Particle Shape Effect on Internal Instability of Cohesionless Soils

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ABSTRACT

Fine grains movement may occur within the pores of the adjacent soil layer or within the network of the same layer known as suffusion. Soil particle shape could influence pore geometry, pore size distribution, and transport of finer fraction; however, there is not sufficient knowledge on the effect of grain shape on internal erosion. In this study, the suffusion tests were performed on the samples with three types of particle size distribution curves and containing the particles with five different grain shapes to evaluate the effect of particle shape on the internal stability. Particle shape was assessed in terms of three features including sphericity, roundness, and roughness. The test was carried out in a plexiglas under a multistage hydraulic gradient and downward seepage flow. Results of suffusion tests showed that grain morphology influences washed out fine grains, mass loss rates, mass loss observed in plexiglas sidewall, and the percentage of mass loss increases with respect to particle sphericity and roundness. Furthermore, samples with the same gradation and different grain shapes were found to have different levels of internal stability/ instability.

Keywords: *Internal Instability, Suffusion, Particle Shape, Sphericity, Roundness.*

1- INTRODUCTION

All soils have a coarser fraction and a finer fraction creating the soil skeleton. If finer particles can move freely through pores between larger particles, that fabric is an internally unstable grading (Kenney and Lau 1985). Internal instability is a mode of internal erosion that causes the most common embankment dams failure (ICOLD 2015).

In the evolution of internal erosion and suffusion, the physical properties of the soil structure (geometrical criteria) and hydrodynamic conditions (hydro-mechanical criteria) are important. Factors controlling soil structure are particle size distribution (PSD), particle morphology, density, porosity, and constriction size distribution (CSD). Further, effective factors in hydrodynamic conditions include seepage velocity, hydraulic gradient, seepage direction, effective surcharge or confinement stresses, and seepage duration (Kezdi 1979; Wan and Fell 2008; Zhong et al. 2018).

Geometrical criteria can be categorized into two general groups. Most of the proposed methods in the first group are directly or indirectly dependent upon shape or slope of grain size distribution curve and investigates the possibility of filtering finer portion by coarser one in the soil (self-filtering) (Chapuis 1992; Chapuis and Saucier 2019; Shen et al. 2018; Wan and Fell 2008). Some of the available geometrical criteria for internal stability are presented in Table 1.

Table 1- Summary of available geometrical criteria for internal stability

References	*Criteria*		*Definition*
Istomina (1957)	*$Cu \leq 10$: internally stable* *$10 \leq Cu \leq 20$: transition zone* *$Cu \geq 20$: internally unstable*		*C_U: uniformity coefficient*
Kezdi (1979)	*$(d^c_{15}/d^f_{85})_{max} \leq 4$: internally stable*		*d^c_{15}: particle size corresponding to 15% finer in the coarser fraction* *d^f_{85}: 85th percentile of particle size in the finer fraction*
Kenney and Lau (1985)	*$(H/F)_{min} \geq 1.0$: internally stable*		*F: percentage smaller than arbitrary D* *H: mass percentage between grain size D and 4D*
Burenkova (1993)	*$0.76 \log(h'')+1 < h' < 1.68 \log(h'')+1$: internally stable*		*$h'' = d_{90}/d_{15}$, $h' = d_{90}/d_{60}$*
Wan and Fell (2008)	*$30/\log(d_{90}/d_{60}) < 80$, or* *$30/\log(d_{90}/d_{60}) < 80$ and $15/\log(d_{20}/d_5) > 22$ internally stable*		
Chang and Zhang (2013)	$P < 10$ $10 < P < 35$ $P > 35$	$G_r < 3$ $G_r < 0.3P$ *Stable*	*P: fines content* *Gr: gap ratio* *$G_r = d_{max}/d_{min}$ which d_{max} and d_{min}: maximum and minimum particle diameter in the gap, respectively*

In the second group of geometrical criteria, named the capillary tube model, the possibility of movement of fine grains within the pores of coarser particles due to the seepage force is studied. If the diameter of the pores (d_1) is less than that of the smallest particles (D_{min}), ($d_1 \leq D_{min}$), the particles would not move into an adjacent layer or within the layer.

The Kovacs (1981) criterion takes into consideration the influence of grain shape with the shape factor (α). The shape factor for granular soil is commonly calculated by the theatrical formula and is approximated by grain shape comparing with regular geometric shapes such as sphere and polyhedron. This factor is suggested to be equal to 6, 7-9, 9-11, and 20, respectively for spheroid, rounded, angular, and laminated particles (Kovacs 1981). This is indicated that as an increase in the angularity of particles, the shape coefficient is increased, and the mean diameter of pores is decreased. The shape of soil grains also influences the sample porosity. In the capillary tube model, the porosity of the sample has also been taken into account. The proposed capillary tube model and shape coefficient for predicting the suffusion potential are shown in Table 2.

Table 2. Capillary tube model and shape coefficient proposed for predicting the suffusion potential

Reference	*Formula*	*Particle shape*	*Shape coefficient (a, SF)* [#*]	*Definition*
Kovacs, 1981 (Kovacs 1981)	$d_0 = \frac{4n}{1-n}\frac{D_h}{a} \le d_{min}$ *and* $d_{min} = d_{85}^{f}$	*Spheroid* *Rounded* *Angular* *Laminated*	6 7-9 9-11 20	d_1 *: smallest pores size* d_0 *: mean pore diameter* $d_{cont.}$ *: controlling constriction size,* (Kenney et al. 1985) d_{85}^{f} *: particle diameter 85th percent in the finer fraction* d_h^c *and* n_c *effective diameter and porosity of the coarser fraction, respectively that* $n_c = n + f(1-n)$
Li and Fannin, 2013 (Li and Fannin 2013)	$d_0 = 4.0\frac{n_c}{1-n_c}\frac{D_h^c}{\alpha}$ *and* $d_{min} = 2.3d_{85}^{f}$	*rounded* *angular*	6 8	
Dallo and Wang, 2016 (Dallo and Wang 2016)	$d_{cont.} = 1.4545\frac{n_c}{1-n_c}\frac{D_h^c}{\alpha}$ *and* $d_{min} = d_{85}^{f}$	*rounded* *angular*	6 8	

Marot et al. (2012) performed suffusion tests on three types of sand with different roundness. Their results indicated that an increase in the grain angularity caused a decrease in the hydraulic conductivity and suffusion erodibility. (Marot et al. 2012). Further, a limited study of four paired-tests on glass bead and sub-angular sand was reported (Slangen and Fannin 2017); their experiments showed that the Suffusion was evident in spherical glass bead specimens, nevertheless, the onset of suffusion did not occur at an equivalent, or even higher, the hydraulic gradient in soil samples with nearly identical gradations and sub-angular particles (Slangen and Fannin 2017).

Heretofore, limited experimental works have been carried out in the effect of grain shape on internal instability, and thus there is a need for further investigations. In the current research, the effect of particle shape on the suffusion susceptibility of soil samples was studied. Samples with five different shapes and three different grain size distributions curves were prepared and under a downward flow and stepwise gradient were tested.

2- MATERIAL

2-1. Sample Gradation

To study the effect of particle shape on suffusion, tests were carried out on internally stable, transition, and internally unstable soils. All samples were made from two materials, glass bead and four soil particles with different shapes. Moreover, three different grain size distributions were investigated to study the effect of PSD. Therefore, a total of 15 samples were prepared and tested. These soil gradations consisted of a widely distributed, two upward concave gradations, and two gap graded gradations. Selected PSD curves included (Fig 1):

- K gradation, a widely distributed, upward concave and internally stable grading (Kenney and Lau 1985);
- A gap graded soils and internally unstable gradations, G3-13 (Marot et al. 2016);
- B gradation, an upward concave grading with a transitional stable zone predicted as internally stable by some criteria, and judged as internally unstable according to other criteria (Skempton and Brogan 1994).

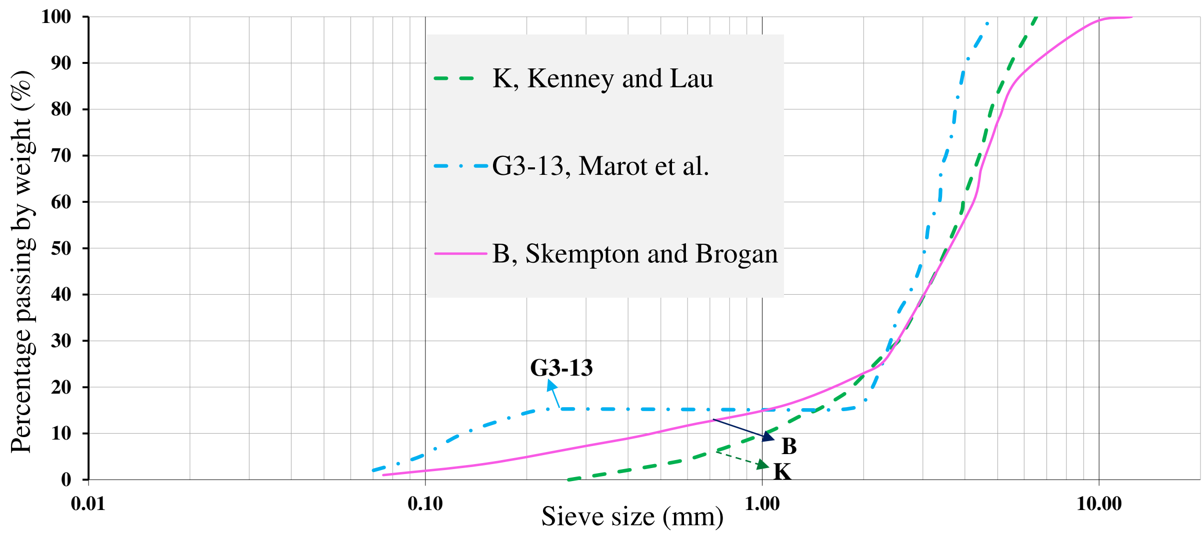

Figure 1. Particle size distribution of test materials

2-2. Particle Shape

The effect of grain shape on suffusion susceptibility was studied by selecting five different shapes. Particle shape can be described by three distinct features from macro to micro scales including sphericity, roundness, and roughness (Barrett 1980; Mitchell and Soga 2005). Besides, flatness and elongation ratio is used to describe the overall particle form (ASTMD 2488-09a 2009).

Particle sphericity, S, was calculated using the 3D image of particles extracted from X-ray micro-computed tomography images (Maroof et al. 2020): $S = \frac{d_{i-s}}{d_{c-s}}$, In which d_{i-s} and d_{c-s} are diameters of the inscribed sphere and circumscribed sphere, respectively. Particle sphericity is graded into seven classes as suggested in (Maroof et al. 2020). For all soil samples, particle roundness was measured by Wadell's roundness (Wadell 1932), R, and classified by the verbal scale proposed by Powers (Powers 1953). Besides, surface roughness described by visual comparison. For flaky and elongated particles, flatness and elongation ratio were also measured. Table 3 indicates the number of particles analyzed for each grain shape with respect to the classification/ description of particle shape.

Table 3. Particle shape classification/description and shape coefficient

Particles	*Average number of measured particles*	*S*	*Sphericity class*	*Wadell's Roundness*	*Roundness class*	*Roughness †*	*shape coefficient*
Glass bead	*1*	*0.99*	*High sphericity*	*0.99*	*Well rounded*	*glassy*	*6*
Rounded particle	*30*	*0.46*	*Medium sphericity*	*0.65*	*Rounded*	*relatively smooth*	*7.2*
Crushed aggregate	*36*	*0.39*	*Low sphericity*	*0.15*	*Very Angular*	*rough*	*8.9*
Slate	*38*	*0.13*	*Slab*	*0.46*	*SubRounded*	*relatively smooth*	*14.8*
Weathered pyramid basalt	*25*	*0.096*	*Elongated*	*0.18*	*Angular*	*relatively rough*	*16.9*

† *attained qualitatively based on the visual comparisons*

3- EXPERIMENTS

3-1. Experimental Setup

Internal stability was assessed by suffusion permeameter device as devices have also been used by other researchers (Kenney and Lau 1985; Moffat and Fannin 2006; Sail et al. 2011; Skempton and Brogan 1994). The cell is typically a plexiglas cell of 91 mm internal diameter and 340 mm length. The sample was located on a wire mesh screen that placed on 15 mm diameter glass beads. A drainage layer at the top of the seepage cell is consists of a 10 mm mono-size glass bead, supported with a perforated top plate.

3-2. Sample Preparation and Test Method

Concerning the possibility of segregation of grains and movement of finer fraction within the pores during sample preparation, water was added to the soil samples with moisture content up to 3-7%. The samples were prepared in three layers each of which had a thickness of about 45mm and were compacted using a tamping rod with 50-55% of relative density.

After installation of the samples, a surcharge load equal to 25 kPa was gradually applied to the sample to allow settlement and formation of probable changes in the arrangement of soil grains. Then, water enters the sample under a small head from bottom Seepage flow occurs downward with a constant head and stepwise in specific time intervals with gradients varying from 0.15 to 8.0. The test duration per gradient is variable from 30 minutes to 3 hours. Often, finer fraction erosion was observed temporarily after each increase in the gradient then the process fades rapidly. For each gradient, the test was stopped after a lack of observing erosion of the grains and also observing a constant outflow and constant level at the piezometers. Eroded particles from the samples at the end of each applied gradient were collected on the 0.075mm mesh at the downstream basin.

4- RESULTS

Internal instability described by seepage induced mass loss, reduction in volume, and change in flow rate. In the current study, mass loss, vertical strain, and erosion rate were reported. Further, visible migration of fine particles through the cell wall can be used to describe the occurrence of internal instability qualitatively.

4-1. Visual Observation and Hydrodynamic Condition

Visual observations were used to describe the occurrence of fine migration through the wall of the plexiglas during the tests and after each applied hydraulic gradient.

The time that washes out of fine particle was observed since the start of fine erosion were measured. Often, finer fraction erosion was observed temporarily after each increase in the gradient. In internal stable and transient samples (K and B) the erosion time, since the start of fine erosion increases in higher hydraulic gradient. Nevertheless, in the internally unstable sample (G3-13), the suffused time was greater for low hydraulic gradients and was reduced for i_{av}=3.0 and i_{av}=8.0.

Some samples of the K and B gradation at low hydraulic gradient only show slight changes in the cell wall. Images of G3-13 samples at the end of tests are presented in Figure 2. In glass bead and rounded grains samples, mass loss of fine grains on the sidewall of plexiglas cell was found to be high like a straight pipe. In the sample with crushed, flaky, and elongated grains, mass loss of finer fraction at the cell wall was relatively high.

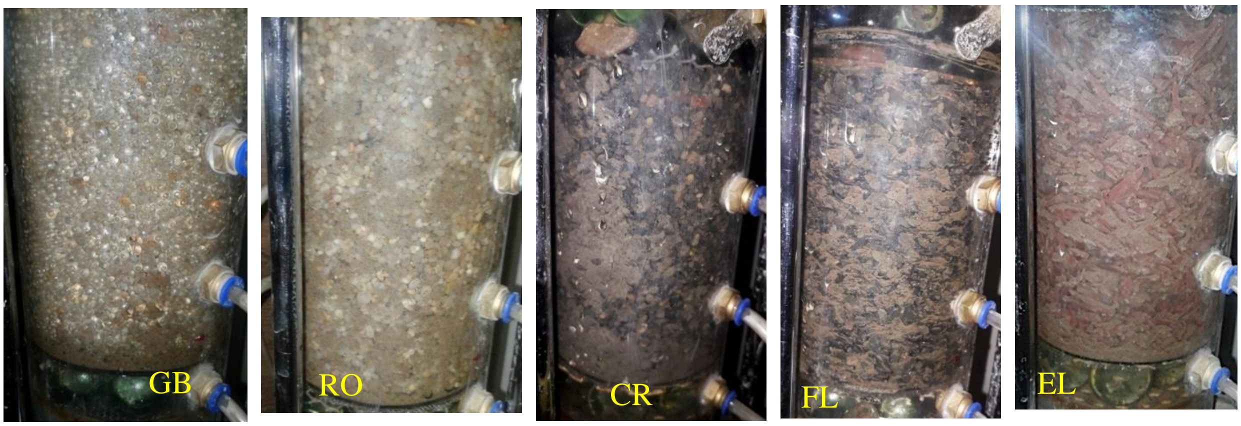

Figure 2. Images of B grading with different grain shapes, GB: Glass bead, RO: rounded, CR: angular, FL: flaky and EL: elongated, at the end of the tests

Visual observation of fine erosion in the plexiglas sidewall and the maximum erosion rate are given in Table 4.

Table 4. plexiglas side wall visual observation

PSD	*Particle shape*	*Max. erosion rate at i_{av} $(g.s^{-1}.m^{-2})$*	*observation of fine erosion in the plexiglas sidewall*			
			i_{av}=0.15	*i_{av}=1.0*	*i_{av}=3.0*	*i_{av}=8.0*
K	*GB*	*1.91 (i=0.15)*	*No sign*	*No sign*	*No sign*	*Moderate*
	SR	*051 (i=0.15)*	*No sign*	*No sign*	*Moderate*	*Relatively High‡*
	A	*0.14 (i=0.15)*	*No sign*	*No sign*	*No sign*	*No sign*
	F	*0.12 (i=8.0)*	*No sign*	*No sign*	*Moderate*	*Moderate‡*
	E	*0.53 (i=0.15)*	*No sign*	*No sign*	*No sign*	*Moderate*
B	*GB*	*3.71 (i=8.0)*	*Moderate*	*Moderate*	*High*,‡*	*High*,‡*
	SR	*2.61 (i=8.0)*	*Moderate*	*Moderate*	*High*,‡*	*High*,‡*
	A	*0.60 (i=1.0)*	*Low*	*Moderate*	*Moderate*	*Moderate,‡*
	F	*1.43 (i=8.0)*	*Low*	*Moderate*	*Moderate*	*High*,‡*
	E	*0.89 (i=8.0)*	*Low*	*Low*	*Moderate*	*Moderate‡*
G13	*GB*	*3.44 (i=0.15)*	*Moderate*	*Moderate*	*High*,‡*	*High*,†,‡*
	SR	*3.78 (i=3.0)*	*Moderate*	*Moderate*	*High*,‡*	*High*,†,‡*
	A	*2.97 (i=1.0)*	*Moderate*	*Moderate*	*High*,‡*	*High*,‡*
	F	*3.13 (i=1.0)*	*Moderate*	*High**	*High**	*High**
	E	*2.45 (i=3.0)*	*Moderate*	*Moderate*	*Moderate‡*	*High*,‡*

**) BL: Broken Line, †) SL: Straight Line, ‡) partially accumulate by a layer of fines against the wire mesh*

4-2. Effect of Particle Size Distribution and Particle Shape on Mass Loss

4-2-1. K Gradation

The k gradation has already been studied and is an internally stable widely distributed grading. Experiments were performed on sandy gravels in an apparatus with 125mm diameter, and results showed no change in the gradation after the test (Kenney and Lau 1985).

In the current tests, K gradation samples were made with four types of grain and glass bead. At a gradient of 0.15, a small amount of gains were eroded while at a gradient of 1, no fraction loss of fine grains has occurred. Part of this erosion may have occurred during sample preparation or sample saturation, as reported in previous researches (Sail et al. 2011; Zhong et al. 2018).

By increasing the gradient to 3 and 8, the rate of eroded grains increased. The highest amount of dry mass loss is related to the glass bead sample followed by rounded particles. For all the samples of K gradation, no sign of instability was found and all the samples were internally stable.

4-2-2. B Gradation

The B gradation has already been studied (Skempton and Brogan 1994). It is a widely distributed grading with about 15% finer fraction, $(H/F)_{min}$= 0.98, a filter ratio of components $D'_{15}/d'_{85} = 3.7$, and a uniformity coefficient of $C_U = 9.7$. B gradation seemed to lie on a boundary between internal stability and instability. However, with 37% of porosity, the sample had a low relative density, and test results showed that it is definitely unstable (Skempton and Brogan 1994).

In the experiments manipulated by Skempton and Brogan, the shape of soil grains was sub angular, with moderately high sphericity. In the Skempton and Brogan̉s tests the amount of eroded grain for sample B comprised of 12% finer fraction, which was about 1.8% of total sample mass, that is compatible with the test performed on the sample with rounded to sub rounded grains in the present study. Besides, fraction loss of glass bead sample was measured at an average rate of 2.6 g/m^2 per second in about 30 minutes since the start of fine erosion, which is in agreement with the results of Skempton and Brogan̉s test, since the start of slight local piping.

According to tests results and visual observations of the sidewall, in the downward flow direction, B gradation at the moderate relative density and for spherical and rounded grains was categorized as internally unstable, and the sample with angular was categorized as transition. Moreover, flaky, and elongated grains were classified as internally stable.

4-2-3. G3-13 Gradation

The effect of grain shape on internal instability of gap graded soils were examined by the G3-13 gradation with a gap ratio (Gr) equal to 10. The portion of particles finer than 0.063 mm, P, was less than 10 % and these soils were unstable for Gr > 3 (Chang and Zhang 2013).

In a reported experiment on G3-13 grading with sample diameter equal to 50 mm and applied hydraulic gradient varying from 0.1 to 6 this grading (G3-13) was classified as unstable and based on erodibility classification, it was moderately erodible (Marot et al. 2016).

The total percentage of fraction loss for all the samples of this gradation exceeded 3%, and all of them were internally unstable. The mass loss of the glass bead sample at a gradient of 0.15 was about 6% of the total sample weight and it is internally unstable at this gradient.

4-3. Effect of Particle Shape on Internal Instability

In this research, the initiation of internal instability is judged based on one or a group of manifestations. The samples with mass loss of higher than 3% of the initial sample mass, categorized as internal unstable and suffusion potential and samples with mass loss effect on plexiglas wall like a broken line in cell sidewall during the tests and/or mass erosion rate exceeds 2.0 $g.m^{-2}.s^{-1}$, classified as transient. Further, samples with vertical strain more than 1.0 % considered internally unstable. Samples with a straight pipe in the sidewall and vertical strain less than 1.0 %, classified as transient. Table 5 summarizes obtained results on different grading with different particle shapes as well as the Chang and Zhang and Li and Fannin criteria.

Table 5. Summary of obtained the experimental result on specimens with different grading and particle shape

PSD	*Material*	*Washed out in sidewall*	*Pipe in sidewall*	*Max. erosion rate at i_{av} ($g.s^{-1}.m^{-2}$)*	*Vertical strain (%)*	*Limit Mass loss (%) at i_{av}*	Chang and Zhang (2013)	*Li and Fannin, (2013)*	Experimental result, this study
K	*GB*	*Moderate*	*N*	*1.91 (i=0.15)*	*0.17*	--	*S*	*S*	*S*
	R	*Relatively High*	*N*	*051 (i=0.15)*	*0.09*	--		*S*	*S*
	A	*No sign*	*N*	*0.14 (i=0.15)*	*0.09*	--		*S*	*S*
	F	*Moderate*	*N*	*0.12 (i=8.0)*	*0.11*	--		*S*	*S*
	E	*Moderate*	*N*	*0.53 (i=0.15)*	*0.09*	--		*S*	*S*
B	*GB*	*High*	*BL*	*3.71 (i=8.0)*	0.21	--	*T*	*U*	*U*
	R	*High*	*BL*	*2.61 (i=8.0)*	0.17	--		*S*	*U*
	A	*Moderate*	*N*	*0.60 (i=1.0)*	0.09	--		*U*	*S*
	F	*High*	*BL*	*1.43 (i=8.0)*	0.12	--		*S*	*T*
	E	*Moderate*	*N*	*0.89 (i=8.0)*	0.09	--		*S*	*S*
G3-13	*GB*	*High*	*BL&SL*	*3.44 (i=0.15)*	2.89	*6.05 (i=0.15)*	*U*	*U*	*U*
	R	*High*	*BL&SL*	*3.78 (i=3.0)*	1.11	*3.97 (i=1.0)*		*U*	*U*
	A	*High*	*BL*	*2.97 (i=1.0)*	0.34	*4.05 (i=1.0)*		*U*	*U*
	F	*High*	*BL*	*3.13 (i=1.0)*	0.45	*4.18 (i=1.0)*		*U*	*U*
	E	*High*	*BL*	*2.45 (i=3.0)*	0.36	*3.05 (i=1.0)*		*U*	*U*

GB: Glass bead, R: Rounded particle, A: Angular (Crushed aggregate), F: Flaky (Slate), E: Elongated (Weathered pyramid basalt), S: Stable, U: Unstable, T: Transient,

For all the samples of K gradation, no sign of instability was found, and all the samples were internally stable. According to the test results and visual observations of the sidewall, in the downward flow direction, B gradation specimen for spherical glass bead and medium sphericity/rounded particles were suffusive and categorized as internally unstable. Angular and elongated grains were classified as internally stable, and specimens containing flaky grains were transient. Further, all the samples of G3-13 gradation were internally stable.

5- CONCLUSIONS

Results of suffusion tests showed that grains' morphology effectively changes the amount of washed out grains. For nearly identical gradations and hydraulic conditions, the samples with different grain shapes could be internally stable or unstable.

In K gradation, the sample with glass bead and rounded particles had the highest mass loss and all samples were internally stable. According to B-gradation test results, the glass bead and rounded shape samples were internally unstable, and the sample with flaky particles was categorized as a transition. Further, crushed and elongated grains were internally stable. All G3-13 samples were internally unstable.

The amount of eroded grains increased with sphericity and roundness of grains and specimens with various particle shapes have different levels of internal instability. Spherical glass bead and rounded/ medium sphericity specimens were more prone to suffusion at an equivalent or even lower hydraulic gradient than the soil samples with angular/low sphericity grains.

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