A review of floodwater impacts on the stability of transportation embankments

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Abstract

Infrastructure embankment failures due to flooding have been recorded in many countries. The consequences of flood-induced embankment failures have mainly been limited to infrastructure downtime; however, failures have caused fatalities and include multiple near-miss events. Here we review the types of flood which cause transportation embankment failure and the associated types of failure, processes which cause failure, and the potential for lasting slope weakening after flooding. Four types of flood which cause transport embankment failure are identified; offset head, overtopping, basal floods at slope toes and floods above slopes. Failure is caused by flood-specific processes including rapid drawdown, sliding, scour and internal erosion in addition to the development of destabilisation from effective normal stress decrease and saturation loading. Existing destabilisation modelling tends to focus on single flood events which cause failure, with limited consideration of repeat flooding and the long-term degradation of embankment strength which may occur following rainfall and flooding. Although there is a well-developed understanding of generic landslide development, we suggest that that there has been limited consideration of the destabilising effects caused by dynamic conditions which develop during repeat flooding. Furthermore, while the effects of live traffic loading from high speed trains during flooding have previously been considered and shown to cause destabilisation, such previous work is found to be limited to specific embankment structures which are not representative of the wider rail network and considerable uncertainty exists for older earthworks. We conclude this review by identifying future research priorities to help improve prediction and mitigation of flood-induced embankment instability.

Keywords: *flooding, landslide, slope instability, internal erosion*

1. Introduction

Flooding has caused structural transport infrastructure failures in countries including the UK, Italy and Japan (e.g. Tsubaki et al., 2017, Polemio and Lollino, 2011, Network Rail, 2016) and is considered one of the most prominent weather-related concerns for railways in the USA (Rossetti, 2007). While consequences of flood-driven embankment failures have largely been limited to infrastructure disruption, five people were killed in Italy in 2005 following a road embankment collapse (Mossa, 2007). Additionally, incidents have included trains travelling over failed embankments (RAIB, 2013b, RAIB, 2017, Bisantino et al., 2016) and embankment failures during train passage (RAIB, 2013a).

In the context of this review, “failure” is considered as a shear displacement of an asset which compromises the performance of the embankment itself or causes a measurable displacement of the road or track bed. This displacement is sometimes identified as a “rough ride” by train drivers at early stages of movement. Other processes that might contribute to displacement, such as dynamic compaction, are not considered in this review. ‘Triggers’ of failure are considered as the direct events which caused failure to occur; ‘causes’ of failure move a slope towards instability but may not be directly attributed to failure in themselves. For the purposes of this review, flooding is defined as the temporary presence of surface water on, or in close proximity to an embankment.

In this review we draw on global literature and datasets where possible. Nevertheless, a significant portion of our findings utilise data and experience from UK rail networks, with which the authors are most familiar. UK rail embankment systems often have an aged legacy and may therefore be susceptible to a wide range of failure types and a long period of exposure to environmental conditions. However, the identified processes and recommendations are applicable to, and draw upon, the broader context of global scenarios and infrastructure asset types.

In China, approximately £40 million were spent per year between 2000 and 2010 on flood-related railway disruption (Hong et al., 2015) and in Austria flooding caused over £100 million of damage to railways between 2006 and 2013 (Kellermann et al., 2016). In the USA, there were 48 flood-related train accidents between 2001 and 2010, causing 38 derailments (Federal Railroad Administration, 2001-2010). In Japan, an average of 202 interruptions to rail operation occurred per year due to flooding between 1991 and 2000 (Noguchi et al., 2000). Globally, approximately 7.5% of road and rail infrastructure assets are potentially vulnerable to 1 in 100 year flood events (Koks et al., 2019). However, while there are frequent media reports of incidents from around the world, there is no global database of flood-driven transportation infrastructure failures, so their true frequency is not known.

Transportation infrastructure landslides are relatively common in the UK, with over 160 failures recorded across UK road and rail networks in the winter of 2000-2001 alone (Ridley et al., 2004, Rail Engineer, 2012) and 381 rail earthwork failures between 2014 and 2019 (Network Rail, 2018). In addition to the obvious cost implications of network downtime and the challenges created for users, multiple near-miss incidents have been recorded in recent years. These include derailments and the trapping of 57 people on a road section between two failures during the Glen Ogle landslides in 2004 following heavy rainfall (Gibson et al., 2013, Winter et al., 2005, Winter et al., 2016). While only a subset of landslides on infrastructure assets are directly related to flooding, disentangling the mechanisms resulting from the presence of standing water, as opposed to effects of intense rainfall remains challenging. The 2017 UK Climate Change Risk Assessment stated that 17% of UK railway tracks are susceptible to river flooding, 9% to coastal flooding and 17% to groundwater and surface water flooding (Dawson et al., 2017). The report further highlighted that circa 2400 km of UK tracks are considered at a high risk of flooding. Network Rail (2016), who maintain and operate the rail infrastructure in the UK, suggested that 35% of UK rail embankments are at risk of flooding. Recent evidence suggests changing rainfall patters will result in an increased incidence of flooding (Field et al., 2012). In addition, the growth of road and rail traffic leads to larger live load application and an aging asset inventory mean there is a growing vulnerability to damage. This is particularly true for rail embankments where larger and faster trains are being used on the rail network.

UK rail embankments were primarily built during the late 19th Century meaning there is often little known about the geotechnical history of individual sites. The construction techniques and materials used are rarely well recorded and there are limited data on maintenance and historical instability (Nelder et al., 2006, Network Rail, 2018). The majority of rail embankments were constructed using locally sourced materials. Additional fill, often granular material, has been added to many assets to allow for rail expansion or to accommodate for settlement, failure or subsidence of original fill materials (Figure 1). Assets were often constructed via end-tipping with little or no compaction and little regard for long term stability. Although more modern highway embankments utilise low permeability materials, maintained drainage and compaction (Loveridge et al., 2010), this is less true of rail embankments due to highly permeable ballast toppings.

Unlike in constructed levees, water impoundment is not a primary design focus during transport embankment construction. Construction of levees includes seepage control through substrata, using impermeable blankets or cut-offs, and through embankment bodies, using drainage and low permeability barriers. Granular fills are not generally used in levees protecting human life due to high permeability, low resistance to overtopping erosion and susceptibility to liquefaction (USACE, 2000). Liquefaction susceptibility is higher in poorly consolidated, loose, granular materials (Marto and Soon, 2011). Furthermore, transportation infrastructure has the potential to form linear barriers to flow over large areas of land where it intersects natural flow paths (Figure 2). This can cause flood head development against transport embankments following rainfall (e.g. in *Whalley v. Lancashire and Yorkshire Railway Company* (Bennett, 1884), following dam breach (e.g. Brown et al., 2008), or following river level rise (e.g. the Conwy valley (Wales) failures in 2015 (Rail Engineer, 2016) and flooding of the Asa River (Japan) in 2010 (Tsubaki et al., 2016).

Through assessment of slope failure databases, individual flood-induced earthwork failure reports, geotechnical testing studies of soils subjected to seepage and other flood processes and studies monitoring and modelling slopes subjected to flooding, the aims of this review are to identify:

1) The types of flood and related processes which cause failure, long-term degradation and weakening of slopes;
2) Good practice in the recording of asset deformations associated with flood events;
3) The effects of traffic loading during flooding;
4) Current understanding of how flooding acts as a trigger of landslides and how this can be applied to geotechnical assets.

2. Landslide types and destabilisation processes affecting infrastructure

Landslide threats posed to geotechnical assets can be classed as internal (those that happen on the asset itself, such as material softening due to slope wetting and drying cycles) and external (those that have an origin outside the asset, such as floodwater induced head loading). External processes predominantly have an immediately deleterious effect on the stability of the slope; internal processes mainly cause long-term changes in material properties. Longer-term alterations may be thought of as preparatory processes which allow later triggers to be effective. Figure 3 illustrates the key processes driving asset failure and the timescales over which they occur.

One of the most significant challenges in examining the impact of flooding on geotechnical assets is that no one single dataset in the public domain is sufficiently detailed to allow for primary research, nationally or internationally. Therefore, observations examined herein are a combination of a review of the published literature informed by additional UK-based field data provided by Network Rail and Highways England.

2.1 Landslide types recorded in embankments and cuttings

It is important to consider asset type when assessing failure types; cuttings, embankments and natural slopes have different predominant failure modes due to their composite materials and construction (Table 1). Flooding effects on landslides are dependent on both asset and flood type.

Generally, earth and debris falls and topples as defined by (Hungr et al., 2014) do not occur in embankments as the slopes are insufficiently steep; rock falls and topples are common in cuttings (Lato et al., 2012). Embankment oversteepening may occur due to rapid erosion during flooding, leading to debris and earth falls and topples. Debris flows which affect infrastructure commonly develop at structure intersections, such as tunnel portals and the end of embankments, due to focusing of runoff. Translational failures often occur in cover layers overlying embankment cores (Perry, 1989). Rotational failures can develop following live loading of embankments over clays (Lehtonen et al., 2015).

Loveridge et al. (2010) indicated that while shallow failures occur both in rail and road asset groups, deep seated failures ($\gtrsim$2m depth (Briggs et al., 2016)) are currently rare in highway slope assets but occur more commonly in rail cuttings and embankments. Differences in the occurrence of deep seated failures between assets groups were assigned to younger ages of highway assets (Loveridge et al., 2010) and the increased height of rail earthworks to maintain shallower route gradients. Shallow translational failures occur due to increasing pore pressures near the slope surface, following rainfall (Briggs et al., 2016). In embankments, deep-seated, rotational failures occur in most commonly in slopes formed of cohesive materials (Perry et al., 2003) and are often triggered by prolonged periods of rainfall, flooding or slope load variations (Network Rail, 2018).

Infrastructure earthwork failures are commonly recorded as “washouts”, a broad term encompassing post-failure slope morphologies where material is removed from a supporting structure or a slope face by water flow. Failures recorded as ‘washouts’ range from full slope loss to the localised removal of material from soil pipe outflow. Classification of failures recorded as washouts (following Cruden and Varnes (1996)) include flow-slides (e.g. Railrodder, 2011), localised and full slope debris flows (RAIB, 2013b), translational failures and scour-erosion from runoff (RAIB, 2017). Washout geomorphologies may be formed by ‘complex’ landslide events, described according to their final morphology but with differing initial and secondary failure types; these data are not routinely recorded for failures in infrastructure.

Due to the broad usage and ill-defined nature of the term ‘washout’, we suggest that the term washout or phrase ‘a slope washout occurred’ should not be used to describe failure in slopes. Instead, the term ‘washout’ should only be used to describe post failure slope geomorphology with, where applicable, an additional description of the mechanism of slope failure - i.e. ‘a debris flow failure resulting in a washout’.

2.2 Landslides originating outside of geotechnical assets

External landslide risks to infrastructure are primarily related to failures which develop on slopes outside of asset boundaries before travelling across open land. These failures are primarily debris flows such as at Rest and Be Thankful, Scotland (BGS, 2012). Individual rock blocks can travel significant distances through bounding/rolling on steep, rough terrain. Jaboyedoff and Labiouse (2011) outlined a methodology where such hazards can be assessed. External risks are often difficult to predict, or account for, due to the increased number of factors which must be considered during analysis – many of which may be unknown. While important to consider, risks from external landslides that originate elsewhere in the landscape that might then impact rail infrastructure are not discussed further in this review as they develop on natural slopes due to a wide array of additional processes not further discussed.

3. Floods as a cause or trigger of slope failure and weakening

One of the challenges associated with understanding the role that flooding has on geotechnical assets is disentangling the effects of the flood and the effects of intense rainfall. Such rainfall has the capacity to create slope instability regardless of whether ponding of water occurs. Therefore, to identify a landslide as being caused or triggered by flooding it must meet the following criteria:

1) The landslide is spatially related to, and interacts with, floodwater prior to or during failure;

2) The landslide occurs after water has started to accumulate. That water can be ponded or flowing;

3) The floodwater causes a stress state response in the slope;

4) The proximity of floodwater is appropriate to mechanism of movement (e.g. if the landslide is triggered by erosional processes downslope, the floodwater should not be on the other side of the embankment).

On the basis of these criteria, we identified forms of instability related to flooding, outlined in section 4.

3.1 Types of flood

We collated information available on failure events which developed from flooding for UK road and rail infrastructure, as well as notable events recorded in news reports and academic literature globally. Events with direct impact on live loads are recorded in Table 2. From the identified failures, we suggest four key types of floods which cause failures, as illustrated in Figures 4 and 5. These are:

Offset Head Floods (Figure 4a): Offset head development occurs when embankments act as a temporary dam; flood head primarily develops behind one side of a slope. Partial drainage (e.g. through culverts) and/or water input on the leeside of the slope can cause differential increases in head on both sides of a slope. Internal erosion can develop through embankments, and / or substrata, causing slope weakening without external expression.

Overtopping Floods (Figure 4b): Overtopping floods occur when floodwaters go over the top of an embankment. Overtopping floods often initiate as offset head flood events prior to further floodwater rise. Overtopping floods can cause complete submergence of a slope. It is more common for overtopping floods to flow down the leeside of an embankment, prior to potential breach and lee-slope erosion. Although processes common with offset head floods may develop prior to slope overtopping, these are superseded by overtopping processes, removing altered material.

Basal Flood Development (Figure 4c): Basal floods develop with or without ground saturation. Shallow water presence at the toe of a slope, either an embankment or cutting, increases water levels in slopes, increasing pore pressures and reducing slope strength. Although slope weakening develops, basal floods are primarily causes of failure. In all identified events, live loading was reported as being needed to act as a failure trigger.

Above Slope Floods (Figure 4d): Above slope floods develop above cuttings. During above slope floods, flow occurs down slopes from open land or at the end of constrictions (for example where a cutting stops and an embankment starts), or through slope faces. If above slope floods form in depressions behind slope crests, overtopping may not occur and seepage into and through slopes may be the primary destabilisation method. Mass failures can develop due to wetting front development and saturation. Piping development (Bernatek-Jakiel and Poesen, 2018) and seepage outflow on slope faces can cause localised failures in addition to large scale slope weakening.

Mechanisms associated with each of these four flood types are broadly outlined in Table 3.

4. Flood induced landslide observations

Prior detailed analysis of the number of earthwork landslides following flooding was not identified; this is thought to be related to limited public recording of failures and prioritisation of re-establishing network operation. Available public datasets are predominantly comprised of summary information, without detailed information of material properties or factors such as failure type, flooding history and flood duration. Our analysis of failures comprises data collected from Network Rail and Highways England in the UK, in addition to failures reported in public literature and media globally. Failures identified in media reports were classified using observations of photographic evidence. Agency data was acquired from database extracts and individual failure reports. Offset head floods are identified as the most likely cause of slope failure, accounting for 36% of recorded flood induced failure events. A total of 23 offset head floods, 12 above slope floods, 13 basal floods and 16 cases of overtopping were identified as causing failure (Table 3). The three most commonly recorded causes of slope failure due to flooding in the USA are recorded as overtopping (50%), soil softening due to saturation (31%) and internal erosion (19%) (Transportation Research Board et al., 2016).

Shear failures through embankment bodies, as opposed to underlying strata, have been recorded following basal floods and offset head floods. Above slope floods can cause debris flows, when flow channelisation occurs, and shallow translational failures when water runs down the sides of slopes. Debris flows also occur following offset head and overtopping floods, however these may form as latter stages of complex failures and do not necessarily represent initial failure type. All identified flood related failures in the UK occurred in rail assets. Due to the scarcity of recording internationally, quantification of landslide types most commonly caused by flooding, and asset types most vulnerable to flood related failure, was not possible.

Differences between types of flood-triggered failures categorised above and those identified in previous studies (e.g. Network Rail, 2016, Transportation Research Board et al., 2016) are attributed to the size and consequence of failures associated with each flood type, and the likelihood of their recording in open literature. Small breaches caused by overtopping are less likely to be widely, accurately, and precisely recorded and reported than large-scale individual, discrete failures which are directly consequential. The disparity between the prevalence of overtopping failures (25% of recorded events) found by our investigations, which combines data from public literature and news reports with agency information from Network Rail, and the study by Transportation Research Board et al. (2016) (where overtopping failures comprise 50% of recorded events) is likely due to the Transportation Research Board et al. (2016) study including a greater number of small-scale localised floods.

Failures recorded in the literature show that following flooding there are often groups of smaller failures, rather than large discrete events. Examples include the Conwy Valley (Wales) failures in 2015 (Rail Engineer, 2016) and the failures in Sayo, Japan, in August 2009 (Tsubaki et al., 2017, Tsubaki et al., 2012) where fluvial floods caused embankment failures at multiple locations during individual flooding events. Full details of such failures are generally not recorded. There is limited recording of specific details of multiple failures which occur following widespread flooding in open literature. Therefore, failure reviews conducted by agencies (e.g. Transportation Research Board et al., 2016) are likely to include more inconsequential and small scale failures. Differences in recording practice between agencies and asset owners increase uncertainties in identifying how many failures have occurred in different locations. Two conclusions can be drawn from the lack of failures in road assets: i) when flooding does occur, the more modern road earthwork network is more resilient against flooding; ii) road embankments are constructed in less flood prone areas, or with better drainage, and road earthworks may be equally susceptible to failure as rail embankments if flooding does occur. As limited recorded information is available for flood events affecting transport infrastructure but not causing failure, it is not possible to differentiate between these two potential scenarios.

The lack information about inconsequential floods inhibits development of accurate empirical models of slope degradation due to flooding and the effects of repeat flooding on slope properties. The lack of detailed failure descriptions in the UK creates difficultly in improving reactive maintenance practices, due to a poor understanding of the frequency of individual failure types and slope alterations caused by different flood types. Re-establishing embankment operability, rather than understanding failure process development, is the main focus of asset owners post-failure. We suggest that for slopes impacted by flooding, the following should be, where available, routinely recorded to allow for a developed understanding of how flooding alters slope behaviour: the absolute and relative height of flooding, duration of flood presence, flood flow direction. Additionally, in the event that a failure occurs, the initial failure mechanism and post failure geomorphology should be recorded.

5. Active processes in embankment slopes

Although properties of materials are often assumed to be static over the design life of any given structure, it has to be recognised that there are numerous process ongoing in slopes that will impact on the in-service performance of any geotechnical asset. Such process involving weathering, strain softening (or hardening) or anything that alters the state of effective stress in the ground will result in changes in the slope forming materials. In many cases, these changes may be negligible. However, there are suites of processes that act in embankments which are deleterious to the performance of the asset over design timescales.

5.1 Internal erosion

Internal erosion develops in embankments during flooding when a hydraulic gradient is induced through a slope, causing seepage. Hydraulic gradients primarily develop due to offset head development across slopes. Internal erosion develops through embankment substrata if ground is sufficiently permeable in comparison to embankment permeability (Chang and Zhang, 2013). Particle loss from internal erosion can cause changes in soil density, structure, strength, stiffness, differential settlement and the formation of in-slope permeability barriers. In extreme cases, internal erosion can sufficiently weaken slopes to cause failure. There are three main types of internal erosion (Table 4); suffusion / suffosion, concentrated leakage erosion and backwards erosion / piping development (Polemio and Lollino, 2011, USBR, 2015, Bonelli et al., 2007).

Although an individual flood event may not cause slope failure, or visible changes in slope morphology, consideration needs to be made of the lasting slope degradation caused by a flood. Internal erosion has been shown to cause changes in soil strength behaviour (Figure 6), permeability, stiffness (Yang et al., 2018) and void ratio amongst other factors (e.g. Ke and Takahashi (2012), Chang and Zhang (2011), Ouyang and Takahashi (2015), Sato and Kuwano (2016)). Additionally, internal migration development from the collapse of pipes causes embankment subsidence (Polemio and Lollino, 2011, Bonelli et al., 2007). Localised subsidence may also develop following weathering or dissolution of embankment materials (Ingles and Aitchison, 1969). If subsidence does not occur, material property change development may not be noted by infrastructure owners. Particle migration development is dependent on hydraulic gradient. Internal erosion testing is most commonly undertaken in flexible skinned triaxial apparatus (e.g. Chang and Zhang, 2011) and rigid wall permeameters (e.g. Ke and Takahashi, 2012). Bian et al. (2016) showed internal erosion can cause loss of track support in rail embankments, however slope-scale internal erosion studies are lacking in the wider literature.

Materials are considered internally unstable if they are susceptible to internal erosion development. The primary factor that controls the vulnerability of a soil to internal erosion development is grain size distribution. Gap-graded and well-graded materials, with fines contents of 10-35% and 5-25% respectively, are considered as potentially internally unstable. Above these maximum values, fine particles become loaded, preventing migration (Chang and Zhang, 2013). Internal stability of soils with fines contents between 10-35% for gap-graded soils and 5-25% for well-graded soils can be assessed using stability criteria, based on the relative distribution of coarse and fine particles (e.g.

Wan and Fell, 2008, Chang and Zhang, 2013, Kenney and Lau, 1985, Indraratna et al., 2011, Fannin and Moffat, 2006). Increased angularity and reduced roundness of soil particles reduces the susceptibility of a soil to internal erosion development, due to increased interparticle contact and resistance to particle rotation (Slangen and Fannin, 2017, Shire and O'Sullivan, 2013). Additionally, initial soil density (Ke and Takahashi, 2012) can alter the susceptibility of soil to internal erosion.

Experimental results from Chang and Zhang (2011), and Ouyang and Takahashi (2015) show that the removal of fines from upstream sections of soils does little to reduce the angle of shearing resistance of the soil material and there is a potential increase in strength on the downstream side of the embankment. However, the implication of this loss is the soil may become highly contractive in shear, resulting in the collapse of the soil skeleton (Chang and Zhang, 2011) and there may be reductions in the strength of the material at constant volume shearing. The associated processes are shown in Figure 7. Reductions in soil strength, and increases in contraction, are greater with larger amounts of fine particle removal. Redeposition of fine particles can cause localised increases in soil strength. Strength increases have been attributed to the re-distribution of fine particles into the contacts between coarse-grained particles. Prior to seepage, fine particles are located in void spaces and coat coarse-grained particles (Alramahi et al., 2010). In strength testing undertaken using triaxial apparatus, failure develops through the weakest part of samples. Particle loss is non-linear and causes vertical sample stratification due to particle movement with seepage (e.g. Chang and Zhang, 2011).

Fine particle removal from soils causes increases in soil permeability. However, localised changes in permeability develop when material is moved through soils. Laboratory testing undertaken by Xiao and Shwiyhat (2012) and Chang and Zhang (2011) has shown differential permeability change in samples following seepage. Pore spaces open in upstream zones due to particle removal, increasing sample permeability. Permeability reduces in areas of particle deposition downstream, clogging pore spaces and blocking flow pathways. In embankments, differential particle movement across slopes following flooding has the potential to form permeability gradients across slopes and permeability barriers in depositional zones. Pore-water pressure increases and slope strength reductions are expected in slopes with permeability barriers. Rapid drawdown is the recognised phenomenon that occurs when a water body recedes more rapidly than pore pressures are able to dissipate (Moregenstern, 1963). This pore pressure change can combine with the rapid reduction of the toe weight applied by water. Destabilisation is generated by the onset of strong out-of-slope seepage forces and excess pore water pressure build up in the slope (Figure 8) (Rickard, 2009, Pinyol et al., 2008). Although rapid drawdown failures in granular embankments are rare, reductions in slope permeability following particle clogging will increase the likelihood of rapid drawdown development following flood recession.

In laboratory tests, shear wave velocity (V_s) reductions of up to 40% (Kelly et al., 2012) and 26% (Truong et al., 2010) have been observed following removal of fine particles via dissolution. Reductions in surface wave velocity of up to 30% at the point of failure caused by piping development have been reported in large scale (28 m long x 4 m high) physical model tests (Planès et al., 2016). Parekh (2016) also recorded reductions in V_s following internal erosion throughout a soil mass in a limited number of internal erosion tests. Reductions in acoustic velocity were attributed to reductions in sample stiffness and density, caused by the removal of fine particles and the loss of particle contact (Truong et al., 2010). Fine particle removal allows for a lack of constriction of load-bearing, coarser-grained particles forming the soil skeleton, allowing for increased material movement. Although laboratory testing has shown overall decreases in sample stiffness following internal erosion development, localised increases in stiffness may occur due to the redeposition of fine particles and increases in density. Additionally, the transport of fine particles during seepage causes re-distribution of fine particles to inter-particle contacts during seepage flow (Alramahi et al., 2010). This can cause localised increases in soil stiffness. Stiffness reductions have the potential to cause exacerbations of ground vibrations caused by train passage due to reductions in embankment critical velocity (Madshus and Kaynia, 2000). While internal erosion testing has not been undertaken on materials specific to infrastructure embankments, these processes are applicable to such materials.

5.2 Effects of live loading during flooding

Changes in shear modulus have multiple impacts on embankment function. During flooding, increased saturation and pore water pressures reduce soil shear modulus, increasing deformation and reducing V_s in embankments (Jiang et al., 2016). This is important because of the potential for excessive vibrations in embankments where V_s is low. This concept is known as critical velocity and describes the state where train speed exceeds the velocity of the Rayleigh wave (a type of surface wave) generated by the train. When this condition is reached it can result in excessive ground vibration and material weakening. This problem is generally associated with high speed rail, and soft ground (e.g. low density materials such as peat), where Rayleigh wave velocities are as low as 40 m s^{-1} (Madshus and Kaynia, 2000). Critical velocity exceedance has been recorded occurring in railways over soft ground in Sweden, causing excessive vibrations and restrictions on rail speed (Madshus and Kaynia, 2000, Bian et al., 2016). Jiang et al. (2016), Bian et al. (2016), and Jiang et al. (2015) analysed the effects of high speed rail loading on slopes with varying water tables and flood conditions using a full-scale ballastless embankment model. Water tables at the top of the subgrade caused saturation, which reduced subgrade resonant frequency. In turn, this saturation reduced the critical velocity required to cause embankment degradation and failure, resulting in failure during loading, mimicking high speed rail traffic, up to velocities of 360 km hr^{-1}. Failure was attributed to internal erosion processes, including piping, developing in the outer embankment. Loss of support at the outer embankment section caused increased loading by the central portion of the rail slab which could potentially overcome subgrade strength. These behaviours are different from the behaviour of ballasted tracks (Jian et al., 2014). Additionally, although loading from low-speed rail, which has velocities lower than 200km hr^{-1} (UIC, 2018), is less likely to exceed critical velocities, in areas of soft ground there is the potential for low speed rail to exceed critical velocity thresholds – more so following ground weakening by flooding. Trains may continue to travel at speeds >40 m s^{-1} during flooding. For example, significant train damage was only prevented during flooding and embankment failure in Acquavivia, Italy (October 2005), during train transit due to the high train speed which allowed the train to move past the developing landslide (Ficarella, 2005). Additionally, during a derailment at Stonehaven, Scotland, in August 2020 the train was travelling close to the permitted line speed while flooding was present in the area (Haines, 2020). Consideration is generally not given to the performance of embankments when applying speed restrictions due to flooding; rail speed reductions during flooding are generally applied by operators to prevent train damage RSSB (2015). However, in environments where earthworks are vulnerable to flood inundation, we argue that slope instability should be considered as an important factor influencing the implementation of speed restrictions.

5.3 Scour

There is a significant body of research considering effects and consequences of scour on bridge foundations and other transportation structures (e.g. Lamb et al., 2019, Van Leeuwen and Lamb, 2014, Landers and Mueller, 1996), but earth embankment scour and breaching processes are poorly understood (Schmocker and Hager, 2012) and research is lacking in specific areas. Two distinct types of flood scour develop on embankments: i) overtopping, transverse flow causing cutdown into embankment crests (Tsubaki et al., 2017); ii) parallel flow, causing scour of individual embankment batters. Overtopping is a more commonly a cause of embankment slope failure (ASCE, 2011).

Parallel flow-induced scour is most commonly found in fluvial environments. Basal floods are rarely voluminous enough to cause damage beyond surface erosion and translational failures of near-surface materials. Scour-induced failures initiate as concentrated flow erosion, causing slope instability, followed by mass wasting of destabilised slopes (Qin et al., 2018). Localised features, such as fence posts, overhead rail power line stanchions, and trees, have been shown to cause increased scour and localised failure (Gilvear et al., 1994). River morphology and bank roughness also alter scour occurrence (Blanckaert, 2011, Blanckaert et al., 2012); scour induced failure has increased prevalence on the outside of meanders. Although particle entrainment occurs at a large scale when threshold flow velocities are exceeded, turbulence can cause entrainment when mean velocities are below threshold entrainment values (NiÑo et al., 2003, Thorne, 1982). Threshold entrainment velocities are variable for given grain sizes or lithologies due to variations in angularity, inter-particle forces, compaction and sorting (Buffington and Montgomery, 1997). Additionally, there is a poor understanding of cohesive sediment erosion during different flow conditions and of relationships between physical soil properties and erodibility (Thorne, 1982, Julian and Torres, 2006, Utley and Wynn, 2008).

Susceptibility to entrainment is also dependent on antecedent conditions and the wetting-drying history of a slope (Table 5). These factors make it difficult to assess if specific floods will develop near-bank shear stresses capable of causing localised or mass slope failures. However, flooding scour of slopes is important to consider due to toe scour and undercutting as potential causes of landslides (Freeborough et al., 2016, Perry, 1989). Parallel flow is more likely to cause scour and failure of slopes with granular faces, due to reduced erodibility of cohesive materials (Julian and Torres, 2006, Thorne, 1982, Hooke, 1980).

Overtopping-driven scour cuts down into embankments. In rail embankments, ballast removal forms an initial breach, leading to water downcutting into embankment bodies (Tsubaki et al., 2017). Breach development in granular embankment bodies has been shown to develop in two stages. Initially, a breach channel forms due to erosion, followed by mass wasting events to cause breach widening (Mohamed et al., 2002, Pickert et al., 2011). In embankments formed of cohesive and less erodible soils, breach formation develops through back cutting – i.e. a series of retrogressive ‘steps’ form on the downstream embankment face (Morris et al., 2009, Zhu et al., 2011). These differences are important to consider in relation to duration and size of downcutting until crest height begins to reduce, and the stability of slopes remaining after flooding ceases. Embankment breaches caused by overtopping flow form a washout morphology, either in topping ballast or through full embankment height. Initial soil saturation (Al-Riffai and Nistor, 2013), compaction (Asghari Tabrizi et al., 2017) and grain size (Schmocker et al., 2014, Pickert et al., 2011) have influence on the erosion potential and speed of breach development for embankments constructed from non-cohesive materials. Breach development can lead to localised increases in embankment stability due to breached faces acting as a drainage pathway, increasing slope drainage, reducing *u* in the slope forming materials (Pickert et al., 2011). No evidence has been identified of lasting slope weakening of un-scoured slope regions. Numerical modelling to identify the probability of slopes failing due to overtopping flow has been undertaken. Tsubaki et al. (2016) identified broad regions of rail embankments susceptible to failure, with the accuracy of their models limited by the precision and accuracy of localised topography mapping and knowledge of embankment properties and construction methods. Morris et al. (2009) and ASCE (2011) provided comprehensive reviews of earth embankment breaching processes. Ultimately, the role of scour in generating slope instability comes in terms of changing the state of effective stress. Most commonly, this results from a change to σ_3, however overtopping scour potentially changes σ_2 (σ_2 and σ_3 are the intermediate and minor principle stresses, respectively). Given that the majority of 2D plane strain slope stability models do not consider σ_2, this is potentially a change which is not factored into embankment analysis.

Antecedent conditions have a greater effect on the erodibility of cohesive soils as they are more prone to cracking following desiccation than granular soils (Bell, 2000). However, the impact of desiccation is dependent on the intensity and development of rainfall and flooding (Lawler et al., 1997, Bell, 2000). Longer periods between flood events allows accumulation of weathered material, which can increase permeability and creates a system more susceptible to rapid erosion during flooding (Network Rail, 2018, Lawler, 1995); high river flows erode weakened material which has accumulated over the preceding period of low flow (Prosser et al., 2000). The duration since previous scour events can be used as a proxy for the amount of weakened weathered material and should be considered when assessing embankment stability and scour susceptibility. In the majority of infrastructure assets, slow weathering rates and active infrastructure management will prevent significant accumulation of weakened material between flooding events.

The influence of antecedent conditions is dependent on the type of failure and scale of slope being considered. Scour and shallow failures, such as debris flows and shallow translational slides of surface material layers, are less dependent on long term antecedent conditions than deep seated failures as smaller amounts of water are needed, and at shallower depths, in order to promote failure (Van Asch et al., 1999, Bunce, 2008). The lower permeability of fine grained and un-fissured soils makes them more responsive to longer durations of water input – from flooding and rainfall – as water is not able to drain as freely. Antecedent soil moisture content has also been considered as a correlating factor for landslide development (e.g. Posner and Georgakakos, 2015, Ponziani et al., 2012). Additionally, multi-peak and prolonged flood events have the potential to cause material weakening by increasing in slope water levels and reducing effective stress; large flood events following preceding dry periods are less likely to cause erosion (Simon et al., 2000).

5.4 Sliding

The pushing effect caused by a flood behind embankments can have a destabilising effect, with the potential to cause basal sliding (Figure 9) (Morris et al., 2007). Although translational mass failures may occur, sliding movements are often minor, causing substrata damage. Affected ground may have increased permeability, increasing the chances of under-embankment seepage. The small scale of many geotechnical assets, such as rail and road embankments, does not allow sufficient head for basal sliding to develop solely from changes in pressures (Tsubaki et al., 2017).

5.5 Wetting front development

During prolonged floods there is adequate water supply to allow for infiltration rate to exceed infiltration capacity, allowing a saturated wetting front to develop to an extended depth - increasing pore water pressures and reducing or eradicating matric suctions. These strength reductions have been shown to cause translational landslides at depths of 1-2 m due to reductions in mobilised shear strength (Fourie, 1996, Simon et al., 2000, Zhang et al., 2011). Shallow failures often occur in cover material or weakened surface layers which overlie more competent slope core materials (Perry, 1989). Large-scale, deep-seated, instabilities are produced by longer periods of inundation and pore pressure development as more water is needed to cause slope destabilisation (Van Asch et al., 1999). Infiltration periods must be longer than the time taken for wetting fronts to reach a given depth (Pradel and Raad, 1993, Fourie, 1996, Zhang et al., 2011). In addition to failures caused by wider wetting front development, macropore presence can allow for rapid water infiltration to depth in soils, creating localised zones of high pore-water pressure and failure (Zhang et al., 2011). Permeability barrier development in slopes, caused by internal migration, can lead to pore water pressure development during flooding and increased chances of slope failure. A detailed review of rainfall and infiltration-based slope destabilisation is provided by Zhang et al. (2011).

Failures associated with rapid drawdown are most commonly observed in reservoirs where water levels are rapidly reduced following semi-permanent high water levels (Alonso and Pinyol, 2016, Pinyol et al., 2008, Johansson and Edeskär, 2014). Flooding has been shown to cause rapid drawdown after sustained or prolonged flood events (Rickard, 2009, USBR, 2015) or following periods of prolonged rainfall (USBR, 2015). Rapid drawdown failures have been recorded in transport embankments (Transportation Safety Board, 1997). In addition, river embankments landslides often occur during the falling limb of flood hydrographs (Thorne, 1982, Lawler et al., 1997, Simon et al., 2000) suggesting the influence of rapid drawdown effects, despite minor changes in flood head. Localised partial failures, for example caused by macropore fluid input or low levels of rapid drawdown, have the potential to develop into larger scale 'retrogressive failures' due to localised stress redistributions (Jia et al., 2009).

While susceptibility to rapid drawdown is identified as a 'common fault' and regular cause of failure in flood embankments (Bettess and Reeve, 1995), there is limited rapid drawdown research on small-scale scenarios (Alonso and Pinyol, 2016, Pinyol et al., 2008). The scarcity of detailed embankment failure analyses is partly due to a lack of case examples (Dyer, 2004). There has been some consideration of smaller slopes using physical models (e.g. Jia et al., 2009); river embankment and flood defence monitoring scenarios, which show rapid drawdown as a cause of slope failure with as little as 1m of head loss (Rinaldi et al., 2004, Liang et al., 2015, Dyer, 2004); and numerical models (e.g. Moregenstern, 1963). However, this physical model work has only considered situations where initial water levels are at slope crests - not the rate of water level rise, height of water level rise or duration of standing water presence. Sensitivity analysis undertaken by Franczyk et al. (2016) indicated flood stage, duration of high water and the rate of fall of water are important to consider during rapid drawdown analysis. Furthermore, in many scenarios, floodwaters will not reach the full height of embankments – and when they do, overtopping processes often dominate failures. Seepage from rapid drawdown can cause development of internal erosion due to strong out of slope seepage forces (Li et al., 2019), causing lasting slope weakening. Flooding is most likely to cause rapid drawdown related instability following prolonged flood events, and instability is more likely following repeated hydraulic loading cycles (Jadid et al., 2020). Given the potential for flood events to cause rapid drawdown failure, if there is the possibility of floodwater forming next to a slope for a prolonged period, the effects of rapid drawdown should be considered during stability analysis.

5.6 Discussion of process effects

Menan Hasnayn et al. (2017) showed that flooding significantly reduced the long-term quality of rail subgrade materials, with settlement increasing significantly following flooding due to soil suction reduction. However, only one flood cycle was used during their testing programme. Without maintenance it is possible that additional destabilisation events could further reduce material quality. This is important for embankments which are repeatedly loaded over a wet season or multiple seasons without visible degradation. The importance of the dynamic nature of railway assets has also been highlighted by results from physical models. Take and Bolton (2004), for example, identified the role of cyclic loading in the development of pore pressures. Physical models have also been used to investigate the role of vegetation on embankment stability. Generally, physical and process models have been used to understand the fundamental processes occurring in slopes subject to flood processes. These models have not been used as a design tool, and there is little evidence of their use in a forensic capacity.

Lasting strength reductions, such as the loss of peak material strengths, mean that future flooding and live loading events may act on pre-weakened structures and unexpectedly cause failure. This is of additional concern when there is not visible evidence of material property alteration, for example following suffusion. It is likely that any material property changes and internal erosion derived subsidence will be spatially variable across an embankment site due to directional seepage gradients. Furthermore, subsidence caused by internal erosion during flooding can lead to embankment overtopping, creating larger-scale failures (Wan and Fell, 2008). Grain structure collapse, due to vibrations from vehicle passage with time, may cause subsidence in flooding-altered materials. We are not aware of any completed monitoring programmes which assess the condition change of transport embankments which have been subjected to flooding.

Failures which develop in rail embankments often begin with ballast breaching, developing into lee-slope erosion. Tsubaki et al. (2017) suggested overtopping failures should be considered the primary failure cause in low embankments, as sufficient head to drive other processes is not able to develop. This is consistent with failure causes recorded by the Transportation Research Board et al. (2016), but not with all failures we identified in this study (Table 3). The trigger of flood induced landslide failures is likely to be due to pore pressure increase from wetting front development. Without other destabilising factors including internal erosion and scour, failure likelihood is reduced.

6. Conclusions and further research

We classified four major types of flooding impacting rail embankments: offset head, overtopping, basal and above slope floods. These can cause slope failure during individual flood events and progressive weakening during repeat flooding. Rapid flood recession can also lead to failure via rapid drawdown. Slope destabilisation and failure are triggered by scour, live loading and pore water pressure increases. Internal erosion was identified as a major cause of lasting slope and substrata weakening. Overtopping floods most frequently cause failure. However, failures from all flood types have been identified. Factor of safety changes in slopes that have been affected by flooding and not failed should be considered, as should the effects of live loading events. A fully developed understanding of flood effects on slopes and the development of empirical flood - failure relationships is limited by the poor recording of embankment flooding data. Further work is needed to understand how alteration following repeat flooding events develops. Challenges related to producing such understanding are partially caused by the dearth of records of floods which occur on embankments but do not cause failure, and also by the inconsistent phraseology adopted in record keeping. Specifically, the term 'washout' should be reserved for describing post-failure slope morphology and not used to describe failure processes. There is a well-developed understanding of the ground response to rainfall and the landslide activation processes that develop on infrastructure embankments. However, there are important elements for which there is considerably less information. The most significant of these knowledge gaps relate to:

1) Dynamic interactions which develop between slopes, flooding and traffic loading;

2) The effects of repeat flood events and how materials properties change over the design life of an asset;

3) The intensity of flooding, based on flood height and duration, required to cause slope failure.

Developing a wider understanding of infrastructure failures, including failure types, would allow for identification of how different processes, including flooding, cause failures and also may inform prevention methods which could be utilised. For this to be achieved, geotechnical assessment of landslides in infrastructure should be undertaken prior to clearance and reconstruction. Additional research is needed to assess the lasting impacts of flooding on embankment slopes and this may also help us understand appropriate mitigation measures. The redistribution of fines and how it affects strength, permeability and shear modulus are all potentially significant knowledge gaps for the rail industry especially with the growth of high speed rail globally. Although strength and property degradation have been analysed to some extent in material samples, and potential mechanisms for lasting reductions in the strength of slope forming materials have been identified, it remains unclear what the quantifiable impacts on material degradation of such effects may be during repeat flooding events acting on a slope. Developing an understanding of degradation processes will help to inform the identification of floods which cause failure of embankments, and how these differ with varying initial conditions, lithologies, construction methods, loading histories and loading scenarios. Better understanding of the processes causing failure would allow for identification of the size and type of floods which are likely to cause failure for a given site. Although flood events have been shown to cause failure without traffic loading, the effect of dynamic traffic loads on embankments during floods is an area with little research. Further numerical and physical modelling work is needed to assess traffic speeds which may cause failure during flood conditions for ballasted and ballastless tracks with differing substrate lithologies and structures. Research into flood-destabilisation analysis should also develop process models which predict whether forecasted flood events will cause failure and the potential operational restrictions which may be needed to prevent failure. For this to be undertaken accurately, a detailed understanding of flood destabilisation processes will be needed.

Acknowledgements

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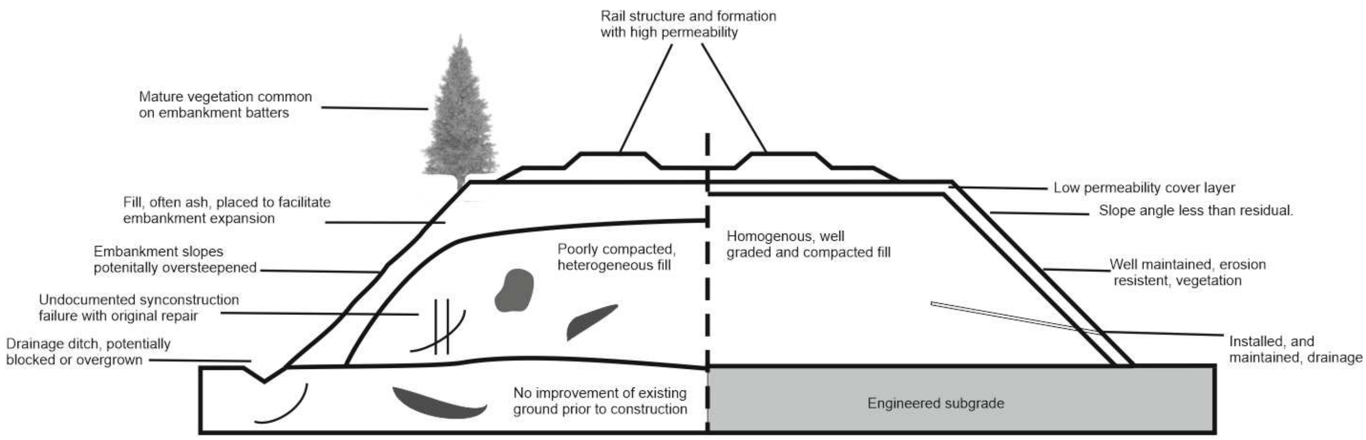

Figure 1: *Schematic comparisons between cross sections of a typical UK embankment (left) and a modern road or rail embankment (right). After Briggs et al. (2017)*

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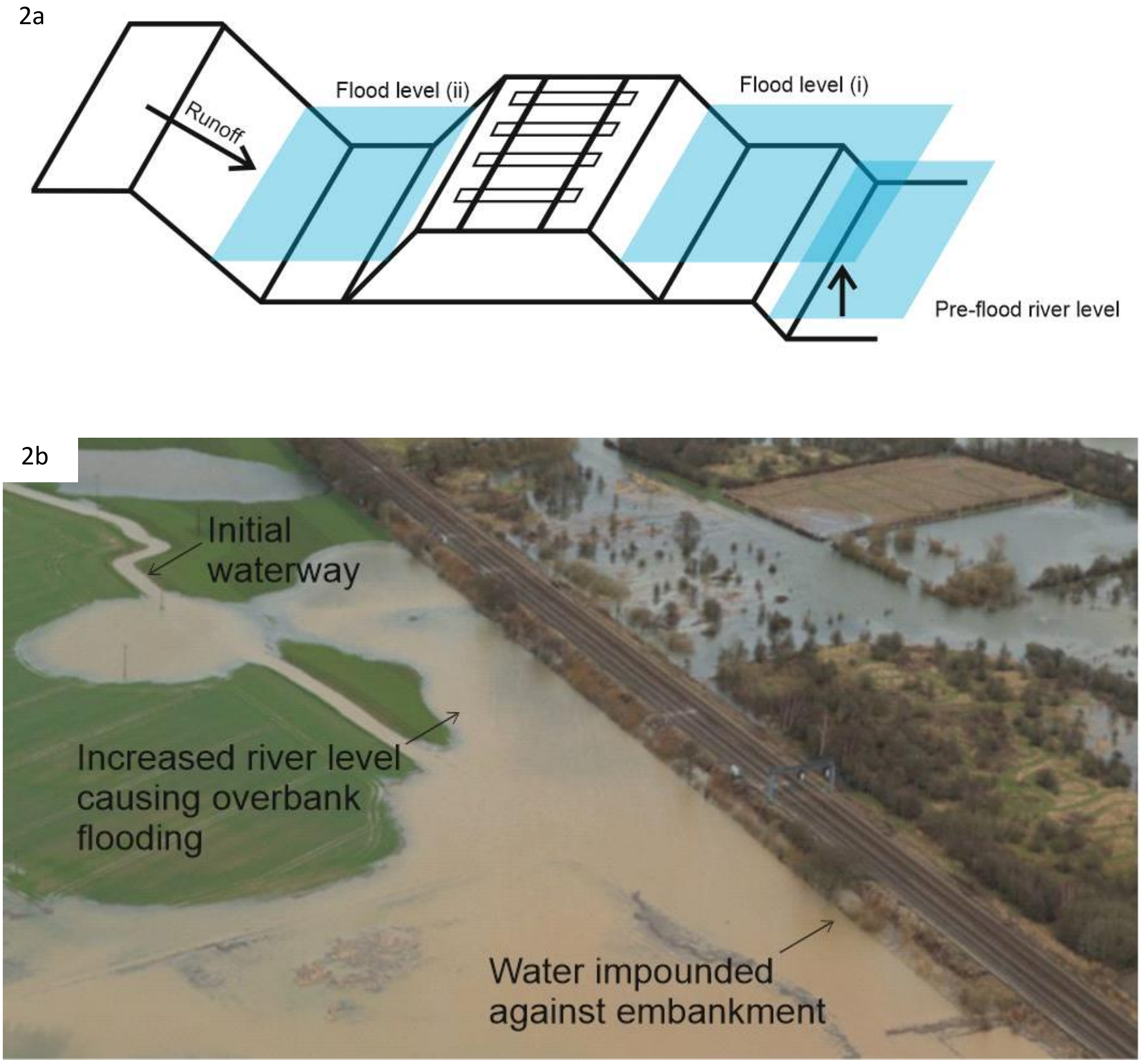


Figure 2: *Embankments form linear barriers to flow: a) representation of flow interception - during river flooding, water level increases causing impoundment (i) where embankments cross floodplains; at the bottom of slopes, or where embankments are formed across slopes, runoff is trapped behind the embankment causing impoundment (ii); b) embankment intercepting river overbank floodwaters during flooding at Church Fenton, UK (copyright Network Rail, 2020).*

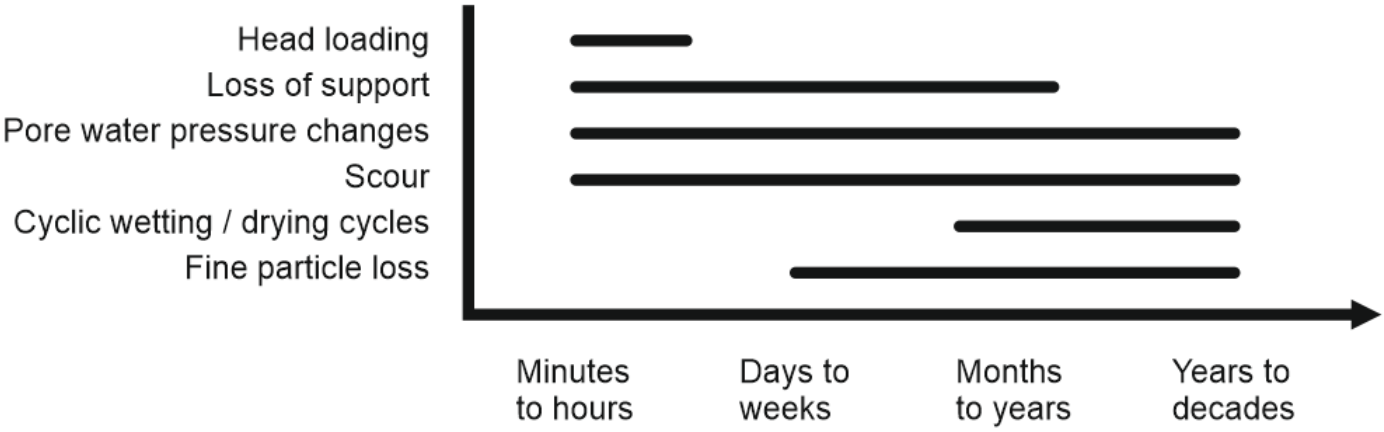
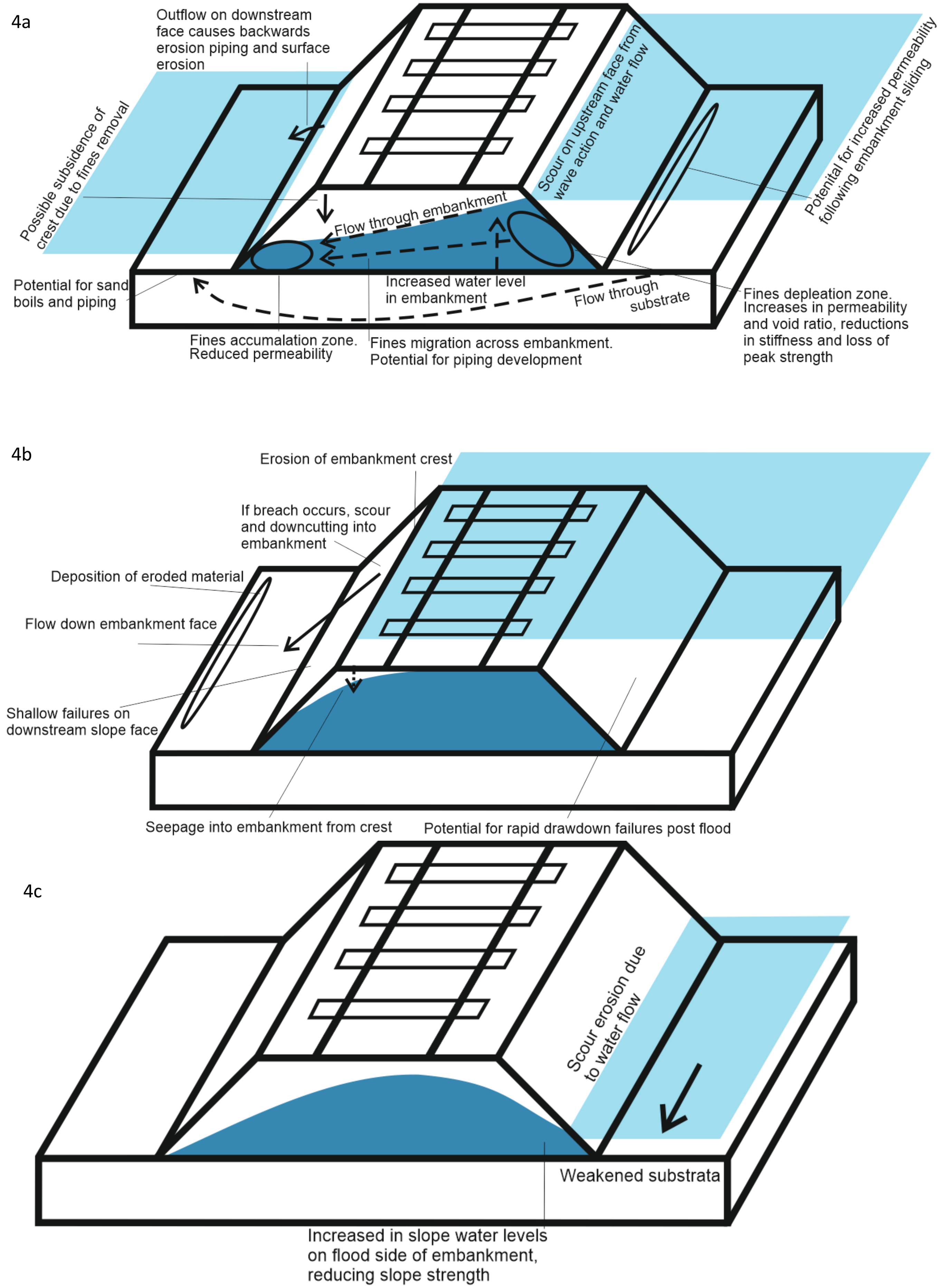


Figure 3: *Timescales over which flood related effects act on geotechnical assets.*


4a
Outflow on downstream face causes backwards erosion piping and surface erosion
Possible subsidence of crest due to fines removal
Scour on upstream face from wave action and water flow
Potential for increased permeability following embankment sliding
Flow through embankment
Potential for sand boils and piping
Increased water level in embankment
Flow through substrate
Fines depleation zone. Increases in permeability and void ratio, reductions in stiffness and loss of peak strength
Fines accumalation zone. Reduced permeability
Fines migration across embankment. Potential for piping development
4b
Erosion of embankment crest
If breach occurs, scour and downcutting into embankment
Deposition of eroded material
Flow down embankment face
Shallow failures on downstream slope face
Seepage into embankment from crest
Potential for rapid drawdown failures post flood
4c
Scour erosion due to water flow
Weakened substrata
Increased in slope water levels on flood side of embankment, reducing slope strength

4d

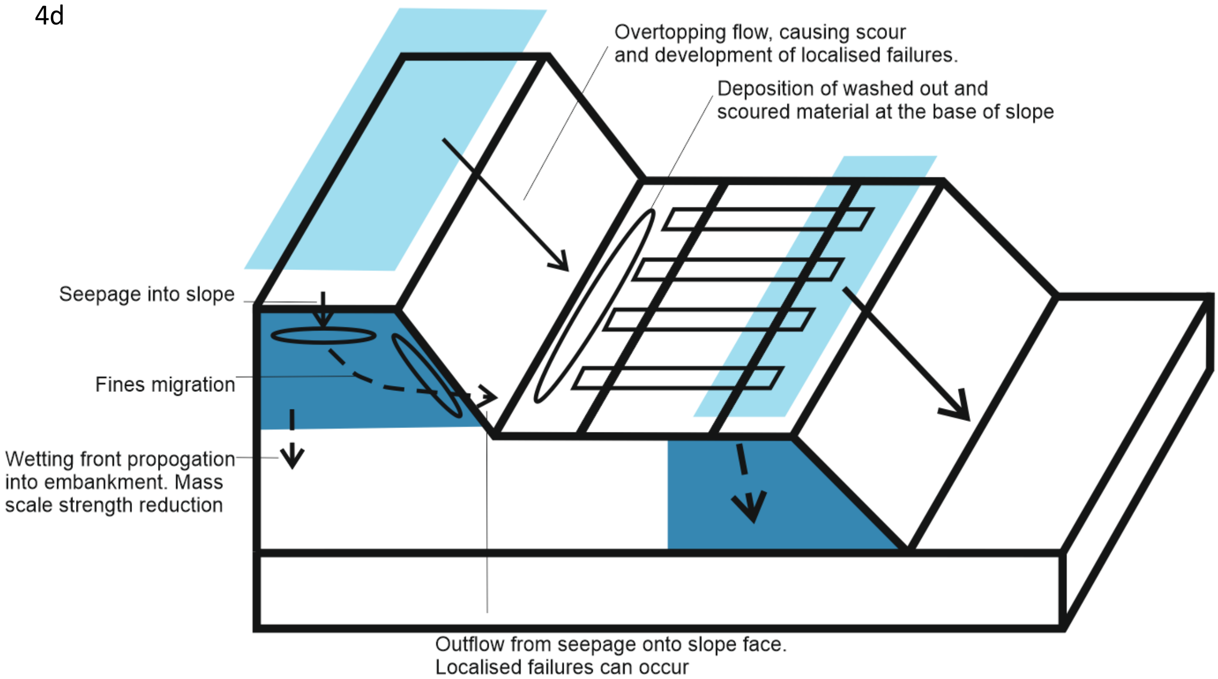


***Figure 4**: Process models of weakening and failure processes developing in slopes during flooding: a) offset head flood; b) overtopping flood; c) basal flood; d) above slope flood. Solid arrow denotes surface water movement. Dashed arrow denotes ground water movement.*

***Figure 5**: Illustrations of rail slopes subjected to flooding: a) embankment failure following offset head flooding in Acquivavia, Italy (October 2005); b) Embankment failure in Conwy, UK, following overtopping flood (March 2019); c) failure of embankment following train loading during basal flooding in Ohio, USA (June 2018); d) floodwater development above slope, causing infiltration in UK (a) reproduced from Polemio and Lollino (2011); b) and d) courtesy of Network Rail; c) courtesy of Sioux County Sherriff.*

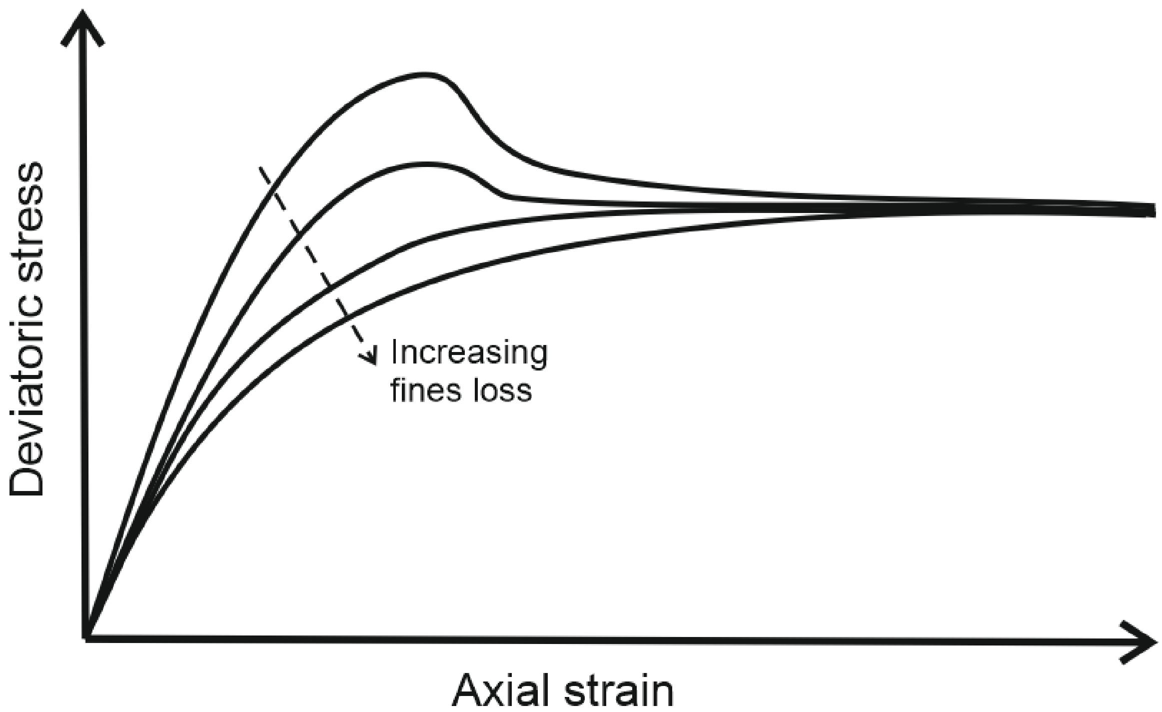


Figure 6: *Schematic representation of strain development during shearing post-seepage and associated fines loss. Increased particle loss causes material softening and samples to fail without displaying peak strength. Critical state strength is consistent between samples of differing amounts of fines loss.*

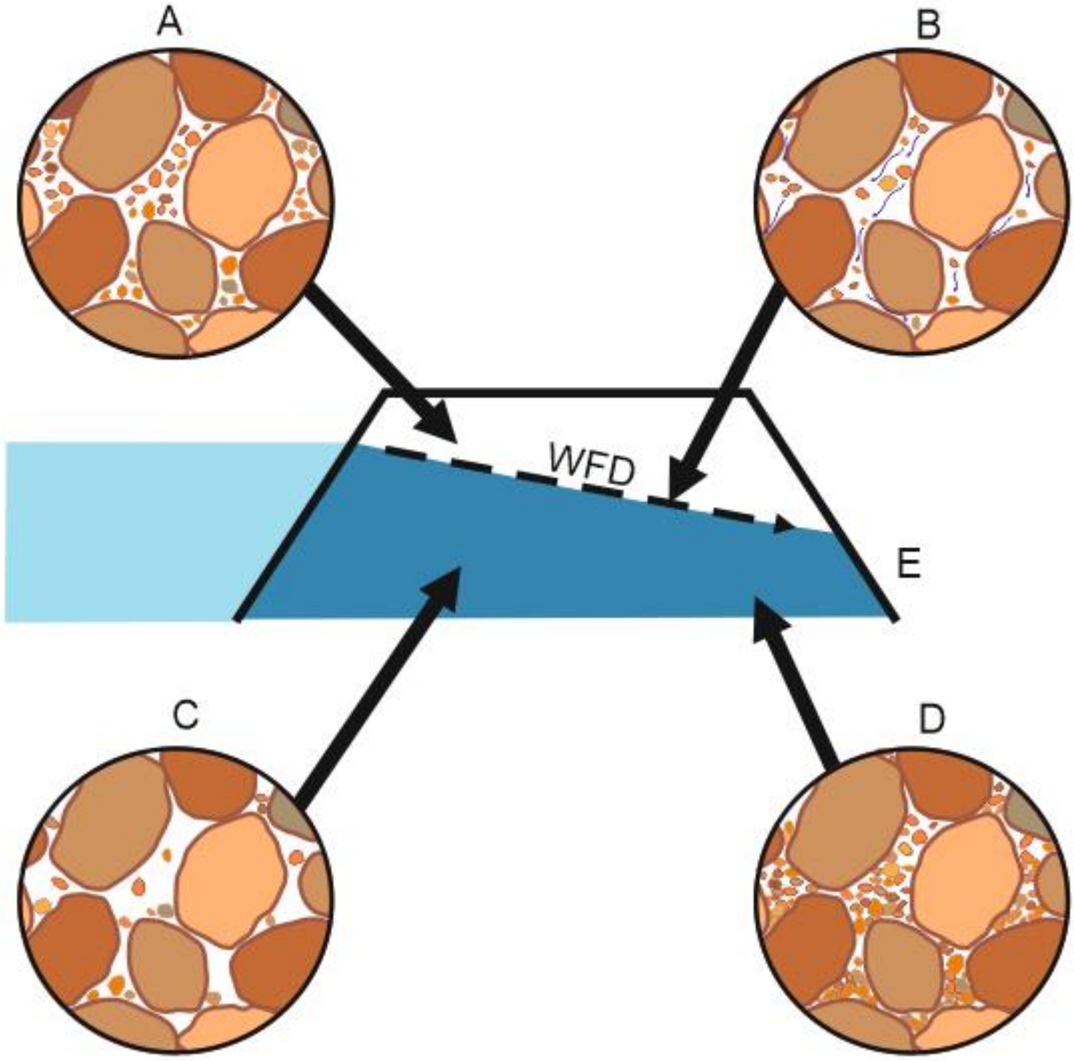


Figure 7: *Soil structure development during seepage.*

***A**: Pre-flood soil skeleton. Fine particles are located in pore spaces and coat coarser grained particles. **B**: Water seepage drives particle motion through soil. **C**: Loss of fine particles forms an unstable soil skeleton. Higher strength and stiffness reductions and contraction behaviour development during shear are expected up-flow due to the loss of fine particles. **D**: Fines redeposition reduces pore space and creates a permeability barrier. Fine particles are concentrated at particle contacts. Strength increases may occur in zones where there is an accumulation of fine particles. WFD – water flow direction.*

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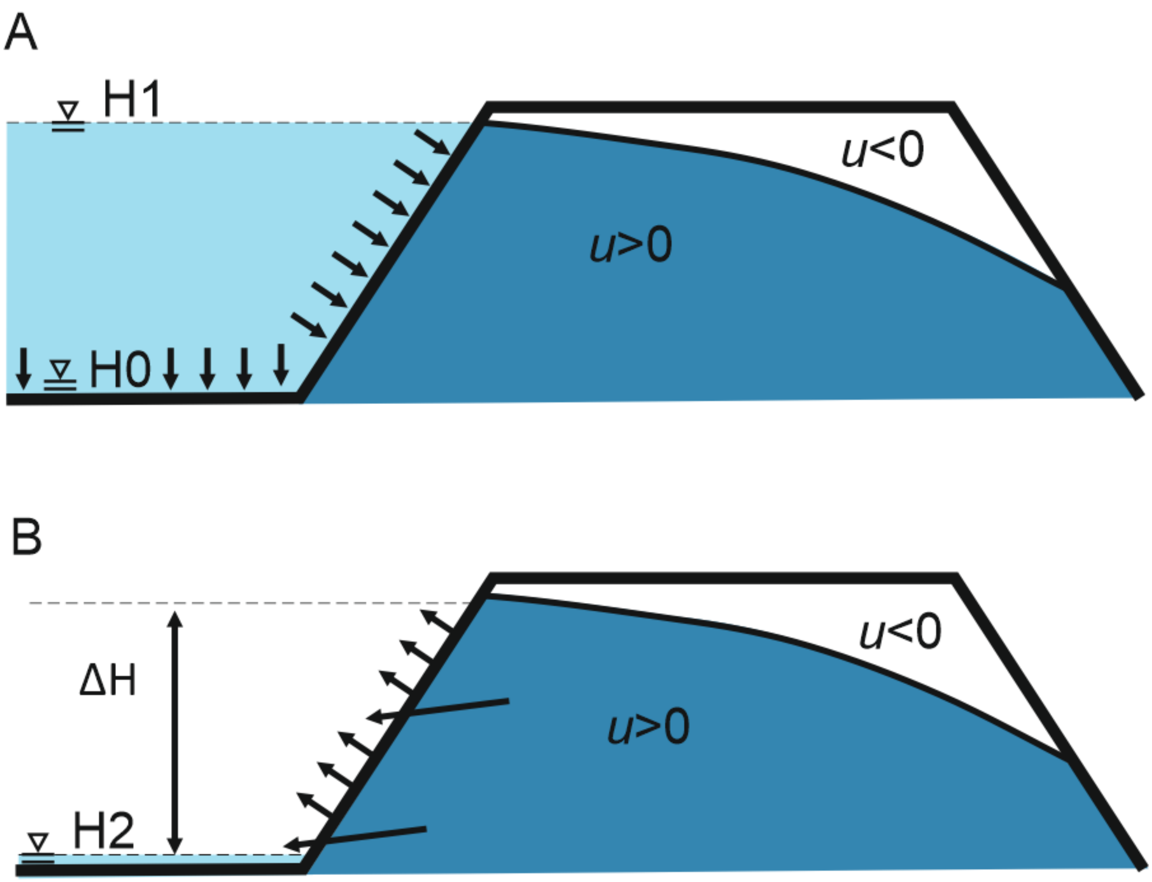

Figure 8: *Rapid drawdown development (u = pore pressure)*

A, Stage 1: *Flood head increase. Initial water level (H0) raises due to flooding to H1, increasing slope saturation and pore pressures, decreasing slope stability. Floodwaters apply confining pressures and aid slope stability.*

B, Stage 2: *Drawdown phase. Floodwaters recede to a new level (H2) and the stabilising effect of floodwater weight is lost. In-slope pore water pressures remain high and strong out of slope seepage forces form. Slope stability decreases when pore water pressures dissipate more gradually than surface waters recede, potentially resulting in slope failure. Soils with higher permeability undergo more rapid u reductions, reducing drawdown effects.*

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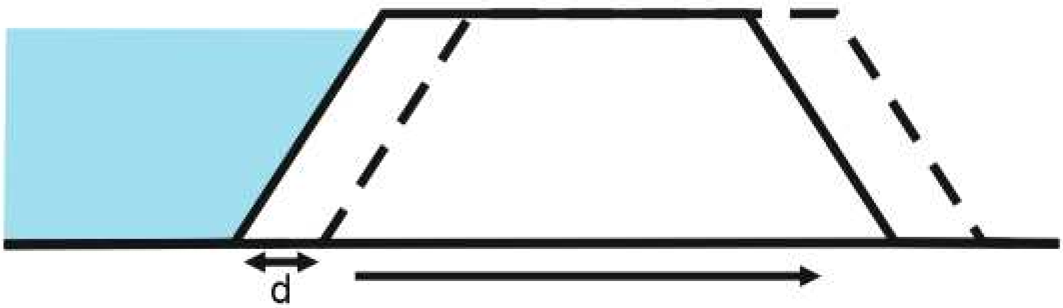

Figure 9: *Basal sliding develops when the shearing force applied by floodwaters overcomes the resistance caused by embankment mass. Displacement, d, can cause increases in substrata permeability and flow pathway development due to rupturing. If embankments are founded on weak substrata, the sliding plane may develop below the embankment-substrata interface.*

Table 1: *Summary of slope destabilisation caused by flooding by asset type and landslide type. Flood effects are based on all failures identified in this review. Landslide types are after Cruden and Varnes (1996). Y = slope is susceptible to this failure. N = slope is not commonly susceptible to this failure. R = slope is rarely susceptible to this landslide type.*

<table>
<tr><th rowspan="2">Landslide type</th><th colspan="2">Cuttings</th><th rowspan="2">Flood effects</th><th colspan="2">Embankments</th><th rowspan="2">Flood effects</th></tr>
<tr><th>Rock</th><th>Debris/ earth</th><th>Cohe-sive</th><th>Gran-ular</th></tr>
<tr><td>Falling</td><td>Y</td><td>N</td><td rowspan="2">Erosion along discontinuities; development of water pressures in tension cracks</td><td>R</td><td>N</td><td rowspan="2">Rapid erosion relating to flooding can result in localised oversteepening.</td></tr>
<tr><td>Toppling</td><td>Y</td><td>N</td><td>R</td><td>N</td></tr>
<tr><td>Sliding</td><td>R</td><td>Y</td><td>Erosion along discontinuities; development of water pressures in tension cracks; changes in effective stress state</td><td>Y</td><td>Y</td><td rowspan="2">Changes in effective stress state; scour of embankment toe; weakening of materials through internal erosion processes.</td></tr>
<tr><td>Slumping</td><td>R</td><td>Y</td><td>Rare in rock cuttings due to limited height and insufficient driving forces; in soil cuttings slumping can occur due to changes in water pressures (see text)</td><td>Y</td><td>Y</td></tr>
<tr><td>Flowing</td><td>N</td><td>Y</td><td>Water flow localisation, causing debris flows, are common phenomena in soil and weak rock assets. These can result in washouts. Large debris flows are more likely to be external risks.</td><td>R</td><td>Y</td><td>Erosion of top of embankment develops into breach; flow down embankment batters causes debris flows and washouts.</td></tr>
<tr><td>Complex</td><td>Y</td><td>Y</td><td></td><td>Y</td><td>Y</td><td>Changes in stress state cause rotational failures; these can develop into flows or flow-slides due to high liquid contents.</td></tr>
</table>

Table 2*: Examples of consequential flood-induced transport infrastructure failures identified during this review.*

Failures	Country and Year	Failure type and number.	Failure result and damage	Flood type	Detail	Reference
Acquaviva,	Italy, 2005	Single major + multiple minor	Washout, injuries to 27 people	Offset head	6.3m of water impoundment against rail embankment in six hours. Embankment was constructed of rockfill core with soil cladding. Failure occurred as a high speed train drove over the failure site. Additional translational failures of cladding material.	Bisantino et al. (2016), Polemio and Lollino (2011).
Knockmore	N. Ireland, 2012	Single major	Washout	Offset head	0.7m head developed across the rail embankment, with water increases on both sides following heavy rain. Construction was a clay base overlain by ash and ballast. Failure occurred when impounded water overtopped clays, causing granular ash to washout.	RAIB (2013b).

Barrow upon soar	United Kingdom, 2012	Single Rotational	Train derailment	Basal flood	The rail embankment was constructed of a clay core with an outer ash layer. Failure occurred as a freight train passed over the site.	RAIB (2013a)
Baildon	United Kingdom, 2016		Washout	Above slope flood	Water running along rail tracks exited at the end of an embankment, causing erosion and washout.	(RAIB, 2017)
Sayo River	Japan, 2009		Multiple failures over 13km	Overtopping + base of slope	12 embankment failures, 9 severe embankment breaches and 56 ballast washouts occurred. Flooding was caused by record breaking rainfall, up to 327mm causing the Sayo River to overflow.	Tsubaki et al. (2017)
Bietto	Italy, 2005		Five fatalities	Impoundment		Mossa (2007)
Stackpool	Canada, 2011	Initial rotational	Washout	Impoundment	Floodwaters are reported to have occurred due to the break of a beaver dam upstream of the site, causing the rail embankment to fail.	Railrodder (2011)

Desert Road	USA, 2008		Washout	Offset head + overtopping	Floodwaters formed against one side of the road, however the culvert was not big enough to prevent water level rise and overtopping.	Fowler (2008)
Paris	France, 2018		Washout. Derailment	Impoundment	During heavy rains, floodwaters in drainage ditch impounded against rail embankment. Train drove over failed section, causing derailment.	RATP (2018)
Doon	USA, 2018		Derailment. Oil spill	Base of slope	Floodwaters at the base of both sides of rail embankment. Train drove onto embankment, causing failure and derailment.	(Independent, 2018)
Black hills	USA,		Washout	Impoundment	Water impounded against rail embankment, causing failure.	USGS (2009)
Julia Creek	Australia, 2015		Train derailment	Base of slope	Floodwaters formed against a rail embankment, causing failure during freight train passage and train derailment.	(Australian Transport Safety Bureau, 2016)
Navarro County	USA		Derailment	Overtopping	Floodwaters overtopping rail embankment. Train drove onto failed section, derailing.	(CNN, 2015)

Stonehaven	Scotland, 2020	Debris flow	Derailment and three fatalities	Above slope flood	Floodwaters overtopped a drainage culvert, causing localised debris flow onto tracks. A train hit the landslide debris, causing derailment.	(Haines, 2020)

***Table 3**: Descriptions and occurrence of the four classified types of flood. The number of failures is recorded as the number of discrete flooding events which have been identified where failure has occurred. Multiple landslides may develop during a single flooding failure event*

Type of Flood	Mechanisms *(less common italicised)*	Materials	Case examples (Table 2)	Number of identified failure event	References
Offset head	Internal erosion Sliding Force Subsidence Rapid drawdown	Poorly sorted, Gap-graded	Acquaviva Knockmore	23 (36%)	Polemio and Lollino (2011), Transportation Research Board et al. (2016)
Overtopping	Surface erosion on lee-side of slope Ground saturation causing material weakening Rapid drawdown	Granular	Sayo River, Japan Conwy Valley	16 (25%)	Tsubaki et al. (2017) (Rail Engineer, 2016)
Basal flood development	Water egress prevented, increasing water level in slope. Scour during flows, causing toe erosion and over steepening.	Scour most prominent in granular materials	Barrow-upon-soar Doon, Iowa	13 (20%)	RAIB (2013a) (Independent, 2018)
Above Slope	Surface erosion from water flowing down embankment batters. Saturation from ponded water, causing pore pressure increase. Internal erosion and piping development through slopes	Erosion most prominent in granular	Baildon	12 (19%)	(RAIB, 2017) Zhang et al. (2011).

Process	Process description	Susceptible materials	References
Suffusion and Suffosion	The movement of fines through the soil skeleton under due to seepage forces without volume change (suffusion) due to skeleton contact or with change in volume suffosion) due to pore collapse.	Internally unstable soils - Gap graded and / or poorly sorted materials. Soils with angular grains are thought the be less susceptible to suffosion	Slangen and Fannin (2017), Wan and Fell (2008), Chang and Zhang (2013)
Concentrated leakage erosion / Contact erosion	Entrainment of particles in existing soil pathways, e.g. voids, and contacts of coarse and fine grained materials, causes macropore development.	Existing pathways in soils	Polemio and Lollino (2011)
Piping / backwards erosion	Erosion initiates at the seepage discharge point on the downstream face of an embankment when seepage forces are strong enough to cause fluidization of material on the free surface. Erosion develops towards the upstream embankment face, forming macropores / pipes.	Most common in uniform sands. Less common in slopes with cohesive, low permeability, outer layers	Bonelli et al. (2007), Beek et al. (2013)

Table 4: *Internal erosion processes*

Table 5: *The effects of antecedent conditions on material preparation.*

Condition	Effect	References
Ground desiccation	Detachment of desiccated blocks increases scour Moisture content decrease increases soil strength Desiccation crack formation increases infiltration into slope	Thorne (1982), Lawler et al. (1997), Lawler (1991), Couper and Maddock (2001)
Freeze thaw weathering	Increased erosion due to loosening of upper soil layers which causes weakening and increases in permeability.	Papanicolaou et al. (2006), Lawler et al. (1997), Lawler (1991), Wolman (1959)
Rainfall intensity	Low intensity rainfall allows desiccation cracks to swell and close. High rainfall intensity exploit desiccation features.	Bell (2000), Lawler et al. (1997)
Prolonged flooding and rainfall	Weakening of bank materials due to increased water content.	Simon et al. (2000)
Vegetation	Increased cohesion and reductions in soil moisture content from roots increase stability. Dense, low level, vegetation is shown to decrease erosion rates. Increased scour can occur around trees and exposed root networks during flood flows.	Lawler et al. (1997), Papanicolaou et al. (2006), Abernethy and Rutherfurd (2000), Keller and Swanson (1979)

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