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Anisotropic permeability evolution of high void ratio soil under static compression (a case study on clayey loess soil)

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Abstract:

Decreasing the void ratio of soil due to static compression causes soil structure changes and developing anisotropic structure. This phenomenon as a common result causes the development of anisotropic permeability ratio (k_h/k_v or r_k). When the soil shows a high void ratio, it generally contains macropores that have the most effect on the permeability, soil structure changes, and r_k evolution during compression. Thus, in this research, two high void ratio samples of clayey loess soil with a granular structure (containing macropores) were prepared to investigate the r_k evolutions during one-dimensionally static compression. So, horizontal and vertical permeability of samples were measured at each new void ratio, from high to low values. The tests implemented by a 3D permeameter apparatus that was designed for this research. This apparatus was equipped with a camera to study the soil macrostructure changes during tests. The results show that r_k have different trends during compression, so, three stages of permeability anisotropy variations recognized as A, B and C. At high void ratios (stage A), the connected macropores produce high pseudo anisotropic permeability that rapidly decreased during compression. At low void ratios, r_k increased due to particle orientation. The Stage B that has minimal values of r_k with low variations is the transition stage from A to C stage.

Keywords: Vertical and horizontal permeability; soil structure; void ratio; macropore; particle orientation

1. Introduction

When a saturated fine-grain soil sample is put one-dimensionally and statically under compression, the structure of the soil would be anisotropic since the soil particles move and rotate perpendicular to the load axis. Low compressed soils present less anisotropy consequently, higher compression or consolidation causes higher anisotropy (Basak, 1972; Chapuis and Gill, 1989; Cetin, 2004; Adams et al., 2013; Chai et al., 2015; Laskar and Pal, 2018; Chow et al., 2019).

Permeability parallel to the soil particles is higher than any other direction (e.g. perpendicular as Min. value), so the maximum and minimum permeability named k_h and k_v respectively (Yong and Warkentin 1975; Chapuis et al. 1989). The k_v and k_h are both the common permeability that are standard; the difference is that in k_h the direction of water movement inside the sample is different and is perpendicular to the usual test or the same k_v.

The ratio of maximum to minimum permeability is (k_h/k_v) called anisotropic ratio (r_k) (Al-Tabbaa and Wood, 1987; Chapuis and Gill, 1989; Arch and Maltman, 1990; Leroueil et al., 1990; Brown and Casey Moore, 1993; Dewhurst et al., 1996; Zhang et al., 1999; O'Kelly, 2006; Scholes et al., 2007; Malinowska and Szymanski, 2015).

As a common result of previous researches, when the void ratio (e) of soil decreased due to static compression or consolidation, the anisotropic permeability increased (Basak, 1972; Wilkinson and Shipley, 1972; Al-Tabbaa and Wood, 1987; Scholes et al., 2007; Adams et al., 2013; Bayesteh and Mirghasemi, 2015; Chai et al., 2015; Dai et al., 2019).

When the soil has a high void ratio, it generally contains macropores that could affect the permeability and soil structure during compression, because:

Firstly, macropores have the most effect on the permeability due to controlling water flows (Mesri and Olson, 1971; Beven and Germann, 1982; Jang et al., 2011). Reducing the void ratio eliminated macropores and increased the contri-

bution of micropores to permeability (Yong and Warkentin, 1975; Dexter et al., 2004). Such a phenomenon is expressed as a cluster model by (Olsen, 1962). This model assumes the porous equidimensional clusters with uniform size. Fluid flow in such a system is dominated by the flow through the intercluster pores rather than the intracluster pores due to their larger size.
Secondly, as load advances, the macropores sizes reduce faster than micoropores (Alakukku, 1996; Olsen, 1962). During the soil consolidation, larger pores are closed first (Delage and Lefebvre, 1984; Griffiths and Joshi, 1989; Assouline et al., 1997; Dijck and Asch, 2002; Lipiec et al., 2012; Yu et al., 2016; Chow et al., 2019). Such phenomenon could affect the soil permeability, and thus, rk varies as static load applies further.
Thirdly, preferential orientation appears in soil due to the deformation of the pores Murphy et al. (1977), Berli (2006), Eggers et al. (2007), and Chow et al. (2019) and in soils, pore orientation is related to its consolidation (Cetin, 2004). Therefore, macropores shape and size changed during compression and affected the soil anisotropic structure and consequently the r_k.
So, it is expected that the above three points affect the evolution of anisotropic permeability of high void ratio soils during the void ratio decreasing. In the present research, it's tried to investigate this phenomenon under one-dimensional static compression of soil. For the experiment series, the samples were selected from loess soil in Golestan province because of the wide distribution over a vast area in northern Iran. Irrigation in loess soil is always a challenge in northern Iran, due to the difference in void ratio generated during the deposition of the particles or human activities. This soil often used as the construction material for earth dams and artificial ponds in which the phenomenon of leakage is vital. Besides, infiltration of surface water through this widespread soil to the groundwater and subsequent effects such as groundwater recharge or pollution are matters of concern.
Thus, a uniaxial stress was forced on the two selected clayey loess soil samples made with the highest possible void ratio values (e) to determine r_k variation from high to low void ratios. The horizontal and vertical permeability (k_h and k_v) of samples was measured at each step of generating a new void ratio during compression by a 3D permeameter apparatus designed for this purpose (k_{h1} and k_{h2} as components of k_h).
One of the important requirements for conducting this research was to study the soil structure changes especially macropore deformation on the permeability. There are some methods to observe soil structure and study its changes during compression. But during continuous compression of samples by this apparatus, there are limitations to employ the observation methods, so, the apparatus was equipped with a camera located on the cell to capture images used for studying soil macrostructure changes and interpretation of the results. It must be noted that macropores generally defined as pores larger than 75 μm (Clothier, 2008). Since our camera could only recognize pores larger than 50 μm, this research is focused on studying the macropores.

2. Loess samples and specifications

Loess is an aeolian deposit that is abundant in north eastern Iran, particularly in Golestan province. Khajeh et al. (2004) found that the gradation of these soils varies in different locations. In Golestan province, due to the sedimentation facies and geotechnical characteristics, loess soil deposits would be divided into three regions. (Fig. 1) (Rezaee et al., 2011).
Clayey loess soils in region-1 (Fig. 1) spread in foothills and have a higher percentage of fine particles. Often populated

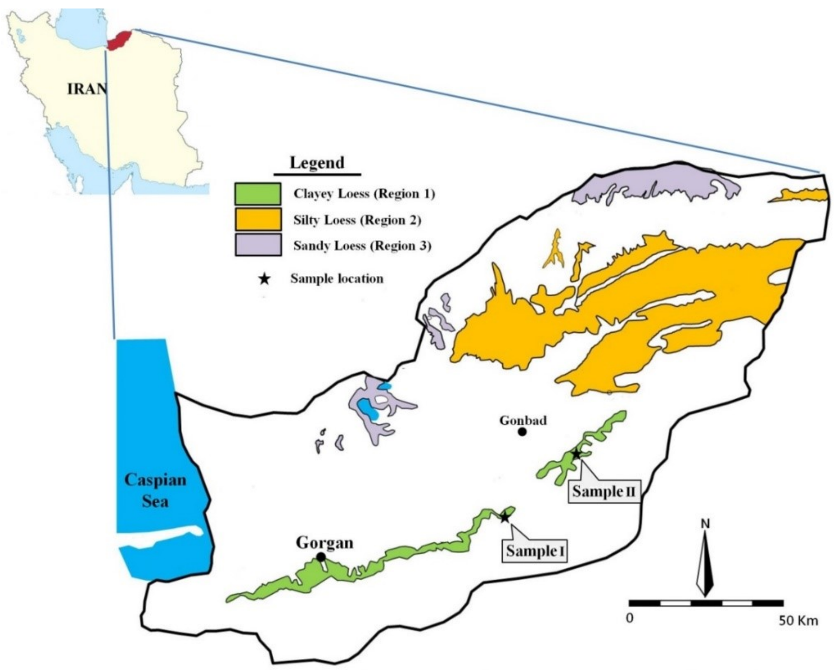

Figure 1. Schematic diagram of photocatalytic mechanisms of ZnO nanoparticles to destruct the bacteria.

areas such as towns and villages are located in this region. Thus, two clayey loess samples with no organic matter were selected from region-1 and from materials used for the construction of Ramian dam (sample I) and Narmab dam (sample II). Their particle size distribution prepared by sieve analysis and hydrometer test (Fig. 2). Some specifications of the samples are shown in Table 1.

3. Test apparatus

Various researchers have used various methods to control the movement of water and obtain k_h (Rowe and Barden, 1966; Al-Tabbaa and Wood, 1987; Chapuis and Gill, 1989; Arch and Maltman, 1990). To implement the tests, a special 3D permeameter apparatus designed and built to apply the static load for consolidating the loose soil with high void ratio one-dimensionally. The consolidation started from a high void ratio. Then, the permeability was measured horizontally and vertically at the end of each compression step. The layout of the test apparatus is illustrated in Fig. 3. Both k_h (k_{h1} and k_{h2}) and k_v values would be measured by this apparatus using falling and constant head methods.
The k_v is measured through passing water flow from the whole bottom section of the cell via porous stone toward the upper part of the cell. Four sides of the cell have openings provided by porous stones with a diameter of 2.5 cm. Two components of k_h (i.e., k_{h1} and k_{h2}) are measured from these openings. Another capability of the test apparatus is to observe soil macro-structure by the cell wall-mounted camera. Pictures captured from this camera help to monitor the soil macro-structure evolution during soil deformation. To validate the permeability values measured by the apparatus, a Darcian based model was run to investigate the effect of cross-section discrepancy in horizontal and vertical flow. The results confirmed that no adjustment is required in the values of measured permeability.

4. Samples preparation and test method

Soil samples selected from excavated loess soil and extracted for the construction of Ramian and Narmab earth dams. These loose soils with natural moisture passed through sieve No. 10 (2mm) to obtain a homogenous soil. To generate a very loose sample, soil was poured slowly into the cell through a long funnel to make high void ratio. Then, the load piston was placed on the sample and the valves were properly closed and sealed.
Then, the valves were being opened to saturate the soil slowly by replacing air within the sample (Fig. 3).
The weight of the soil poured into the cell is known, so by having the cross section of the cell and the height of the soil sample that can be read from the gauge, the soil volume and e value can be determined at each stage of the experiment. After each step of soil compression by increasing the static load, the sample was left to reach a new equilibrium state. Like the consolidation test, the consolidation was allowed to complete for at least 24 hours and the vertical displacement to end. Even if 24 hours were not enough to end the vertical displacement, time was still allowed for the vertical displacement to end. When the displacements value reached zero, the k_{h1}, k_{h2} and k_v values were measured separately by assuring the steady state water flow. To achieve steady state conditions, permeability was not measured immediately after opening the valves, but water was allowed to pass through the sample for some time until the effect of stress and other factors on the flow through disappear and the flow reaches a uniform state.

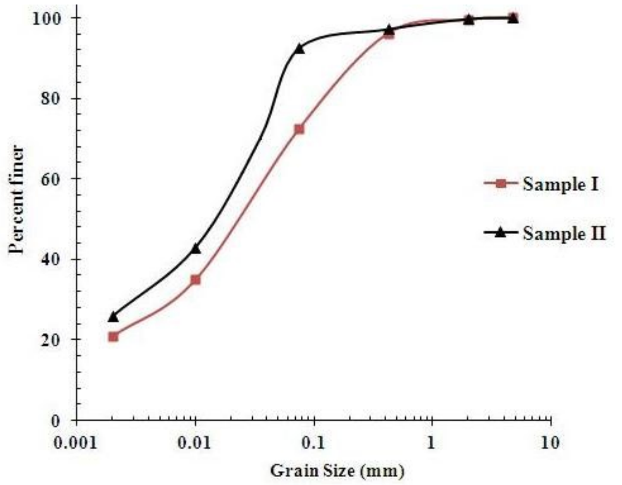

Figure 2. Schematic diagram of photocatalytic mechanisms of ZnO nanoparticles to destruct the bacteria.

5. Results and discussion

5.1 Macro-structure changes

Soil structure was examined through each experiment using camera images. This camera provides a nearly 3 mm field of the sample view with pore sizes larger than 0.05 mm. Some of the selected images illustrated in Figs. 4 and. 5 for the samples I and II, respectively.
Before starting the tests, the dry soil samples had loose compaction due to the preparation process which lead to a high void ratio with a granular structure. These soil samples are dominantly composed of large aggregates of clay and silt Liu et al. (2016), which make the sample skeleton. The large units composed of fine particles such as fine sand, silt

Table 1. Soil samples specifications

sample	Location	Unified Classification	Texture	Liquid Limit (%)	Plasticity Index (%)	Gs	Sand 0.075-2 mm	Silt 2-75μm	Clay <2 μm
I	Ramian Dam	CL	Silt Loam	30	11	2.68	28%	51%	21%
II	Narmab Dam	CL	Silt Loam	34	14	2.72	8%	66%	26%

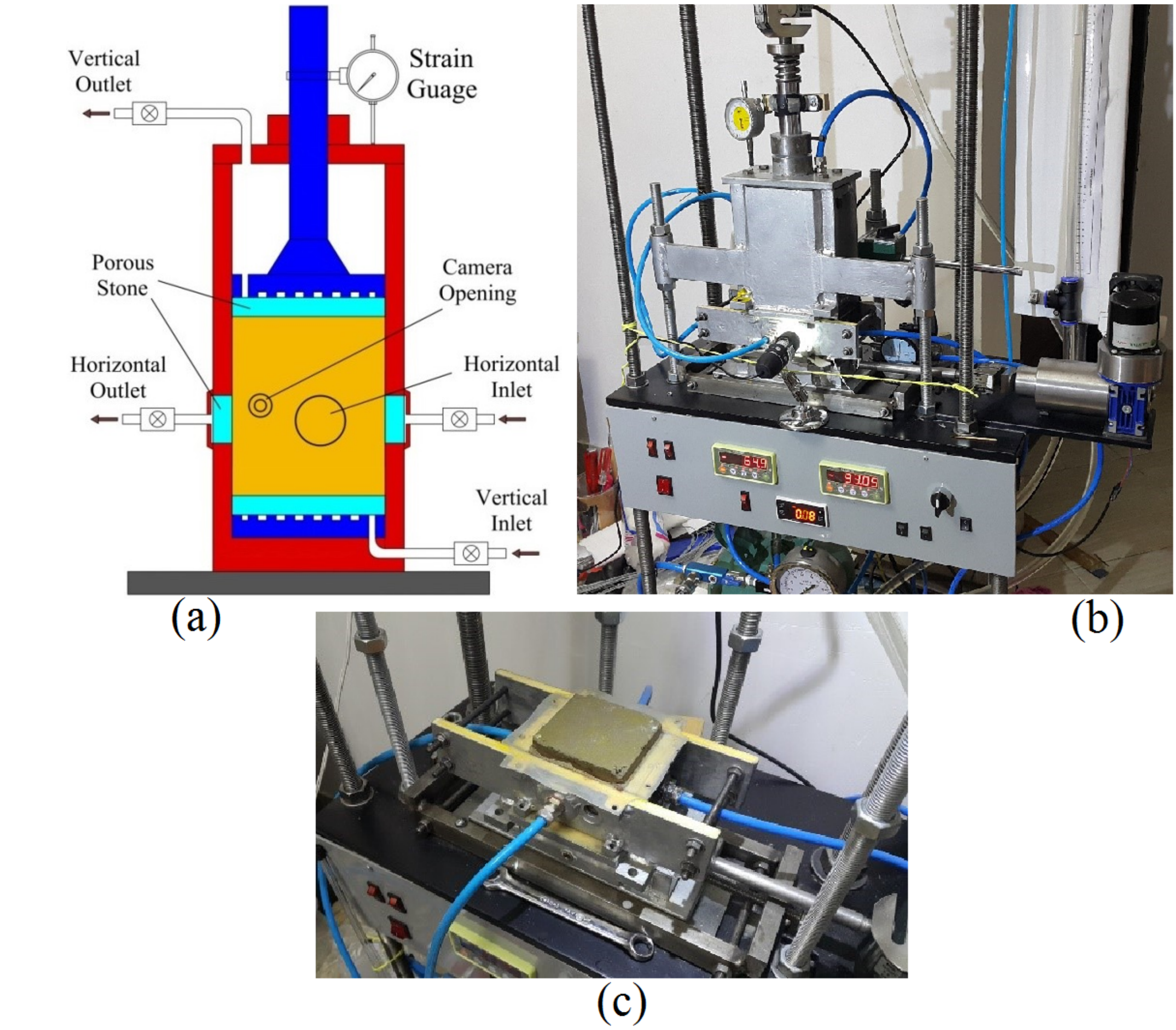

Figure 3. (a): The layout of the 3D permeameter apparatus, (b): The apparatus during test, (c): Consolidated sample after testing (here, the blue pipes are used for water flow to measure the k_{h1} and k_{h2}).

and clay particles. (Figs. 4 a and. 5 a). A simplified soil sample structure illustrated in Fig. 6.

Distribution of micro and macropores in such soil structures has been reported by Yong and Warkentin (1975), Delage and Lefebvre (1984), and Alaoui et al. (2011). Macropores distributed among large units, whereas, micropores distributed within large units (Fig. 6).

After saturation and before applying a static load, the void ratio of samples decreases due to the soil and water interaction and natural disturbance of soil structure (Figs. 4 a and. 5 b). Then, the soil compression occurred just by applying static load. As void ratio decreases, macropores size and number and consequently the pore size distribution change (Yu et al., 2016; Chow et al., 2019) (Figs. 4 c-i and. 5 c-i). Here, some differences of large units' deformation and macropores distribution patterns in two samples could be recognized. During static compression, the large units in the sample I crushed and caused the macropores to develop intra large units rather than around them; whereas the large units in sample II do not crush but deform as flexible grain and macropores concentrated their borders. The likely reason is that the sample II has more plasticity index than the sample I (Table 1) that caused large units to behave like a deformable grain (Enayat et al., 2018). So, the mechanical behavior (friability or flexibility) of large units during deformation affects the pore size distribution pattern and also the permeability.

From the beginning of test, the large units started to deform and merge. Simultaneously, the macropores began to deform and usually flatten. Although, some of them do not show any observable flattening but some deformation due to isotropic closing of macropores. Flattening of macropores might be observed perpendicular to the loading axis. A closer look revealed that incomplete macropore flattening and their orientation perpendicular to the applied load is due to the effect of adjacent large units. In fact, during compression, large units show a relatively stable structure that determines the macropores geometry. As macropores closed during compression, they concentrated among the large units. Following this process, a single macropore at a small scale may not show flattening perpendicular to load axis but they can connect horizontally together and make

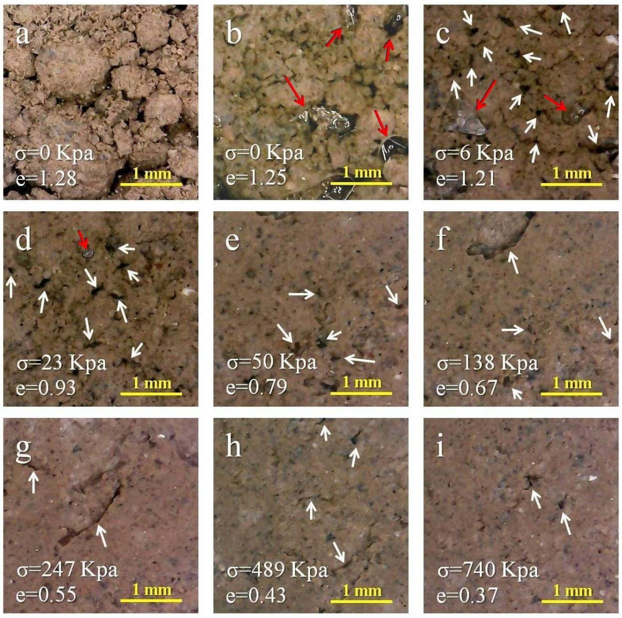

Figure 4. Soil macro-structure evolution under one-dimensional and static compression for sample I (load axis direction is from top of the image. The white arrows are macropores and red arrows indicate air bubbles).

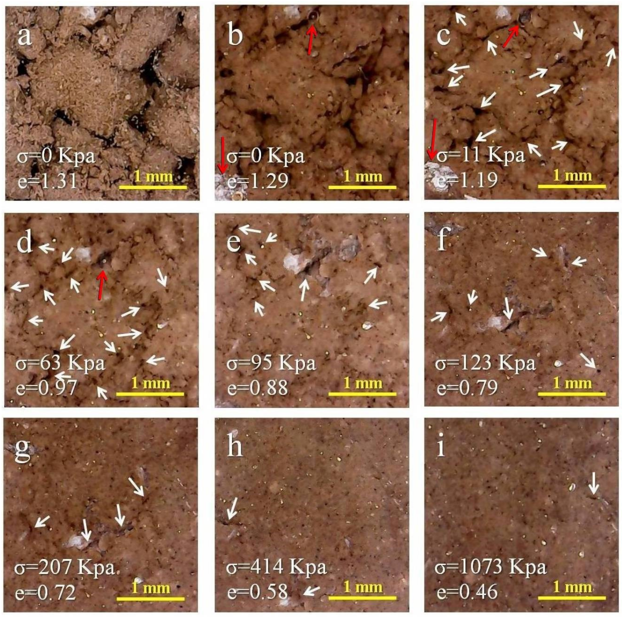

Figure 5. Soil macro-structure evolution under one-dimensional and static compression for sample II (load axis direction is from top of the image. The white arrows are macropores and red arrows indicate air bubbles).

anisotropic structure at large scale.

As compression proceeds, the macropore sizes become smaller and their number and also their connection decrease, so, at low void ratio values, whole macropores close and samples have dense appearance (Figs. 4i and. 5i). Here, few small macropores may have remained that will be closed by applying the higher static load.

5.2 Permeability test results

Variations of horizontal (k_{h1} and k_{h2}) and vertical (k_v) permeability values corresponding to the void ratio at each step of progressive compression for sample I and sample II, are illustrated in Figs. 7 and. 8, respectively. The permeability values were measured in relatively equal intervals of void ratio reduction. Unfortunately, in high void ratios ($e>1$ to 1.1), measuring permeability was difficult or caused errors and thus, results had uncertainty. In a high void ratio, the soil sample is very loose and behaves like a fluid. Applying even a little water head for the permeability test disrupted soil structure. Based on our experience, measuring the permeability with very low water head to prevent sample disturbance caused the results to be much underestimated. Besides, existed large voids and channels in the sample body might produce some preferential flow paths with variable throats that strongly affect the permeability. Hence, the measuring permeability in very high void ratios cannot be trusted by regular methods. Several samples were prepared to find out the permeability changing behavior in a very high void ratio.

Presented results in this paper gained from samples that have the least changes and the most logical outcomes. However, failed or uncertain data (for $e>1$ to 1.1) for these samples were removed and relatively certain results were plotted. Increasing static load, the samples become more densified and integrated which eliminated these problems. Generally, the permeability variation pattern of samples I and II was similar (Figs. 7 and. 8). The decrease in k_v is relatively uniform resulting a linear relationship between e and k_v in logarithmic scale. This finding agrees with what is reposted by other researchers (Taylor, 1948; Lambe and Whitman, 1969; Nishida and Nakagawa, 1969; Mesri and Rokhsar, 1974; Bryant et al., 1975; Tavenas et al., 1983; Al-Tabbaa and Wood, 1987; Leroueil et al., 1990; Daigle and Screaton, 2015). However, as shown in the Figs. 7 and. 8, the reduction of k_h is different from the decrease of k_v and is not linear. This point might be arises from evolution of soil structure such as particle orientation, pore size and pore geometry especially in macropores during compression. For example, probably there is the lack of effective continuity between macropores in the vertical direction; i.e., discontinuity. When the load is applied to the soil column, the peds are flattened. Afterward, due to the fixed cross section area through the one-dimensional deformation, peds connect together, leading to the prevented continuity of inter-ped pores in the vertical direction. This will eliminate the effect of macropores on k_v especially at high void ratio and causes it change linearly unlike k_h.

5.3 Anisotropic permeability evolutions

Anisotropic permeability ratio (r_k) of samples I and II show a varying trend during the compression (Fig. 9). The general variations of r_k (including the reducing r_k with reduction of e) are similar for both samples I and II: from the start of the experiment, r_k reaches the maximum level. By adding the compression level, a rapid decrease in r_k was observed falling to a minimum level. Then, around the average value of void ratios, r_k has reached the minimal with relatively small variation through compression increments; however,

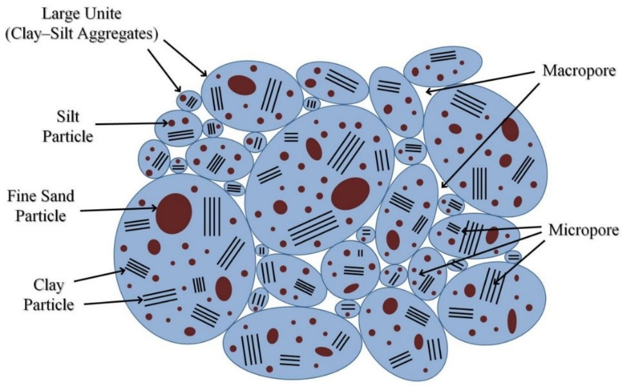

Figure 6. The concept of large unit and other soil components in a simplified soil structure of samples.

it rises again at low void ratios.

Nevertheless, there are some differences in the variations of r_k for two samples. Sample II has a higher percentage of clay particles and plasticity index (Table 1) that caused its ped grains have more cohesion and Integrity. So, at high void ratio ped grains of sample I disintegrated sooner than sample II (As seen in Figs. 4 and. 5) that caused affect macropore size and its connections. This phenomenon causes sample II shows larger k_v and as a result r_k at high void ratio due to existence of larger pores relative to sample I. also, at low void ratio, due to the higher percentage of clay in sample II, parallel orientation of particles develop better relative sample I and show higher r_k value. The r_k variations imply the soil structure evolutions. Thus, three stages might be recognized as stages A, B and C (Figs. 7, 8 and 9).

In Stage A, when the void ratios are high, there are high r_k values, because of the effects of macropores. A high amount of anisotropic permeability in this stage shows that connected macropores have the main role in controlling water flow and producing anisotropic structure; it might be due to a pseudo anisotropic permeability (Yong and Warkentin, 1975). Most macropores rapidly closed by proceeding compression (Figs. 4c-e and 5c-e). This process is along with the previous researcher results stated during compression, the macropores first closed relative micropores (Delage and Lefebvre, 1984; Griffiths and Joshi, 1989; Assouline et al., 1997; Dijck and Asch, 2002; Lipiec et al., 2012; Yu et al., 2016; Chow et al., 2019). So in this stage, the void ratio decreases via macropore deformation and closing. Although fine particles resort within larger units, they do not show a preferential orientation.

This stage begins with an increase in the r_k, then due to the additional compression, the r_k reduces to reach minimum level. The rise of the r_k at the beginning of the experiment might be because of the deformation of macropores and the role they play in generating a large pseudo anisotropic permeability. Subsequently, a reduction in r_k happens when the large soil units merge, macropores loss, and interruptions in the flow paths.

At B stage, large units relatively disappeared and some closing macropores can be seen as scattered with no connection between them (Figs. 4f-g, 5f-g). Consequently, the void ratio is likely to reduce at this stage through decreasing the size and number of macropores as well as micropores. By disappearing the large units due to merging and macropores closing, the soil particles started to make the soil body skeleton instead of large units and thus, applied load would directly be transferred to them. However, the minimum value of r_k is observed in this stage because of the lack of macropores and their effective connections, and the particles orientation is not developed enough to present a major effect.

At the Stage of C, the sample is completely compressed and few remained macropores are closing. The small macropores may exist in the soil body (Fig. 4h,. 4i,. 5h, and. 5i). It is expected that the void ratio decreasing continues mostly by a decrease in micropore dimensions and freeing space via particle rotation. The rk gradually increases during the compression due to the development of particle orientation. Although rearrangement of soil particles occurred in stages A and B, real preferential orientation is shaped only in stage C. In other words, the anisotropic permeability changing behavior in stage C coincided with the common results of the previous researches. Therefore, it can be concluded that as long as macropores are present in the soil, they prevent the formation of particle preferential orientation.

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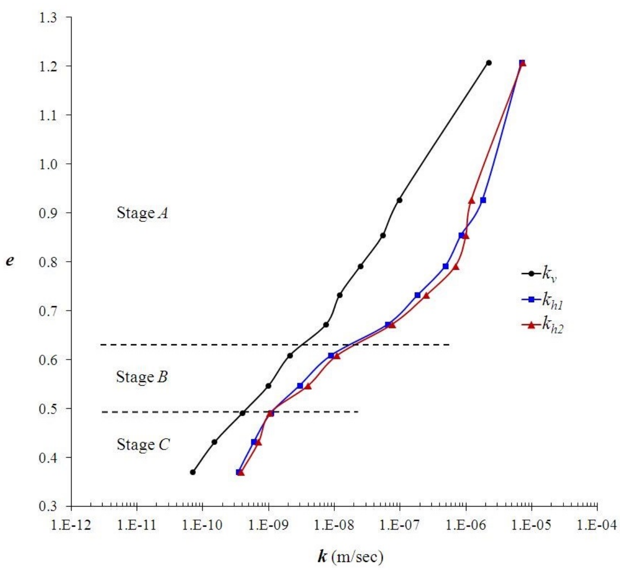

Figure 7. Variations of the k_h (including both components of k_{h1} and k_{h2}) and k_v values of sample I during static compression.

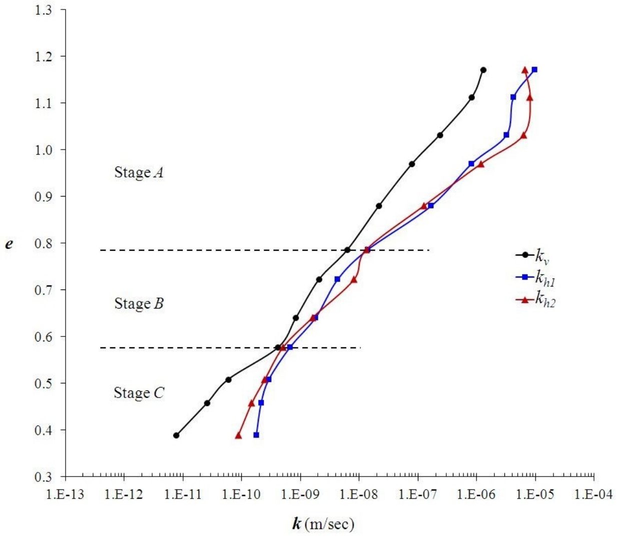

Figure 8. Variations of the k_h (including both components of k_{h1} and k_{h2}) and k_v values of sample II during static compression.

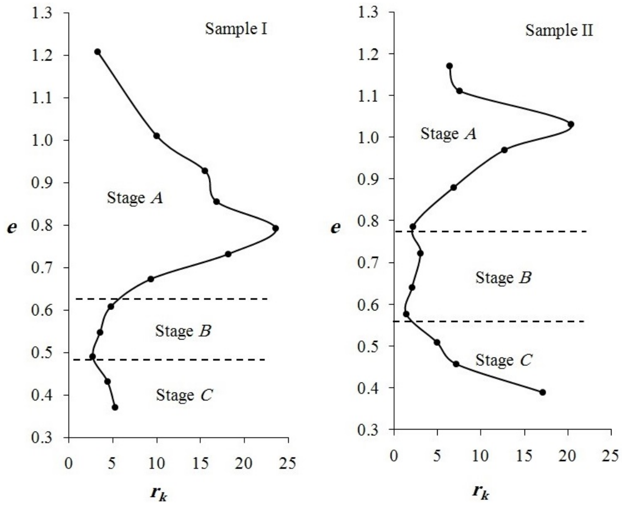

Figure 9. Anisotropic permeability ratio (r_k) variations of the samples during the static compression (Here the r_k is average of k_{h1}/k_v and k_{h2}/k_v values).

size and number of macropores as well as micropores. By disappearing the large units due to merging and macropores closing, the soil particles started to make the soil body skeleton instead of large units and thus, applied load would directly be transferred to them. However, the minimum value of r_k is observed in this stage because of the lack of macropores and their effective connections, and the particles orientation is not developed enough to present a major effect.

At the Stage of C, the sample is completely compressed and few remained macropores are closing. The small macropores may exist in the soil body (Fig. 4h,. 4i,. 5h, and. 5i). It is expected that the void ratio decreasing continues mostly by a decrease in micropore dimensions and freeing space via particle rotation. The r_k gradually increases during the compression due to the development of particle orientation. Although rearrangement of soil particles occurred in stages A and B, real preferential orientation is shaped only in stage C. In other words, the anisotropic permeability changing behavior in stage C coincided with the common results of the previous researches. Therefore, it can be concluded that as long as macropores are present in the soil, they prevent the formation of particle preferential orientation.

In addition to stages A and B, macropores may be found even in the stage C, but the effects of macropores on permeability and r_k can only be seen in stage A. The reason is that in high void ratios such as stage A, macropores are connected to each other and control water flow. But in stages B and C, they do not have a definite effect on permeability due to their disconnection from each other. Therefore, the connection of macropores to each other plays an important role in permeability and the variation of permeability anisotropy.

Step B is the transition from stage A to stage C. During this stage, the effects of macropores are eliminated and by tolerating the applied load by soil particles instead of large units, preferential orientation of the soil particles begins, but their orientation has not yet been developed to some extent that affects r_k.

6. Conclusions

The test results show that samples r_k values have different trends (incremental and decremental) during compression. Generally, these r_k variations pattern is similar for both samples and implies that changes resulted from soil structure variations. So, three stages of r_k variations recognized as A, B and C.

However, in detail, there are some differences in the variations of r_k for two samples. Sample II with higher percentage of clay particles and plasticity index, has more durable ped grains under static load that causes this sample to have relatively larger pores at high void ratio. So sample II shows larger r_k at high void ratio due to existence of large pores and pseudo anisotropic permeability. Also, at low void ratio, parallel orientation of particle relatively developed better in sample II due to the higher percentage of clay in sample II and show higher r_k value.

Due to sample preparation process, samples have a high void ratio with the granular structure, where there are many large-scale macropores among large units. As the void ratio decreases, the number and size of macropores decreases rapidly, but even at low void ratios, few number can be observed. However, the results of experiments show that the effect of macropores on r_k can only be seen in relatively high void ratios (stage A); Because at high void ratios, r_k decreases rapidly as the compression increases, contrary to the usual results. Because in the stage A and at high void ratios, the macropores are interconnected, controlling the flow of water and causing a high pseudo anisotropic permeability. In this stage, decreasing void ratio, in addition to reducing the number and dimensions of macropores also causes them to disconnect from each other and brings a rapid decrease in r_k.

However, in the case of moderate void ratios (stage B) and despite the presence of macropores, r_k does not change much. In the case of low void ratios (stage C), where some macropores are still detectable, the amount of r_k shows an increasing trend. This suggests that in the stage A and at high voids ratio, the macropores are interconnected, controlling the flow of water and causing a high pseudo anisotropic permeability. In this stage, decreasing void ratio, in addition to reducing the number and dimensions of macropores, also causes them to disconnect from each other and brings a rapid decrease in r_k.

In stages B and C, the macropores are seen separately from each other and scattered in the sample, which is not effectively related to each other. At low void ratios (stage C), the r_k value increases with increasing compression, indicating that the preferred orientation of the particles is developing. In moderate void ratios (stage B), the amount of r_k is the lowest and shows limited changes during the reduction of the void ratio. This stage is a transition from stage A to C. That is, the effect of the macropores disappears and the load applied to the sample is transferred to the soil particles instead of large units, and the particles begin to orient. However, because the preferred orientation is not sufficiently developed, the r_k value at this stage is minimal.

Therefore, in high void ratio soils containing macropores, in addition to the orientation of soil particles, the macropores also affect the anisotropic permeability changes. Besides, the connection of macropores to each other plays a very important role in controlling water flow and creating a high pseudo anisotropic permeability. Macropores also prevent the development of preferential orientation in soil particles unless they are closed.

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Authors Contributions
All authors have contributed equally in preparing the paper.

Availability of Data and Materials
Data is available on request from the authors. The data supporting this study's findings are available from the corresponding author, upon reasonable request.

Conflict of Interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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