# A Review of Surfactant Role in Soil Clogging Processes at Wastewater Exfiltration Locations in Sewers

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# A Review of Surfactant Role in Soil Clogging Processes at Wastewater Exfiltration Locations in Sewers

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**ABSTRACT:** Wastewater contains significant sources of pollutants and contaminants. often the failure of a pipe, inadequate sealing or corrupt pipe-connections cause the loss of raw sewage, which percolates into the nearby soil. As a consequence, a colmation layer in conjunction with soil clogging is developing, which regulates the exfiltration rate. Recently, literature has emerged that offers findings about the effects of wastewater surfactants on the change of physical properties of the soil. A survey of published literature in this field provides information highlighting the influential mechanisms of surfactants in soil clogging through physical, chemical and biological processes. Therefore, to provide a comprehensive approach, this review describes the adsorption mechanisms of surfactants on organic and inorganic particles, at gas-bubbles and at biomass. We also provided our own input to the description of the adsorption of surfactants at fluid/fluid and fluid/solid interfaces in porous media associated with the clogging process. *Water Environ. Res.*, **89**, 714 (2017).

**KEYWORDS:** Surfactant, exfiltration, colmation layer, clogging, sewer systems

## Introduction

Engineered sewer systems are considered important structures for maintaining hygienic status in urban areas. Structural failure of sewer pipes is known to be a typical way of losing raw sewage to the adjacent soil layer when the groundwater level is below the pipe base. This sewer effluent loss process is defined as exfiltration.

The problems associated with accurately defining sewer exfiltration rate data and the associated control of impacts on groundwater pollution point toward two focal points of research interest in urban sanitary systems in terms of both technical analysis and potential health risks (Chisala and Lerner, 2008; Ellis et al., 2009; Selvakumar et al., 2004). Whilst new and innovative methods for determining sewage exfiltration rate are being continuously developed (Leschik et al., 2009; Fenz et al., 2005), the potential impact of such losses on groundwater resources is less known and understood (Schaider et al., 2014). Effects of exfiltration of untreated sewage are often identified following the detection of marker pollutants in groundwater, which can be referred to as wastewater constituents introduced by residential, commercial and industrial process discharges as well as from the release of pollutants from wastewater treatment system overflows (Re et al., 2011; Sercu et al., 2011; Yang et al., 2013; Nikpay, 2015).

All sewers are liable to leakage loss particularly in urban areas where the drainage system is ageing and subject to various pressures such as heavy traffic loads or substantial rises in the groundwater (Ellis and Bertrand-Krajewski, 2010). Sewer exfiltration has become a priority concern in most metropolitan regions of Europe and North America but surprisingly little work has been undertaken to investigate the properties of the clogging materials associated with the sewer fracture area or how such properties might influence the exfiltration rate (Nikpay, 2015).

One principal area of interest to this clogging process is that relating to the potential effects of surfactant wetting agents and emulsifiers and which are known to lead to modifications of wastewater sediment properties (Matthijs et al., 1995; Nikpay et al., 2015a,b,c). Detergents are formulations designed to have solubilization and cleansing properties and consist of surface-active agents (surfactants) together with various subsidiary compounds. In 2013, the annual consumption of surfactants in Europe was estimated to be 2.98 Mt of which 1.45 Mt was non-ionic and 1.19 Mt was anionic according to the data reported by the European Committee of Organic Surfactants and their Intermediates (CESIO, 2013). Laundry detergents alone comprise nearly 40% of the total with an average 8 kg/capita/year consumption (Ecolabel Denmark, 2011). The major surfactant in current use is the biodegradable anionic surfactant, linear alkylbenzene sulphonate (LAS). Surfactants are amphiphilic

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molecules consisting of a polar head group at the end of a long hydrophobic carbon chain. Polar or hydrophilic substances dissolve in water, forming hydrogen bonds and electrostatic interactions with water molecules, whereas non-polar or hydrophobic substances are immiscible with water.

In terms of understanding the process of wastewater-soil interaction, the focus is directed to the surfactants where the aggregation function at the interfaces is emphasized in modifying process mechanisms such as flocculation, flotation, dispersion, wettability and solubility (Somasundaran and Zhang, 2006). One of the main difficulties in the comprehensive understanding of the exfiltration process, particularly in microscale, is associated with the complex physicochemical conditions between wastewater properties and soil, e.g., interfaces, electrostatic charges, chemical interactions, as well as particles. The adsorptive attachment of surfactants to the solid constituents of the fluid in the clogging layer can additionally result in a number of synergistic forces which can increase the pollution potential of the exfiltrate. It is also well known that surfactants can affect metal lability and algal toxicity with the detergent complexation modifying the soil adsorption properties (Morrison and Florence, 1988).

A further aspect of the surfactant adsorption mechanism is the interaction with living cells in the biomass clogging of the colmation layer as well as changes in the permeability/hydraulic properties of the fluid by stabilization of gas bubbles or the transport of particles within sediment conduits. Surfactant adsorption at interfaces can therefore be considered as a key factor in the clogging process. Thus the type and composition of surfactant, their synergic effect and degree of aggregation at the liquid-sediment interface are important considerations for the colmation process.

As the above indicates, a significant increase in wastewater surfactants leads to complex adsorption processes on soil particles in the area of the sewer leak. While studies have been carried out to explain the exfiltration, infiltration and pollution transfer caused by leaky sewers, the process of clogging still requires more descriptive detail of the role of organic chemicals and namely of the surfactants in the clogging phenomenon (Nikpay, 2015).

This article is an investigative review of recent theoretical and experimental works on the potential role of wastewater surfactants in amending the hydraulic properties of the clogging layer and surrounding soil and in the development of preferential flow paths.

## Adsorption of Surfactants at Fluid-Solid Interfaces

It is likely that with an increase of the surfactant concentration in an aqueous phase, molecules of surfactants start to adsorb at the interfaces as well as aggregates in the solution (Schott, 1980; Gurkov et al., 2005). By adding another monomer to the solution as a new active center, the opposite interaction between surfactant polar molecules and water molecules increases, which results in assembling surfactant molecules into

a micellar cluster at the critical micelle concentration (CMC) (Blesic et al., 2007), e.g., CMC value for sodium dodecyl sulfate (SDS) is about $8\times10^{-3}$ molL$^{-1}$ (Dominguez et al., 1997). Above CMC, the increase in surfactant concentration accelerates the extra formation of micelles. Micellar solutions can solubilize in a variety of substances in the micellar core and this capacity of solubilization is an important property of surfactants (Rangel-Yagui et al., 2005). The nonionic surfactants have a lower CMC level than anionic and cationic surfactants; a feature apparently related to the alkyl chain length (Holmberg et al., 2003). The micellization process can be described by $nS \leftrightarrow S_n$ where $S_n$ is a micelle-aggregate, $S$ is the surfactant and $n$ aggregation number (Patist et al., 2002).

Surfactants are active molecules at different interface systems including liquid/liquid, liquid/gas or liquid/solid, in which surfactant molecules are adsorbed or aggregate to minimize surface free energy (Burlatsky et al., 2013). Thus, free energy measurement comprises a basis for the efficient shifting of surfactant molecules from bulk flow to the interfaces and can be explained by reference to the following equation (Rosen, 2004):

$$C_{\text{interface}}/C_{\text{bulk}} = \exp(-\Delta G/RT) \qquad (1)$$

Where $\Delta G$ is free energy change, $C$ is surfactant concentration, $R$ is 1.99 cal K$^{-1}$mol$^{-1}$ and $T$ absolute temperature.

To improve the cleansing performance of detergents, mixed types of surfactants are used and a similar "cocktail" of mixed surfactants types occur in wastewater effluents. A few studies are available on this subject which have noted that the combined effects of various surfactant types are synergic, potent and distinct in relation to their respective electrostatic charges (Varade et al., 2004). The synergistic effects of surfactant mixtures at the interfaces have not been well understood while the interaction of mixed surfactants can influence the adsorption efficiency at liquid-liquid and liquid-solid interfaces (Xu et al., 2016; Chiappisi et al., 2015). Zhang and Somasundaran (2006) indicate that adsorption of mixed surfactants is the cumulative result of several bonding forces between certain types of monomers and solid surfaces. The adsorption of surfactant ions on oppositely charged minerals is controlled by two main mechanisms of electrostatic and hydrophobic forces (Carrasco et al., 2009). In 1988, Meguro et al., reported a bilayer formation of mixed cationic and anionic surfactants in oppositely charged material. In another case, anionic surfactant adsorption on silica was increased by mixing it with cationic surfactants (Huang, 1989). On the contrary, in an anionic-nonionic surfactant mixture, a decreased adsorption of nonionic surfactant on negatively charged silica gel was reported whilst at the same time increasing the ionic surfactant concentration above CMC (Gu and Huang, 1989).

## The Effect of Surfactants on Colloidal Particles

One of the principal hypotheses put forward to explain the decrease in exfiltration rate over time at a sewer defect and which has been noted to occur in both experimental and field

studies, is that organic and inorganic wastewater micro-particles, accumulate in the void space of the porous colmation medium causing a decrease in its effective porosity (Rice, 1974; Rauch and Stegner, 1994; Karpf et al., 2009).

To encompass the waste water particulate, they are ordered into three size classes, which are: suspended solids with a size range of 1 $\mu$m to a 1 mm, colloids with sizes ranging from 0.001 $\mu$m to 0.1 $\mu$m and dissolved around .02 $\mu$m or less in size (Tchobanoglous et al., 2003; Gregory, 2006). The total suspended solids (TSS) fraction smaller than about 0.5 $\mu$m, which impact micro and mesopores, can be the main contributing factor in the loss of percolation capacity within the clogged layer (Mayer et al., 2004). However, for the larger particle size, the formation of a thin surface film is expected (Boulding and Ginn, 2016). Nevertheless, the specific size of colloidal phase of the percolating exfiltrate including both organic and inorganic particles is widely considered to play a crucial role in the self-sealing mechanism of the clogging layer (Auset and Keller, 2006), which can effectively influence the permeability of porous media through physicochemical, mechanical and biological processes (Bradford et al., 2002). McDowell-Boyer et al. (1986), argued that there was an initial accumulation of fine solids at the surface of the porous media by particles larger than the pore sizes. This shrouding particle layer would then control the internal clogging potential of the porous medium by reducing the drainage capacity (Platzer and Mauch, 1997). However, the various researches to date have tended to focus on the physical side of the clogging process rather than chemical or physicochemical aspects. More importantly, there has been little discussion addressing the potential significance of surfactants in the clogging process itself.

Taking into account the overall consensus of research observations, it would seem logical to conclude that surfactant adsorption by changing the charge and electrokinetic potential of organic particles increases their tendency to coagulate or be dispersed (Joó et al., 2015), e.g., improving the aggregation of titanium dioxide ($TiO_2$) nanoparticles and the disaggregation/dispersion of carbon nanotubes by the adsorption of surfactant (Raza et al., 2016; Vaisman et al., 2006). The adsorption or desorption process can be controlled by soil properties, pH and the nature of organics and organic chemicals in a saturated soil (Ertli et al., 2004; Joó et al., 2015; Jahan et al., 1997). Despite the fact that many organic particles carried by wastewater effluent are hydrophobic in nature with a tendency to interact with soil and organic matter in liquid and solid phases, surfactants are able to adsorb onto their surface and create an electrostatic charge, (Das et al., 2011; Ertli et al., 2004). For instance, adsorption of cationic surfactant hexadecyl trimethyl ammonium bromide, $C_{16}TAB$, onto the hydrophobic cellulose surfaces forms a monolayer similar to the air-water adsorption mechanism while the surface layer and surfactant monolayer are fused together (Penfold et al., 2007). As a result, the effect of coagulation leads to pore-throat clogging as well as permeability reduction (Figure 1). Figure 1 summarizes the sequence of adsorption mechanisms that results in a decrease in overall permeability following surfactant application to the pore fluid.
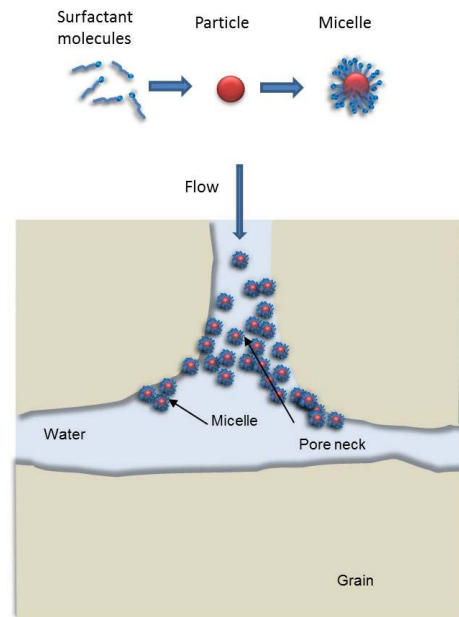


**Figure 1—The process of micelle formation in a mixed colloid-surfactant system. Adsorption/aggregation of hydrophobic particles at the pore throat can reduce its porosity. Initially limited particles are attached to the surface of the pore throat to maintain their positioning by the attractive force and then adsorption/trapping of extra particles which leads to pore clogging.**

The attachment of hydrophobic particles occurs primarily at the pore throat using a hydrodynamic process, which later with decrease in water movement can cause more particles to become immobilized and settle at the pore throat (Crist et al., 2005). More specifically, the creation of positive or negative electrostatic charges by surfactants becoming attached to the surface of particles causes them to become destabilized, e.g., the dispersion mechanism of carbon nanotube (CNT) by surface adsorption of surfactants (Vaisman et al., 2006). This effect will decrease the repulsive energy force sufficiently for two (or more) particles to coagulate (Rosen, 2004). At this instant, attractive or repulsive forces are bringing the particles into very close contact facilitating particle "collision." Thus, when two or more aggregated particles accumulate as larger particle forms, they are dragged forward by the tractive force of fluid flow.

In general, the transport of larger particles inside the porous media is controlled by the fluid flow while the submicron size particles are able to move by Brownian motion. Nevertheless, after aggregation and an increase in their size, Brownian motion is considered to be a lesser degree of importance compared to that of fluid flow (Kusters et al., 1997).

On the other hand, surfactants can solubilize large organic particles into smaller sizes, which can feasibly amplify the clogging process due to throat clogging (Figure 2). What is known about this process is largely based upon survey information from demonstrations using surfactants for the dispersion/dissolution of petroleum oils such as bitumen (Sarbar
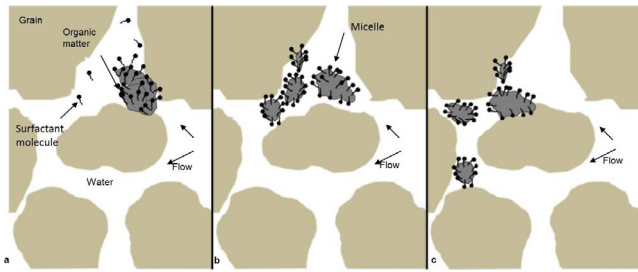
**Figure 2—Sketch of suggested surfactants role in solubilization of organic macro-particles and the decrease in permeability a) aggregated organic matter before the surfactant b) after the surfactant solubilizing and displacement of smaller organic particles inside the conduit c) new positioning of particles can intensify the clogging.**

et al., 1984), non- aqueous phase liquids (NAPLs) or polychlorinated biphenyls (PCBs) (Martel and G´elinas, 1996; Abdul et al., 1992; Martel et al., 1998; Shiau et al., 1994). In addition, surveys such as those conducted by Arnold et al. (2011) have underpinned simulation models of surfactant aggregation at the surface of hydrophobic colloidal particles, which has been verified by increasing the surfactant concentration, initially lower than the CMC threshold, successfully generating the final micelle formation.

When an ionic surfactant is added to water and adsorbed at hydrophobic particle surfaces, this results in a higher level of hydrophobicity, which facilitates transportation inside and through the pore voids. Whilst the repulsive energy of the solution should theoretically reject the particles, it would appear that they would prefer stabilization inside the pore (Figure 2). As reported by Crist et al. (2005), a greater retention time is needed for the drainage of hydrophobic particles from the partially saturated porous media vs. hydrophilic particles as indicated by the decline in pore volume of colloidal breakthrough curves and shown in the images taken using visualization techniques. This result indicates that attractive forces between the hydrophobic particles outweigh the repulsive forces at close distances. Accordingly, the hydrophobic particles are more capable of being adsorbed on the surface of the pores through the attractive energy rather than hydrophilic particles (see Figure 3).

The adsorption of surfactants to fine inorganic particles in wastewater or to micro-minerals in the soil matrix can be equally important in permeability reduction (Curbelo et al., 2007). It has been suggested that the infiltration of wastewater into the soil increases the potential for soil clogging by combining with wastewater minerals (Cooke et al., 2001). The results will be physical changes in the soil matrix as a consequence of the movement of fine minerals, which have a size less than the minimum diameter of an access conduit size.

Similarly, during the process of detergency, surfactants are able to separate the fine particles via adsorption at their surfaces (Rubingh and Jones, 1982) (see Figure 4). The basic theory behind this process is that attractive forces between the fines and
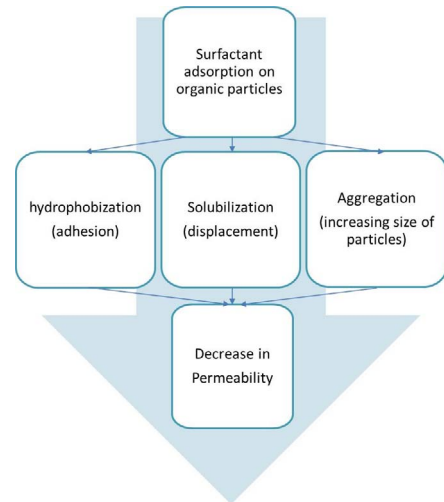


**Figure 3—Mechanism series that can decrease the permeability of porous media by surfactant adsorptions to organic particles.**

the solid substrate cause a decrease in the separation of fines from the soil matrix. The separation of the fines which serve as the "cement" between the larger grains-void leads to disaggregation of the soil skeleton. That is to say, increasing the fine-surfactant micelles clogs the pore throats and reduces the permeability (Mohamed and Antia, 1998).

The surfactant electrostatic charge has been found to be very important in stable and rapid adsorption at the solid surfaces particularly with oppositely charged minerals (Yeskie and Harwell, 1988). Clays, for example, comprise an important fraction of basic soil, having a diameter range less than 2 $\mu$m, and exhibit a large surface area per unit mass,
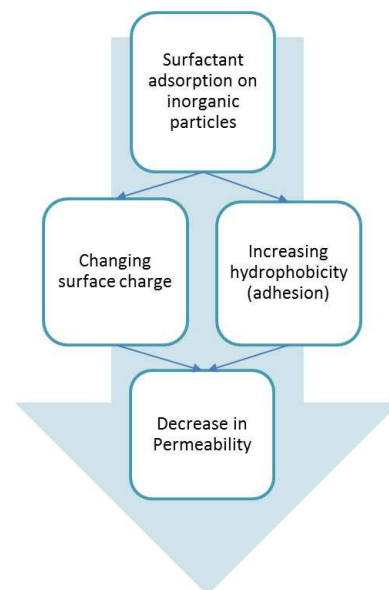


**Figure 4—Mechanism series that can decrease the permeability of porous media by surfactant adsorptions to inorganic particles.**

**Table 1—Some Examples of Surfactant Adsorption on Mineral Surfaces**

| Adsorbent | Surfactant | Test method | Major result | Reference |
|---|---|---|---|---|
| Silica | nonionic | atomic force microscopy (AFM) | adsorption at silica even in the presence of added water | Sakai et al. (2016) |
| Zeolite | cationic quaternary ammonium | high speed disperser | monolayer formation at zeolite | de Gennaro et al. (2016) |
| Rock contained minerals, e.g., [*]SiO$_2$,Si, Al, K, Ca, Fe,Na | cationic | inverse gas chromatography | recovery of the rock surface with the surfactant | Bendada et al. (2016) |
| Mica (negatively charged) | [**]cationic quaternary ammonium (DTAC and CTAC) | atomic force microscopy (AFM) imaging technique | different adsorption morphologies of [**]DTAC and CTAC on mica | Xie et al. (2016) |
| Calcite (CaCO$_3$) | [**]anionic (SDS),cationic (DTAB), zwitterionic (CAPB) | zeta potential technique | steep adsorption of [**]SDS, significant adsorption of DTAB, difficult adsorption of CAPB | Durán-Álvarez et al. (2016) |
| Montmorillonite | [**]cationic (CTAB) | fourier transform infrared spectroscopy (FT-IR) | adsorption of CTAB on montmorillonite | Moslemizadeh et al. (2016) |
| Quartz, Montmorillonite, Illite, Kaolinite | [**]anionic (SDS) and nonionic (TX-100) | X-ray diffraction (XRD) | Nonionic surfactant was adsorbed at all minerals shows highest value for montmorillonite. Adsorption of anionic surfactant was insignificant. | Bera et al. (2013) |

[*] Silicon dioxide, Silicon, Aluminum, Potassium, Calcium, Iron, Sodium
[**] Dodecyltrimethylammonium chloride (DTAC), cetyltrimethylammonium chloride (CTAC), sodium dodecyl sulfate (SDS), dodecyltrimethylammonium bromide (DTAB), cocamidopropyl betaine (CAPB), cetyltrimethylammonium bromide (CTAB), Triton X-100 (TX-100)

which strongly affects soil behavior (Kuila and Prasad, 2013). This poses a rather important question concerning clay hydrophobicity or hydrophilicity. Prakash (2004) indicated that clay hydrophilicity or hydrophobicity is determined by the total interactive energy between the clay particles and the liquid. In a prior study by Van Oss and Giese (1995), they demonstrated that the ultimate zero angle explained in the Young equation is only achieved at high energy surfaces such as that for mica where $\gamma$ the contact value, measured 65 mJ/m$^2$. Thus, taking this value as a practical upper limit, the maximum hydrophobicity for clay minerals exceeds the hydrophilicity by almost a factor of two. Hence, cationic surfactants are predisposed to adsorb at the surface of clay minerals via electrostatic attraction. By contrast, Hower (1970) demonstrated that anionic surfactants show a similar tendency toward adsorption on clay due to the adsorption of monomers at their positive sites. A number of studies have likewise found that the adsorption of non-ionic surfactants in the soil matrix increases with a higher percentage of clay soil minerals (Junin et al., 2012; Shen, 2000). With that said, the adsorption process can be influenced through different system conditions such as pH and ionic strength as well as difficulties in applying a perfect electrical double layer (EDL) modeling by using natural soil minerals (Sperry and Peirce, 1999). Collectively, these various studies, as well as examples in Table 1, emphasize the crucial role played by the soil mineral composition and which is necessary (if not a precondition) to interact with surfactants.

## The Effect of Surfactants on Gas Bubbles

Gas bubbles can often form in saturated soil as a result of biological activities, fluctuations in the water table or changes in fluid pressure (Kellner et al., 2005). Surfactant molecules can stabilize the generated gas bubbles by adsorption at the gas-liquid interface prior to any rupture. This constructed mono-layer film increases the lifetime of the microbubble and its level of stability depends on the type of surfactant (Denkov et al., 2009). Furthermore, on a pore scale, the gas bubbles flow for a given length of continuous paths through the soil matrix before they are trapped inside the pores thus slowing down the liquid drainage (Osei-Bonsu et al., 2015).

Significantly, hydrophobic interaction between the particles and the surface of the bubbles is increased by the adsorption mechanism of surfactants at the interfaces (Goldenberg et al., 1989; Aksoy, 1997). As a result, a package of colloidal particles is formed in the bubble, which can be delivered after the rupture to the pore and thus permeability decreases by the reduction in the pore volume (Wan and Wilson, 1994) (Figure 5).

In a survey conducted by Wan and Wilson (1994), a micro-model was used to simulate the adsorption of hydrophilic and hydrophobic colloidal particles at the gas-water interface by using trapped gas inside the pore space of the model. The result showed the affinity for adsorption of both hydrophilic and hydrophobic particles while the adsorption was enhanced due to the increase of the hydrophobicity at the particle's surface (Wan and Wilson, 1994) (see Figure 6). Goldenberg et al. (1989), demonstrated that the adsorption of clays to bubbles at the gas-
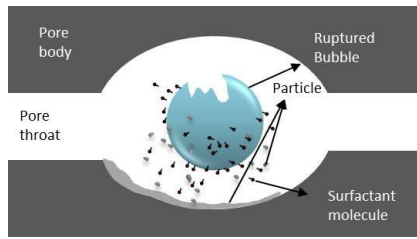
**Figure 5—Sketch of colloidal particle delivery in a pore space after bubble breaking.**

water interface could transport colloids 20 to 30 times more than the average transport suspended in liquid. However, it is also feasible that the blocking and subsequent rupture of micropores with gas bubbles might be the catalyst for a quasi-periodic increase in the flow and exfiltration rate.

## The Effect of Surfactants on the Biomass

Attention has been recently directed to biomass effects in controlling wastewater infiltration into the soil (Pintelon et al., 2012; Rodgers et al., 2004; Gette-Bouvarot et al., 2013; Baveye et al., 1998; Winstanley and Fowler, 2013). Based on biological studies, the infiltration of nutrient-rich wastewater into the enveloping soil of a sewer pipe is highly likely to increase microbial activity in the clogging zone (Fuchs et al., 2004; Van Cuyk et al., 2001) attaching to the solid surface in order to reduce mobilization. Consequently, the immobilized matrix of microbial cells could offer a protective and nutrient rich environment for further microbial growth.

The adhesion between a microbial cell and a solid surface is the result of electrostatic attraction and hydrophobic interaction (Geoghegan et al., 2008; Daeschel and McGuire, 1998). Notably, an electrical gradient between the exterior and interior cell membrane forms a voltage across the cell which is usually negative (James, 1991; Lanyi and Schobert, 2004). At a greater distance from the cell membrane ($> 50$ nm), hydrophobic interaction becomes a particular force of adhesion whilst at short distances ($< 20$ nm), electrical attraction is dominant (Daesche and McGuire, 1998).

Torkzaban et al., (2008) provides a critical review of the literature on the process of microbial cell transportation in a porous media and their controlling factors including: cell types, hydrophobic interactions, surface charge characteristic, motility and surface features. Nevertheless, Torkzaban et al., (2008) concluded that the mechanism of microbial retention in porous media is not yet fully understood. Other studies have focused on how microorganisms behave in a liquid system, suggesting that microbial cells are very similar to particles (Donlan, 2002). Therefore, the adsorption of surfactant monomers on microbial cells (Chen et al., 2000; Kaczorek et al., 2011) can increase their mobility in a liquid system (Streger et al., 2002; Powelson and Mills, 1998).

Coupled with previous findings, the surface electrical charge of adsorbed bacterial cells apparently can change, which in turn increases cell surface hydrophobicity (Sotirova et al., 2009;
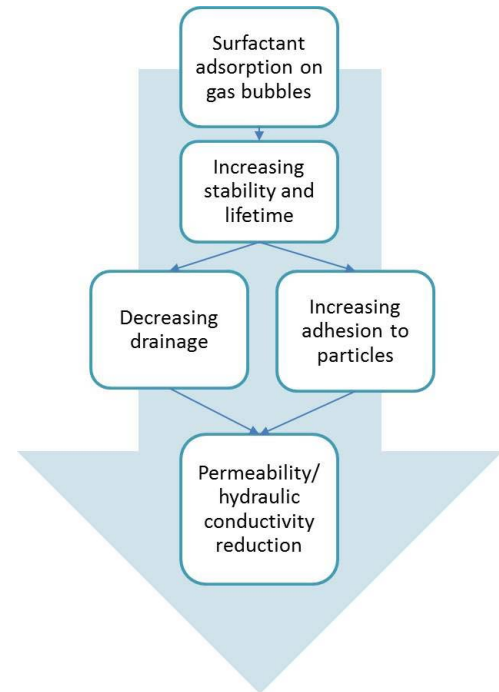


**Figure 6—Role of surfactants through a series of mechanisms that decrease permeability/hydraulic conductivity of porous media.**

Zhong et al., 2008). Consequently, the repulsive force between microbial cells and the liquid increases, which results in improved mobility or fluidity of the cells and which is driven by adhesive force dominating over hydrodynamic drag (Naclerio et al., 2009; Nikpay et al., 2015b). In other words, an increase in the surfactant concentration of the fluid reduces the attractive forces inside the pores, which results in the facilitation of the bacterial transportation mechanisms inside the porous media.

Stelmack et al. (1999) described the biodegradation of NAPL in an aqueous phase in which an increase in surfactant fluid concentration rendered bacteria unable to adhere to the NAPL or to additional solid surfaces. However, the mobility of the bacterial cells increased, which in turn extended the bioeffect in the porous medium, by promoting the mobility of individual cells. In another study demonstrated by Jackson et al. (1994) using the anionic surfactants, sodium dodecylbenzene sulfonate (DDBS), also noted an increase in bacterial transport within a saturated porous media with a concurrent reduction in the cellular aggregation and formation of microcolonies.

On the other hand, it has been suggested that surfactant adsorption on microbial cells could increase the cell's hydrophobicity making them easier to adhere to the solid surfaces (Yaminsky et al., 1996). By this means, the activity and environment of microorganisms can be affected (Van Loosdrecht et al., 1990) and lead to a reduction in the microbial population (Stelmack et al., 1999). The adverse effects of surfactants on bacterial population have been noted in the work of Colores et al. (2000), where it was found that an increase in surfactant concentration reduced the bacterial populations of

hydrocarbon-amended soil. Hrenovic and Ivankovic (2010) also showed that the population of phosphate-accumulating bacteria is remarkably decreased during contact with both anionic and cationic surfactants. A similar impact of surfactants on bacterial populations was found in the case of the long chain cationic agent quaternary ammonium compounds (QACs) used as a bactericide in healthcare products (McDonnell and Russell, 1999). These materials are known to contribute to disorganization and breakdown of the cell membranes (Salton, 1968). Additionally, surfactants are able to solubilize some of the toxic materials, which results in an increase of toxic substances while decreasing certain microbial diversity (Singh et al., 2007).

A biofilm assembly which produces a gel-type layer consisting of polysaccharides, protein and DNA called extracellular polymeric substances (EPS) can increase the stability of the biofilm structure on the surface and also provide other essentials required by the microbial community including nutrients, protection and communication (Flemming and Wingender, 2002; Stewart and Costerton, 2001). There is evidence suggesting that anionic surfactants have a tendency to bind with net positively charged protein at a concentration lower than CMC (Macakova, 2007). However, this binding between cationic groups and negatively charged protein is very close to the CMC (Goddard and Ananthapadmanabhan, 1993). The most interesting product of the research into this issue is that, the EPS tendency to bind with surfactants brings disorder in the biostructure by weakening the protective ability of the EPS as well as cell-to-cell communication or quorum signals (LaSarre and Federle, 2013). On the other hand, the adsorption mechanism of surfactants on the surface of the cell increases the repulsive forces, whereby weakening the interconnection of the biofilm matrix. Thus, the biofilm structure becomes unstable and vulnerable to hydraulic and mechanical changes which might occur in a porous media (Schreiberová et al., 2012).

The structural failure of biofilm during the development of the porous media is limited or suspended as a result of the detachment of energy sources due to an increase in clogging of the upper layer of the porous media (Rodgers et al., 2004) (Figure 7). Consequently, the destruction of the biofilm generates micro and macro organic particles which lead to pore clogging and a reduction in porous media permeability.

## Conclusion

The process of exfiltration from leaky sewers and subsequent percolation into the soil is still facing many unanswered questions concerning the clogging process. These include: the role of associated microbial diversities, organic chemicals particularly surfactants, soil properties, hydraulic conditions and transport modeling in porous media.

Where surfactant is present in wastewater at significant amounts there are a number of possible interactions between their molecules with solid, liquid and gas systems in the area of a sewer leak. Nevertheless, the lack of supportive experimental studies to corroborate the theoretical works discussed herein is a major problem.
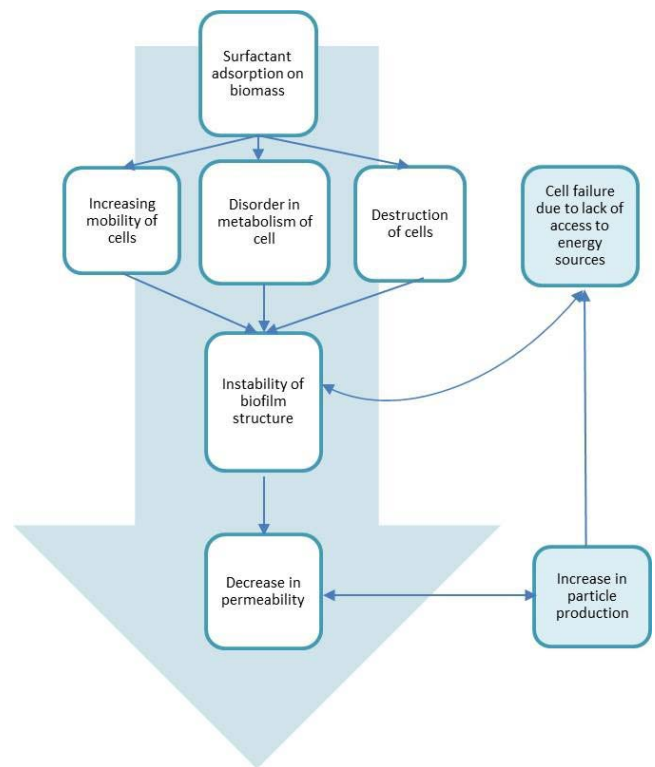


**Figure 7—Role of surfactants through mechanisms that decrease permeability of porous media.**

In the adsorption mechanism of surfactants on organic/inorganic particles, the change of electrostatic charges of the particles is the major controlling factor. Attractive or repulsive forces, respectively control the particles displacement by means of aggregation or desorption, leading to an alteration in permeability of the soil. Notably, the assessment of available literature on the adsorption process of surfactants to the soil's mineral surfaces shows that the adsorption kinetic can be effected by soil mineral composition. Likewise, adsorption of surfactants on gas bubbles, leading to an increase in their stability as well as their affinity for adsorption of particles, can effectively reduce the hydraulic conductivity and permeability of the soil matrix by delivering the particles to the pore spaces once the bubble breaks. Moreover, the surfactant adsorption at bacterial cells can change their transport mechanisms. There are several types of surfactants that induce toxic effects on biomass, causing destruction of the bacterial cells. This is the cause of instability in the biofilm structure and which generate particulate organic materials that exhibit a potential for further reducing permeability of the soil.

After the review of research articles, the evidence appears to point to this conclusion: that the major interactive mechanism leading to permeability reduction is the adsorption of surfactants at solid surfaces. However, there is still a lot to learn about the interaction potential of surfactants at interfacial areas and the formation of a stable aggregate as well as on the initial mixing condition of constituents in a system with various types of surfactants.

Finally, it is evident that soil clogging during wastewater percolation is a surface and inner surface process influenced by physical, chemical and biological agents that work synergistically or antagonistically in a complex system while striving to reach a state of equilibrium in the system.

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