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Assessing the Suffusion Susceptibility of the Homogeneous Earth Dam Body Considering Spatial Variability of Soil Properties

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Abstract: The suffusion susceptibility of the soil samples is evaluated through an erosion resistance index. The erosion resistance index is estimated from several soil parameters thanks to existing statistical analyses. In actual exploitation, the soil properties with the input parameters are 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 modeled as a random field. The usual problems used to assess the suffusion susceptibility maybe not give accurate results or fully evaluate the actual working ability of the ground in each case. That is one of the reasons why dams are still eroded when they are put into use. The paper aims to assess the suffusion susceptibility of the earth dam body using a two-dimensional (2D) Stochastics random field, modeling the initial problem, considering the variability spatial of soil properties, using the assumption of a Normal random field of soil characteristics parameters. The research goals predict the two-dimensional spatial variability of erosion resistance index of the dam body, probability of suffusion susceptibility, and the variability spatial of density and internal friction angle. An illustration of a numerical simulation of a homogeneous earth dam body is presented in this paper. The scientific novelty of the paper shows the predicted results of the two-dimensional spatial variability of erosion resistance index with a contour map and probability of suffusion susceptibility of the homogeneous earth dam body. Furthermore, the two-dimensional spatial variability maps of density and internal friction angle are also shown.

Keywords: internal erosion, suffusion susceptibility, numerical simulation, random field, earth dam.

考虑土壤性质的空间变异性评估均质土坝体的渗流敏感性

摘要：土壤样品的渗透敏感性通过抗侵蚀指数进行评估。由于现有的统计分析，侵蚀阻力指数是根据几个土壤参数估算的。在实际开采中，输入参数的土壤性质与土壤的颗粒分布有关。受多种因素影响，与原设计值相差较大。因素之一是固有的可变性。固有的土壤变异性被建模为随机场。用于评估渗透敏感性的常见问题可能无法给出准确的结果或无法充分评估每种情况下地面的实际工作能力。这也是大坝在投入使用时仍然受到侵蚀的原因之一。本文旨在使用二维（2D）随机随机场评估土坝体的渗透敏感性，对初始问题进行建模，考虑土壤特性的空间变异性，使用土壤特征参数的正态随机场假设. 研究目标预测坝体抗冲刷指数的二维空间变异性、渗透敏感性概率、密度和内摩擦角的空间变异性。本文介绍了均质土坝体的数值模拟说明。该论文的科学新颖性显示了均质土坝体的等值线图和渗流敏感性概率的抗侵蚀指数的二维空间变异性的预测结果。此外，还显示了密度和内摩擦角的二维空间变异图。

关键词：内蚀，渗流敏感性，数值模拟，随机场，土坝。

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1. Introduction

Internal erosion is one of the main causes of instabilities within hydraulic earth structures such as dams, dikes, or levees [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 regressive (i.e., from the downstream part of the earth structure to the upstream part). It includes backward erosion piping and global backward erosion. Contact erosion occurs when coarse soil is in contact with 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 soil's hydraulic conductivity and mechanical parameters. This suffusion process may increase hydraulic conductivity, seepage velocities, and hydraulic gradients. The development of suffusion may cause the incidents of the dam, including piping and sinkholes.

Some researchers assume that its initiation in the literature best represents suffusion.

In the literature, the suffusion susceptibility characterization was mainly researched through grain size based on criteria for the initiation of the process. Several criteria based on the study of grain size distribution have been proposed in the literature in [3].

The value of critical hydraulic gradient is affected significantly by the hydraulic loading history in [4]. Therefore, these approaches cannot evaluate the suffusion susceptibility of dam scales. Besides, Reference [5] focused on estimating the whole suffusion process. Reference [6] 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 [7] performed many of 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 erosion rate 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 I_{α} index, Reference [8] proposed six categories of suffusion susceptibility from highly erodible to highly resistant (corresponding susceptibility categories: highly erodible for $I\alpha < 2$; erodible for $2 \leq I\alpha < 3$; moderately erodible for $3 \leq I\alpha < 4$; moderately resistant for $4 \leq I\alpha < 5$; resistant for $5 \leq I\alpha < 6$; and highly resistant for $I\alpha \geq 6$). Since the erosion resistance index $I\alpha$ has been proven to be intrinsic, i.e., independent of the sample size in [9] and the loading path in [8], at least at the laboratory scale, it may be applied to the structure scale a dam. Reference [10] 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, particularly the hydraulic conductivity, the dry unit weight, and the grain size distribution, which affect the erosion resistance index. However, the suffusion susceptibility of the earth dam body through the erosion resistance index needs to be assessed the two-dimensional spatial variability. A two-dimensional contour map of the erosion resistance index would provide additional valuable information.

Reference [11] 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 different locations, we do not get the same result. To suppress or eliminate the influence of this source, we often use a very large number of samples. However, this implementation is not feasible in practice because the experimental conditions do not allow it, or the cost is too great. So, in the current calculation, there is always this unexpected source. The paper's objectives are to assess the suffusion susceptibility of earth dams considering the variability spatial of soil properties. For tackling this objective, the contour map of 2D spatial variability of the erosion resistance index of the earth dam body is presented. This approach is based on a two-dimensional Stochastics random field.

2. Description

2.1. Assessment of Soil Suffusion Susceptibility

Reference [7] performed many suffusion tests on 32 different soils to measure the value of the erosion resistance index. The erosion resistance index $I\alpha$ was measured at the 'final state' in [4] for each test. Statistical analysis was developed from studying several grain size-based criteria to predict the erosion resistance index $I\alpha$. With the same grain size distribution, the angularity of coarse fraction grains contributes to increasing the suffusion resistance. Thus, the shape parameter of grains plays an important role in suffusion susceptibility.

The physicochemical characteristics of the fluid and solid phases are also crucial, particularly in the case of cohesive soils. Reference [7] showed the correlation equation between physical parameters and erosion resistance index $I\alpha$ for all soils

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

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

where dry unit weight γ_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 Gr, 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)

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

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

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

The distinction between widely graded or gap-graded is based on the gap ratio in [7]. Gap graded soils are defined by $G_r > 1$. If this distinction is not obvious, the smallest value of Iα should be taken from the two values calculated by equations (2) and (3) to ensure a conservative estimation. Equation (2) may be viewed as a resilient tool that can be adapted to the available parameters of a given construction site. The erosion resistance index (Iα) 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' [10]. This distinction requires the estimation of the hydraulic loading additionally. The erosion resistance index is estimated from several soil parameters using a 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 Iα. A contour map shows the suffusion susceptibility at the homogeneous earth dam body locations through the erosion resistance index value Iα. A cross-section of the earth dam will be pointed out with the spatial variability of Iα, which may be low or high resistance to suffusion. Two other maps show the 2D spatial variability of density internal friction angle.

3. Numerical Simulation

3.1. A Numerical Example of Homogeneous Earth Dam Body

This section may be divided into subheadings. It should provide a concise and precise description of the experimental results, their interpretation, and the experimental conclusions are drawn.

An example of the cross-section of the homogeneous earth dam body is illustrated in fig. 1.

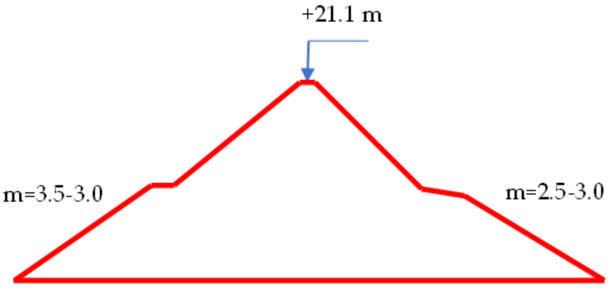

Fig. 1 A cross-section of homogeneous earth dam body

The earth dam has a homogeneous structure with assumed parameters: the height of the dam crest is +21.1 m, and the width of the dam crest is 6.0 m. The dam slope in upstream: m = 3.5 ÷ 3.0 and in downstream: m = 2.5 ÷ 3.0. The data of the 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 γ_d =17 kN/m^3; internal friction angle φ=27^0; percentage of fines (%) (based on Kenny and 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 the erosion resistance index.

3.2. Simulation Methodology

In this paper, the characteristic soil parameters are modeled as a random field. These parameters are inputted in the model using the two-dimensional (2D) Stochastics random field, researched in [11]. In a random finite element method, the spatial variability γ, φ, Finer KL, P, d_5, d_{60} are simulated by a random field with the 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 shown.

3.3. Numerical Results

3.3.1. Forecasting the Erosion Resistance Index and the Probability of Suffusion Susceptibility

The result of the erosion resistance index with contour map 2D is shown in fig. 2. Several locations in the map pointed out with a low resistance to suffusion (blue color). Some zones with yellow color represent the high resistance to suffusion. The predicted values of Iα lies within the range from 2 to more than 9. The map result shows the spatial variability of the erosion resistance index. These results may be explained by soil spatial variability. According to reference [10], 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 not be given accurate results at different locations. Based on the two-dimensional random field model, the two-dimensional spatial variability of the erosion resistance index is predicted in the whole dam.

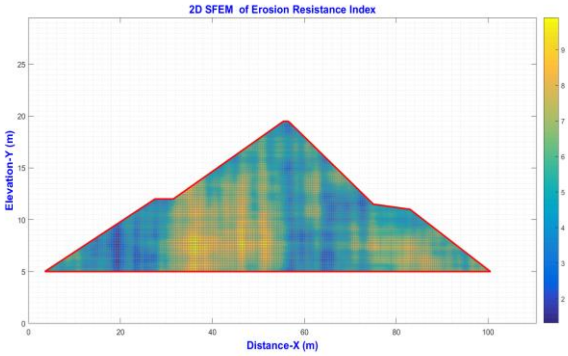

Fig. 2 Contour map 2D of erosion resistance index

Fig. 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 [8], the probability of suffusion susceptibility of the earth dam corresponds to the classification suffusion susceptibility shown in table 1. This table shows that 10% is the probability of high erosion, 8% is erosion, 14% is moderately erodible, 18% is moderately resistant, 22% is resistant, and 28% is highly resistant.

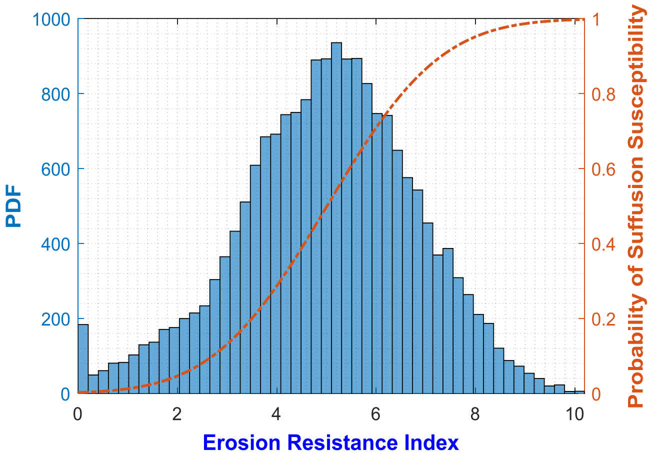

Fig. 3 Histogram plot of erosion resistance index and probability of failure

Table 1 Probability of classification of suffusion susceptibility

Classification of suffusion susceptibility through the Iα based on [11]	**Probability of suffusion susceptibility (forecasting)**
highly erosion $I\alpha < 2$	10%
erosion $2 \le I\alpha < 3$	8%
moderately erodible $3 \le I\alpha < 4$	14%
moderately resistant $4 \le I\alpha < 5$	18%
resistant $5 \le I\alpha < 6$	22%
highly resistant $I\alpha \ge 6$	28%

3.3.2 Spatial Variability of Density and Internal Friction Angle

To illustrate the spatial variability of soil parameters, two parameters in equation (2) significantly affect suffusion susceptibility: dry unit weight and internal friction angle. Fig. 4 and Fig. 5 show the spatial variability of dry unit weight and internal friction angle. The values of dry unit weight lie from 14 kN/m^3 to 22 kN/m^3, internal friction angle ranges from 22^0 to more than 34^0. Fig. 2 and fig. 5 indicate that φ has an important spatial influence on the erosion resistance index. With some locations with high internal friction angles, the erosion resistance index is large. Therefore, one way to improve the actual state of practice would be to account for the spatial variability (2D) of internal friction angle rather than taking a single value for the whole dam.

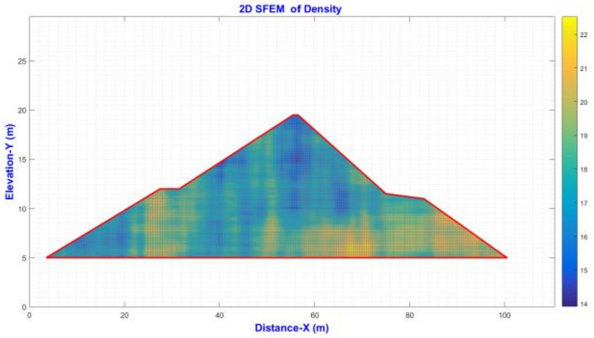

Fig. 4 Contour map 2D of density

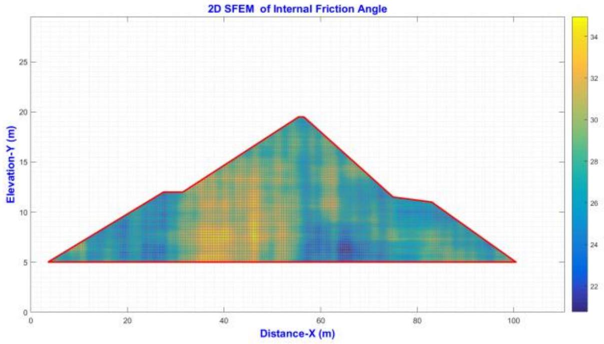

Fig.5 Contour map 2D of internal friction angle

4. Conclusion

The result of the paper assesses the suffusion susceptibility of the dam body using a two-dimensional random field considering soil spatial variability. With the illustration of a numerical simulation, a two-dimensional contour map shows the new predicted result of spatial variability of erosion resistance index. The different locations in the dam body have different predicted values of erosion resistance index. The predicted values of Iα lies within the range from 2 to more than 9. Several zones in the map pointed out with a low resistance to suffusion (blue color). The high resistance to suffusion at some zones with yellow color is also shown in the map. The new probability of suffusion susceptibility is also forecasted to correspond to the classification of suffusion susceptibility. The corresponding percents: 10% is the probability of high erosion, 8% is erosion, 14% is moderately erodible, 18% is moderately resistant, 22% is resistant, and 28% is highly resistant. This result demonstrates that the actual state of practice would account for the two-dimensional spatial variability. Furthermore, the new maps of dry unit weight and internal friction angle display the two-dimensional spatial variability of these parameters. The values of dry unit weight lie from 14 kN/m^3 to 22 kN/m^3, internal friction angle ranges from 22^0 to more than 34^0.

The study's limitations: The assumed coefficient of variance (cov) is assumed cov = 0.05, and the earth dam body is homogeneous. The research perspective simulates the spatial variability 2D with other cases of coefficient of variance.

4.1. Acknowledgments

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