An experimental study of contact erosion between a till core and coarser crest and filter materials

Pierre-Olivier Dionne & Jean-Marie Konrad
Department of Civil Engineering, Laval University, Québec City, Québec, Canada

GEOQuébec 2015
Challenges from North to South
Des défis du Nord au Sud

ABSTRACT
Contact erosion is an internal erosion process found in embankment dams and dikes which can lead to failure. It is defined as the pullout and dragging of fines from a base material through an adjacent coarser material under seepage parallel to the interface. This study intends to understand and to identify the mechanisms that control contact erosion with a well-graded base soil (till) combined with different filter materials. To study the erosion process, a new experimental setup has been developed. It was found that the grading of the base material as an impact on the initiation and progression of erosion as different mechanisms such as paving and clogging can develop to limit or even stop the erosion. A conceptualization of the erosion process depending on the grain size of both filter and base soils and on the hydraulic solicitation is proposed.

RÉSUMÉ
L'érosion de contact est un processus d'érosion interne retrouvé dans les barrages en remblai et les digues qui peut mener à la rupture de l'ouvrage. Elle se définit comme le détachement et l'entraînement au travers d'un sol grossier de particules d'un sol fin, sous l'effet d'une sollicitation hydraulique parallèle à l'interface entre les deux matériaux. Cette étude vise à comprendre et à identifier les processus contrôlant l'érosion de contact avec un sol fin étalé (till) combiné à différents matériaux grossiers. Pour étudier le processus d'érosion, un dispositif expérimental original a été développé. Il s'avère que l'étalement granulométrique du sol fin a un impact important sur l'initiation et la progression de l'érosion alors que different mécanismes comme le pavage et le colmatage peuvent se développer et limiter l'érosion, ou même l'arrêter. Une conceptualisation de l'évolution de l'érosion de contact en fonction de la dimension des particules du sol fin et du sol grossier ainsi que de la solicitation hydraulique est proposée.

1 INTRODUCTION

Contact erosion is initiated at the interface between two materials which properties (grain size) are greatly different when subjected to a parallel water flow. The flow through the coarser soil is much larger than the one in the fine layer. This induces a shear stress at the interface between the soils which, if important enough, can cause the erosion of the particles of the finer material. Once eroded the flow transport the particles through the pores of the filter layer. The initiation and progression of this internal erosion process may lead to important damages of a structure like earthfill and rockfill dams or dikes.

In a dam, contact erosion can take place, for example, during a *core overtopping* (i.e. the reservoir level is situated above the crest of the core but below the crest of the dam) as shown on figure 1 (water level B). The geometry encountered at the crest of the core (coarse-soil layer above a fine-soil layer with flow perpendicular to gravity) is the one considered in this paper. Core overtopping must not be confused with overtopping which is a completely different phenomenon.

Based on the definition of contact erosion given above, two conditions must be met so it can be initiated. First, the pores of the filter layer (coarse-soil) have to be sufficiently large to allow the passage of the fine particles through it. This condition directly refers to the well-known modern filter criteria (Sherard & Dunnigan, 1989; USBR, 2011) and is called the geometrical condition. Secondly, and only if the first condition is fulfilled, the hydraulic solicitation in the filter layer must be important enough to pullout and transport the fine soil particles. The latter is called the hydraulic condition.

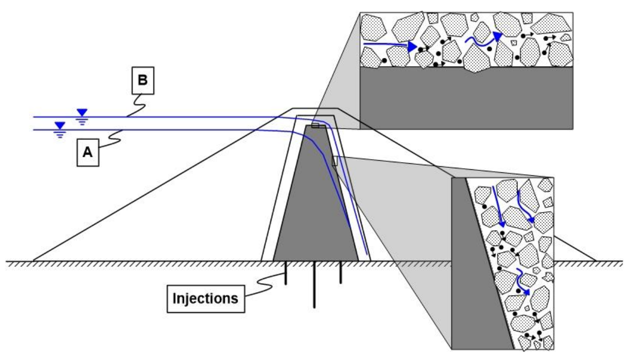


Figure 1. Representation of a core overtopping

Until recently, most of the work done on the subject has been concentrated on uniform sands or gravels base soils. These studies focussed on two aspects of contact erosion: the initiation of the process and its progression once it is triggered.

The global approach of the authors to predict the initiation (critical velocity) is based on an adaptation of the work done by Shields (1936) for the initiation of river bed erosion. It specifies that erosion cannot occur for a shear stress induced by the flow in the coarse material smaller than the threshold (critical) shear stress. These predictive models have been proposed by authors such as Brauns (1985b), Bezuijen et al. (1987), Hoffmans et al. (2008) and Béguin et al. (2012).

Some transport models have also been proposed for cohesionless uniform sands and gravels. Especially, those developed by Den Adel et al. (1994) and Wörman and Olafsdottir (1992) are particularly well adapted to contact erosion. Wörman (1996) also investigated briefly the relation between the gradation of the base soil and clogging of the filter. He found that only a small quantity of particles which can be block is sufficient to cause clogging.

More recently, Guidoux et al. (2010) and Béguin (2009) studied both well-graded and gap-graded fine soils such as clay, silts and sand-clay mixtures which can be influenced by inter-granular forces such as Van der Waals forces which cause cohesion. They added a correction to the model of Brauns to account for these forces and proposed the use of a threshold law to quantify erosion as function of the hydraulic solicitation. Béguin (2009) also studied the configuration with a base soil over a coarse soil.

This short review of the literature enables us to note that other than the study of Wörman (1996), no investigation of the influence of the grading of the base soil with cohesionless materials has been done. However the understanding of the the impact of the base soil grading is of primary importance tills, which are well-graded materials, are extensively used in the construction of modern dams.

Thus, the main objective of this paper is to characterize the influence of the base soil grading on the initiation and progression of contact erosion with experiments done with a well-graded till as the fine soil and different uniform sands and gravels materials as filters. More precisely, this study aims to characterize the mechanisms that can influence the development of contact erosion. Also, a verification of the applicability of the modern filter to contact erosion is made. Finally, a conceptual approach is proposed to clarify the different mechanisms which can affect erosion as a function of the filter and base soil particle-size and of the hydraulic solicitation.

2 EXPERIMENTAL SETUP & PROCEDURE

2.1 Experimental setup

To study the erosion process, an experimental setup (figure 2) has been developed. It consists of a rigid wall permeameter made of acrylic in which the investigated soils are placed with a horizontal interface. The permeameter is detailed on figure 3. Its inner dimensions are 0,62 m long per 0,153 m wide and 0,16 m high. What differentiates our setup from those developed by other authors is that the cell is equipped with many piezometers connected to pressure sensors. This allow the continuous recording of the pressure in the soil sample and the detection of clogging or preferential erosion.

A sedimentation tank is placed at the exit of the permeameter where the eroded particle settle. The water level in the sedimentation tank is kept above the top of the cell.

A vertical pressure of 60 kPa was applied during each test through a pressurization cell. This cell was placed on a balance to estimate volume variation of the sample during the tests. The pressure sensors, flowmeters, thermistor and balance are all connected to a data logger.

2.2 Experimental procedure

The till is compacted wet of the Proctor optimum near the optimal density. The base-soil layer thickness is 8 cm. Filter material is placed and only slightly compacted to avoid fracturing of the grains. The thickness of the filter layer is about 7 cm. The contact between the filter and base soils is 42 cm long.

During the experiments, a constant controlled flow is applied and increased stepwise. The duration of each step is 5 hours, at the exception of the last one which usually lasts longer. Inflow is measured from flowmeters connected to two water sources. As the hydraulic conductivity contrast between the coarse material and the finer one is very important (many orders of magnitude), most of the flow takes place in the filter layer. The mean filter flow velocity (v_{filter}) can then be estimated by dividing the inflow by the filter transversal area ($v_{filter}=Q/A_{filter}$). Therefore, the velocity is also increased stepwise as shown on figure 5. The increment of filter velocity vary from 0,003 to 0,005 m/s.

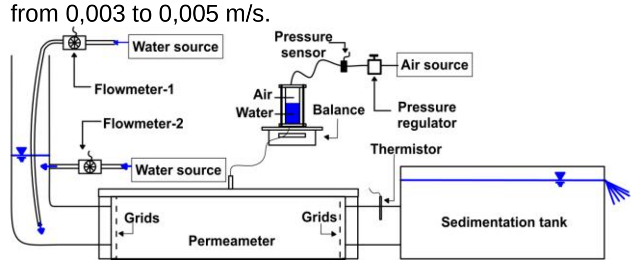


Figure 2. Representation of the experimental setup

Eroded particles are collected in the sedimentation tank placed at the end of the setup. These sediments are pumped away, dried and weighed a few times during each velocity step to quantify the progression of erosion. The experiment is stopped when excessive erosion happens or if the maximal capacity of the system is reached and the erosion is null. Water temperature is measured during the test.

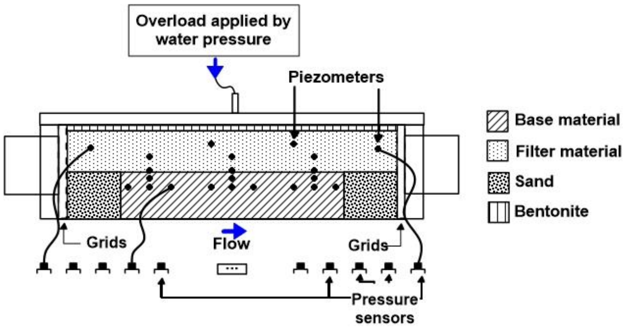


Figure 3. Detail of the permeameter

3 TESTED MATERIALS

The particle size distributions of the soils used for the experiments are presented on figure 4. The notation used in this paper for the particle size is D_{FX} and d_{BX}, respectively for the particle size of the filter and of the base material corresponding to X% passing in mass. The fine soil tested is a well-graded till (C_u=9.2, d_{B50}=0.17mm, d_{B85}=0.88mm). The filter materials are all uniform soils with D_{F50} ranging from 0.59 to 16.7mm and D_{F15} ranging from 0.27 to 14.8 mm. Their properties are presented at table 1. Prior to each test, the filter material is thoroughly washed to make sure that all the eroded particles come from the base layer.

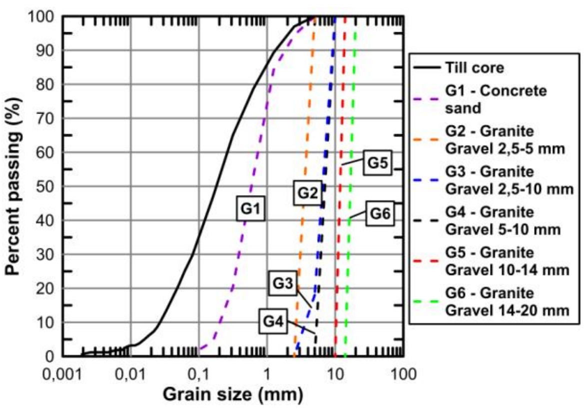


Figure 4. Particle-size distribution of the base and filter materials

The experimental program has been divided into two parts. The first one was dedicated to the verification of the applicability of the modern design filter criteria to the situation where the flow is parallel to an interface, i.e. where contact erosion can be initiated. It included tests with coarse soils G1 to G3. The second part was concentrated on the initiation and progression of contact erosion and includes the tests done with G4 to G6.

The filter ratios D_{F15}/d_{B85} (-) (Sherard et al., 1984) are also presented at table 1. The modern filter design criteria proposed by Sherard and Dunnigan (1989) and the USBR (2011) suggest that a ratio of D_{F15}/d_{B85} lower than 2.1 should be respected to ensure that no erosion occurs with the till. Only the coarse soil G1 respects this criterion.

Table 1. Coarse soils properties

	G1	G2	G3	G4	G5	G6
D_{F15} (mm)	0.27	2.8	4.5	5.6	10.5	14.8
D_{F50} (mm)	0.59	3.6	6.6	7.1	11.8	16.7
D_{F15}/d_{B85} (-)	0.3	3.2	5.1	6.4	11.9	16.8
C_u (-)	3.3	1.4	1.9	1.4	1.2	1.2

4 TYPICAL EXPERIMENTAL RESULTS

Typical experimental results of a test during which erosion was triggered are presented on figures 5 and 6. The transport rate (q) (kg/m/s) is null or negligible up to the fifth step of mean filter flow velocity (v_{filter}) (m/s) (see figure 5). At this initiation velocity ($v_{Finit.}$) (m/s) , the erosion is triggered and the transport rate then globally increases with increasing velocity. However, each time the velocity is incremented, the transport rate initially increases steeply then decreases with time. The drop can be as much as an order of magnitude over the step duration of 5 hours.

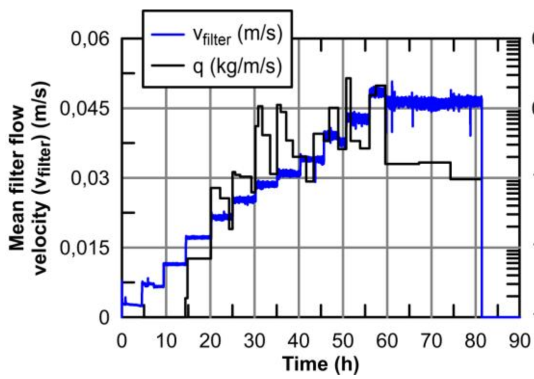


Figure 5. Typical results of a contact erosion test (G6 coarse material).

The eroded base soil collected in the outflow and the material at the contact at the end of the tests were subjected to a particle size analysis (figure 6). As the filter velocity increases during the experiments, the eroded material becomes coarser. Also, the base soil at the contact between the soils evolved during the experimentations. At the end of the tests, this material which is exposed to the hydraulic solicitation of the flow in the filter became coarser (figure 6). It can then be understood that the base soil exposed to the flow in the filter layer evolves progressively until it reaches the final state. Under this modified contact layer, the base soil did not show any change in gradation.

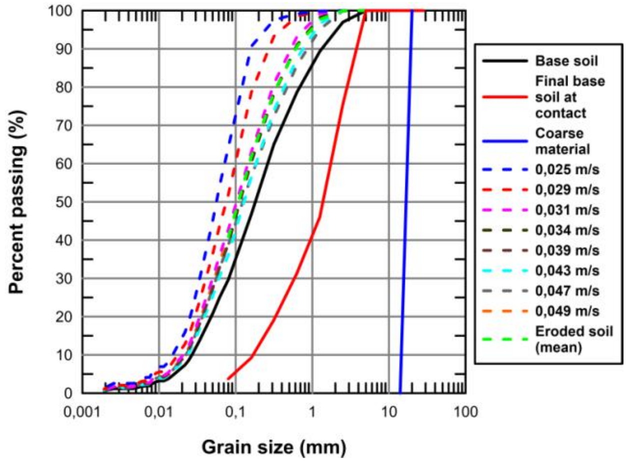


Figure 6. Particle size evolution of the base soil at the interface and of the eroded soil compared to the original base and filter materials.

5 ANALYSIS

The analysis of the tests presented in this section is divided into three parts. First, the geometric condition for stability of the till to erosion is presented. It is followed by an analysis of the initiation of erosion in order to establish the critical velocity. Finally, the progression of the erosion once it triggered is discussed. These elements will lead us to the suggestion of a conceptual approach for contact erosion.

5.1 Geometric condition for stability (no erosion)

For filter ratios $D_{F15}/d_{B85} \leq 5.1$, no erosion occurred during the experimental investigation. When compared to the modern filter design criteria proposed by Sherard and Dunnigan (1989) and the USBR (2011) a corresponding factor of safety of 2,4 is obtained (D_{F15MAX}=2,4 $D_{F15DESIGN}$). This latter value is in agreement with those obtained by Foster and Fell (2001) (D_{F15MAX}=1,6 to 2,5 $D_{F15DESIGN}$) in the context of concentrated leak erosion tests with soils having particle-size distributions similar to the till.

As these modern filter criteria are based on geometric considerations (i.e. the pores of the filter are not sufficiently large to allow the passage of the fine particles) it is normal to get similar results to those obtained by other authors with different erosion processes. Indeed, the filtration mechanism is the same no matter the type of erosion.

Moreover, it is important to specify that the hydraulic solicitations applied to the sample during these contact erosion tests where quite larger and applied longer than those expected during a core overtopping.

To avoid completely risks of contact erosion, the modern filter design criteria proposed by the above authors should be used. These criteria have a built-in factor of safety which is not excessive or too restrictive.

5.2 Initiation of contact erosion

Different methods are proposed in the literature to identify the critical (or threshold) velocity. What this research allowed us to understand is that while the criteria has small or no effect on the determination of the initiation velocity for a uniform soil, it is of primary importance for a well-graded soil.

Indeed, some definitions found in the literature concern the initiation of the process (i.e. the first particle eroded) (Brauns, 1985a) as the others are related to exploitation criteria (i.e. particle motion such that the integrity of the structure is threatened) (Bezuijen et al., 1987; Hoffmans et al., 2008; Istomina, 1957). For a uniform soil, these criteria almost refer to the same velocity as all the particles of the base soil are of the same size. Also these critical velocities represent the initiation of a continuous contact erosion process.

However, these criteria are not adapted to well-graded soils as they all refer to different velocities. Also, the latter does not necessary refers to a continuous erosion process as many mechanisms can stabilize the erosion process once it has been triggered. This mean that even for a velocity lower than the flow velocity needed to cause continuous erosion or the reach a given transport rate, an excessive but non-continuous erosion can happen. Accordingly great care must be given to the criterion chosen.

The determination criteria chosen for this research is a no erosion criteria such as the one proposed by Brauns (1985a). It can also be defined as the velocity step for which a subsequent small increment of the velocity will result in a non-negligible increase of the total eroded soil mass. As this velocity indicates the trigger of erosion and not the initiation of continuous erosion, it will be referred to as the “initiation velocity” ($v_{Finit.}$). The term “critical velocity” ($v_{Fcrit.}$) will refer to a continuous erosion process. The latter will develop only if the velocity is high enough in order to erode all particle size of the base soil. The values of initiation velocity determined for each test are presented at table 2, along with the D_{F15}/d_{B85} ratio and three predictive models for the critical velocity of base soils from the literature.

As mentioned before, the approach adopted by different authors for predicting the critical velocity was to adapt the Shields (1936) criterion (Eq.1) for open-channel flow to the situation of a two-layer porous media.

$$\psi = \tau/((\rho_s - \rho_w)\, g\, d_{B50}) \qquad [1]$$

Where ψ is the Shields number (-), ρ_s the volumetric mass of the base soil (kg/m^3), ρ_w the volumetric mass of water (kg/m^3) and g the gravitational acceleration (m/s^2). Brauns (1985b) was the first to adapt the Shields criterion (Eq. 2).

$$v_{Fcrit.} = 0{,}7 n_F((G_s-1) g d_{B50})^{1/2} \qquad [2]$$

Where n_F is the filter porosity (-) and G_s the relative density of the base soil (-). A little later, Bezuijen et al. (1987) proposed a similar relation (Eq.3)

$$v_{Fcrit.} = \kappa\, n_F(\psi(G_s-1) g d_{B50})^{1/2} \qquad [3]$$

Where κ is a coefficient (-). Béguin et al. (2012) used a similar approach by considering the stress induced at the interface equal to the average stress in the porous media (Bear, 1988; Wörman & Olafsdottir, 1992) (Eq 4)

$$\tau_{.} = n_F \, \rho_w \, g \, i \, / \, A_s \qquad [4]$$

Where i is the hydraulic gradient (-) and A_s the specific surface of the filter. The velocity can then be deduced from the hydraulic gradient.

Table 2. Initiation velocity (m/s) for each test compared with models from literature.

Coarse soil	D_{F15} / d_{B85}	$v_{Finit.}$	Brauns (1985b)	Bezuijen et al. (1987)	Shields (1936)
	-	cm/s	cm/s	cm/s	cm/s
G4	6.4	3.0 ±0.4	1.4	2.0	0.6
G5	11.9	2.6 ±0.1	1.4	2.3	0.8
G6	16.8	2.5 ±0.2	1.4	2.5	0.9
G6	16.8	2.0 ±0.2	1.4	2.5	0.9

As shown on table 2, these models developed with uniform base materials underestimate the measured initiation velocities. Only the model of Bezuijen et al. (1987) seems to give a good estimate of the threshold velocity, but keep in mind that his criterion is quite more permissive (exploitation criterion) than the one used in this study (initiation criterion). This study shows that the resistance to contact erosion is larger for well-graded soils when compared to uniform soils. Moreover, the initiation velocity is underestimated when using the average particle size distribution d_{B50} of these well-graded soils. Obviously d_{B50} is well adapted to uniform materials as all the particle almost have the same size. But for well-graded cohesionless materials, it seems that this parameter is less adapted as coarse particles play an important role in the erosion process as will be discussed in the next section.

The initiation velocity tends to increase with decreasing filter ratio D_{F15}/d_{B85}. This is probably due to some filtration effects induced by the narrowing of the pores as the filter ratio decreases.

5.3 Progression of erosion after initiation

As mentioned earlier, once triggered, contact erosion progresses as a function of the hydraulic solicitation and of time. The latter aspect is unique to well-graded soils as erosion of uniform base materials is, at first, independent of time.

Transport laws proposed by Den Adel et al. (1994) and Wörman and Olafsdottir (1992) were developed for uniform sands and gravels so they are not suitable to base materials such as the till studied. For well-graded fine soils, Guidoux et al. (2010) proposed the use of a classic trigger law. This approach is interesting but does not seem appropriate for well-graded soils as it is not time dependant. The parameters of the law will then be sensitive to the test duration. This has been confirmed with two tests of different duration.

This influence of time is due to two different mechanisms that takes place during the erosion process: paving and clogging. In the latter case, some conditions must although be met so it can develop.

5.3.1 Paving

Paving is the first phenomenon that develops to stabilize contact erosion. It consists in the sorting of the particule of the base material at the contact between the soils. The weakest particles (the lightest and smallest) are preferentially eroded, leaving in place the bigger and heavier particles. This progressively creates a coarse armor layer which protects the underlying soil and reduce the supply in fine particles. A conceptualization of sorting is presented at figure 7. It can be seen that as the velocity increases, the interface becomes coarser. Indeed, the higher the velocity, the larger is the diameter of the biggest erodible particle (figure 8). This agrees with the evolution of the particle-size distribution of the eroded material shown on figure 6. The results presented at figure 8 also indicates that the velocity needed to erode a specific grain size part of the base soil corresponds well to the model developed to predict the critical velocity of uniform soils.

To develop, the process of paving also takes time. For a constant flow, the quantity of erodible particles progressively decreases with time. This is reflected by the diminution of the transport rate for each velocity step. It can be expected that at some point, all the erodible particles will be eroded and that the erosion stops. To reactivate erosion, the velocity will then have to be increased.

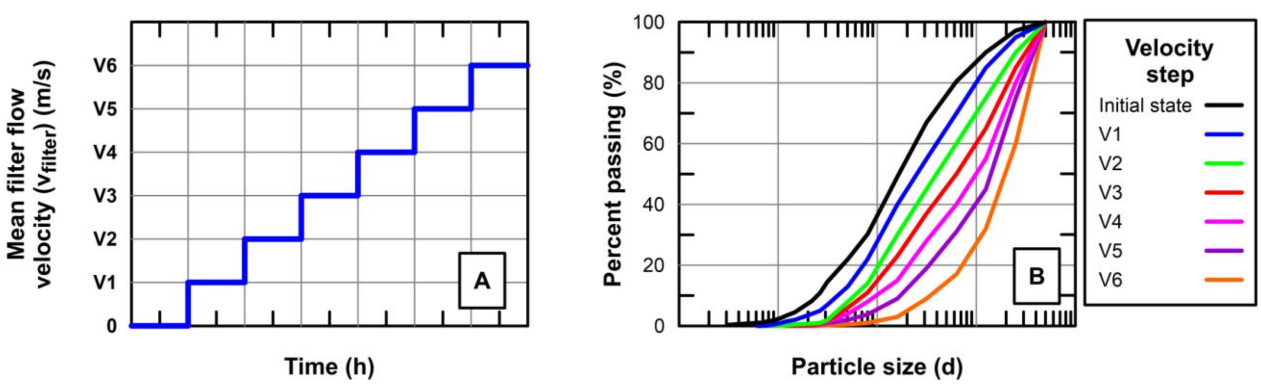


Figure 7. Conceptualization of the sorting process for a well graded soil (b) as it evolves with water velocity (a).

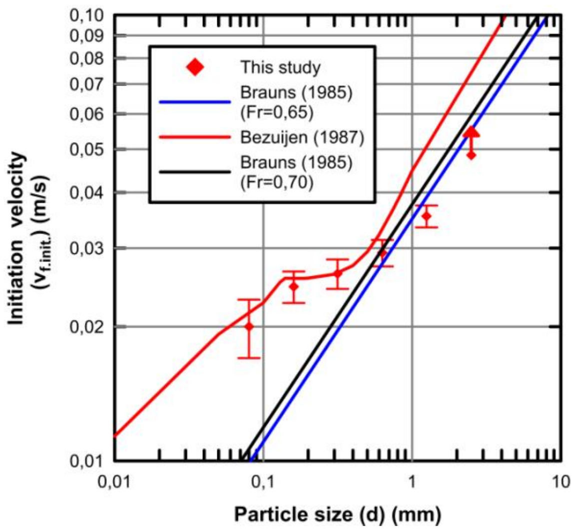


Figure 8. Measured velocity that causes the initiation of erosion for each particle size of the till.

This cessation of erosion may however take a long time because the flow at pore scale is not uniform (Beguin et al., 2013) and may fluctuate spatially causing erosion locally. The effect of time has been confirmed during the experimental program. The same test was run twice but with shorter step after the initiation of erosion. At the end of the test, the soil at the contact was coarser for the longer test.

The paving process that takes place during a step also likely impacts the intensity of the erosion of the next step. The modification of the base material at the contact is important since it increases its resistance to erosion and limits the quantity of base material that can be eroded with higher velocity. This should be true until the v_{Fcrit} at causes continuous erosion is reached. At this velocity, all the particles may be eroded, if the openings of the filter are large enough.

The importance of the paving in the erosion process is also reflected in the evolution of the filter ratio D_{F15}/d_{B85}. For example, for the test with the coarse soil G5, the final ratio was of 3.2 (lower than the 5.1 limit mentioned earlier) compared to an initial ratio of 12.2. Without any surprise, a clogging process took place during this test.

5.3.2 Clogging

Clogging is initiated when the velocity in the filter is high enough to pull out and transport particles with dimensions such that they are too large to progress through the filter layer. Thus, the filter velocity needed to cause clogging of the filter layer increases with the diameter of the filter particles. Therefore, the eroded mass of base soil before clogging increases with the filter ratio. Nevertheless, it is not the size of the grains of the coarse material that control clogging, but its opening size. Indeed, Sherard et al. (1984) specified that continuous erosion cannot occur for geometrical conditions specified by equation 5.

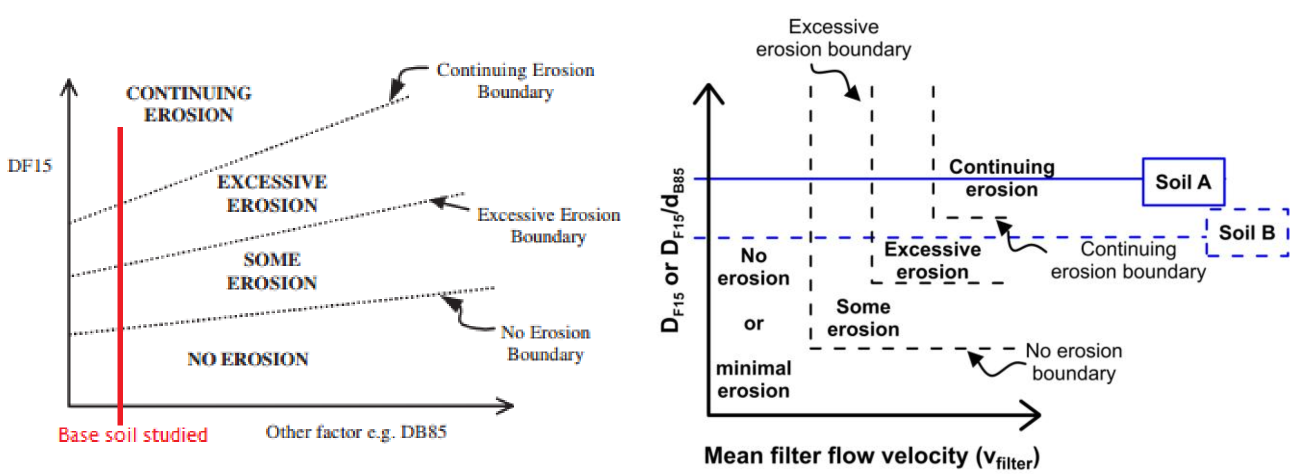
$$D_{F15}/9 > d_{B95} \qquad [5]$$

No test done in this experimental campaign respected this criterion and continuous erosion did not develop.

When clogging of the filter begins, an increase of the head loss occurs at the exact place where it happens. The monitoring with the piezometers allows to identify the location and the moment of its initiation and the corresponding flow velocity that generates it. Since clogging causes the sealing of the filter, the erosion intensity progressively decreases. For the tests with the coarse soils G4 and G5, once clogging occurred, the erosion practically stopped, even if the flow velocity was further increased.

Experimental results confirmed that only a small quantity of base material is needed to clog the filter layer.

..



a b

Figure 9. Conceptualization of the erosion boundaries as defined by Foster and Fell (2001) (a) adapted to contact erosion (b)

6 A CONCEPTUAL APPROACH OF CONTACT EROSION

The elements presented so far highlighted that the approaches existing to predict the threshold of contact erosion and to quantify the progression of erosion once it is initiated present some important shortcomings for cohesionless well-graded base soils. Thus, a new conceptual approach is proposed to account for the grading of the base soil. This simple approach present the advantage of being applicable to both uniform and well-graded materials.

The proposed conceptual model is an extension of the conceptual erosion boundaries developed by Foster and Fell (2001) which is presented on figure 9a. For a given base material, it specifies the particle size of the filter, which will lead to the different categories of erosion behavior presented in their paper. These categories refer to the eroded mass before the filter seals. For example, "Excessive erosion" refers to an erosion which is judged too important for the safety of the structure before erosion stops. "Continuous erosion" refers to a filter material too coarse so clogging or filtration cannot happen and the erosion cannot be stopped. As discussed earlier, both criteria defining the continuing and no erosion boundaries are well adapted to contact erosion. Thus, this model can be applied to our experiments.

However this conceptualization lacks one important aspect to contact erosion: the hydraulic solicitation. The experimental data have demonstrated that even if filter criteria are not met and erosion is possible, the flow velocity in the filter still has to be high enough to initiate erosion.

Therefore, to account for both criteria, we suggest to add the mean filter velocity as a third axis to the model of Foster and Fell (2001) (figure 9b). The different categories of erosion are now dependant of two conditions, which reflect more adequately the conditions needed for erosion to develop. This proposition relies on the hypothesis that erosion can be stopped by paving of the interface.

To adapt this conceptualization to contact erosion, we also have to modify a little the definitions of the erosion categories defined by Foster and Fell (2001). The categories now refer to the eroded mass before the interface stabilizes or before the filter seals.

As mentioned earlier, this conceptualization applies to both uniform and well-graded materials. The difference between these two soil classes is that the ranges between "no erosion" and "continuous erosion", both for filter flow velocity and filter particle size, will be smaller for a uniform base soil than for a well-graded one.

Furthermore, this conceptualization allows us to suggest an approach to quantify the erosion process for well graded materials (Figure 10). Also, this proposition is a good example of the application of the conceptualization (Figure 9b). It is suggested that as long as the filter velocity is below the critical velocity which allows continuous erosion the erosion is limited and is time independent. This means that there is a maximum erodible mass for a given velocity. Thus, this approach avoids the difficulties of the quantification due the history of solicitation and to time (progressive evolution of the interface). As velocity increases, two cases are possible, depending on the filter grains dimensions. First (soil A), if the continuous erosion boundary is not met (eq.5), a continuous erosion process takes place as soon as the filter velocity is high enough to erode all particle sizes which constitute the base soil. Second (soil B), if continuous erosion is not possible, the erosion stops when the filter velocity is high enough to erode particles that can clog the openings of the coarse material. After this velocity erosion is stopped or limited due to the clogging/sealing of the filter layer.

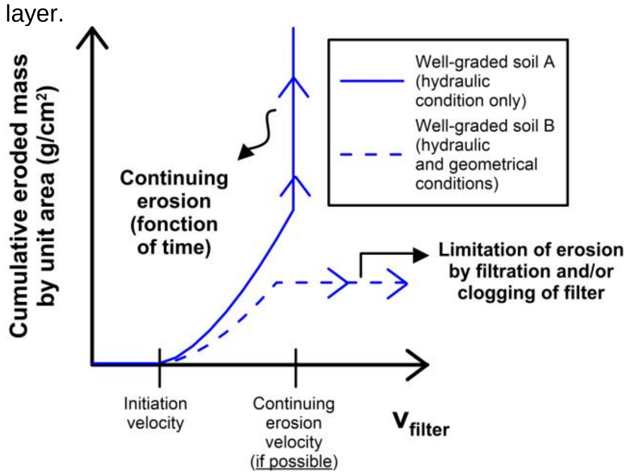


Figure 10. Proposition of an approach for well-graded soils and example of the application of the conceptualization proposed.

7 CONCLUSION

An experimental setup has been developed to study contact erosion with a well-graded base soil (till) and different uniform coarse soils. This setup allowed to identify and to characterize the mechanisms which control contact erosion. First the conditions for no erosion have been investigated. It has been proven that modern filter criteria are well adapted to contact erosion. Secondly, the threshold of erosion has been studied. Cohesionless well-graded soils have a higher resistance to erosion than uniform soils with the same d_{B50}. Thirdly, two mechanisms, paving and clogging, which may increase the resistance of well-graded fine soil have been described. Finally, a conceptualization of erosion limits for contact erosion was presented. This conceptualization illustrates the different mechanisms that can take place when a groundwater flow parallel to an interface between two different soils occurs.

ACKNOWLEDGEMENTS

The authors acknowledge the financial support of NSERC (Natural Sciences and Engineering Research Council of Canada) industrial research chair on the optimization of life cycle of rockfill dams. The authors also extend their appreciation to our industrial partners Hydro-Quebec, SNC-Lavalin, Qualitas, AECOM, WSP, and SRK consulting. The authors would like to thank François Gilbert for his contribution to the laboratory work involved in this study.

REFERENCES

Bear, J. (1988). *Dynamics of fluids in porous media*. New York: Dover.

Béguin, R. (2009). *Érosion de contact entre un filtre granulaire et divers sols fins, en présence d'un écoulement d'eau parallèle àl'interface*. Paper presented at the 19[ème] Congrès Français de Mécanique, Marseille.

Béguin, R., Faure, Y., Guidoux, C., & Philippe, P. (2012). Contact erosion. In S. Bonelli (Ed.), *Erosion of geomaterials*. London: ISTE.

Beguin, R., Philippe, P., & Faure, Y. (2013). Pore-Scale Flow Measurements at the Interface between a Sandy Layer and a Model Porous Medium: Application to Statistical Modeling of Contact Erosion. *Journal of Hydraulic Engineering, 139*(1), 1-11.

Bezuijen, A., Klein Breteler, M., & Bakker, K. (1987). Design criteria for placed block revetments and granular filters. *2de copedec, Beijing, China*.

Brauns, J. (1985a). Erosionsverhalten geschichteten Bodens bei horizontaler Durchstromung [in German]. *Wasserwirtschaft*(75), 448-453.

Brauns, J. (1985b). *Stability of layered granular soil under horizontal groundwater flow*. Paper presented at the 15th International Congress on Large Dams : transactions, Lausanne, Suisse.

Den Adel, H., Koenders, M. A., & Bakker, K. J. (1994). The analysis of relaxed criteria for erosion-control filters. *Canadian Geotechnical Journal, 31*(6), 829-840. doi: doi:10.1139/t94-100

Foster, M., & Fell, R. (2001). Assessing Embankment Dam Filters That Do Not Satisfy Design Criteria. *Journal of Geotechnical and Geoenvironmental Engineering, 127*(5), 398-407. doi: doi:10.1061/(ASCE)1090-0241(2001)127:5(398)

Guidoux, C., Faure, Y. H., Béguin, R., & Ho, C. C. (2010). Contact Erosion at the Interface between Granular Coarse Soil and Various Base Soils under Tangential Flow Condition. *Journal of Geotechnical and Geoenvironmental Engineering, 136*(5), 741-750. doi: doi:10.1061/(ASCE)GT.1943-5606.0000268

Hoffmans, G., den Adel, H., & Verheij, H. (2008). *Horizontal Granular Filters*. Paper presented at the ICSE-4 Tokyo 2008; Fourth International Conference on Scour and Erosion, Tokyo.

Istomina, V. S. (1957). *Soil Stability to Seepage [en Russe]*. Moscou.

Sherard, J., & Dunnigan, L. (1989). Critical Filters for Impervious Soils. *Journal of Geotechnical Engineering, 115*(7), 927-947. doi: doi:10.1061/(ASCE)0733-9410(1989)115:7(927)

Sherard, J., Dunnigan, L., & Talbot, J. (1984). Basic Properties of Sand and Gravel Filters. *Journal of Geotechnical Engineering, 110*(6), 684-700.

Shields, A. (1936). *Anwendung der Aehnlichkeitsmechanik und der Turbulenzforschung auf die Geschiebebewegung [Application of similarity mechanics and turbulence research on shear flow] (traduit de l'allemand).* (Thèse de doctorat), Berlin, Allemagne.

USBR. (2011). *Protective Filters*. (DS-13(5)-9). Washington, D.C.: United States Department of the Interior, United States Bureau of Reclamation (USBR).

Wörman, A. (1996). *Constitutive equation for filtration of well graded base soil with flow parallel to base/filter interface*. Paper presented at the Geofilters'96, Montréal, Québec.

Wörman, A., & Olafsdottir, R. (1992). Erosion in a granular medium interface. *Journal of Hydraulic Research, 30*(5), 639-655.