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Clogging of Noncohesive Suspension Flows

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Abstract

When flowing through narrow channels or constrictions, many-body systems exhibit various flowing patterns, yet they can also get stuck. In many of these systems, the flowing elements remain as individuals (they do not aggregate or merge), sharing strong analogies among each other. This is the case for systems as contrasting as grains in a silo and pedestrians passing through tight spaces. Interestingly, when these entities flow within a fluid medium, numerous similarities persist. However, the fluid dynamics aspects of such clogging events, such as interstitial flow, liquid pressure, and hydrodynamic interactions, has only recently begun to be explored. In this review, we describe parallels with dry granular clogging and extensively analyze phenomena emerging when particles coexist with fluid in the system. We discuss the influence of diverse flow drive, particle propulsion mechanisms, and particle characteristics, and we conclude with examples from nature.

1. AN INTRODUCTION TO CLOGGING

When stuff is forced through constrictions, it is natural to enter into transport problems, especially when the elements forming the stuff can interact with one another and with the confining walls. Regardless of the nature of the elements being forced, whether they are particles (To et al. 2001), animals (Garcimartín et al. 2015), or people (Garcimartín et al. 2016), numerous analogies are used to characterize their flow through a narrowing passage. Such analogies are not only qualitative. Intermittent flows are often observed, following similar statistical distributions, which led Zuriguel et al. (2014) to propose a unified description, providing a general framework for the study of intermittent clogging systems. This framework has been applied to cases in which the force pushing the elements through the system is approximately constant. However, when the elements are being forced by the drag of a liquid phase in which they are immersed, the picture can change substantially.

Transport of particles suspended in liquids through conduits is ubiquitous in our daily lives. It can be found in a broad variety of industrial applications, including civil engineering (cement and concrete) (Khajeh et al. 2020), the oil industry (drilling muds and fracturing fluids) (Sivasankar & Kumar 2019), the food industry (milk, soups, and beverages) (Vilela et al. 2018), and even the pulp and paper industry (paper muds and wooden powder suspensions) (Hubbe et al. 2016). Particulate suspensions transported in conduits are also common in nature, including in geophysics (lava and debris flows and mud trails) (Kolzenburg et al. 2022), in numerous biological settings such as oxygen transportation in blood vessels (Richardson et al. 2020), and in nutrient transport in the xylem of leafy plants (Yadeta & Thomma 2013). Occasionally the transported particles become trapped, accumulate in the conduit, and severely restrict the flow; this condition, herein referred to as clogging, has been referred to in the literature with a vast range of terms, including blocking, plunging, fouling, congestion, bridging, arching, and even caking. Although always ending in a disruption of particle flow through a constricted area, most of these various terms refer to different aspects of the same phenomenon, depending on the mechanisms at play in the configuration under consideration.

In the last 10 years, the number of publications dealing with this problem has doubled, with the majority of works coming from engineering, material sciences, physics, and chemistry. Perhaps one reason for the recent boost of interest in clogging, apart from its fundamental interest and its ubiquity in everyday life, is the development of process intensification in several engineering fields, which aims for a substantial increase in the efficiency of engineering processes by reducing sizes and increasing yield rates (Stankiewicz et al. 2000). This, of course, is a perfect recipe for clogging, especially in flowing particulate suspensions where the suspending fluid plays a crucial yet still unclear role. However, clogging is a two-faceted phenomenon that can either be seen as a nuisance or be exploited as a beneficial tool.

While the literature on clogging in dry granular systems is abundant [see the reviews by Iker Zuriguel and Ángel Garcimartín (Zuriguel 2014, Zuriguel & Garcimartín 2020)], research on the clogging of suspensions has just started to yield interesting results in the last decade. A recent article by Dincau et al. (2023) covered basic aspects of clogging, describing different kinds of mechanisms and suspensions, including both cohesive and noncohesive suspensions. In the present review we focus on the clogging of noncohesive suspensions, a field that involves complex fluid mechanics yet to be revealed and that are key to understanding a surprisingly rich phenomenology, and that has multiple analogies with other nonfluid systems. Rather than covering the most recent results on the clogging of noncohesive suspensions, we aim to set up a conceptual framework in which we sort out the analogies and the crucial differences with cohesive suspension clogs and with noncohesive dry granular matter, as well as to define the questions that intrigue us the most.

1.1. Clogging Mechanisms

Clogging is a phenomenon occurring in a wide variety of systems of very diverse nature and size. Clogging can manifest in different ways depending on the size of the moving objects relative to the constriction, the nature of the material being transported (Dincau et al. 2023), and the possible presence of cohesive forces (Agbangla et al. 2014). Once a clog is formed, it prevents the particles from flowing through the constriction. When more particles keep arriving upstream of the clog, they accumulate and form what is commonly referred to as a cake or filter cake. Depending on the nature of the clogging mechanism, the driving force, the material properties, and the presence of external energy input for inert matter or internal energy for active matter, the formed clog may either be everlasting (also referred to as a permanent clog) or have a finite lifetime. Although this review focuses on clogging by bridging of noncohesive particulate suspensions, clogging mechanisms can be divided in three categories:

- Sieving; i.e., particles are too large to pass a constriction
- Aggregation; i.e., particles form clusters and block the constriction or are deposited on walls and cause a narrowed constriction
- Bridging; i.e., particles arrive simultaneously at a constriction and form an arch

Filter cake: formed by substances that are retained on a filter; in the context of clogging of cohesive suspensions by aggregation, the cake is basically aggregated particles at the constriction

Sieving: often referred to in the literature by terms such as blocking, sealing, plugging, and screening, among others

Aggregation: often referred to in the literature by various terms such as fouling, caking, agglomerating, soiling, and blinding, among others

Bridging: is often referred to in the literature by various terms such as blocking, sealing, plugging, and screening, among others

1.2. Clogging by Sieving: When Steric Effects Prohibit the Flow

Irrespective of the presence of cohesive forces, when an object is too large to pass a constriction of width D, this leads to the simplest case of clogging, known as sieving. The clog formation process in such an instance solely depends on the particle size distribution; as soon as a particle reaches a constriction that is smaller than itself, the system is clogged. For nonspherical particles, it is the projected dimension d_{proj} of the particle on the constriction when it reaches the latter that controls sieving. If the particle reaches the constriction with an orientation such that $d_{\mathrm{proj}} > D$, then sieving will occur. Consequently, for fiber-filled polymer printing with extrusion-based additive manufacturing processes, printers often utilize very gradually tapered nozzles (with an angle $<5°$) (Croom et al. 2021).

Clogging formation by sieving has been extensively studied and can be described as a random process that depends on the number of particles larger than the constriction or pore sizes. For systems composed of a network of many pores, sieving can be modeled as a Poisson distribution in which the clogging of each pore represents an independent event whose probability depends on the particle size distribution (Sauret et al. 2014).

1.3. Clogging by Aggregation: When Cohesion Restricts the Flow

In the presence of cohesive forces, either particle–particle or particle–wall interactions, both clog formation and destruction processes are driven by a different mechanism than in sieving or bridging (Agbangla et al. 2014). The mechanism relies on the relative strength of the particle–particle and particle–wall forces compared to the flow's shear stress. For instance, colloidal particles often experience a van der Waals attraction toward one another, resulting in colloidal clusters that can grow (Kim et al. 2017) before reaching a downstream constriction and blocking it. The formation of aggregates in solutions of monoclonal antibodies is a typical example that can lead to the formation of clusters larger than the constriction width (Duchêne et al. 2020).

When there are attractive forces between the particles and the wall, cohesive suspensions can also provoke clogs by successive deposition, i.e., through particles progressively depositing on the constriction wall, thus reducing the constriction size (Agbangla et al. 2014, Delouche et al. 2020, Dersoir et al. 2015, Dincau et al. 2022, Duru & Hallez 2015). Most configurations exhibit attractive cohesion forces both among the particles and between the particles and the wall. In such situations, clogging results from a combination of the aforementioned mechanisms. Particle aggregates tend to preferentially grow in the vicinity of walls, where they are slowly detached by the shear flow and transported downstream, eventually blocking any potential constriction whose width (which may have decreased due to successive deposition on the constriction wall) is smaller than the aggregate size (Delouche et al. 2021, Wyss et al. 2006). Acute cardiovascular accidents resulting from the detachment of large clusters of fat plaques (originally formed on the walls of arteries) obstructing downstream arteries are a dramatic example of such a configuration (Malhotra et al. 2017). An in-depth review by Dressaire & Sauret (2017) covers such fouling processes.

1.4. Clogging by Bridging: When Too Many Objects Try to Get Through Simultaneously

Particles can also clog a constriction in the absence of cohesive forces, even if they are smaller than the constriction width. This can easily occur when several particles (typically between 2 and 10, depending on their shape) simultaneously arrive at a constriction and form a local structure (an arch in two dimensions, a dome in three dimensions, or a bridge in general) due to the geometric confinement that blocks the outlet or the narrow channel. This makes clogging by bridging the most likely obstruction mechanism for noncohesive suspensions. The lack of cohesive forces makes bridges naturally unstable, leading easily to intermittent flow regimes, especially for large bridges, which are characterized by constrictions in which D is several particle diameters d (see **Figure 1**). Consequently, bodies flow in erratic bursts separated by short periods of arrest due to the formation of bridges at the constriction that remain stable only for a finite duration. The physics of intermittent clogging is a rich phenomenon as it provides a succession of bridge formation and bridge destruction processes, both requiring specific detailed descriptions. The remainder of this review focuses on clogging by bridging for noncohesive material.

2. CLOGGING OF NONCOHESIVE GRANULAR MATTER

In this section we describe two important processes that can be observed in the clogging of dry and noncohesive granular systems, in which typically only the solid phase plays a significant role in the dynamics. We describe here the processes of bridge formation and bridge destruction, as well as the probability distributions that these follow.

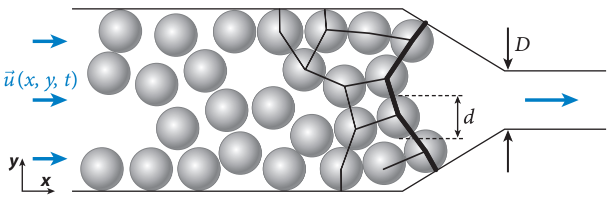

Figure 1

Typical geometry for a clogged flow of a noncohesive suspension through an arbitrary constriction. A monodisperse suspension of particles of size d is forced by liquid flow (*blue arrows*) from left to right through a constriction. The system is clogged by a particle arch, which prevents particles from passing through the constriction. However, liquid is still flowing through the constriction. Note that clogging in suspensions can occur at an arbitrary concentration of particles per unit volume. Only in the vicinity of the clog does the concentration increase, while it can remain diluted upstream.

2.1. Bridge Formation

The most striking common feature among all configurations involving clogging by bridging concerns the number of particles s that get through the constriction before a clog is eventually formed, which we refer to from now on as escapees. While particles pass through the area of the constriction, microstates are continuously and randomly sampled (Thomas & Durian 2015) until a stable bridge is eventually found. It turns out that the probability distribution for the number of escapees faithfully follows an exponential distribution, as first identified by Clément et al. (2000) and later developed by Zuriguel et al. (2003). This observation reveals that the clog formation follows a stochastic Poissonian process. As highlighted by Zuriguel & Garcimartín (2020), this implies the following:

1. Since the process is naturally stochastic, there is no way to predict exactly when a bridge will be formed.
2. Bridge formation is independent of the system's history. Every bridge is independent of the previous one.
3. If the flow of particles resumes, there is no correlation among the size of consecutive bursts of escaping particles.
4. The average number of escapees $\langle s \rangle$ is well defined, which allows us to give a precise probability distribution of escapees as $P(s) = \frac{1}{\langle s \rangle} e^{-s/\langle s \rangle}$.

The number of escapees s has been repeatedly found to follow an exponential distribution for a myriad of systems, no matter whether particles are soft (Thackray & Nordstrom 2017) or rigid (Zuriguel et al. 2005), including active particles such as pedestrians (Garcimartín et al. 2016), active microparticles (Knippenberg et al. 2022), microalgae (Al Alam et al. 2022), and animal flocks (Garcimartín et al. 2015, Saloma et al. 2003) (see **Figure 2**).

Since the seminal observations 25 years ago by Clément et al. (2000), there has been an open debate regarding the existence of a clogging transition, i.e., whether there is a critical outlet size above which bridges would never be stable. This idea was soon challenged by To (2005), who showed that the experimental data for $\langle s \rangle$ could be fitted by rapidly growing but nondivergent expressions. Instead, Janda et al. (2008) for 2D systems, and later on Thomas & Durian (2015) for 3D dry systems, showed empirically that the average number of escapees grows as a stretched-exponential function of the outlet diameter:

$$\langle s \rangle \propto e^{cD^{\beta}}, \qquad 1.$$

where β is the dimension of the system and c a constant. Examples of such a trend are shown in **Figure 2** for various 3D configurations of diverse natures, highlighting how the neck-to-particle size ratio D/d is a control parameter for the clog formation process: A higher D/d means more escapees s before a clog forms, and hence a lower probability of forming clogs. This empirical law is compatible with the idea that new microstates in the vicinity of the constriction are continuously and randomly sampled while particles arrive (Thomas & Durian 2015), until a stable bridge is eventually found. A first consequence of such a clogging mechanism is that there is no sharp clogging transition for a given critical outlet size; i.e., there is always a nonzero probability that a bridge will be formed. Consequently, bridging is akin to jamming and glass transitions: There is no sharp discontinuity in the behavior but rather a dramatic increase of the relaxation times as the orifice size is enlarged (Zuriguel 2014). The lack of a robust physical argument responsible for the transition and the abundant experimental data indicating that clogging seems to be always possible have settled the debate for the moment.

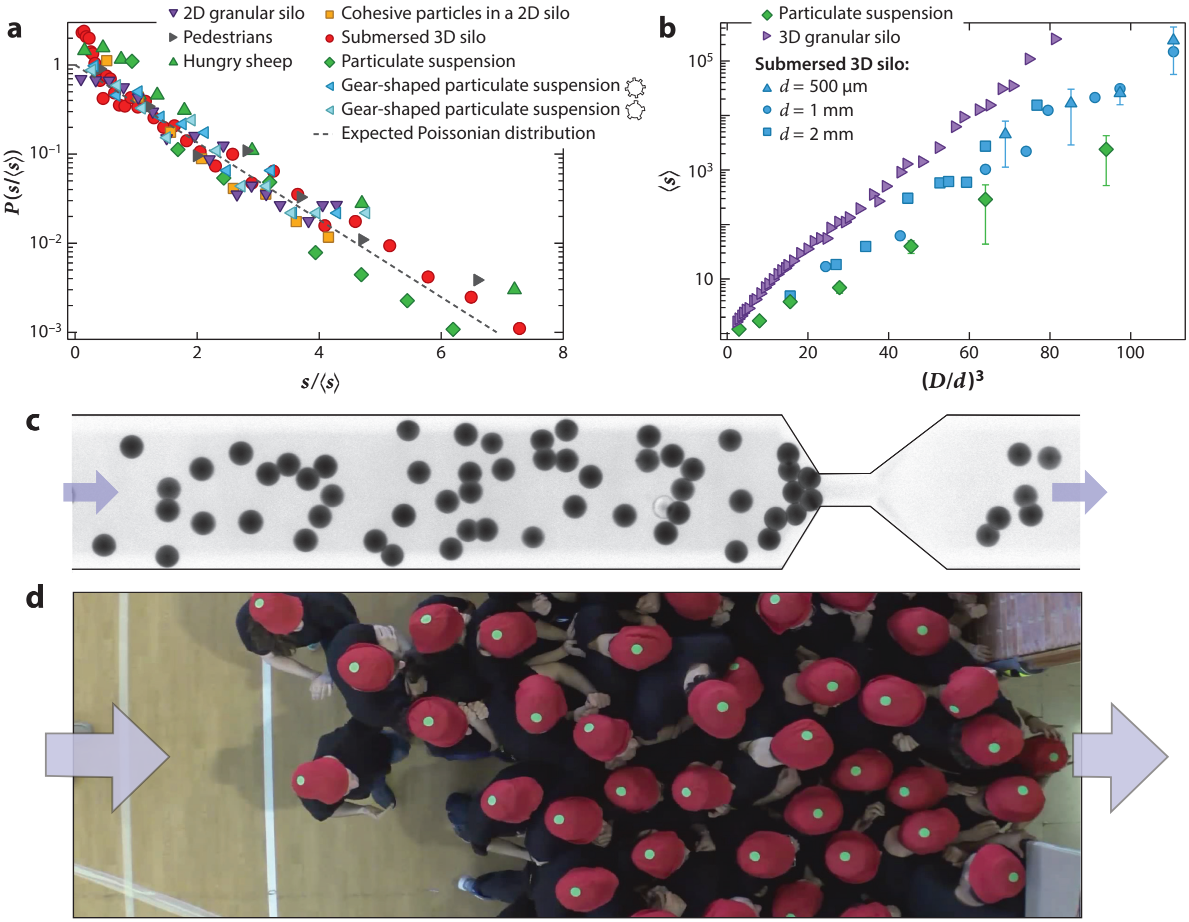

Figure 2

(*a*) The distribution of escapees $P(s/\langle s\rangle)$ follows an exponential distribution for a wide variety of configurations. 2D granular silo data are from Clément et al. (2000), pedestrian data from Garcimartín et al. (2016), hungry sheep data from Garcimartín et al. (2015), cohesive particles in 2D silo data from Knippenberg et al. (2022), submersed 3D silo data from Koivisto et al. (2017), particulate suspension data from Ortega-Roano et al. (2023), and gear-shaped particulate suspension data from Tampier et al. (2024). (*b*) The average number of escapees $\langle s\rangle$ increases exponentially with the aperture size following Equation 1, here exemplified for 3D systems. Particulate suspension data are from Ortega-Roano et al. (2023), dry 3D granular silo data from Zuriguel et al. (2005), and submersed 3D silo data from Koivisto et al. (2017). The varying slopes result from the distinctive features of the different configurations: A higher slope means more escapees before a clog forms, hence a lower probability of clog formation. Both suspensions and pedestrians follow the same statistical distribution: In panel *c*, we can see an arch being formed at the constriction of a dilute suspension of polystyrene particles with a constriction ratio of 1.7 after a few hundred particles successfully escaped. Panel adapted from Marin et al. (2018). (*d*) An intermittent human clog during an experiment on the evacuation of pedestrians through narrow doors carried out by Garcimartín et al. (2016). Image provided by Iker Zuriguel and Angel Garcimartín.

2.2. Bridge Destruction

If the number of particles passing through the constriction per unit time is constant during a burst and the average number of particles follows an exponential distribution, then the duration of a burst t_f must also follow an exponential distribution. The question now is, in an intermittent regime, what statistics does the duration of a bridge follow? Measuring the time between

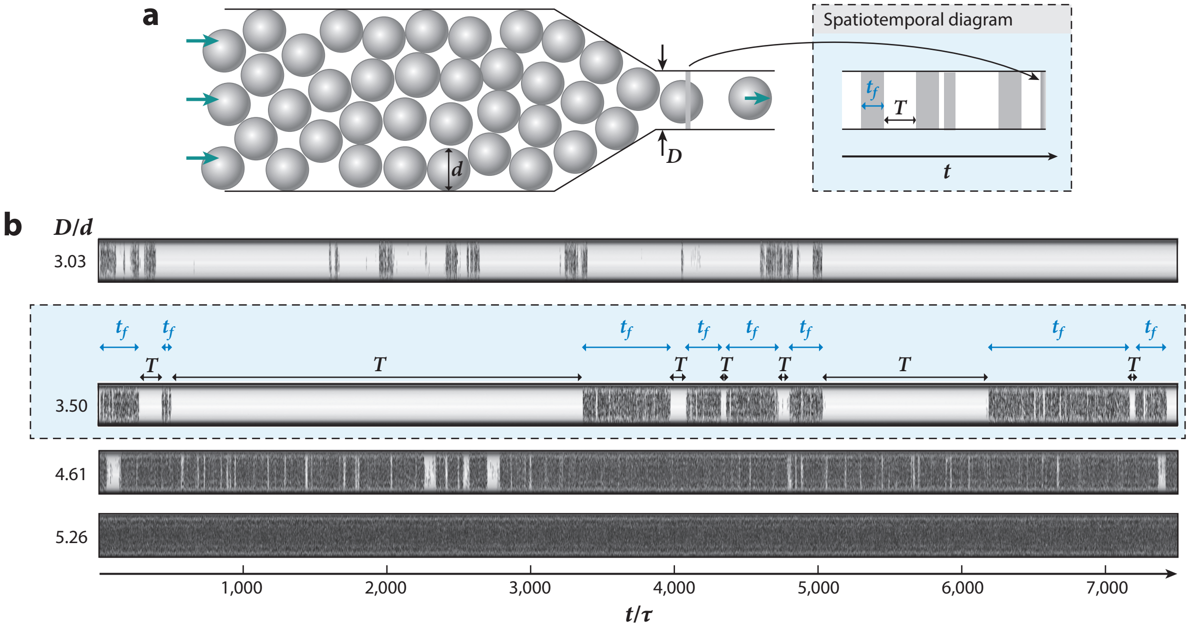

Figure 3

(*a*) Schematic of the construction of a spatiotemporal diagram. Periods of bursts of escaping particles lasting for t_f are followed by periods of clog when the flow of particles is temporarily interrupted during an arrest time T. (*b*) Spatiotemporal diagrams of volume-driven flow of noncohesive particulate suspension through a constriction. A distinct transition can be observed when the constriction ratio D/d is increased, leading eventually to an uninterrupted flow of particles for a large enough D/d. Time is normalized by the characteristic Stokes time $\tau = d/\langle U \rangle$, which is the characteristic timescale it takes for a particle to travel one diameter d in the case of a sphere or a disk moving at an average particle velocity $\langle U \rangle$. Figure adapted from Souzy et al. (2020).

consecutive bursts (arrest time T; see **Figure 3**) in intermittent flowing regimes, it was shown that the distribution $P(T)$ always displays a power-law tail $P(T) \propto T^{-\alpha}$ (Zuriguel et al. 2014, Zuriguel & Garcimartín 2020). This implies that the distribution of the arrest time follows a heavy-tailed distribution, where very long events have a nonnegligible probability of occuring. These power-law tails for the arrest time distribution, akin to the time that bridges last before collapsing, have been repeatedly reported in systems such as hungry sheep herds (Garcimartín et al. 2015), pedestrian crowds (Garcimartín et al. 2016, Helbing et al. 2005, Krausz & Bauckhage 2012), mice escaping a water pool (Saloma et al. 2003), and vibrated silos of dry granular material (Janda et al. 2009, Lastakowski et al. 2015, To & Tai 2017).

As explained in the sidebar titled Statistical Distributions: Exponential and Power-Law Distributions, an average can be defined in power-law distributions as long as $\alpha > 2$. In the context of intermittent clogging events, this would mean that, despite the frequent flow arrests, an average arrest time $\langle T \rangle$ for the system can still be defined, which translates into a finite (nonzero) average flux of particles. On the other hand, if $\alpha < 2$, extremely long arrest events dominate the process, leading to a diverging $\langle T \rangle$. Despite the frequent flowing periods, the system is effectively considered clogged as eventually an everlasting clog will form.

In the case of particle discharge from a granular silo, intermittency often results from induced vibrations in the outlet area. However, other disturbances can be externally induced, like social force fluctuations for herds of animals, human crowds, and car traffic jams (Garcimartín et al. 2016,

STATISTICAL DISTRIBUTIONS: EXPONENTIAL AND POWER-LAW DISTRIBUTIONS

Perhaps among the simplest stochastic processes that one can think of are those in which a certain event occurs randomly at a constant average rate, which becomes a property of the system. Such processes are also known as Poisson point processes, and their probability density decays exponentially with the number of events:

$$p(n) = \lambda e^{-n\lambda}, \tag{SB1.}$$

where n is the number of events and $1/\lambda$ is the average number of events. The fact that the probability is a constant means that such processes are memoryless and therefore not dependent on the history of the system. There are a myriad of natural processes following such a Poissonian statistics. In the context of clogging by bridging, the probability of a particle passing through the constriction in a dense system of particles can be considered constant, which leads to an exponential distribution for the number of particles escaping before a clog is formed (Zuriguel et al. 2003). Interestingly, if the number of particles per unit time passing the constriction is constant, then the time that the system is unclogged also follows an exponential distribution. Note that exponential distributions also arise for other clogging mechanisms such as sieving and aggregation (Sauret et al. 2014, 2018), but through different processes from those described for bridging.

Processes with a higher level of complexity also involve less obvious probability distributions. Exponential and also normal distributions represent processes in which the data cluster around typical values, well-represented by averages and standard deviations (Clauset et al. 2009). This is not the case for more complex processes. For example, in our everyday lives, we do not send emails at a constant average rate, and therefore it does not make sense to discuss an average time between emails. We instead have long periods of time in which we do not send any email, followed by bursts of emails of different time intervals (Barabasi 2005). Many processes based on human decisions follow such dynamics, but so do many natural processes such as earthquakes (Corral 2004) and neural avalanches (Priesemann et al. 2014). In the context of clogging of noncohesive granular matter or suspensions, intermittent flowing regimes are characterized by such a bursting statistics. If T is the time between two bursts, a typical power-law distribution would take this form:

$$p(T) \propto T^{-\alpha}, \tag{SB2.}$$

where α is the exponent of the decaying density probability distribution. A well-defined power-law distribution typically fulfills $\alpha > 2$, which permits us to define averages and other higher moments of the distribution. However, some clogging processes might show exponents $\alpha < 2$, which have crucial physical consequences that are discussed in this review.

Helbing et al. 2005, Krausz & Bauckhage 2012) or an air convective countercurrent in sand hourglasses (Wu et al. 1993). In all these systems, inherent perturbations eventually destabilize the bridges, thus resuming the flow of entities. Noticeably (and thankfully), for all configurations involving living entities such as pedestrians, drivers, sheep, and mice, the reported exponent is always $\alpha > 2$; i.e., these are systems where no clog could last indefinitely.

3. CLOGGING OF NONCOHESIVE SUSPENSIONS

It has been useful to describe the phenomenology of clogging by bridging in granular flows since only one phase (the discrete, solid phase) needs to be considered. Interestingly, much of the phenomenology observed in the clogging of granular systems can also be seen when dealing with noncohesive suspension flows. However, there are important differences to be considered.

3.1. Main Differences with Dry Granular Systems

A noncohesive suspension, formed by a certain number of particles per unit volume, flows by an arbitrary mechanism through a constriction. Once a bridge is formed, the particle flow through the constriction is blocked, and particles accumulate progressively upstream of the bridge while the interstitial fluid is able to flow, only with higher hydrodynamic resistance. In this simple but typical description of a clogging event by bridging in a noncohesive suspension, there are several important disparities with dry systems.

3.1.1. Initial concentration. The initial concentration of particles in the suspension is well-defined, and it is a crucial parameter. In the absence of a clog, the product of the particle concentration and the liquid flow rate gives us the number of particles that reach the constriction per unit time. When particles pass by the constriction, the particle flow can be seen as a random sampling of bridge configurations in a region of a size given by the constriction size D. This description is reminiscent of the one used in dry granular matter, with the crucial distinction that the sampling rate here is dependent on the number of particles per unit volume, the initial value of which (far upstream) is a controlled parameter. We discuss diluted and semidiluted cases in Section 3.2 and concentrated cases in Section 3.3, and we explain what this classification is based on.

3.1.2. Driving force. The force driving particles toward the constriction could be gravity (as typically in dry granular matter), but they can also be driven by the viscous drag of the flowing liquid. The differences are very important. In a gravity-driven case, a volume force drives the particles toward the constriction, and the liquid phase might or might not flow along, which makes an important subcategory. In closed hourglasses, for example, it was shown that the backflow of air could have an important role in the dynamics of the system (Wu et al. 1993). In the flow-driven case, a surface force drags the particles along through the constriction. Determining whether the flow is volume-controlled (pushed by a syringe pump or by a piston) or pressure-controlled (forced by an imposed constant pressure upstream) is crucial, as the driving mode can have major consequences on the response of the system upon clogging, as we discuss further below. The presence of a flowing continuous phase leads to rearrangements of the solid particle microstructure, inducing fluctuations and intermittency in the force chain network (Kulkarni et al. 2010), which may result in bridge destabilization. This coupling between the solid and the liquid phase for particulate suspension configurations is the most noticeable difference with their dry counterpart.

3.1.3. Particle interactions. Particle interactions are another essential difference to take into account. In dry granular matter, particle interactions are dominated by solid friction. In suspensions, both solid friction and hydrodynamic interactions need to be taken into account. Fortunately, we have accurate tools and models to account for the hydrodynamic interactions, at least in the limit in which viscosity dominates over inertia (Brady & Bossis 1988). Unfortunately, the role of solid friction in suspensions is an even more complex topic that is still under strong active debate (Guazzelli & Pouliquen 2018, Morris 2020), but it is of great importance for the topic under discussion.

3.2. Diluted and Semidiluted Cases

Rather than defining a precise range of initial particle concentrations in suspension, we have established a classification based on the dynamics of the system when both phases flow through the constriction. We begin by describing diluted regimes, which can be described as those in which the concentration of particles is so diluted that the particle separation distance remains larger than a particle diameter at all times until a bridge is formed (see **Figure 4*a***).

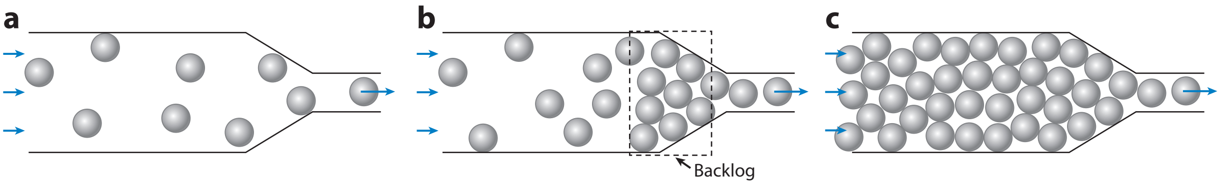

Figure 4

We propose classifying the different regimes in the constricted flow of noncohesive suspensions into three groups. (*a*) Diluted suspension flow, in which the particle concentration is stationary, homogeneous, and low enough that the interparticle distance is typically larger than one particle diameter. (*b*) Semidilute suspension flow, in which the concentration is nonstationary and inhomogeneous, and it is characterized by the formation of a backlog in the region of the constriction. The size of such a backlog might vary over time, growing upstream or shrinking, or it might remain an average constant. (*c*) Concentrated suspension flow, in which the particle concentration is stationary and homogeneous (upstream of the constriction) and high enough that the interparticle distance is typically lower than one particle diameter. The clogging mechanisms are identical in all these regimes. The main difference is the sampling rate of microstates to form a bridge that the particles perform at the constriction.

Clogging by bridging has been described as a random sampling of bridge configurations in the constriction region (Koivisto & Durian 2017, Thomas & Durian 2015, Zuriguel et al. 2003) for granular systems in which the particle concentration is typically close to its maximum random packing fraction. One might wonder if the same kind of mechanism could be invoked for a diluted suspension passing through a constriction. A very common related phenomenon can occur during filtration. It has been shown (Roussel et al. 2007) that even when the particle size is smaller than the pore size, clogging by bridging in filtration processes is possible. Making use of the configuration shown in **Figure 1** in a microfluidic setup, which allowed for hundreds of uncorrelated repetitions, Marin et al. (2018) showed that the probability of escapees faithfully follows an exponential distribution and provided a simple model based on the fact that the probability of bridge formation followed a Poissonian process. These results have been recently confirmed in a 2D microfluidic system for other particle concentrations (Vani et al. 2022), as the proposed stochastic model suggested. In dilute cases with volume fractions ranging from 10% up to 40% (Marin et al. 2018, Vani et al. 2022), the constriction ratio D/d can be rather low, approaching values of $D/d \approx 1$, which are typically impractical for larger concentrations. There is no fundamental difference in the physics of the clogging process for different concentrations: The discrepancies only arise from a need to improve the assumptions for the stochastic models depending on the concentration. For example, in dilute regimes, the minimum bridge possible, i.e., that formed by $n_{\mathrm{min}} = (D/d)^2 + 1$ particles, is in practice the only bridge possible, which allows for a simple stochastic modeling (Marin et al. 2018). However, as the particle concentration increases, the likelihood of bridges with $n > n_{\mathrm{min}}$ increases significantly, and a probability distribution for the bridge length needs to be computed, similarly to what has been done by To et al. (2001) for granular silos.

Backlog: similar to a filter cake but applied to noncohesive suspensions; it is formed typically with semidiluted noncohesive suspensions forced through a rather narrow constriction

We choose to define semidiluted regimes as those regimes in which the particle concentration is neither stationary nor homogeneous along the channel in the time prior to clogging (see **Figure 4*c***). This occurs due to the formation of a dynamic backlog: a highly concentrated region growing from the constriction while the particles are still flowing. This typically leads to a faster sampling of bridges by the particles and therefore to a higher probability of a clogging event.

This situation may occur when the concentration is high, but not high enough to reach a homogeneous maximum packing condition. It can also occur in fairly diluted situations in which the constriction ratio D/d is low or the constriction angle is very sharp, and consequently the particles slow down significantly at the constriction area. This means that our classification depends on the geometry of the system for a certain range of intermediate concentrations. Such backlog formation is also typical in experimental and numerical protocols in which a limited number of particles are available and are delivered as a highly concentrated pack toward the constriction (Bielinski et al. 2021, Guariguata et al. 2012, Lafond et al. 2013). This protocol works fine when the total number of particles available N is much larger than the average number of escapees $\langle s \rangle$. In that situation, the backlog grows rapidly, leading to a stationary concentrated flow. However, if $N \leq \langle s \rangle$, this can lead to a backlog formation and a nonstationary sampling at the constriction area.

We would like to emphasize that the clogging mechanisms are identical for all the classifications of constricted flows in noncohesive suspensions. The only difference is the sampling rate of microstates in the area of the constriction. While the diluted and concentrated regimes can be easily modeled using fairly simple stochastic models (Marin et al. 2018, Thomas & Durian 2015) due to the well-defined sampling rate, the semidiluted regime is more challenging due to its inherent nonstationary particle flow and lack of homogeneity. However, such regimes are very common, for example, in the clogging due to debris flows in rivers (see Section 5).

For practical reasons, diluted and semidiluted regimes are typically studied in the low range of constriction ratios D/d. For a constriction ratio of $D/d \approx 3$, $\langle s \rangle$ lies typically on the order of 10^6 escapees, which can take at least 1 h to go through for the typical liquid flow rates employed in such systems at a fairly diluted packing fraction of 20%. Acquiring statistics in such conditions is therefore tedious and also challenging due to the amount of data that are typically produced. For this reason, diluted regimes are more conveniently studied at low constriction ratios D/d, which form shorter bridges more rapidly, characterized by their high stability and permanency. Intermittent flow regimes, characterized by longer and unstable bridges, might be present at such low concentrations for larger constriction ratios D/d, but they are not observed in practice due to the lengthy experiments required.

3.3. Concentrated Cases

For dense noncohesive particulate suspensions flowing through a constriction, the probability of forming a bridge in a finite time is increased as the interparticle distance is reduced and the sampling rate is higher. As discussed for the diluted and semidiluted cases above, the bridge formation mechanism is identical for the concentrated case, only the sampling rate is higher. The most important difference is that, for the practical reasons describe above, concentrated suspensions are more suitable to study clogging processes at constriction ratios typically larger than $D/d \approx 3$. Interestingly, the stability of bridges beyond this constriction ratio becomes compromised and they tend to break more easily under the inherent perturbations of the system, which leads to intermittent clogging regimes. Such perturbations originate in the liquid flow itself at the bridge, as well as in possible particle rearrangements in the vicinity of the bridge (since the system does not need to be jammed upon a clogging event; see the sidebar titled A Jam Typically Leads to a Clog, but a Clog Does Not Always Involve a Jam). This means that the way the liquid and particle flow is driven in the system is expected to have a crucial impact on the stability of the bridges. Consequently, we discuss the different modes of flow driving and the potential differences.

3.3.1. Gravity driven. Perhaps the easiest way to move on from dry granular hoppers is to submerge the system into liquid. There are different ways to do this. The most obvious is to submerge a granular hopper in a large tank of liquid and run the experiments in the same fashion as in the dry counterpart. That has been the approach of Durian, Koivisto, and coworkers (Koivisto & Durian 2017, Koivisto et al. 2017) in their analysis of the role of the interstitial fluid in the discharge process. Note that in this approach, particles are still driven by gravity and not by the liquid flow. In this sense, this setup is ideal to study the role of solid friction and hydrodynamic interactions in the clogging of suspensions. Their surprising conclusion by comparing experiments with simulations is that submerging the particles (soda lime silica glass beads) only slightly changes the sliding

A JAM TYPICALLY LEADS TO A CLOG, BUT A CLOG DOES NOT ALWAYS INVOLVE A JAM

Dense discrete systems under tension can transition into a jammed state when a significant number of particles form force chains along the direction in which the tension is applied (Cates et al. 1998), such that the motion of the system is arrested. From this point of view, jamming is a general state of the system. Contrarily, clogging is defined as the blockage of a certain path by a finite number of discrete particles, which prevent others from being transported beyond the blockage. This definition does not require the whole system to be jammed (see **Figure 1**). Additionally, a system can be clogged only temporarily, allowing for intermittent periods of flow. Therefore, clogging is a local and temporal feature of the system and not necessarily a global and permanent state, as jamming is. A very illustrative recent study showed transitions between jamming and clogging states using numerical simulations with particles flowing through a network of obstacles (Péter et al. 2018). In dry granular media, especially when dealing with particles driven by gravity in silos, a clog might often imply a jamming state (Zuriguel & Garcimartín 2020). This is not the case in a suspension, where the particle concentration can vary significantly, from a maximum at the constriction area where a bridge is formed to a dilute particle concentration without contact between the particles. In conclusion, a jammed system is naturally clogged, but clogged systems are not necessarily jammed.

friction coefficient μ (from 0.15 in the dry case to 0.13 in the submerged case). This friction coefficient was obtained from simulations analyzing evacuation times in continuously flow regimes (for relatively large constriction ratios $D/d > 5$). Despite the presence of lubrication forces, we conclude from these results that such bridges are stabilized by solid friction, which is essentially the same regardless of the fluid surrounding the particles. Another interesting conclusion in their study was that the inertia of the particles does not seem to play a significant role in the evacuation flow (as long as friction is present). Unfortunately, all results concerned the formation of bridges and not their stability, which requires arrest time distributions. We interpret the results of these studies for submerged silos as evidence of the important role of the interstitial liquid flow in the formation and stability of the bridge formation. In the absence of such a liquid flow, the dynamics of the system is essentially identical to the dry granular cases.

3.3.2. Liquid flow driven. Forcing suspensions through constrictions using liquid flow has the obvious advantage of enhancing control over the process. However, it is not so obvious how the system will respond upon an increase in flow velocity. Does a higher local liquid flow velocity at the constriction promote particle transport or does it instead stabilize bridges by pushing particles harder together? Similar questions already received attention in dry configurations (Valdes & Santamarina 2008). Using numerical simulations, Arévalo et al. (2014) studied the role of the gravitational force, with values extending across four decades, and concluded that increasing the driving force in a dry granular silo discharge results in a fairly weak increase in the clogging probability, while the unclogging probability exhibits a noticeable decrease, suggesting that gravity has a stabilizing effect over the formed bridges. Although a similar scenario was once proposed for colloidal suspensions (Muecke 1979), no evidence of such a stabilizing effect has been reported up to now. Indeed, in a recent study, Souzy & Marin (2022) performed experiments at different flow speeds on the flow of non-Brownian and noncohesive suspensions through constrictions and reported striking distinctions for the clog destruction process depending on how the flow is driven. Suspensions dragged by liquid flow are driven either by forcing a constant volume of fluid per unit time or by imposing a pressure difference. For volume-controlled systems, when a bridge is formed, the flow encounters higher hydrodynamic resistance in the constriction and the local

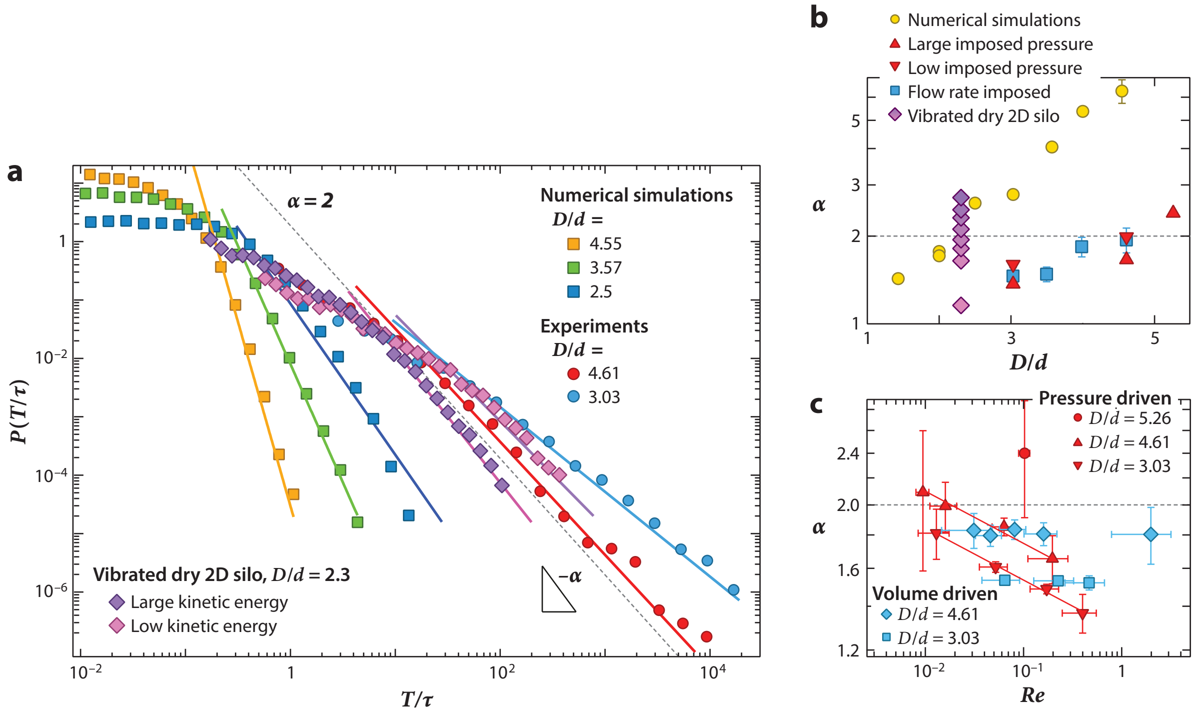

Figure 5

(*a*) Distribution of the arrest time lapses T/τ. Data are from numerical simulations of particulate suspensions (Ortega-Roano et al. 2023), experiments of constricted particulate suspensions (Souzy et al. 2020), and a vibrated dry 2D granular silo (Caitano et al. 2021). The solid lines correspond to the best power-law fits with their exponent α, and the dashed line corresponds to $\alpha = 2$. (*b*) The value of α increases with the constriction ratio D/d: A larger D/d results in longer and less stable bridges. For a dry 2D silo, applying vibrations with increasing kinetic energy (from *pink* to *purple diamonds*) weakens the bridge's stability, resulting in an increase in α. Data are from numerical simulations of particulate suspensions (Ortega-Roano et al. 2023), experiments of constricted particulate suspensions (Souzy et al. 2020, Souzy & Marin 2022), and a dry 2D silo (Caitano et al. 2021). (*c*) For particulate suspensions, the value of α depends not only on D/d but also on how the flow is driven. For a pressure-imposed flow, higher imposed pressure (i.e., a higher Reynolds number *Re*) results in lower α (*red symbols*), while for a volume-imposed flow, α is insensitive to the flow rate (*blue symbols*). Data from Souzy & Marin (2022).

liquid velocity at the constriction will increase to comply with the demanded volume rate. On the contrary, if the system is driven by a hydrodynamic pressure difference, the liquid flow velocity will reduce at the constriction upon clogging. A constant pressure configuration can thus be considered as self-regulated: The clog reduces both the liquid and the particle flow.

The conclusions of the experiments of Souzy & Marin (2022) for the same range of liquid flow velocity can be summarized as follows (see **Figure 5*c***).

1. For a volume-controlled configuration, increasing the liquid flow rate results in a decrease of $\langle s \rangle$ (higher probability of clogging events), but α is practically constant (no effect on bridge stability).
2. For a pressure-controlled configuration, increasing the pressure results in a decrease of both $\langle s \rangle$ (higher probability of clogging events) and α (higher probability of longer clogs, i.e., higher stability of bridges).

These results suggest that, on one hand, bridge formation follows generally similar trends for both liquid-driving configurations: A higher liquid velocity at the neck induces a higher number

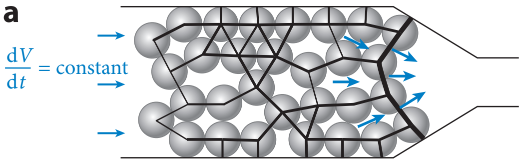

Figure 6

(*a*) A volume-controlled suspension flow upon clogging increases its pressure and flow in the constriction area, enhancing the compaction of the particle network and leading to a jam. (*b*) A pressure-controlled suspension flow upon clogging decreases its pressure and flow in the constriction area, leaving a noncompacted region behind the arch.

of escaping particles per unit time during burst periods. However, this leads to faster bursts, with a somewhat decreased number of particles per burst. Souzy & Marin (2022) suggest that such a decrease might be related to the larger hydrodynamic shear that the particles are subjected to, associated with the higher liquid flow velocity, which would bring particles closer together and facilitate the formation of bridges. Quantitatively speaking, the average burst size does not depend strongly on the choice of liquid driving. This makes sense since the flow driving method (volume or pressure controlled) only becomes relevant when a bridge is formed.

On the other hand, the arrest time statistics, and hence the unclogging mechanism, exhibits a higher sensitivity to the driving method: The arrest time statistics is practically independent of the flow rate in a volume-controlled system. In such a system, whenever a clog is formed, the liquid flow responds by increasing the pressure locally in the region of the bridge and therefore the flow velocity too (see **Figure 6*a***). Particles progressively accumulate behind the newly formed bridge, increasing the hydrodynamic resistance further as the aggregate's length increase. Since the liquid flow rate needs to be kept constant, the liquid velocity, and therefore the drag pushing particles together, increases. Following Cates's (1998) definition, this would lead to an increased and more stable contact chain force network, probably close to jamming. Such a liquid drag increase upon clogging should be independent of the flow rate value, and therefore applying different flow rates does not change the stability of the arch significantly. Consequently, α remains effectively constant when varying the imposed flow rate.

However, in a pressure-controlled system, the local pressure, and therefore the liquid velocity, decreases in the vicinity of the bridge, leaving a rather loose packing in this region (see **Figure 6*b***). A higher pressure upstream would lead to higher compaction in the near region downstream of the bridge, stabilizing it further. Therefore, lower pressure actually results in less stable bridges, which translate into better net particle transport. While driving the flow with a low pressure results in intermittent nonpersistent clogs, increasing the imposed pressure results in longer-lasting clogs that eventually become everlasting, thus mitigating the particle transport rate: a fluid-dynamical version of the faster-is-slower effect observed in pedestrians (Zuriguel et al. 2014). Interestingly, such an effect was already suggested by Arévalo et al. (2014), who concluded that an increased gravitational force increased the arch stability and hypothesized that a similar effect should occur with suspensions. While the systems and the nature of the forces applied are very different, the fact that both driving forces push particles closer together might be an important common key feature.

The results of Souzy & Marin (2022) need to be further understood, and numerical simulations could be a great tool. However, the coupling of discrete numerical solvers (for the discrete phase) with continuum ones (for the continuous phase) is nontrivial and requires quite some computing power (Hidalgo et al. 2018, Koivisto et al. 2017), which is not compatible with the amount of statistics required in these studies. To solve this issue, Ortega-Roano et al. (2023) used a discrete particle solver, MercuryDPM (Weinhart et al. 2020), and instead of solving the flow in the fluid phase exactly, they used an approximated numerical model for the liquid drag on the particles. This approach allows for low computational costs, and their results show that resolving the fluid phase is not necessary to reproduce the intermittent burst phenomenology, as both the exponential distribution of escapees and the power-law tail of the time-lapse distribution are well reproduced (see **Figure 5**). However, the results also reveal that resolving the interparticle flow with a computational fluid dynamic solver is necessary when a quantitative comparison with experiments is required, as both the bridge formation and destruction processes are enhanced within the nonresolved simulations, resulting in higher quantitative values of $\langle s \rangle$ and α when compared to experiments.

Using a different numerical approach, Hidalgo et al. (2018) studied the flow of a Brownian and noncohesive suspension through a narrow constriction using lattice Boltzmann simulations. In their case, the flow was pressure driven and the temperature of the system was taken as a control parameter, which was the main source of fluctuations in the system. While the probability distribution for the number of escapees $\langle s \rangle$ followed an exponential distribution as expected, they showed that thermal fluctuations reduced the size of the particle bursts through the orifice. This contrasts strongly with shaken dry granular silos, in which the flow of particles per burst is favored by the vibrations of the system (Janda et al. 2008, 2009). Interestingly, temperature has an even stronger effect on the bridge stability. High thermal fluctuations prevent the occurrence of extremely long clogging events by disturbing the particle bridges.

Studies on the flow of suspensions through constrictions forced by pressure-driven flows with large constriction ratios D/d have also shown interesting effects. Initially reported by Haw (2004) and later revisited by Kulkarni et al. (2010), the work showed that a self-dilution effect could lead to dilatancy of the suspension. Self-dilution refers to a reduction in suspension concentration downstream of the constriction relative to the suspension upstream. This can indeed occur even in the absence of clogging events, and Kulkarni et al. (2010) showed that it can lead to a substantial pressure reduction that is strongly dependent on the suspension concentration. The explanation was based on dilatancy effects, in which the suspension in the constriction region would dilate due to the increased shear, leading to a local pressure drop in that region. It is unclear whether such an effect occurs in suspensions flowing through constrictions with lower constriction ratios D/d, which lead to more frequent clogs, but it could certainly occur for larger D/d in continuous flow regimes and it should be considered.

3.4. Active Particles

To be able to break a bridge or prevent its formation, some kind of baseline energy is required. In granular matter, energy is quickly dissipated to a minimum. In flow-driven passive suspensions, the interstitial fluid flow can provide some energy, although its directionality can be detrimental for the particle flow. On the contrary, the flow of active suspensions through constrictions, similarly to the flow of pedestrians, is unique in the sense that the energy baseline is inherent to the particle.

Apart from the popular studies on pedestrians (Garcimartín et al. 2016) and sheep (Garcimartín et al. 2015), a simple experiment at the centimetric scale was done using vibration-driven self-propelled vehicles by Patterson et al. (2017). The vehicles have a rectangular shape and develop a unidirectional motion. Interestingly, when they were directed toward a constriction of only twice their frontal width, they managed to evacuate in bursts characterized by power-law arrest time distributions with $\alpha > 2$, i.e., flowing regimes.

The complexity of the propelling mechanisms of active colloidal particles (Bechinger et al. 2016) makes it nontrivial to deal with high concentrations directed toward constrictions, and therefore studies on the clogging of active colloidal particles are scarce. A recent study (Knippenberg et al. 2022) made use of programmable janus active colloids with tunable interactions, using an optical control feedback loop, to study the role of cohesion in the flow of self-propelled particles toward a narrow constriction. As expected, the results showed that, as cohesion among particles is increased, the stability of the bridges also increases, manifested by a decrease in the values of α to a minimum of $\alpha \approx 2$ for the strongest cohesion tested. Interestingly, in many of the bridges shown in this work, there was practically no solid contact among the particles. This can be tuned by a repulsive force, which is kept at a fairly large value in this work to prevent particle agglomeration. Interestingly, viscous friction seems to be enough to hold the bridges formed by these active particles.

Among biological active particles, the bacterium *Escherichia coli* is known to have a complex behavior when forced with a shear flow toward a constriction, since it tends to reorientate and swim upstream (Figueroa-Morales et al. 2015), preventing the formation of clogs. On the other hand, the microalga *Chlamydomonas reinhardtii* swims away from light sources, such that it can easily be driven toward microfabricated constrictions (Al Alam et al. 2022). In a recent paper Al Alam et al. (2022) revealed that *C. reinhardtii* exhibit the same behavior evacuating from a constriction as pedestrians, particles in silos, or particles in a suspension. Interestingly, when *C. reinhardtii* are driven at high velocities through constriction ratios $D/d \leq 3$, they show features compatible with the faster-is-slower effect, with intermittent regimes characterized by power-law arrest time distributions with decreasing α, although the reasons for such an effect are yet unknown.

3.5. Particle Properties

While the role of friction has been extensively investigated in the clogging of dry granular matter, several aspects remain unclear in the context of the clogging of noncohesive suspensions. Clearly, increased roughness among particles facilitates the formation of bridges, as is well-known in dry granular materials (To et al. 2001) and also in suspensions: Hsu et al. (2021) performed experiments on noncohesive but tailored colloidal suspensions in which the nanoscopic roughness could be tuned and showed that, when particles are pushed by a pressure-controlled flow toward a constriction, clogging is indeed favored as the particle roughness is increased (see **Figure 7*a***). By measuring the minimum flow velocity required for clogging events to occur within 15 s of flow, the authors reported a strong dependency of the minimum clogging velocity on the particle roughness. As concluded by Souzy & Marin (2022), it is probably not the increased particle velocity itself but the increased shear flow when increasing the upstream pressure that facilitates the formation of bridges at the constriction, which should be even more favored by increased roughness. In a different setting, using photopolymerization of a photosensitive solution through a mask, Tampier et al. (2024) synthesized 2D microscopic disk-shaped particles inside microfluidic channels and pushed them using a pressure-driven flow toward a constriction (see **Figure 7*b*,*c***). Interestingly, they showed that essentially no clogging occurs unless features are added to the surface of the particles. Indeed, their gear-shaped particles can be seen to clearly engage with each other, which stabilizes arches at the constriction. Accordingly, arch formation followed exponential distributions as expected (see their data in **Figure 2*a***). While the experiments mentioned clearly show the influence of the particle surface roughness on the formation and stability of bridges, a systematic investigation in terms of friction is still lacking. This is necessary in order to develop numerical models that we can use to complement the information obtained from experiments.

In addition to roughness, particle shape also plays a crucial role in both the formation and the stability of bridges in the clogging of noncohesive suspensions. Despite roughness's clear importance, most of the studies that can be found in the literature are dedicated to spherical particles, perhaps due to the difficulty of synthesizing large numbers of nonspherical particles with uniform features. In particular, fiber-like particles are of special interest due to the recent discovery

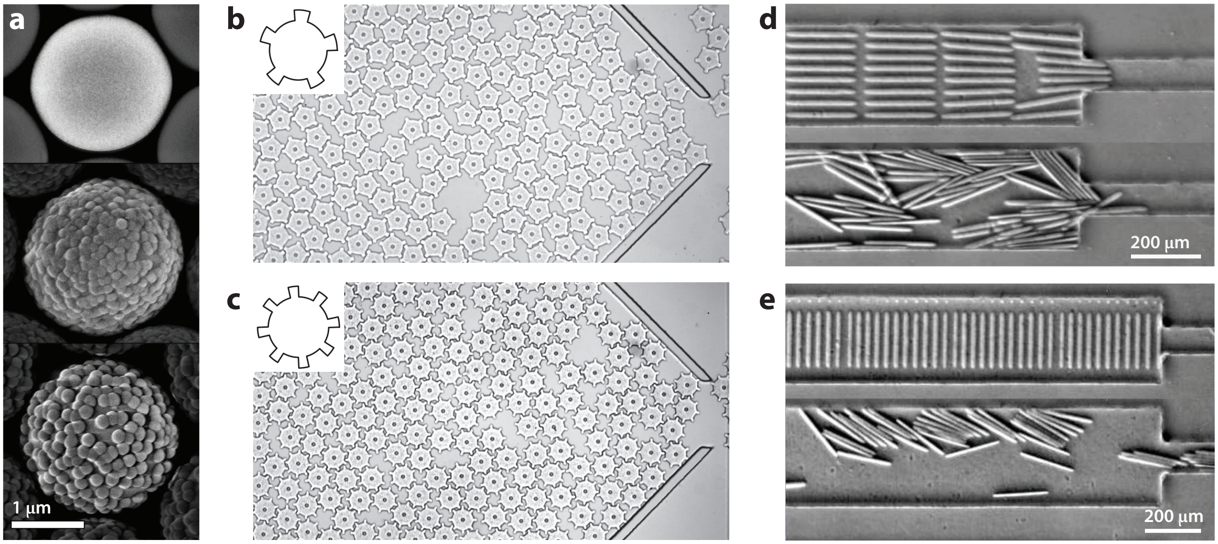

Figure 7

(*a*) Raspberry-shaped colloidal particles used to study the role of roughness in microfluidic clogging. Shown, from top to bottom, are a smooth silica colloid, a silica colloid with 50-nm particles adsorbed at its surface, and one with 100-nm particles. (*b*,*c*) Gear-shaped particles of different roughness evacuating through a constriction (of 600 µm). (*d*,*e*) Clogging experiments using fiber-like particles generated by on-chip photolithography in two different initial configurations. At the top of panel *d*, fibers are initially aligned parallel to the flow. At the bottom of panel *d*, fibers end up forming a stable arch. At the top of panel *e*, fibers start perpendicular to the flow and end up, in the bottom of panel *e*, with fibers successfully escaping with no stable arch formation. Image for panel *a* provided by Lucio Isa. Images for panels *b* and *c* provided by Jules Tampier. Panels *d* and *e* adapted from Berthet et al. (2016) (CC BY 4.0).

of significant amounts of plastic microfibers in the environment and the need for more efficient filtration (Napper & Thompson 2016). But it is also of great interest for studying logjams, i.e., clogs or jams produced by wood-laden flows in rivers (see further discussion of this phenomenon in Section 5). Kennedy & Mahadevan (2019) made use of a miniature laboratory setup for studying logjams in an open water channel with a sharp constriction using floating rigid fibers. They identified different types of clogging events characterized by different global ordering and orientation of the fibers, from ordered clogs where all fibers are characterized by long-range orientational order (and also higher fiber compactness) to disordered clogs lacking both orientational order and compactness. The transition between such states was found to be dependent on the fiber aspect ratio (the higher the aspect ratio, the more susceptible to disorder) and the injection rate (the more fibers per unit time, the more prone to disorder). The on-chip photolithography method used in Anke Lindner's lab (Tampier et al. 2024) has proved to be tremendously efficient for studying the role of particle shape. Berthet et al. (2016) not only managed to fabricate fiber-like microparticles on chip, but also generated them in different orientations. This initial orientation seems to be crucial for the formation and stability of the arches. An initial parallel configuration (see the top of **Figure 7*d***) can lead ultimately to a permanent clog (bottom of **Figure 7*d***). Surprisingly, the perpendicular configuration shown at the top of **Figure 7*e*** does not lead to a permanent clog in this particular example (bottom of **Figure 7*e***).

One of the conclusions of the study by Berthet et al. (2016) is that the elasticity of the fiber-like particles is crucial for the dynamics of the system. Here we find another aspect that remains rather unexplored: the role of particle deformability. The challenge here is to be able to decouple friction and deformability, due to the negative correlation between deformability and friction one typically finds in materials. Perhaps the most extreme case is that of liquid droplets, which have been shown to only clog for constriction ratios from $D/d \approx 1$ up to 3 (Hong et al. 2017). Interestingly, a similar range has been found for gravity-driven silos with deformable and almost frictionless hydrogel particles (Harth et al. 2020, Hong et al. 2017). In such cases, we expect the bridge stability to be strongly dependent on the driving flow, since it would induce particle deformations that would disturb the bridge stability.

4. PREVENTION AND UNCLOGGING STRATEGIES

Across the last decades, a wide variety of strategies have been proposed and investigated to either alleviate clog formation or facilitate clog removal once they are formed. The most intuitive and efficient way of preventing clogging by bridging is obviously to increase the relative size of the aperture with regard to the flowing entities. Unfortunately, whether for technical, financial, or biological reasons, such a solution cannot always be implemented and other options have to be considered.

4.1. Dry Granular Silos

Dry granular silos driven by gravity have been extensively studied and a few prevention strategies have been proposed to reduce the clogging probability, such as placing an obstacle in front of the exit (Zuriguel et al. 2011), adding smaller particles to the batch (Madrid et al. 2021), adding magnetic particles to enhance the flow (Carlevaro et al. 2022), using soft grains instead of hard frictional ones (Wang et al. 2021), and increasing the effect of gravity (Arévalo et al. 2014).

It is good to remember that once an arch is formed in a granular silo and all the energy in the system is dissipated, this arch is in principle forever stable. Therefore, arch-breaking strategies in dry granular systems rely on injecting energy into the system, typically by applying vibrations. Applying vibrations to the whole system in the same axis of gravity and above a critical vibration amplitude (Caitano et al. 2021) decreases the clogging probability and also causes the remaining clogs to break more easily (Janda et al. 2009, Mankoc et al. 2009), which makes this a particularly efficient and widespread technique as it is easier to prevent arch formation than to destabilize already formed arches (Valdes & Santamarina 2008). Interestingly, when oscillating in the horizontal direction (To & Tai 2017) at the silo exit, vibrations lead to a mitigation of the particle flow rate.

4.2. Thermal Fluctuations

Thermal fluctuations have been proposed as a mitigation/unclogging strategy for constricted noncohesive Brownian suspensions. Hidalgo et al. (2018) showed using simulations that increasing the thermal fluctuations in Brownian suspensions leads to competing effects: On one hand, the thermal fluctuations disrupt the bridge stability, but on the other hand, they also increase the probability of bridge formation. The latter result contrasts strongly with the vibration strategy used traditionally in dry granular matter but could be compared with the horizontal vibrations found by To & Tai (2017), due to the lack of directionality of thermal fluctuations.

4.3. Hydrodynamic Interstitial Flow

The hydrodynamic interstitial flow in flow-driven suspensions is the reason why energy is not completely dissipated upon clogging, as happens in dry granular systems. In fact, since the liquid flow continues even when a bridge is formed, we could conclude that such a flow would induce perturbations that could eventually break bridges. Nonetheless, Souzy & Marin (2022) showed that this mechanism does not work. Actually, increasing the driving pressure leads to an increase in the clogging probability, evidenced by a decrease in the number of escapees $\langle s \rangle$ with the flow velocity. Additionally, it results in an increase in bridge stability, evidenced by long-lasting bridges following power-law distributions with $\alpha < 2$. Consequently, and somewhat counterintuitively, an efficient strategy for limiting clogging of a noncohesive particle suspension is to drive the liquid flow at the lowest pressure possible. Interestingly, this conclusion is analogous to those of Arévalo et al. (2014). Even though the system they studied was a dry granular silo, they showed via simulations that increasing the gravitational force on the particles seems to stabilize bridges by pushing particles closer together. Note that this conclusion applies to rigid particles, as applying an increased pressure on soft particles will eventually squeeze them and thus allow for their passage through a constriction.

Hydrodynamic interstitial flow is crucial in closed hourglasses containing both solid particles and either a gas or a liquid with a significant density difference, with the particles driven by gravity. As the particles flow through the constriction to the bottom of the hourglass (or upward, depending on the density ratio), fluid needs to travel in the opposite direction toward the other side of the hourglass (Wu et al. 1993). Muite et al. (2004) showed that such a fluid countercurrent flow in an hourglass containing different kinds of fluids can prevent clogging by mitigating bridge formation.

Unsteady pulsatile fluid flows, including reverse flow direction cycles (backflushing) and/or high flow intensity cycles (high-pressure flushing), have also been widely used to prevent clogging in a broad variety of applications, ranging from microfluidic systems to cell and blood separation. One can trace the anticlogging potential of pulsatile flow in the literature back to the 1970s (Karmeli & Peri 1974) in the context of reducing clogging problems in trickle emitters for irrigation applications, as the unsteady shear environment associated with pulsatile flows is expected to mitigate several clogging mechanisms. Pulsatile flows with a periodic increase in the applied shear have also proved to be efficient in preventing or removing clogging by aggregation, as particles can detach when a higher shear rate is applied (Schwarze et al. 2019), thus resuming the particle flow if the pulsatile timescale compares to the timescale associated with the clogging and the growth of the filter cake in the system (Dincau et al. 2022).

In the case of clogging by bridging in dilute conditions, reversing the flow is typically a good way to dismantle a bridge. However, given the reduced number of particles, long cycles of backflushing are necessary to ensure that the reversibility of the Stokes flow does not restore the bridge in the same position (Marin et al. 2018, Metzger et al. 2013). Such long backflushing cycles would be highly detrimental for the transport in the system, though. In the case of clogging by bridging in concentrated suspensions, given the complex response of the concentrated system to changes in the hydrodynamic pressure (Souzy & Marin 2022), it is unclear whether an unsteady flow will prevent clog formation or alter the stability of an already built bridge. As discussed in Section 3.3, the response of the system upon clogging depends strongly on the microstructure formed in the constriction area and on whether it is the hydrodynamic pressure or the flow rate being controlled. A deeper understanding of the response of concentrated and constricted particle systems to hydrodynamic pressure and/or flow rate is needed to determine which unsteady flow conditions, if any, are favorable for transport in the system.

4.4. Natural Unclogging Strategies

Natural unclogging strategies related to flow instabilities can be found inside our own bodies. The flow of red blood cells (RBCs) within the circulatory system is of paramount importance for living beings. As one of the main functions of RBCs is to transport vital oxygen throughout the body, avoiding clogging is of utmost importance, and nature has developed a tremendous panoply of solutions to avoid clogging of RBCs. Healthy RBCs are nonadhesive (Telen 2000), soft, and deformable such that they can even squeeze and flow through circulatory channels when $D/d < 1$ (Roman et al. 2016). On top of this, RBCs preferentially travel in the shear-free zone around the channel center, a feature known as the Fåhræus–Lindqvist or plasma-skimming effect, which manifests as a locally higher concentration of RBCs in the center of smaller branch vessels resulting in a few-micrometer RBC depletion layer near the endothelial walls, thus contributing to prevent clogging by bridging (Ascolese et al. 2019). However, such RBC migration toward the center of the channel also marginates stiffer particles such as white blood cells, platelets, and synthetic microparticles (e.g., drugs) to the channel wall area. Recent numerical simulations (Bächer et al. 2017) have shown that, in order to pass through a constriction, such particles need to leave the wall and squeeze into the densely packed RBC layer, inducing a clustering effect that could eventually lead to bridge formation.

4.5. External Fields

External fields are needed when neither passive methods nor the hydrodynamics of the system can help to mitigate or disrupt bridges. A very efficient approach is the use of acoustic forces. A standing acoustic wave with a central node in the middle of a channel induces acoustic radiation forces on the suspended particles, leading to particle migration toward the center of the channel (Muller et al. 2013). Using this approach in a dilute suspension forced through a microchannel and simply attaching a piezoelectric actuator to it, Marin & Barnkob (2020) showed that the number of escapees before clogging could be increased by a factor of four. It is, however, unclear whether such an improvement in delaying the bridge formation was due to the migration of the particles to the center (reducing the probability of bridge formation) or due to a preferential orientation of particle groups in the channel's center. Interestingly, the use of such acoustic focusing has been proposed for constriction-free printing nozzles of multiphase materials (Collino et al. 2016), in which the material distribution can be tailored on a single printing line without the need for geometrical constrictions, which typically clog the print nozzle.

5. NONCOHESIVE SUSPENSION CLOGGING IN THE ENVIRONMENT

Most of the cases discussed up to now could be connected with generic processes in which suspensions need to be transported through a fluidic system, e.g., for industrial applications. Nonetheless, there are a myriad of processes in nature that could eventually be described using the framework proposed here. We discuss a few of them in this section.

5.1. River Ice Jams

Advected ice in rivers can accumulate on natural topological features of the terrain similar to the constrictions discussed here, but also at obstacles like bridges and river islands (Ashton 1978, Beltaos 1983). Such ice blocks can accumulate, form arches, and provoke ice jams, which can significantly reduce the flow of a river and cause severe floods. Significant effort goes into predicting and controlling the formation of such jams every year (Lindenschmidt 2020). The formation of ice blocks is a complex process that often starts with the nucleation of frazil ice at the surface of the river at subzero temperatures. Frazil ice formation soon leads to millimetric disk-shaped ice particles that might be noncohesive depending on the atmospheric temperature (Ashton 1978). They are transported downstream where they collide and interact, forming larger blocks that might eventually generate an ice jam (see **Figure 8*a*,*c***). Ice blocks can also be formed by broken ice platforms advected downstream. One of the main missions of the European Space Agency's satellite Copernicus Sentinel (Eur. Union 2021) is to monitor the formation of river ice in order to prevent the formation of such jams, which can cause substantial personal and material damage.

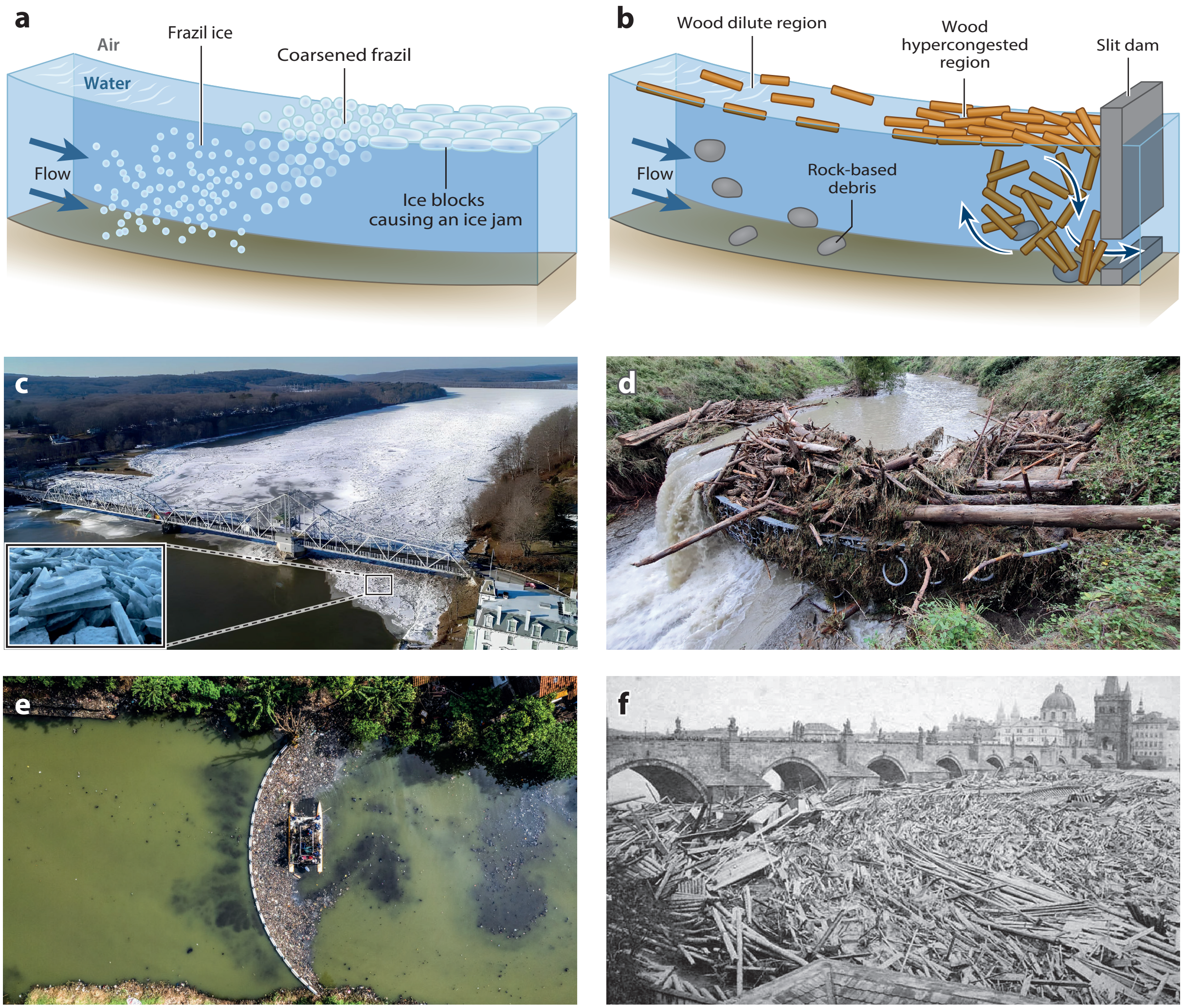

Figure 8

(*a*) Sketch of an idealized process of frazil ice formation leading to an ice jam on a river. Panel modeled after concepts presented in Lindenschmidt (2020). (*b*) Illustration of a wood-laden flow on a riverbed and its consequence on the clogging of dams, particularly slit dams. Panel modeled after concepts presented in Ruiz-Villanueva et al. (2019). (*c*) River ice jam on the Connecticut River, New England, in January 2018. Photograph provided by Frank Dinardi (Instagram @frank_dinardi); inset provided by Bryan D. (Instagram @beingdareful). (*d*) Woody debris trapped in flexible barriers in New Zealand. Photograph provided by Geobrugg, NZ (©Geobrugg). (*e*) A TrashBoom, a floating barrier deployed by the social enterprise Plastic Fischer on the Citarum River in Indonesia to trap plastic and waste pollution before it gets to the oceans. Photograph provided by Plastic Fischer CEO Karsten Hirsch (**https://plasticfischer.com**). (*f*) Charles Bridge in Prague after a flash flood in May 1872. Photograph by František Fridrich (public domain).

5.2. Riverbed Clogging

Riverbeds and canyons can become easily clogged by debris carried by the river flow. Debris in rivers can be generated either progressively, in which case the concentration can be pretty homogeneous until a constriction is found, or by natural catastrophes such as landslides, snowfall,

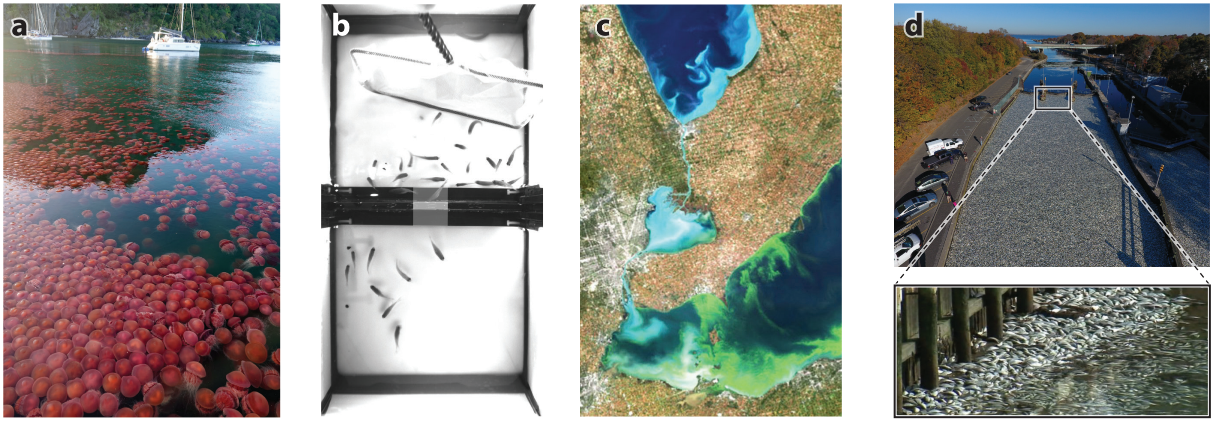

Figure 9

(*a*) Pink jellyfish bloom in Palawan, Philippines, in April 2020. Photograph provided by Sue Muller Hacking. (*b*) Evacuation of a school of fish (the tank width is 20 cm and each fish ≈3 cm long). Image provided by Aurelie Dupont. (*c*) Satellite picture of Lake Erie during an algal bloom. Panel reproduced from European Space Agency ESA/MERRIS (CC BY-SA IGO 3.0). (*d*) Tens of thousands of lifeless bunker fish, asphyxiated in a stampede, floating in Shinnecock Canal on New York's Long Island. Drone footage provided by Tom Jones (Hampton Watercraft).

floods, and dam breakages, in which case the debris flow is highly concentrated and localized in time and space (Takahashi 1981). The latter situations thus resemble the semidiluted suspension flow regimes discussed in Section 3.2, which are characterized by an unsteady and nonhomogeneous distribution of particles. Occasionally, river flow can be strong enough to carry groups of boulders, which can then get stuck in constrictions, especially in canyons and human-made structures such as slit dams, which mimic some of the constriction geometries discussed here (Piton et al. 2022). While boulders can be approximated as pseudospherical particles, large wood debris consists of tree trunks advected downstream with large aspect ratios, which facilitate the formation of clogs (Piton et al. 2020). Such wood-laden river flows (Ruiz-Villanueva et al. 2019) (see **Figure 8*b*,*d*,*e***) can be tremendously damaging due to their longer advected distances and capacity for dragging other debris along, and their description and modeling become more challenging than those of pseudospherical debris. Interestingly, wood debris arrives at constrictions typically as floating carpets (single floating layers) and generates quasi-2D arches at low velocities. However, debris can also be dragged deeper into the riverbed for slit dams that allow for large flow rates, leading to complex 3D bridges. Additionally, sudden arch breaking in riverbeds at a large flow rate can lead to dramatic consequences downstream, especially when both wood debris and rocks contributed to the arch (Piton et al. 2020). A consequence of such flow obstruction is the accumulation of other debris within the backlog such as algae, which can lead to lethal concentrations of certain toxic species for the surrounding fauna and flora during an algal bloom (see **Figure 9*c***). Another terrible environmental situation is garbage-laden river flows, especially when passing through certain urban areas, where the garbage density is the highest. Particularly dramatic are the cases of the Citarum River in Indonesia (see **Figure 8*e***) and the Pasig River in the Philippines, where the floating garbage is dense enough to clog and jam the river surface. To make things worse, most of this garbage consists of nonrecyclable plastics that will eventually make it to the oceans. To prevent this situation, the social enterprise Plastic Fischer (**https://plasticfischer.com**) has designed low-cost floating barriers to confine and promote controlled garbage clogs. They are deployed at hot spots in contaminated rivers to prevent the garbage from traveling downstream; it is then patiently collected by their employees (see **Figure 8*e***).

5.3. Animal Clogging

Clogs in water channels in the environment can be caused not only by inanimate ice or debris, but also by animals, such as a swarm of jellyfish (see **Figure 9*a***). These spineless, brainless, bloodless creatures behave like noncohesive deformable entities passively dragged by the seas and ocean currents. Jellyfish swarms regularly cause clogging of the intake screens of power and desalination plants, seriously limiting the pumping of seawater needed for the plant, with huge daily interruption costs (1.5 million dollars per day for the Torness nuclear power plant in Scotland in 2011). The presence of swarms of jellyfish can also impair the production of freshwater, halving production for several days following the appearance of jellyfish in a pretreatment system (Rahav et al. 2022). Considering that the flow rate of jellyfish has already been reported to reach up to 100 tons/h (Azis et al. 2000), control measures against this worldwide problem have been deployed, consisting of physical removal, development of underwater devices to release a bubble curtain in front of the intake structure (Larson 2015), and the usage of jellyfish-eradicating robots (Kim et al. 2016).

The forced evacuation of a school of neon fish has been experimentally investigated by Larrieu et al. (2023), who did not report any clogging or intermittency (see **Figure 9*b***), presumably due to the fact that neon fishes are elongated, deformable, slippery, and active beings that avoid contact while evacuating through a constriction. Interestingly, a similar behavior has also been reported for groups of ants escaping from a room (Altshuler et al. 2005, Wang et al. 2015), highlighting that ants are highly social animals as they behave in a way that prevents any arch formation when escaping through a constriction, a behavior that is in striking contrast with what is reported for crowds of pedestrians escaping in a panic situation (Garcimartín et al. 2016). Although living fish act like active social entities, the flow of tens of thousands of dead fish floating in a river behaves like a flow of noncohesive passive objects, which may lead to dramatic clogging of rivers such as was observed in November 2016 in Shinnecock Canal (see **Figure 9*d***), when a massive school of bunker fish was chased by a predatory school of bluefish, which caused a stampede through a narrowing channel where the concentration of fish was decreased and their oxygen depleted.

SUMMARY POINTS

1. The bridge formation mechanism is essentially identical in both dry gravity-driven flow and noncohesive suspension flow through constrictions; i.e., the liquid phase plays a minor role in it.
2. There is no critical concentration of particles for clogging by bridging. Even at the lowest concentrations, it is theoretically possible for a clog to occur.
3. Interstitial liquid flow plays a major role in bridge stability, stabilizing the bridges as the hydrodynamic pressure increases at the constriction.
4. Once a clog is formed in a granular hopper and all the energy in the system is dissipated, bridges are stable practically forever. However, liquid flow keeps running after a bridge is formed in constricted suspension flows, inducing perturbations that seem to prevent efficient formation of bridges but do not seem to be strong enough to break bridges as efficiently.

FUTURE ISSUES

1. Clarifying the role of solid and fluid friction in bridge stability in noncohesive suspensions requires further studies in which numerical simulations could play a significant role. Unfortunately, these simulations are computationally very expensive.
2. While the faster-is-slower effect has been shown in a wide variety of systems, the forces at play and therefore the nature of the effect seem to arise from different causes for each case. While reporting and invoking the effect are first steps, understanding and explaining the physical mechanisms involved in these processes deserve dedicated in-depth analysis.
3. Clogging of nonspherical particles, especially elongated shapes and fibers, remains rather unexplored and deserves attention.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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