro erosion processes observed in embankment dams and levees.
- Clarification of scale effects is necessary, including how laboratory scaling might distort behaviors compared to real embankment dam breaches. Experimental tests often use standard Proctor compaction, which does not accurately scale to field size, potentially replicating only the upper layers of real embankments. A consensus on scaling criteria in experimental breaching tests is lacking in the scientific community.
- Investigation into the effect of embankment height on breach development and dimensions is required, as few studies have explored this. It is worth examining whether soil deposited at the toe of the embankment hinders breach development.
- Analysis of the interaction between overflow and suspended sediment concentration is essential to determine its impact on overflow erosivity and flow shear stress distribution along the slope.
- Exploration of the interaction between overflow and seepage along the slope is needed to understand how this may affect flow shear stresses at this boundary. To date, no studies have addressed this issue.

- Accurate quantification of flow shear stresses along the downstream slope through direct measurements is urgently needed. Most experimental studies currently rely on simplified estimates, the applicability of which to the steep slopes typical of embankments and breaches remains questionable and could potentially lead to inaccuracies.
- Given the huge number of variables associated with the failure of dams and levees, many of them interdependent, future research should focus on the use of dimensional or dimensionless variables (already used in engineering or yet to be defined) to narrow down the number of variables to be studied.

All future research on dam and levee failure should aim to provide practical data that can help reduce uncertainty in predicting the consequences of such failures, critical for risk and safety management.

CFD models, based on fundamental physical laws, offer the highest theoretical precision. However, simulating real-size particles and complete grading curves remains computationally unfeasible in practice.

Physically based models are more computationally efficient but rely heavily on expert judgment to predict dominant erosion mechanisms, and headcut or surface erosion, which is especially complex for well-graded soils. Traditionally, headcut erosion is linked to cohesive soils, while surface erosion is associated with non-cohesive ones. However, this review shows that non-cohesive embankments can also develop near-vertical breach profiles. In small-scale models, this occurs through particle detachment rather than block failure, but in full-scale embankments, headcut-like erosion may still trigger block failures, something that has not been captured in laboratory tests due to scale effects on soil strength.

Moreover, physically based models require input data such as soil erodibility, typically derived from laboratory tests. While effective for cohesive soils, these tests are less suited to well-graded, non-cohesive materials.

Therefore, the research gaps identified in this review (and others yet to be addressed) should be addressed by focusing on reducing uncertainties related to well-graded soils. This would support the development of improved physically based models capable of simulating headcut-like processes in non-cohesive embankments, for example.

Author Contributions: Conceptualization: R.M.-A., R.M., M.Á.T., C.P. and J.-R.C.; writing—original draft preparation: R.M.-A.; writing—review and editing: R.M. and R.J.-R.; supervision: M.Á.T.; funding acquisition: C.P. and J.-R.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by Électricité de France (EDF) and Compagnie Nationale du Rhône (CNR), through funding provided under the OVERCOME Project, a private research within which this state-of-the-art review was carried out.

Acknowledgments: We would like to thank Mark Morris for the supervision of the OVERCOME Project and, in particular, for all the technical inputs that made this state-of-the-art review possible. We also gratefully acknowledge Kamal El Kadi Abderrezzak for his valuable guidance and support throughout the development of this work.

Conflicts of Interest: Author Christophe Picault was employed by the company Compagnie Nationale du Rhône (CNR). Author Jean-Robert Courivaud was employed by the company Electricité de France (EDF). The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. The authors declare that this study received funding from CNR and EDF. The funder was not involved in the study design, collection, analysis, interpretation of data, the writing of this article or the decision to submit it for publication.

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