Soils and Rocks
www.soilsandrocks.com
An International Journal of Geotechnical and Geoenvironmental Engineering
ISSN 1980-9743
ISSN-e 2675-5475

Experiments on suffusion of coarse soils from an ageing British dam

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Article

Keywords
Ageing earth dam
Internal erosion
Suffusion
Coarse soils
Laboratory tests

Abstract

This study presents a laboratory investigation on the susceptibility of suffusion in soil samples collected from a very old earth dam. The dam, rebuilt around 1800, is composed of two earth fills and lacks a clay core or filtration components, making it vulnerable to internal erosion. Following an inspection in 2006, concerns were raised about the dam's vulnerability to internal erosion during strong floods. Boreholes and vibro-cores were performed to collect samples, which were then tested for suffusion susceptibility. The study found that four out of six samples were highly susceptible to suffusion erosion, with the erosion process starting at gradients much lower than unity. The opposite was observed for samples with fines content greater than 30% and showing some plasticity. The results were compared to predictions from seven geometric criteria found in the literature, but none of the methods could forecast the behaviour of all tests. The study highlights the need for laboratory tests when there is no agreement between the predictions from available criteria. The findings of this study were used to inform the rehabilitation of the dam, which included installing sand filters designed to capture the smallest particles and relief wells distributed along the entire length and height of the eastern embankment. The study demonstrates the importance of assessing suffusion susceptibility in embankment dam safety control and the need for laboratory tests to validate predictions from geometric criteria.

1. Introduction

The assessment of suffusion is of utmost importance in embankment dam safety control. Suffusion occurs when the finer particles of the soil are carried away by seepage through the constrictions between the coarser particles (ICOLD, 2015). This paper presents a laboratory investigation on the susceptibility of suffusion of soil samples collected from a very old earth dam. It was rebuilt by about 1800 and is composed of two earth fills. The main eastern earth fill is 560 metres long with a maximum height of 12 metres, a crest width of 15 metres and maximum width at its base of 70 metres. The secondary western earth fill is 1300 metres long with a maximum height of 14 metres. The dam fill is heterogeneous with sand, gravel and clay fill, the sands and gravels predominate. The dam has no core or other waterproofing element or filter protection, consequently it is vulnerable to failure by internal erosion. The engineers were concerned about erosion by suffusion, by contact erosion and-or by backward erosion and piping causing unravelling of the downstream slopes (ICOLD, 2017).

Following an inspection in 2006, in which leakages in the Eastern dam were identified, some concerns were raised about the vulnerability of the dam to internal erosion during strong floods (Thompson, 2011). Boreholes were drilled and trial pits were dug to assess the composition of the dam and its foundations. The findings from these investigations reveal that the dam is best defined as unzoned heterogeneous dam, lacking a clay core or filtration components. Core samples of the dam have also been collected to test their resistance to internal erosion.

Prediction of internal erosion in compacted heterogeneous soils is a recurrent challenge for civil engineers. Gravel-sand-silt-clay mixtures used as fill materials in earthen structures are subjected to seepage flows that can induce suffusion (Benamar et al., 2019). Kezdi (1979) introduced the term suffusion as a phenomenon in which water, seeping through the pores, transports finer particles without disrupting the soil structure. Kovács (1981) defined soil suffusion as the rearrangement of fine grains within a layer, wherein the solid volume remains constant, and only the local permeability undergoes alteration. Soils prone to suffusion are typically recognized based on the configuration of their particle size distribution curve. Soils exhibiting concave upward or gap-graded curves are anticipated to be susceptible to suffusion (Lafleur et al., 1989; Skempton & Brogan, 1994; Fannin & Moffat, 2006; Wan & Fell, 2008).

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Submitted on January 12, 2024; Final Acceptance on August 7, 2024; Discussion open until February 28, 2025.
https://doi.org/10.28927/SR.2024.000624

The onset of internal instability in soils is determined by a blend of hydromechanical and geometrical factors (Moffat & Fannin, 2006). There is significant apprehension regarding the safety of embankment dams and levees constructed using soils with the susceptibility for internal instability (Ke & Takahashi, 2012; Liang et al., 2017). A significant volumetric deformation may also arise from the washing out of fine particles (Liang et al., 2019). The migration of finer grains toward an exit point can induce substantial settlement, resulting in the loss of freeboard, subsequent overtopping, and eventual dam failure (Fell et al., 2003; Wan & Fell, 2008; Douglas et al., 2019).

There is a need, in professional practice, to better understand the phenomenon and to develop improved methods to evaluate the susceptibility of an embankment soil to suffusion (Correia dos Santos et al., 2015, 2017). In literature focus has been placed on establishing geometric criteria to classify soils in terms of internal stability (Istomina, 1957; Kezdi, 1979; Sherard, 1979; Kenney & Lau, 1985, 1986; Burenkova, 1993; Wan & Fell, 2008).

Kenney & Lau (1985, 1986) emphasized the internal instability and susceptibility to suffusion in soils, asserting that the percentage of the finer fraction (beyond the inflection point on the particle size plot) must be smaller than the available void space. They suggested a threshold of 20% for well-graded soils and 30% for narrowly graded soils. Wan & Fell (2008) expanded the theoretical limit to 40%, revealing this potential in soil samples with fines content ranging from 22% to 33% for broadly graded soils and 29% to 38% for gap-graded soils.

More recently, Deng et al. (2023) carried out large-scale erosion tests on sandy gravels (without fines content) under different hydraulic loading and surcharge pressures, concluding that the seepage velocity is a better measure for the hydraulic loading than hydraulic gradient. Additionally, the findings indicated that the erosion rate exhibits a proportional decrease with the volume fraction of remaining erodible fine sand particles at a given seepage velocity.

Visual observation and turbidity measurements carried out in the laboratory tests provide a comprehensive description of samples internal instability, enabling the identification of the onset of the suffusion process. The critical hydraulic gradient that initiates suffusion of particles is explored. Criteria proposed in the literature to determine the susceptibility to suffusion erosion is assessed for the tested soils and then compared against the experimental data. In many foundations with heterogeneous soil structures, suffusion and contact erosion can interact simultaneously, especially in double-layered or multilayered soil foundations with a cut-off wall. The retention ratio *Dc35*/*D85SA* (*Dc35* is the constriction size corresponding to 35% finer in coarser fraction and *D85SA* is the grain size corresponding to 85% finer by surface area) between soil layers was used in an experimental study (Zhang et al., 2023) and the results reveal that the effect of the retention ratio on suffusion and contact erosion exhibits a consistent trend. When this ratio exceeds the value of 1, simultaneous suffusion and contact erosion can occur.

2. Materials tested

The two embankments are built with materials consisting of a mixture of silty sands with some gravel, glacial till, and residual soils. Boreholes and vibro-cores were performed in the embankment of the eastern dam and samples were extracted to carry out suffusion tests. The samples for suffusion testing were retrieved from the dam by vibro-core (VC) drilling (Figure 1). This drilling method enables samples to be taken less remoulded below the water table and avoids loss of fine material inherent with cable tool boring in such material. Vibro coring uses a 150 mm diameter steel tube vibrated into the ground below water table to recover ‘grading complete’ samples of granular materials, which are retained as a continuous core sealed within a plastic sleeve inside the tube. Samples were selected from the plastic tubes by the authors for specialist testing to assess their vulnerability to suffusion. Table 1 presents the description of the samples from the boring logs, as well as the fines content and the estimated

Table 1. Main features of tested soil specimens from boreholes.

Soils collected	Layer (m)	Fines content* (%)	Dry density (g/cm^3)	Description of soil layer
VC101-1	3 – 3.5	14.3	2.17	Brown to grey silty sand with gravels, disturbed, very soft – silty sand with gravel
VC101-2	3.5 – 4.5	15.2	1.62	Brown silty sand with gravels, disturbed, very soft - silty sand with gravel
VC101A	3 – 3.5	44.4	1.63	Grey to black silty sand with gravels, disturbed, very soft - silty sand with gravel
VC103-1	4.5 – 5	17.0	1.50	Brown silty sand with gravels, disturbed, soft- silty sand with gravel
VC103-2	7 – 7.3	16.9	1.61	Brown silty gravel with sand matrix, disturbed, very soft- silty sand with gravel
VC103-3	7.8 – 8.1	30.3	1.51	Red silty fine sand with gravels, less disturbed – silty, clayey sand with gravel

*Fraction passing no. 200 ASTM sieve. All samples shown low plasticity index ($PI < 6$).

dry density of each sample. Six samples are obtained from three bore holes VC101, VC101A (in the vicinity of VC101) and VC103, at depths between 3 m and 8.1 m.

Samples to be tested against suffusion were carefully collected from each core and placed in the same conditions (density, moisture) as in field in the testing cell. To get less remoulded sample, the testing cylinder was used to core a subsample from the provided core sample (VC103-3) owing to its fine grading. Previously, a small amount of each sample was collected for sieving and plasticity analysis, and the resulting grain size distribution curves are presented in Figure 2. The sample VC101A is a widely graded soil with 44.4% of fines and 26.2% of gravel. All remaining samples show a gap-graded curve with a deficiency of particles in the 0.08 to 0.30 mm range. According to the literature relating to grading shape, these gap-graded samples are expected to be susceptible to internal instability. The missing middle size fraction in the grading may lead to the finer particles being moved within the pores of coarser matrix. Sample VC103-3 contains a fines content around 30% and has no gravel particles. All samples showed a low plasticity, with plasticity index less than 6, and sample VC101A was the more plastic one.

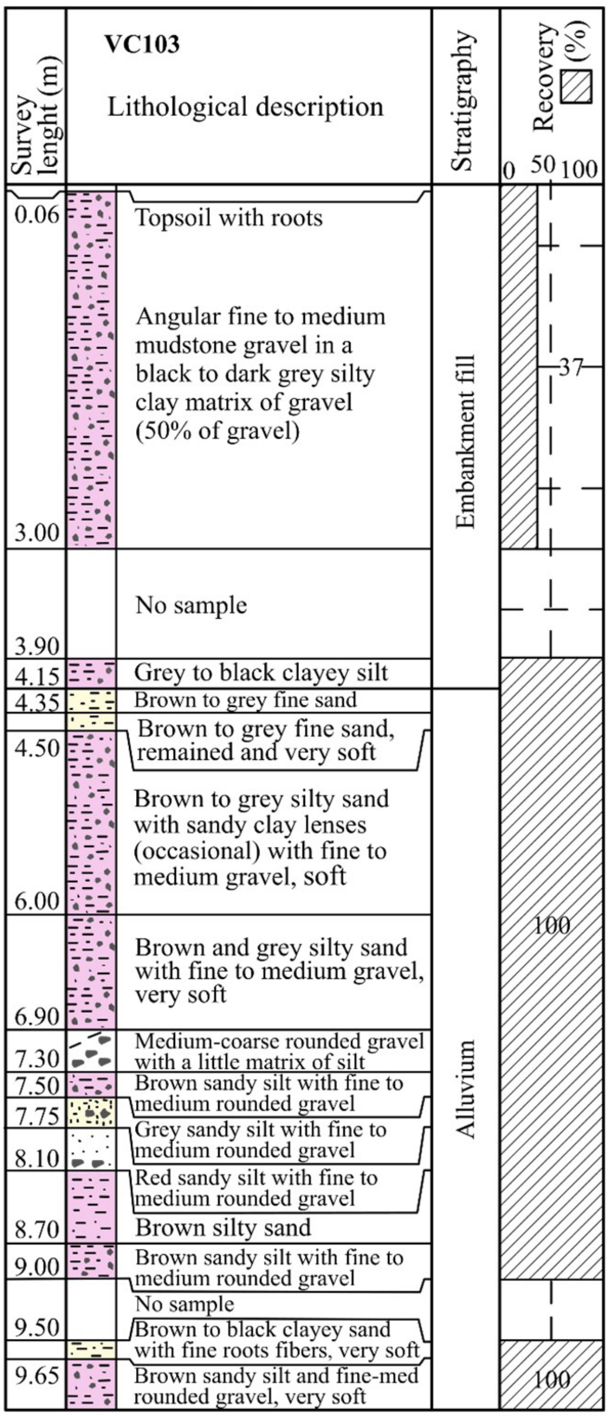

Figure 1. Stratigraphy of one collected core sample VC103 (Dam Safety, UK).

3. Test setup and procedures

Figure 3 shows the experimental arrangement used for suffusion tests. The samples are placed inside a cylinder mould made of acrylic glass that is then connected to a freshwater tank and subjected to upward flow. Two sizes of mould were used. The larger one is 90 mm in diameter and 150 mm long, and the smaller one is 40 mm in diameter and 120 mm long. The soil sample extracted from the disturbed core was compacted at the same wet density into the larger test mould. This method of sample preparation is applied for all the tests, except for sample VC103-3 (with no gravel content), in which a sub core is sampled to be used in the 40 mm diameter mould. The specimen rests over a 30 mm glass spheres layer used to diffuse uniformly the fluid in the sample. There is a rigid metal grid (opening size of 1.1 mm) covered by a mesh screen (80 μm opening size) that prevent loss of fines between the soil and the glass beads layer. A mesh with an opening size of 1.2 mm is used on the upper face to allow free washing out of eroded particles. The mould is kept

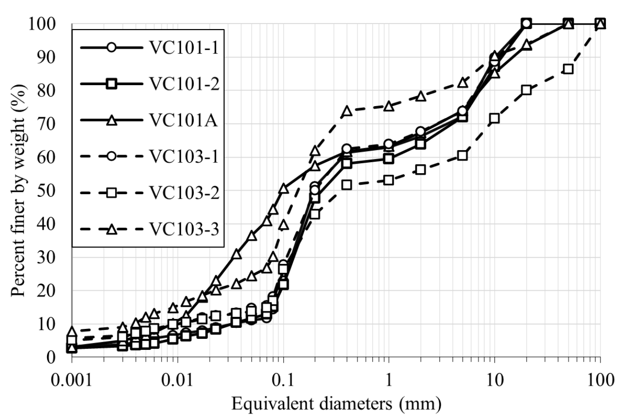

Figure 2. Particle-size distribution curves of tested soils.

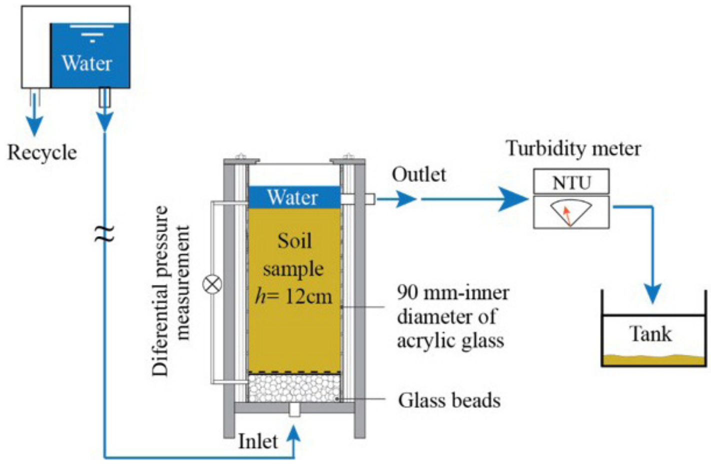

Figure 3. Schema of the typical experimental arrangement.

vertical during the test and is fed by a water supply which can be moved up to increase the hydraulic load applied to the specimen.

To closely match the chemical composition of the reservoir water, salt (NaCl and $CaCl_2$) is added into the water, aiming for a target *pH* value near 8.1. The outlet flow is directed towards a turbidity meter (Kobold 5000 NTU), with its readings previously correlated to fines concentrations in the effluent. A differential pressure transducer, positioned between the upstream and downstream extremities of the sample, measures the water head difference, providing the average hydraulic gradient along the sample. The volumetric discharge rate is measured periodically (minute-by-minute) to determine the corresponding hydraulic conductivity. Eroded particles are gathered in a container, and samples from the outlet flow are collected every minute for the analysis of particle size distributions with an automatic particle measuring system (Mastersizer 2000MU from Malvern).

The main objectives of the tests are the investigation of the critical gradient at which suffusion is initiated and the erosion kinetics. For this purpose, the water head in the tank is increased until suffusion is initiated and is then held as long as particles are being washed out from the soil sample. When turbidity falls to no significant value, the water head is increased to the next step and kept constant if suffusion continues. Several hydraulic loads are thus applied successively to the sample. The observation of the suffusion process together with the turbidity measurements allows the identification of the critical hydraulic gradient which initiates the migration of particles.

4. Test results and analysis

4.1. Suffusion results and evolution of soil parameters

In each test, the total hydraulic gradient is increased in steps of 0.1. The gradient of each step is left constant, at least,

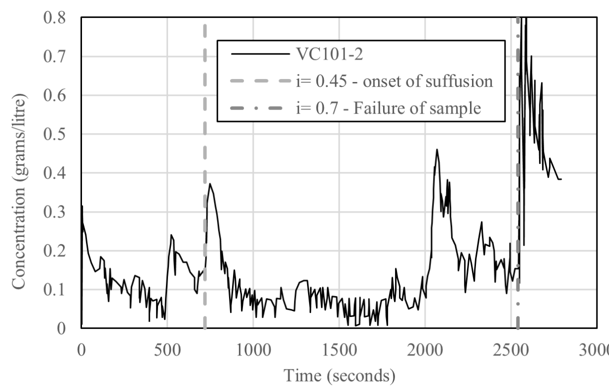

Figure 4. Typical turbidity curve measured during test (sample VC101-2).

until stabilization of the outlet flowrate. The critical gradient occurs for the minimum head at which erosion is clearly first initiated. Erosion of fines typically occurs at the start of the tests at low gradients, leading to some effluent turbidity. This is caused by the boundary conditions of the soil resulting in an initial wash of dirt and dry powder surrounding the soil specimen and is thus disregarded. Figure 4 illustrates a representative record (sample VC101-2) depicting the turbidity of the effluent and its progression with an increasing hydraulic gradient.

Suffusion starts at a hydraulic gradient close 0.45, and prior to this threshold value no significant erosion has been observed. The failure occurs when strong “boiling phenomenon” is visible at the specimen surface, for an average gradient of approximately 0.7, at an elapsed time of $t = 2500$ seconds. The maximum erosion rate is also used as quantitative mass erosion information because the erosion rate in the tests reached its maximum value quickly and did not remain constant during a single hydraulic load increment. In a typical test with occurrence of suffusion (Figure 5), preferential pathways for erosion are clearly identified along the sample for low hydraulic gradients.

Table 2 summarizes the results obtained from the six suffusion tests, including the critical gradient, the cumulative eroded mass, the percentage of the fines eroded, the initial and final hydraulic conductivity of the samples, and the maximum applied hydraulic gradient. Sample VC103-3 proved to be highly resistant to suffusion erosion for upward flow, with the sample exhibiting uplift. For that reason, the sample VC103-3 was tested using the smaller mould and subjected to horizontal flow. The critical gradient observed in tests on samples VC101-1, VC102-2, VC102-1 and VC103-2 are considerable smaller than the theoretical critical hydraulic gradient (Terzaghi et al., 1996) which is expected to be around the unity. This is an indication of the high susceptibility of suffusion of those samples. The samples VC101A and VC103-3, which have fines content above 30%, showed critical gradients much higher than the unity. Sample VC103-3 only show signs of erosion for very high gradients (above 7.5). Among the samples with higher fines content, VC103-3 is the only one that does not have gravel, which justifies its high erosion resistance, owing to its higher plasticity (*PI* close to 6).

Figure 5. Aspect of sample VC103-1 at the end of test.

4.2. Assessment of internal stability using the available methods

Several studies investigate the geometrical conditions of internal erosion using the particle size distribution. Empirical approaches have been proposed to evaluate the potential for internal instability. They are based on the shape of the gradation curve and, more specifically, on the variation in grain size over a designated portion of the curve. Istomina (1957) proposes three criteria concerning suffusion erosion: absence of erosion if $U < 10$; transitional state for $10 < U < 20$; and occurrence of erosion when $U > 20$. U is the uniformity coefficient of the material, given by Equation 1, being D_{60} and D_{10} the diameters of soil particles for which 60% and 10% of the particles mass are finer, respectively.

$$U = D_{60} / D_{10} \quad (1)$$

The Sherard (1979) criterion defined by the ratio D_{15}/D_{85} equal to 5 involves dividing the gradation at arbitrary points along the curve, to obtain the D_{15} for the coarse fraction and D_{85} for the fine fraction. The results obtained using this criterion show that the assessing of the internal instability of the soil depends on the particle size of the gradation splitting. In addition, Sherard method is formulated and intended to identify soils that do not exhibit self-filtering, a process distinct from internal

Table 2. Testing program, soil properties and main findings.

Soil specimens tested	Initial hydraulic conductibility (10^{-4} m/s)	Critical gradient from test, i_{cr}	Maximum gradient in test	Final hydraulic conductibility (10^{-4} m/s)	Mass loss (g)	Relative eroded mass of fines (%)	Visual assessment of soil stability
VC101-1*	3.0	0.35	1.7	3.0	5.0	2.0	Unstable
VC101-2*	12.0	0.45	0.8	19.0	6.7	3.3	Unstable
VC101A*	6.6	1.87	2.2	7.8	6.3	1.0	Stable
VC103-1*	30.0	0.32	0.6	6.1	10.2	4.8	Unstable
VC103-2*	50.0	0.22	0.5	269.4	8.4	3.7	Unstable
VC103-3**	2.0	7.50	10.0	1.9	14.1	24.5	Stable

* Test with upward flow in permeameter with 90 mm diameter and 150 mm length. ** Test with horizontal flow in permeameter with 40 mm diameter and 120 mm length.

instability. Kezdi (1979) suggests a criterion for internal erosion based on the index ratio D_{15}/D_{85} equal to 4. Fannin & Moffat (2006) experimentally demonstrate that gradations near that ratio exhibit stability, while a soil with $D_{15}/D_{85} = 7$ displayed instability behaviour at a relatively low gradient. Similarly, Kenney & Lau (1985, 1986) propose a graphical technique for evaluating a soil's susceptibility to internal erosion by examining the grading curve's shape. F represents a mass fraction smaller than D, where D is the particle size, and H is the mass fraction measured between particle size D and $4D$. The gradation curve is divided to determine the incremental mass fraction passing (H) across a range of particle diameter D to $4D$, which is then compared with the mass passing (F) at the lower limit of the interval D. Thresholds of $H = F$ are recommended for soils with a widely graded coarse fraction when $F < 0.2$ and for soils with a narrowly graded coarse fraction when $F < 0.3$. The area above $H = F$ corresponds to the stable zone. his approach was validated through laboratory permeameter tests (Skempton & Brogan, 1994). Li & Fannin (2008) showed that the Kezdi (1979) method tends to be more conservative for $F < 0.15$, while the Kenney & Lau (1985, 1986) method exhibits greater conservatism for $F > 0.15$. The Burenkova (1993) method relies on the rations h' (Equation 2) and h'' (Equation 3), where d_{90} represents the sieve size at which 90% of the sample by weight passes.

$$h' = D_{90} / D_{60} \tag{2}$$

$$h' = D_{90} / D_{15} \tag{3}$$

The h' ratio reflects the steepness of the particle size distribution's coarse section, while the h'' ratio serves as an indicator of the filtration effect between the coarse and finer fractions. Although the Burenkova (1993) method better but not totally accurate predictions of the internal stability of soils tested by Wan & Fell (2008). These authors expand Burenkova's criteria to encompass clay–silt–sand–gravel soils with limited clay-sized particles and introduce a probabilistic approach for predicting suffusion. Wan & Fell (2008) estimate that P the probability that a soil is internally unstable is given by Equation 4, where z is given by Equation 5. Wan & Fell (2008) also propose an alternative criterion, with alternative boundaries that are defined by D_{90}/D_{60} and D_{20}/D_5.

$$P = e^z / \left(1 + e^z\right) \tag{4}$$

$$z = 2.38 \log(h'') - 3.65h' + 3.7 \tag{5}$$

The six soil samples tested have been assessed for internal instability using methods previously described. Figure 6 plots H *versus* F curves for each sample, and shows the boundaries defined in Kenney & Lau (1986) and Kezdi (1979) criteria. Figure 7 plots the pairs h' and h'' for each sample, and shows the boundaries defined by Burenkova (1993). Figure 8 plots the results of application of the alternative method proposed by Wan & Fell (2008). Table 3 presents a summary of the classification about internal stability of the soils for all criteria mentioned, as well as the findings from the experimental data.

Relevant findings are that none of the applied criteria met the test results for all samples, and that, for some samples, the different criteria produce conflicting results with each other. Sherard (1979) and Kezdi (1979) criteria are clearly non conservative, suggesting that all samples are stable when selecting a slip gradation at the sizes 0.08 mm and 0.1 mm. For a higher slip size of 0.2 mm the sample VC101A exhibits D_{15}/D_{85} of 12.4. This exceeds the value of 4 proposed by Kezdi (1979) for gap gradations, indicating susceptibility to suffusion (Figure 6). However, contrasting results are obtained from the laboratory suffusion test. Istomina (1957) and Burenkova (1993) criteria suggests

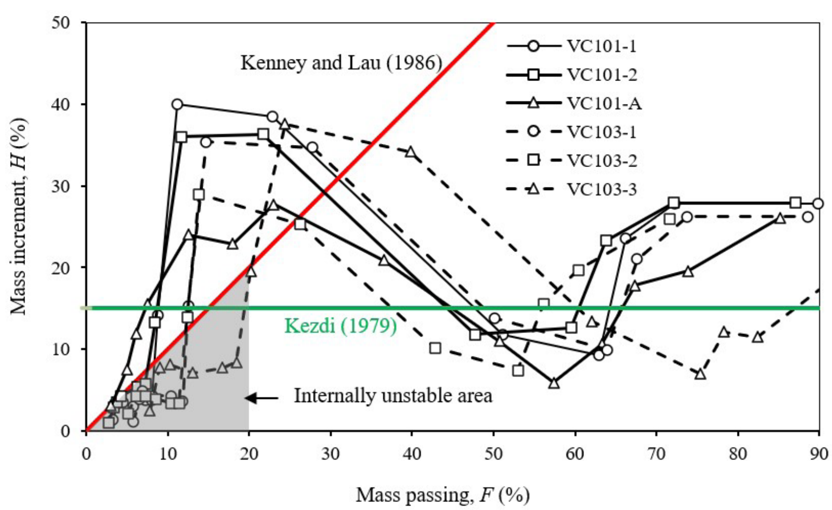

Figure 6. Kenney & Lau (1986) criterion and Kezdi (1979) criterion applied to tested soils.

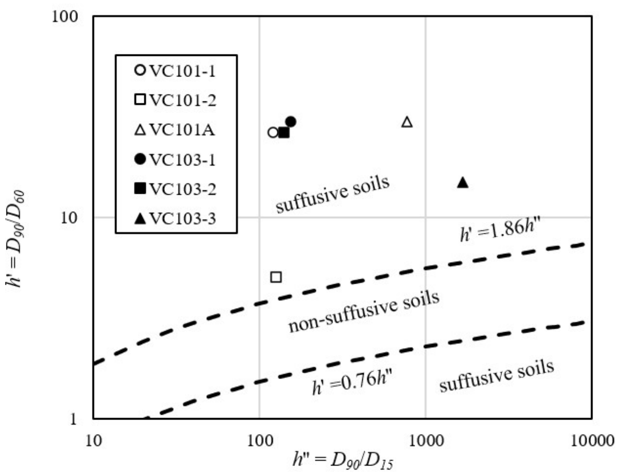

Figure 7. Burenkova (1993) method for assessment of internal stability of tested soils.

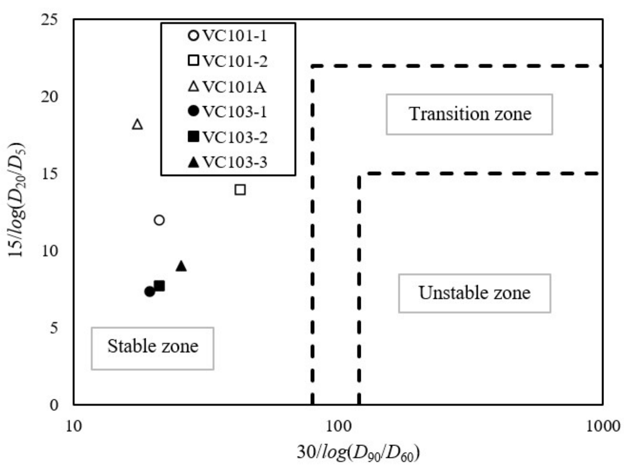

Figure 8. Wan & Fell (2008) alternative criteria for internal instability applied to tested soils.

that almost all tested soils are deemed unstable (Figure 7), indicating the conservative nature of such methods. Kenney & Lau (1985, 1986) method fails at predicting the suffusive behaviour shown in tests on samples VC101-1 and VC101-2, and, in addition, classifies sample VC103-3 as unstable, when laboratory tests show otherwise. One should note however that Kenney & Lau (1985, 1986) criteria is derived from experiments on clean coarse sand-gravel soils (with no fines). Sample VC103-2 that has the higher gravel content and one of the lowest fines content showed suffusive behaviour in experiments. That behaviour is well predicted by Kenney & Lau (1985, 1986), since most of the sample shape curve shows $H < F$ in the region defined by F<20% (Figure 6). Both methods (probabilistic and deterministic) criteria defined by Wan & Fell (2008) are over-optimistic at predicting all samples as internally stable. The probabilities of soils being susceptible to suffusion are very low ($P < 10^{-5}$), and the parameter $30/\log(d_{90}/d_{60})$ is in all samples smaller than the threshold of 80 (Figure 8). So, many criteria which were assessed for coarse soils are not applicable for soils containing more than 30% fines (VC101A and VC103-3).

4.3. Eroded particles analysis

The washed-out material deposited at the downstream tank is collected at the end of the tests, and then subjected to particle size analysis. Table 4 shows the maximum gradient applied to the samples, i_{max}, as well as the total mass of dry soil collected, and the corresponding medium size, d_{50}, and maximum size, d_{max}, of the eroded particles. One should state that the mass of eroded soil is not by itself a measure of soil instability and it is not comparable between tests. This is because some of the samples are subjected to high gradients

Table 3. Summary of results of upward flow tests and assessment of internal instability.

Criteria	Size split	VC101-1	VC101-2	VC101A	VC103-1	VC103-2	VC103-3
D_{15}/D_{85}	0.08 mm	0.07	0.07	0.06	0.07	0.07	0.06
	0.1 mm	1.56	1.67	3.13	1.67	1.89	1.56
	0.2 mm	2.24	2.00	12.44	1.88	2.50	1.84
$U = D_{60}/D_{10}$		10.86	28.57	42.22	38.00	500.00	45.00
Sherard		Stable	Stable	S/U*	Stable	Stable	Stable
Kezdi		Stable	Stable	S/U*	Stable	Stable	Stable
Istomina		Transition	Unstable	Unstable	Unstable	Unstable	Unstable
Burenkova		Unstable	Unstable	Unstable	Unstable	Unstable	Unstable
Kenney & Lau **		Stable	Stable	Stable	Unstable	Unstable	Unstable
Wan & Fell ***		Stable	Stable	Stable	Stable	Stable	Stable
Experimental results		Unstable	Unstable	Stable	Unstable	Unstable	Stable

* S/U means that sample is stable for size split of 0.08 mm and 0.1 mm and unstable for size split of 0.2 mm. ** Considering the criteria H/F<1. ** Probability of soils being internally unstable, P, is lower than 10^{-5} for all samples.

Table 4. Size of eroded particles and comparison of measured and estimated critical gradient.

Sample	Applied gradient, i_{max}	Cumulative mass of eroded soil (g)	Eroded particle sizes	
			d_{50} (µm)	d_{max} (µm)
VC101-1	1.7	5.0	8	60
VC101-2	0.8	6.7	8	60
VC101A	2.2	6.3	20	200
VC103-1	0.6	10.2	8	80
VC103-2	0.5	8.4	11	260
VC103-3	10	14.1	11	100

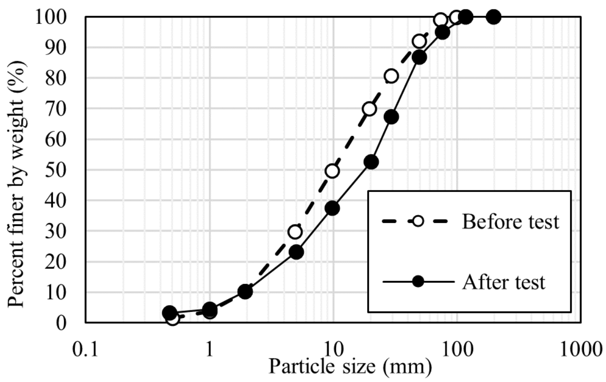

Figure 9. Particle size distributions of fines (VC103-3) before and after suffusion test.

that are unlikely to occur in dams, and the duration of tests and applied hydraulic gradients are significantly different.

Particle size analysis of the eroded soil collected is compared against the fraction of the original soil that has particles of equal or smaller size than the size of the maximum particle eroded. As example, Figure 9 shows the gradation curve of the material eroded in the suffusion test on sample VC103-3, and the corresponding fraction of the original soil. One can deduce that lost particles are those of size ranging between 2 and 80 µm. Wan & Fell (2008) inferred that approximately half of the finer fraction, determined by the point of inflection in broadly graded soils and the fine limit of the gap in gap-graded soils, undergoes erosion. This statement is verified for sample VC103-3 where the point of inflection on the grading curve is close to 80 µm. No relation is established between the susceptibility to suffusion and the grain size of eroded particles. However, particles washed out are mainly fines (<80 µm) with a mean diameter close to 10 µm. Comparison of the mean size (d_{50}) of eroded particles from the different samples indicates that the coarser particles eroded from the soils have a maximum size close to 0.26 mm and sample VC101A has the coarsest size distribution of eroded particles.

5. Conclusion

Visual inspections revealed leakages in the Eastern embankment of a British dam, prompting concerns about its vulnerability to internal erosion during extreme storms and floods. In response, erosion tests were conducted on samples from various dam sections. Boreholes and vibro-cores were utilized to collect samples from the earth fill. Physical characterization unveiled the gap-graded nature of most samples and their low plasticity, raising doubts about their susceptibility to suffusion erosion.

Subsequently, upward flow suffusion tests were performed on six samples. Experimental data showed that four samples (VC101-1, VC101-2, VC103-1 and VC103-2) are indeed highly susceptible to suffusion erosion, with erosion process phenomenon starting at gradients much lower than the unity (as low as 0.22). The opposite happens with VC101A and VC103-3, whose fines content is greater than 30% and showing some plasticity. Sample VC103-3 proved to be resistant to suffusion for upward flow, with uplift occurring for a high gradient of 7.5, which is likely due to the well graded property of this sample and its plasticity.

The results of the laboratory tests are compared to predictions from seven geometric criteria found in the literature, provided by six different research teams, to assess the potential for suffusion and internal stability of soils. It is found that none of the methods proved to be capable of forecasting the behaviour of all tests. It is also interesting that, in many cases, opposite conclusions are suggested between different methods. Istomina (1957) and Burenkova (1993) criteria are quite conservative, whereas the criteria by Sherard (1979) and Kezdi (1979) and two criteria by Wan & Fell (2008) are very optimistic. Kenney & Lau (1986) criteria appear to predict well the suffusive behaviour of the samples with lower fines content. The apparent contradictions between methods are certainly because the various criteria are based in experiments on different soil types and using distinct test setups and hydraulic loads.

The paramount finding from this study is about the absolute need to carry out suffusion tests when there is no agreement between the predictions from the available criteria. Most of tested samples from the eastern embankment dam exhibits a susceptibility to suffusion.

Following this conclusion, the dam was subjected to rehabilitation, and measures to improve its resistance to erosion have been taken. The suggested remedy includes installing sand filters designed to capture the smallest particles, complemented by relief wells distributed along the entire length and height of the eastern embankment (Thompson 2011). This solution entailed removing the topsoil and vegetation from the surface, installing a 200 mm layer of graded fine filter material, covering it with a second layer of coarser graded filter material to a depth of approximately 200 mm, and finally, surfacing it with the replaced topsoil. In addition, the gradient of the downstream face was reduced from a typical 1H:3V slope to 1H:2.5V.

Acknowledgements

We are thankfully to Rodney Bridle (Dam Safety Ltd, England) for his help and comments.

Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Ahmed Benamar: conceptualization, test conduction, writing, supervision, validation – original draft. Ricardo Correia dos Santos: data curation, analysis of test results, methodology, writing.

Data availability

All data produced or examined during the current study are included in this article.

List of symbols and abbreviations

d_{50}	Grain medium size of sample
d_{max}	Maximum grain size of sample
i	Hydraulic gradient
i_{cr}	Critical gradient
i_{max}	Maximum gradient applied
h'	Ratio of gradation for estimation of soil instability
h''	Ratio of gradation for estimation of soil instability
pH	Potential of hydrogen
t	Elapsed time
z	Parameter influencing probability of soil being unstable-
ASTM	American Society of Testing Materials
$CaCl_2$	Calcium chloride
D	Particle size
D_{10}	Diameter of soil particles for which 10% of the particles mass are finer
D_{15}	Diameter of soil particles for which 15% of the particles mass are finer
D_{60}	Diameter of soil particles for which 60% of the particles mass are finer
D_{90}	Diameter of soil particles for which 90% of the particles mass are finer
$D_{85}SA$	Grain size corresponding to 85% finer by surface area
Dc_{35}	Constriction size corresponding to 35% finer
F	Mass fraction
H	Mass fraction measured
H:V	Slope geometric ratio between horizontal and vertical
ICOLD	International Commission on Large Dams
NaCl	Sodium chloride
NTU	Nephelometric Turbidity Unit
P	Probability that a soil is internally unstable
PI	Plasticity index
S	Stable soil
U	Unstable soil
U	Uniformity coefficient
UK	United Kingdom
VC	Vibro-core drilling
VCx	Vibro-core sample with number x

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