EXAMINING THE IMPACT OF THE INTER-COARSE VOID RATIO (ICVR) ON SUFFUSION SUSCEPTIBILITY AND EROSION PREDICTION MODEL

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Abstract - Suffusion, one of the primary types of internal erosion, preferentially erodes fine grains inside the skeleton of coarse particles due to interstitial permeability. The occurrence of suffusion damages earthen dams and affects the living environment around these structures. To avoid the effect of suffusion, many previous studies in the literature have investigated physical parameters influencing suffusion triggers or predicted suffusion potential. Yet, the precise impact of physical parameters, namely the inter-coarse void ratio (ICVR), on suffusion susceptibility was not considered. Thus, the crucial objectives of this article are devoted to investigating the effects of ICVR on suffusion susceptibility. The results show that suffusion susceptibility decreases until the minimum value at ICVR is 1.1 before increasing again. In addition, models for erosion prediction were proposed based on two physical parameters: ICVR and grain size distribution, which are easily determined in the laboratory.

Key words - Erosion; Void ratio; Erosion resistance index; prediction model; Grain size distribution.

1. Introduction

Suffusion, one of the primary forms of internal erosion, selectively erodes the fine particles inside the skeleton of the coarse particles under the action of interstitial permeability [1-3]. Moreover, this is a complex phenomenon due to mobilized or filtered particles during the suffusion process, leading to considerable alterations in terms of porosity and modifications in the soil's hydraulic and mechanical properties [4-5].

Suffusion onset occurs depending on three conditions: (1) Eroded particle size must be small enough to pass through the constriction; (2) the number of fine particles in the voids of the coarse particles that do not participate in effective stress, and (3) the permeability flow must be continuous [2, 6-7]. Many previous studies in the literature have focused on predicting the internal erosion potential based on geometric criteria regarding particle size distribution [8-13]. Alternatively, using geometric criteria requires conservative [6, 14]. Additionally, many researchers have proposed expressions for the critical hydraulic gradient linked to the inception of internal erosion [12, 15-18].

Likewise, some authors have tried to investigate the physical parameters that influence erosion-internal potential. Kézdi [19] pointed out that several physical parameters of soil structure such as density, pore sizes, and resistance of soil play significant roles in controlling internal erosion. Marot et al [14] investigated the effect of three-grain shapes on suffusion susceptibility under similar conditions in terms of particle size distribution and hydraulic gradient and found that particle angularity can change the soil resistance and influence the separation of loose fine particles [14]. Wan and Fell [6]; Le et al [20] postulated that dry density affects the erosion potential with increased density resulting in increased soil resistance [6, 20]. Chang and Zhang [21] indicated that soils having fine content exceeding 35% with gap-graded or 20% with well-graded are referred to as stable soils due to floating coarse particles in the fine-grained matrix. Alternatively, Taha et al [22] studied the impacts of fine content on the mechanical properties of gap-graded soil based on the discrete element method and found that the fine-critical content contained within the void size between coarse particles is not bear effective stress. In addition, Kenny and Lau [9] suggested that soil resistance is related to fine content and the pore sizes of coarser particles. Thevanayagam and Mohan [23] addressed the void size of coarse particles by ICVR (e_c) based on solid unit weight, dry density, and fine content at the specimen's scale. Recently, few studies have focused on the effect of coarse grain porosity on erosion potential [24]. However, the above studies have not clearly shown the extent of this coarse-grained pore influence, especially on the effects of ICVR on suffusion susceptibility.

Furthermore, seepage-induced eroded mass, variation of hydraulic conductivity, and observation of piping are commonly used to determine internal instability [21]. After that, some studies have quantified suffusion susceptibility based on the erosion resistance (ER) index [25-28]. Recently, Marot et al [28] proposed an adoption that addressed erosion susceptibility depending on the value of the ER index (I_α) thanks to the cumulative eroded fines and the cumulative expended energy (E_{flow}). However, since earth structures are typically quite large, numerous tests are required to determine suffusion susceptibility, making it challenging to characterize. This difficulty suggests an interest in predicted expression in terms of the ER index based on physical parameters to optimize suffusion susceptibility characterization [20, 25, 29]. Yet, the equations of the aforementioned authors used many physical parameters and a few physical parameters are difficult to measure.

The crucial objectives of this article are devoted to investigating the effects of ICVR on suffusion susceptibility based on the experiment dataset collected from Le [20] and our accommodation suffusion tests [30]. Furthermore, we propose an estimation of the ER index using two easily measurable physical parameters (ICVR and particle distribution curving), which are easily obtained through laboratory testing.

2. Physical parameters

ICVR (e_c): The overall porosity factor is the ratio between the pore volume and the volume of soil particles in a soil sample. This factor plays a special role in measuring the strength of the soil structure. The study of Thevanayagam [23] showed that the overall void ratio does not fully describe the porosity density of the soil structure. Therefore, they defined one more category as the void ratio of the coarser grain fraction (e_c). This parameter is calculated through the formula thanks to overall porosity and fine content as follows:

$$e_c = \frac{e + f_f}{1 - f_f} \tag{1}$$

$$e = \frac{\gamma_h}{\gamma_k} - 1 \tag{2}$$

where: e is overall porosity; f_f is fine content; γ_h is particle density; γ_k is dry density.

According to Tran [31], it is confirmed that the transport capacity of fine particles through the intergranular voids can be related to the void ratio between the coarse particles. It can be concluded that typical for the voids of soil is e_c. From Equation (1), it is found that as the fine content and the overall porosity coefficient increase, the e_c increases. This means that the voids of the coarse particles formed increase. In addition, the above Equations show that the denser the soil (the greater the dry density), the lower the e_c decreases. Meanwhile, dry density and fine content are almost the crucial parameters influencing the ER index [20]. Therefore, it is considered to use e_c, because it represents dry density and fine content, as a proxy for soil porosity to assess the impact on the degree of erosion as well as to correlate it with the ER index I_α.

Table 1. *Physical parameters that govern the ER index [20, 30]*

Specimen	ERI ($I\alpha$)	Dry density (kN/m^3)	Finer KL (%)	min (H/F)	d_{20} (mm)	d_{50} (mm)	d_{60} (mm)	e_c
1-T-1	3.47	16.43	23.00	0.13	0.45	2.97	3.27	1.09
4-T	3.50	16.13	16.50	0.09	2.08	3.12	3.35	0.97
5-T	3.89	17.00	25.00	0.00	0.15	4.12	4.55	1.08
6-T	3.64	17.00	25.00	0.12	0.39	2.92	3.25	1.08
B-q	3.28	17.39	25.00	0.04	0.26	2.92	3.25	1.03
B-i	3.25	17.39	25.00	0.04	0.26	2.92	3.25	1.03
B-90	3.36	17.39	25.00	0.04	0.26	2.92	3.25	1.03
C	2.73	17.39	27.50	0.03	0.25	2.86	3.22	1.10
DR-A	4.49	17.87	20.00	0.11	0.25	1.56	1.69	0.85
DR-B	3.02	16.00	25.00	0.00	0.15	2.41	2.71	1.21
DR-C	2.59	16.00	25.00	0.00	0.15	2.99	3.67	1.21
G3-11	2.90	16.00	25.00	0.00	0.15	2.92	3.25	1.21
G3-13	3.47	16.00	15.00	0.00	2.13	3.15	3.36	0.95
G3-14	3.98	16.00	20.00	0.00	0.25	3.05	3.31	1.07
A	4.30	17.39	15.00	0.04	2.13	3.15	3.36	0.79
B	3.77	17.39	25.00	0.04	0.26	2.92	3.25	1.03
3-T1	4.72	17.00	51.84	0.45	0.17	0.54	0.89	2.24
3-T2	3.95	15.50	51.84	0.45	0.17	0.54	0.89	2.55
R1	5.13	17.39	15.26	0.59	0.63	2.67	3.03	0.80
R2-90	2.83	17.39	25.04	0.20	0.26	2.59	3.01	1.03
R2-97	3.41	18.74	25.04	0.20	0.26	2.59	3.01	0.89
CH-5	4.71	16.54	60.01	0.41	0.26	0.55	0.75	3.01
CH-10	5.49	18.90	40.61	0.44	0.37	1.38	3.18	1.36
CD	5.70	19.14	76.46	0.11	0.04	0.14	0.18	4.88
R3	4.34	18.66	25.00	0.20	0.25	2.59	3.01	0.90
R4	4.21	18.66	20.00	0.24	0.33	2.75	3.13	0.78
R5	4.30	18.66	15.00	0.29	1.33	2.88	3.24	0.68

Grain size distribution (GSD): Numerous prior studies have established that multiple grading curve parameters impact the extent of erosion. Specifically, given parameters that represent GSD significantly influence the ER index, including the fine particle content calculated based on FinerKL [15], particle distribution by the minimum value $(H/F)_{min}$ [9], and the grain diameter values at 20% (d_{20}), 50% (d_{50}), and 60% (d_{60}) [20].

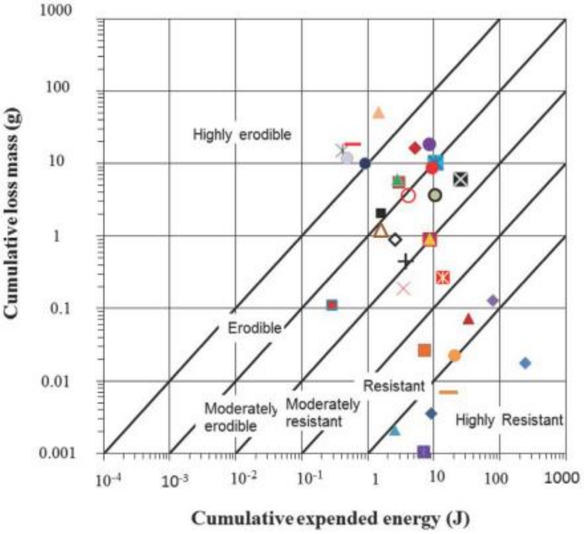

Figure 1. *Suffusion classification of soils [28]*

ER index (I_α): From the experimental results, Marot et al [28] exhibited a formula for determining the ER index based on the energy of seepage flow (E_{flow}) and eroded dry particles. ER index was determined as follows [28].

$$I_\alpha = -log\left(\frac{Accumulative\ eroded\ dry\ particles}{E_{flow}}\right) \tag{3}$$

The ER index's value allows for confirming the degree of erosion. The erosion susceptibility is divided into six levels: high erosion, erosion, light erosion, light resistance, resistance, and high resistance, in the range of ER index values from 2 to 6, as shown in Figure 1.

3. Results and discussion

3.1. Effect of ICVR on ER index

Soil structure is formed from soil particles and alternately arranged from particles of different sizes. This arrangement creates voids containing gas and water. The structure of the soil is categorized into two types: coarse and fine particles, as described by Chang and Zhang [21] and Kenny and Law [9]. It is conceivable that coarse particles act as skeletons to hold soil texture and vary in size for voids to be formed. Thus, they significantly affect the movement of smaller grains through the constrictions formed by coarse particles.

As mentioned, the ICVR e_c allows for describing the intergranular voids that form the main skeleton of the coarser grains. In addition, we propose to depict the fine particle part based on the diameter d_{20}. Figure 2 shows the ER index versus ICVR e_c and d_{20} for the 27 tested soil samples. The physical parameters of these soil samples are detailed in Table 1.

The results of Figure 2 make it challenging to establish a linear relationship between the ICVR e_c and the ER index. Nevertheless, the findings exhibited two distinct patterns at the e_c-value threshold of 1.1. Specifically, the index of ER increases when e_c is on the right side of 1.1 and decreases when e_c is on the left side of 1.1. This occurrence may be accounted for by the fact that when the e_c value is below 1.1 the pore sizes among larger particles decrease, impeding the displacement of smaller particles from within the pores. Conversely, when e_c is greater than 1.1; the size of the pores between coarse particles increases, thereby enhancing the soil erosion resistance caused by the buoyancy of coarse particles within the fine-grain structure.

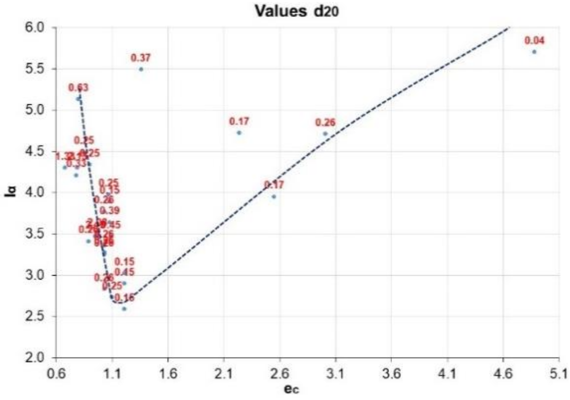

Figure 2. *ER index versus ICVR (e_c) and d_{20}*

3.2. Regression analysis

Nonlinear regression analysis allows the observation of data modeled as a function describing the relationship between the dependent and independent variables. In this way, in the erosion prediction model, we use this analysis to analyze the correlation between the ER index I_α and ICVR e_c.

The coarse grain voids are described through ICVR e_c. In other words, e_c is a representation of the voids created by the coarse particles. Therefore, e_c is used to analyze the correlation with ER index I_α. The analysis results from Figure 2 can not provide a specific erosion prediction model by e_c. The above analysis shows that the relationship of I_α and e_c is divided into two trends, the value of I_α tends to decrease gradually with $e_c < 1.1$ and increase when e_c is higher than or equal to 1.1. By analyzing these trends, the study proposed correlations between the ER index and parameters with two different trends of e_c.

The construction of erosion prediction formulas I_α through physical parameters that are easy to determine in the laboratory. These forecasting formulas were divided into two equations based on ICVR value e_c at 1.1. The predicted model utilized physical parameters listed in Table 1 to establish a correlation with ER index I_α. Whereas, d_{20} and e_c represented the fine and coarse fractions used in the analytical model, respectively. The ratio $(H/F)_{min}$, as Kenny and Law [9] findings, reflects the minimum value of the ratio of fine to coarse particles in the soil sample and has an impact on fine-grained erosion that should be used in the analytical model. d_{50} and d_{60} represented medium particle fraction of soil.

Based on the selected physical parameters, equations 4 and 5 are the new correlations which are determined using formula functions through a multivariable linear regression algorithm by XLSTAT software.

For soils with $e_c < 1.1$: (N= 18)

$$I_\alpha = 6.90 + 2.39(\frac{H}{F})_{min} - 0.66d_{20} + 7.26d_{50} - 6.37d_{60} - 3.66e_c$$

$$(R^2 = 0.80;\ p\text{-value} = 0.0008) \qquad (4)$$

For soils with $e_c \geq 1.1$: (N= 9)

$$I_\alpha = 5.62 - 3.70\left(\frac{H}{F}\right)_{min} + 3.33d_{20} - 2.54d_{50} + 1.13d_{60} + 0.09e_c$$

$$(R^2 = 0.95;\ p\text{-value} = 0.034) \qquad (5)$$

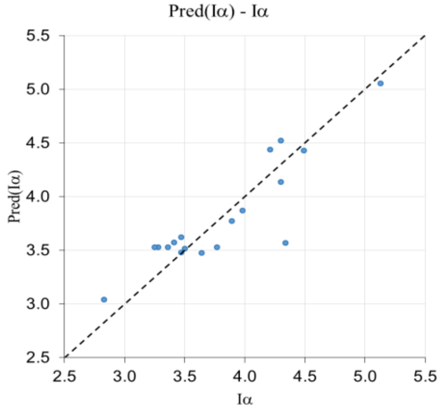

Figure 3. *Estimated value (Pred(I_α)) versus actual value (I_α) of soils with $e_c < 1.1$*

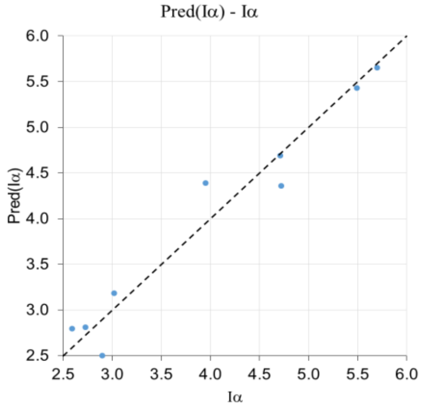

Figure 4. *Estimated value (Pred(I_α)) versus actual value (I_α) of soils with $e_c \geq 1.1$*

From Equations (4) and (5), the coefficient of determination R^2 in the range of 0.8 to 1.0 showed that the two models are well-defined [32]. On the other hand, both correlation models gave a p-value < 0.05, which explains that the overview of the predictive models is consistent with a confidence level of 95%. In addition, the estimated value compared with the actual value of I_α of the two soils tends to be different, as shown in Figures 3 and 4.

4. Conclusion

This study shows that the influence of the void ratio on erosion needs to be considered, especially the void ratio between coarse particles. Analyzing experimental data from previous studies revealed two contrasting trends. The ERI value decreased when $e_c < 1.1$ and increased when $e_c \geq 1.1$.

A new erosion prediction model was proposed based on the ERI index and its correlation with the void ratio of the coarse fraction and physical parameters including diameters passing through 20%, 50%, and 60%, as well as the minimum ratio (H/F), which can be easily determined in the laboratory. Multiple regression algorithms were used to create these models, which were confirmed to be accurate and reliable.

Compared to previous studies, the model, that can be quickly determined, has been simplified by removing physically uncertain parameters. This allows managers to quickly assess the degree of soil erosion in dams with reasonable accuracy based on proposed models and take adaptive measures to increase their safety.

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