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Laboratory study on the effects of hydraulic and granulometric parameters on the response of granular soil to internal erosion

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ABSTRACT

Erosion is a major environmental problem to agricultural land as well as to civil engineering infrastructures. Rainwater infiltration into granular soils can lead to the migration of fine particles by suffusion. This experimental study is conducted to evaluate the susceptibility to erosion of cohesionless soils. The soil under investigation was collected from the coastal region of Mostaganem (West of Algeria) where erosion has recently caused several damages. To assess soil instability to erosion, two approaches have been proposed in the literature: the geometric approach and the hydraulic approach. Few studies have examined the combination of the two methods. The objective of our study is the combination of the two approaches by determining the critical hydraulic load responsible for triggering erosion as a function of soil characteristics. An experimental parametric study was conducted to determine the influence of initial amount of fines, hydraulic gradient and axial stress on the initiation and evolution of suffusion. A combination of the interactions between these parameters allowed us to express the critical hydraulic gradient and to identify the hydraulic behavior of the soil according to the studied parameters. This approach can better estimate the erodibility of cohesionless soils. It can be used in future development studies at this site to reduce the risk of erosion.

1 Introduction

Erosion is a major environmental problem to agricultural land as well as to civil engineering infrastructures. This natural hazard with social, economic and environmental consequences has been increased in arid and semi-arid regions due to climate changes [1-3]. Algeria is located in a region that is very vulnerable to the effects of climate change, the consequences of which are increasingly visible and alarming.

The climatic warming led to an increase in temperature and a change in rainfall in terms of intensity, duration and spatial distribution of precipitation. These parameters have direct consequences on water erosion [4, 5]. Algeria is therefore one of the most countries endangered in the world by erosion [3, 6]. About 14 million hectares are exposed to active erosion in the north of the country [7]. The direct consequences of this problem in Algeria are permanent degradation of soil and water quality, the destruction of the retaining structures and many damages whose costs are considerable [8].

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The risk of erosion has increased in Algeria during the last decade [9-11]. The increase in the risk of erosion was confirmed in Kharrouba area located in Mostaganem (northwest of Algeria) where the soil under investigation was collected for this experimental work, by a continuous monitoring of the evolution of the phenomenon in space and time. The chronology of the incidents, since 2006, showed us the irreversibility of the phenomenon. Recently, many events have been recorded causing serious damage to various structures. For example, the destruction of roads and canals (Fig. 1), road floods (Fig. 2), the destruction of the retaining walls (Fig. 3) and the collapse of natural embankments (Fig. 4) (Figures 1-4 were taken by the authors indicating part of the damages to the various structures caused by erosion in the Kharrouba region).

Fig. 1 –Destruction of roads and canals

Fig. 2–Road floods

Fig. 3 – Destruction of the retaining walls

Fig. 4 – Collapse of natural embankments

A diagnosis of the disorders showed us that the evolution of the risk of erosion in this zone is related mainly to the erosive nature of the soils and to the climatic and topographic factors associated to accelerated and anarchic urbanization. Kharrouba zone is therefore a favorable environment for the phenomenon of erosion. This risk has not been taken into consideration in the soil studies and land management projects conducted on this site. Our study aims to understand the dynamics of erosion and the analysis of the influence of different parameters on the susceptibility of Kharrouba soil to erosion. A new approach for identifying the onset and evolution of erosion is proposed. This approach can be used to avoid such disastrous phenomenon in future studies in land management.

Rainwater infiltration into cohesionless soil can cause the migration of particles from the soil to downstream of the flow. This mass transfer, conditioned by the geotechnical characteristics of the soil and the hydraulic condition, can cause enormous loss of material threatening the internal stability of structures and natural slopes. Erosion can occur if two processes are satisfied: the particle detachment and their transport. The process of erosion is usually described following four phases: the initiation, the continuation, the progression and the breach [12]. In this work, we are interested in the initiation of internal erosion by suffusion, because it is the main cause of the onset of erosion in cohesionless soils.

Suffusion is defined by the detachment and transport of fines through the constrictions formed by the coarse grains constituting the skeleton of the soil [13]. The movements of fine particles contained in a cohesionless soil play an important role in its behavior with respect to internal stability and rupture.

Studies have shown that the amount of fines has a significant influence on soil microstructure and that the participation of particles at different sizes in inter-particle contact forces changes with the amount of fines [14]. The particles mobilized by the flow can be drained from the soil matrix; others can be trapped at different scales of the medium causing clogging. Suffusion is thus defined by three processes the detachment, transport and filtration of fines. These three processes cannot be separated in the investigation of the phenomenon [15]. The movement of particles by suffusion produces a rearrangement of grains that changes the porosity of the soil. In the zones where the particles have been detached the porosity increased while in the deposition zones it decreased. This can lead to important modifications in the hydraulic and mechanical properties of the soil [16-19].

The initiation of suffusion in a soil is conditioned by three parameters: the susceptibility of the material to erosion, sufficient hydraulic loading to cause the detachment and the transport of grains and the critical stress condition [20]. Several methods have been proposed for evaluating the initiation of suffusion. These methods can be classified into two categories: models based on a geometric approach and others on a hydraulic approach. The geometric (or granulometric) approach is based on the study of the grain size distribution of the soil and to check if the fines can be transported by the flow through the constrictions formed by the coarse grains. Several models have been proposed [13], [21-23]. The hydraulic approach is based on the determination of the critical value of the hydraulic load under which internal erosion can be triggered. Some authors have set a critical value of the hydraulic gradient [24-26]; others set the critical shear stress [27] and the critical pore velocity [28].

According to Wan and Fell [13], Marot et al. [15], Chang and Zhang [16], Bendahmane et al. [29], Li and Fannin [30]; most methods based on the particle size distribution are conservative because they classify stable soils as unstable. These models developed from the results of experimental studies do not include all types of soils at risk of erosion. In this experimental study, the applicability of some geometric models proposed in the literature will be verified for the tested soil.

The hydraulic criterion must also be discussed, as so far any particular model has accurately provided a hydraulic level from which erosion can be initiated. It should be noted that erosion cannot occur in geometrically unstable soil if the hydraulic load is not sufficient to cause the detachment and the transport of particles, and contrary, a high gradient (or velocity) cannot produce suffusion in a geometrically stable soil. This means that the accurate assessment of susceptibility to erosion requires a combination of both approaches (hydraulic and geometric). Few studies have examined the combination of the two criteria [31].

The main objective of our study is the combination of hydraulic loading and soil characteristics for a better assessment of the susceptibility of cohesionless soils to erosion. To establish this relationship a parametric study was conducted on sand-fine mixtures. The studied parameters are the initial percentage of fines, the hydraulic gradient and the axial stress. The soil response has been identified as a function of the interactions between the studied parameters. A critical value of the hydraulic stress and the hydraulic behavior of eroded soil were determined according to the studied parameters.

2 Materials and methods

2.1 Tested materials

Erosion tests were conducted on mixtures of sand and fines. The sand extracted from the Kharrouba region (Mostaganem, Algeria) which is considered a vulnerable area for erosion, and the fines are silica flour marketed by the company ‘Adwan Chemicals’. The silica flour is obtained by crushing siliceous sand. In the different mixtures, the sand presents the coarse fraction and the silica flour models the fine particles. The criterion for selecting silica flour as fines is principally its non-dispersive character on the one hand, and on the second hand, to prevent cohesive action between grains. The particles can be considered as inert where their reaction with the granular matrix in the presence of water can perturb their mobility will be neglected. The grain size distributions of both materials are shown in Fig. 5.

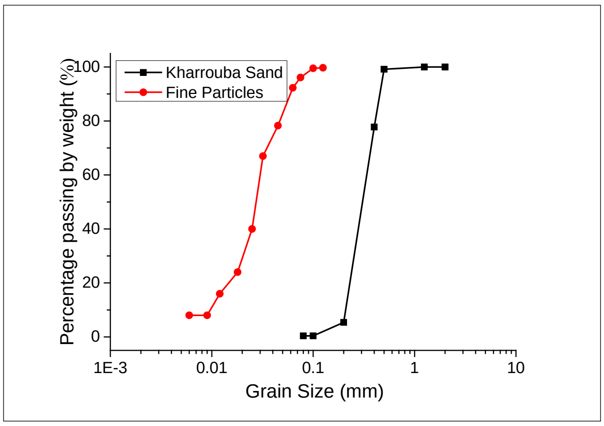


Fig. 5 – Grain size distribution of tested materials

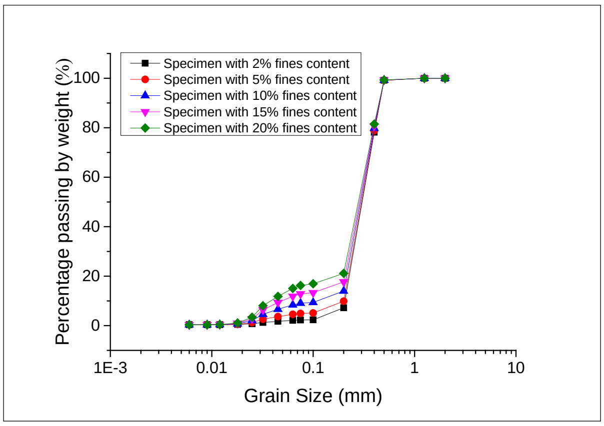


Fig. 6 – Grain size distribution curves of the mixtures

The grain size distribution and the physical properties of the sand, fines and the different mixtures are presented in Fig. 6 and Table 1 respectively. The grain size distribution curves (Fig. 5) indicate that the grain diameter of Kharrouba sand ranges from 0.08 mm to 1.00 mm, and that of fines between 0.006 mm and 0.10 mm. Fig. 6 indicates that the mixtures with different percentages in mass of fines do not contain clay particles. All the tested soils can be classified as non-plastic. Their plasticity index is almost null or unmeasurable. The uniformity coefficients (Cu) of the samples S-2F, S-5F and S-10F are less than 5 and their curvature coefficients (Cc) are less than 3, which indicate that the soils are gap-graded. The samples S-15F and S-20F have (Cu) greater than 5 and (Cc) greater than 3, which indicate that the grain size distribution is widely-graded.

Table 1- Physical properties of tested soil

Physical property	**Karrouba sand**	**Fines**	**Specimen (S-F2)**	**Specimen (S-F5)**	**Specimen (S-F10)**	**Specimen (S-F15)**	**Specimen (S-F20)**
Specific gravity S.G (-)	2.65	2.65	2.65	2.65	2.65	2.65	2.65
Median particle size D_{50}	0.30	0.02	0.30	0.30	0.29	0.29	0.28
Effective particle size D_{10}	0.21	0.01	0.21	0.20	0.11	0.05	0.04
Uniformity coefficient Cu (-)	1.62	0.30	1.62	1.68	3.00	6.40	8.29
Curvature coefficient Cc (-)	0.95	0.13	0.91	0.93	1.59	3.39	4.23
Grain form	Angular to sub-angular						

S-F2: specimen with 2% of fines.S-F5: 5% of fines. S-F10: 10% of fines. S-F15: 15% of fines. S-F20: 20% of fines

The chemical analysis of the used materials is given in the table 2. The two materials are mainly composed of silica. The sand has a significant quantity of lime.

Table 2 - Chemical analysis of tested materials

	SiO_2 (%)	**CaO (%)**	**MgO (%)**	**Al_2O_3(%)**	**Fe_2O_3(%)**	**SO_4(%)**	**M.O (%)**
Sand	76.97	11.02	00.14	00.76	00.37	00.00	10.89
Fines	98.42	00.02	00.01	00.90	00.08	00.00	00.32

2.2 Experimental device and test procedure

The soil samples were hydraulically stressed by a downward flow using a constant head permeameter. This device has been used in the study of erosion by several researchers [13, 21, 27, 32].The advantages of the permeameter in the study of erosion are its simplicity of implementation and the easiness to use. The device is composed of a cylindrical mold measuring 10.50 cm in diameter and 12.00 cm in height. Piezometers are placed over the height of the mold to indicate the changes in pressure in the sample during the test. The mold is closed at the two ends by covers, the lower one is equipped with a nozzle to discharge the water, and the upper one is connected to a reservoir of water. A porous plate covers the sample on both sides of the mold. A filter is placed between the bottom of the sample and the lower plate to control the eroded particle diameter. In our study, the filter mesh size used is 80 µm, i.e. only fine particles (diameter < 80µm) can be drained during the test. The mass of the eroded particles is determined by weighing.

The preparation of the samples is conducted following to a procedure based on the works of Bendahmane et al. [29] and that of Ayadat et al. [32]. The methodology consists firstly to mix the sand only with a quantity of water lower than the optimal Proctor for a period of three minutes. By continuing the mixing, the fines are added progressively according to the desired quantity. The mixing of the two materials will be effected for ten minutes. This mixing step is very important for sample preparation because it provides homogeneity of the samples. A bad mixing leads to heterogeneous samples exhibiting different behaviors during the tests. After mixing, the material is placed in the cylindrical mold by compacting in three layers with a specific energy. The sample is then mechanically loaded by a vertical stress using a hydraulic press. Then, using a vacuum pump, a depression is applied to the sample. After saturation, the sample is hydraulically loaded by a downward vertical gradient. The effluent is collected at the exit of the mold for specific time intervals. After measuring the volume of the effluent, the mass of the eroded particles will be determined by weighing after drying.

3 Results and discussion

3.1 Parametric study of erosion

A parametric study is performed in this series of seepage tests. Three variables are used in this study, the initial fines content (2, 5, 10, 15 and 20%), the hydraulic gradient (5, 15, 17 and 20 m/m), and the axial stress (50, 100 and 150 kPa).These parameters have a great influence on the phenomenon of suffusion. The amounts of fines used in the different mixtures were selected based on the particle size analyses conducted on several soil samples from different locations and at different depths. The mixtures with the different percentages of fines represent the granulometries of the soils that can be found in the studied area. The range of hydraulic gradients was chosen to model the flow conditions related to the site and the axial stresses fixed at 50, 100 and 150kPa represent a soil depth of 2.5, 5 and 7.5 meters approximately.

3.1.1 Influence of the initial percentage of fines

Evolution of particle loss during erosion for different initial percentages of fines is presented in Fig. 7(i =15m/m, σ_a=50kPa) and Fig. 8 (i =20m/m, σ_a= 50kPa).

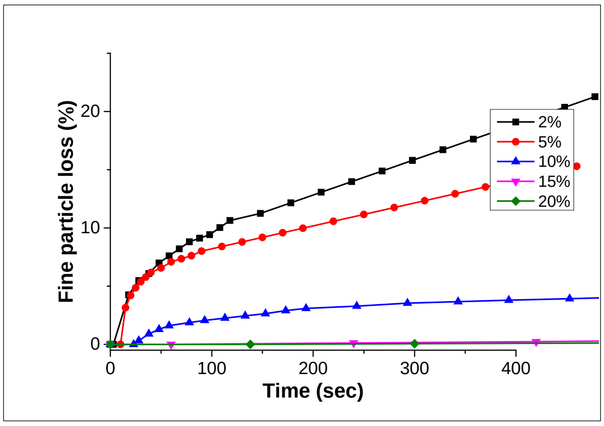


Fig. 7 – Particle loss during erosion(i = 15m/m, σ_a= 50kPa)

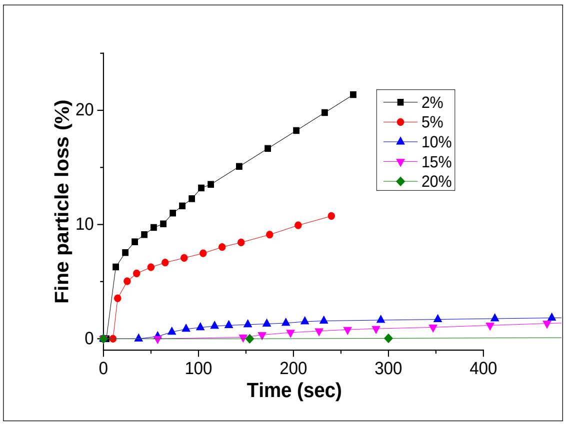
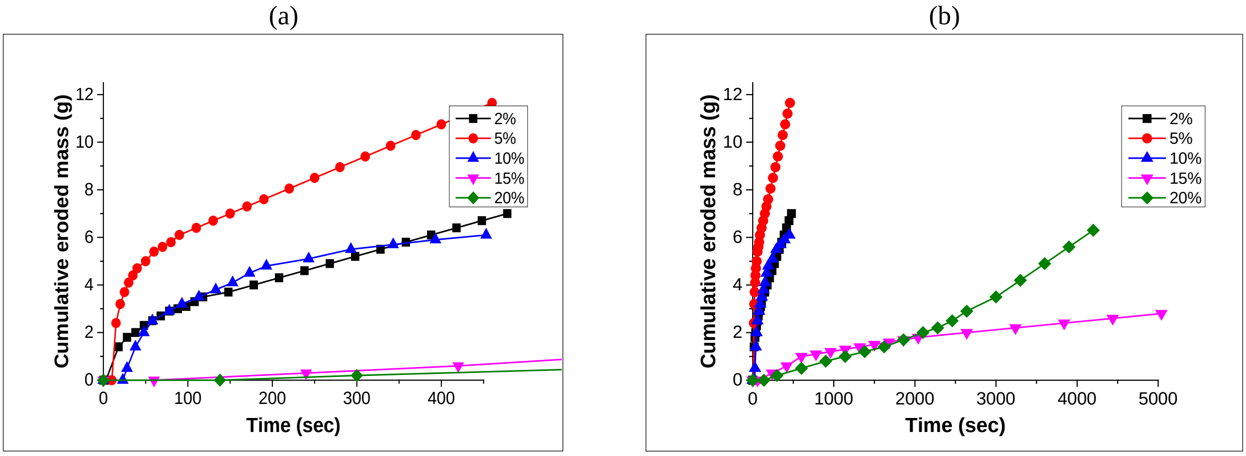


Fig. 8 – Particle loss during erosion(i = 20m/m, σ_a= 50kPa)

The relative cumulative eroded masse for mixtures with 15 and 20% of fines is very small than that of the mixtures with 2, 5 and 10% for the two samples (Fig. 7 and 8). It can be noticed also that the amount of eroded particles is always lower than the maximum possible erodible fraction (which presents the initial quantity of fines C_0). This can be explained that during suffusion, only a part of the particles solicited by the flow is discharged from the sample. The other part is filtered through the soil.

Evolutions of cumulative eroded soil mass for different percentage of fines are shown in Fig. 9. The analysis of the curves shows that the kinetics of the erosion differs according to the initial percentage of the fines. For 2, 5 and 10% fines, the shape of the curves is marked by a rapid increase during the first seconds (0 sec <t <50 sec) followed by a slow and quasi-linear evolution until the end of the test. For higher percentages of fines (15 and 20%), the quantities of eroded particles are very low during the first minutes (Fig.9.a). This evolution, very weak, will be followed by an almost linear tendency from t> 500 sec (Fig. 9.b).


(a)

(b)

Fig. 9 – Evolutions of cumulative eroded soil mass (i = 20m/m, σ_a= 50kPa) a) 0sec < t < 500sec, b) 0sec < t < 5000sec

The high porosity of the samples containing 2, 5 and 10% fines means that the hydraulic stress causes massive erosion during the first seconds of the test. A new equilibrium state is established after a certain time characterized by an almost linear tendency of erosion until the end of the test. Porosity decreases with increasing initial amount of fines. Particle mobility becomes more and more difficult for samples with 15 and 20% fines. This explains the small quantities of particles drained from these samples, particularly at the beginning of the tests.

The difference in behaviour between the mixtures having a percentage of fines less than or equal to 10% and the samples containing 15 and 20% of fines can be explained by monitoring the evolution of the hydraulic conductivity of the media. The hydraulic conductivity is an indirect parameter that could tell us about the processes of particle migration in the soil. The influence of internal erosion on the variation of the permeability of sand and bentonite mixtures has been studied by Kaoser et al. [33] where they established a relationship between erosion rate and hydraulic conductivity. Fig. 10 shows the variation of the overall permeability of the medium over time for two samples (10% and 15% fines).

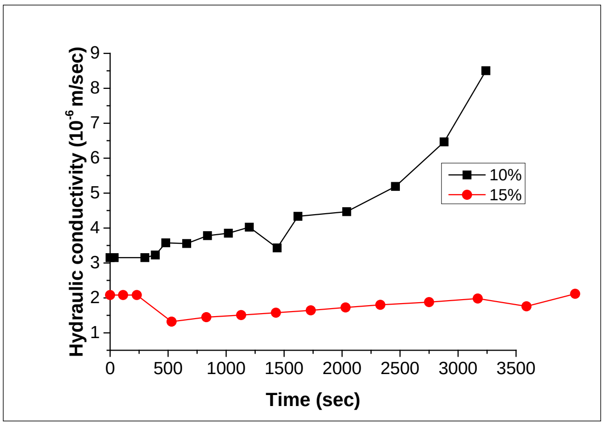


Fig. 10 – Hydraulic conductivity variation during tests (i=20m/m, σ_a= 50kPa)

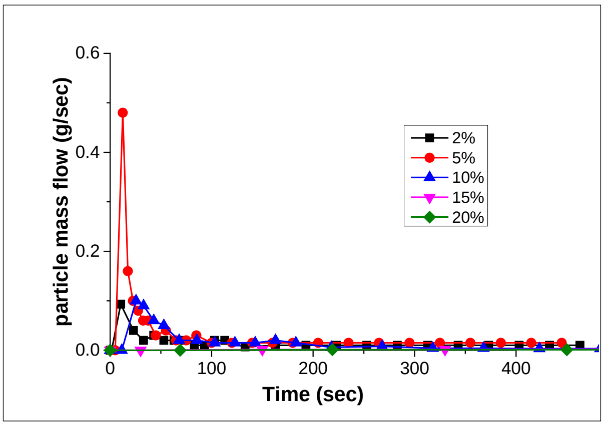


Fig. 11 – Solid flow evolution as a function of time tests (i=20m/m, σ_a= 50kPa)

For 10% of fines (Fig. 10), it can be noticed a marked increase in permeability at the beginning of the test. The large amount of suffused eroded particles causes an increase in porosity thus facilitating the flow of water through the porous medium. For the mixture containing 15% of fines, the permeability decreases during the first minutes, then it increases, but this increase is very small compared to that of the sample with 10% of fines.

The decrease in permeability at the beginning of the test is explained by the clogging of the medium. The torn particles were trapped in the soil. Their accumulation causes a reduction in the local porosity causing a drop in the hydraulic conductivity. The clogging of the medium has favorized the appearance of suppression in the clogging zones, a process of unclogging occurred causing the increase of the permeability and the increase of the quantity of the eroded particles. Suffusion continued afterwards accompanied by a (low) increase in the hydraulic conductivity of the medium. It can be noticed that the formation and dissipation of a medium clogging occurs quickly and in a very short time. This is due to the great value of the hydraulic conductivity of the tested soil.

The hydraulic behavior of the soil during erosion is an important parameter for the determination of soil response. Koaser et al. [33] and Ke and Takahashi [17, 25] indicated in their works that suffusion causes an increase in the porosity of the medium causing an increase in its permeability, whatever the granulometric compositions of the soils studied. On the other hand, Sibille et al. [18]; Bendahmane et al. [29] and Sghir et al. [34]have indicated that the migration of fines by suffusion causes clogging of the medium and that cause a decrease in its hydraulic conductivity. Our results indicate that soil hydraulic behavior is strongly dependent on the amount of fine particles present in the medium. At low amounts of fines, the permeability of the medium increases during erosion, while the mixtures with an important percentage of fines showed a decrease in their hydraulic conductivity.

Another very decisive parameter to characterize the phenomenon of erosion is the solid flow, which expresses the mass of fines discharged per unit of time. Fig. 11 shows the evolution of the solid flow as a function of time for different percentages of fines (i = 20 m/m ; σ_a= 50kPa). It can be seen that the curves have the same shape and that can be divided into three phases:

(1) in the first phase, the solid flow rate undergoes a sharp growth to reach a high peak.

(2) In the second phase, the flow rate decrease strongly

(3) In the third phase, the flow rate stabilizes at a low value.

Solid flows measured at the third phase are always very low whatever the tested material. The peaks of eroded solid flow are pointed for samples with a fine amount less than or equal to 10%, while the peaks are more spread over time for 15 and 20% of fines. The large amount of fines makes the media less permeable. The particles mobilized by the flow take longer to be evacuated outside the sample.

Fig. 12 displays the maximum eroded solid flow for different percentages of fines. It can be seen clearly that the rate of erosion decreases with the increase of the initial quantity of fines. A correlation between the maximum flow rate and the percentage of fines is proposed (Qs max= -0.002+2.254 e-(0.305 x % fines), r=0.98). According to this equation, the soil will no longer be erodible if the percentage of fines exceeds 30% (with i = 20m/m and σ_a= 50KPa). These observations remain to be confirmed by other test results.

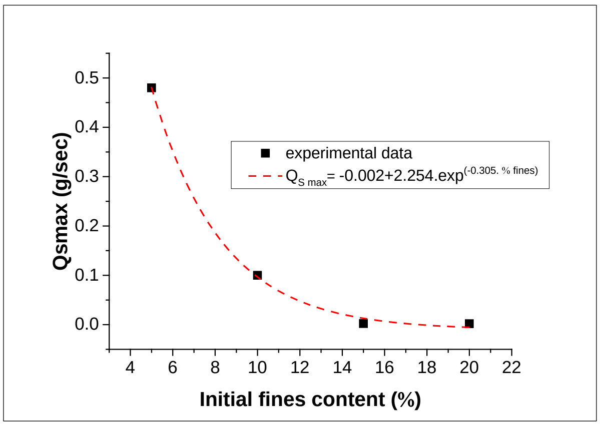


Fig. 12 – Max solid flow according to the percentage of fines

The evolution of the quantity of eroded particles, the fine particle loss, the evolution of the hydraulic conductivity during erosion and that of the eroded solid flow indicated that the quantity of fines in a cohesionless soil plays a key role in his erodibility. Increasing the amount of fines in the mixtures leads to a decrease in porosity. This will hinder the evacuation of particles outside the sample. According to these results, the increase in the initial percentage of fines improves the resistance of the soil to suffusion.

3.1.2 Influence of the hydraulic gradient

Fig. 13 shows the evolution over time of the cumulated mass of eroded particles for different values of the hydraulic gradient of a soil sample containing 10% of fines and consolidated at a pressure equal to 50kPa. The amount of mobilized particles is very small for a gradient of 5m/m. For the other gradients, the curves show a similar trend characterized by a rapid increase during the first minutes followed by an almost linear evolution. The eroded mass increases with increasing gradient. Indeed, a high hydraulic gradient encourages the removal and transport of suspended particles and their drainage outside the sample.

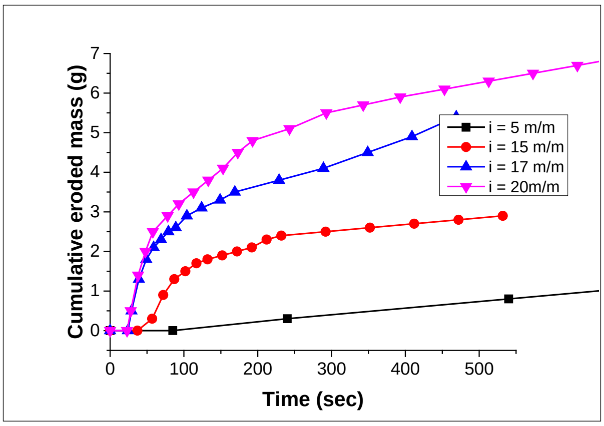


Fig. 13 –Evolution of a cumulative eroded mass (10%, σ_a=50kPa)

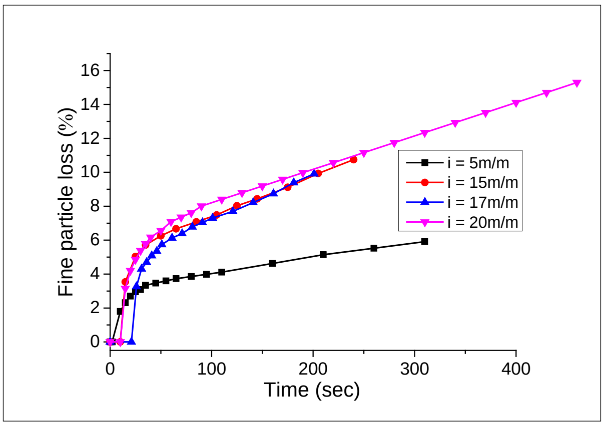


Fig. 14 –Cumulative fine loss within seepage test period (5%, σ_a= 50kPa)

The evolution of the particle loss according to the imposed hydraulic gradient is shown in Fig. 14 for 5% of fines. It can be found that the quantity of particle loss is proportional to the value of the applied hydraulic gradient. A high gradient promotes detachment and transport of fines.

The evolution of the hydraulic conductivity during the tests for different gradients is presented in Fig. 15. For the same percentage of fines after the initiation of erosion, the hydraulic conductivity increases with the imposed hydraulic gradient.

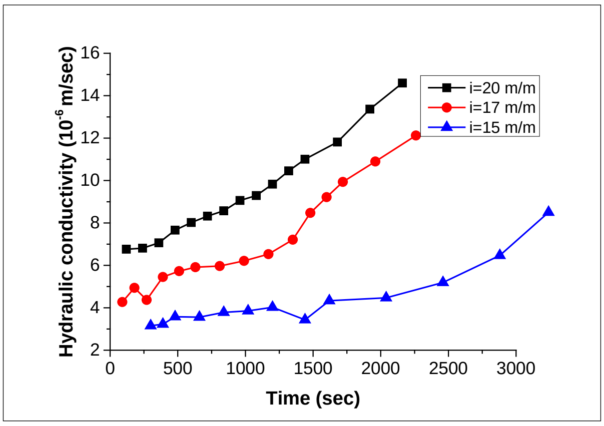


Fig. 15 –Permeability time dependent (10% fines, σ_a=50kPa)

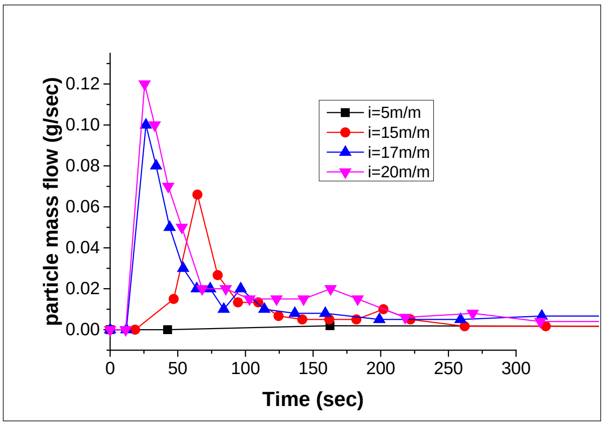


Fig. 16 –Solid flow evolution as a function of time (10% fines, σ_a= 50kPa)

The forces that are generated by the load gradient play an important role in the detachment and transport of the particles which subsequently alter the pore structure of the soil. The analysis of the graphs in Fig. 15 led us to two important observations: (1) the overall permeability of the sample stressed by a hydraulic gradient equal to 15 m/m is small compared to that of the samples solicited by greater gradients. (2) The evolution of the permeability is much less important for i = 15m/m than for the other loads. This means that the increase in the intensity of the hydraulic stress facilitates the detachment and the transport of particles causing the increase in the porosity of the medium and consequently an increase in its permeability. This evolution is proportional to the value of the applied gradient.

The evolution of the eroded solid flow over time for different values of (i) is presented in Fig. 16. The solid flow increases to a peak then decreases very rapidly over time to stabilize at a very low value which will depend on the applied gradient.

3.1.3 Influence of the axial stress

The evolution of eroded cumulative masses for different values of axial stress is presented in Fig. 17.

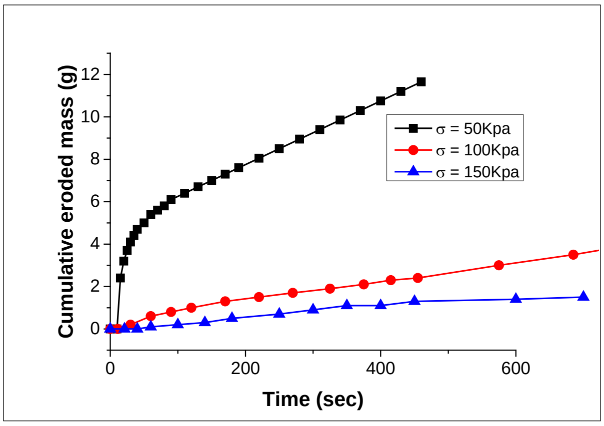
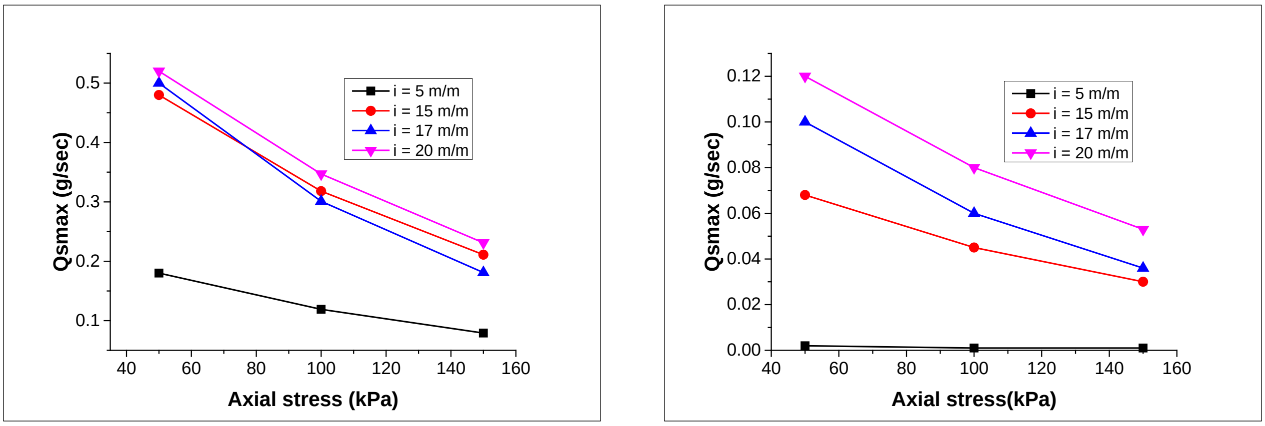


Fig. 17 –Eroded masses as a function of time (5% fines, i = 20m /m)

The amount of eroded particles decreases with increasing a vertical pressure. This observation is valid for the other samples with different percentages of fines. The initial state of compactness of the soil has an influence on the internal erosion process. Compaction reduces porosity; the migration of particles becomes increasingly difficult through the soil structure and therefore its erodibility decreases. Fig. 18show the decay of the maximum solid erosion rate when the axial stress increases.



(a) (b)

Fig. 18 –Max flow rate depending on the axial stress a) 5% of fines, b) 10% of fines

The decay of the eroded cumulative mass and the maximum solid flow with the increase of the axial stress can be explained by the induced increase in the consolidation of the samples. This over-consolidation increases the inter-granular bonding and causes the improvement of the resistance of the soil to erosion.

3.2 Geometric methods to evaluate internal stability

The vulnerability to internal erosion by suffusion of the five soil mixtures is evaluated by the application of some geometric criteria proposed in the literature.

The Istomina model (1957) cited by (Wan and Fell 2004 [12]) classifies the internal instability of soils according to their uniformity coefficient (the soil is stable if Cu < 10).

The Kenney and Lau [21] method consists to create an H=f (F) curve from the soil's granulometric distribution curve. Where 'H' is increment of % passing that occurs over a designated grain size interval of D to 4D and 'F' is the % passing at grain size D. The comparison between the values of H and F is used to classify the soil as stable or unstable (if H<F the material is unstable while if H>F the material is stable).

Burenkova [22] assumes that the internal stability of a soil depends on the shape of its grain size distribution curve. Using the most representative fractions of the grain size distribution curve: d_{15}, d_{60} and d_{90} (where d_{15}, d_{60} and d_{90} presents respectively the sieve sizes for which 15, 60 and 90 % of the weighed soil is finer), the soil heterogeneity has been defined by the uniformity factors ($h' = d_{90}/d_{60}$ and $h''=d_{90}/d_{15}$). On the basis of these factors, the author proposed a boundary between stable and unstable soils.

Mao [23] divided the granulometric distribution curve of the soil at a given point (d_f, P_f) with $d_f=1.3\sqrt{d_{85}.d_{15}}$ and P_f is the percentage by mass corresponding to the diameter d_f. The soil will be considered stable if $P_f< 100(1/4(1-n))$ with n is the porosity of the soil.

The method of Wan and Fell [13] is based on two ratios: d_{90}/d_{60} and d_{20}/d_5 (where d_{90}, d_{60}, d_{20} and d_5 are the sieve sizes for which 90, 60, 20 and 5 % respectively of the weighed soil is finer).

The application of these models to the tested soil has been reported in the table 3. The geometric criteria of Istomina and those of Wan and Fell and Kenney and Lau (for the mixtures with less than 10% of fines) classify our soil as stable, while experimental results indicated that the soil is suffusive. The Burenkova and Mao criteria appear the most appropriate for predicting the stability of the tested soil. However, a closer analysis indicates that the Burenkova method has better predictive ability. But according to this method, the instability increases with the increase of the quantity of fines and that is contradictory with our results. For that, the influence of the initial percentage of particle fines must be taken into account for the use of this method.

Table 3 - Assessment of the mixtures vulnerability to suffusion

Criteria	Specimen S-F2	Specimen S-F5	Specimen S-F10	Specimen S-F15	Specimen S-F20
Istomina (1957) cited by [12]	Stable	Stable	Stable	Stable	Stable
Kenney and Lau [21]	Stable	Stable	Unstable	Unstable	Unstable
Burenkova [22]	Unstable	Unstable	Unstable	Unstable	Unstable
Mao [23]	Unstable	Unstable	Unstable	Unstable	Unstable
Wan and Fell [13]	Stable	Stable	Unstable	Unstable	Unstable

3.3 Determination of a critical hydraulic gradient

The results obtained in the previous sections show that the response of cohesionless soil to internal erosion depends on the composition of the soil matrix, its state of stress, on the hydraulic conditions (the hydraulic load) as well as on the combination of these different parameters.

The application of a geometric criterion is insufficient to evaluate the soil stability because at hydraulic loads below a critical value, suffusion is not triggered even if the soil is classified as geometrically unstable.

The suffusion is initiated in a geometrically unstable soil if the hydrodynamic forces generated by the flow are able to cause the detachment and the transport of the particles. The hydraulic gradient governing the onset of erosion is called the 'critical hydraulic gradient'. The value of the critical hydraulic gradient has been determined according to several authors by the measurement of the hydraulic gradient just after the appearance of the first signs of erosion (detachment of particles inside the simple).That can cause an underestimation of the value of the critical gradient because of probable errors of manipulation and reading.

For the determination of the critical hydraulic gradient, the methodology proposed in this work consists in calculating the rate of erosion per unit surface area of the sample at time t (g/sec.m2) for a given quantity of fines and axial stress. Then the variation of this erosion rate according to the applied hydraulic gradient is represented. The value of the critical hydraulic gradient corresponds to the value of the hydraulic gradient for a zero erosion rate. For example, the variations of the erosion rate as a function of the applied hydraulic gradient for the specimen with 10% of fines and solicited with axial stress equal to 50 kPa is presented in Fig.19. A correlation between the erosion rate and the applied hydraulic gradient is presented by the following formula: (E = 0.893 i – 3.550, r = 0.99).The interpolation of this curve for a zero erosion rate allows us to determine the value of the critical hydraulic gradient(i_{crt}= 3.97 m/m for 10% of fines and σ_a= 50kPa).

In the same way, the value of i_{crt} is determined for the different percentages of fines under the same axial stress. The critical gradient for suffusion was linearly correlated with the fine content (Fig.20, σ_a = 50KPa).

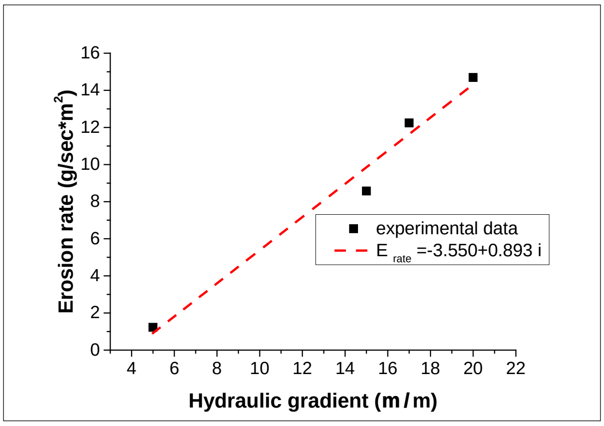


Fig. 19 –Erosion rate as a function of the hydraulic gradient (10% fines, σ_a= 50kPa)

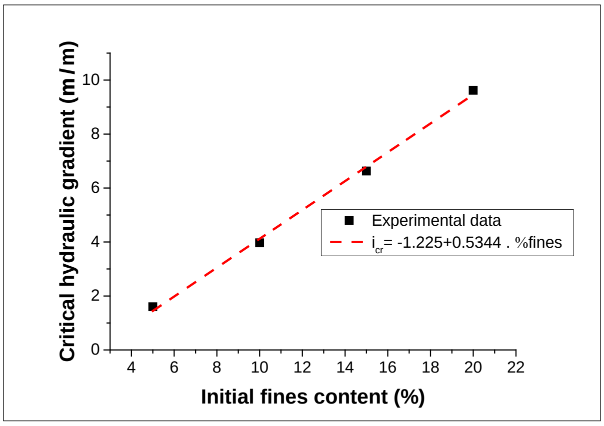


Fig. 20 –Critical hydraulic gradient as a function of the initial fine content (σ_a= 50kPa)

The variations of the critical gradient as a function of the percentage of fines for the different values of the axial stress are given by the following relationships:

$$\sigma_a = 50\text{ kPa}: i_{crt} = -1.225+0.5344*\%\text{ fines } (r = 0.98)$$

$$\sigma_a = 100\text{ kPa}: i_{crt} = -1.205+0.5426*\%\text{ fines } (r = 0.95)$$

$$\sigma_a = 150\text{ kPa}: i_{crt} = -0.705+0.7416*\%\text{ fines } (r = 0.98)$$

The susceptibility of the cohesionless soils composed of sand and non-plastic fine particles will therefore be evaluated hydraulically by comparing the hydraulic stress and the critical gradient given according to percentage of fines and the state of stress of the soil.

4 Conclusion

To estimate the initiation and development of suffusion two methods are proposed: a geometric approach and the hydraulic approach, little work was interested in the combination of the two approaches to evaluate the soil erodibility. The aim of our work is to determine a relation between the hydraulic loading and the soil characteristics to evaluate the susceptibility to suffusion of the cohesionless soils. A parametric experimental study was conducted on mixtures of sand and fines. A tested soil is collected from Kharrouba region situated in the north east of the city of Mostaganem (North West of Algeria). Silica flour is used to model the fine fraction. Mixtures of sand and fines with different percentage are subjected to a seepage flow. The parameters studied are the initial percentage of the fines, the hydraulic gradient and the axial stress. Our experimental approach is based on the quantification of the fine particles drained by the flow as well as the monitoring of the evolution of the hydraulic characteristics of the medium. On the basis of the combination of the interactions between the studied parameters and their contribution on the response of the soil, an empirical formula linking the erosion rate and the hydraulic gradient has been proposed. A critical value of the gradient can be determined from this correlation. A relationship is proposed to evaluate the hydraulic gradient which triggers the internal erosion according to the quantity of fine particles and the state of stress of the soil.

Although the proposed methodology must be checked for other soil types, it can be used as a decision support tool for future development works in the studied zone; this will contribute to the reduction of risks and to the improvement of the protection of the site against erosion.

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