# A 2D numerical simulation to predict erosion resistance index in Phu Vinh-Quang Binh earth dam

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**Abstract**. The suffusion susceptibility of the soil samples is evaluated through an erosion resistance index. Thanks to existing statistical analyses, the erosion resistance index is estimated from several soil parameters. In actual exploitation, the soil properties with the input parameters related to the grain distribution of the soil… vary greatly from the original design value due to the influence of many factors. One of the factors is the inherent variability. Inherent soil variability is modelled as a random field. The usual problems used to assess the suffusion susceptibility may be not give accurate results or fully evaluate the actual working ability of the ground in each case. This is one of the reasons why dams are still eroded when they are put into use. The paper aims predict erosion resistance index of the earth dam using two-dimensional (2D) Stochastics random field, modelling the initial problem, considering the variability spatial of soil properties, using the assumption of a Normal random field of soil characteristics parameters. The paper shows the predicted results of the variability spatial of erosion resistance index of Phu Vinh dam-Vietnam. Furthermore, the paper also represents the happened probability of suffusion susceptibility at the different zones in the earth dam body.

**Keywords:** Internal erosion, suffusion susceptibility, erosion resistance index, numerical simulation, random field

## 1. Introduction

Internal erosion is one of the main causes of instabilities within hydraulic earth structures such as dams, dikes, or levees in [1]. According to reference [2], there are four types of internal erosion: concentrated leak erosion, backward erosion, contact erosion and suffusion. Concentrated leak erosion may occur through a crack or hydraulic fracture. Backward erosion mobilizes all the grains in regressive way (i.e., from the downstream part of earth structure to the upstream part) and includes backward erosion piping and global backward erosion. Contact erosion occurs where a coarse soil is in contact with a fine soil. The phenomenon of suffusion corresponds to the process of detachment and then transport of the finest particles within the porous network under seepage flow. The finer fraction eroded and leaving the coarse matrix of the soil will further modify the hydraulic conductivity and mechanical parameters of the soil. This suffusion process may result in an increase of hydraulic conductivity, seepage velocities and hydraulic gradients, possibly accelerating the rate of suffusion in [3]. The development of suffusion may cause the incidents of dam including piping and sinkholes.

In the literature, some researchers assume that suffusion is best represented by its initiation. Reference [4] take into account the main initiation conditions for suffusion include three components: material susceptibility, critical hydraulic load and critical stress condition. Several methods have been proposed to characterize the initiation of suffusion confronting material susceptibility criteria and hydraulic criteria in [5].

In the literature, the suffusion susceptibility characterization was mainly researched through grain size based on criteria for the initiation of process. Several criteria based on the study of grain size distribution have been proposed in literature in [6–7]. Reference [8] concluded that the most widely used methods based on particle size distribution are conservative. In the case, the geometrical conditions allow particle movements, the hydraulic conditions must be studied in [9]. The hydraulic loading on the grains is often described by three distinct parameters characterizing the hydraulic loading: the hydraulic gradient in [10], the hydraulic shear stress in [11] and the pore velocity in [12].

The critical values of these three quantities can then be used to characterize the suffusion initiation in [10, 13, 12]. However, suffusion tests carried out with permeameters of different sizes indicate that scale effects exist when measuring critical hydraulic criteria in [14].

Reference [14] showed the critical hydraulic gradient concept depends on the length of the seepage path. Moreover, the value of critical hydraulic gradient is affected significantly by the hydraulic loading history in [15]. Therefore, the suffusion susceptibility of dam scales cannot be evaluated by these approaches. Besides, Reference [16] focused on the estimation of whole suffusion process. Reference [17] proposed a new analysis based on the energy expended by the seepage flow which is a function of both the flow rate and the pressure gradient. Reference [18] performed many the suffusion tests to “final state”. This ‘final state’ is obtained towards the end of each test when the hydraulic conductivity is constant while the rate of erosion decreases. The expended energy $E_{flow}$ is the time integration of the instantaneous power dissipated by the water seepage for the test duration. For the same duration the cumulative eroded dry mass is determined, the erosion resistance index is expressed by:

$$I_{\alpha} = -\log\left(\frac{\text{Eroded dry mass}}{E_{\text{flow}}}\right)$$

Depending on the values of Iα index, Reference [19] proposed six categories of suffusion susceptibility from highly erodible to highly resistant (corresponding susceptibility categories: highly erodible for $I\alpha < 2$; erodible for $2 \le I\alpha < 3$; moderately erodible for $3 \le I\alpha < 4$; moderately resistant for $4 \le I\alpha < 5$; resistant for $5 \le I\alpha < 6$; and highly resistant for $I\alpha \ge 6$). Since the erosion resistance index Iα has been proven to be intrinsic, i.e., independent of the sample size in [20] and of the loading path in [15], at least at the laboratory scale, it may be applied to the structure scale of a dam. Reference [21] gave a method to assess the suffusion susceptibility of low permeability core soil in compacted dams based on construction data. They showed the one-dimensional (1D) spatial variability of all material parameters, in particular the hydraulic conductivity, the dry unit weight and the grain size distribution which affect the erosion resistance index. However, the suffusion susceptibility of earth dam body through the erosion resistance index needs to be assess the two-dimensional spatial variability. A two-dimensional contour map of the erosion resistance index would provide additional valuable information.

Reference [22] showed the disparate sources of uncertainties. One of the primary sources of geotechnical uncertainties is inherent soil variability. When we repeat the experiment many times at the same location, or at different locations, we always don't get the same result. To suppress or eliminate the influence of this source, we often use a very large number of samples. However, in practice, this implementation is not feasible because the experimental conditions do not allow, or the cost is too great. So, in the current calculation, there is always this random source. The objectives of the paper are to assess the suffusion susceptibility of earth dam considering variability spatial of soil properties. To tackle this objective, the contour map of 2D spatial variability of erosion resistance index of earth dam body is presented. This approach is based on two-dimensional Stochastics random field.

## 2. Description

### *2.1. Assessment of soil suffusion susceptibility*

Reference [18] performed many suffusion tests on 32 different soils to measure the value of erosion resistance index. For each test, the erosion resistance index $I_\alpha$ was measured at the 'final state' in [15]. Reference [18] showed the correlation equation between physical parameters and erosion resistance index Iα for all soils

$$I\alpha = -13.57+0.43\gamma_d + 0.18\varphi - 0.02\text{Finer KL} +0.49V_{BS} + 189.70k_i+3.82 \min(H/F)$$

$$+0.18P +0.28G_r +19.51d_5 +1.06d_{15} - 0.84d_{20}+0.81d_{50} -0.98 d_{60} -0.10d_{90} \qquad (1)$$

Where: dry unit weight $\gamma_d$, blue methylene value $V_{BS}$, internal friction angle φ, initial hydraulic conductivity $k_i$, minimum value of ratio H/F, percentage of finer fraction (based on Kenney and Lau's criteria) Finer KL, gap ratio $G_r$, $d_5$, $d_{15}$, $d_{20}$, $d_{50}$, $d_{60}$, $d_{90}$ (diameters of the 5%, 15%, 20%, 50%, 60%, 90% mass passing, respectively) and P (percentage of finer than 0.063mm)

For widely graded soils, the correlation of physical parameters with the erosion resistance index: (N=10, $R^2$ =0.99)

$$I\alpha = -26.34+0.43\gamma_d + 0.66\,\varphi - 0.16\,\text{Finer KL} + 1.15V_{BS} +0.37P +6.82d_5 -1.26d_{60} \qquad (2)$$

For gap-graded soils, the correlation of physical parameters with the erosion resistance index: (N=21, $R^2$=0.90)

$$I_\alpha = -37.62+0.67\,\gamma_d + 0.64\,\varphi + 0.09\,\text{Finer KL} - 0.03V_{BS} -1.43P + 0.63G_r + 0.76d_5 -0.97d_{60} +0.61d_{90} \quad (3)$$

### *2.2. Assessment of the relative suffusion potential*

The erosion resistance index ($I_\alpha$) is just a material parameter that characterizes the susceptibility of a given soil to suffusion. Hence, it cannot be interpreted as a 'security factor' to distinguish between 'probable occurrence of erosion' and 'no erosion' in [21], This distinction requires additionally the estimation of the hydraulic loading. The erosion resistance index is estimated from several soil parameters using 2D Stochastics random field. Therefore, the relative suffusion potential of the earth dam body may be characterized by the 2D contour map of the erosion resistance index $I_\alpha$. A contour map shows the suffusion susceptibility at locations in the homogeneous earth dam body through the erosion resistance index value $I_\alpha$. Cross-section of the earth dam will be pointed out with the spatial variability of $I_\alpha$, may be low of high resistance to suffusion. Two other maps show the 2D spatial variability of density, internal friction angle.

## **3. Numerical simulation**

### *3.1 A Case study in Vietnam-Phu Vinh earth dam*

An of cross-section of Phu Vinh earth dam body is illustrated in figure 1.

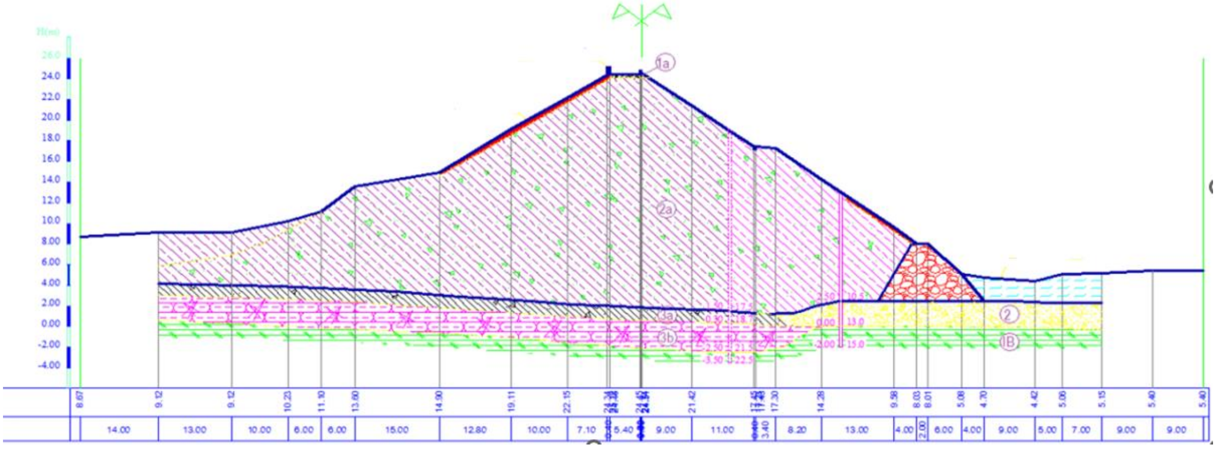

Figure 1. A cross-section of Phu Vinh earth dam

The data of dam include full grain size distributions with widely graded soil, dry unit weight, internal friction angle, initial hydraulic conductivity, and other parameters with the following assumed average values: dry unit weight $\gamma_d$ =16.9 kN/m$^3$; internal friction angle $\varphi$=13$^0$; percentage of fines (%) (based on Kenny &Lau, 1985 criterion) Finer KL=20%; the percentage finer than 0.063 mm P=24%; $d_5$ =0.1mm; $d_{60}$ =1mm. The suffusion susceptibility will be estimated through erosion resistance index.

*3.2 Simulation methodology*

In this paper, the soil characteristic parameters are modeled as a random field. These parameters are inputted in the model using the two-dimensional (2D) Stochastics random field which is researched in [23]. In a random finite element method, the spatial variability $\gamma$, $\varphi$, Finer KL, P, $d_5$, $d_{60}$ are simulated by a random field with assumed coefficient of variance (cov) cov = 0.05 and mapped onto the finite element mesh. This estimation is based on equation (2) since all soil samples are widely graded. Among the seven parameters of equation (2), the blue methylene value ($V_{BS}$) was considered constantly $V_{BS}$=0.5g/100g in the dam. The forecasting result of spatial variability of erosion resistance index with the contour map 2D is showed.

*3.3 Numerical results*

These results may be explained by soil spatial variability. According to reference [21], they show the one-dimensional spatial variability of erosion resistance index which erosion resistance index is estimated equally for one layer in the dam core. These results may be not given accurate results at different locations.  Based on two-dimensional random field model, the two-dimensional spatial variability of erosion resistance index is predicted in the whole dam.

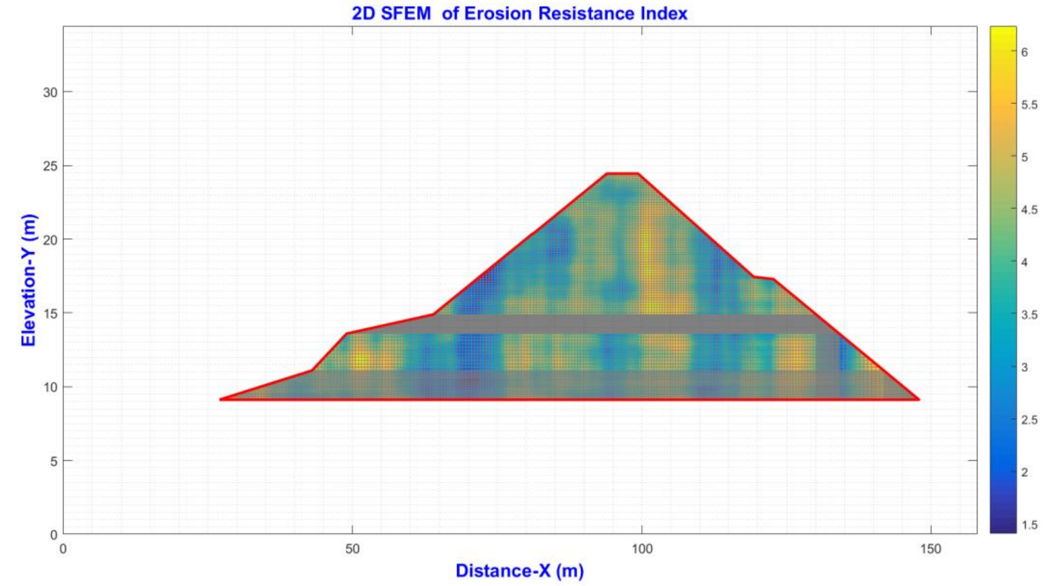

Figure 2. Contour map 2D of erosion resistance index

Figure 3 shows the histogram plot of erosion resistance index (blue color) with the normal distribution. The probability results are run from 500 random times with matlab code. The red curve is the probability of suffusion susceptibility of the earth dam. According to the classification of suffusion susceptibility of reference [19], the probability of suffusion susceptibility of the earth dam correspond to classification suffusion susceptibility shows in table 1. This table shows that 1% is the probability of highly erosion, 7% is erosion, 40% is moderately erodible, 40% is moderately resistant, 11% is resistant and 1% is highly resistant.

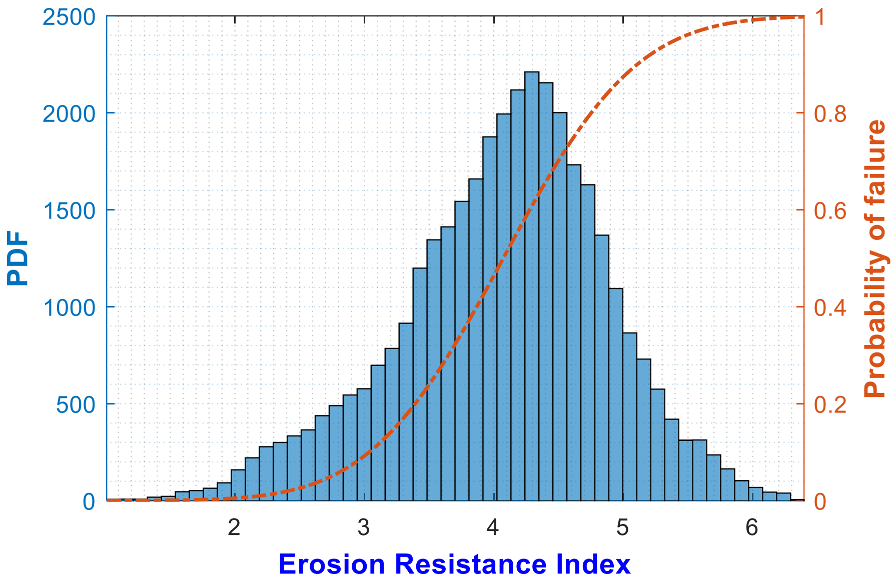

Figure 3. Histogram plot of erosion resistance index and probability of suffusion susceptibility

Table 1. Probability of classification of suffusion susceptibility

| Classification of suffusion susceptibility through the Iα based on [19] | Probability of suffusion susceptibility (forecasting) |
|---|---|
| highly erosion Iα < 2 | 1% |
| erosion 2 ≤ Iα < 3 | 7% |
| moderately erodible 3 ≤ Iα < 4 | 40% |
| moderately resistant 4 ≤ Iα < 5 | 40% |
| resistant 5 ≤ Iα < 6 | 11% |
| highly resistant Iα ≥ 6 | 1% |

## 4. Conclusions

The result of paper assesses the suffusion susceptibility of the dam body using two-dimensional random field considering soil spatial variability. With illustration of a numerical simulation, the predicted result of spatial variability of erosion resistance index is showed in a contour map 2D.

Furthermore, the probability of suffusion susceptibility is also forecasted correspond to classification of suffusion susceptibility. This result demonstrates that the actual state of practice would be to account for the two-dimensional spatial variability

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