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Quantifying soil surface erosion

Quantifier l'érosion de surface des sols

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Abstract. This review first introduces the general context of soil erosion, an omnipresent natural process involving a wide variety of spatial and temporal scales. While this loss of solid matter induced by all kinds of fluid flows on the surface of soils is often a source of beauty in the landscapes that surround us, it also constitutes a major risk and poses growing threats in the context of global change as loss of agricultural soil fertility, decline in coastal ecosystems or increase in safety standards for flood protection structures. It is therefore essential to be able to predict future soil removal rates at multiple scales, in order to anticipate or mitigate their impacts. This requires experimental quantification of soil's vulnerability to erosion. In order to describe this type of measurement in deeper detail, we restricted the scope of our review to situations of concentrated surface erosion of homogeneous soils, on moderate spatial and temporal scales, as typically studied in the fields of civil or environmental engineering. Measuring erosion itself is challenging, both in terms of determining the rate of mass removal from a surface, and in terms of selecting and quantifying a relevant hydrodynamic quantity to reflect the strength exerted by the flow. A conceptual framework is then required to correctly define soil's erodibility, which is defined as an intrinsic property of the material through an empirical erosion law. In the most commonly accepted approach, this erodibility combines two distinct parameters: an erosion initiation threshold, generally chosen as a critical shear stress, and an erosion kinetic coefficient. The various types of erodimeters found in literature are then presented and compared, with a specific and more complete description of the three main devices used in geomechanics (EFA, HET and JET). Finally, before concluding and suggesting some perspectives on the topic, we outline the various advantages and applications of the erodibility values derived from experimental tests, while showing the limitations of the approach and the questions raised by them.

Résumé. Cet article de synthèse introduit tout d'abord le contexte général de l'érosion des sols, un processus naturel omniprésent impliquant des échelles spatio-temporelles extrèmement variées. Si cette perte de matière solide induite par toutes sortes d'écoulements fluides à la surface des sols est souvent source de beauté des paysages qui nous entourent, elle n'en constitue pas moins un risque majeur et fait peser des menaces croissantes dans le contexte du changement global comme la perte de fertilité des sols agricoles, le déclin des écosystèmes littoraux ou le besoin accru de sureté des ouvrages de protection contre les inondations. Par conséquent, il est essentiel de pouvoir prédire aux différentes échelles les niveaux futurs de retrait des sols afin de mettre en oeuvre de possibles mesures d'anticipation ou d'atténuation. Il convient pour cela de connaître la sensibilité à l'érosion d'un sol via une quantification expérimentale. Pour décrire plus en détail ce type de mesures, le choix est fait ici de restreindre le cadre considéré aux situations d'érosion

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de surface concentrée de sols homogènes, sur des échelles spatiales et temporelles restant modérées, et telle que typiquement étudiée dans les domaines de l'ingénierie civile ou environnementale. La mesure de l'érosion en elle-même est délicate et complexe, aussi bien pour déterminer le taux de matière érodée à une surface que pour sélectionner et quantifier une grandeur hydrodynamique pertinente, capable de rendre compte de la force exercée par l'écoulement. Un cadre conceptuel est ensuite nécessaire pour définir correctement une érodabilité du sol, condidérée comme une propriété intrinsèque du matériau à travers une loi empirique d'érosion. Dans l'approche la plus communément acceptée, cette érodibilité regroupe deux paramètres distincts : un seuil d'initiation de l'érosion, généralement choisi comme une contrainte de cisaillement critique, et un coefficient cinétique. Les différents types d'érodimètres issus de la litérature sont ensuite présentés et comparés, avec un descriptif spécifique et plus complet sur les trois principaux dispositifs utilisés en géomécanique (EFA, HET et JET). Enfin, avant de conclure et de suggérer quelques perspectives futures sur la thématique, nous présentons les nombreux avantages et utilisations possibles des valeurs d'érodabilité issues de ces essais, tout en montrant les limites de l'approche et les questions que celles-ci soulèvent.

Keywords. Erosion, Measurement, Soil's erodibility.

Mots-clés. Erosion, Mesure, Erodabilité des sols.

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1. Context of soil erosion and related issues

1.1. *A ubiquitous process on a variety of scales*

Quoting Wikipedia[1], *erosion is the action of surface processes (such as water flow or wind) that removes soil, rock, or dissolved material from one location on the Earth's crust and then transports it to another location where it is deposited.* Adopt this definition, which is already rather broad, nevertheless excludes several adjacent mechanisms likely to lead to the dislocation and crumbling of solid matter but which involve no motion, such as weathering [1, 2] or others physico-biological actions [3]. We therefore strictly define our object of study as being the erosion generated by the detachment and entrainment of solid matter from the surface of a soil under the action of a fluid flow. Soil is understood here as a geomaterial in the broadest sense, encompassing all types of soil, including clay, sand or silt, as well as coarser materials, from pebbles to boulders, or even snow. The variety is rather vast, with highly contrasting levels of internal cohesion between constituent particles that also vary greatly in size: from cohesion-less granular soils to coherent materials or soft rocks.

As defined above, the erosion of solid matter is difficult to dissociate from, and in fact includes, the subsequent transport induced by the eroding flow. This complementary removal process enabling the loosened soil to be evacuated, more or less rapidly, thereby allowing erosion to possibly continue. Thus, the major problems associated with soil erosion stem directly from the combination of conditions that initiate soil removal and enable its transport, wether over a few millimeters or thousands of kilometers. There is a wide variety of soil erosion types [4–6] and the main natural processes involved include: Sediment transport (in mountain streams, rivers, oceans, or deserts) [4, 7–10]; Coastal erosion [11, 12]; Rain splash and runoff erosion (including rill erosion, gullies, etc) on farmland or hill-slope [5, 13, 14], with essential role of plant covers [15, 16]; Piping in natural soils [17, 18]; Scouring of riverbanks [19, 20] or bridge pier foundations [21, 22]; Internal and external erosion of earthen hydraulic structures [23–26]. From a geomorphological point of view, the different spatial scales involved vary tremendously, from a simple sand ripple to mountains, from a drop of water to the confluence of the Amazon. Similarly, the timescales of erosion range from a few seconds to several million years [27]! Mountains are thus erased or

[1] https://en.wikipedia.org/wiki/Erosion

Figure 1. Example of gullies sculpted by erosion in farmland as strikingly painted by Alexandre Hogue in "The crucified Land" (1939). Licence: CC BY-NC-SA 4.0.

valleys carved out on geological periods, while violent events such as a massive landslide may last a very short time.

As a result, erosion leaves its omnipresent imprint on relief and landscape, through riverbeds and deltas, cliffs and coastlines, or inspiring country fields (see for instance Figure 1) . . . We enjoy this imprint daily as we contemplate the exceptional beauty of nature. But we also endure it by living under the threat of natural events more or less directly responsible for various erosional processes, such as floods, landslides, coastal storms or torrential flows. Soil erosion thus has a feedback effect on our environment through the increasing construction of protective systems, as it poses a major hazard to many sensitive natural and man-made elements: beaches, dunes, farmland, building foundations, bridge piers, earthen engineering structures . . .

1.2. *A primary vector of risks*

Sediment transport is part of a natural geological cycle, based on land subduction balanced by gradual relief degradation and subsurface erosion. However this equilibrium is increasingly disrupted by human activity [6]. The global average rate of soil erosion by water is estimated to be somewhere between 0.1 and 0.15 mm/year, exhibiting significant local disparities [28,29], with a strong upward trend in erosion rate due to climate change, land use and other socio-economic factors [30–33]. In itself, this acceleration threatens the geological balance between formation and removal of natural soils, endangering both human food security and global ecosystem sustainability [28]. Soil erosion of agricultural fields, mainly due to rainfall and surface runoff, is another threat suspected of reducing agricultural potential, particularly fertility, or inducing soil thinning [34]. For instance, in the US, the Department of Agriculture (USDA) recommends a soil loss rate below 1 mm/year for soil conservation [29], but research work continues on this soil loss tolerance [35]. Agricultural erosion also has an impact on the global carbon cycle, but whose effect is still uncertain and debated [36–38].

As mentioned earlier, the erosion of sediments can lead to the transport of solid or dissolved matter over long distances, posing the risk of pollution through the dispersion of contaminants.

Figure 2. Photographs from an artistic perspective of Le Signal building (Soulac-sur-Mer, France). This construction, built between 1967 and 1970, was definitely abandoned in 2014 under the threat of coastal erosion and finally demolished in 2023. Credit: Le Signal@Olivier Crouzel (https://www.oliviercrouzel.fr).

These dangerous elements include radioactive particles [39], heavy metals [40, 41], or microplastics [42, 43], whose proliferation is of particular concern due to their notoriously harmful effects on virtually all ecosystems.

The desertification of entire regions, such as the Sahel and the Sahara, has been greatly intensified by anthropogenic climate change [44], and is partly induced by wind erosion and subsequent transport [10], which contribute to both the degradation of agricultural soils and the invasion of land through the displacement of large volumes of sand.

The sharp decline in coastline due to increased shoreline and beach erosion is also a cause for great concern [11, 12], particularly in the current and, above all, future context of rising sea levels and more frequent ocean storms [45, 46]. The main threats concern the coastal ecosystem and human activities, the sea, which is gradually moving closer to natural or anthropic habitats, as illustrated in Figure 2.

In addition, the safety of man-made structures in permanent or intermittent contact with water is constantly threatened by the erosion that can be generated by subsequent flows. This hazard seems to be growing, particularly in the alarming context of global change, which is very likely to lead to an intensification of extreme climatic events (storms, precipitation, flooding). Major concerns include scouring around rigid structures such as bridge piers [47] or concrete dikes, or direct water flow erosion of earthen hydraulic structures, such as flood defence works, earthen dams and levees, river and canal embankments [23–26].

1.3. *A need for predictive modeling*

Given these severe risks posed, directly and indirectly, by soil erosion, the human response cannot be solely focused on protection, although this is an essential element. For effective management, we should also be able to predict the effects of erosion over time as reliably as possible, which requires the development of models capable of incorporating to varying degrees the complexity of the processes involved. Before attempting any modeling, the scales to be considered must first be defined, both in terms of time and space. These scales are constrainted by the global dimensions of the system in question and the total duration targeted, and require the introduction of elementary time and space steps at the scale of the basic processes under consideration.

For example, erosion of the Earth's crust is a central feature of long-term landform modelling, combining tectonics and surface processes [27, 48]. However, many soil erosion models are built on a catchment scale, focusing on shorter durations, typically decades, to assess over time both sediment production and transport capacity. In an extremely active field of research, a number of operational tools have been proposed [49, 50]. Such distributed models are specifically designed for a particular area, on a regional, national or continental scale, and include, among others: the European Soil Erosion Model EUROSEM [51], the Water Erosion Prediction Project WEPP [52], the Pan European Soil Erosion Risk Assessment PESERA coarse scale model [53], the (Revised) Universal Soil Loss Equation (R)USLE [32, 54] (see Figure 3 as an illustration), or else the Limburg Soil Erosion Model LISEM [55]. Empirical, conceptual and physical process-based approaches can be distinguished, all requiring a large number of input data explicitly accounting as much as possible for climate variation (rainfall, temperature, etc.) and vegetation characteristics. A highly critical parameter is land erodibility, mostly derived from soil characteristics [56, 57] and used as an integrated coefficient at the model mesh scale. However, despite significant progress in model spatial resolution, the elementary mesh incorporates a large number of heterogeneities and spatial variabilities in subsoil characteristics, remaining well above the micro-scale where a homogeneous material behavior can be found, known as Representative Elementary Volume (REV) in the field of soil mechanics [58]. Despite the obvious interest and need for these large-scale models, they still have significant limitations [57]. In particular, they suffer from the wide dispersion of available data and their usually limited calibration domain, with no effective validation outside of it [59].

Another approach consists in studying and modeling soil surface erosion at the representative material scale that is considerably smaller, typically on soil sections of a few hundred square centimetres. The number of input parameters for these models is significantly reduced, and calibration is generally simpler, often based on well-controlled laboratory experiments. This line of research was particularly initiated to analyze river erosion and sediment transport, especially in the case of granular (i.e. non-cohesive) sediments, for which an empirical modeling framework has long been established. This framework is essentially based on the dimensionless Shields number, which compares fluid stress and buoyancy weight for grains or pebbles at the riverbed interface. The Shields number governs the sediment transport and a specific curve empirically determining its critical value at the threshold of erosion initiation [9, 60, 61]. The case of cohesionless sediments corresponds to a straightforward situation where the physical origin of grain movement is clear. The understanding is much more complex for cohesive soils, where soil composition, grain size distribution and internal interactions within the material play major role, rendering the previous Shields'approach inadequate in most cases [62, 63]. Moreover an erosion threshold alone is not sufficient to describe the phenomenon, which has its own kinetics controlling the rate of soil removal once erosion has initiated. The mechanisms responsible for material entrainment appear obviously more complex and varied for cohesive soils, necessitating a better physical and physico-chemical understanding of the processes [64]. This is all the more true as the cohesion of a soil can have several possible origins: macroscopic expression of microscopic inter-molecular interactions within very fine soils, but also emerging property from the presence of binding agents between larger grains (partially saturated granular soils, cemented or bio-cemented soils, etc.). To the best of the authors' knowledge, it is currently impossible to present an exhaustive and coherent physical picture of the mechanisms of cohesive soil erosion, as understanding of the phenomenon is still very limited in the community concerned. A few fragments of theory do exist, often quite disconnected from each other, and will be mentioned in this article. Advances in numerical modeling have been much more significant, and a recent review article provides an up-to-date synthesis of modeling of soil surface erosion [65], but again with very few elements specific to cohesive soils. While awaiting a clearer understanding, developments mainly relied on empirical approaches, particularly through the formulation of erosion laws at material scale [66].

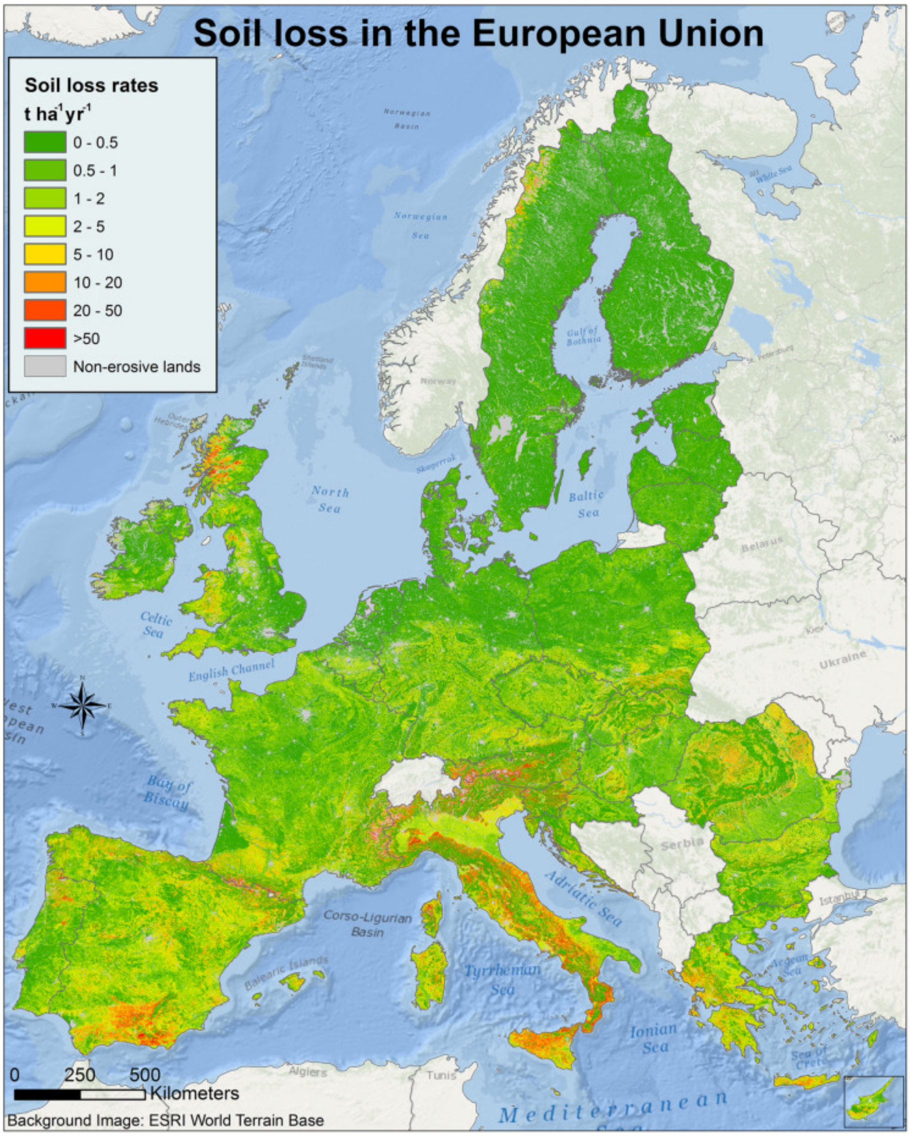


Figure 3. An example of results achievable with large-scale models is shown here with the map of soil loss rates in the European Union (for reference year 2010) based on RUSLE2015 [54].

Whatever the scale considered, modeling requires establishing a relationship between the quantity of soil eroded, typically described by an erosion rate or a sediment transport capacity, and the force exerted by the hydraulic flow. Such relationships effectively introduce parameters that account for the soil's resistance to concentrated water flow [66]. These parameters can be seen as integrated erodibility coefficients or indexes in large-scale models, deduced from many input parameters, by contrast with intrinsic soil properties at the material level. A critical aspect concerns the selection of a proxy indicator for the hydraulic strength [66]. For instance, runoff erosion intensity on a ground plot is generally expressed in terms of the transport capacity, as a function of shear stress [52, 67] or unit stream power [55, 68]. However, alternative choices exist, such as flow rate, water head or Froude number [66]. These integrated or more local erosion laws are primarily empirical, with some being based on a conceptual framework [69], proposing a unified formulation [70, 71], or including a stochastic component [72, 73], as will be discussed further in Section 2.2.

However, as a prerequisite to any modeling, obtaining reliable and varied experimental data, both in field and from the lab, is essential for supplying, calibrating and validating the various types of erosion and transport models. With this objective in mind, and in order to build up the most reliable predictions possible, methodologies have been developed to measure soil and sediment erosion or, in other words, to determine the erodibility parameters of the material or elementary ground unit under consideration with maximum precision. Given the vast range of different mechanisms at the root of soil loss by water flow [13], adopting a global approach appears impractical and, as Knapen and co-authors have pointed out [66], *it is obvious that soil erosion should be considered as a process-specific concept with different erodibility indices*. The forward corollary is that specific measurement approaches are obviously needed for each of these erodibility quantifications.

1.4. *Scope of the present review*

In this review, we have chosen to focus on experimental methods developed to determine the resistance of consolidated cohesive soils against surface erosion, subject to submerged and concentrated flow conditions, over reduced time and space scales, excluding any additional impact of slope with respect to the horizontal in our discussion. The main practical applications concern scouring and interfacial erosion on coherent geomaterials such as seabed sediment, mostly constituted of sand-mud mixtures [8, 63] and subject in particular to intense and increasing coastal erosion [46], or compacted clayey soils in earthen hydraulic structures, typically levees or embankment dams [26]. In this particularly sensitive application, two types of erosion can occur: external erosion, where there is overflow on the face of the structure, and internal erosion, associated with mechanisms induced by infiltration flows within the structure and its foundations. These two causes are responsible, in nearly the same proportion, for almost 100% of reported earth dam failures [23, 24]. The mechanisms of internal erosion, which have been extensively studied over the last twenty years and are now well identified, involve, for some, zones within or below the structure where cohesive constituent soils can be superficially eroded by a head of water. This is notably the case for the so-called concentrated leak erosion, contact erosion or backward piping erosion in its development phase [26]. Within soils with a granular structure, there also exist internal erosion processes that occur not at the surface but within the volume of the material [74], although these will not be discussed here.

In what follows, we will present the different methods to assess, for a soil subjected to a concentrated submerged hydraulic flow along an initially flat and horizontal surface, the same parameters, hereinafter referred to as *erodibility*. These parameters will be defined conceptually in greater detail below.

2. Experimental determination of soil's erodibility

2.1. *Difficulties and challenges*

Developing a device and protocol adapted to the study of soil erosion is a major experimental challenge. It requires simultaneous and independent quantification of both the rate of solid matter loss and the hydrodynamic load exerted by the eroding flow. However, each of these measurements proved difficult to implement for several reasons.

The rate of erosion at the surface of a soil sample is straightforwardly defined as the mass of solid matter lost per unit of time and per unit of surface area. The most direct method of determining it would be to measure the gradual loss of mass over time for the sample under test but this, however, poses major practical difficulties. While weighing a given initial mass, it is necessary to detect very small variations in mass, particularly when identifying an erosion threshold. As a result, weighing accuracy is severely limited, especially considering significant noise expected due to the supplementary force generated by the water flow, usually in a turbulent regime with substantial hydrodynamic fluctuations. Consequently, the use of direct mass measurements for erosion monitoring remains marginal.

Assuming soil homogeneity and measuring the corresponding density, the change in mass of the eroded sample can be deduced from the change in volume and therefore, more directly, from the progressive deepening of the surface exposed to the flow. Since the long-existing point gauge measurements [75,76], the techniques used have become increasingly sophisticated, particularly with the use of 2D or 3D laser systems [77–79] and imaging processing methods such as digital photogrammetry [80] or light attenuation [81]. However, there are several major obstacles to accurately tracking the eroded area: the upper surface can rapidly develop a complex and evolving morphology; the rapid build-up of suspended matter in the flow makes the water turbid, preventing the use of certain probes, particularly optical ones, or even direct visualization; the presence of heterogeneity or defects at the scale being investigated compromises the validity of the approach.

In the end, the quantity of soil removal is often deduced from other complementary experimental data rather than being directly measured at the eroded area. The resulting sediment loss can be straightforwardly determined from the concentration in eroded material inside the flow emerging from the active zone. Erosion rate is then obtained through the conservation of solid matter exchanges. However, this procedure may suffer from a time lag induced by the distance imposed between the measurement zone and the erosion zone. The concentration of eroded material can be determined by regular sampling and weighing of the downward flow, but solely on a high periodicity basis, or, for fine sediment transported in suspension, by continuous time monitoring using a turbidimeter, which in practice requires prior calibration for each test. In an even more indirect manner, and subject to strong simplifying assumptions, the measurement of the flow-pressure relationship in the erosion zone can be used to estimate the soil removal rate, based on the increase in flow cross-section and therefore in the associated hydraulic radius [82]. However, this method is rather approximate and is also directly linked to hydrodynamic measurements of the eroding flow, unlike previous approaches.

Measuring soil erosion rates involves considering factors, including the history and aging of the soil being studied. There are typically two options for real soil assessment: conducting tests on-site using portable devices or collecting soil samples for laboratory testing. This second procedure generally enables more precise measurements under better-controlled conditions, with sophisticated equipment. However, in some cases, the original sampled soil cannot be tested intact, due to damage or the presence of interfering elements (large particles, roots, etc.). The soil is then reconstituted under the same conditions as those found on the site. However, this reconstituted soil may lose the memory it has gained from in situ consolidation and, as will be discussed later, its resistance to erosion tends to be consistently reduced. It should be noted that for specific comprehensive studies, model soil samples can be prepared on demand using the same methodology for systematic testing.

Linking erosion rate with flow intensity requires accurately measuring the flow and deriving appropriate and relevant characteristic quantities. This also poses a number of difficulties, firstly in selecting the flow features that closely reflect the physics of erosion, and, secondly, in implementing the accompanying measurements in practice, particularly considering that the flow regime is most often turbulent. In such turbulent flow, the movement of fluid is chaotic, characterized by irregular fluctuations in velocity and pressure. This turbulence complicates the measurement process as traditional techniques may not capture all relevant flow features accurately.

Many competing quantities can be used to characterize a flow, generally presenting direct or semi-empirical relationships between them, with a strong dependence on the specificity of the hydrodynamic configuration considered, which can vary widely (flow in a channel, flow in a pipe with cross-sectional variation, submerged impact jet . . .). Classically accepted quantities for characterising flow include discharge, stream power, flow shear stress, or shear velocity [66]. As already mentioned, a key challenge lies in ensuring that the chosen hydrodynamic indicator adequately represents the erosion mechanisms which, by definition, take place at the interface between soil and water flow. A volume-averaged magnitude is therefore unlikely to be straightforwardly relevant for describing this type of superficial phenomenon and requires prior calibration to correlate with a more local characterization. In this respect, the bottom shear stress (or equivalently shear velocity) at the soil surface appears to be a flow predictor with significant potential. Consequently, it has often been selected, although it's not the most straightforward to determine, as will be discussed below.

Once a hydrodynamic reference variable has been selected, it is essential to consider whether its mean value is representative of the effective flow loads generating erosion. While this question does not arise in the case of a perfectly stationary ideal flow, the same is no longer true in more realistic situations where the hydrodynamic regime is generally turbulent, inducing more or less pronounced fluctuations within the flow [83, 84]. A moderate average value can therefore mask much higher extreme values, likely to induce localized erosion puffs. To take these fluctuations into account, it is then necessary to characterize the complete statistical distribution, particularly in the upper tail [73]. Note that a perfectly similar approach can be adopted in the presence of spatial variations in flow along the erosion surface [85]. Furthermore, variability in erosion does not solely arise from flow dynamics but also from the eroded material itself, which is rarely homogeneous, particularly in field conditions [86].

Monitoring basic hydrodynamic quantities involves measuring the overall discharge rate, using a suitable flowmeter, and the pressure difference between upstream and downstream of the erosion zone, using either two absolute pressure transducers or directly a differential pressure gauge. This standard instrumentation can be exceptionally accompanied by more sophisticated measurements, such as for calibration purposes, in particular to reconstruct the velocity field in space, whether using normal profiles at the interface of interest, 2D maps in the vertical plane, or even full 3D velocity fields. To achieve this, precision instruments are required, such as laser or acoustic Doppler velocimeter, particle image velocimetry systems, or hot-wire measurements [87–89]. Most interestingly, it is next possible to derive the time-averaged shear stress from this mean velocity profile using various correlation strategies with established laws [90, 91]. Direct measures of bottom shear stress are also available [91], either at a single point with a Preston tube [92, 93] or over a surface with MEMS-based, oil-film interferometry, floating element or hot wire techniques [94–96]. In all cases, the measurement of bottom shear stress relies on inferring it from another quantity, necessitating the use of these inventive and sometimes unexpected methods, such as for example shear-induced bioluminescence [97], electrochemical technique [84] or ferrofluid spike deformation [89]. It is important to note that high time resolution is crucial when fluctuations, rather than mean value, have to be obtained, especially in turbulent flow conditions where fluctuations play a major role in erosion process.

In practice, from the perspective of routinely carrying out tests to quantify soil erosion resistance, implementing high-tech measurement systems to tackle all the key issues raised above can be impractical. To circumvent this limitation, interpretation models, specific to each test and its own hydraulic configuration, have been developed. Based on a number of simplified (or even oversimplified) and/or known empirical correlations, such models make it possible to propose reduced relationships between key hydrodynamic and geometric quantities, related to flow and erosion. This approach helps limit the number of input quantities that need to be measured, rendering testing more feasable in practical settings. Pre-calibration is also usually required. For example, in a test involving flow through a pipe, the lateral shear stress can be deduced from either overall head loss or discharge rate [82]. Similarly, in a test involving an impinging submerged jet, the tangential shear stress can be expressed as a function of both height and flow rate of the jet [75].

2.2. *Conceptual framework for intrinsic soil's erodibility*

Since knowledge of the elementary physics involved in the removal and transport of cohesive soils by flow is still limited to date, erosion laws, i.e. laws relating erosion rate to relevant hydrodynamic quantities, have primarily been formulated empirically. Several competing formulations have been proposed, mostly but not exclusively based on fluid shear stress [18,66,69–71,86, 98–104]. As the existence of a threshold for erosion is fairly widely accepted in the scientific community, although this is still open to debate [105], excess shear stress models are most frequently proposed, using as control variable the amount of shear stress exerted by the flow in excess with respect to a threshold indicative of the material's resistance. For simplicity's sake, these expressions take typically the form of power laws. This approach is reminiscent of long-established empirical laws describing solid transport, as initially suggested by Duboys [106] and later refined by Meyer-Peter Müller equation for the bedload of sand and gravel [7,8]. This type of law is also often proposed for the stream capacity in large-scale integrated approaches of landscape evolution models, as illustrated in [107].

Although there are a few other alternative formulations [18, 100, 102], the most common surface erosion law is generically expressed as:

$$E_{\mathrm{m,v}} = \begin{cases} K_{\mathrm{m,v}}(\tau-\tau_{\mathrm{c}})^n & \text{if } \tau \geq \tau_{\mathrm{c}} \\ 0 & \text{if } \tau < \tau_{\mathrm{c}} \end{cases} \tag{1}$$

where the erosion rate E_{m} (respectively E_{v}) is defined as the soil mass (respectively volume) loss by surface and time units (see previous Figure 4) while τ is the bottom shear stress exerted by the flow. The new parameters introduced in this formulation are: (i) the proportionality coefficient K (being equivalently K_{m} or K_{v}), called the coefficient of soil erosion, the detachment rate coefficient, the concentrated flow soil erodibility, or simply erodibility according to various authors; (ii) the stress threshold τ_{c}, which quantifies the soil's resistance to erosion and is commonly referred to as critical shear stress; (iii) the exponent n of the power law, where $n > 0$.

In practical terms, especially concerning the units of the proportionality coefficients, this erosion law can also be conveniently written in dimensionless form as follows:

$$E_{\mathrm{m,v}} = \begin{cases} E^*_{\mathrm{m,v}}\left(\frac{\tau}{\tau_{\mathrm{c}}}-1\right)^n & \text{if } \tau \geq \tau_{\mathrm{c}} \\ 0 & \text{if } \tau < \tau_{\mathrm{c}} \end{cases} \tag{2}$$

where $E^*_{\mathrm{m,v}} = K_{\mathrm{m,v}}\tau_{\mathrm{c}}^n$ appears as a standard (mass or volume) erosion rate, which coincides with the actual erosion rate obtained for a flow shear stress equal to twice the soil's critical threshold τ_{c}. This quantity is also occasionally referred to as the rate coefficient [108].

The exponent n of the power law is certainly of practical interest as it accounts for non-linear relationship between erosion rate and excess stress, both for concave curvature ($0 < n < 1$) and convex curvature ($n > 1$). However, unlike the other two parameters, K and τ_{c}, which will be discussed just beyond, it is much more difficult to provide for n a straightforward physical

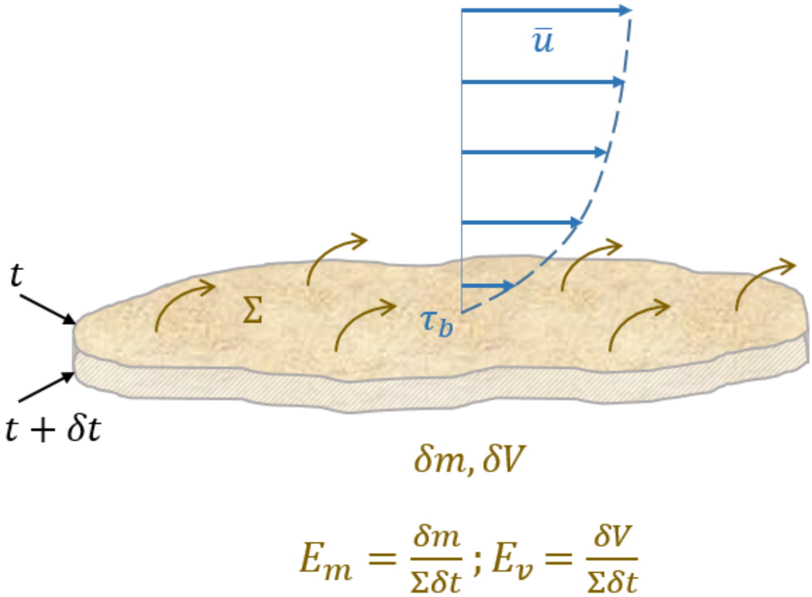


Figure 4. Sketch of a soil surface Σ subject to erosion by a flow characterised by a given mean velocity $\overline{u}$ profile and related bottom shear stress τ_b. The mass (respectively volume) loss is denoted δm (respectively δV) and the erosion rate $E_{\rm m}$ in mass (respectively $E_{\rm v}$ in volume) is directly derived.

interpretation, or even a more indirect one. While Walder proposed a generalized erosion law where $n = 7/4$ [71], other authors have shown that a value strictly greater than 1 leads to a divergence[2] in erosion kinetics and therefore appears non-physical [109]. Consequently, the linear excess-shear stress erosion law, where $n = 1$, is the one commonly used in practice. The preference for $n = 1$ is most likely due to several factors. Firstly, it offers conceptual simplicity. Additionnally, determining an exponent $n \neq 1$ that would be used as a free fitting parameter is challenging, given the wide dispersion frequently observed in most erosion rate measurements, as illustrated in Figure 5 by several examples involving natural or reference soils [110–113]. Note that selecting $n = 1$ also provides convenient units for $K_{\rm m}$ and $K_{\rm v}$, which are $\text{s}\cdot\text{m}^{-1}$ and $\text{m}^2\cdot\text{s}\cdot\text{kg}^{-1}$, respectively.

In the simplified modelling of surface erosion, the physical interpretation of the K and $\tau_{\rm c}$ parameters is relatively straightforward. Assuming there exists a threshold for initiating the erosion process, this threshold is directly reflected by $\tau_{\rm c}$ in a bottom shear stress-based representation of hydrodynamic loading. From a phenomenological perspective, it is natural to introduce the excess shear stress $\tau - \tau_{\rm c}$ more precisely. Therefore, under constant imposed shear stress $\tau > \tau_{\rm c}$, the proportionality coefficient K will control the intensity of the erosion rate and thus directly the kinetics of the process. Each of these two parameters contributes to quantifying a soil's sensitivity to erosion, both in terms of resistance, with an initiation threshold that must not be exceeded if the risk of erosion is to be inhibited, and in terms of kinetics once the process has been initiated, in relation to the survival time of a structure in a crisis situation. In summary, K and $\tau_{\rm c}$ collectively capture a soil's sensitivity to erosion, that is referred to as *soil's erodibility*. This conceptual framework, as defined by this local linear law, implicitly

[2]More precisely, in a pipe flow configuration assuming uniform radial extension by erosion, the authors of this study demonstrated that the pipe radius diverges in finite time if ever $n > 1$.

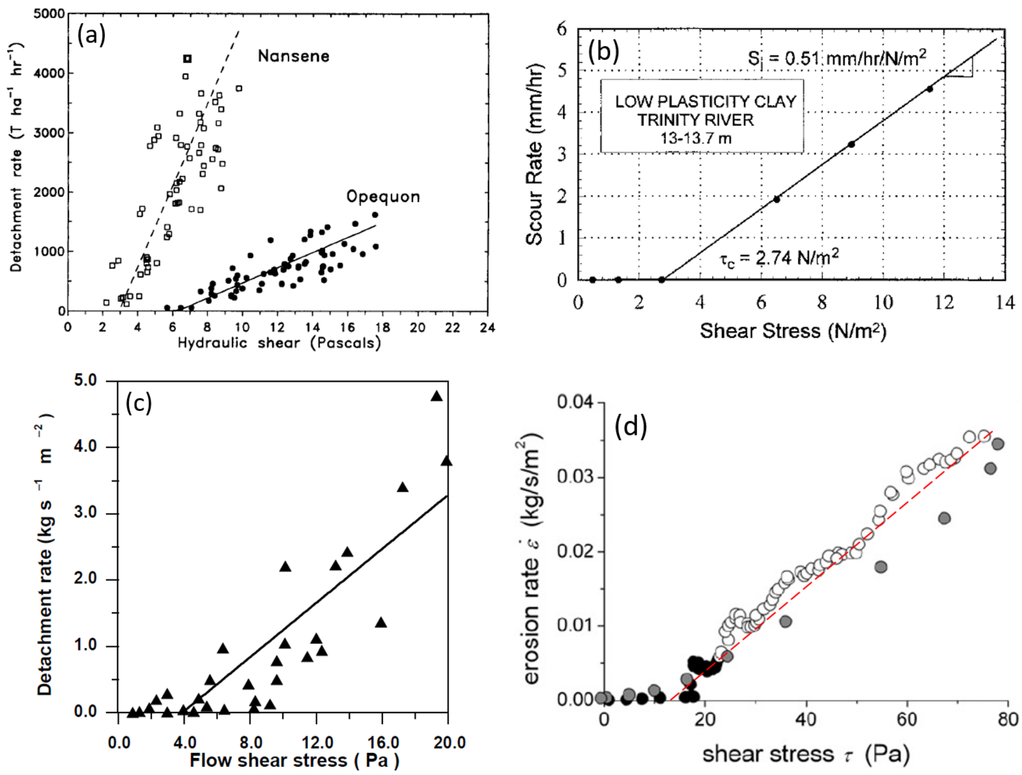


Figure 5. Some illustrative comparisons of the linear excess shear stress model with experimental data of either the mass E_m or volume E_v erosion rate obtained for: (a) cropland soils [110]; (b) low plasticity clay [111]; (c) sandy-clay silty soil [112]; (d) kaolinite-sand mixture [113].

assumes that the action exerted by the flow on the soil surface is fully described by the bottom shear stress alone, regardless of the hydrodynamic configuration generating the erosion. The corollary leads directly to considering the erodibility parameters K and τ_c as intrinsic material properties, independent of all other external influences. Undoubtedly, this question is highly debatable. While it is obvious that erodibility depends on soil properties [114, 115], it is by no means evident that it depends exclusively on them. In reality, there are likely other external factors that can influence erosion sensitivity, such as environmental conditions, vegetation cover, land use, variations in the hydraulic regime, etc. These external influences can interact with the properties of the soil to affect the erosion rates. Therefore, it may be more accurate to consider erodibility as a dynamic property that can vary depending on the specific conditions and context in which erosion occurs.

Despite the simplistic assumption of applying a minimalist model with a linear relationship between erosion rate and flow stress, the comparison with experimental measurements is generally acceptable and sometimes even very satisfactory, as demonstrated in previous Figure 5 with results from studies using a wide variety of devices and soils [110–113]. Considering in addition the broad to very broad dispersion almost systematically observed in these erosion data, the excess shear stress model appears to be reasonably acceptable. This explains why little effort has been made to complicate further the conceptual framework starting from this consistent although minimalist basis. However, there is a more sophisticated modeling approach in which this

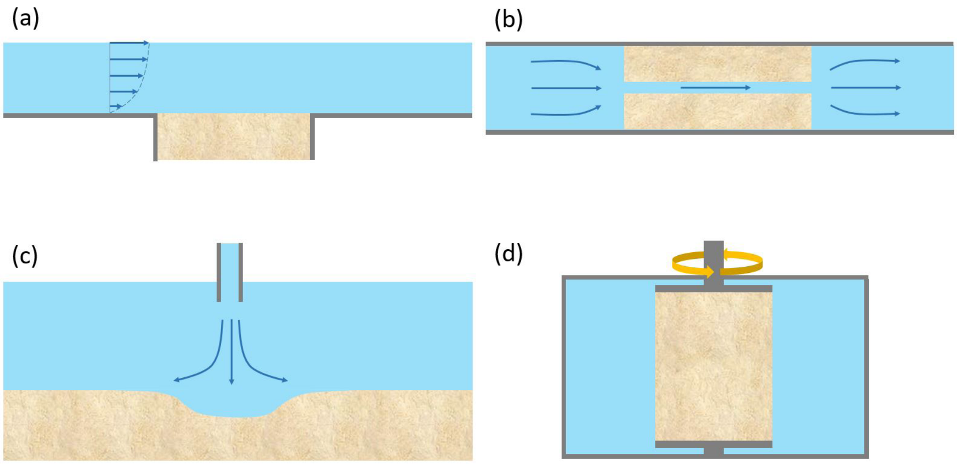


Figure 6. Sketches of the most typical flow configurations in erosion testing devices: (a) tangential flume flow; (b) through-pipe flow; (c) jet flow; (d) rotation flow.

excess shear stress law is used as part of a probabilistic description of soil erosion [73,82,85]. Such probabilistic approaches allow to consider substantial deviations from the average phenomenon represented by a unique mean field erosion law. This variability can be temporal and is particularly important with respect to flow stress in turbulent regimes. It can also occur in space, either due to intrinsic variability in soil properties, or if the eroding flow at the surface of the material is not uniform, as in the case of porous flow for instance [85]. In this case, this also means that there may be a dependence on the size of the eroded sample, as long as the latter is too small to fully reflect the whole range of variation of the key parameters. These probabilistic models enable for instance to address the structure scale [116] or to question the existence of a threshold on a macroscopic scale [82, 85, 105].

2.3. *Developments of a wide range of dedicated erodimeters*

The systematic evaluation of the two *erodibility* parameters, allowing quantification of the absolute value of erosion resistance and relative classification of soils, has driven the development of numerous specific erosion devices. These devices involve various types of flow, with the tested soil being submerged or not, and where the flow features can vary widely: free surface or confined flow, tangential or impingement flow, stationary or time evolving regime. The main hydrodynamic configurations of these erosion tests include longitudinal channels, annular flume, pipe flow, submerged impinging jet and, more seldom, rotating flow. For example, as suggested by [117] and sketched in Figure 6, these devices can be broadly classified into four different categories: flume erosion tests [63,77,98,100,111,118–132], through-pipe erosion tests [113,133–142], jet erosion tests [75, 76, 81, 143–147] and rotating apparatus tests [143, 148–151]. These different types of erosion tests offer a variety of experimental setups to study erosion processes under different hydrodynamic conditions. Each type of test has its advantages and limitations, and the choice of test method depends on the specific research objectives and conditions being studied.

Measurements of erosion and sediment transport in channels represent some of the first devices used to study these processes. Flows are generally free surface, although confined configurations also exist, especially for in-situ purpose as will be discussed later. Erosion occurs at the bottom of the channel, either over a large area of sediment, or limited to the upper surface of one or more soil samples, which are generally cylindrical in shape and vertically oriented. In the latter case, the sample must be raised either manually or by a piston, as regularly as possible to ensure that its eroded top remains aligned with the rest of the floor. Depending on the device, this is achieved either by visual criteria (operator-dependent) or by more sophisticated feedback systems [77, 130]. These channels are usually straight and rectangular in cross section, with a flow rate regulated by a pump, within a recirculating closed-loop system [98,111,118,122,124,127,128,130,152] or not [63,77,120,121,123,125,126]. However, flow establishment length in such flumes can be relatively large, a condition which is not always met in practice or may require large dimensions for the device to achieve. From this perspective, another common geometry for studying erosion and sediment transport is the annular flume, where flow, confined or not, is generated from above using a speed-controlled rotation drive system, sometimes called carousel [119]. Symmetry (i.e., invariance by rotation) and the absence of a pump result in a periodic condition in the flow direction, as a replica of infinite river, enabling the investigation of long-time processes [100, 119, 120, 131, 132, 153]. However, this is of interest mainly for sediment transport issues, but less suitable for studying erosion alone.

As mentioned in previous Section 1.4, one of the main mechanisms of internal erosion in an earthen hydraulic structure is driven by concentrated flow along a through pipe creating a preferential path for erosion. To reproduce this phenomenon in the laboratory, the Pinhole test was the pioneer test for characterising qualitatively the soil dispersivity [133]. Afterwards, for quantitative assessment of erosion, the Drill Hole test was proposed [135]. Later, Wan and Fell developed the original version of the device referred to as Hole Erosion Test (HET) [137, 138]. In this type of test, a hole is first drilled longitudinally through a soil sample before immersion in water. Then, to generate erosion, a controlled flow is imposed along this pipe. The soil must possess specific cohesion properties to withstand the drilling of the hole and not subsequently collapse. To avoid this problem and, above all, to enable the erosion phenomenon to be visualized, few variants of the device have been proposed, with, instead of a pipe, a slot carved in the soil at the interface with a transparent wall, and called either Slot Erosion Test (SET) [137], viewable HET [141] or Groove test [142]. Intrinsically, all these test configurations based on a pipe across the sample induces a strong and immediate feedback between soil surface erosion and the eroding flow through the progressive geometric evolution of the pipe, or slot.

The impinging jet tests are inspired by the hydraulic configuration of scour as observed in field. These devices were mainly developed in North America [81, 143, 144], where significant advancements have been made, notably by Hanson's group with their Jet Erosion Test (JET) [75, 145, 154–156]. Generally speaking, these tests consist in completely submerging the soil zone or sample under study, then applying in the upper water column a downward jet flow of adjustable velocity impinging, usually perpendicular, on the surface to be eroded. A scour crater is thus gradually excavated and its dimensions regularly measured, requiring the jet to be temporarily stopped, or deflected, for measurement. The latter is difficult to achieve, and is often limited to the depth beneath the jet. Nevertheless, more sophisticated techniques have been developed to determine the overall shape of the scour crater [76, 81, 122]. However, the volume or mass of soil eroded can only be an estimate. In the same category of tests relying on jet flow perpendicular to the soil, is the Borehole Test [146, 157], which differs significantly from the other impinging tests in that the flow takes place through a vertical tube previously introduced into the soil. Last but not least, this cratering configuration is also highly relevant to the case of high-speed gas jets, particularly in the context of extraterrestrial landings (Moon, Mars) [158–160].

Devices based on rotating flows are relatively limited in number, probably due to their rather complex application. Two examples of such devices are the Rotating Cylinder Test (RCT) [143,149, 150] and the Rotating Erosion Testing Apparatus (RETA) [151]. In principle, a flow is generated by an external rotating cylinder while a soil sample is placed at the center, around the axis. Shear stress at the soil surface is deduced from a direct or indirect measurement of the torque exerted on the sample, while erosion is assessed by weighing the remaining soil and/or the eroded soil, requiring regular pauses in the spinning system to make these measurements. While these devices offer a unique approach to studying erosion under rotating flow conditions, their complexity and the need for frequent interruptions in testing may limit their widespread use compared to other erosion testing methods.

There are several fundamental differences between these various devices and configurations. Apart from the variable degree of turbulence in the flows, they are distinguished by their permanent or evolving features. Flume configurations typically maintain a relatively constant flow throughout the test, with the eroded soil sample being continuously re-positioned at the bottom of the channel. In contrast, the other configurations involve a regular receding of the water–soil interface, leading to a gradual evolution of the flow geometry that may be more or less pronounced depending on the testing method, such as through-pipe or jet erosion compared to flume erosion. Flow control methods also differ among the configurations, with some using regulated discharge (by pump or rotary drive for carousel configuration) and others imposing constant pressure difference (in the case of pipe flow). The hydrodynamic configurations encountered present a variety of complexities, requiring different degrees of reliance on empirical laws to determine relevant flow quantities serving as input variables for the interpretation models (see Section 2). This is particularly the case with the impinging jet whose flow is slowed down on its axis and sharply deflected radially until it tangents the ground surface [161]. Combined with the additional dependence on several jet parameters (nozzle size and shape, distance from the soil surface, etc.), the direct determination of flow features is a real challenge, especially in the presence of a developing crater [162]. Furthermore, differing situations can be highlighted with regard to flow direction in relation to soil intrinsic anisotropy. This anisotropy, directly linked to a gradient of soil properties, results either from natural consolidation under gravity, or from static pressure or dynamic layer compaction during the soil sample reconstitution in the laboratory. Erosion resistance will therefore differ depending on whether the flow stress is exerted perpendicularly (i.e. flume tests) or tangentially (i.e. through-pipe and rotating tests) to the consolidation or compaction orientation of the soil. Additionally, there exist various methods in soil mechanics practice to prepare a specimen under predetermined conditions [163], and the choice made for an erosion test can have an impact on the erodibility values measured.

Conducting measurements on site is also a critical point, particularly in the context of submarine hydraulics, necessitating the development of in-situ devices that prioritize portability and robustness [86]. This is especially important when dealing with mechanically fragile or environmentally sensitive soils, such as soft/loose muds or soils subject to biological activity which may have a strengthening (bio-stabilization) or weakening (bio-turbation) effect on erosion [86, 108]. These on-site devices include the Jet Erosion Test [145], the In Situ Erosion Flume (ISEF) [122], the IFREMER erodimeter [63, 126], the Mobile Recirculating Flume (MORF) [164], the VIMS Sea Carousel [120], the Adjustable Shear Stress Erosion and Transport (ASSET) flume [165] and several versions of the Cohesive Strength Meter (CSM) [124, 166]. However, in the cases where soil cores can be extracted under good conditions and without risking material disturbance, there is an obvious advantage in carrying out erosion measurements in the laboratory, on a set-up that generally provides far better possibilities in terms of instrumentation, metrology and control of ambient conditions allowing for more precise and controlled experimentation. Additionally, aside from in-situ tests, it is worth noting that erosion tests can also be conducted on real structures or specific physical models of comparable size, particularly in overflowing or wave overtopping configurations [167–173].

To further illustrate some of these different types of erodimeters, the following section describes in more detail the three main erodimeter systems encountered in the field of geomechanics: Erosion Function Apparatus (EFA), Hole Erosion Test (HET), and Jet Erosion Test (JET).

3. Focus on principal erosion devices in geomechanics

3.1. *Erosion function apparatus (EFA)*

A well-known illustration of linear erosion channel (i.e. configuration of Figure 6a) is the Erosion Function Apparatus (EFA) developed in the early 1990's by Briaud and collaborators from Texas A&M University (College Station, Colorado, US) [111]. This apparus has been standardized and commercialized by a company specialized in construction materials testing equipment[3]. It has become widely used in geotechnical engineering research and soil erosion studies, providing valuable insights into erosion mechanisms and helping to inform engineering practices related to erosion control.

Typically, the soil sample to be tested is collected in the field using a Shelby tube and then placed in a circular opening at the bottom of the hydraulic flume. The latter, depicted in Figure 7a, is a rectangular channel with pump-driven re-circulation. In the setup illustrated in Figure 7b, it is crucial to maintain alignment between the top of the sample and the bottom of the channel. This alignment is achieved by regularly pushing up the Shelby tube with a piston, following as closely as possible the rate at which the sample erodes. A side window allows visual monitoring of the sample to determine when the piston should be raised incrementally, typically in 1 mm steps under manual control. The progression of the piston provides the volumetric erosion rate E_{v}. A global test protocol was developed and adapted for the critical visual detection step to ensure accurate monitoring of erosion progression. A flow-meter installed in the flume measures the average flow velocity, from which the bottom shear stress τ can be determined using the Moody's chart. The average velocity can be varied across a wide range, from 0.2 to 6 $\mathrm{m{\cdot}s^{-1}}$, enabling for multiple data points to be collected for a single sample in order to plot the relationship between erosion rate and either flow velocity or bottom shear stress. The test provides a classification of the soil's resistance to erosion, as detailed in forthcoming Section 4.1. Additionally, through regression analysis, quantitative values for the critical shear stress τ_{c} and erosion coefficient K_{v} can be determined.

3.2. *Hole erosion test (HET)*

There is no real standard for the Hole Erosion Test (HET), and several research teams have developed their own devices. All of them can be considered direct descendants of the original HET device developed by Wan and Fell at University of New South Wales (Sydney, Australia) in the early 2000's [137, 138]. Figure 8 shows pictures of the first HET device alongside several examples of later versions that incorporate various improvements. These improvements may include enhancements to the testing methodology, modifications to the setup for increased accuracy or efficiency, or adaptations to accommodate specific research requirements. Overall, these developments reflect ongoing efforts within the research community to refine and optimize erosion testing techniques for better understanding of soil erosion.

The distinctive feature of the HET test is the presence of a through-hole in the soil sample as sketched in Figure 6b. By imposing flow along this pipe, high stresses can be generated in a straightforward manner. However, the use of undisturbed soils is challenging since the drilling

[3] https://www.humboldtmfg.com/erosion-function-apparatus.html

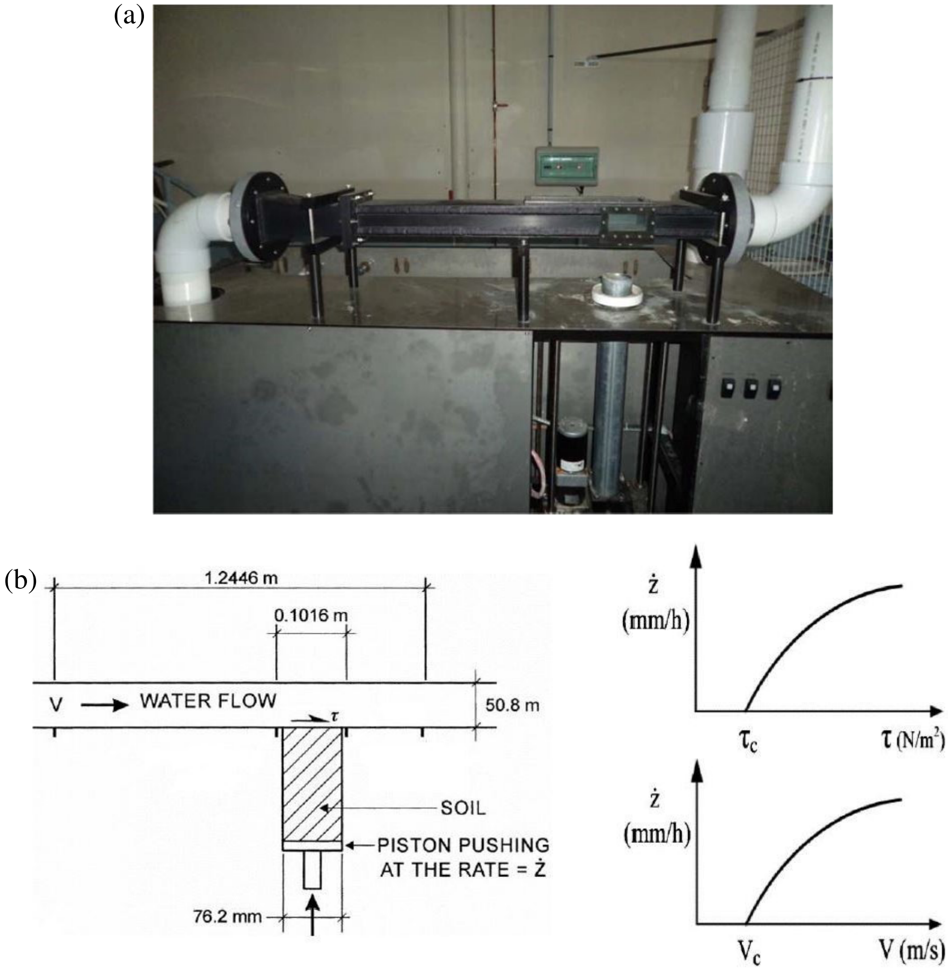


Figure 7. (a) Picture of the Erosion Function Apparatus in operation at ESTP (Paris) [174, 175]. (b) Sketch of the soil sample in the Shelby tube and of typical erosion curves from [176].

phase, even in a reconstituted soil specimen, is delicate, as some materials may be too fragile to withstand the drilled pipe, and may experience slaking either before or during the test [180]. Depending on the protocol, the initial diameter of the hole varies from 3 to 6 mm. Once the tube containing the soil sample is assembled with the rest of the device, the whole system is saturated and a flow is applied, either at a imposed flow rate or imposed pressure. As erosion occurs and the diameter of the hole increases with mass loss, interpolation laws are used to estimate its size at any time, assuming a cylindrical geometry and, the final diameter is measured or estimated post-test to refine the interpolation. The measured quantities typically include flow rate, downstream turbidity and pressure at various positions. The pressure measurements are particularly crucial for accurately determining the pressure drop induced by the flow through the pipe. This involves considering singular pressure losses at the pipe inlet and outlet. For instance, the HET-P device uses a Pitot static tube for local pressure measurement, positioned right at the exit of the hole [140, 181]. Interpretation models may vary among research teams, but all manage to derive the erosion rate and wall shear stress (in a hole geometry assumed to be

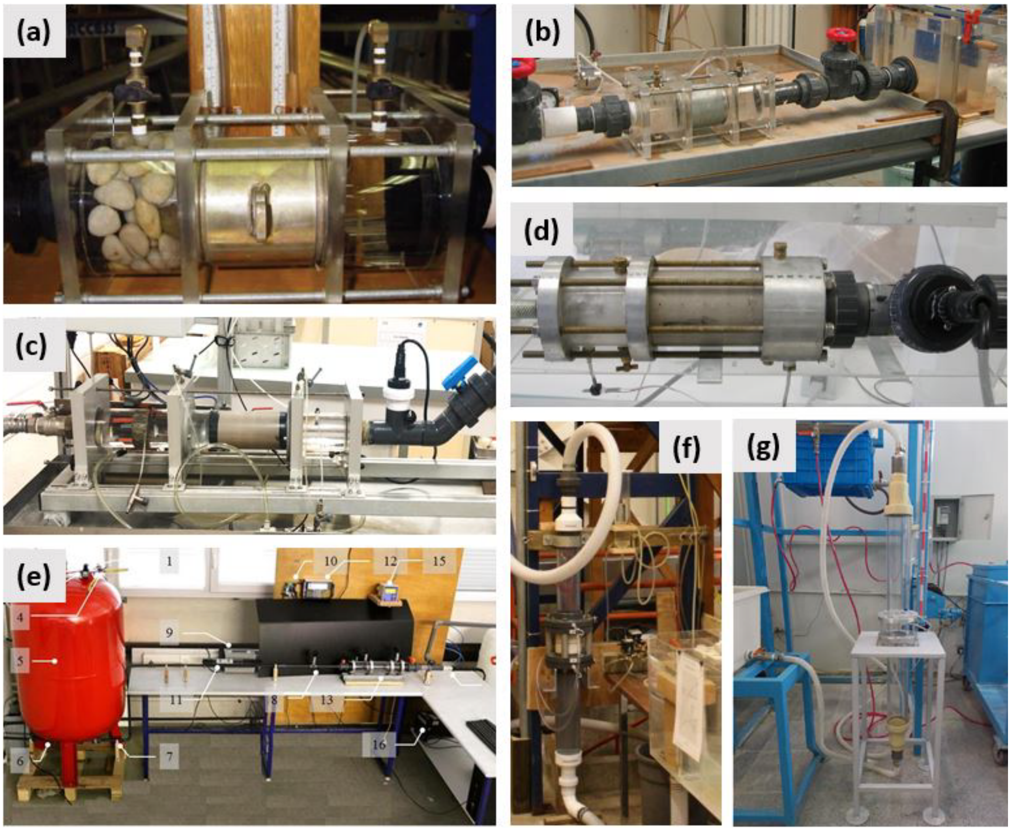


Figure 8. (a) Original HET by Wan and Fell at University of New South Wales (Sydney, Australia) [137]. (b) HET developed at US Bureau of Reclamation (Denver, Colorado, US) [177]. (c) HET developed at INRAE (Aix-en-Provence, France) [82,175]. (d) HET developed at University Gustave Eiffel (Champs-sur-Marne, France) [113]. (e) HET developed at University of Lorraine (Nancy, France) [178]. (f) HET-P developed at University of British Columbia (Vancouver, Canada) [179]. (g) HET developed at Shiraz University of Technology (Shiraz, Iran) [140].

cylindrical) from measurements (pressure, flow rate and turbidity if available), in order to deduce the erodibility parameters τ_c and K by linear regression.

3.3. *Jet erosion test (JET)*

The Jet Erosion Test (JET) device is probably the most widely used erosion testing device due to its versatility for both laboratory and field experiments. Inspired by the practical case of soil scour, the JET device is the eponymous and certainly the best-known among the jet erosion tests. It was originally developed in the late 1980's by Hanson and his colleagues at the Agricultural Research Service Hydraulic Engineering Research Unit in Stillwater, Oklahoma, US. Since then, it has undergone a succession of upgrades and improvements [75,145,154]. The testing apparatus, as shown in Figure 9b, and its accompanying interpretation method are described in ASTM Standard D5852 (2003). Additionally, there are two field versions: the original one and a more compact mini-JET [155], as depicted in Figure 9b. These field versions allow for erosion testing

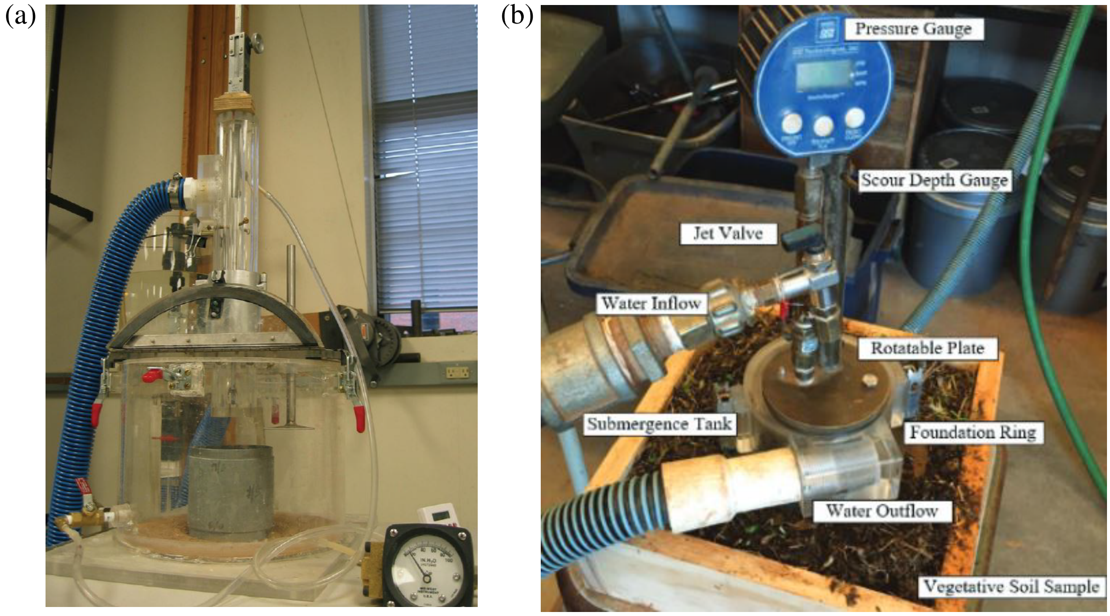


Figure 9. (a) Picture of the Jet Erosion Test at ESTP (Paris) [177]. (b) Picture of the mini-JET [182].

in real-world environments, providing valuable insights into soil erosion processes under natural conditions.

In practice, after full immersion of a soil sample or the ground area to be tested on site, a submerged jet is generated at the outlet of a delivery tube, positioned perpendicular to the soil surface, in the configuration shown in Figure 6c. The jet is supplied by a pump, either via an adjustable head tank or by direct connection when high stresses are required. The circular nozzle at the bottom of the tube is fixed at 6.4 mm, but the distance to the soil surface is adjustable. The estimated maximum erosion stress can thus be varied over a very wide range, from 4 to 1500 Pa. Variations in maximum bed scour depth are measured using a point gauge. The latter is tightly fitted to pass exactly through the nozzle, temporarily interrupting the flow while the measurement is being taken when the gauge comes into contact with the bottom of the erosion crater.

There have been several developments and improvements in the interpretation method for the JET, which ultimately provides the two expected parameters τ_c and K_v. However, despite using consistent input variables such as jet velocity, presumably constant during the test, and measured depth, there are significant disparities in the erodibility parameters obtained, depending on the method employed [183, 184]. This underscores the importance of refining interpretation methods and ensuring consistency in experimental procedures to obtain reliable and accurate results in soil erosion testing.

3.4. *Comparative analysis of the three erosion devices: EFA, HET, JET*

The comparison of the three erosion testing devices, JET, EFA, and HET, reveals various advantages and drawbacks in terms of their applicability, erosion rate measurement methods, and hydrodynamic complexities. This provides the following comparative overview [177, 185].

JET and EFA offer the possibility of testing all types of soil, even those that are weakly or even non-cohesive, although in the case of JET, the grains tend to fall back into the crater and may distort the scour depth measurement. On the other hand, HET, which requires hole drilling, cannot be implemented on soils that are not cohesive enough or are too soft, as they risk collapsing [26]. Similarly, swelling soils should be avoided. Even on resistant sample, drilling can cause some damage to the soil. Regarding erosion rate, it is measured directly with the EFA, but using a visual procedure that is thus operator-dependant and rather critical. In the other two devices, the erosion rate is simply deduced from other measurements, such as turbidity or scour depth, with varying degrees of accuracy. Indeed, assuming that the cylindrical geometry is maintained during the test, HET modelling enables volume loss to be quantified, whereas JET interpretation is limited to the cavity depth under the jet in a simplistic 1D approach. With regard to the possibility of testing natural soils, while the HET and EFA are only laboratory tests, the JET can also be used in-situ, on flat or inclined (and even vertical) surfaces, especially its compact version mini-JET that is easy-to-use and inexpensive. It should be noted, however, that unlike HET where soil samples generally have to be reconstituted, those tested at EFA can be preserved in conditions close to those on site, thanks to the use of a Shelby tube.

In terms of hydrodynamics, the three devices display very different flow configurations of increasing complexity. The simplest situation is clearly that of the EFA, which is based on a steady channel flow whose characteristics have long been known, even if they require the use of empirical laws for the friction factor. It should be noted, however, that the transition between the bottom of the channel and the flush surface of the soil sample can create local flow disturbances, which may compromise the assumption of flatness preservation on the eroded interface, as well as the critical visual detection controlling the 1 mm piston increment. The hydrodynamics of the HET are more complex, firstly because of the flow reduction and expansion at the inlet and outlet of the hole, which generate singular head losses and intensified erosion. Secondly, while flows in cylindrical pipes are also well known, this is an atypical case where the length is small and the radius grows during the test. As already mentioned, the modelling of the HET flow has been developed and perfected in great depth to take account of these different aspects, although it requires the assumption, which is therefore questionable, that the hole remains cylindrical. However, the experimental validation of analytical scaling laws definitely supports the interpretation model [109]. In contrast to the other two systems, it's also worth noting the ability to impose either flow or pressure hydraulic conditions. Finally, the JET configuration seems to be the most complex, from the initial situation of a jet impacting a flat surface, but even more so as the scouring crater develops. Approximate flow modelling therefore requires drastic simplifications, as is done for JET test interpretation.

4. Benefits and limitations of quantifying soil erodibility

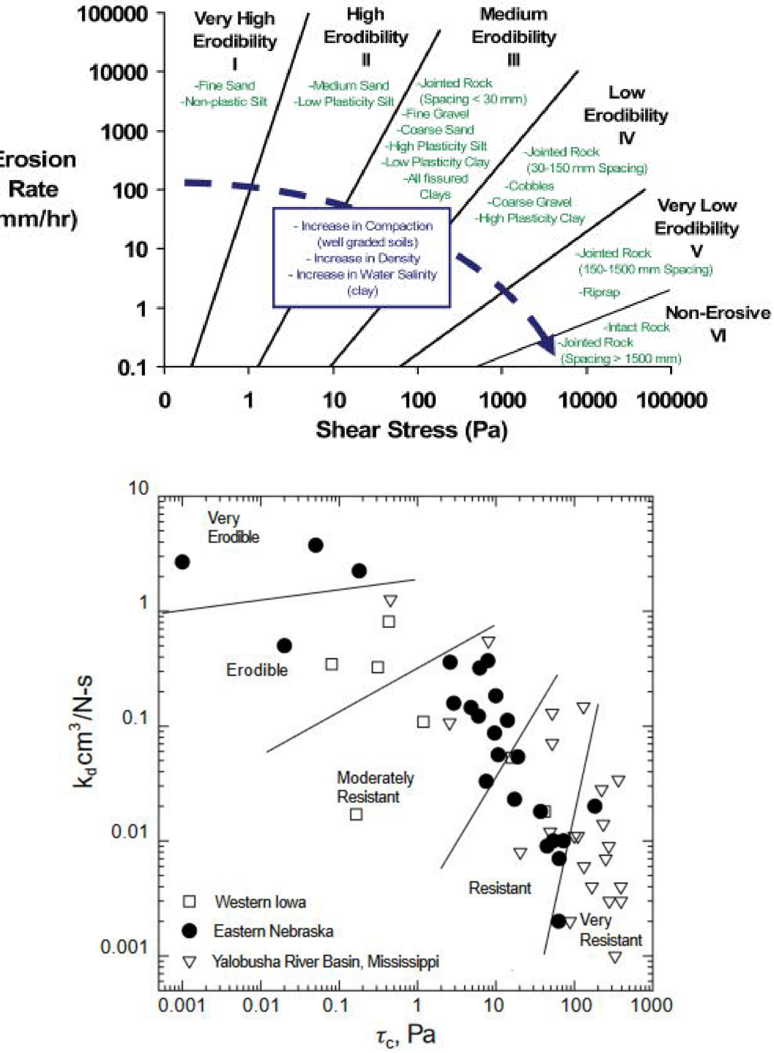
4.1. *Classification of soil's erodibility*

Several classification rules have been proposed, based on the extensive databases of experimental values of erodibility parameters that have been progressively built up with the results of erosion tests on a very wide range of soils with highly variable properties and compositions. Each classification rule likely offers insights into soil erosion behavior under specific testing conditions and may be tailored to different applications or soil types. Basically, there are three competing proposals, originating from EFA, JET and HET data, respectively.

Briaud's classification system, based on EFA tests carried out on a wide variety of soils, categorizes soils into six distinct categories of materials, ranging from non-erosive to very high erodibility [176]. As can be seen in Figure 10, this classification, with various soil categories,

(a)

(b)



(c)

Erosion rate index	Description
<2	Extremely rapid
2–3	Very rapid
3–4	Moderately rapid
4–5	Moderately slow
5–6	Very slow
>6	Extremely slow

Figure 10. The different charts for soil's erodibility classification: (a) Chart proposed by Briaud based on EFA test results [176]; (b) Chart proposed by Hanson based on JET tests [145]; (c) Erosion rate index based classification as suggested by Wan and Fell [138].

is developed using a log-log diagram displaying the rate of erosion as a function of stress, in some words the same type of representation as that of the erosion law. In this diagram, each test corresponds to multiple data points, with the eventually of straddling two categories, which can complicate classification. The boundaries between the categories are represented as linear, implying power law relationships between erosion rate E_v and exerted shear stress τ, with increasing exponent. This type of relationship is therefore substantially different from the linear excess shear stress erosion law of Equation (2) (with $n = 1$). It is also important to note that this classification may have limitations, particularly in cases where soils exhibit behavior that falls between two categories as already mentioned.

A second classification has been proposed by Hanson on the basis of the very large number of tests carried out with JET device, primarily through in-situ testing across various locations in the United States [75, 145, 156]. This classification is based on a log–log representation of the erosion coefficient K_v (here denoted k_d) as a function of critical shear stress τ_c, with each soil tested corresponding to a single point. As shown in Figure 10, the chart is divided into five zones by linear boundaries, representing power law relationships, which categorize soils from resistant to very erodible. It is noteworthy that K_v is expressed in unconventional units, in $cm^3 \cdot N^{-1} \cdot s^{-1}$.

Alternatively, Wan and Fell introduced the erosion rate index I_m, derived from HET test results, which is defined as $I_m = -\log(K_m)$ with K_m expressed in $s \cdot m^{-1}$ [138]. They proposed a classification into six categories for the expected soil erosion ranging from extremely rapid, for $I_m < 2$, to extremely slow, for $I_m > 6$ (See Figure 10).

Although these classifications are all derived from test-specific databases and established by rather arbitrary boundaries between soil categories, they appear reasonably applicable across various types of test. Overall, these classification systems provide a framework for categorizing soils based on their erosion characteristics, offering insights into their behavior under different stress conditions. They serve as practical tools for understanding and assessing soil erosion potential, aiding in the planning and management of erosion control measures.

4.2. *Erodibility parameters in practice*

The various erosion tests presented and discussed in previous Section 3 enable positioning a given soil in the various classifications proposed above, and hence, offer valuable tools for qualitatively assessing soil's resistance against erosion. By knowing the erosion characteristics of a soil, particularly one present on a construction site, engineers and researchers can position it within the classifications proposed earlier, which enables them to identify the soil's category in terms of erosion sensitivity. Therefore, they can make informed decisions regarding erosion risk management. This knowledge helps ensure that appropriate measures are taken to prevent erosion-related issues during and after the construction or repair of hydraulic structures.

From a more quantitative point of view, critical shear stress is the key parameter of interest as regards soil's resistance against erosion in civil engineering conception, including design and safety requirement. It serves as a crucial threshold, defining the maximum bottom shear stress that a soil can withstand before experiencing erosion. This parameter is essential for ensuring the stability and longevity of earthen structures subjected to hydraulic forces such as infiltration or overflow. The main difficulty lies in accurately estimating the actual stresses potentially generated by water flows on the surface and within the hydraulic structure under consideration.

On the other hand, erosion coefficient K becomes crucial in crisis situations or emergency scenarios, when erosion is occurring within an hydraulic structure. In fact, as a variable representative of the kinetics of soil removal, K controls the rate of pipe expansion by erosion. For example, in the case of a through pipe with constant upstream water level and continuous erosion, and considering that the soil's critical shear stress is virtually negligible compared to that exerted

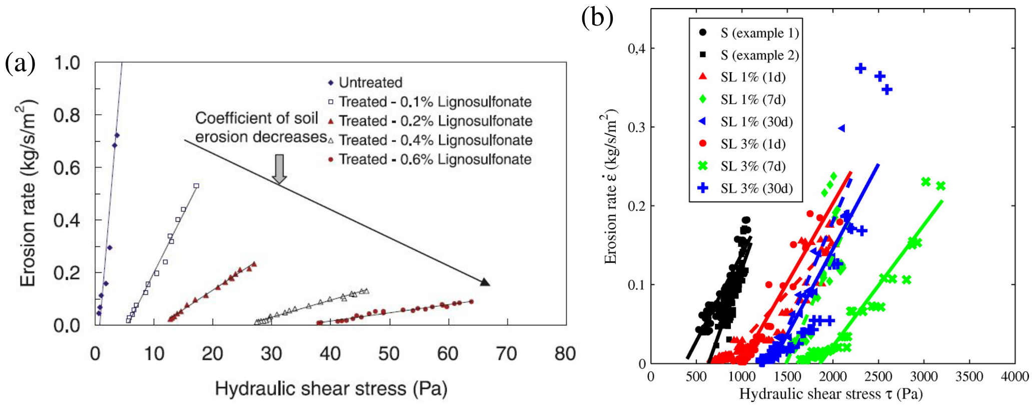


Figure 11. Examples of quantitative evidence of enhanced soil erosion resistance through (a) lignosulfonate treatment [189] and (b) lime treatment [178].

by the flow, the expansion rate of a through pipe can be shown to be highly dependent on the erosion index I_m. For instance, the time required for a pipe to expand from 25 mm to 1 m in diameter can vary over four orders of magnitude, from a few tens of minutes to several months depending on the value of I_m which ranges from 2 to 6 [186]. Going a step further, Bonelli and Benahmed proposed a simple model, with several mechanical quantities inferred from fourteen case studies, to estimate the remaining time until breaching for an earthen dam once a downstream leak due to piping flow erosion has been detected [82, 187]. From this model, the following relation was obtained:

$$\Delta t_c = t_c - t_d < \frac{2\rho_{dry}}{K_m \nabla P} \ln\left(\frac{H_{dam}}{2R_d}\right) \tag{3}$$

where Δt_c is the remaining time to dam roof collapse with t_d and t_c the time of initial leak detection and the time of ultimate collapse, ρ_{dry} is the soil's dry density, ∇P denotes the pressure gradient (assumed constant) through the pipe, H_{dam} is the dam height and R_d is the estimated radius of the pipe at detection. As the upper limit is inversely proportional to K_m, it potentially varies over 4 to 5 orders of magnitude. However, this variation may be less pronounced for soils that are sufficiently clay-rich and compacted during construction, such as those found in dams (through perhaps less so in a levee).

Erodibility parameters can also be useful indicators for validating and quantifying soil reinforcement achieved through various treatments, such as biocementing [188], chemical stabilization [189] and cement or lime addition [178, 190–192]. Figure 11 shows two illustrations of erodibility strengthening obtained by lignosulfonate [189] and lime [178] treatment with obvious critical shear stress increase in both cases while erosion coefficient substantially decreases as shown on the left graph. Another example depicted in Figure 12 shows the progressive increase in both critical shear stress τ_c and erosion index I_m during curing period after a lime treatment [191, 193]. These illustrations highlight the effectiveness of various soil treatments in enhancing resistance to erosion, as evidenced by changes in erodibility parameters.

4.3. *Lack of predictability from soil properties*

It is still a widely debated question whether there is a sufficiently conclusive connection between soil's susceptibility to erosion and usual properties, as commonly characterized in the laboratory (see e.g. in [163] for details on definitions and measurement methods for the usual characteristics

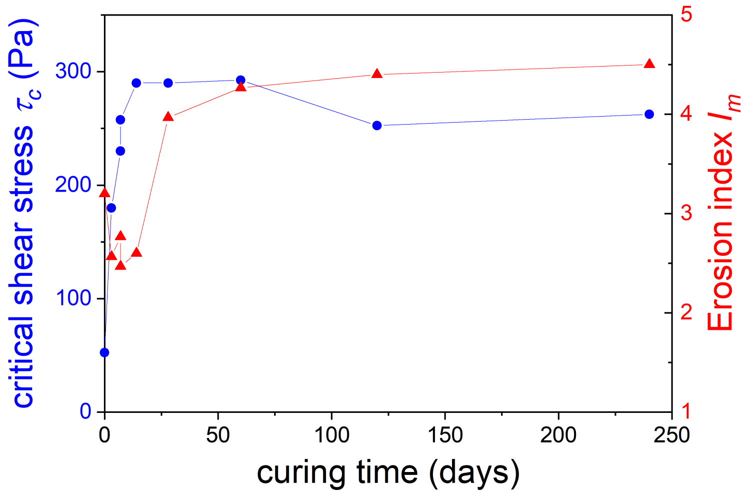


Figure 12. Example of gains in erodibility, i.e. critical shear stress τ_c and erosion index I_m, as a function of curing time during lime treatment of a Rhône river soil specimen (with $t = 0$ corresponding to untreated soil). Figure adapted from [191, 193].

of soils). All the more so since behind this issue is that of the intrinsic character of erodibility parameters, as postulated in the conceptual framework commonly proposed and which would be directly confirmed by such an immediate correlation with other inherent soil features.

Much effort has been devoted to finding quantifiable relationships, mostly on an empirical basis, between erodibility and the main measurable properties in natural soils, including particle size distribution, density, water content, plasticity index, consolidation time and many other quantities [63, 100, 108, 115, 185, 193–197]. A wide variety of empirical relationships have emerged in the literature, partially listed for instance by Winterwerp [64, 69], Grabowski [115] and Kimiaghalam [196], but further enriched since then. These relationships mainly concern the critical shear stress τ_c, with numerous correlations, more or less convincing, the essential ones of which have been synthesized by various authors [64, 115, 193, 197–199]. It is also a parameter for which theoretical approaches are frequently proposed, most often by extension of known results on the threshold for incipient motion of a purely frictional grain without cohesion or adhesion [62, 63, 199–201]. A power law with the plasticity index is also suggested [64, 69, 196]. By comparison, the kinetic erodibility parameter K has been less studied, which is most likely due to the greater experimental difficulty in determining it with confidence, particularly in-situ. Nonetheless, a theoretical model linking K to some consolidation parameters for fine soils can be reported [64] while some empirical or semi-empirical laws can be also mentioned [155, 183]. What all these studies have in common is the wide dispersion in erodibility data, which severely restricts the extent of the empirical relationships they attempt to support. The main reasons for this are undoubtedly the difficulties in measuring soil erosion already mentioned in Section 2.1, and the high degree of spatial variability in soil properties due to lack of uniformity, which is particularly acute for field measurements. A further consideration is the additional impact of ambient conditions such as temperature [202–204], for which an Arrhenius-type activation factor on erosion rate has been proposed and experimentally validated [202], or, more specifically for fine soils with clay fractions, salinity or pH [136, 202, 203, 205].

Independently of the investigation of direct relationships with other soil properties, some authors have also argued the existence of an underlying correlation between τ_c and K, thereby reducing the characterization of soil erodibility to the knowledge of a unique parameter, in line with the previous classification by Wan and Fell [138], which is based solely on K_m (see Section 4.1). Thus, supported by many JET test results, Hanson was the first to suggest the existence of an inverse power relationship of the form $K \propto \tau_c^{-\gamma}$ with $\gamma \approx 0.5$ [145]. Interestingly, it turns out that such an exponent equal to 1/2 can be recovered by dimensional analysis [206]. However, a broader review of the literature reveals a much wider range of exponent values, from $\gamma \approx 0.4$ to $\gamma \approx 2.4$, as reported by several authors [20, 76, 183, 184, 190, 207, 208]. Together with the huge dispersion of the data almost systematically observed and the dependence of the erodibility parameters on the choice of protocol or interpretation model (at least for JET measurements) [183, 184, 209], it appears more than hazardous to make any attempt of generalization. Especially since some contradictory analyses seem to conclude that there is no universal correlation between τ_c and K [66]. All in all, it seems difficult to go beyond the simple qualitative observation that a soil with less (more) resistance in terms of critical shear stress τ_c generally undergoes higher (lower) erosion rates under equivalent hydrodynamic conditions, i.e. when exposed to the same excess shear stress, thus corresponding to a greater (lower) erosion coefficient K.

In short, the compilation of all these correlation analyses leads to the conclusion that there are no standardized relationships from a quantitative point of view, and only very few general trends from a more qualitative point of view.

4.4. *Ongoing questions, difficulties and limits*

Additionally to the lack of strong correlations, several results highlight problems and raise questions about some limitations of the proposed conceptual framework.

One of the first issues encountered is beyond the simple scope of laboratory erosion tests, and relates more broadly to the ability of a reconstituted soil sample to reflect the effective hydro-mechanical behavior of the same soil under its natural conditions on site, leading to significant discrepancies in erosion tests results. In particular, it is known that one key issue is the loss of strength exhibited by reconstituted soil sample compared with that measured on undisturbed state [210]. In the specific case of erosion, detachment rates of disturbed samples were measured to be more than an order of magnitude higher than those observed for natural soil [211], although approximately proportional, as shown in Figure 13. This discrepancy is illustrated in the same Figure where data by an extract from HET database of INRAE reveals in the previous Wan and Fell's classification that intact soils consistently placed in the most erosion-resistant soil categories, contrasting with reconstituted samples. Consequently, the observed disparity underscores the challenge of accurately assessing soil erodibility in laboratory settings, where reconstituted samples may not faithfully represent the behavior of soils in their natural state. As a result, the extrapolation of laboratory-derived erodibility parameters to real-world conditions may be subject to considerable uncertainty and may not capture the true erosion susceptibility of soils in the field.

The variability in erodibility parameters across different experimental devices presents another significant challenge in erosion testing. Studies have highlighted wide disparities in erodibility parameters such as critical shear stress and erosion coefficient when the same soil sample is tested using different devices [174, 175, 177, 180, 182, 193, 212, 213]. For instance, from a comparison of results obtained with the Rotating Cylinder and the Hole Erosion Test (HET), Lim (2006) has shown a clear correlation between the two sets of data, but without achieving equality between the respective values of critical shear stress and erosion coefficient [180]. This discrepancy was particularly pronounced when distinguishing between dispersive[4] and non-dispersive

[4] A dispersive soil is structurally unstable when exposed to water, and particularly susceptible to erosion, due to a high concentration of exchangeable sodium ions and a large specific surface area [214].

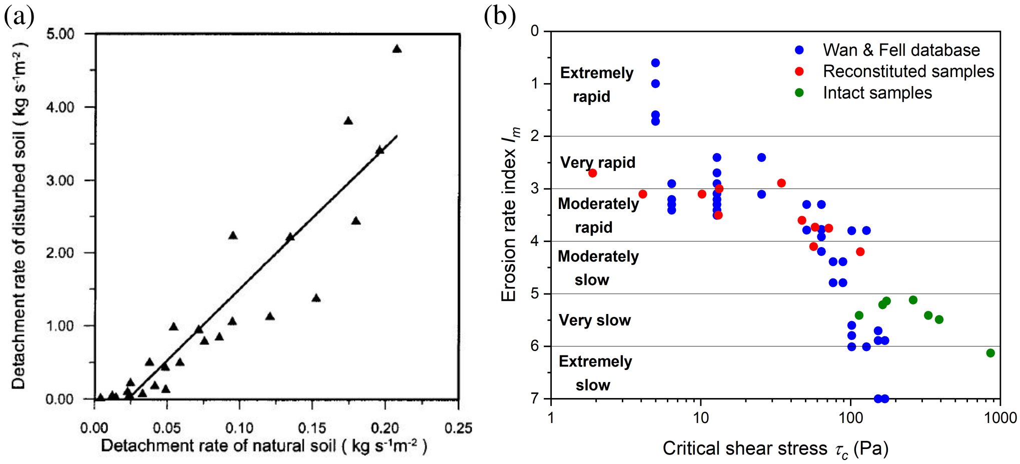


Figure 13. (a) Comparison of the erosion rates measured for disturbed and natural soil samples [211]. (b) Distinct ranking in Wan and Fell's chart according to the intact or reconstituted nature of several soil samples from INRAE's HET database.

soils. In cases involving non-dispersive soils, this work has shown that a much greater difference in erosion indexes I_{m} is observed for the second category, the erosion index I_{m} derived from the HET systematically yielded higher values as can be seen in Figure 14. Similarly, extensive analyses comparing JET and HET have consistently shown that HET tends to yield slower erosion rates K, or equivalently higher erosion indexes I_{m}, and larger critical shear stresses τ_{c}, up to more than an order of magnitude as observed in Figure 14, thus overestimating soil resistance to erosion compared to JET [177, 179, 193, 212]. Erdogan and collaborators (2008) found particularly large discrepancies for soils with heterogeneous structures, composed for example of clay aggregates while the difference is still significant, but much smaller, for more homogeneous materials [177]. It was suggested that the complex hydraulic configuration of the JET test, along with the simplifying assumptions required for interpretation, may contribute to the discrepancies observed. However, comparisons between mini-JET and flume erosion test suggest that variations are more moderate on average despite substantial dispersion, and perhaps a weaker correlation between erodibility values [182, 213]. In addition, a 2D axisymmetrical numerical modelling of surface erosion by a submerged turbulent impinging jet showed that there was no major inconsistency between measured erosion rates and those calculated on the basis of the erodibility parameters provided by the corresponding JET interpretation [215]. Furthermore, comparisons between HET and EFA have similarly indicated an overestimation of soil resistance, and therefore an underestimation of its erodibility, with the HET results [174, 175]. Note however that the same type of overall agreement between simulation and experiment is obtained for the HET configuration [216].

In conclusion, using the HET rather than another device therefore can lead to category changes in Fell's classification based on erodibility parameters, even though the relative position between two given soils may remain the same. However, note that a more global energy-based method enables identical categories to be found between HET and JET results [102]. Overall, as suggested by Mahalder and co-authors [213], τ_{c} and K estimates appear to be significantly influenced by the specific hydrodynamics induced by the testing device configuration. This raises a number of fundamental concerns. To be, or not to be intrinsic, that is the question for soil's erodibility if we are to paraphrase Shakespeare in light of these inconsistent comparative results! One may indeed wonder whether a unique and generic framework can effectively apply

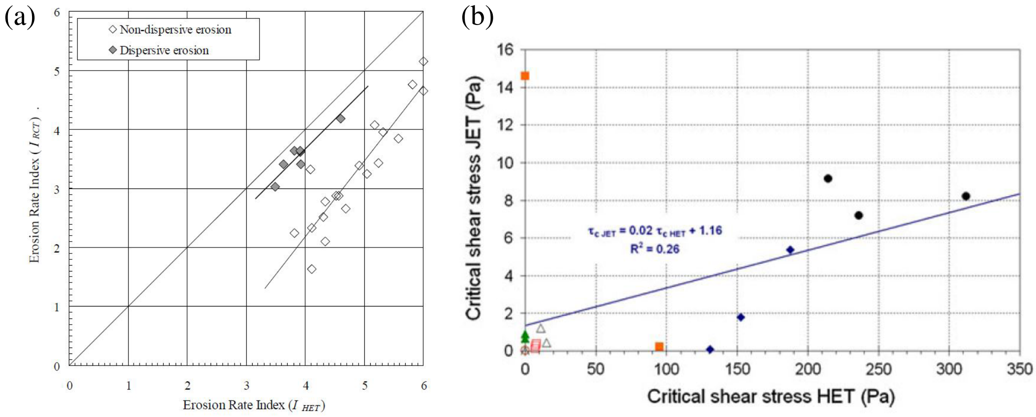


Figure 14. (a) Confrontation between the erosion indexes I_m obtained from HET and RCT tests, with distinction between non-dispersive and dispersive erosion [180]. (b) Confrontation between the critical shear stresses τ_c obtained from HET and JET tests [212].

for all types of soils and whatever the nature of the eroding flow at their exposed surface. The underlying question behind this line of thought is what erosion really is, particularly in terms of small-scale processes. There remains considerable exploration work to be continued, given the great variety of situations in terms of soil composition, physico-bio-chemical aspects and soil/runoff interactions, with widely varying lengths and characteristic times, including ageing.

5. Summary and perspectives

At a very broad scope, we can conclude that each disciplinary field has its own perception and definition of soil erosion, with quite specific scales of time and space. This vision derives organically from the object of study under consideration, the elementary mechanism of one discipline corresponding sometimes to the ultimate scale of another. In view of this vast spectrum of phenomena with many associated challenges and threats, we have chosen to emphasize the field of soil mechanics, i.e. for typical eroded soil surfaces of a few tens of centimetres with durations of minutes to hours.

Throughout this review, the reader has been able to appreciate the vast amount of work carried out on the subject, but also the intrinsic difficulties of soil erosion. The importance of quantifying the erosion resistance of soils has been demonstrated, in order to characterize their performance or predict topological changes in heterogeneous ground. We have shown how challenging it is to measure, both in terms of accurately determining the mass loss at an exposed soil interface, and in terms of correctly evaluating the most relevant quantities accounting for the load exerted by rather complex flows. Despite some limitations, the development of a conceptual framework for surface erosion has proved its worth and validity, enabling erodibility parameters to be defined explicitly for any coherent soil, for the purposes of own characterization, relative classification or even modeling. Yet questions remain as to the assumed intrinsic nature of this new material property. Finally, the description and comparison of the three leading erodimeters used in the field of soil mechanics, namely EFA, HET and JET, provided practical insights into these erodibility assessment tests.

From a purely fundamental point of view, a research perspective consists in improving our knowledge of the elementary processes involved in soil erosion, since this generic term actually covers different local mechanisms, some of which have already been identified but are still poorly understood [217]. Accordingly, Winterwerp and Kesteren propose the existence of 4 erosion modes for cohesive marine sediments: entrainment, floc erosion, surface erosion and mass erosion [64]. This approach represents a major scientific bottleneck that precludes the development of non-empirical models or realistic scenarios to explain how, and through which successive steps, a fragment of soil is ultimately removed from the surface of a compact material under hydraulic stress of sufficient intensity and/or duration. These mechanisms should be able to provide us with valuable information on the size (or more likely the size distribution) of the elementary soil aggregates thereby eroded and on the characteristic time, or even on the hydraulic conditions, required for such a process. This effort needs to be based on theoretical approaches, but must also involve specific experimental investigations, which require a high degree of customization in order to explore small scales, particularly on natural geomaterials. An interesting alternative is to substitute real soils by purely artificial materials, specifically developed, whose key characteristics are well under control and capable of facilitating this local exploration [201, 217]. The contribution of numerical simulation could also be essential, particularly with the Discrete Element Method (DEM) integrating both microscopic laws modeling internal cohesion and coupling between fluid and grains, which requires significant methodological developments [218–220]. However, this raises the question of how representative such over simplified systems can be, given that erosion appears to be highly material-dependent, as revealed by the poor correlation between erodibility and soil properties.

From a more practical perspective, there is still room for further improvement in soil erodibility tests, both from a technical perspective and in terms of interpretation models, possibly by extending the conceptual framework used. Progress in this respect could hopefully address some of the questions raised in the preceding section. At the same time, it is essential to promote the implementation of routine tests of this kind in geotechnical and environmental engineering, particularly when safety considerations prevail. Beyond the usual properties associated with composition and structure of a soil, erodibility could then simply become an additional standard parameter for material identification, on an equal basis with other parameters such as shear strength or plasticity index. Many of the researchers involved in some of the works summarized in this review have been working towards this goal in their respective networks for several years, with notable advances and real prospects. Undoubtedly, erosion testing devices have proved their merits and are increasingly finding their place in the hydraulic engineering community. EFA is widely used, mainly in the United States, and notably played an important role in the post-crisis expertise carried out on New Orleans levees after Hurricane Katrina in 2005 [221]. JET also remains a very common test, particularly because of its ability to be conducted on site. A recent workshop brought together a large number of current operators to draw lessons and propose future prospects for this instrument [156]. As for HET, this device has undergone several improvements since its original version and is increasingly being used in civil engineering. In France, for example, several companies have licensed the version developed by INRAE, and a new standard on HET testing (PR XP P94-065[5]) has just been certified at the end of 2023, including soil sample preparation and testing protocol. Progress is definitely on the right course!

Declaration of interests

The authors do not work for, advise, own shares in, or receive funds from any organization that could benefit from this article, and have declared no affiliations other than their research organizations.

[5] https://www.boutique.afnor.org/fr-fr/norme/xp-p94065

References

[1] J. Gaillardet, B. Dupré, P. Louvat, C. Allègre, "Global silicate weathering and CO2 consumption rates deduced from the chemistry of large rivers", *Chem. Geol.* **159** (1999), no. 1, p. 3-30.

[2] P. A. Dinis, E. Garzanti, A. Hahn, P. Vermeesch, M. Cabral-Pinto, "Weathering indices as climate proxies. A step forward based on Congo and SW African river muds", *Earth-Sci. Rev.* **201** (2020), article no. 103039.

[3] A. B. Murray, M. A. F. Knaapen, M. Tal, M. L. Kirwan, "Biomorphodynamics: Physical-biological feedbacks that shape landscapes", *Water Resour. Res.* **44** (2008), article no. W11301.

[4] W. Merritt, R. Letcher, A. Jakeman, "A review of erosion and sediment transport models", *Environ. Model. Softw.* **18** (2003), p. 761-799.

[5] H. Aksoy, M. L. Kavvas, "A review of hillslope and watershed scale erosion and sediment transport models", *CATENA* **64** (2005), no. 2, p. 247-271, 25 Years of Assessment of Erosion.

[6] J. Poesen, "Soil erosion in the Anthropocene: research needs", *Earth Surf. Process. Landf.* **43** (2018), no. 1, p. 64-84.

[7] L. C. van Rijn, *Principles of Sediment Transport in Rivers, Estuaries and Coastal Seas*, vol. 1006, Aqua Publications, Amsterdam, 1993.

[8] R. Soulsby, *Dynamics of Marine Sands*, Thomas Telford Publishing, 1997.

[9] T. Pähtz, A. H. Clark, M. Valyrakis, O. Durán, "The physics of sediment transport initiation, cessation, and entrainment across aeolian and fluvial environments", *Rev. Geophys.* **58** (2020), no. 1, article no. e2019RG000679.

[10] Y. Shao, *Physics and Modelling of Wind Erosion*, Atmospheric and Oceanographic Sciences Library, vol. 37, Springer, 2009, 1-452 pages.

[11] L. Mentaschi, M. I. Vousdoukas, J.-F. Pekel, E. Voukouvalas, L. Feyen, "Global long-term observations of coastal erosion and accretion", *Sci. Rep.* **8** (2018), no. 1, article no. 12876.

[12] A. Williams, N. Rangel-Buitrago, E. Pranzini, G. Anfuso, "The management of coastal erosion", *Ocean Coast. Manag.* **156** (2018), p. 4-20.

[13] R. B. Bryan, "Soil erodibility and processes of water erosion on hillslope", *Geomorphology* **32** (2000), no. 3, p. 385-415.

[14] C. Castillo, J. Gómez, "A century of gully erosion research: urgency, complexity and study approaches", *Earth-Sci. Rev.* **160** (2016), p. 300-319.

[15] G. Gyssels, J. Poesen, E. Bochet, Y. Li, "Impact of plant roots on the resistance of soils to erosion by water: a review", *Prog. Phys. Geo.: Earth Environ.* **29** (2005), no. 2, p. 189-217.

[16] V. H. D. Zuazo, C. R. R. Pleguezuelo, "Soil-erosion and runoff prevention by plant covers: a review", in *Sustainable Agriculture* (E. Lichtfouse, M. Navarrete, P. Debaeke, S. Véronique, C. Alberola, eds.), vol. 2009, Springer, Netherlands, p. 785-811.

[17] A. Bernatek-Jakiel, J. Poesen, "Subsurface erosion by soil piping: significance and research needs", *Earth-Sci. Rev.* **185** (2018), p. 1107-1128.

[18] G. V. Wilson, R. Wells, R. Kuhnle, G. Fox, J. Nieber, "Sediment detachment and transport processes associated with internal erosion of soil pipes", *Earth Surf. Process. Landf.* **43** (2018), no. 1, p. 45-63.

[19] D. M. Lawler, "The measurement of river bank erosion and lateral channel change: A review", *Earth Surf. Process. Landf.* **18** (1993), no. 9, p. 777-821.

[20] J. P. Julian, R. Torres, "Hydraulic erosion of cohesive riverbanks", *Geomorphology* **76** (2006), no. 1, p. 193-206.

[21] C. Wang, X. Yu, F. Liang, "A review of bridge scour: mechanism, estimation, monitoring and countermeasures", *Nat. Hazards* **87** (2017), p. 1881-1906.

[22] K. Gao, C. Naito, M. T. Suleiman, "Erosion mitigation of bridge abutment backfill during flood events", *J. Perform. Constr. Facil.* **37** (2023), no. 6, article no. 04023054.

[23] M. Foster, R. Fell, M. Spannagle, "The statistics of embankment dam failures and accidents", *Can. Geotech. J.* **37** (2000), no. 5, p. 1000-1024.

[24] K. S. Richards, K. R. Reddy, "Critical appraisal of piping phenomena in earth dams", *Bull. Eng. Geol. Environ.* **66** (2007), p. 381-402.

[25] C. F. Wan, R. Fell, "Assessing the potential of internal instability and suffusion in embankment dams and their foundations", *J. Geotech. Geoenviron. Eng.* **134** (2008), no. 3, p. 401-407.

[26] S. Bonelli, *Erosion in Geomechanics Applied to Dams and Levees*, ISTE Ltd and John Wiley & Sons Inc, London, Hoboken, 2013.

[27] F. Ahnert, F. Ahnert, *Introduction to Geomorphology*, Hodder Arnold Publication, Arnold, 1998.

[28] D. Wuepper, P. Borrelli, R. Finger, "Countries and the global rate of soil erosion", *Nat. Sustain.* **3** (2020), p. 51-55.

[29] D. R. Montgomery, "Soil erosion and agricultural sustainability", *Proc. Natl. Acad. Sci. USA* **104** (2007), no. 33, p. 13268-13272.

[30] J. Boardman, J. Poesen, R. Evans, "Socio-economic factors in soil erosion and conservation", *Environ. Sci. Policy* **6** (2003), no. 1, p. 1-6.

[31] Z. Li, H. Fang, "Impacts of climate change on water erosion: a review", *Earth-Sci. Rev.* **163** (2016), p. 94-117.

[32] P. Borrelli, D. A. Robinson, L. R. Fleischer *et al.*, "An assessment of the global impact of 21st century land use change on soil erosion", *Nat. Commun.* **8** (2017), no. 1, article no. 2013.

[33] P. Borrelli, D. A. Robinson, P. Panagos, C. Ballabio, "Land use and climate change impacts on global soil erosion by water (2015–2070)", *Proc. Natl. Acad. Sci. USA* **117** (2020), no. 36, p. 21994-22001.

[34] P. V. G. Batista, D. L. Evans, B. M. Cândido, P. Fiener, "Does soil thinning change soil erodibility? An exploration of long-term erosion feedback systems", *SOIL* **9** (2023), no. 1, p. 71-88.

[35] L. Li, S. Du, L. Wu, G. Liu, "An overview of soil loss tolerance", *Catena* **78** (2009), no. 2, p. 93-99.

[36] K. V. Oost, T. A. Quine, G. Govers *et al.*, "The impact of agricultural soil erosion on the global carbon cycle", *Science* **318** (2007), no. 5850, p. 626-629.

[37] N. J. Kuhn, T. Hoffmann, W. Schwanghart, M. Dotterweich, "Agricultural soil erosion and global carbon cycle: controversy over?", *Earth Surf. Process. Landf.* **34** (2009), no. 7, p. 1033-1038.

[38] S. Doetterl, A. A. Berhe, E. Nadeu, Z. Wang, M. Sommer, P. Fiener, "Erosion, deposition and soil carbon: A review of process-level controls, experimental tools and models to address C cycling in dynamic landscapes", *Earth-Sci. Rev.* **154** (2016), p. 102-122.

[39] O. Evrard, J. P. Laceby, H. Lepage, Y. Onda, O. Cerdan, S. Ayrault, "Radiocesium transfer from hillslopes to the Pacific Ocean after the Fukushima Nuclear Power Plant accident: a review", *J. Environ. Radioact.* **148** (2015), p. 92-110.

[40] J. P. Brady, G. A. Ayoko, W. N. Martens, A. Goonetilleke, "Development of a hybrid pollution index for heavy metals in marine and estuarine sediments", *Environ. Monit. Assess.* **187** (2015), article no. 306.

[41] J. B. Kowalska, R. Mazurek, M. Gąsiorek, T. Zaleski, "Pollution indices as useful tools for the comprehensive evaluation of the degree of soil contamination—A review", *Environ. Geochem. Health* **40** (2018), p. 2395-2420.

[42] L. C. M. Lebreton, J. van der Zwet, J.-W. Damsteeg, B. Slat, A. Andrady, J. Reisser, "River plastic emissions to the world's oceans", *Nat. Commun.* **8** (2017), article no. 15611.

[43] H. Zhang, "Transport of microplastics in coastal seas", *Estuar. Coast. Shelf Sci.* **199** (2017), p. 74-86.

[44] A. L. Burrell, J. P. Evans, M. G. De Kauwe, "Anthropogenic climate change has driven over 5 million km^2 of drylands towards desertification", *Nat. Commun.* **11** (2020), article no. 3853.

[45] K. Zhang, B. C. Douglas, S. P. Leatherman, "Global warming and coastal erosion", *Clim. Change* **64** (2004), p. 41-58.

[46] T. Pang, X. Wang, R. A. Nawaz, G. Keefe, T. Adekanmbi, "Coastal erosion and climate change: A review on coastal-change process and modeling", *Ambio* **52** (2023), no. 12, p. 2034-2052.

[47] L. Brandimarte, P. Paron, G. D. Baldassarre, "Bridge pier scour: A review of processes, measurements and estimates", *Environ. Eng. Manag. J.* **11** (2012), p. 975-989.

[48] P. Bishop, "Long-term landscape evolution: linking tectonics and surface processes", *Earth Surf. Process. Landf.* **32** (2007), no. 3, p. 329-365.

[49] A. Pandey, S. K. Himanshu, S. Mishra, V. P. Singh, "Physically based soil erosion and sediment yield models revisited", *CATENA* **147** (2016), p. 595-620.

[50] P. Borrelli, C. Alewell, P. Alvarez *et al.*, "Soil erosion modelling: A global review and statistical analysis", *Sci. Total Environ.* **780** (2021), article no. 146494.

[51] R. P. C. Morgan, J. N. Quinton, R. E. Smith *et al.*, "The European Soil Erosion Model (EUROSEM): a dynamic approach for predicting sediment transport from fields and small catchments", *Earth Surf. Process. Landf.* **23** (1998), no. 6, p. 527-544.

[52] D. C. Flanagan, J. C. Ascough, M. A. Nearing, J. M. Laflen, "The Water Erosion Prediction Project (WEPP) model", in *Landscape Erosion and Evolution Modeling* (R. S. Harmon, W. W. Doe, eds.), Springer US, Boston, MA, 2001, p. 145-199.

[53] M. J. Kirkby, B. J. Irvine, R. J. A. Jones, G. Govers, P. team, "The PESERA coarse scale erosion model for Europe. I. – Model rationale and implementation", *Eur. J. Soil Sci.* **59** (2008), no. 6, p. 1293-1306.

[54] P. Panagos, P. Borrelli, J. Poesen, C. Ballabio, E. Lugato, K. Meusburger, L. Montanarella, C. Alewell, "The new assessment of soil loss by water erosion in Europe", *Environ. Sci. Policy* **54** (2015), p. 438-447.

[55] A. P. J. De Roo, C. G. Wesseling, C. J. Ritsema, "LISEM: A single-event physically based hydrological and soil erosion model for drainage basins. I: Theory, input and outpout", *Hydrol. Process.* **10** (1996), no. 8, p. 1107-1117.

[56] Y. Le Bissonnais, "Aggregate stability and assessment of soil crustability and erodibility: I. Theory and methodology", *Eur. J. Soil Sci.* **47** (1996), no. 4, p. 425-437.

[57] C. Alewell, P. Borrelli, K. Meusburger, P. Panagos, "Using the USLE: chances, challenges and limitations of soil erosion modelling", *Int. Soil Water Conserv. Res.* **7** (2019), no. 3, p. 203-225.

[58] R. Al-Raoush, A. Papadopoulos, "Representative elementary volume analysis of porous media using X-ray computed tomography", *Powder Technol.* **200** (2010), no. 1, p. 69-77.

[59] D. Favis-Mortlock, J. Boardman, V. MacMillan, "The limits of erosion modeling", in *Landscape Erosion and Evolution Modeling* (R. S. Harmon, W. W. Doe, eds.), Springer US, Boston, MA, 2001, p. 477-516.

[60] J. M. Buffington, "The legend of A. F. Shields", *J. Hydraul. Eng.* **125** (1999), no. 4, article no. 17211.

[61] S. Dey, S. Z. Ali, "Bed sediment entrainment by streamflow: State of the science", *Sedimentology* **66** (2019), no. 5, p. 1449-1485.

[62] M. Righetti, C. Lucarelli, "May the Shields theory be extended to cohesive and adhesive benthic sediments?", *J. Geophys. Res. Oceans* **112** (2007), article no. C10020.

[63] W. Jacobs, P. Le Hir, W. Van Kesteren, P. Cann, "Erosion threshold of sand-mud mixtures", *Cont. Shelf Res.* **31** (2011), no. 10, supplement, p. S14-S25, Proceedings of the 9th International Conference on Nearshore and Estuarine Cohesive Sediment Transport Processes.

[64] J. C. Winterwerp, W. G. M. van Kesteren, *Introduction to the Physics of Cohesive Sediment in the Marine Environment*, Developments in Sedimentology, vol. 56, Elsevier, Amsterdam, 2004, 121-159 pages.

[65] H. Feng, Z.-Y. Yin, M. Peng, Q. Guo, "State-of-the-art review of continuum mechanics-based modelling of soil surface erosion", *Archives Comput. Meth. Eng.* (2024).

[66] A. Knapen, J. Poesen, G. Govers, G. Gyssels, J. Nachtergaele, "Resistance of soils to concentrated flow erosion: a review", *Earth-Sci. Rev.* **80** (2007), no. 1, p. 75-109.

[67] G.-H. Zhang, Y.-M. Liu, Y.-F. Han, X. C. Zhang, "Sediment transport and soil detachment on steep slopes: II. Sediment feedback relationship", *Soil Sci. Soc. Am. J.* **73** (2009), no. 4, p. 1298-1304.

[68] G. Govers, G. Rauws, "Transporting capacity of overland flow on plane and on irregular beds", *Earth Surf. Process. Landf.* **11** (1986), no. 5, p. 515-524.

[69] J. C. Winterwerp, W. G. M. van Kesteren, B. van Prooijen, W. Jacobs, "A conceptual framework for shear flow–induced erosion of soft cohesive sediment beds", *J. Geophys. Res. Oceans* **117** (2012), no. C10, article no. 10020.

[70] L. P. Sanford, J. P.-Y. Maa, "A unified erosion formulation for fine sediments", *Mar. Geol.* **179** (2001), no. 1, p. 9-23.

[71] J. S. Walder, "Dimensionless erosion laws for cohesive sediment", *J. Hydraul. Eng.* **142** (2016), no. 2, article no. 04015047.

[72] A. Sidorchuk, "Stochastic components in the gully erosion modelling", *Catena* **63** (2005), no. 2, p. 299-317, Gully Erosion: A Global Issue.

[73] B. C. Van Prooijen, J. C. Winterwerp, "A stochastic formulation for erosion of cohesive sediments", *J. Geophys. Res. Oceans* **115** (2010), article no. C01005.

[74] S. Bonelli, *Erosion of Geomaterials*, ISTE Ltd and John Wiley & Sons Inc, London, Hoboken, 2012.

[75] G. J. Hanson, K. R. Cook, "Apparatus, test procedures, and analytical methods to measure soil erodibility in situ", *Appl. Eng. Agric.* **20** (2004), no. 4, p. 455-462.

[76] V.-N. Nguyen, J.-R. Courivaud, P. Pinettes, H. Souli, J.-M. Fleureau, "Using an improved jet-erosion test to study the influence of soil parameters on the erosion of a silty soil", *J. Hydraul. Eng.* **143** (2017), no. 8, article no. 04017018.

[77] O. Witt, B. Westrich, "Quantification of erosion rates for undisturbed contaminated cohesive sediment cores by image analysis", *Hydrobiologia* **494** (2003), no. 1–3, p. 271-276, 9th International Symposium on the Interactions between Sediments and Water, Banff, Canada, May 05–10, 2002.

[78] C. Lee, C. H. Wu, J. A. Hoopes, "Automated sediment erosion testing system using digital imaging", *J. Hydraul. Eng.* **130** (2004), no. 8, p. 771-782.

[79] E. Foti, I. C. Rabionet, A. Marini, R. E. Musumeci, A. Sánchez-Arcilla, "Experimental investigations of the bed evolution in wave flumes: performance of 2D and 3D optical systems", *Coast. Engng* **58** (2011), no. 7, p. 606-622.

[80] D. H. Rieke-Zapp, M. A. Nearing, "Digital close range photogrammetry for measurement of soil erosion", *Photogramm. Rec.* **20** (2005), no. 109, p. 69-87.

[81] B. R. Sutherland, S. Dalziel, "Bedload transport by a vertical jet impinging upon sediments", *Phys. Fluids* **26** (2014), no. 3, article no. 035103.

[82] S. Bonelli, R. Fell, N. Benahmed, "Concentrated leak erosion", in *Erosion in Geomechanics Applied to Dams and Levees*, John Wiley & Sons, Ltd, London, Hoboken, 2013, p. 271-341.

[83] N.-S. Cheng, A. W.-K. Law, "Fluctuations of turbulent bed shear stress", *J. Eng. Mech.* **129** (2003), no. 1, p. 126-130.

[84] L. Keirsbulck, L. Labraga, M. G. el Hak, "Statistical properties of wall shear stress fluctuations in turbulent channel flows", *Intl J. Heat Fluid Flow* **37** (2012), p. 1-8.

[85] R. Beguin, P. Philippe, Y.-H. Faure, "Pore-scale flow measurements at the interface between a sandy layer and a model porous medium: application to statistical modeling of contact erosion", *J. Hydraul. Eng.-ASCE* **139** (2013), no. 1, p. 1-11.

[86] T. J. Tolhurst, K. S. Black, D. M. Paterson, "Muddy sediment erosion: insights from field studies", *J. Hydraul. Eng.* **135** (2009), no. 2, p. 73-87.

[87] B. C. Khoo, Y. T. Chew, C. J. Teo, "Near-wall hot-wire measurements. Part II: turbulence time scale, convective velocity and spectra in the viscous sublayer", *Exp. Fluids* **31** (2001), no. 5, p. 494-505.

[88] W. Nimmo Smith, P. Atsavapranee, J. Katz, T. Osborn, "PIV measurements in the bottom boundary layer of the coastal ocean", *Exp. Fluids* **33** (2002), no. 6, p. 962-971.

[89] A. S.-A. Rosaria, E. Musumeci, V. Marletta, E. Foti, "A ferrofluid-based sensor to measure bottom shear stresses under currents and waves", *J. Hydraul. Res.* **56** (2018), no. 5, p. 630-647.

[90] H. Schlichting, K. Gersten, *Boundary-Layer Theory*, 8th ed., Springer-Verlag, Berlin, Heidelberg, 2000.

[91] J. Klewicki, W. Saric, I. Marusic, J. Eaton, "Wall-bounded flows", in *Springer Handbook of Experimental Fluid Mechanics* (C. Tropea, A. L. Yarin, J. F. Foss, eds.), Springer, Berlin, Heidelberg, 2007, p. 871-907.

[92] V. C. Patel, "Calibration of the Preston tube and limitations on its use in pressure gradients", *J. Fluid Mech.* **23** (1965), no. 1, p. 185-208.

[93] J. D. Ackerman, T. M. Hoover, "Measurement of local bed shear stress in streams using a Preston-static tube", *Limnol. Oceanogr.* **46** (2001), no. 8, p. 2080-2087.

[94] D. Sturzebecher, S. Anders, W. Nitsche, "The surface hot wire as a means of measuring mean and fluctuating wall shear stress", *Exp. Fluids* **31** (2002), no. 3, p. 294-301.

[95] J. W. Naughton, M. Sheplak, "Modern developments in shear-stress measurement", *Prog. Aerosp. Sci.* **38** (2002), no. 6, p. 515-570.

[96] W. J. Baars, D. T. Squire, K. M. Talluru, M. R. Abbassi, N. Hutchins, I. Marusic, "Wall-drag measurements of smooth- and rough-wall turbulent boundary layers using a floating element", *Exp. Fluids* **57** (2016), article no. 90.

[97] E. Foti, C. Faraci, R. Foti, G. Bonanno, "On the use of bioluminescence for estimating shear stresses over a rippled seabed", *Meccanica* **45** (2010), p. 881-895.

[98] E. Partheniades, "Erosion and deposition of cohesive soils", *J. Hydraul. Div.-ASCE* **91** (1965), no. 1, p. 105-139.

[99] R. Ariathurai, K. Arulanandan, "Erosion rates of cohesive soils", *J. Hydraul. Div.-ASCE* **104** (1978), no. 2, p. 279-283.

[100] T. M. Parchure, A. J. Mehta, "Erosion of soft cohesive sediment deposits", *J. Hydraul. Eng.-ASCE* **111** (1985), no. 10, p. 1308-1326.

[101] R. B. Krone, "Effects of bed structure on erosion of cohesive sediments", *J. Hydraul. Eng.* **125** (1999), no. 12, p. 1297-1301.

[102] D. Marot, P.-L. Regazzoni, T. Wahl, "Energy-based method for providing soil surface erodibility rankings", *J. Geotech. Geoenviron. Eng.* **137** (2011), no. 12, p. 1290-1293.

[103] A. R. Sharif, J. F. Atkinson, "Model for surface erosion of cohesive soils", *J. Hydraul. Eng.* **138** (2012), no. 7, p. 581-590.

[104] M. J. Bora, W. Cai, S. Pekkat, A. Garg, S. Sekharan, "Development of a simplified theoretical model to determine erodibility of compacted soil in hole erosion test based on fluid energy transformation", *Acta Geotech.* **18** (2023), no. 10, p. 5441-5455.

[105] J. W. Lavelle, H. O. Mofjeld, "Do critical stresses for incipient motion and erosion really exist?", *J. Hydraul. Eng.-ASCE* **113** (1987), no. 3, p. 370-385.

[106] P. Duboys, "Le Rhône et les rivières à lit affouillable", *Annales des Ponts et Chaussées* **18** (1879), p. 141-195.

[107] P. Davy, D. Lague, "Fluvial erosion/transport equation of landscape evolution models revisited", *J. Geophys. Res. Earth Surf.* **114** (2009), article no. F03007.

[108] K. Black, T. Tolhurst, D. Paterson, S. Hagerthey, "Working with natural cohesive sediments", *J. Hydraul. Eng.* **128** (2002), no. 1, p. 2-8.

[109] S. Bonelli, O. Brivois, "The scaling law in the hole erosion test with a constant pressure drop", *Int. J. Numer. Anal. Meth. Geomech.* **32** (2008), no. 13, p. 1573-1595.

[110] J. M. Laflen, W. J. Elliot, J. R. Simanton, C. S. Holzhey, K. D. Kohl, "WEPP - soil erodibility experiments for rangeland and cropland soils", *J. Soil Water Conserv.* **46** (1991), no. 1, p. 39-44.

[111] J. L. Briaud, F. C. K. Ting, H. C. Chen, Y. Cao, S. W. Han, K. W. Kwak, "Erosion function apparatus for scour rate predictions", *J. Geotech. Geoenviron. Eng.* **127** (2001), no. 2, p. 105-113.

[112] G. Zhang, B. Liu, M. A. Nearing, C. Huang, K. Zhang, "Soil detachment by shallow flow", *Trans. ASAE* **45** (2004), no. 2, p. 351-357.

[113] I. Haghighi, C. Chevalier, M. Duc, S. Guédon, P. Reiffsteck, "Improvement of hole erosion test and results on reference soils", *J. Geotech. Geoenviron. Eng.* **139** (2013), no. 2, p. 330-339.

[114] H. Mitchener, H. Torfs, "Erosion of mud/sand mixtures", *Coast. Engng* **29** (1996), no. 1, p. 1-25.

[115] R. C. Grabowski, I. G. Droppo, G. Wharton, "Erodibility of cohesive sediment: the importance of sediment properties", *Earth-Sci. Rev.* **105** (2011), no. 3, p. 101-120.

[116] M. Andreini, P. Gardoni, S. Pagliara, M. Sassu, "Probabilistic models for the erosion rate in embankments and reliability analysis of earth dams", *Reliab. Eng. Syst. Saf.* **181** (2019), p. 142-155.

[117] M. Z. Karim, S. E. Tucker-Kulesza, "Predicting soil erodibility using electrical resistivity tomography", *J. Geotech. Geoenviron. Eng.* **144** (2018), no. 4, article no. 04018012.

[118] A. Shaikh, J. F. Ruff, S. R. Abt, "Erosion rate of compacted NA-Montmorillonite soils", *J. Geotech. Eng.* **114** (1988), no. 3, p. 296-305.

[119] C. L. Amos, J. Grant, G. Daborn, K. Black, "Sea Carousel—A benthic, annular flume", *Estuar. Coast. Shelf Sci.* **34** (1992), no. 6, p. 557-577.

[120] J.-Y. Maa, L. Wright, C.-H. Lee, T. Shannon, "Vims Sea Carousel: a field instrument for studying sediment transport", *Mar. Geol.* **115** (1993), no. 3, p. 271-287.

[121] J. Mcneil, C. Taylor, W. Lick, "Measurements of erosion of undisturbed bottom sediments with depth", *J. Hydraul. Eng.* **122** (1996), no. 6, p. 316-324.

[122] E.-J. Houwing, L. C. van Rijn, "In Situ Erosion Flume (ISEF): determination of bed-shear stress and erosion of a kaolinite bed", *J. Sea Res.* **39** (1998), no. 3, p. 243-253.

[123] T. M. Ravens, P. M. Gschwend, "Flume measurements of sediment erodibility in boston harbor", *J. Hydraul. Eng.* **125** (1999), no. 10, p. 998-1005.
[124] T. Tolhurst, K. Black, D. Paterson, H. Mitchener, G. Termaat, S. Shayler, "A comparison and measurement standardisation of four in situ devices for determining the erosion shear stress of intertidal sediments", *Cont. Shelf Res.* **20** (2000), no. 10, p. 1397-1418.
[125] J. Aberle, V. Nikora, R. Walters, "Effects of bed material properties on cohesive sediment erosion", *Mar. Geol.* **207** (2004), no. 1, p. 83-93.
[126] P. L. Hir, P. Cann, B. Waeles, H. Jestin, P. Bassoullet, "Chapter 11 Erodibility of natural sediments: experiments on sand/mud mixtures from laboratory and field erosion tests", in *Sediment and Ecohydraulics* (T. Kusuda, H. Yamanishi, J. Spearman, J. Z. Gailani, eds.), Proceedings in Marine Science, vol. 9, Elsevier, Amsterdam, 2008, p. 137-153.
[127] R. W. Crowley, D. Bloomquist, J. R. Hayne, C. M. Holst, F. D. Shah, "Estimation and measurement of bed material shear stresses in erosion rate testing devices", *J. Hydraul. Eng.* **138** (2012), no. 11, p. 990-994.
[128] R. W. Crowley, D. Bloomquist, F. D. Shah, C. M. Holst, "The Sediment Erosion Rate Flume (SERF): a new testing device for measuring soil erosion rate and shear stress", *Geotech. Test. J.* **35** (2012), no. 4, p. 649-659.
[129] T. Sutarto, A. N. T. Papanicolaou, C. G. Wilson, E. J. Langendoen, "Stability analysis of semicohesive streambanks with CONCEPTS: coupling field and laboratory investigations to quantify the onset of fluvial erosion and mass failure", *J. Hydraul. Eng.* **140** (2014), no. 9, article no. 04014041.
[130] H. Shan, O. Wiblishauser, K. Kerenyi, M. Uhrig, C. Huang, "Efficient automated laboratory testing of erosion resistance forfine-grained soils", in *Proceedings of the 10th International Conference on Scour and Erosion, Arlington, VA, USA*, vol. 147, 2021.
[131] B. G. Krishnappan, "Review of a semi-empirical modelling approach for cohesive sediment transport in river systems", *Water* **14** (2022), no. 2, article no. 256.
[132] P. Yao, M. Su, Z. Wang, L. C. van Rijn, M. J. F. Stive, C. Xu, Y. Chen, "Erosion behavior of sand-silt mixtures: revisiting the erosion threshold", *Water Resour. Res.* **58** (2022), no. 9, article no. e2021WR031788.
[133] J. L. Sherard, L. P. Dunnigan, R. S. Decker, E. F. Steele, "Pinhole test for identifying dispersive soils", *J. Geotech. Eng. Div.* **102** (1976), no. 1, p. 69-85.
[134] E. I. Hjeldnes, B. V. Lavania, "Cracking, leakage, and erosion of earth dam materials", *J. Geotech. Eng. Div.* **106** (1980), no. 2, p. 117-135.
[135] G. Lefebvre, K. Rohan, S. Douville, "Erosivity of natural intact structured clay: evaluation", *Can. Geotech. J.* **22** (1985), no. 4, p. 508-517.
[136] L. N. Reddi, I.-M. Lee, M. V. S. Bonala, "Comparison of internal and surface erosion using flow pump tests on a sand-kaolinite mixture", *Geotech. Test. J.* **23** (2000), no. 1, p. 116-122.
[137] C. F. Wan, R. Fell, "Investigation of rate of erosion of soils in embankment dams", *J. Geotech. Geoenviron. Eng.* **130** (2004), no. 4, p. 373-380.
[138] C. F. Wan, R. Fell, "Laboratory tests on the rate of piping erosion of soils in embankment dams", *Geotech. Test. J.* **27** (2004), no. 3, p. 295-303.
[139] N. Benahmed, S. Bonelli, "Investigating concentrated leak erosion behaviour of cohesive soils by performing hole erosion tests", *Eur. J. Environ. Civil Eng.* **16** (2012), no. 1, p. 43-58.
[140] S. Fattahi, A. Soroush, P. Shourijeh, "The hole erosion test: a comparison of interpretation methods", *Geotech. Test. J.* **40** (2017), no. 3, p. 494-505.
[141] L. Xie, X. Liang, T.-C. Su, "Measurement of pressure in viewable hole erosion test", *Can. Geotech. J.* **55** (2018), no. 10, p. 1502-1509.
[142] I. Sharma, A. Thomas, "Experimental evaluation of internal erosion using groove erosion test", *Int. J. Geomech.* **22** (2022), no. 6, article no. 04022056.
[143] W. L. Moore, F. D. Masch Jr., "Experiments on the scour resistance of cohesive sediments", *J. Geophys. Res. (1896–1977)* **67** (1962), no. 4, p. 1437-1446.
[144] O. Aderibigbe, N. Rajaratnam, "Erosion of loose beds by submerged circular impinging vertical turbulent jets", *J. Hydraul. Res.* **34** (1996), no. 1, p. 19-33.
[145] G. J. Hanson, A. Simon, "Erodibility of cohesive streambeds in the loess area of the midwestern USA", *Hydrol. Process.* **15** (2001), no. 1, p. 23-38.
[146] J.-L. Briaud, M. Chedid, H.-C. Chen, A. Shidlovskaya, "Borehole erosion test", *J. Geotech. Geoenviron. Eng.* **143** (2017), no. 8, article no. 04017037.
[147] C. Dong, G. Yu, H. Zhang, M. Zhang, "Scouring by submerged steady water jet vertically impinging on a cohesive bed", *Ocean Eng.* **196** (2020), article no. 106781.
[148] K. Arulanandan, R. B. Krone, P. Loganathan, "Pore and eroding fluid influences on surface erosion on soil", *J. Geotech. Eng. Div.* **101** (1975), no. 1, p. 51-66.
[149] R. P. Chapuis, T. Gatien, "An improved rotating cylinder technique for quantitative measurements of the scour resistance of clays", *Can. Geotech. J.* **23** (1986), no. 1, p. 83-87.

[150] S. S. Lim, N. Khalili, "An improved rotating cylinder test design for laboratory measurement of erosion in clayey soils", *Geotech. Test. J.* **32** (2009), no. 3, p. 232-238.

[151] D. Bloomquist, D. Sheppard, S. Schofield, R. Crowley, "The rotating erosion testing apparatus (reta): a laboratory device for measuring erosion rates versus shear stresses of rock and cohesive materials", *Geotech. Test. J.* **35** (2012), no. 4, p. 641-648.

[152] F. Ternat, P. Boyer, F. Anselmet, M. Amielh, "Erosion threshold of saturated natural cohesive sediments: modeling and experiments", *Water Resour. Res.* **44** (2008), article no. W11434.

[153] B. G. Krishnappan, "Rotating circular flume", *J. Hydraul. Eng.* **119** (1993), no. 6, p. 758-767.

[154] G. J. Hanson, L. S. Hunt, "Lessons learned using laboratory JET method to measure soil erodibility of compacted soils", *Appl. Eng. Agric.* **23** (2007), no. 3, p. 305-312.

[155] A.-S. Al-Madhhachi, G. Hanson, G. Fox, A. Tyagi, R. Bulut, "Deriving parameters of a fundamental detachment model for cohesive soils from flume and jet erosion tests", *Trans. ASABE* **56** (2013), p. 489-504.

[156] G. A. Fox, L. Guertault, C. Castro-Bolinaga *et al.*, "Perspectives on the Jet Erosion Test (JET): lessons learned, challenges and opportunities in quantifying cohesive soil erodibility", *ASABE Papers* **65** (2022), no. 2, p. 197-207.

[157] A. Shidlovskaya, M. Bahmani, J.-L. Briaud, H.-C. Chen, "Improvements in test procedure and data reduction for the Borehole Erosion Test", *Geotech. Test. J.* **46** (2023), no. 2, p. 295-315.

[158] P. T. Metzger, C. D. Immer, C. M. Donahue, B. T. Vu, R. C. Latta III, M. Deyo-Svendsen, "Jet-induced cratering of a granular surface with application to lunar spaceports", *J. Aerosp. Eng.* **22** (2009), no. 1, p. 24-32.

[159] C. Q. LaMarche, A. Benavides Moran, B. van Wachem, J. S. Curtis, "Two-fluid modeling of cratering in a particle bed by a subsonic turbulent jet", *Powder Technol.* **318** (2017), p. 68-82.

[160] S. D. Guleria, D. V. Patil, "Experimental investigations of crater formation on granular bed subjected to an air-jet impingement", *Phys. Fluids* **32** (2020), article no. 053309.

[161] S. Beltaos, R. N., "Impinging circular turbulent jets", *J. Hudraul. Div.-ASCE* **100** (1974), no. HY10, p. 1313-1328.

[162] Z. Benseghier, P. Cuellar, L.-H. Luu, J.-Y. Delenne, S. Bonelli, P. Philippe, "Relevance of free jet model for soil erosion by impinging jets", *J. Hydraul. Eng.* **146** (2020), no. 1, article no. 04019047.

[163] K. Head, R. Epps, *Manual of Soil Laboratory Testing, Third Edition: Volume Two: Permeability, Shear Strength and Compressibility Tests*, Whittles Publishing, Caithness, 2011.

[164] K. Black, A. Cramp, "A device to examine the in situ response of intertidal cohesive sediment deposits to fluid shear", *Cont. Shelf Res.* **15** (1995), no. 15, p. 1945-1954.

[165] J. D. Roberts, R. A. Jepsen, S. C. James, "Measurements of sediment erosion and transport with the adjustable shear stress erosion and transport flume", *J. Hydraul. Eng.* **129** (2003), no. 11, p. 862-871.

[166] T. Tolhurst, K. Black, S. Shayler, S. Mather, I. Black, K. Baker, D. Paterson, "Measuring the in situ erosion shear stress of intertidal sediments with the Cohesive Strength Meter (CSM)", *Estuar. Coast. Shelf Sci.* **49** (1999), no. 2, p. 281-294.

[167] G. J. Hanson, K. R. Cook, S. L. Hunt, "Physical modeling of overtopping erosion and breach formation of cohesive embankments", *Trans. ASAE* **48** (2005), no. 5, p. 1783-1794.

[168] C. Thornton, S. Hughes, B. Scholl, "Full-scale testing of levee resiliency during wave overtopping", in *Proceedings from Annual Innovative Dam and Levee Design and Construction for Sustainable Water Management*, Elsevier, 2012, p. 721-735.

[169] T. Kakinuma, Y. Shimizu, "Large-scale experiment and numerical modeling of a riverine levee breach", *J. Hydraul. Eng.* **140** (2014), no. 9, article no. 04014039.

[170] F. S. R. D. Jan Olschewski, S. Cantré, R. Ossowski, "Overflowing tests at the Polish DredgDikes research dike – stability of the dike surface against erosion", *Eng. Struct. Technol.* **6** (2014), no. 4, p. 159-168.

[171] S. Cantré, J. Olschewski, F. Saathoff, "Full-scale flume experiments to analyze the surface erosion resistance of dike embankments made of dredged materials", *J. Water. Port, Coast. Ocean Eng.* **143** (2017), no. 3, article no. 04017001.

[172] S. Bonelli, S. Nicaise, G. Charrier, N. Chaouch, F. Byron, Y. Grémeaux, "Quantifying the erosion resistance of dikes with the overflowing simulator", in *Proceedings of the 3rd International Conference on Protection against Overtopping, 6–8 June 2018, Grange-over-Sands, United Kingdom*, 2018.

[173] C. Picault, F. Crampette, S. Bonelli *et al.*, "Field testing of the overflow erosion of rhone river levees", in *Proceedings of the 4th International Seminar on Dam Protections against Overtopping, 30 Nov 2 Dec 2012, Madrid, Spain*, 2023.

[174] A. Bennabi, T. Karoui, A. Benamar, H. Wang, "Some elements of comparison between two laboratory devices for soil erosion testing", in *Proceedings of the 6th International Conference on Scour and Erosion 27–31 August 2012, Paris, France*, 2012.

[175] S. Youssef, *Soil surface erosion: local law and influence of soil and flow properties on the erosion resistance of hydraulic structures*, Phd thesis, Aix Marseille University, 2023.

[176] J.-L. Briaud, A. V. Govindasamy, I. Shafii, "Erosion charts for selected geomaterials", *J. Geotech. Geoenviron. Eng.* **143** (2017), no. 10, article no. 04017072.

[177] Z. M. Erdogan, "Determining erosion indices of cohesive soils with the hole erosion test and jet erosion test", 2008, Report DSO-08-05, https://api.semanticscholar.org/CorpusID:52839129.

[178] A. Mehenni, O. Cuisinier, F. Masrouri, “Impact of lime, cement, and clay treatments on the internal erosion of compacted soils”, *J. Mater. Civil Eng.* **28** (2016), no. 9, article no. 04016071.
[179] M. Lüthi, *A modified Hole Erosion test (HET-P) to study erosion characteristics of soil*, Phd thesis, University of British Columbia, 2011.
[180] S. S. Lim, *Experimental investigation of erosion in variably saturated clay soils*, Phd thesis, School of Civil and Environmental Engineering, The University of New South Wales, 2006.
[181] M. Lüthi, R. Fannin, R. Millar, “A modified hole erosion test (HET-P) device”, *Geotech. Test. J.* **35** (2012), article no. 104336.
[182] B. Mcnichol, K. Kassa, G. Fox, R. Miller, L. Guertault, “Erodibility parameters derived from jet and flume erosion tests on root-permeated soils”, *J. Contemp. Water Res. Educ.* **160** (2017), p. 119-131.
[183] E. R. Daly, G. A. Fox, A.-S. T. Al-Madhhachi, D. E. Storm, “Variability of fluvial erodibility parameters for streambanks on a watershed scale”, *Geomorphology* **231** (2015), p. 281-291.
[184] M. Karamigolbaghi, S. M. Ghaneeizad, J. F. Atkinson, S. J. Bennett, R. R. Wells, “Critical assessment of jet erosion test methodologies for cohesive soil and sediment”, *Geomorphology* **295** (2017), p. 529-536.
[185] Transportation Research Board and National Academies of Sciences, Engineering, and Medicine, *Relationship Between Erodibility and Properties of Soils*, The National Academies Press, Washington, DC, 2019.
[186] R. Fell, J.-J. Fry, “State of the art on the likelihood of internal erosion of dams and levees by means of testing”, in *Erosion in Geomechanics Applied to Dams and Levees* (S. Bonelli, ed.), Civil Engineering and Geomechanics Series, John Wiley & Sons, Ltd, 2013, p. 1-99.
[187] S. Bonelli, N. Benahmed, “Piping flow erosion in water retaining structures”, *Int. J. Hydrop. Dams* **18** (2011), no. 3, p. 94-99.
[188] N.-J. Jiang, K. Soga, M. Kuo, “Microbially induced carbonate precipitation for seepage-induced internal erosion control in sand–clay mixtures”, *J. Geotech. Geoenviron. Eng.* **143** (2017), no. 3, article no. 04016100.
[189] B. Indraratna, T. Muttuvel, H. Khabbaz, “Modelling the erosion rate of chemically stabilized soil incorporating tensile force – deformation characteristics”, *Can. Geotech. J.* **46** (2009), no. 1, p. 57-68.
[190] B. Indraratna, T. Muttuvel, H. Khabbaz, R. Armstrong, “Predicting the erosion rate of chemically treated soil using a process simulation apparatus for internal crack erosion”, *J. Geotech. Geoenviron. Eng.* **134** (2008), no. 6, p. 837-844.
[191] G. Herrier, S. Bonelli, “Internal erosion resistance of soils treated with lime: an evolutive benefit”, in *Scour and Erosion: Proceedings of the 7th International Conference on Scour and Erosion, Perth, Australia, 2–4 December 2014* (L. Cheng, S. Draper, H. An, eds.), CRC Press, London, 2014, p. 73-80.
[192] M. Konstadinou, G. Herrier, T. Stoutjesdijk, F. Losma, C. Zwanenburg, R. Dobbe, “Lime treatment: evaluation for use in dike applications in the Netherlands”, *J. Mater. Civil Eng.* **35** (2023), no. 3, article no. 04022465.
[193] R. Fell, G. Hanson, G. Herrier, D. Marot, T. Wahl, “Relationship between the erosion properties of soils and other parameters”, in *Erosion in Geomechanics Applied to Dams and Levees* (S. Bonelli, ed.), Civil Engineering and Geomechanics Series, John Wiley & Sons, Ltd, 2013, p. 343-381.
[194] M. H. C. Tarek, S. Mostafa, J. Imran, I. B. Kahn, “Erosion resistance of cohesive soils”, *J. Hydraul. Res.* **46** (2008), no. 6, p. 777-787.
[195] P.-L. Regazzoni, D. Marot, “Investigation of interface erosion rate by Jet Erosion Test and statistical analysis”, *Eur. J. Environ. Civil Eng.* **15** (2011), no. 8, p. 1167-1185.
[196] N. Kimiaghalam, S. P. Clark, H. Ahmari, “An experimental study on the effects of physical, mechanical, and electrochemical properties of natural cohesive soils on critical shear stress and erosion rate”, *Int. J. Sediment Res.* **31** (2016), no. 1, p. 1-15.
[197] I. Shafii, Z. Medina-Cetina, A. Shidlovskaya, J.-L. Briaud, “Relationship between soil erodibility and soil properties”, *J. Geotech. Geoenviron. Eng.* **149** (2023), no. 1, article no. 04022121.
[198] National Academies of Sciences, Engineering, and Medicine, *Relationship Between Erodibility and Properties of Soils*, The National Academies Press, Washington, DC, 2019.
[199] D. Chen, J. Zheng, C. Zhang, D. Guan, Y. Li, Y. Wang, “Critical shear stress for erosion of sand-mud mixtures and pure mud”, *Front. Marine Sci.* **8** (2021), article no. 713039.
[200] D. Chen, Y. Wang, B. Melville, H. Huang, W. Zhang, “Unified formula for critical shear stress for erosion of sand, mud, and sand–mud mixtures”, *J. Hydraul. Eng.* **144** (2018), no. 8, article no. 04018046.
[201] F. Brunier-Coulin, P. Cuéllar, P. Philippe, “Generalized shields criterion for weakly cohesive granular materials”, *Phys. Rev. Fluids* **5** (2020), article no. 034308.
[202] R. Gularte, W. Kelly, V. Nacci, “Erosion of cohesive sediments as a rate process”, *Ocean Engng* **7** (1980), no. 4, p. 539-551.
[203] S. Hoomehr, A. I. Akinola, T. Wynn-Thompson, W. Garnand, M. J. Eick, “Water temperature, pH, and road salt impacts on the fluvial erosion of cohesive streambanks”, *Water* **10** (2018), no. 3, article no. 302.
[204] A. I. Akinola, T. Wynn-Thompson, C. G. Olgun, S. Mostaghimi, M. J. Eick, “Fluvial erosion rate of cohesive streambanks is directly related to the difference in soil and water temperatures”, *J. Environ. Qual.* **48** (2019), no. 6, p. 1741-1748.

[205] V. Ravisangar, K. E. Dennett, T. W. Sturm, A. Amirtharajah, “Effect of sediment pH on resuspension of Kaolinite sediments”, *J. Environ. Eng.* **127** (2001), no. 6, p. 531-538.

[206] B. Andreotti, Y. Forterre, O. Pouliquen, *Granular Media: Between Fluid and Solid*, Cambridge University Press, New York, 2013.

[207] A. L. Layzell, R. D. Mandel, “An assessment of the erodibility of Holocene lithounits comprising streambanks in northeastern Kansas, USA”, *Geomorphology* **213** (2014), p. 116-127.

[208] R. W. Thoman, S. L. Niezgoda, “Determining erodibility, critical shear stress, and allowable discharge estimates for cohesive channels: case study in the powder river basin of Wyoming”, *J. Hydraul. Eng.* **134** (2008), no. 12, p. 1677-1687.

[209] A. Khanal, G. A. Fox, A. T. Al-Madhhachi, “Variability of erodibility parameters from laboratory mini jet erosion tests”, *J. Hydrol. Eng.* **21** (2016), no. 10, article no. 04016030.

[210] K. Høeg, R. Dyvik, G. Sandbækken, “Strength of undisturbed versus reconstituted silt and silty sand specimens”, *J. Geotech. Geoenviron. Eng.* **126** (2000), no. 7, p. 606-617.

[211] G.-H. Zhang, B.-Y. Liu, G.-B. Liu, X.-W. He, M. A. Nearing, “Detachment of undisturbed soil by shallow flow”, *Soil Sci. Soc. Am. J.* **67** (2003), no. 3, p. 713-719.

[212] P.-L. Regazzoni, D. Marot, “A comparative analysis of interface erosion tests”, *Nat. Hazards* **67** (2013), no. 2, p. 937-950.

[213] B. Mahalder, J. S. Schwartz, T. M. Wynn-Thompson, A. M. Palomino, J. Zirkle, “Comparison of erodibility parameters for cohesive streambank soils between in situ jet test device and laboratory conduit flume”, *J. Hydraul. Eng.* **148** (2022), no. 1, article no. 04021055.

[214] A. H. Vakili, M. Salimi, İ. Keskin, M. Jamalimoghadam, “A systematic review of strategies for identifying and stabilizing dispersive clay soils for sustainable infrastructure”, *Soil Tillage Res.* **239** (2024), article no. 106036.

[215] F. Mercier, S. Bonelli, P. Pinettes, F. Golay, F. Anselmet, P. Philippe, “Comparison of computational fluid dynamic simulations with experimental jet erosion tests results”, *J. Hydraul. Eng.* **140** (2014), no. 5, article no. 04014006.

[216] F. Mercier, S. Bonelli, F. Golay, F. Anselmet, P. Philippe, R. Borghi, “Numerical modelling of concentrated leak erosion during Hole Erosion Tests”, *Acta Geotech.* **10** (2015), no. 3, p. 319-332.

[217] P. Philippe, P. Cuéllar, F. Brunier-Coulin, L.-H. Luu, N. Benahmed, S. Bonelli, J.-Y. Delenne, “Physics of soil erosion at the microscale”, *EPJ Web Conf.* **140** (2017), article no. 08014.

[218] D. K. Tran, N. Prime, F. Froiio, C. Callari, E. Vincens, “Numerical modelling of backward front propagation in piping erosion by DEM-LBM coupling”, *Eur. J. Environ. Civil Eng.* **21** (2017), no. 7–8, p. 960-987.

[219] Z. Benseghier, P. Cuellar, L.-H. Luu, S. Bonelli, P. Philippe, “A parallel GPU-based computational framework for the micromechanical analysis of geotechnical and erosion problems”, *Comput. Geotech.* **120** (2020), article no. 103404.

[220] Z. Benseghier, L.-H. Luu, P. Cuellar, S. Bonelli, P. Philippe, “On the erosion of cohesive granular soils by a submerged jet: a numerical approach”, *Granul. Matt.* **25** (2023), no. 1, article no. 8.

[221] J.-L. Briaud, H.-C. Chen, A. V. Govindasamy, R. Storesund, “Levee erosion by overtopping in new Orleans during the Katrina Hurricane”, *J. Geotech. Geoenviron. Eng.* **134** (2008), no. 5, p. 618-632.