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1 **A review of floodwater impacts on the stability of transportation embankments**

2

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7

8 **Abstract**

9 Infrastructure embankment failures due to flooding have been recorded in many countries. The
10 consequences of flood-induced embankment failures have mainly been limited to infrastructure
11 downtime; however, failures have caused fatalities and include multiple near-miss events. Here we
12 review the types of flood which cause transportation embankment failure and the associated types
13 of failure, processes which cause failure, and the potential for lasting slope weakening after flooding.
14 Four types of flood which cause transport embankment failure are identified; offset head,
15 overtopping, basal floods at slope toes and floods above slopes. Failure is caused by flood-specific
16 processes including rapid drawdown, sliding, scour and internal erosion in addition to the
17 development of destabilisation from effective normal stress decrease and saturation loading.
18 Existing destabilisation modelling tends to focus on single flood events which cause failure, with
19 limited consideration of repeat flooding and the long-term degradation of embankment strength
20 which may occur following rainfall and flooding. Although there is a well-developed understanding
21 of generic landslide development, we suggest that that there has been limited consideration of the
22 destabilising effects caused by dynamic conditions which develop during repeat flooding.
23 Furthermore, while the effects of live traffic loading from high speed trains during flooding have
24 previously been considered and shown to cause destabilisation, such previous work is found to be

25 limited to specific embankment structures which are not representative of the wider rail network
26 and considerable uncertainty exists for older earthworks. We conclude this review by identifying
27 future research priorities to help improve prediction and mitigation of flood-induced embankment
28 instability.

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

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31

32 **1. Introduction**

33 Flooding has caused structural transport infrastructure failures in countries including the UK, Italy
34 and Japan (e.g. Tsubaki et al., 2017, Polemio and Lollino, 2011, Network Rail, 2016) and is considered
35 one of the most prominent weather-related concerns for railways in the USA (Rossetti, 2007). While
36 consequences of flood-driven embankment failures have largely been limited to infrastructure
37 disruption, five people were killed in Italy in 2005 following a road embankment collapse (Mossa,
38 2007). Additionally, incidents have included trains travelling over failed embankments (RAIB, 2013b,
39 RAIB, 2017, Bisantino et al., 2016) and embankment failures during train passage (RAIB, 2013a).

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

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

54 In China, approximately £40 million were spent per year between 2000 and 2010 on flood-related
55 railway disruption (Hong et al., 2015) and in Austria flooding caused over £100 million of damage to
56 railways between 2006 and 2013 (Kellermann et al., 2016). In the USA, there were 48 flood-related
57 train accidents between 2001 and 2010, causing 38 derailments (Federal Railroad Administration,
58 2001-2010). In Japan, an average of 202 interruptions to rail operation occurred per year due to
59 flooding between 1991 and 2000 (Noguchi et al., 2000). Globally, approximately 7.5% of road and
60 rail infrastructure assets are potentially vulnerable to 1 in 100 year flood events (Koks et al., 2019).
61 However, while there are frequent media reports of incidents from around the world, there is no
62 global database of flood-driven transportation infrastructure failures, so their true frequency is not
63 known.

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

80 aging asset inventory mean there is a growing vulnerability to damage. This is particularly true for
81 rail embankments where larger and faster trains are being used on the rail network.

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

92 Unlike in constructed levees, water impoundment is not a primary design focus during transport
93 embankment construction. Construction of levees includes seepage control through substrata, using
94 impermeable blankets or cut-offs, and through embankment bodies, using drainage and low
95 permeability barriers. Granular fills are not generally used in levees protecting human life due to
96 high permeability, low resistance to overtopping erosion and susceptibility to liquefaction (USACE,
97 2000). Liquefaction susceptibility is higher in poorly consolidated, loose, granular materials (Marto
98 and Soon, 2011). Furthermore, transportation infrastructure has the potential to form linear barriers
99 to flow over large areas of land where it intersects natural flow paths (Figure 2). This can cause flood
100 head development against transport embankments following rainfall (e.g. in *Whalley v. Lancashire
101 and Yorkshire Railway Company* (Bennett, 1884), following dam breach (e.g. Brown et al., 2008), or
102 following river level rise (e.g. the Conwy valley (Wales) failures in 2015 (Rail Engineer, 2016) and
103 flooding of the Asa River (Japan) in 2010 (Tsubaki et al., 2016).

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

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

113

114

115

116 **2. Landslide types and destabilisation processes affecting infrastructure**

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

124 One of the most significant challenges in examining the impact of flooding on geotechnical assets is
125 that no one single dataset in the public domain is sufficiently detailed to allow for primary research,
126 nationally or internationally. Therefore, observations examined herein are a combination of a review

127 of the published literature informed by additional UK-based field data provided by Network Rail and
128 Highways England.

129 **2.1 Landslide types recorded in embankments and cuttings**

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

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

141 Loveridge et al. (2010) indicated that while shallow failures occur both in rail and road asset groups,
142 deep seated failures (≥ 2 m depth (Briggs et al., 2016)) are currently rare in highway slope assets but
143 occur more commonly in rail cuttings and embankments. Differences in the occurrence of deep
144 seated failures between assets groups were assigned to younger ages of highway assets (Loveridge
145 et al., 2010) and the increased height of rail earthworks to maintain shallower route gradients.

146 Shallow translational failures occur due to increasing pore pressures near the slope surface,
147 following rainfall (Briggs et al., 2016). In embankments, deep-seated, rotational failures occur in
148 most commonly in slopes formed of cohesive materials (Perry et al., 2003) and are often triggered by
149 prolonged periods of rainfall, flooding or slope load variations (Network Rail, 2018).

150 Infrastructure earthwork failures are commonly recorded as “washouts”, a broad term
151 encompassing post-failure slope morphologies where material is removed from a supporting
152 structure or a slope face by water flow. Failures recorded as ‘washouts’ range from full slope loss to
153 the localised removal of material from soil pipe outflow. Classification of failures recorded as
154 washouts (following Cruden and Varnes (1996)) include flow-slides (e.g. Railrodder, 2011), localised
155 and full slope debris flows (RAIB, 2013b), translational failures and scour-erosion from runoff (RAIB,
156 2017). Washout geomorphologies may be formed by ‘complex’ landslide events, described according
157 to their final morphology but with differing initial and secondary failure types; these data are not
158 routinely recorded for failures in infrastructure.

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

164 **2.2 Landslides originating outside of geotechnical assets**

165 External landslide risks to infrastructure are primarily related to failures which develop on slopes
166 outside of asset boundaries before travelling across open land. These failures are primarily debris
167 flows such as at Rest and Be Thankful, Scotland (BGS, 2012). Individual rock blocks can travel
168 significant distances through bounding/rolling on steep, rough terrain. Jaboyedoff and Labiouse
169 (2011) outlined a methodology where such hazards can be assessed. External risks are often difficult
170 to predict, or account for, due to the increased number of factors which must be considered during
171 analysis – many of which may be unknown. While important to consider, risks from external
172 landslides that originate elsewhere in the landscape that might then impact rail infrastructure are
173 not discussed further in this review as they develop on natural slopes due to a wide array of
174 additional processes not further discussed.

175

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

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

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

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

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

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

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

189 **3.1 Types of flood**

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

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

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

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

210 *Above Slope Floods (Figure 4d)*: Above slope floods develop above cuttings. During above slope
211 floods, flow occurs down slopes from open land or at the end of constrictions (for example where a
212 cutting stops and an embankment starts), or through slope faces. If above slope floods form in
213 depressions behind slope crests, overtopping may not occur and seepage into and through slopes
214 may be the primary destabilisation method. Mass failures can develop due to wetting front
215 development and saturation. Piping development (Bernatek-Jakiel and Poesen, 2018) and seepage
216 outflow on slope faces can cause localised failures in addition to large scale slope weakening.
217 Mechanisms associated with each of these four flood types are broadly outlined in Table 3.

218

219 **4. Flood induced landslide observations**

220 Prior detailed analysis of the number of earthwork landslides following flooding was not identified;
221 this is thought to be related to limited public recording of failures and prioritisation of re-
222 establishing network operation. Available public datasets are predominantly comprised of summary
223 information, without detailed information of material properties or factors such as failure type,
224 flooding history and flood duration. Our analysis of failures comprises data collected from Network
225 Rail and Highways England in the UK, in addition to failures reported in public literature and media
226 globally. Failures identified in media reports were classified using observations of photographic
227 evidence. Agency data was acquired from database extracts and individual failure reports. Offset
228 head floods are identified as the most likely cause of slope failure, accounting for 36% of recorded
229 flood induced failure events. A total of 23 offset head floods, 12 above slope floods, 13 basal floods
230 and 16 cases of overtopping were identified as causing failure (Table 3). The three most commonly
231 recorded causes of slope failure due to flooding in the USA are recorded as overtopping (50%), soil
232 softening due to saturation (31%) and internal erosion (19%) (Transportation Research Board et al.,
233 2016).

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

242 Differences between types of flood-triggered failures categorised above and those identified in
243 previous studies (e.g. Network Rail, 2016, Transportation Research Board et al., 2016) are attributed

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

253 Failures recorded in the literature show that following flooding there are often groups of smaller
254 failures, rather than large discrete events. Examples include the Conwy Valley (Wales) failures in
255 2015 (Rail Engineer, 2016) and the failures in Sayo, Japan, in August 2009 (Tsubaki et al., 2017,
256 Tsubaki et al., 2012) where fluvial floods caused embankment failures at multiple locations during
257 individual flooding events. Full details of such failures are generally not recorded. There is limited
258 recording of specific details of multiple failures which occur following widespread flooding in open
259 literature. Therefore, failure reviews conducted by agencies (e.g. Transportation Research Board et
260 al., 2016) are likely to include more inconsequential and small scale failures. Differences in recording
261 practice between agencies and asset owners increase uncertainties in identifying how many failures
262 have occurred in different locations. Two conclusions can be drawn from the lack of failures in road
263 assets: i) when flooding does occur, the more modern road earthwork network is more resilient
264 against flooding; ii) road embankments are constructed in less flood prone areas, or with better
265 drainage, and road earthworks may be equally susceptible to failure as rail embankments if flooding
266 does occur. As limited recorded information is available for flood events affecting transport
267 infrastructure but not causing failure, it is not possible to differentiate between these two potential
268 scenarios.

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

280 **5. Active processes in embankment slopes**

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

288 **5.1 Internal erosion**

289 Internal erosion develops in embankments during flooding when a hydraulic gradient is induced
290 through a slope, causing seepage. Hydraulic gradients primarily develop due to offset head
291 development across slopes. Internal erosion develops through embankment substrata if ground is
292 sufficiently permeable in comparison to embankment permeability (Chang and Zhang, 2013).
293 Particle loss from internal erosion can cause changes in soil density, structure, strength, stiffness,

294 differential settlement and the formation of in-slope permeability barriers. In extreme cases,
295 internal erosion can sufficiently weaken slopes to cause failure. There are three main types of
296 internal erosion (Table 4); suffusion / suffosion, concentrated leakage erosion and backwards
297 erosion / piping development (Polemio and Lollino, 2011, USBR, 2015, Bonelli et al., 2007).

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

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

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

324 Experimental results from Chang and Zhang (2011), and Ouyang and Takahashi (2015) show that the
325 removal of fines from upstream sections of soils does little to reduce the angle of shearing resistance
326 of the soil material and there is a potential increase in strength on the downstream side of the
327 embankment. However, the implication of this loss is the soil may become highly contractive in
328 shear, resulting in the collapse of the soil skeleton (Chang and Zhang, 2011) and there may be
329 reductions in the strength of the material at constant volume shearing. The associated processes are
330 shown in Figure 7. Reductions in soil strength, and increases in contraction, are greater with larger
331 amounts of fine particle removal. Redeposition of fine particles can cause localised increases in soil
332 strength. Strength increases have been attributed to the re-distribution of fine particles into the
333 contacts between coarse-grained particles. Prior to seepage, fine particles are located in void spaces
334 and coat coarse-grained particles (Alramahi et al., 2010). In strength testing undertaken using triaxial
335 apparatus, failure develops through the weakest part of samples. Particle loss is non-linear and
336 causes vertical sample stratification due to particle movement with seepage (e.g. Chang and Zhang,
337 2011).

338 Fine particle removal from soils causes increases in soil permeability. However, localised changes in
339 permeability develop when material is moved through soils. Laboratory testing undertaken by Xiao
340 and Shwiyhat (2012) and Chang and Zhang (2011) has shown differential permeability change in
341 samples following seepage. Pore spaces open in upstream zones due to particle removal, increasing
342 sample permeability. Permeability reduces in areas of particle deposition downstream, clogging pore
343 spaces and blocking flow pathways. In embankments, differential particle movement across slopes
344 following flooding has the potential to form permeability gradients across slopes and permeability

345 barriers in depositional zones. Pore-water pressure increases and slope strength reductions are
346 expected in slopes with permeability barriers. Rapid drawdown is the recognised phenomenon that
347 occurs when a water body recedes more rapidly than pore pressures are able to dissipate
348 (Moregenstern, 1963). This pore pressure change can combine with the rapid reduction of the toe
349 weight applied by water. Destabilisation is generated by the onset of strong out-of-slope seepage
350 forces and excess pore water pressure build up in the slope (Figure 8) (Rickard, 2009, Pinyol et al.,
351 2008). Although rapid drawdown failures in granular embankments are rare, reductions in slope
352 permeability following particle clogging will increase the likelihood of rapid drawdown development
353 following flood recession.

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

370 been undertaken on materials specific to infrastructure embankments, these processes are
371 applicable to such materials.

372 **5.2 Effects of live loading during flooding**

373 Changes in shear modulus have multiple impacts on embankment function. During flooding,
374 increased saturation and pore water pressures reduce soil shear modulus, increasing deformation
375 and reducing V_s in embankments (Jiang et al., 2016). This is important because of the potential for
376 excessive vibrations in embankments where V_s is low. This concept is known as critical velocity and
377 describes the state where train speed exceeds the velocity of the Rayleigh wave (a type of surface
378 wave) generated by the train. When this condition is reached it can result in excessive ground
379 vibration and material weakening. This problem is generally associated with high speed rail, and soft
380 ground (e.g. low density materials such as peat), where Rayleigh wave velocities are as low as
381 40 m s^{-1} (Madshus and Kaynia, 2000). Critical velocity exceedance has been recorded occurring in
382 railways over soft ground in Sweden, causing excessive vibrations and restrictions on rail speed
383 (Madshus and Kaynia, 2000, Bian et al., 2016). Jiang et al. (2016), Bian et al. (2016), and Jiang et al.
384 (2015) analysed the effects of high speed rail loading on slopes with varying water tables and flood
385 conditions using a full-scale ballastless embankment model. Water tables at the top of the subgrade
386 caused saturation, which reduced subgrade resonant frequency. In turn, this saturation reduced the
387 critical velocity required to cause embankment degradation and failure, resulting in failure during
388 loading, mimicking high speed rail traffic, up to velocities of 360 km hr^{-1} . Failure was attributed to
389 internal erosion processes, including piping, developing in the outer embankment. Loss of support at
390 the outer embankment section caused increased loading by the central portion of the rail slab which
391 could potentially overcome subgrade strength. These behaviours are different from the behaviour
392 of ballasted tracks (Jian et al., 2014). Additionally, although loading from low-speed rail, which has
393 velocities lower than 200 km hr^{-1} (UIC, 2018), is less likely to exceed critical velocities, in areas of soft
394 ground there is the potential for low speed rail to exceed critical velocity thresholds – more so
395 following ground weakening by flooding. Trains may continue to travel at speeds $>40 \text{ m s}^{-1}$ during

396 flooding. For example, significant train damage was only prevented during flooding and
397 embankment failure in Acquaviva, Italy (October 2005), during train transit due to the high train
398 speed which allowed the train to move past the developing landslide (Ficarella, 2005). Additionally,
399 during a derailment at Stonehaven, Scotland, in August 2020 the train was travelling close to the
400 permitted line speed while flooding was present in the area (Haines, 2020). Consideration is
401 generally not given to the performance of embankments when applying speed restrictions due to
402 flooding; rail speed reductions during flooding are generally applied by operators to prevent train
403 damage RSSB (2015). However, in environments where earthworks are vulnerable to flood
404 inundation, we argue that slope instability should be considered as an important factor influencing
405 the implementation of speed restrictions.

406 **5.3 Scour**

407 There is a significant body of research considering effects and consequences of scour on bridge
408 foundations and other transportation structures (e.g. Lamb et al., 2019, Van Leeuwen and Lamb,
409 2014, Landers and Mueller, 1996), but earth embankment scour and breaching processes are poorly
410 understood (Schmocker and Hager, 2012) and research is lacking in specific areas. Two distinct types
411 of flood scour develop on embankments: i) overtopping, transverse flow causing cutdown into
412 embankment crests (Tsubaki et al., 2017); ii) parallel flow, causing scour of individual embankment
413 batters. Overtopping is a more commonly a cause of embankment slope failure (ASCE, 2011).

414 Parallel flow-induced scour is most commonly found in fluvial environments. Basal floods are rarely
415 voluminous enough to cause damage beyond surface erosion and translational failures of near-
416 surface materials. Scour-induced failures initiate as concentrated flow erosion, causing slope
417 instability, followed by mass wasting of destabilised slopes (Qin et al., 2018). Localised features, such
418 as fence posts, overhead rail power line stanchions, and trees, have been shown to cause increased
419 scour and localised failure (Gilvear et al., 1994). River morphology and bank roughness also alter
420 scour occurrence (Blanckaert, 2011, Blanckaert et al., 2012); scour induced failure has increased

421 prevalence on the outside of meanders. Although particle entrainment occurs at a large scale when
422 threshold flow velocities are exceeded, turbulence can cause entrainment when mean velocities are
423 below threshold entrainment values (Niño et al., 2003, Thorne, 1982). Threshold entrainment
424 velocities are variable for given grain sizes or lithologies due to variations in angularity, inter-particle
425 forces, compaction and sorting (Buffington and Montgomery, 1997). Additionally, there is a poor
426 understanding of cohesive sediment erosion during different flow conditions and of relationships
427 between physical soil properties and erodibility (Thorne, 1982, Julian and Torres, 2006, Utley and
428 Wynn, 2008).

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

436 Overtopping-driven scour cuts down into embankments. In rail embankments, ballast removal forms
437 an initial breach, leading to water downcutting into embankment bodies (Tsubaki et al., 2017).

438 Breach development in granular embankment bodies has been shown to develop in two stages.

439 Initially, a breach channel forms due to erosion, followed by mass wasting events to cause breach
440 widening (Mohamed et al., 2002, Pickert et al., 2011). In embankments formed of cohesive and less
441 erodible soils, breach formation develops through back cutting – i.e. a series of retrogressive ‘steps’
442 form on the downstream embankment face (Morris et al., 2009, Zhu et al., 2011). These differences
443 are important to consider in relation to duration and size of downcutting until crest height begins to
444 reduce, and the stability of slopes remaining after flooding ceases. Embankment breaches caused by
445 overtopping flow form a washout morphology, either in topping ballast or through full embankment

446 height. Initial soil saturation (Al-Riffai and Nistor, 2013), compaction (Asghari Tabrizi et al., 2017) and
447 grain size (Schmocker et al., 2014, Pickert et al., 2011) have influence on the erosion potential and
448 speed of breach development for embankments constructed from non-cohesive materials. Breach
449 development can lead to localised increases in embankment stability due to breached faces acting as
450 a drainage pathway, increasing slope drainage, reducing u in the slope forming materials (Pickert et
451 al., 2011). No evidence has been identified of lasting slope weakening of un-scoured slope regions.
452 Numerical modelling to identify the probability of slopes failing due to overtopping flow has been
453 undertaken. Tsubaki et al. (2016) identified broad regions of rail embankments susceptible to failure,
454 with the accuracy of their models limited by the precision and accuracy of localised topography
455 mapping and knowledge of embankment properties and construction methods. Morris et al. (2009)
456 and ASCE (2011) provided comprehensive reviews of earth embankment breaching processes.
457 Ultimately, the role of scour in generating slope instability comes in terms of changing the state of
458 effective stress. Most commonly, this results from a change to σ_3 , however overtopping scour
459 potentially changes σ_2 (σ_2 and σ_3 are the intermediate and minor principle stresses, respectively).
460 Given that the majority of 2D plane strain slope stability models do not consider σ_2 , this is
461 potentially a change which is not factored into embankment analysis.

462 Antecedent conditions have a greater effect on the erodibility of cohesive soils as they are more
463 prone to cracking following desiccation than granular soils (Bell, 2000). However, the impact of
464 desiccation is dependent on the intensity and development of rainfall and flooding (Lawler et al.,
465 1997, Bell, 2000). Longer periods between flood events allows accumulation of weathered material,
466 which can increase permeability and creates a system more susceptible to rapid erosion during
467 flooding (Network Rail, 2018, Lawler, 1995); high river flows erode weakened material which has
468 accumulated over the preceding period of low flow (Prosser et al., 2000). The duration since
469 previous scour events can be used as a proxy for the amount of weakened weathered material and
470 should be considered when assessing embankment stability and scour susceptibility. In the majority

471 of infrastructure assets, slow weathering rates and active infrastructure management will prevent
472 significant accumulation of weakened material between flooding events.

473 The influence of antecedent conditions is dependent on the type of failure and scale of slope being
474 considered. Scour and shallow failures, such as debris flows and shallow translational slides of
475 surface material layers, are less dependent on long term antecedent conditions than deep seated
476 failures as smaller amounts of water are needed, and at shallower depths, in order to promote
477 failure (Van Asch et al., 1999, Bunce, 2008). The lower permeability of fine grained and un-fissured
478 soils makes them more responsive to longer durations of water input – from flooding and rainfall –
479 as water is not able to drain as freely. Antecedent soil moisture content has also been considered as
480 a correlating factor for landslide development (e.g. Posner and Georgakakos, 2015, Ponziani et al.,
481 2012). Additionally, multi-peak and prolonged flood events have the potential to cause material
482 weakening by increasing in slope water levels and reducing effective stress; large flood events
483 following preceding dry periods are less likely to cause erosion (Simon et al., 2000).

484 **5.4 Sliding**

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

491 **5.5 Wetting front development**

492 During prolonged floods there is adequate water supply to allow for infiltration rate to exceed
493 infiltration capacity, allowing a saturated wetting front to develop to an extended depth - increasing
494 pore water pressures and reducing or eradicating matric suctions. These strength reductions have
495 been shown to cause translational landslides at depths of 1-2 m due to reductions in mobilised shear

496 strength (Fourie, 1996, Simon et al., 2000, Zhang et al., 2011). Shallow failures often occur in cover
497 material or weakened surface layers which overlie more competent slope core materials (Perry,
498 1989). Large-scale, deep-seated, instabilities are produced by longer periods of inundation and pore
499 pressure development as more water is needed to cause slope destabilisation (Van Asch et al.,
500 1999). Infiltration periods must be longer than the time taken for wetting fronts to reach a given
501 depth (Pradel and Raad, 1993, Fourie, 1996, Zhang et al., 2011). In addition to failures caused by
502 wider wetting front development, macropore presence can allow for rapid water infiltration to
503 depth in soils, creating localised zones of high pore-water pressure and failure (Zhang et al., 2011).
504 Permeability barrier development in slopes, caused by internal migration, can lead to pore water
505 pressure development during flooding and increased chances of slope failure. A detailed review of
506 rainfall and infiltration-based slope destabilisation is provided by Zhang et al. (2011).

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

518 While susceptibility to rapid drawdown is identified as a 'common fault' and regular cause of failure
519 in flood embankments (Bettess and Reeve, 1995), there is limited rapid drawdown research on
520 small-scale scenarios (Alonso and Pinyol, 2016, Pinyol et al., 2008). The scarcity of detailed

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

537 **5.6 Discussion of process effects**

538 Menan Hasnayn et al. (2017) showed that flooding significantly reduced the long-term quality of rail
539 subgrade materials, with settlement increasing significantly following flooding due to soil suction
540 reduction. However, only one flood cycle was used during their testing programme. Without
541 maintenance it is possible that additional destabilisation events could further reduce material
542 quality. This is important for embankments which are repeatedly loaded over a wet season or
543 multiple seasons without visible degradation. The importance of the dynamic nature of railway
544 assets has also been highlighted by results from physical models. Take and Bolton (2004), for
545 example, identified the role of cyclic loading in the development of pore pressures. Physical models
546 have also been used to investigate the role of vegetation on embankment stability. Generally,

547 physical and process models have been used to understand the fundamental processes occurring in
548 slopes subject to flood processes. These models have not been used as a design tool, and there is
549 little evidence of their use in a forensic capacity.

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

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

567 **6. Conclusions and further research**

568 We classified four major types of flooding impacting rail embankments: offset head, overtopping,
569 basal and above slope floods. These can cause slope failure during individual flood events and
570 progressive weakening during repeat flooding. Rapid flood recession can also lead to failure via rapid
571 drawdown. Slope destabilisation and failure are triggered by scour, live loading and pore water

572 pressure increases. Internal erosion was identified as a major cause of lasting slope and substrata
573 weakening. Overtopping floods most frequently cause failure. However, failures from all flood types
574 have been identified. Factor of safety changes in slopes that have been affected by flooding and not
575 failed should be considered, as should the effects of live loading events. A fully developed
576 understanding of flood effects on slopes and the development of empirical flood - failure
577 relationships is limited by the poor recording of embankment flooding data. Further work is needed
578 to understand how alteration following repeat flooding events develops. Challenges related to
579 producing such understanding are partially caused by the dearth of records of floods which occur on
580 embankments but do not cause failure, and also by the inconsistent phraseology adopted in record
581 keeping. Specifically, the term 'washout' should be reserved for describing post-failure slope
582 morphology and not used to describe failure processes. There is a well-developed understanding of
583 the ground response to rainfall and the landslide activation processes that develop on infrastructure
584 embankments. However, there are important elements for which there is considerably less
585 information. The most significant of these knowledge gaps relate to:

- 586 1) Dynamic interactions which develop between slopes, flooding and traffic loading;
- 587 2) The effects of repeat flood events and how materials properties change over the design life of an
588 asset;
- 589 3) The intensity of flooding, based on flood height and duration, required to cause slope failure.

590 Developing a wider understanding of infrastructure failures, including failure types, would allow for
591 identification of how different processes, including flooding, cause failures and also may inform
592 prevention methods which could be utilised. For this to be achieved, geotechnical assessment of
593 landslides in infrastructure should be undertaken prior to clearance and reconstruction. Additional
594 research is needed to assess the lasting impacts of flooding on embankment slopes and this may also
595 help us understand appropriate mitigation measures. The redistribution of fines and how it affects
596 strength, permeability and shear modulus are all potentially significant knowledge gaps for the rail

597 industry especially with the growth of high speed rail globally. Although strength and property
598 degradation have been analysed to some extent in material samples, and potential mechanisms for
599 lasting reductions in the strength of slope forming materials have been identified, it remains unclear
600 what the quantifiable impacts on material degradation of such effects may be during repeat flooding
601 events acting on a slope. Developing an understanding of degradation processes will help to inform
602 the identification of floods which cause failure of embankments, and how these differ with varying
603 initial conditions, lithologies, construction methods, loading histories and loading scenarios. Better
604 understanding of the processes causing failure would allow for identification of the size and type of
605 floods which are likely to cause failure for a given site. Although flood events have been shown to
606 cause failure without traffic loading, the effect of dynamic traffic loads on embankments during
607 floods is an area with little research. Further numerical and physical modelling work is needed to
608 assess traffic speeds which may cause failure during flood conditions for ballasted and ballastless
609 tracks with differing substrate lithologies and structures. Research into flood-destabilisation analysis
610 should also develop process models which predict whether forecasted flood events will cause failure
611 and the potential operational restrictions which may be needed to prevent failure. For this to be
612 undertaken accurately, a detailed understanding of flood destabilisation processes will be needed.

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616 additional colleagues at Network Rail and Highways England are acknowledged for discussion, advice
617 and access to records of landslides on their assets.

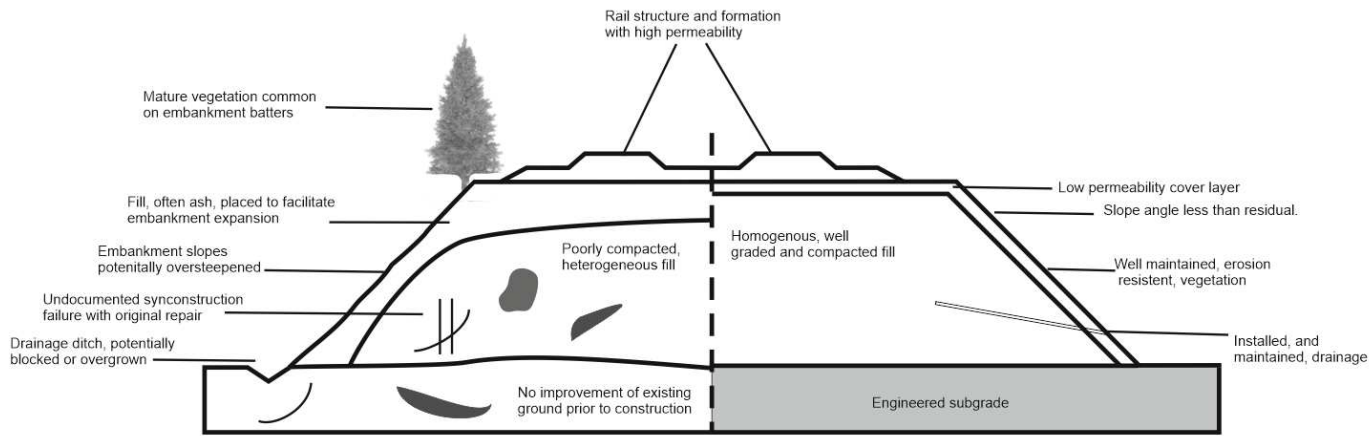
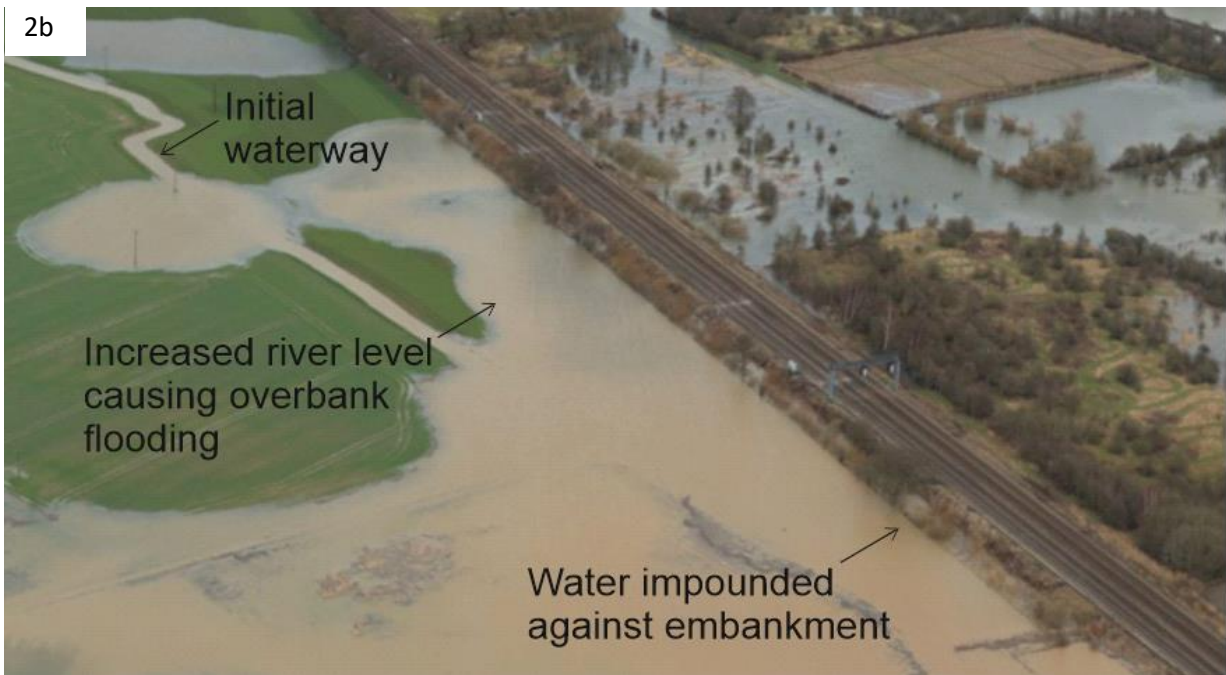
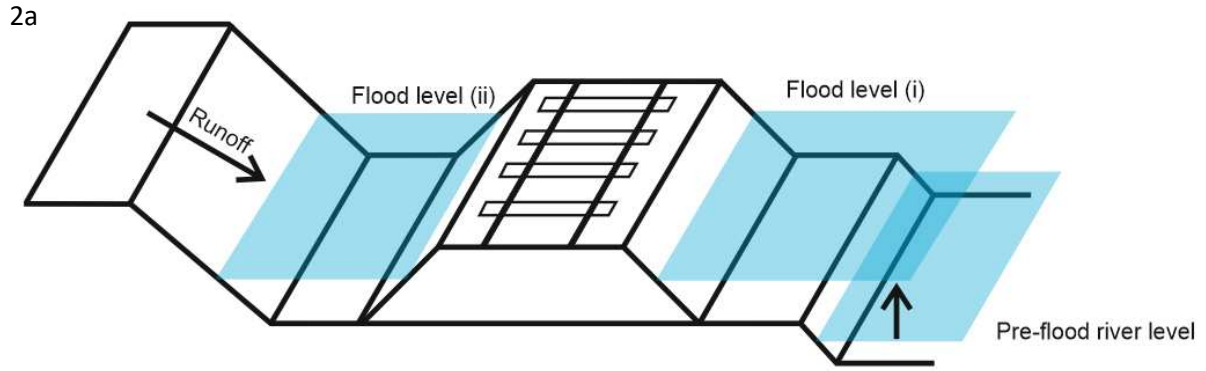


Figure 1: Schematic comparisons between cross sections of a typical UK embankment (left) and a modern road or rail embankment (right). After Briggs et al. (2017)



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

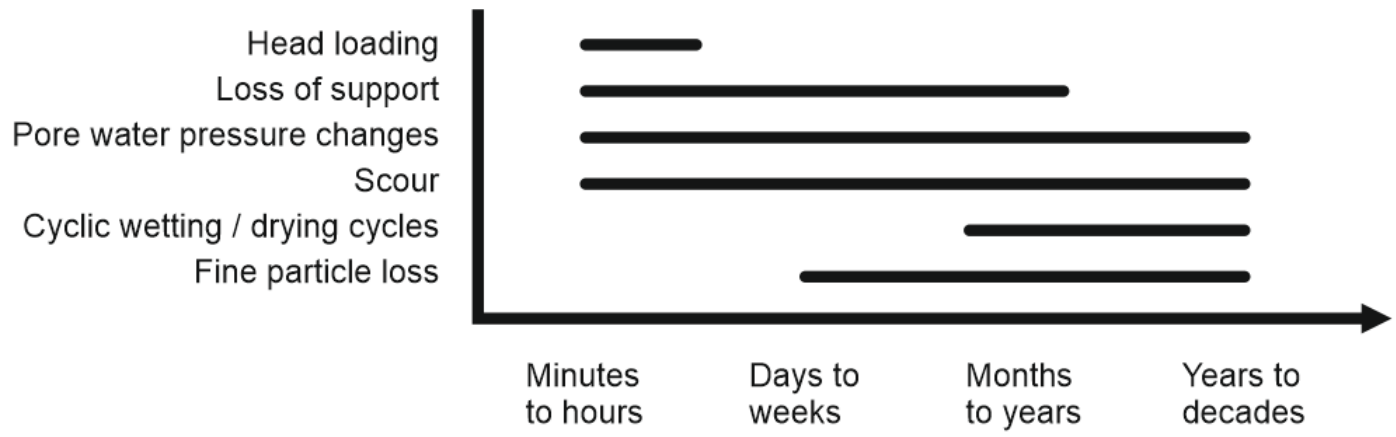
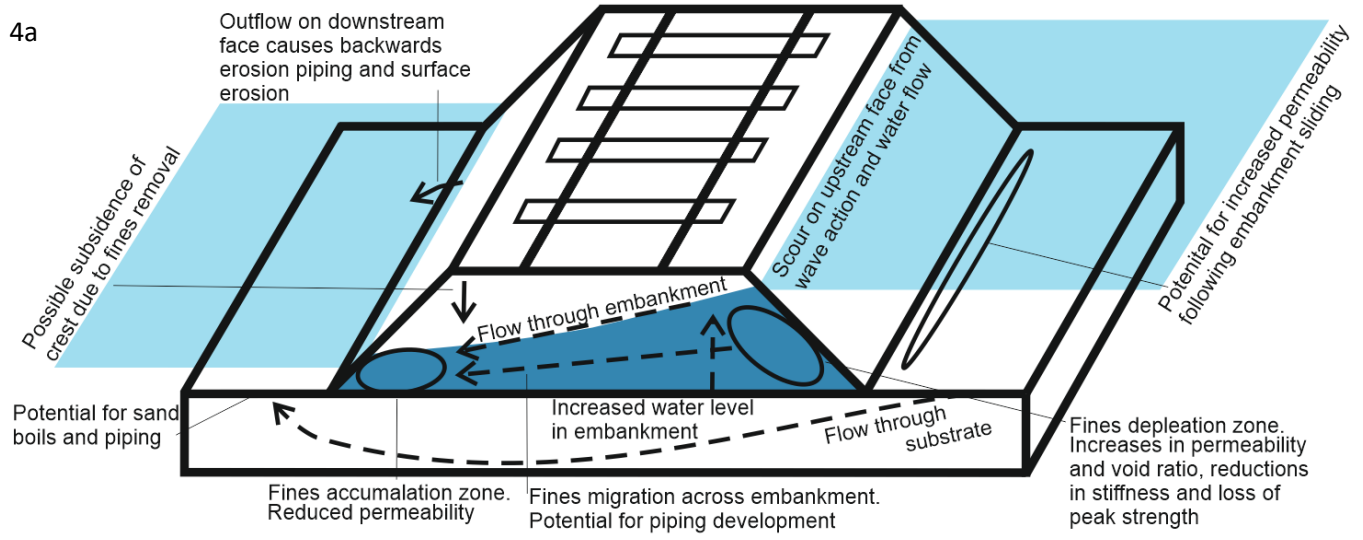
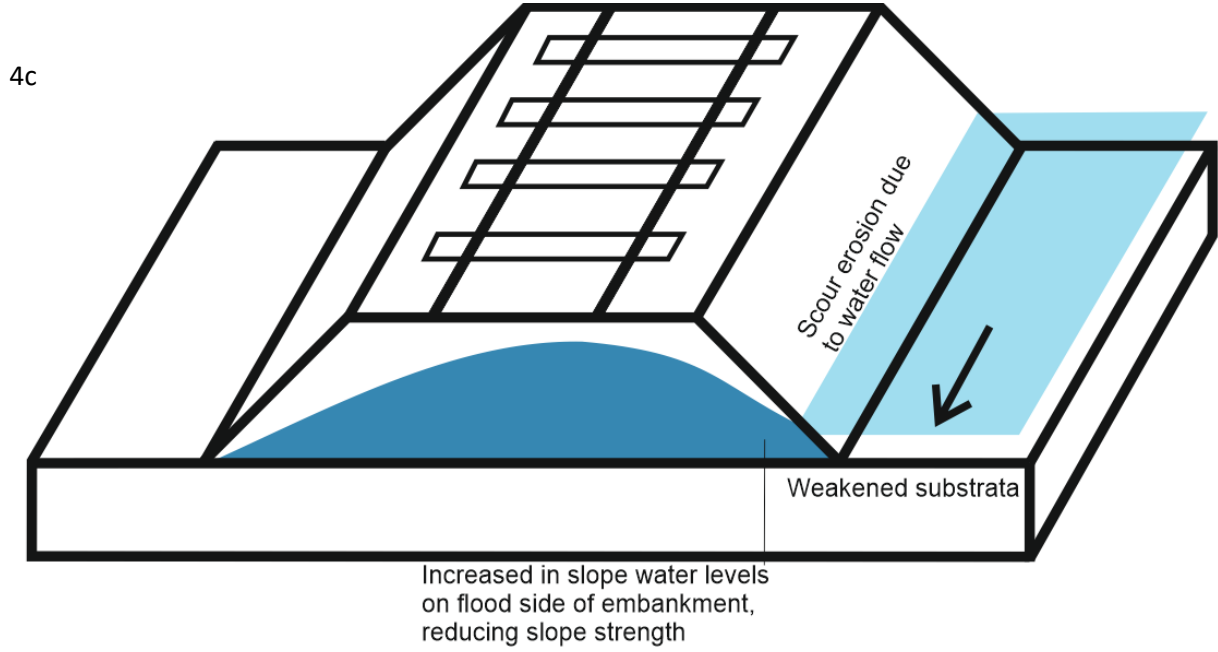
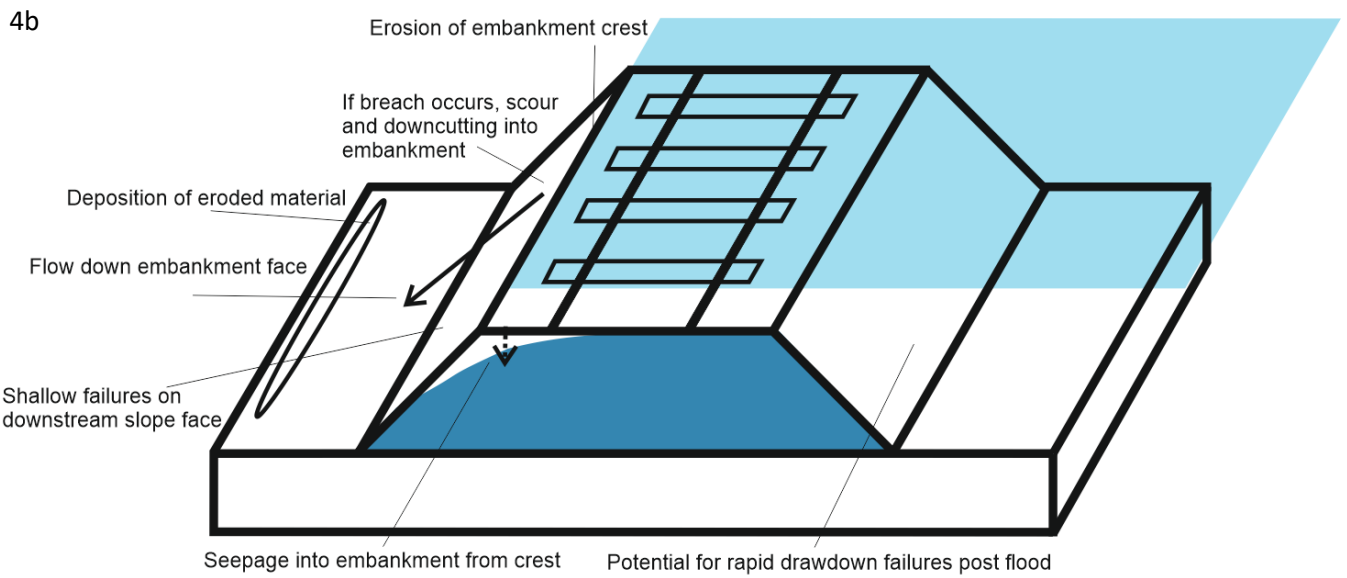


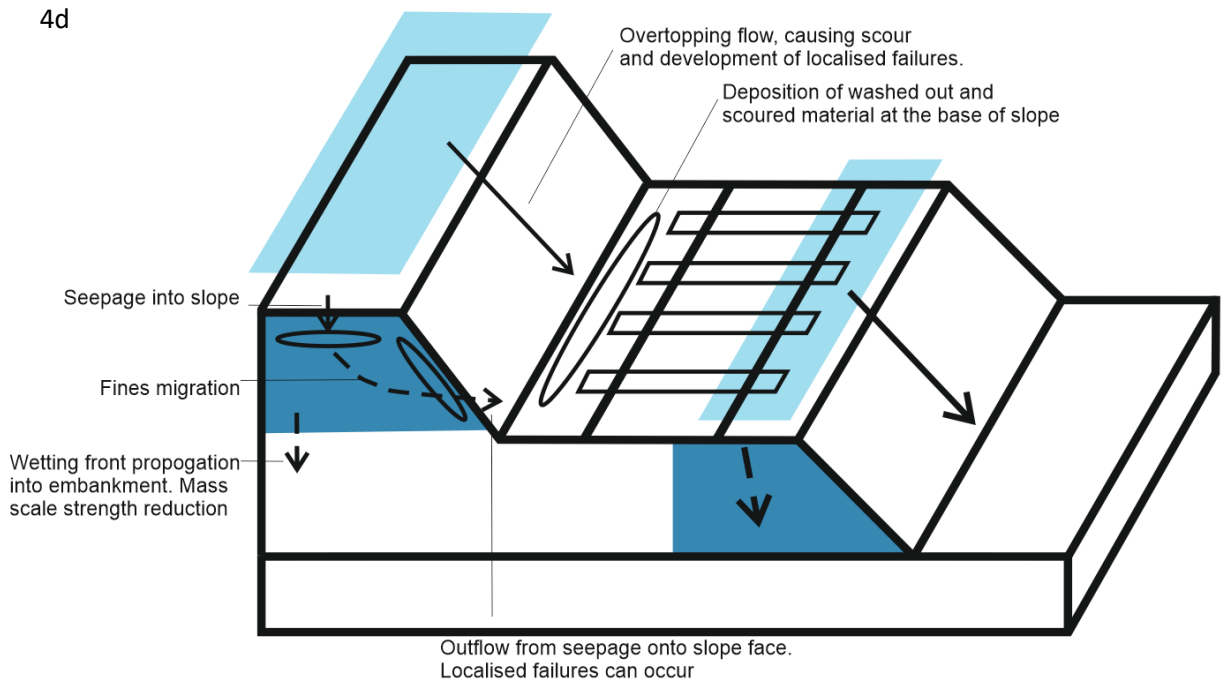
Figure 3: Timescales over which flood related effects act on geotechnical assets.



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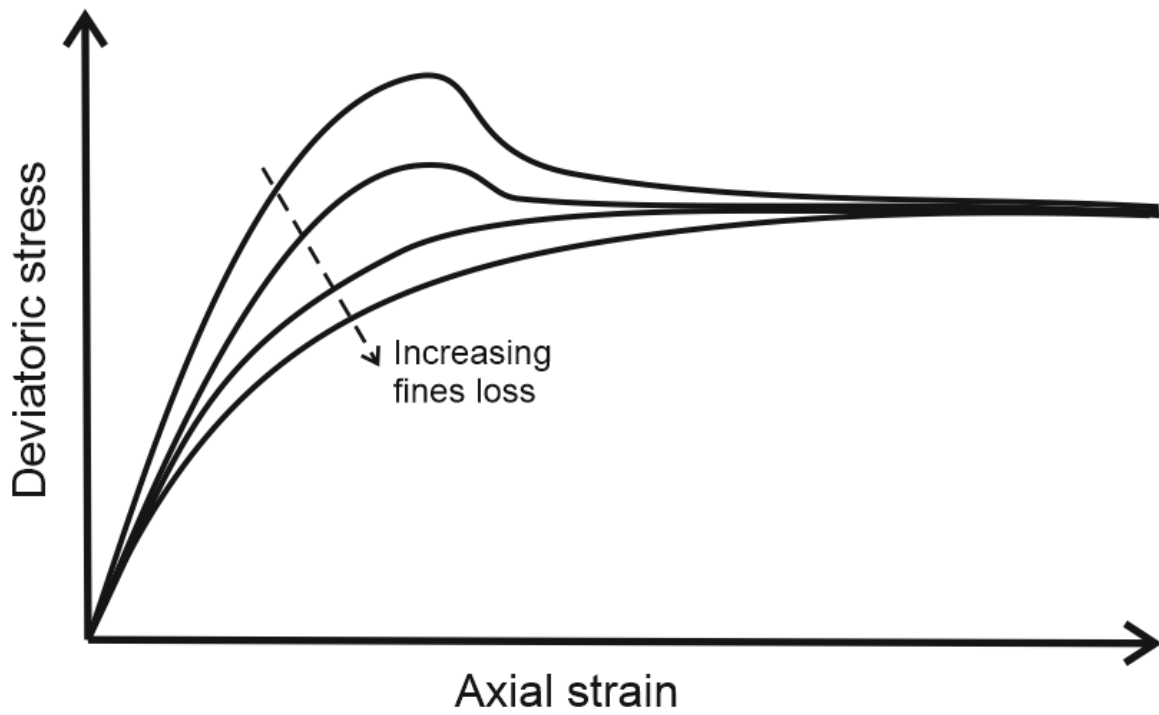
Figure 4: Process models of weakening and failure processes developing in slopes during flooding: a) offset head flood; b) overtopping flood; c) basal flood; d) above slope flood. Solid arrow denotes surface water movement. Dashed arrow denotes ground water movement.

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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.



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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.

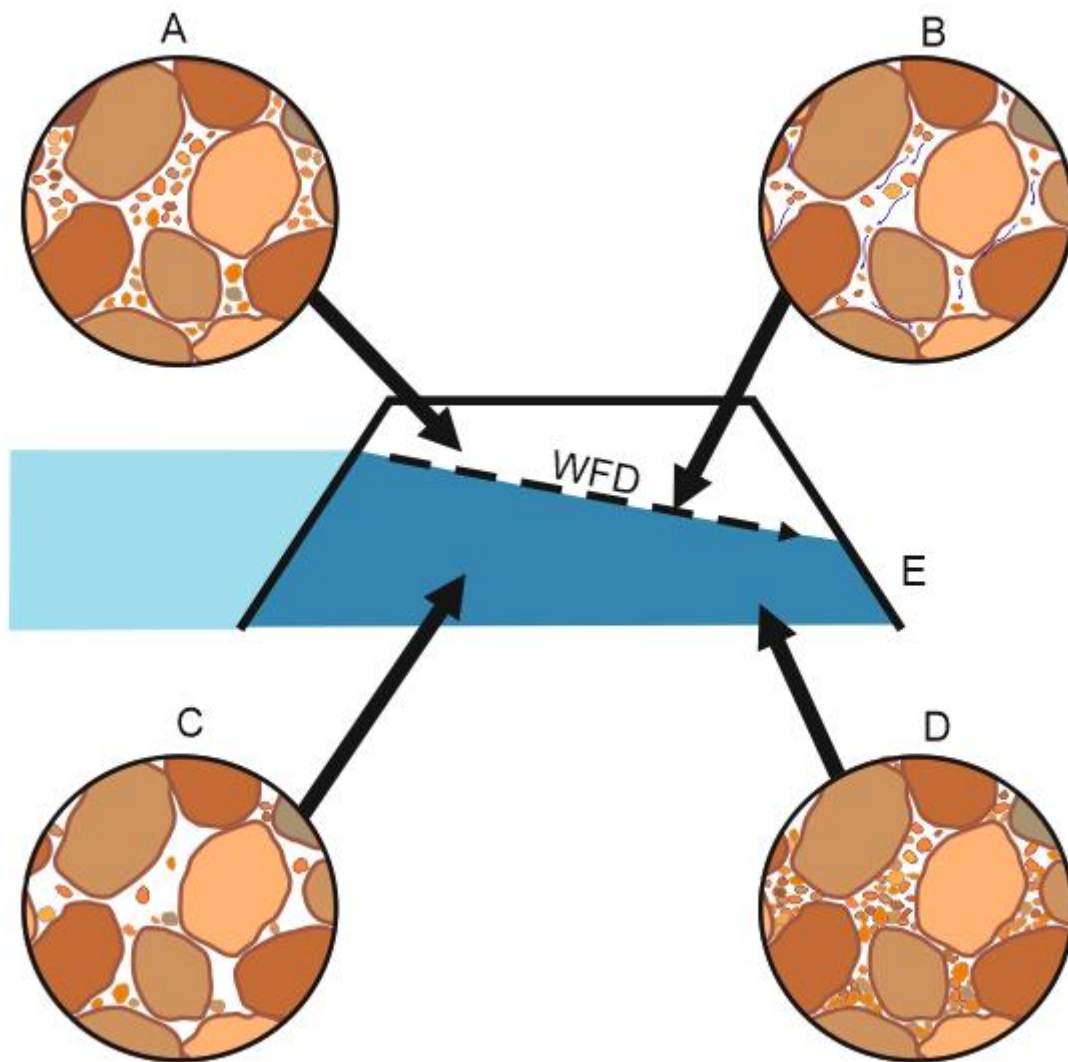


Figure 7: Soil structure development during seepage.

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.

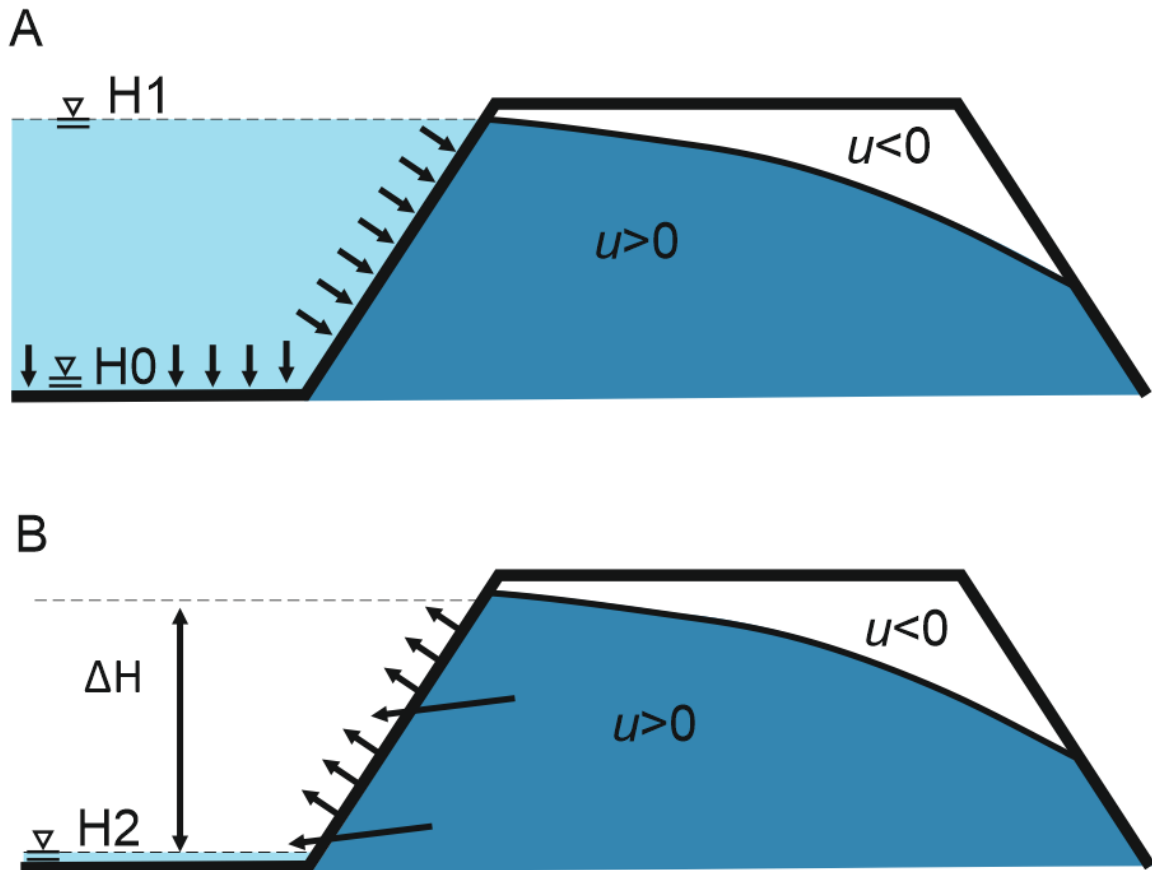


Figure 8: Rapid drawdown development (u = pore pressure)

A, Stage 1: Flood head increase. Initial water level (H_0) raises due to flooding to H_1 , 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 (H_2) 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.

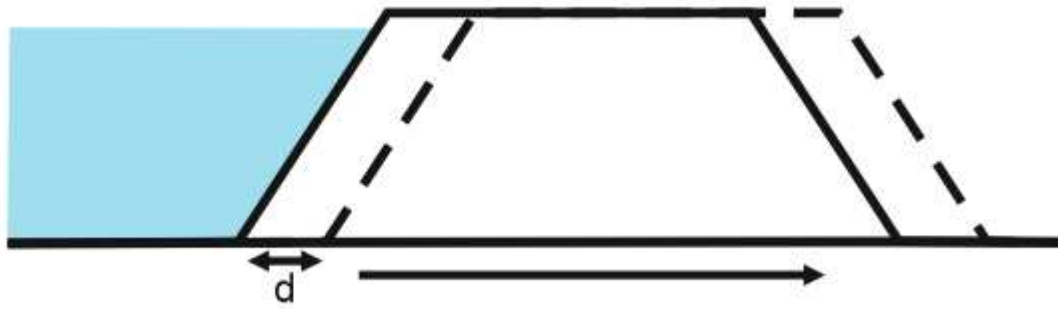


Figure 9: Basal sliding develops when the shearing force applied by floodwaters overcomes the resistance caused by embankment mass. Displacement, d , can cause increases in substrata permeability and flow pathway development due to rupturing. If embankments are founded on weak substrata, the sliding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

634 **Table 1:** Summary of slope destabilisation caused by flooding by asset type and landslide type. Flood
 635 effects are based on all failures identified in this review. Landslide types are after Cruden and Varnes
 636 (1996). Y = slope is susceptible to this failure. N = slope is not commonly susceptible to this failure. R =
 637 slope is rarely susceptible to this landslide type.

| Landslide type | Cuttings | | Flood effects | Embankments | | Flood effects |
|----------------|----------|--------------|--|-------------|-----------|---|
| | Rock | Debris/earth | | Cohe-sive | Gran-ular | |
| Falling | Y | N | Erosion along discontinuities; development of water pressures in tension cracks | R | N | Rapid erosion relating to flooding can result in localised oversteepening. |
| Toppling | Y | N | | R | N | |
| Sliding | R | Y | Erosion along discontinuities; development of water pressures in tension cracks; changes in effective stress state | Y | Y | Changes in effective stress state; scour of embankment toe; weakening of materials through internal erosion processes. |
| Slumping | R | Y | 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) | Y | Y | |
| Flowing | N | Y | 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. | R | Y | Erosion of top of embankment develops into breach; flow down embankment batters causes debris flows and washouts. |
| Complex | Y | Y | | Y | Y | Changes in stress state cause rotational failures; these can develop into flows or flow-slides due to high liquid contents. |

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) |
|------------|-------------------|----------------|---------------------------------------|----------------------|---|----------------|

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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 (<i>less common italicised</i>) | 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 | Baldon | 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 to 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) |

642 **Table 4:** Internal erosion processes

645 **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 Rutherford (2000), Keller and Swanson (1979) |

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