Guidance to spillway failure mechanisms

FCERM Research & Development Programme

Research report

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Executive summary

The recent spillway incidents at the Oroville Dam in the USA and at the Toddbrook Reservoir brought attention to the weaknesses of historic spillway designs. They also raised awareness of the vulnerabilities of these structures to poor maintenance and repair.

Many of the physical mechanisms responsible for spillway failure have been researched in the past and are well known both in the UK and internationally. However, the recent Toddbrook Reservoir Independent Review Report (Balmforth, 2020) concluded that there is “potential for improvement” in the UK in this respect. The report recommended, among other things, that the Environment Agency should commission a “new guidance on the failure mechanisms of spillways.”

This guidance therefore aims to identify and describe systematically the various physical mechanisms that could lead to spillway failure. Where available, any supporting evidence from spillway incident case studies and other reference documents has been provided.

The spillway failure mechanisms have been categorised into 2 broad categories: stability failure mechanisms and structural failure mechanisms.

The stability failure mechanisms have been associated with failure of the spillway or elements of it to resist uplift, overturning or sliding.

The structural failure mechanisms have been mainly discussed with reference to reinforced concrete spillways. They are associated with failure of the structure to resist the internal forces and bending moments induced by external actions and self-weight.

The document also discusses the possible use of the information provided and its implications for the UK industry, while highlighting the current gaps in knowledge and making recommendations for further research.

1. Introduction

The failure mechanisms of impounding reservoir dams have been widely documented in the technical literature. A specific dam failure mechanism, which has received increased attention in recent years, is associated with the failure of the dam spillway to perform its intended flood relief function. The failures of the stepped masonry spillways at Boltby Reservoir (2005) and Ulley Reservoir (2007) led to the commissioning by the UK Environment Agency of a research project, the results and conclusions of which were summarised in a ‘Guidance for the design and maintenance of stepped spillways’ published in 2010. Two recent incidents in the USA and in the UK raised further awareness of the significance of spillway failure mechanisms and their potential consequences. In the case of Oroville Dam in USA in 2017, a spillway failure had the potential to cause the release of the very large volume of water stored behind the emergency spillway, which could have resulted in a major flooding event affecting large areas of California. The spillway failure incident at the Toddbrook Reservoir in the UK in 2019 initiated erosion of the embankment and therefore posed a serious threat to the nearby town of Whaley Bridge in Derbyshire, UK. These incidents reinforced the understanding of reservoir owners and regulatory organisations of the need for thorough assessment, surveillance and maintenance of the reservoir spillways structures as an intrinsic part of the activities involved in ensuring the reservoir safety.

In order to assist the UK industry in further improving reservoir safety practices, this document provides guidance on the potential spillway failure mechanisms based on a literature review of reports on past spillway failure incidents or defects, research publications, guidance documents, technical papers and presentations.

For this guidance, a total of 35 documented spillway case studies related to structural or stability failure mechanisms were examined along with other relevant reference documents. Literature on these was sourced from leading UK and international organisations, including:

- the Environment Agency
- British Dam Society (BDS)
- Construction Industry Research and Information Association (CIRIA)
- International Commission on Large Dams (ICOLD)
- Association of State Dam Safety Officials (ASDSO)
- United States Bureau of Reclamation (USBR)
- Federal Emergency Management Agency (FEMA)

For the purposes of this guidance, a reservoir spillway failure is defined as a situation where the spillway condition has deteriorated such that it can no longer reliably perform its intended function to “pass normal (operational) and/or flood flows in a manner that protects the structural integrity of the dam.” (USBR, 2019).

Failure mechanisms

The spillway failure mechanisms have been categorised into 2 broad categories: stability failure mechanisms and structural failure mechanisms.

The stability failure mechanisms are associated with failure of the spillway or elements of it to resist uplift, overturning or sliding. Bearing pressure failure has not been considered due to it being a rather uncommon type of failure mechanism for such structures.

The structural failure mechanisms, mainly discussed with reference to reinforced concrete spillways, are associated with failure of the structure to resist the internal forces and bending moments induced by external actions and self-weight. The effects of internal and external erosion have also been considered as factors contributing to the development of structural failure mechanisms.

For each of the above categories, any additional sub-categories have been defined based on a root-cause analysis. Therefore, the spillway failure mechanisms have been systematically described for each specific category and sub-category.

Where no case studies, illustrating particular failure mechanisms, were identified, reference has been made to any relevant publications instead.

It should be noted that a spillway failure could often be attributed to several failure mechanisms and therefore in many cases there would be a degree of uncertainty as to the actual root cause of the failure.

Failure of the spillway to allow safe passage of the reservoir outflow due to blockage at its inlet was also reported on several occasions. In some cases, this was due to mechanical or electrical failure of spillway gates to operate as intended. In other cases, spillway blockage at the inlet was caused by floating debris. Both of these failure mechanisms would restrict the spillway capacity at the inlet and can lead to failure of the dam as a result of its overtopping. However, for the purposes of this document, these particular failure modes have been excluded from the discussion due to their non-structural or stability related nature. Guidance on this subject is provided in the recently published ICOLD Bulletin 176 on ‘Blockage of reservoir outlet structures by floating debris’. Also, excluded for the same reason is the failure mode where undersized hydraulic control sections could cause overtopping of the dam.

1.1. Stability failure

2.1.1 Stability failure due to excessive uplift pressure

This failure could occur where the external hydrostatic pressure acting on the spillway structure (from groundwater or surface water, including tailwater) exceeds its own self-weight, added weight of water, any added weight of soil and friction and the weight of any rock or soil mass mobilised by anchors. This could be due to:

- inaccurate design assumptions or investigations
- increased seepage of water due to internal erosion and concentrated flow paths
- failure of the drainage system to control ground water level (inadequate design, monitoring or maintenance)
- severe pressure fluctuations within stilling basins due to turbulence in a hydraulic jump, reducing the effective added weight of water
- severe pressure fluctuations within stilling basins due to turbulence in a hydraulic jump, causing water to enter under the slabs through any underdrain outlets located in this area or through any unsealed or defective joints or cracks
- stilling basin sweep-out[1] due to insufficient tailwater depth generating very low supercritical flow depth within the stilling basin, therefore reducing the added weight of water
- stagnation pressures developing at negative offsets[2] of defective joints or cracks causing water to enter under the slabs (discussed in more detail in Appendix A)
- failure of anchors to resist uplift due to inadequate design/construction, corrosion, grout deterioration or bond strength deterioration

Notes:

1. A good description of this phenomenon occurring in a stilling basin is given by Frizell and others (2009): ‘Conventional design guidelines size the basin in order for the tailwater depths in the downstream channel to be nearly equal to the elevation of the conjugate depth of the hydraulic jump. If the tailwater is too low, sweep out occurs and excessive scouring of the downstream riverbed and basin structure are possible. If the tailwater is too high, the jump is submerged, resulting in less than expected energy dissipation and potential for adverse standing waves within or downstream of the basin.’
2. The USBR report DSO-07-07 ‘Uplift and crack flow resulting from high velocity discharges over open offset joints (2007)‘ provides insight into the behaviour of uplift pressures and joint/crack flows for a variety of joint parameters’ including negative offsets between 3mm and 12mm which have the potential to generate significant uplift pressures.

In addition, the following reasons for exceedance of the uplift pressure are typically associated with reinforced grass spillway systems:

- Out of balance pressures related both to velocity of flow and the degree of turbulence. Localised uplift forces due to increased turbulence are typically more significant at surface irregularities and where hydraulic jump occurs.

- Insufficient permeability and/or clogging of the armour layer of geotextile grass reinforcement systems or where geotextile is used as an underlayer in conjunction with concrete grass reinforcement systems. This would prevent efficient uplift pressure relief.

This failure mechanism has been discussed in the following reference documents and case studies:

US Department of the Interior Bureau of Reclamation (USBR), 2007. 'Uplift and Crack Flow Resulting from High Velocity Discharges Over Open Offset Joints'. USBR.

The report describes "recent investigations that address unknowns related to uplift pressures and resulting flows into cracks and joints caused by high velocity chute-supported flows."

It states: "The uplift force in a chute-supported flow can consist of a component due to reduced pressures on the flow surface of a slab caused by flow separation resulting in a localized pressure reduction, and the transfer of dynamic pressures to the lower side of the slab through an open crack or joint."

BOLLAERT, E.F.R., 2009. 'Dynamic Uplift of Concrete Linings: Theory and Case Studies'. USSD Annual Meeting, April 24-26, 2009. Nashville, USA.

The paper discusses the dynamic uplift on stilling basins due to severe pressure fluctuations in the context of a proposed new method for designing concrete linings of such structures. It states that:

"initial design rules concentrated on resistance to impact pressures at the slab surface and on sound drainage of static pressure underneath the slabs. The shortcomings of such a design have been experienced during the 1960s by major damage of several concrete linings. Well-known examples are Malpaso Dam (Mexico) and Karnafuli Dam (Bangladesh)."

"The damage was found to be generated by sudden uplift or detachment of the slabs from the bottom (Bowers and Tsai, 1969; Sanchez and Viscaino, 1973). This uplift occurred at discharges much lower than the design discharge and, as an example, at Karnafuli Dam it was found to be generated by severe pressure fluctuations that may enter the outlets of the drain system and the joints between the slabs."

US Department of the Interior Bureau of Reclamation (USBR) and US Army Corps of Engineers (USCE), 2019. 'Best Practice in Dam and Levee Safety Risk Analysis, Chapter F1 – Hydraulic failure of spillway chutes, Version 4.1'.

The document provides, among other things, a description of the hydraulic failure mechanism associated with stagnation pressures developing where unfavourable conditions at joints or cracks exist (refer to Figure 1).

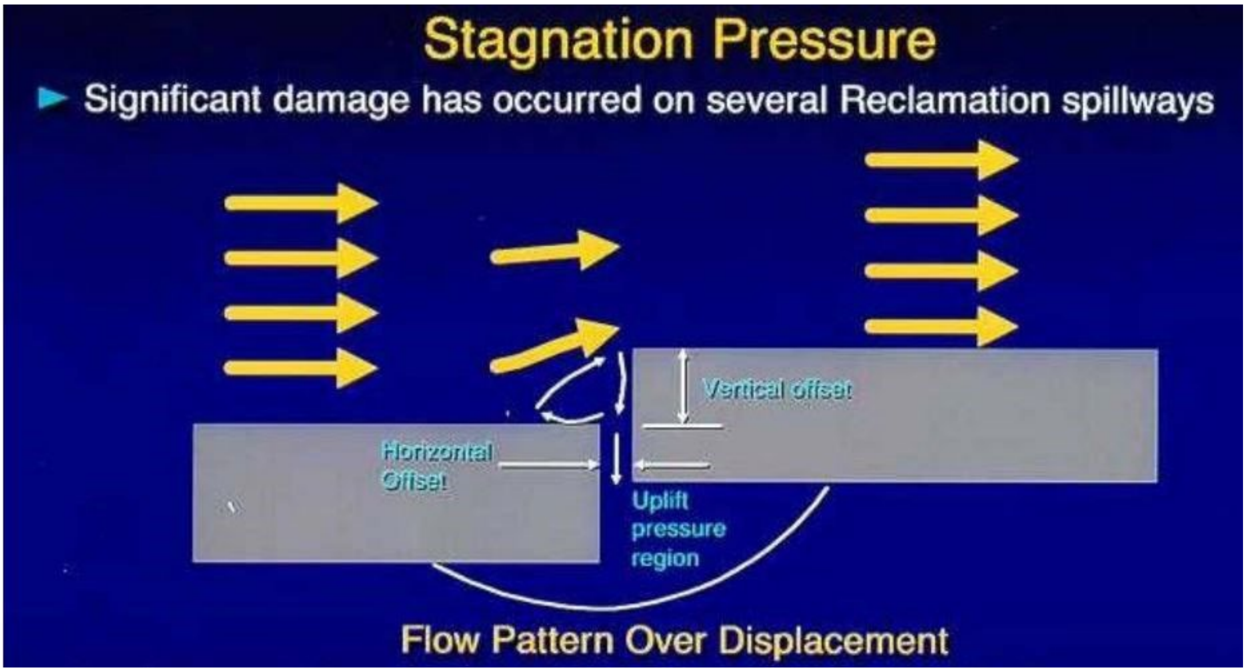


Figure 1: Stagnation pressure development (USBR & USACE, 2019)

It provides information about the spillway failure at Big Sandy Dam (1983) associated with this failure mechanism, stating:

"Cracking occurred in the chute slabs due to excessive water and ice pressures along the foundation-concrete slab interface and some of the slabs heaved and were displaced off the foundation, creating offsets into the flow. The spillway operated from 1957 to 1983 without incident, but a chute floor slab failed in June 1983, due to uplift pressures from flows of 400ft^3/s. Calculations were performed to confirm that the failure was the result of stagnation pressures being generated under the chute slab. The calculations also showed that with anchor bars fully effective, the slab would not have failed. From observations after the failure, it was observed that the anchor bars exposed beneath the slab were not coated with grout, indicating that the anchor bar capacity was not fully developed."

US Department of the Interior Bureau of Reclamation (USBR) and US Army Corps of Engineers (USCE), 2019. 'Best Practice in Dam and Levee Safety Risk Analysis, Chapter F2 – overtopping of walls and stilling basin failure, Version 4.1'.

The document provides information, among other things, about the failure mechanism associated with stilling basin sweepout.

Stilling basin sweepout "occurs with high tailwater surrounding the stilling basin but insufficient to force the hydraulic jump to occur within the structure. With the jump occurring downstream of the stilling basin, very shallow high-velocity flow conditions with minimal water weight are occurring within the stilling basin. This can lead to flotation of the stilling basin due to uplift pressures."

SCHWEIGER, P. AND KLINE, R. AND BURCH, S., 2019. 'You don't know what you don't know: Inspecting and Assessing Spillways for Potential Failure Modes. Sustainable and

Safe Dams Around the World'. Proceedings of the ICOLD 2019 Symposium, (ICOLD 2019), June 9-14, 2019, Ottawa, Canada.

The paper provides an event tree and sequence of events for stagnation pressures developing at unfavourably oriented vertical offsets at joints and cracks leading to lifting of the spillway slabs. The authors show an example figure of a deteriorated transverse joint and state that "similar concrete deterioration is what likely initiated the failure of the Oroville spillway chute." (refer to Figure 2).

Figure 2: Transverse joint damage (Schweiger and others, 2019).

The authors also address the issue of drain outlets and state that:

"a concern with the underdrain system for some spillways is that the drain outlets that are intended to discharge under seepage can also act as inlets for spillway flows to enter the underdrain system and overwhelm the capacity of the drainpipes, resulting in excessive uplift pressures under the spillway slabs. Stagnation pressures or excessive negative pressures can also develop from high-velocity flows over the drain outlets. The flow into the drain outlets, especially those where the flow momentum changes abruptly at the toe of the spillway control section or at the transition to the stilling basin floor, can be a concern as hydrodynamic pressures and stagnation pressures can develop at these."

NAUDASHER, E., 1991. 'Hydrodynamic Forces: IAHR Hydraulic Structures Design Manuals 3'. Florida, USA. CRC Press.

The manual discusses, among other things, the impact of spillway drains discharging within the zone of the hydraulic jump of the stilling basin and state that:

"Such drains convey the pressure pulsations from the location of the drain outlet to the underside of the basin slabs and the chute. Although the pressure pulses may be attenuated in the drain system, even greater uplift pressures may also be generated through resonance in the system."

INTERNATIONAL COMMITTEE ON LARGE DAMS (ICOLD), 1987. Spillways for dams: State of the art (Bulletin 058). Paris France. ICOLD.

The bulletin discusses, among other things, the effects of the pressure fluctuations within stilling basins on the dynamic uplift pressures. It states that: “The uplift pressures tending to lift the slabs are caused by the intermittent conversion of kinetic energy into pressure energy through any openings there may be in the channel floor. When the pressure becomes negative at a point on the invert, one may have a short local instability if there is a steady uplift pressure at the concrete-rock contact or at any other interface within the thickness of the slab (horizontal construction joint) or foundation and this uplift is greater than the submerged weight of the overlying rock or concrete plus the water pressure at that time on that point. The total uplift force may become dangerous if there is a steady uplift pressure under large areas and negative fluctuation of sufficient amplitude appear simultaneously on sufficiently large areas of the invert. Damage to many stilling basins indicates that the probability of occurrence of this unfavourable combination is far from being negligible.”

2.1.2 Stability failure due to overturning

This failure mechanism is typically associated with masonry spillways. Unlike reinforced concrete spillways, masonry spillway walls, which often act as gravity retaining walls, normally have low capacity to resist internal tensile stresses developing as a result of the applied external or internal loading. Since this cannot be reliably quantified, it is normally conservatively disregarded for the purpose of stability analysis. Any increase in loading that could result in internal tensile stresses can therefore cause overturning of the walls. Increase in loading could be due to:

- saturation of the ground adjacent to the spillway, increasing the external hydrostatic pressure. This could be due to inadequate drainage, including as a result of blockage of the drainage system or as a result of sealing of the masonry structure joints without providing alternative drainage
- excessive surcharge load imposed by storage of construction materials or equipment moving or placed adjacent to the spillway walls
- spread of tree or other vegetation roots adjacent to the spillway walls
- excessive negative hydrodynamic pressures within the spillway, potentially combined with positive hydrodynamic pressure transferred to the back of the wall though unsealed joints
- stone dislodgement and resulting loss of structural weight and width of the walls in resisting overturning due to deterioration of the mortar, damage to the masonry blocks or hydrodynamic pressure effects
- external flow erosion and loss of spillway wall back support during high discharge flow
- frost heave occurring behind the spillway walls due to inadequate drainage provisions

This failure mechanism has been discussed in the below reference documents and case studies:

WINTER, C. AND MASON, P. AND BAKER, R. AND FERGUSON, A., 2010. Guidance for the Design and Maintenance of Stepped Masonry Spillways. Bristol, UK. Environment Agency.

The guidance document highlights, among other things, the vulnerability of masonry spillways to failure due to external flow erosion and masonry deterioration stating:

“External flow erosion is associated with rainfall runoff flowing down the area immediately behind the sidewalls, leading to the removal of soil from this location. Where the wall has been designed to assume such support, this can leave the sidewall vulnerable to collapse under high discharge flow. Another possible reason for the loss of such support soil can be overtopping of the spillway walls during spillway discharge.”

“Both the mortar and the masonry blocks are susceptible to damage. The deterioration of the mortar can be associated with both chemical and physical processes. Damage to masonry blocks can also arise from chemical attack, although it tends not to lead directly to the failure of the masonry.”

“Another factor which acts to degrade masonry is dampness. Dampness can result from poor design or maintenance, for example where the tops of walls are not adequately waterproofed or from external factors such as cracks in a spillway caused by ground movement creating a conduit for water to pass into the spillway wall. The likelihood of dampness occurring is increased in areas of high groundwater levels.”

The guidance also discusses a number of specific factors that could adversely affect the spillway wall stability, including frost heave and tree and vegetation growth. It states:

“Frost damage occurs when masonry materials are wet or damp. As the external faces of a spillway are in contact with soil, it is likely that they will remain relatively damp for an appreciable proportion of the year. As a result, in areas prone to frosts, this is likely to lead, over time, to the degradation of one or more aspects of the masonry. It is quite common to see the top 450mm of masonry wall displaced inwards due to frost heave behind the wall, or the coping pushed inwards.”

The document also discusses the distribution of the dynamic pressures acting on the inverts and walls of stepped spillways (refer to Figure 3):

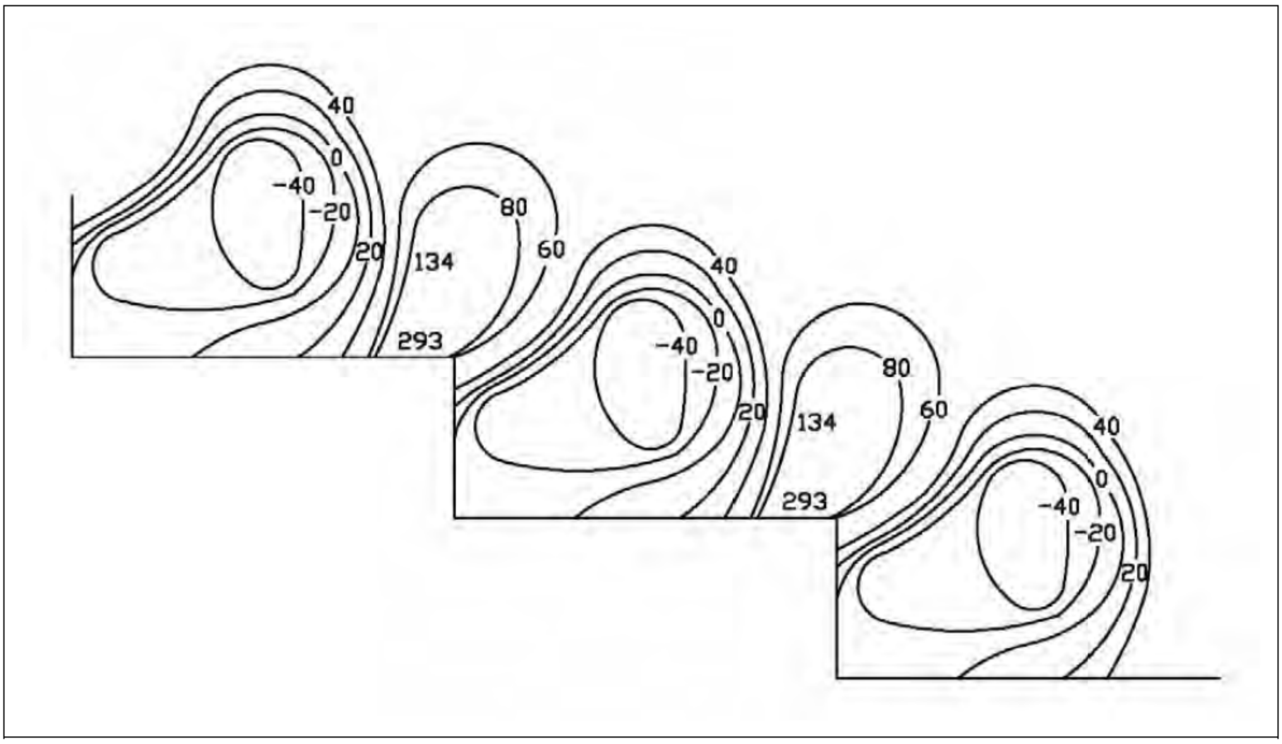


Figure 3: Mean pressure [kPa] contour plot for flow over a set of steps (Winter and others, 2010)

The document concludes that:

“if high pressures are injected into open textured masonry in high pressure zones, such that they create a back pressure behind the masonry elements in low pressures zones, then the elements in the low-pressure zones can be subject to removal. Moreover, testing has shown that there can be considerable turbulence and pressure fluctuations during such flows, with the pressure differentials between transitory maximum and minimum pressures often being considerably higher than between associated mean pressures. Such potential pressure differentials on typical UK spillways can reach 5-10 m of water head.”

MASON, P., 2015. ‘Hydrodynamic Forces and Repairs to Stepped Masonry Spillways’. International Journal of Hydropower and Dams, 22 (6), 74-78.

The paper gives background to the hydrodynamic forces and other factors involved in the deterioration and potential failure of stepped spillways. It concludes that the failures of the Boltby dam spillway (2005) and the Ulley dam spillway (2007) in the UK were due to “vortex forces that had acted on the side walls of the spillways, causing individual masonry elements to be plucked out in a way which eventually led to the complete collapse of the walls.”

The paper briefly discussed the main results from the research on the ‘wall pressures which develop on the wall regions of stepped chutes’ and states:

"Cleary, if high pressures are injected into open textured masonry in high pressure zones, such that they create a back pressure behind the masonry elements in immediately adjacent low pressure zones, then the force combination this produces will tend to remove any loose masonry elements from the wall."

2.1.3 Stability failure due to sliding

This failure would typically occur in transverse or longitudinal direction of the spillway structure. However, the critical plane of weakness may also have a different direction depending on the site conditions.

Failure due to sliding occurs where the shear strength at the spillway foundation is insufficient to resist the sliding forces acting on the structure. This failure mechanism is characterised by a relatively high degree of uncertainty relating to the estimation of the geotechnical parameters governing the resistance to sliding.

Stepped masonry spillways have intrinsically higher resistance to sliding due to their greater weight and a stepped formation profile which can mobilise the shear strength of the underlying soil/rock material.

Possible reasons for insufficient shear strength at the spillway foundation that could lead to failure of reinforced concrete spillways due to sliding include:

- no consideration given to the shear strength reduction due to soil saturation and flow-induced vibrations transferred to the foundation
- too shallow foundation/shear keys, failing to mobilise sufficient earth pressure at rest resistance to prevent sliding. This could result in the development of a new slightly deeper plane of weakness, presenting a similar shear strength
- use of polythene sheeting to control concrete cracking due to thermal effects and shrinkage would reduce the friction at the spillway base and could create a plane of weakness
- reduction of the earth pressure at rest resistance due to erosion or temporary excavation during construction or maintenance work
- reduction of the effective weight of the structure due to increased uplift pressure (refer to section 2.1.1 for possible reasons for this happening)

Stability failure due to sliding could also occur as a result of an increase of the sliding forces acting on the structure. This could be due to:

- failure of the drainage system upstream of the foundation/shear key or behind the side walls to control ground water level (inadequate design, monitoring or maintenance). This would increase the horizontal hydrostatic pressure upstream of the foundation/shear key. In this case, the key may have a destabilising effect on the structure
- excessive surcharge load imposed by storage of construction materials or equipment moving or placed adjacent to the spillway walls

- spread of tree or other vegetation roots adjacent to the spillway walls

Reinforced grass spillways are prone to the following sliding failure mechanisms:

- shallow surface slip under the armour layer and deep rotational and translational failure within the soil mass. This could occur in relatively new systems due to insufficient grass root depth or no roots being established
- deep rotational or translational failure within the soil mass. This could be due to a high soil permeability, a prolonged overflow event and/or insufficient time for grass recovery

This failure mechanism has been discussed in the following document:

HEWLETT, H.W.M. AND BOORMAN, L.A. AND BRAMLEY, M.E., 1987. ‘Design of reinforced grass spillways’. London, UK. Construction Industry Research and Information Association (CIRIA).

With regards to the ‘shallow surface slip’ and ’deep failure within the soil mass’ failure mechanisms, the report states:

“In a situation with no grass roots in the subsoil this could be a serious problem because the stresses imposed on the waterway under flow conditions may exceed the restraining forces in the subsoil and result in a shallow-surface slip**.** The likelihood of such a slip occurring decreases with depth because subsoil at greater depths will not be affected by infiltration and the associated reduction in strength. The effect of grass roots is to reinforce and increase the shear resistance in the subsoil immediately below the armour layer where a shallow slip would be likely to occur. Measurements of shear strength have been carried out which indicate that a good root growth, where roots grow to a depth greater than 200 mm from the surface, will enhance the shear resistance and help to prevent such a slip occurring.”

“This is only likely to occur following operation of the waterway if water has entered the subsoil at a deep level and affected its strength. Failure modes may be rotational or translational (for example, wedge shaped).”

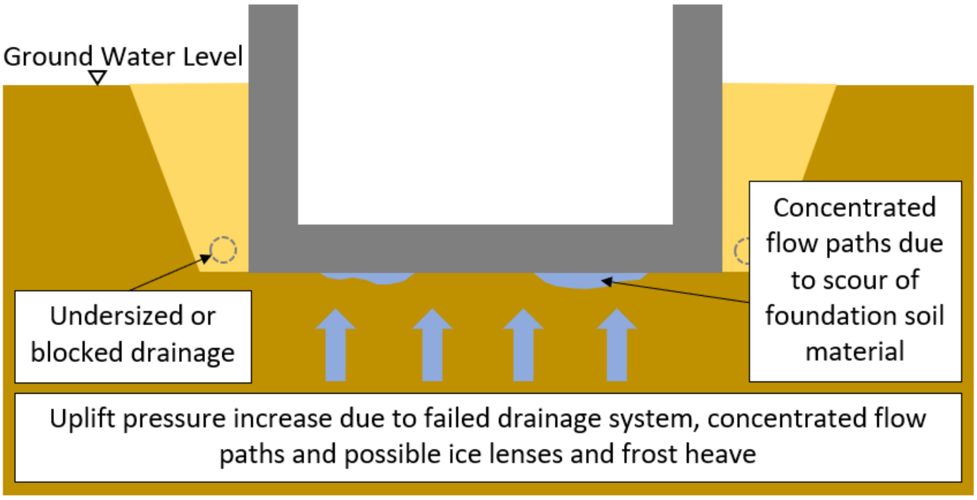
2.2. Structural failure

2.2.1 Structural failure due to excessive uplift pressure

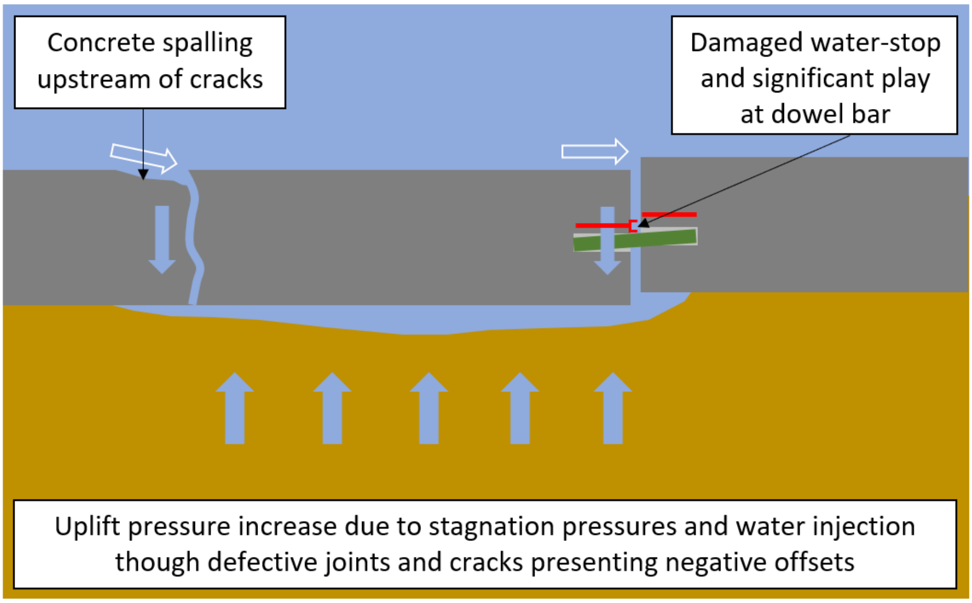
This failure mechanism occurs where the uplift pressure acting on the spillway base slab/armour layer exceeds the design pressure. While uplift stability failure may not occur in this case, due to the effects of friction or other favourable effects and/or safety factors, ultimate limit strength and/or serviceability limit strength structural failures could occur as a result of the increased bending moments (also refer to section 2.2.3). The uplift pressure could exceed the design pressure due to:

- inaccurate design assumptions or investigations. In particular, the design pressure acting on the spillway slabs could be exceeded if the bearing pressure has been considered for design purposes where resistance to uplift is achieved with the aid of side friction. In this case, the uplift pressure acting on the spillway base slab would be greater than the bearing pressure
- increased seepage of water due to internal erosion and concentrated flow paths (refer to Figure 4a)
- failure of the drainage system to control ground water level (inadequate design, monitoring or maintenance) (refer to Figure 4a)
- severe pressure fluctuations within stilling basins due to turbulence in hydraulic jump reducing the effective added weight of water and increasing the net design pressure. (refer to Figure 4b)
- severe pressure fluctuations within stilling basins due to turbulence in the hydraulic jump, causing water under pressure to enter under the slabs through any underdrain outlets located in this area or through any unsealed or defective joints or cracks. (refer to Figure 4c)
- stilling basin sweep-out due to insufficient tailwater depth generating very low supercritical flow depth within the stilling basin, therefore reducing the added weight of water (refer to Figure 4d)
- stagnation pressures developing at negative offsets of defective joints or cracks, causing water to enter under the slabs (discussed in more detail in Appendix A)
- failure of anchors to resist uplift due to inadequate design/construction, corrosion, grout deterioration or bond strength deterioration

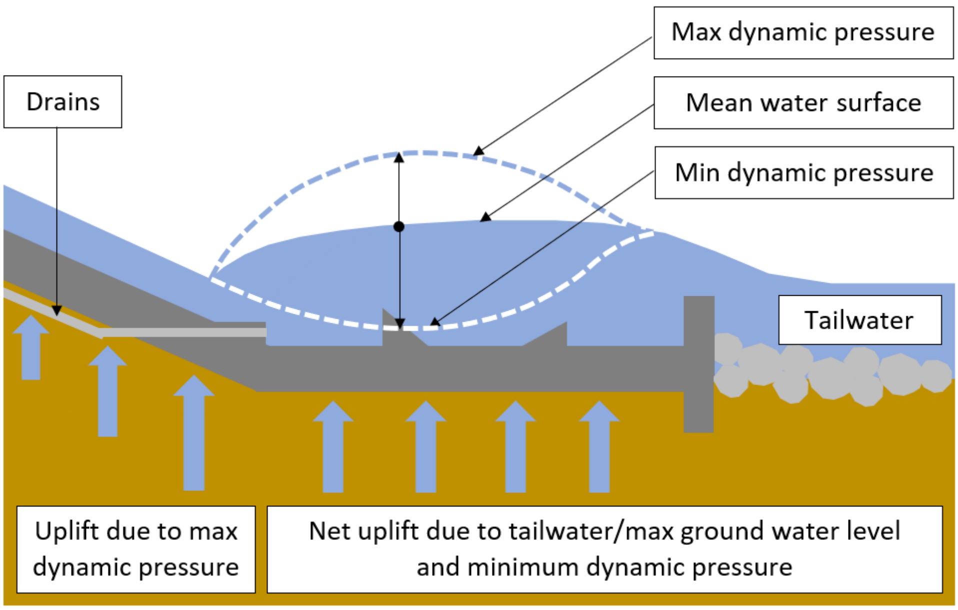
a.


Ground Water Level
Undersized or blocked drainage
Concentrated flow paths due to scour of foundation soil material
Uplift pressure increase due to failed drainage system, concentrated flow paths and possible ice lenses and frost heave

b.


Concrete spalling upstream of cracks
Damaged water-stop and significant play at dowel bar
Uplift pressure increase due to stagnation pressures and water injection though defective joints and cracks presenting negative offsets

c.


Max dynamic pressure
Mean water surface
Min dynamic pressure
Drains
Tailwater
Uplift due to max dynamic pressure
Net uplift due to tailwater/max ground water level and minimum dynamic pressure

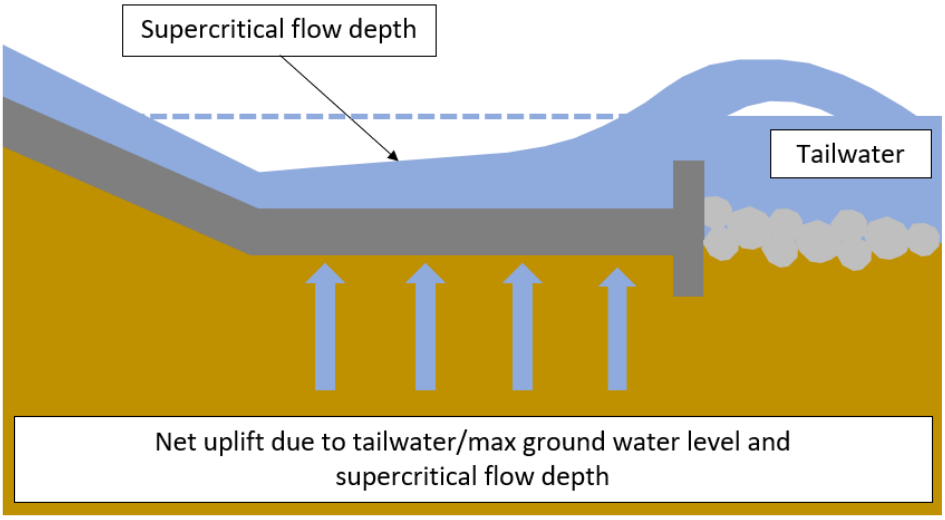
d. 

Figure 4: Structural failure due to excessive uplift pressure

Ice lenses and subsequent frost heave could impose significant loads on relatively thin reinforced concrete slabs founded directly on frost heave susceptible material.

In addition, the following reasons for exceedance of the uplift pressure are typically associated with reinforced grass spillway systems:

- Out of balance pressures related both to velocity of flow and the degree of turbulence. Localised uplift forces due to increased turbulence are typically more significant at surface irregularities and where hydraulic jump occurs.
- Insufficient permeability and/or potential clogging of the armour layer of geotextile grass reinforcement systems or where geotextile is used as an underlayer in conjunction with concrete grass reinforcement systems. This would prevent efficient uplift pressure relief.

This failure mechanism has been discussed in the following reference documents and case studies:

HUGHES, A., 2020. ‘Report on the Nature and Root Cause of the Toddbrook Reservoir Auxiliary Spillway Failure on 1st August 2019’. Consett, UK. Canal and Rivers Trust.

Excessive uplift following prolonged seepage of water underneath spillway slabs was one hypothesised method of failure related to the Toddbrook 2019 incident which was discussed in this report. The author identified a number of flaws with the design which may have contributed to this failure mechanism, including:

“no cut-off into the core/crest of the dam”, “very minimal reinforcement in the slabs”, “no underdrainage” and “no anchorage”.

The author goes further to state:

"I believe evidence from the site suggests that slabs were lifted by forces generated as uplift forces beneath the slab, assisted by suction forces which may have been generated in turbulent water and 'skimming' flows over the slabs. Movement of the slab and removal of material from beneath the slabs was then inevitable."

GRIERSON, R., 2018. 20th Biennial BDS Conference 2018 – Tour 2: Dwr Cymru Welsh Water Reservoirs – Shon Sheffrey and Rhymney Bridge No. 2. Dams and Reservoirs, 29 (1), 13-15.

This paper reports a spillway failure due to high uplift pressures. Unfortunately, it does not provide any details as to the reason for the developed high pressures.

"in 2013 the spillway at Rhymney Bridge 2 reservoir failed due to uplift pressures following a storm event. Emergency repairs were carried out at the time and more recently permanent repairs have been undertaken. These have included a new reinforced concrete spillway and grouting works to stem seepage, as well as the refurbishment of the batter valve (Penstock) at Rhymney N° 1."

FRANCE, J.W. AND ALVI, I.A. AND DICKINSON P.A. AND FALVEY, H.T. AND RIGBEY, S.J. AND TROJANOWSKI, J., 2018. 'Independent Forensic Team Report Oroville Dam Spillway Incident'. Colorado, USA. United States Society on Dams.

The independent forensic team who investigated the Oroville incident in 2017 cited water injection into cracks causing excessive uplift forces, stating:

"over time, chute flows and temperature variations led to progressive deterioration of the concrete and corrosion of steel reinforcing bars and anchors, with likely loss of slab strength and anchor capacity. There was likely also some shallow under slab erosion and some loss of underdrain system effectiveness, which contributed to increased slab uplift forces. The particularly poor foundation conditions at the initial service spillway chute failure location contributed to likely low anchor capacity and shallow under slab erosion."

"Once the initial section of the chute slab was uplifted, the underlying poor-quality foundation materials were directly exposed to high velocity flows and were quickly eroded. Undermining and uplift of other portions of the chute slab resulted in further removal of slab sections and more foundation erosion."

HEPLER, T.E. AND JOHNSON, P.L., 1988. 'Analysis of Spillway Failures by Uplift Pressure'. Proceedings of the 1988 National Conference sponsored by the Hydraulics Division of the American Society of Civil Engineers, August 8-12, 1988, Colorado Springs, USA.

The failure of both Dickinson Dam and Big Sandy Dam in USA outlined by Hepler and Johnson identify uplift pressures as being potential contributing factors to failure. In both cases, various failures with the initial design of the spillways led to water escaping through joints over a prolonged period. The authors discuss a 2-dimensional hydraulic model which was designed to “develop uplift design criteria for unreinforced, concrete-lined canal laterals on steep slopes. Uplift pressures that result when flow passes over offsets (joints or cracks with displacement) in the lining were evaluated as a function of offset geometry and flow velocity.”

In the case of Dickinson Dam, the authors state:

“based on the estimated loads and structural capacity of the slab, an added uplift pressure head equal to approximately one-third of the mean velocity head would have been required to initiate the observed failure. With an average flow velocity of 21 ft/s (6.4 m/s) and an assumed horizontal offset of 0.125 inches (3.2 mm), a vertical offset into the flow of only 0.2 inches (5 mm) would have been sufficient to produce the additional uplift required.”

In the case of Big Sandy Dam, the authors state:

“assuming the anchor bars were only 50 percent effective due to deterioration of the grout-foundation contact, an added uplift pressure head of 49 percent would have been necessary, corresponding to an assumed horizontal offset of 0.125 inches (3.2 mm) and a vertical offset of approximately 0.5 inches (13 mm). Such a combination of offsets is considered reasonable for the slab that failed.”’

INTERNATIONAL COMMITTEE ON LARGE DAMS (ICOLD), 2000. ‘Rehabilitation of Dams and Appurtenant Works (Bulletin 119)’. Paris France. ICOLD.

ICOLD bulletin 119 discusses the increased uplift pressure acting on the spillway chute channel slabs of Seyhan Dam in Turkey in 1994, stating:

“when the spillway discharged small amounts over long periods during its first years of operation, a hydraulic jump occurred on the spillway chute channel causing severe structural damage. Clogged drainage underneath the spillway slab contributed to the generation of uplift pressures at the damaged area.”

INTERNATIONAL COMMITTEE ON LARGE DAMS (ICOLD), 2016. ‘Technical Advancements in Spillway Design: Progress and Innovations from 1985 to 2015’. (Bulletin 172). Paris France. ICOLD.

ICOLD bulletin 172 discusses the impact of the dynamic pressure fluctuation generated by the hydraulic jump on the uplift forces acting on stilling basins, stating:

“the integrity of the basin may also be affected by fluctuating uplift forces whose peaks overcome the weight of the concrete slab and the resistance of the steel anchors that are provided to incorporate the weight of the underlying rock. Examples of serious accidents caused by these fluctuating forces are Malpaso, Mexico (Sanches-Bribiesca and Viscaino, 1973) and Karnafuli, Bangladesh (Bowers and Toso, 1988). The effect of these fluctuating uplift forces results from the transfer of dynamic pressures generated by the turbulent hydraulic jump to the underside of the basin slabs, through joints and drainage system pipes.” (refer to Figure 5).

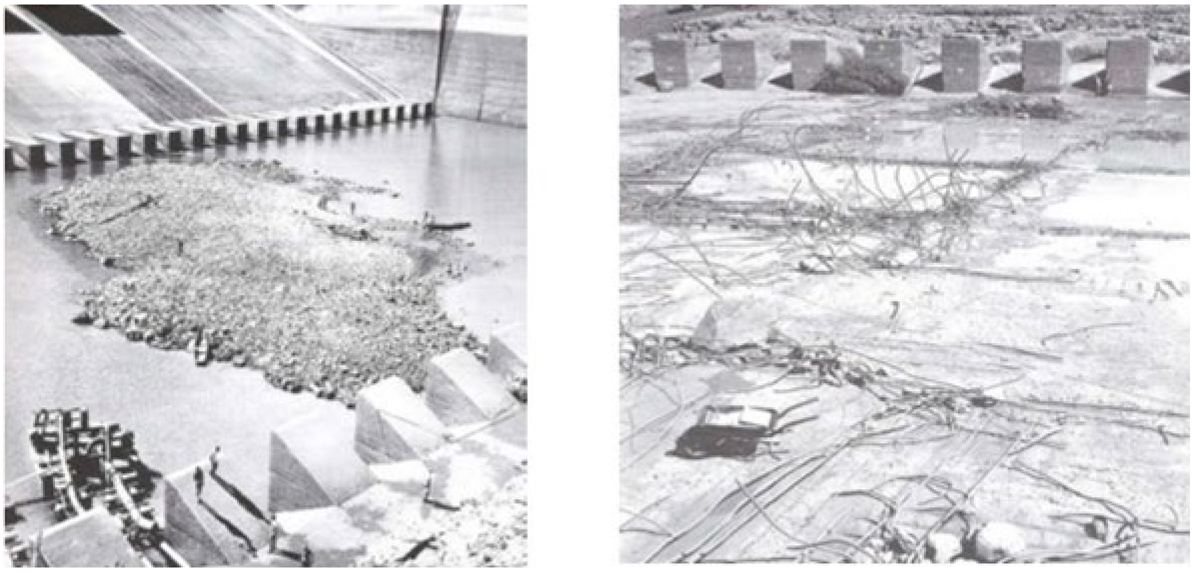


Figure 5: Marimbondo Spillway stilling basin damages from asymmetric operation (ICOLD, 2016).

2.2.2. Structural failure due to loss of side support and undermining

This failure mechanism occurs where the spillway walls lose their side support, or the spillway foundation is undermined as a result of external or internal erosion including external erosion due to spillway overtopping, internal erosion due to seepage, external erosion downstream of energy dissipators and surface erosion under the armour layer of reinforced grass spillways. Such erosion and undermining could cause the structure to collapse under the action of its own weight and any added internal hydrostatic or other action.

2.2.2.1. External erosion due to spillway side wall overtopping

This failure mechanism occurs where the spillway side wall is overtopped during a flood event. The spillage of water onto areas surrounding the spillway can lead to external erosion, potential undermining of the spillway foundation and ultimate collapse of the spillway structure due to the loss of ground support. The causes of such overtopping can be either insufficient hydraulic capacity or blockage by floating debris or ice during cold weather conditions.

Possible reasons for insufficient hydraulic capacity are:

- water depth not predicted correctly due to modelling errors or limitations (scale effects, Froude similarity errors, measurement inaccuracy, complex uncalibrated numerical (CFD) models)

- flow aeration and bulking not predicted correctly or not allowed for - this would normally require a separate analysis as neither physical nor numerical (CFD) modelling can predict it correctly
- stone dislodgement from masonry spillways (missing sets) creating plumes and splashes and leading to increased turbulence and flow bulking
- shock waves, cross waves and super elevations occurring in supercritical flow at abrupt changes in flow direction not predicted correctly
- design and safety check flood underestimated or not updated. There may be various hydrological and other factors that could affect the flood estimation, including the effect of man-made features on catchment delineation, hydraulic capacity of catchwaters and water transfers, wrong weir discharge coefficient adopted or lack of recognition that this coefficient has changed.

Possible reasons for blockage by floating debris or ice (other than restriction at the inlet) are:

- spillway contraction which is significant enough to cause blockage
- splitter walls within chute restricting the free passage of floating debris
- baffles used at baffled chutes or within stilling basins retaining floating debris or ice
- orifices or covered channel sections sometimes used to control shock waves and prevent out-of-channel flow at changes in flow direction
- other restricting fixtures such as fish screens, converging weir inlets, drop shafts (where forested catchments are present) and shallow approaches

This failure mechanism has been discussed in the following reference documents and case studies:

CHARLES, J.A. AND TEDD, P AND WARREN, A.L., 2014. 'Lessons from incidents at dams and reservoirs – an engineering guide (CIRIA guide SP167)'. London, UK. Construction Industry Research and Information Association (CIRIA).

A number of case studies of inadequate spillway capacity at UK reservoirs are discussed by Charles and others (2014), including:

an incident at Kype dam was described as occurring as "the walls of the spillway channel were overtopped and considerable erosion of the ground adjacent to the spillway took place, estimated to be 60 m^3 of rock."

The 1989 incident of Walsham Dean Lower which led to a landslip and spillway and bywash channel damage was described as being due to inadequate spillway capacity. The authors state that following the incident "subsequent statutory inspection recommended that the owners commission a flood study and physical modelling of the three reservoirs. Model tests showed that none of the spillways could pass the design flood. At Walshaw Dean Lower, less than a quarter of the design flood could be passed safely."

A contraction of the spillway by ice was identified as the cause of the Trewhitt incident in 1963. Of a number of case studies examined by the authors of dam incidents, the authors describe it as “the only published overtopping incident entirely due to snowmelt.” The authors describe how freezing cold conditions and a subsequent thaw following the onset of warmer conditions resulted in a cover of ice in the reservoir breaking into large ice flows “some of which became wedged in the spillway shaft, reducing its capacity.”

US Department of the Interior Bureau of Reclamation (USBR) AND US Army Corps of Engineers (USCE), 2019. ‘Best Practice in Dam and Levee Safety Risk Analysis, Chapter F2 – Overtopping of walls and stilling basin failure’. Version 4.1. USBR & USCE.

The 1999 failure of the El Guapo Dam in Venezuela is described in section F-2.5.1 of this USBR and USCE publication.

“Overtopping of the spillway chute walls initiated erosion of backfill behind chute walls and undermining and failure of spillway chute. Head cutting progressed upstream and lead to reservoir breach.” (refer to Figure 6).

Figure 6: Overtopping of chute walls of El Guapo dam (USBR & USCE, 2019)

CHARLES, J.A. AND TEDD, P AND WARREN, A.L., 2011. ‘Lessons from incidents at dams and reservoirs – an engineering guide’. Lessons from historical dam incidents. Bristol, UK. Environment Agency.

The Environment Agency publication ‘Lessons from historical dam incidents’ identifies stone dislodgement as a contributing factor to the Ulley 2007 spillway chute overtopping incident:

“Mechanisms proposed for the spillway collapse included high turbulence flows in the chute plucking out masonry block or pushing them out by water pressure from behind and by overtopping the chute walls causing back pressure on them.”

It goes on to note that:

“similar failures are known to have occurred at not less than nine other masonry spillways including Toddbrook in 1985 and Boltby in 2005.”

2.2.2.2 Internal erosion due to seepage

Unlike the external erosion previously discussed, this failure mechanism occurs where the ground surrounding the spillway, or the spillway foundation, is eroded as a result of seepage. Internal erosion due to seepage could occur for the following reasons:

- absence of drainage to safety convey seepage flow where there is a potential for seepage gradients which are sufficiently high to initiate particle movement in the soil surrounding the spillway
- unfiltered drainage, including unfiltered exit points, (unfiltered relief holes, unsealed joints, large cracks) where erodible material is present, potentially initiating backward erosion piping or contact erosion
- absence of suitably designed cut-offs at the inlet (to control seepage from the reservoir), and down the spillway chute sides and base (normally to lengthen the path of seepage and direct it into the drainage)
- unsealed joints and large cracks serving as entry points for flood water from the spillway into the foundation (including injection of water under stagnation pressure) and also acting as unfiltered exit points for seepage flow (discussed in more detail in Appendix A)
- cracks and gaps around the spillway structure caused by settlement, desiccation or differential movement potentially causing concentrated leak erosion
- suffusion and suffosion eroding the finer particle of susceptible soil materials, increasing their permeability. This would increase the seepage flow, cause clogging of filters and initiate other internal erosion mechanisms

This failure mechanism has been discussed in the following reference documents and case studies:

BALMFORTH, D., 2020. Toddbrook Reservoir Independent Review Report. London, UK. Department for the Environment and Rural Affairs.

In his executive summary of investigation into the Toddbrook 2019 incident, the author suggests that erosion due to seepage could have occurred under the spillway slabs:

“The lack of an effective cut-off between the spillway crest and the impermeable core of the dam would have allowed water to pass into the embankment fill under the spillway chute. While some of this will have drained downwards through the permeable fill, it is likely that some will have flowed beneath the slabs of the spillway chute causing erosion of its foundation.”

The author then goes further into the physics of the failure. He postulates crack injection as being responsible for seepage of water under the spillway slabs that caused the large void into which the slabs subsequently collapsed (refer to Figure 7):

Figure 7: Spillway chute panels collapse into a void at Toddbrook Reservoir (Balmforth, 2020)

The report states:

“from the evidence available, the most likely explanation is that this occurred as a result of a process known as crack injection. Crack injection can occur when high velocity flow impacts against a solid object in its path such that the kinetic energy in the flow is converted into pressure.”

In a later discussion of the design deficiencies of the spillway, the authors mention some features which the spillway design did not incorporate that may have also been contributory factors to the incident:

“the spillway lacked a cut-off into the clay core of the embankment and also underdrainage. The slabs were very thin (150mm) and virtually unreinforced. Some dowel bars and water bars were provided in transverse joints between slabs, but not in the longitudinal joints between the slabs.”

HUGHES, A., 2020. ‘Report on the Nature and Root Cause of the Toddbrook Reservoir Auxiliary Spillway Failure on 1st August 2019’. Consett, UK. Canal and Rivers Trust.

The author of this investigation into the Toddbrook incident also concludes that internal erosion was largely to blame for the collapse of the spillway panels. However, as opposed to the crack injection postulated by Balmforth (2020), the author states that there is evidence to support the hypothesis that such erosion took place gradually over a prolonged period including:

“eye-witness reports at various times over the last 50 years describing water spurting up at the base of the spillway – that water being dirty and clearly carrying material away from the spillway – but only on the left-hand side.”

“Eye-witness reports describing water coming out of the joints in the upper parts of the spillway as well as dirty water, and the sound of air being expelled from beneath the slab.”

“Increased and progressive settlement at the left-hand side of the spillway – compared with the right-hand side.”

“Photographic evidence across the decades of water coming out of various joints and ponding at the base when the spillway is not overflowing.”

WINTER, C. AND MASON, P. AND BAKER, R. AND FERGUSON, A., 2010. Guidance for the Design and Maintenance of Stepped Masonry Spillways. Bristol, UK. Environment Agency.

This paper discusses how undermining of the foundations of masonry spillways can lead to settlement, cracking and potential structural failure:

“In the case of spillways, foundation failures are typically associated with the spillway foundations being undermined by water leaking through the bed, or invert of the spillway and washing material away as it does so. Over time, this can result in the creation of voids beneath the invert leading in turn to the settlement and cracking of both the invert and the sidewalls.”

YOUNG, J.R. AND PAXSON, G.S., 2010. Undermining of Spillway Chutes. ASDSO Dam Safety 2010. 22 September 2010. Seattle, USA.

An extensive discussion of erosion via undermining, and a discussion of 6 case studies in the USA, is provided by Young and Paxson (2010). The authors identify causes of long-term undermining as “inadequate filtering of spillway foundation material’ and ‘inadequate cut-off at the spillway control section.”

With the case studies, the authors demonstrate how the absence of some of those recommended design provisions led to the formation of voids in the spillway foundation that had the potential to cause major incidents.

US Department of the Interior Bureau of Reclamation (USBR) AND US Army Corps of Engineers (USCE), 2019. Best Practice in Dam and Levee Safety Risk Analysis. Version 4.1. USBR & USCE.

In chapter F1, there is a case study about the Hyrum Dam spillway in Utah, USA. The authors describe how an inspection carried out in 2003 identified voids underneath the spillway surface stating:

"In 2003, ground penetrating radar, drilling and closed-circuit television examination of the spillway underdrains and drill holes were used to identify voids underneath the spillway chute. A continuous channel, over two feet deep in places was identified beneath the steeper portion of the chute. The erosion that occurred in the spillway foundation was attributed to the introduction of flows through the cracks and joints in the slab and piping of foundation materials into the unfiltered drainage system."

US Department of the Interior Bureau of Reclamation (USBR) AND US Army Corps of Engineers (USCE), 2019. Best Practice in Dam and Levee Safety Risk Analysis. Version 4.1. USBR & USCE.

In-depth discussion of internal erosion is given in chapter D2 of this USBR publication. The authors identify and describe the various processes of internal erosion within soil foundations of dams. The authors caveat their discussion at the start by stating that:

"unfortunately, this is a potential failure mode that cannot be completely analysed using numerical formulae or models."

Furthermore, the authors discuss a case study which relates to a failure near the spillway of the Fontenelle Dam in Wyoming, USA.

"A very serious internal erosion incident occurred in 1965, when Fontenelle Dam nearly failed during first filling. Significant seepage travelled through the open jointed sandstone foundation rock, emanating 2,000 feet downstream in a low area as well as in the right abutment near the spillway."

"The primary cause of the near failure was thought to be inadequate grouting of the jointed sandstone and the lack of foundation treatment measures such as slush grouting and dental concrete, which led to seepage near the base of the dam that removed embankment material and led to the growth of voids."

ENVIRONMENT AGENCY, 2017. Post-incident reporting for reservoirs Annual report 2017. Bristol, UK. Environment Agency.

An incident at an unspecified location involving voids under spillways were described in the Environment Agency's post incident reporting for reservoirs annual report in 2017. For incident No. 430, it is stated that:

'"excavations revealed large voids beneath the footings of the spillway side wall. Voids were also found beneath the floor of the spillway chute."

The cause was identified as "voiding below the spillway structure occurred as a result of an ineffective cut-off and an absence of filters to prevent the migration of soil particles."

2.2.2.3 External erosion downstream of energy dissipators

This failure mechanism normally occurs where the energy dissipation and/or erosion protection provided downstream of the energy dissipator are insufficient to prevent external erosion. Where the energy dissipation structure is not keyed into competent rock, this could undermine it and, in some cases, could cause head-cutting of the reservoir embankment.

Such external erosion could be due to:

- insufficient stilling basin length to contain the hydraulic jump. This could be due to the additional length of the backwater curve required to generate the required stilling basin water depth where it is controlled by the stilling basin exit geometry and/or by any end sill provided
- insufficient stilling basin water depth to submerge the hydraulic jump. This could be due to inaccurate estimate or progressive reduction of the stilling basin water depth where it is generated by the backwater curve within the natural watercourse. This could also occur where the required stilling basin water depth is controlled by the stilling basin exit geometry and/or by any end sill provided, and the length of the backwater curve required to generate it has not been adequately considered
- inadequate erosion protection provided downstream of the energy dissipator considering the efficiency of energy dissipation, the energy dissipator performance at low flows (such as at 'flip' buckets and energy dissipators provided with end sills), the erodibility of the receiving watercourse and the risk of undermining of the spillway structure

This failure mechanism has been discussed in the following reference documents and case studies:

US Department of the Interior Bureau of Reclamation (USBR) AND US Army Corps of Engineers (USCE), 2019. Best Practice in Dam and Levee Safety Risk Analysis. Version 4.1. USBR & USCE.

Section F.2.1.11 of this USBR publication discusses the consequences that occur when a stilling basin is unable to form a hydraulic jump. It goes further to state:

“if sweepout occurs, failure can initiate and progress in several ways. One mechanism is that the stilling basin sweepout leads to high-velocity flows exiting the downstream end of the stilling basin causing erosion in the downstream river channel, head cutting and a progressive failure up through the spillway chute or erosion of the toe of an embankment dam if erosion progresses laterally.”

“A second mechanism occurs with high tailwater surrounding the stilling basin but insufficient to force the hydraulic jump to occur within the structure. With the jump occurring downstream of the stilling basin, very shallow high-velocity flow conditions with minimal water weight are occurring within the stilling basin. This can lead to flotation of the stilling basin due to uplift pressures, failure of the stilling basin, erosion of the stilling basin foundation and head cutting upstream or erosion of the toe of an embankment dam if erosion progresses laterally.”

TROJANOWSKI, J. 2006. Can your spillway survive the next flood? 26th Annual USSD Conference (The Role of Dams in the 21st Century). 1-5 May 2006. San Antonio, USA.

In a discussion about stilling basin failure and subsequent erosion effects the author states:

“Even if the stilling basin can contain a hydraulic jump, the sweepout conditions at the upstream end can result in unusual differential loading with uplift pressures equal to tailwater on the outside of the structure and low flow depths on the inside. Sweepout or a hydraulic jump that develops beyond the end of the stilling basin can result in excessive erosion and undermining of the structure.”

INTERNATIONAL COMMITTEE ON LARGE DAMS (ICOLD), 2000. Rehabilitation of Dams and Appurtenant Works (Bulletin 119). Paris France.

This bulletin discusses the erosion occurring downstream of the Seyhan dam flip bucket at low flows:

“There is a particular problem immediately downstream of flip buckets where the low flow is not thrown clear and abrades the foundation immediately downstream of the structure.”

2.2.2.4 Surface erosion under the armour layer of reinforced grass spillways

This failure mechanism could lead to structural failure of reinforced grass spillways due to their undermining and could be typically due to:

- excessive hydraulic loading (velocity and duration of flow). This could be the result of an incomplete assessment of all plausible flow/duration operating conditions. It could also result from exceedance of the unit discharge, channel slopes, and flow velocities of the tested conditions for the specific grass reinforcement product used. Excessive loading could also result from flow concentration and increase of local velocity at low points or settlement present at the crest or along the spillway channel. Flow concentration could also occur at the mitre between the downstream face of the dam and the valley

- good grass cover not being established to prevent erosion of the underlayer and the subsoil. Such erosion could occur during spillway operation but could also be due to wind or surface water run-off
- poor or deteriorated contact between the armour layer and the underlayer/subsoil increasing downslope seepage flow under the armour layer. This could be caused by surface irregularities leading overtime to relatively significant movement of individual armour units due to the increased localised drag and uplift forces. Such movement could also be caused by the increased bottom velocities and turbulence where hydraulic jumps are present and at abrupt transitions between 2 or more plane surfaces and at any discontinuities (cracks, voids, appurtenant structures – particularly at the toe, berms, roads, structures). Poor contact may also be due to formation settlement or differential settlement between rigid structures and adjacent grassed waterways. It could also result from damage due to vandalism, floating debris, traffic, mowing machinery and animals
- soil shrinkage within the cells of concrete reinforcement systems, or at junctions between grassed waterways and rigid structures, leading to the formation of gaps and removal of grass and soil under flow conditions. For some reinforcement systems, this could lead to surface erosion and undermining of the armour layer
- exposed leading edges of reinforcement which could be subjected to pressure drag forces
- area immediately upstream of a steep reinforced grass system not being erosion resistant. This could cause erosion developing at this location

This failure mechanism has been discussed in the following reference documents and case studies:

HEWLETT, H.W.M. AND BOORMAN, L.A. AND BRAMLEY, M.E., 1987. Design of reinforced grass spillways. London, UK. Construction Industry Research and Information Association (CIRIA).

This document provides comprehensive guidance on the different types of grass reinforcement and their hydraulic design, geotechnical design, inspection and maintenance.

The authors also list 6 different ways by which plain grass spillways can erode, namely:

- “when flow first occurs, any loose vegetation is removed by the drag force of the flowing water”
- “locally, flow may slowly scour soil away round the roots of a plant, thereby weakening its anchorage until the plant itself is removed by the drag force of the flow”
- “individual grass plants with poorly-developed root structures are either pulled out of the soil or broken off at the roots. Flowing water causes higher drag forces on

plants which present a substantial profile to the flow, in comparison with those which are laid flat"

- "progressive 'rolling up' due to high local drag forces at the leading edge of the mat"
- "shallow surface slip"
- "net uplift pressure arising from excessive seepage flow"

Further discussion is then provided on the physical attributes of the grass plant which determine the effectiveness of plain grass for erosion protection. These are stated to be: "length and stiffness of sward, surface area of grass blades, strength and depth of root structure, density of rhizomes, stolons and surface root structure and area covered by the grass."

FEDERAL EMERGENCY MANAGEMENT AGENCY (FEMA), 2014. Overtopping Protection for Dams: Best Practices for Design, Construction, Problem Identification and Evaluation, Inspection, Maintenance, Renovation, and Repair. Washington D.C., USA. FEMA.

Chapter 6 of this guide discusses grass and vegetation protection and states the potential benefits of the use of grass and vegetation on spillways. It discusses historical research stating:

"vegetation can provide significant protection against the onset of head-cut erosion. This may mean the survival of a structure for some flood loadings or a significant delay in the breach of a spillway or dam in other cases."

It follows this with guidance on design considerations for plain and reinforced vegetative protection, and synthetic turf systems, and also discusses some long-term risks and potential mitigations.

2.2.3. Structural failure due to excessive or unaccounted dynamic actions

This failure mechanism could occur where some of the dynamic actions inherent to the spillway operation have not been adequately accounted for. Such dynamic actions may include mean hydrodynamic forces, flow-induced vibrations, vibrations due to wind turbulence, wave action and dynamic impact from floating debris and/or ice.

Unlike static actions, dynamic actions are normally more difficult to both define and analyse. However, underestimating or omitting these actions could, in some cases, have significant direct effects on the structures.

Some of the main risks and effects associated with dynamic actions include:

- time-mean hydrodynamic forces acting on various parts of the spillway structure subject to high velocity flow, including piers, chute blocs, baffle blocks, baffle walls,

end sills, spillway chute walls or base slabs at changes in horizontal alignment (cross waves) or gradient would increase stresses within the structure. They may have the potential to cause fatigue, opening of cracks, spalling, delamination, damage to joints and water-stops
- flow-induced vibrations are present during the operation of all spillway structures. They are random in nature and have the potential to generate structural resonance which could be particularly pronounced at stilling basins (Pavlov, 2021)
- where the foundation material is susceptible to liquefaction and could be saturated, such vibrations could cause soil liquefaction, excessive settlement and increased uplift (Pavlov, 2021)
- fatigue resulting from cyclic loading has the potential to reduce the bond strength of passive anchors
- vibrations due to wind turbulence, including possible resonance response, may occur with very tall spillway walls during the stage of construction
- wave action on the inlet structure weir, piers and wind walls would increase stresses within the structure with all ensuing effects
- dynamic impact loads could be imposed by floating debris and/or ice on the weir, piers and training walls of the inlet structure as well as on the walls, slabs and other features of the spillway structure, especially where abrupt changes in direction, chute blocks or baffles are present. Such loading would increase stresses within the structure with all ensuing effects

This failure mechanism has been discussed in the following reference documents and case studies:

BOLLAERT, E.F.R., 2009. Dynamic Uplift of Concrete Linings: Theory and Case Studies. USSD Annual Meeting, April 24-26, 2009. Nashville, USA.

A study into the impact of pressure fluctuations leading to dynamic uplift of concrete linings is described by Bollaert (2012). The author describes a shortcoming of previous studies into dynamic pressure fluctuations and its effects on stilling basins and concrete slabs:

“Nevertheless, despite major advances in measurement technology and data acquisition, a safe and economic design method for any kind of concrete lined stilling basins is still missing today. Especially the dynamic or even transient character of pressure pulsations as a function of their two-dimensional spatial distribution above and underneath the lining is not fully assessed and implemented in existing design methods.”

The author presents a new theoretical model for the design of concrete linings that “combines laboratory measurements of net uplift forces, prototype-scaled transient pressure recordings inside artificially generated lining fissures and numerical modelling of air-water pressure pulsations.”

BOWERS, C.E. AND TSAI, F.Y. AND KUHA, R.M., 1964. Hydraulic Studies of The Spillway of The Karnafuli Hydroelectric Project East Pakistan. Minneapolis, USA. University of Minnesota.

A specific incident of spillway structural failure due to fluctuating dynamic pressures is the Karnafuli spillway failure of 1961 in Bangladesh. The incident occurred while the hydroelectric project was still under construction and during a spillway discharge event. Slabs were lifted across the entire width of the spillway channel during the event. An investigation into this incident was reported by Bowers and others (1964). Model studies of the dam were conducted and described by the authors as follows:

"A comprehensive model of the spillway and associated area was constructed to a scale of 1:132. A section model of one full bay and two half bays was constructed to a scale of 1:60. The model studies involved (1) measurements of flow pattern, log retention, and scour in the comprehensive model, and (2) measurements of temporal mean pressures, fluctuating pressures, log velocities and accelerations, and movement of model chute slabs in the section model.'"

In summarising its conclusions on the model study, the authors considered that fluctuating pressures within the chute, transmitted through the drainage system, were the most likely cause of failure, stating:

"It is believed that the flow conditions were such that fluctuating pressures were the primary cause of failure of the slab. Pressure differentials equivalent to 16ft of water probably occurred between the chute block drain openings and the upper surface of the slab in the vicinity of elevation 14ft."

In discussing potential remedial measures to mitigate the risk of such an incident occurring again, the authors state that:

"the increased thickness and new design of the drainage system and the revised chute should provide adequate protection against fluctuating pressures; and consideration should be given to doweling or otherwise holding down the floor of the stilling basin to avoid possible uplift of the basin slabs."

INTERNATIONAL COMMITTEE ON LARGE DAMS (ICOLD), 1987. Spillways for dams: State of the art (Bulletin 058). Paris France. ICOLD.

The bulletin states:

"In the macroturbulence method of energy dissipation, the dominant pulsating components (those with the greatest amplitude) have frequencies between 0 and 10Hz. This means that some parts of the basin, like the invert slabs and any deflectors or splitters it might carry, are in danger of resonant vibration."

"Vibrational movement of the slabs opens interfaces in depth, and throws up the corners of the joints, encouraging dynamic uplift and the lifting of the slab."

"Lastly, these pressure fluctuations can produce fatigue in some structures (especially rock anchors) that is difficult to estimate."

SUZUKI, Y. AND SAKURAI, A. AND KAKUMOTO, N., 1973. 'Design of a chute spillway jointly serving as the roof slab of a hydropower station and its review on the vibration during flood. Proceedings of the 11th ICOLD Congress. 1973. Madrid, Spain.

The paper reports on the results of a spilling test carried out to establish the flow-induced vibrations and dynamic response of the roof slab of the Shin Nariwagawa power station forming part of the reservoir spillway. The power spectrum of the roof slab vibration obtained during the spilling test revealed that power was concentrated near 11Hz at the large span and near 18Hz at the small span of the slab. The paper states:

"From the results of measurement of micro-tremor, it can be conceived that the 11Hz or 18Hz are produced by the excitation of natural vibration of the sab caused by the flowing water."

KUPRIYANOV V.P. AND PROUDOVSKY A.M. AND RODIONOV V.B. AND VOINOV Y.P., 1998. Estimation of safety of separating walls subjected to hydrodynamic loads within zones of energy dissipation. Proceedings of International Symposium on New Trends and Guidelines on Dam Safety. 17 – 19 June. Barcelona, Spain.

The paper describes the results of studies for strength assessment of stilling basin separating walls downstream of the Khojikent project (Uzbekistan). It states:

"After commissioning the powerhouse intensive vibrations of the separating wall was found to take place when opening the bottom outlets just by 0.2 of the full opening. The amplitude of movement of the walls in their upper part exceeded 6 x 10-4m with prevailing vibration frequency of about 5.0Hz close to natural vibrations of the walls."

2.2.4. Structural failure due to cracking and corrosion of reinforcement

With reinforced concrete spillways the reinforcement can become exposed to corrosion where excessive cracking occurs or where the cover to reinforcement is insufficient. This would progressively reduce the strength, and therefore the durability, of the reinforced concrete structure.

Excessive cracking could occur as part of several of the previously mentioned failure mechanisms, including:

- excessive uplift pressures (refer to section 2.2.1)
- loss of side support and undermining (refer to sections 2.2.2.1 – 2.2.2.3)
- excessive or unaccounted dynamic actions (refer to section 2.2.3)

In addition, excessive cracking could be due to several design and/or construction deficiencies, including:

- inadequate reinforcement areas and spacing between joints required to control cracking due to restrained early age and long-term thermal deformations and shrinkage
- concrete tensile strength used in the calculations not reflecting the time when load is first applied
- cracks may not heal if designed to meet the requirements of Tightness Class 0 rather than Tightness Class 1
- the effect of early-age and long-term thermal and shrinkage cracks being additional to cracks due to flexure and direct tension not being considered
- the effect of stagnation pressures developing upstream of baffles, blocks, sills or other features placed on a spillway chute or within an energy dissipator to dissipate energy have not been considered in controlling cracking around such features
- inadequate design and execution measures to control cracking due to early plastic settlement of concrete have not been taken

This failure mechanism has been discussed in the following reference documents and case studies:

FRANCE, J.W. AND ALVI, I.A. AND DICKINSON P.A. AND FALVEY, H.T. AND RIGBEY, S.J. AND TROJANOWSKI, J., 2018. Independent Forensic Team Report Oroville Dam Spillway Incident. Colorado, USA. United States Society on Dams.

As previously mentioned in section 2.1.1, deterioration of the concrete on spillway chute slabs was identified as a possible contributing factor to the Oroville Dam incident. The independent forensic team identified that concrete delamination and spalling in areas along the spillway chute have led to exposed reinforcement and joints, which then became more susceptible to reduction in strength due to corrosion. They stated:

“Spalling occurred almost entirely in delaminated concrete at joints and cracks and at patches from previous repairs, generally in the concrete above the level of the reinforcing steel and dowels. Delamination led to spalling of the slabs near the joints and cracks. The spalling exposed reinforcing steel in the chute slabs and dowel bars at the joints to corrosion, leading to bar failure.” (see Figure 8).

Figure 8: Concrete spalling at Oroville Dam Spillway (France and others, 2018).

BALMFORTH, D., 2020. Toddbrook Reservoir Independent Review Report. London, UK. Department for the Environment and Rural Affairs.

The report makes a note of corrosion in the case of the Toddbrook incident. In discussing the initial slab failure, the authors note:

“the reinforcing wire had either snapped or had failed due to corrosion. The upper section of slab can be seen to be ‘hanging’ on the connecting joint dowel bars.”

2. Main findings of the literature review

There is ample information available in the technical literature regarding the potential spillway failure mechanisms and their root causes.

The limited number of case studies examined in this document illustrates some of the most frequently reported failure mechanisms, including uplift and undermining of the spillway structure due to internal erosion, overtopping and stagnation pressures.

While many of the potential failure mechanisms identified in this document have not been supported by case studies, information about them has been obtained from various research publications, technical papers, guidance documents and presentations referred to in this document.

As a general trend, there appears to be relatively little recent research, guidance and case studies available for reinforced grass spillways. The most comprehensive guide on reinforced grass spillways appears to be the CIRIA Report 116, which is now over 30 years old. A possible explanation for this is that these spillway systems were mainly used for auxiliary or emergency spillways that have rarely operated. Considering the relatively large number of grass spillways that exist in the UK, there is a clear need for further research, guidance and focus on this area in order to improve understanding of the vulnerabilities of these spillways and mitigate their risk of failure.

There is also a strong argument to be made for more focus on the failure mechanisms relating to cracking and subsequent corrosion of reinforcement of concrete spillways. While the number of case studies and other information on this appears to be relatively limited, this issue was highlighted in the reports on the Toddbrook and Oroville incidents. This does suggest the possibility that this failure mechanism may have unknowingly been a factor in other historical spillway failures. Greater knowledge and understanding of how this could be identified during inspections and potentially remediated could help in ensuring such incidents are avoided in future.

Similarly, the effects of flow-induced vibrations are not very well understood and addressed in current design practice and may have contributed to past spillway incidents. It should be noted that these effects could be particularly detrimental to the structural performance of relatively wide and thin reinforced concrete slabs when present at spillway chutes and energy dissipators (Pavlov, 2021).

A full list of the case studies examined as part of the literature review is presented in Appendix B.

3. Implications for UK reservoir stakeholders

The guidance on spillway failure mechanisms provided in this document could be used by design engineers, inspecting engineers, owners and regulatory authorities concerned with reservoir safety in the UK.

In particular, this document could help improve the design process by giving design engineers greater insight into the risks and vulnerabilities inherent to spillway structures in order for them to be designed out.

The guidance could also help those involved in inspecting reservoir spillways, by complementing the information provided in other guidance documents currently available.

Finally, the guidance could help reservoir owners and regulatory authorities in reviewing spillway design and reservoir inspection reports produced by others by improving their understanding of the risks involved.

4. Conclusions and recommendations

In response to the recommendations of the Toddbrook Reservoir Independent Review Report, this document provides guidance on the potential spillway failure mechanisms in order to help the UK industry in further improving reservoir safety practices.

The guidance provided is based on the review of several UK and international research publications, technical papers, guidance documents, case studies and presentations dealing with the subject of reservoir spillway failure.

While the most common failure mechanisms relating to uplift and undermining of spillway structures are well reported in case studies and other technical literature, some gaps still remain with regards to some fewer known effects, including cracking and flow-induced vibrations.

There is also a notable lack of recent research and evidence in the technical literature with regards to historical failures of reinforced grass spillways. Considering the relatively large number of reinforced grass spillways present in the UK, this is an area of particular concern. It is therefore recommended that more research and data gathering be carried out in order to improve understanding of the vulnerabilities and risks posed by these spillway structures, considering factors such their age, geological conditions and operation and maintenance regimes.

It is also recommended that research into the effects of concrete cracking and flow-induced vibrations be commissioned in order to help reservoir owners and inspecting engineers with the assessment of the risks posed by relatively wide and thin reinforced concrete spillway structures.

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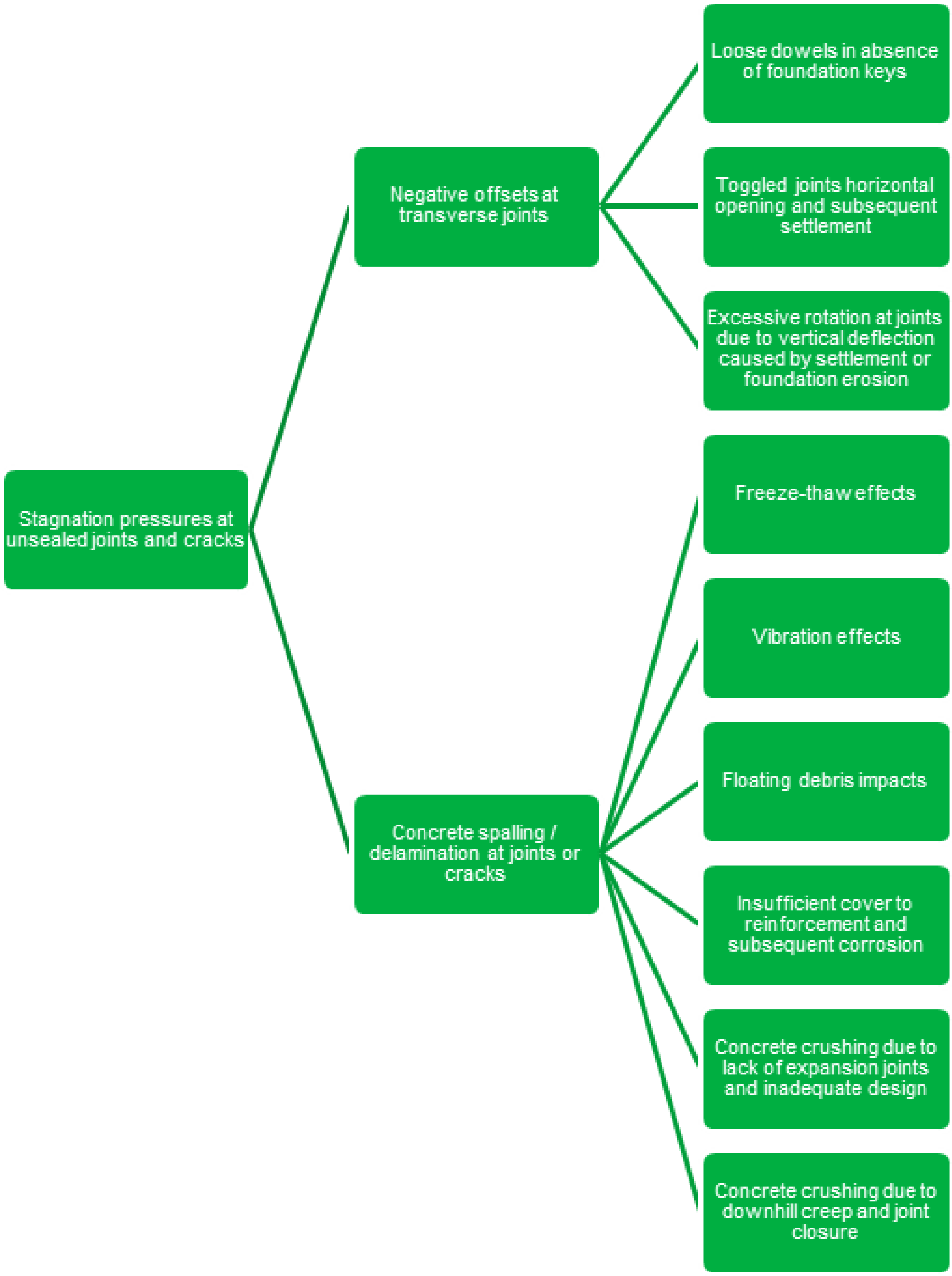
Appendix A: Stagnation pressures at unsealed joints or cracks

Stagnation pressures could develop at unsealed transverse joints and cracks where negative offsets have the potential to form. This root cause diagram below illustrates some of the possible reasons for the formation of such offsets.



Root cause diagram for water injection through unsealed cracks or joints

The report DSO-07-07 'Uplift and Crack Flow Resulting from High Velocity Discharges Over Open Offset Joints' (USBR, 2007) provides a procedure for determining the magnitude of the stagnation pressures and flows into joints and cracks for gaps, ranging from 3mm to 12mm and for offsets into the flow ranging from 3mm to 18mm.

Both the Oroville Dam spillway incident in 2017 and the more recent Toddbrook Reservoir spillway incident in 2019 suggested that stagnation pressures and resulting water injection through defective joints and cracks contributed to the failure of the spillways as follows:

BALMFORTH, D., 2020. Toddbrook Reservoir Independent Review Report. London, UK. Department for Environment, Food and Rural Affairs (Defra).

"The most likely initiation event and mechanism for the introduction of the volumes of water necessary to liquify 800t of fill is joint and/or crack injection due to the development of stagnation pressures on the chute. The sporadic nature of maintenance work, allowing long periods of extensive plant and root growth, would have led to deterioration of the chute, which then allowed the joint and/or crack injection described above."

FRANCE, J.W. AND ALVI, I.A. AND DICKINSON P.A. AND FALVEY, H.T. AND RIGBEY, S.J. AND TROJANOWSKI, J., 2018. Independent Forensic Team Report Oroville Dam Spillway Incident. Colorado, USA. United States Society on Dams.

"During service spillway operation on February 7, 2017, water injection through both cracks and joints in the chute slab resulted in uplift forces beneath the slab that exceeded the uplift capacity and structural strength of the slab, at a location along the steep section of the chute. The uplifted slab section exposed the underlying poor-quality foundation rock at that location to unexpected severe erosion, resulting in removal of additional slab sections and more erosion."

Appendix B: List of case studies examined

Reference	Country of origin	Source	Name of dam	Description of failure or potential failure	Spillway construc-tion date	Year of failure
TEXAS COMMISSION ON ENVIRONMENTAL QUALITY, 2006. Guidelines for Operation and Maintenance of Dams in Texas. Austin, Texas, USA. Texas Commission on Environmental Quality.	USA	Texas commission on environmental quality	Walnut Grove Dam	External erosion due to spillway overtopping. Inadequate hydraulic capacity of the spillway and poor workmanship.	Unknown	1890
GRIERSON, R., 2018. 20th Biennial BDS Conference 2018 – Tour 2: Dwr Cymru Welsh Water Reservoirs – Shon Sheffrey and Rhymney Bridge No. 2. Dams and Reservoirs, 29 (1), 13-15.	UK	British Dam society	Rhymney Bridge Dam	Structural failure due to excessive uplift pressure during a storm event.	1901	2013
BALMFORTH, D., 2020. Toddbrook Reservoir Independent Review Report. London, UK. Department for Environment, Food and Rural Affairs.	United Kingdom	Defra	Toddbroo k Reservoir Dam	Internal erosion due to seepage. Water seeped underneath spillway slabs via crack injection, which occurred due to the deterioration of the chute lining and stagnation pressures. Structural failure due to foundation erosion causing undermining of the chute slabs	1970	2019

				and their collapse, potentially assisted by cracking and corrosion of reinforcement.		
HUGHES, A., 2020. Report on the Nature and Root Cause of the Toddbrook Reservoir Auxiliary Spillway Failure on 1st August 2019. Consett, UK. Canal and Rivers Trust.	United Kingdom	Canal and Rivers Trust	Toddbrook Reservoir Dam	Structural failure due to a combination of excessive uplift pressure, negative (suction) pressure and collapse into a void formed due to foundation erosion and undermining of the chute. Internal erosion due to seepage under the weir and the chute slabs to the lack of effective cut-off and underdrainage system.	1970	2019
YOUNG, J.R. AND PAXSON, G.S., 2010. Undermining of Spillway Chutes. ASDSO Dam Safety 2010. 22 September 2010. Seattle, USA.	USA	Association of State Dam Safety	Colyer Lake Dam	Internal erosion due to seepage. Seepage occurred due to cracking of concrete, open joints along the spillway chute and severely fractured rock materials beneath the spillway.	1966	2002
			Speedwell Forge Lake Dam	Internal erosion due to seepage. Cracking of the spillway chute leading to seepage and development of small voids. Other design deficiencies such as lack of waterstops to prevent flow entering the foundation though joints.	1966	2010
			Leaser Lake Dam	Internal erosion due to seepage. Inadequate cut-off to spillway foundations and severely	1970	2001

				fractured bedrock materials beneath the spillway chute.		
			Township Line Dam	Internal erosion due to seepage. Cracking of the spillway chute due to poor joint details, leading to seepage and development of voids.	1935	1993
			Stoney Creek Dam	Internal erosion due to seepage. Many joint design deficiencies leading to seepage and voids, such as wide openings in joints allowing flow, no waterstop to prevent flow into the foundation though joints and orientation of joints promoting seepage.	1954	1987
			Youngma n Dam	Internal erosion due to seepage. Design deficiencies such as upstream and downstream slabs not dowelled together, corroded and missing copper waterstops in joints and poorly orientated joints allowing water flow through joints.	1951	2001
FRANCE, J.W. AND ALVI, I.A. AND DICKINSON P.A. AND FALVEY, H.T. AND RIGBEY, S.J. AND TROJANOWSKI, J., 2018. Independent Forensic Team Report Oroville Dam Spillway Incident. Colorado, USA. United States Society on Dams.	USA	California Department of Water Resources	Oroville Reservoir Dam	Structural failure due to excessive uplift pressure. Water injection through cracks and joints in the spillway chute leading to uplift forces that exceeded the uplift capacity of the slab. Uplifted section then exposed poor underlying foundations leading to erosion. Structural failure probably assisted by cracking and	1968	2017

				corrosion of reinforcement. Chute flows and temperature variation led to corrosion of reinforcement, reducing slab strength.		
HEPLER, T.E. AND JOHNSON, P.L., 1988. Analysis of Spillway Failures by Uplift Pressure. Proceedings of the 1988 National Conference sponsored by the Hydraulics Division of the American Society of Civil Engineers, August 8-12 1988, Colorado Springs, USA.	USA	American Society of Civil Engineers	Dickinson Dam	Structural failure due to excessive uplift pressure. Offsets in joints developed due to ice pressures beneath the slab and differential settlement between the chute and the dam crest. Absence of waterstops allowing spillway flows to enter the foundation through open joints.	1950	1954
			Big Sandy Dam	Structural failure due to excessive uplift pressure. Cracking in the concrete sidewalls of the stilling basin and chute and lack of pipe drains at points adjoining the chute and stilling basin.	1952	1983
SUNDARAM, M. AND HEDIEN, J. AND DARLING, J., 2018. Design and Construction of The Oakdale Hydroelectric Project Spillway Capacity Expansion. 38th USSD Annual Conference and Exhibition. 30 Apr – 4 May. Miami, USA.	USA	USSD	Oakdale	External erosion due to spillway overtopping.	Unknown	Unknown

MASON, P. AND HINKS, J., 2008. Security of stepped masonry spillways: lessons from Ulley dam. Dams and Reservoirs, 18 (1), 5-8.	UK	BDS	Ulley Dam	Structural failure due to excessive or unaccounted dynamic actions: Loss of mortar pointing, little mortar between masonry blocks and vegetation growth led to development of internal hydrodynamic pressures within walls.	1873	2007
MAUNEY, L., 2021. Case Study: Swift and Two Medicine Dams (Montana, 1964) [online]. Lexington, Kentucky, USA, ASSOCIATION OF STATE DAM SAFETY OFFICIALS. Available from: Swift and Two Medicine Dams (Montana, 1964) | Case Study | ASDSO Lessons Learned (damfailures.org) [accessed 20 May 2021]. [accessed 29 March 2022].	USA	ASDSO	Two Medicines Dam	External erosion due to spillway overtopping. Failure initiation due to erosion at contact point between embankment and spillway retaining walls.	1914	1964
MARGRETT, R., 2018. Llyn Teifi spillway rehabilitation works. Dams and Reservoirs, 28 (3), 102-113.	United Kingdom	ICE	Llyn Teifi	Internal erosion due to seepage. Joint and concrete deterioration allowing flow paths to develop.	1960s	2017
INTERNATIONAL COMMITTEE ON LARGE DAMS (ICOLD), 2012.	China	ICOLD	Fengman Dam	Internal erosion due to seepage. Large plate of poor quality concrete washed away during	1943	1986

Bulletin on Safe Passage of Extreme Floods (Bulletin 142). Paris France. ICOLD.				initial flooding leading to scouring and the formation of a large cavity on the spillway.		
INTERNATIONAL COMMITTEE ON LARGE DAMS (ICOLD), 2000. Rehabilitation of Dams and Appurtenant Works (Bulletin 119). Paris France. ICOLD.	Turkey	ICOLD	Seyhan Dam	Structural failure due to excessive uplift pressure. Hydraulic jump at concrete channel causing severe structural damage, and clogged drainage underneath the spillway contributing to uplift pressures at the damaged area.	1956	1994
US Department of the Interior Bureau of Reclamation (USBR) and US Army Corps of Engineers (USCE), 2019. Best Practice in Dam and Levee Safety Risk Analysis, Chapter F1 – Hydraulic failure of spillway chutes, Version 4.1.	USA	USBR	Hyrum Dam	Internal erosion due to seepage. Cracking and slab movement led to seepage of water, which, in turn, caused erosion and clogging of unfiltered drains.	1935	2003
CHARLES, J.A. AND TEDD, P AND WARREN, A.L., 2014. Lessons from incidents at dams and reservoirs – an engineering guide (CIRIA guide SP167). London, UK. Construction Industry Research and	UK	CIRIA SP167	Chew Magna Dam	External erosion due to spillway overtopping. Erosion from heavy storm leading to four-metre deep hole developing in stilling basin.	1850	1968
			Corsham Lake	Stability failure due to overturning. Spillway unable to cope with flood and becoming partially blocked by collapse of retaining wall.	1880	1968
			Kype	External erosion due to spillway overtopping. Spillway walls overtopped following heavy	1898	1977

Information Association (CIRIA).				rainfall leading to erosion of ground adjacent to the spillway.		
			Walsham Dean Lower	External erosion due to spillway overtopping. Spillway damaged by flood and landslide occurred upstream.	1907	1989
ENVIRONMENT AGENCY, 2017. Post-incident reporting for reservoirs: Annual report 2017. Bristol, UK. Environment Agency.	UK	Environment Agency	Unspecifi ed	Internal erosion due to seepage. Leakage noted at the right-hand side of the overflow spillway led to excavations to investigate the root cause. Excavations revealed large voids underneath spillway side walls and chute. Inadequate cut-off to foundations and absence of filters led to soil migration.	Unknown	2017
			Unspecifi ed	Internal erosion due to seepage. Lack of qualified civil engineer supervising remedial works led to poorly reconstructed spillway. Insufficient compaction of fill against the overflow structure led to internal erosion.	Unknown	2017
ENVIRONMENT AGENCY. 2016. Post-incident reporting for reservoirs: Annual report 2016. Bristol, UK. Environment Agency.	UK	Environment Agency	Unspecifi ed	External erosion due to spillway overtopping. Prolonged period of wet weather led to erosion of areas adjacent to both sides of spillway.	Unknown	2016
WALKER, J., 2008. The discontinuance of Boltby reservoir, North Yorkshire, UK. Dams	UK	BDS	Boltby Reservoir Dam	External erosion due to spillway overtopping. Major flood in 2005 led to spillway damage and erosion of embankment adjacent to spillway. Subsequent physical	1880	2005

and Reservoirs, 18 (1), 17-21.				model testing found spillway to be under capacity for probable maximum flood.		
US Department of the Interior Bureau of Reclamation (USBR) and US Army Corps of Engineers (USCE), 2019. Best Practice in Dam and Levee Safety Risk Analysis, Chapter F2 – Overtopping of Walls and Stilling Basin Failures, Version 4.1.	USA	USBR	El Guapo Dam	External erosion due to spillway overtopping. Spillway walls overtopped during heavy rainfall leading to erosion of surrounding spillway backfill and failure of concrete chute, basin and crest structure.	1980	1999
CHARLES, J.A. AND TEDD, P AND WARREN, A.L., 2014. Lessons from incidents at dams and reservoirs – an engineering guide (CIRIA guide SP167). London, UK. Construction Industry Research and Information Association (CIRIA).	UK	CIRIA SP167	Tumbleton Lake	External erosion due to spillway overtopping. Spillway destroyed by torrential rain.	1885	1946
			Toddbrook 1964	External erosion due to spillway overtopping. Damage to masonry on the lower part of the spillway and erosion of right hand of the embankment adjacent to spillway due to flooding.	1840	1964
CHARLES, J.A. AND TEDD, P AND WARREN, A.L., 2011. Lessons from incidents at dams and reservoirs – an engineering guide. Lessons from historical dam incidents. Bristol,	UK	Environment Agency	Thorters	External erosion due to spillway overtopping.	1900	1948

UK. Environment Agency.						
ENVIRONMENT AGENCY, 2006. Post-incident reporting for reservoirs: Annual report 2006. Bristol, UK. Environment Agency.	UK	Environment Agency	Unspecified	Internal erosion due to seepage. Prolonged deterioration of masonry spillway floor.	Unknown	2006
ENVIRONMENT AGENCY, 2014. Post-incident reporting for reservoirs: Annual report 2014. Bristol, UK. Environment Agency.	UK	Environment Agency	Unspecified	External erosion due to spillway overtopping. Flood reservoir filled and over-spilled and caused erosion of natural ground immediately downstream of dam.	Unknown	2014

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