Assessing suffusion susceptibilities of core dam soils by statistical analysis

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RÉSUMÉ. *La suffusion est l'un des principaux processus d'érosion interne dans les ouvrages hydrauliques en terre et leurs sols de fondation ce qui peut accroitre le risque de rupture. L'objectif de cette étude est d'estimer la variabilité spatiale de sensibilité à la suffusion des sols constituant le noyau d'un barrage hydraulique zoné (noyau en moraine du Nord du Québec). La sensibilité à la suffusion des sols est évaluée avec l'indice de résistance à l'érosion I_α. L'approche utilisant l'indice de résistance à l'érosion se concentre sur la sensibilité du matériau en caractérisant le potentiel de perte d'une portion de particules fines. L'avantage de cette approche est le caractère intrinsèque de I_α. Une analyse statistique qui utilise plusieurs paramètres physiques est utilisée afin d'estimer la valeur de I_α. Ces paramètres, à savoir Finer KL issu de la courbe granulométrique complète, l'angle de frottement interne, la valeur au bleu de méthylène et le poids volumique sec peuvent être facilement mesurés en laboratoire ou in-situ. Ainsi I_α a pu être estimé tout le long de la coupe transversale du noyau du barrage. Les résultats indiquent que les sols sont très résistants à la suffusion et que la variabilité spatiale de I_α est relativement faible.*

ABSTRACT. *Suffusion is one of the main internal erosion processes in earth structures and their foundations which may increase their failure risk. The objective of this study is to assess suffusion susceptibilities of core soils (till from Northern Québec) used to build a particular zoned hydraulic embankment dam. The suffusion susceptibilities of the soils are evaluated based on the erosion resistance index I_α to suffusion. The erosion resistance index I_α approach focuses on the material susceptibility which is related to the potential for the soil to experience the loss of a portion of its finer fraction. The advantage of this approach is the intrinsic character of I_α. A statistical analysis using several soil parameters permits to estimate the value of I_α. These parameters, namely Finer KL issued from the full grain size distribution curve, the friction angle, the Blue Methylene value and the dry unit weight, can be easily measured in laboratory or in situ. Thanks to the statistical analysis, I_α has been predicted along the entire cross section of the dam core. The results indicate that the core soils are highly resistant to suffusion and that the spatial variability of I_α is fairly low.*

MOTS-CLÉS : *barrage hydraulique, analyse statistique, sensibilité à la suffusion, érosion interne, indice de résistance à l'érosion*

KEY WORDS: *embankment dam, statistical analysis, suffusion susceptibility, internal erosion, erosion resistance index*

1. Introduction

Internal erosion is one of the main causes of embankment dam failures [FOS 00]. Suffusion, as one important type of internal erosion, is a very complex process that under seepage flow, the fine solid particles can be detached, transported, for some of them blocked. Suffusion may result in an increase of permeability, greater seepage velocities, and potentially higher hydraulic gradients, possibly accelerating the rate of suffusion [ICO15]. The development of suffusion gives rise to a wide range of dam incidents including piping and sinkholes.

To characterize the initiation of suffusion, several grain size distribution criteria, confronting granular criteria and hydraulic criteria have been proposed [LI 08, MAR12]. However, the dependence of these criteria on loading paths and sample sizes limits their application at embankment dam scales. Recently, [MAR 11] proposed an energy approach to evaluate the erosion susceptibility of soils from highly erodible to highly resistant based on a loading and sample size independent parameter I_α, named erosion resistance index. In addition, statistical analyses [REG 11, LE 16] have been proposed to predict I_α based on easily-measured soil physical parameters which favors the application of the energy approach at the structure scales.

This study is interested in a particular embankment from Northern Quebec which is a large hydraulic structure founded on bedrock foundations. The dimensions of the dam are characterized by *PM*, *ecart* and *elevation* for longitudinal, transversal and vertical direction respectively (Figure 1). This is a zoned dam composed of a central impervious core (zone 1), a downstream filter (zone 2A), an upstream filter (zone 2B) and rockfill (zone 3A, 3B, 3C, 3D and 3E). The central impervious core is made of compacted low plasticity glacial till which is generally a well-graded soil (the maximum particle size is up to 300 mm).

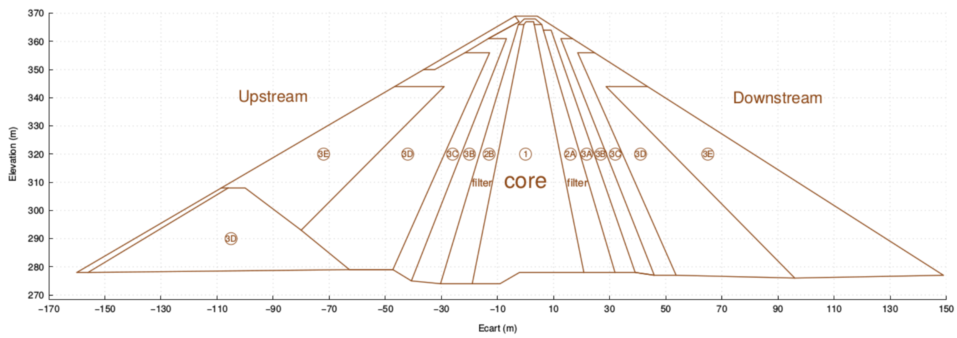

Figure 1. *Section view of the dam at PM=330 m*

The aim of this study is to evaluate the suffusion susceptibility of the core dam soils from a material point of view based on a statistical analysis. The kinetic of the suffusion process is not in the scope of this work.

2. Statistical analysis conducted by [LE 16]

[LE 16] conducted suffusion experiments for soils mixed from 4 widely-graded soils and 10 gap-graded soils to measure I_α. Meanwhile, relevant physical parameters of the soils were measured to predict I_α by statistical analysis. The measured physical parameters include dry unit weight γ_d, internal friction angle φ, Blue Methylene value V_{BS}, Gap ratio G_r for Gap-graded soil, d_5, d_{15}, d_{20}, d_{50}, d_{60}, d_{90} representing the diameters of 5%, 15%, 20%, 50%, 60% and 90% passing, respectively. In addition, two parameters are proposed based on the seminal work of Kenney and Lau [KEN 85], namely min *(H/F)* and *Finer KL*, to define the fine content of a soil, where min *(H/F)* is the minimum value of *H/F*, *Finer KL* is percentage of finer corresponding to min *(H/F)*. For non-plastic and widely-graded soils, the statistical analysis proposed to predict I_α for suffusion [LE 16] results in:

$$I_\alpha = -11.32 + 0.45\gamma_d + 0.20V_{BS} + 0.10\varphi + 0.06FinerKL \quad [1]$$

It is necessary to mention that this statistical approach is validated for the suffusion experiment of till material taken from the dam core sieved at D_{max} equals to 5 mm. The measured φ for the sieved till is 37°, the measured

V_{BS} is 0.7 mg/L. The measured I_α through the suffusion experiment equals 5.70, which is very close to the predicted value (5.72) based on the statistical analysis, Equation [1].

This statistical analysis approach is then applied to investigate the suffusion susceptibilities of many other soil samples issued from the same dam core.

Among the four soil parameters of Equation [1], two are considered constant throughout the core, namely V_{BS} and φ. The Blue Methylene value V_{BS} is estimated to the constant value of 0.49 mg/L (70% of the value measured in experiments based on soil sieved at 5 mm), and the internal friction angle is in turn estimated to 37° (same as that of the sieved soil). Since the till material of the dam core has a maximum grain size up to 300 mm, a particular effort is made to account for the influence of the coarse fraction of the grain size distribution on grain size based parameters and V_{BS}. On the other hand, it is important to assess spatial variability of the dry unit weight γ_d as well as *Finer KL* for the dam core soils based on the measured data from the dam.

3. Suffusion susceptibilities of the core dam soils

The determination of *Finer KL* requires the full grain size distribution of each soil sample, while the most available data lies within 0.08 mm - 80 mm. A detailed investigation highlighted that *Finer KL* for till materials used to build the dam is mainly defined by the coarse fraction of the grading. Yet, the cut-off D_{max} at 5 mm, 80 mm and 300 mm has no significant influence on *Finer KL*. Particularly, using D_{max} = 80 mm underestimates the average value of *Finer KL*, which nicely yields a conservative estimation of erosion resistance index I_α.

Based on specimens located within *PM* = 330 m ± 30 m whose grain size distributions are available, the contour of *Finer KL* is plotted and shown in Figure 2(a) based on D_{max} equals to 80 mm. The locations of the specimens in the figure are marked by the triangular points, the influence of the *PM* coordinates of the specimens are neglected. An interpolation function is used to handle duplicate (*ecart*, *elevation*) points to interpolate values for space between the triangular points. Areas with more data available are predicted more accurately than areas with less data available. The percentage of finer particles *Finer KL* lies within the range of 60% to 95%.

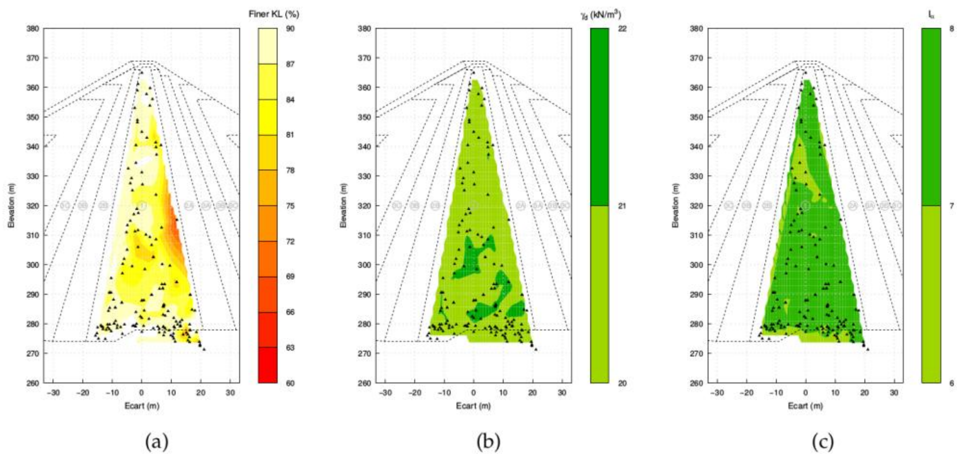

Figure 2. *(a) The spatial distribution of Finer KL based on D_{max} equal 80 mm. (b) Spatial distribution of dry unit weight γ_d in the dam core, (c) The spatial distribution of predicted erosion resistance index I_α for suffusion*

Similarly, the spatial distribution of dry unit weight γ_d of the core dam soils is shown in Figure 2(b). The till samples are characterized with dry unit weights within 20 to 22 kN/m^3 which indicates that the till samples are highly compacted during construction, especially at the lower central part of the core.

Based on the available values of dry unit weight, Blue Methylene value, internal friction angle and *Finer KL*, the erosion resistance index I_α can be predicted based on Equation [1]. The spatial distribution of I_α for suffusion is shown in Figure 2(c). The values of I_α obtained are within the range of 6.73 to 7.50 (I_α > 6). Therefore, according to the classification proposed by [MAR 16], the compacted till soils are highly resistant to suffusion.

It is worth stressing that the erosion resistance index for suffusion is obtained based on soil physical properties and construction procedures, without considering the positive contributions of high confining effective stresses due to the dam weight. In other words, the erosion resistance index is just a material parameter and it cannot be used by itself to describe the kinetic of the erosion process at real earth structure scale. Additional work should be done to evaluate the kinetic of the suffusion process over the dam's lifetime. Also, complementary tests could be conducted to evaluate the influence of the compatibility between the soil and the filter, for instance continuing erosion filter test [FOS 07].

4. Conclusions and perspectives

The paper investigates preliminarily dam safety in terms of internal erosion, based on the prediction of the spatial distribution of the erosion resistance index I_α within the dam core. From a material point of view and without considering the positive contribution of the mechanical confinement, the till is highly resistant to suffusion based on a statistical analysis approach. For dam safety, the hydraulic conductivity is also particularly important to estimate, since larger values of hydraulic conductivities may concentrate the flow and favor the internal erosion process. Further work should therefore focus on the prediction of the spatial distribution of the hydraulic conductivity within the dam core [SMI 11].

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