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SHEAR RATE EFFECT ON GRAIN CRUSHING OF SANDS. A LABORATORY STUDY BY THE BROOMHEAD APPARATUS

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Abstract

Large scale landslides have been related to the dramatic decrease of the undrained shear strength of sands along the slip surface. This decrease of shear strength has been attributed to the crushing of sand grains. Landslides may appear to have a wide spectrum of speeds from extremely low (0.3 meters every 5 years) to moderately fast (1.5 meters per month), to extremely rapid. This paper studies the influence of the shear rate on grain crushing of sands, experimentally. It is reported in the literature that even significant changes in shear rate usually play an insignificant role in the shear stress paths of samples, as long as the tests are kept drained. Nevertheless, according to new studies when the changes in shear rates become very large the changes in grain crushing may be of importance. In order to study the effect of shear rate on grain crushing, a new series of tests was performed. The tests were conducted in the Bromhead Ring Shear device at the Soil Mechanics and Foundation Engineering Laboratory of the Department of Civil Engineering at the Demokritos University of Thrace. The specimens used were of the same geometry, from the same materials (with the same density). They were sheared under equal normal stresses at variable shear rates by taking full advantage of the Bromhead apparatus capabilities. These tests were stopped at increasing displacements up to the final point (1m). This way, the study of progress of the grain crushing phenomenon was possible for each speed as well as the comparison of the grain crushing phenomenon for variable speeds.

Keywords: Bromhead, Ring Shear Apparatus, Sands, Landslides, Grain Crushing.

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1 INTRODUCTION

Landslides occur every year somewhere in the world due to earthquakes, rainfall, and other agencies such as engineering activities [1].The impact of landslides can be extensive as it may include loss of lives, destruction of infrastructure, damage to land, destruction of farmer's livelihoods [2]. Although many parameters affect landslides, grain crushing of sand layers within the shear zone formed is often considered key to rapid motion. In fact, since 1996 Sassa et al [3] proposed the concept of sliding surface liquefaction in which grain crushing was considered to have an important effect on excess pore pressure generation.

In order to study landslides that usually involve large displacements of materials, the most appropriate apparatus is found to be the Ring Shear Device. The Ring Shear Device uses a ring shaped cell which rotates around its central axis, thus eliminating to some degree shear displacement limitations and it is mainly used to find residual shear strength. It was initially developed by Hvorslev [4] and [5]. La Gatta [6] Bishop et al [7] and Bromhead [8] also contributed later on with changes to the initial design. Sassa since 1984 [9] has developed a low stress high speed ring shear apparatus for the research of motion of debris flow. Later on, he made several variations to his initial design. Nevertheless, today the only two types that are commercially available are the Bishop and the Bromhead type. The Bromhead type of ring shear apparatus is today more widely used in laboratories around the world because of its lower cost and ease of use, when compared to the more sophisticated apparatus developed by the Norwegian Geotechnical institute and Imperial College [7] aka the Bishop apparatus. Despite this, it has been showed that drained residual strength values measured at the Bromhead apparatus are in good agreement with those calculated at the Bishop apparatus [10], while similar values coincide with those found by back-calculated analysis for landslides at Warden Point and South California [11] , and the Wenallt slip [12].

The main factor that differentiates the Bromhead apparatus from the Bishop device is the dimensions and mechanism of the cell. The Bromhead apparatus uses a rather shallow ring shape cell, 5 mm deep, and a similar ring shape cap. Torque is applied to the cell and while it rotates, shear stress is measured by measuring the force necessary to keep the cap immobile. Because of the limited dimensions of the cell the Bromhead apparatus is mainly used to test the shear strength of silts, as there is the fear that sands may form a shear zone when tested that is obstructed by the cell's limited depth and the results taken compromised. Nevertheless, it was found that under certain conditions of initial granulometry of the materials tested, normal stress and length of the shear displacement, the Bromhead apparatus is able to provide reliable results for sands [13]. It deserves mentioning that the manuals of the apparatus do not refer any limitation as far as the materials to be tested.

2 SHEAR RATE IN BROMHEAD RING SHEAR APPARATUS TESTS AND ITS INFLUENCE ON THE GRAIN CRUSHING PHENOMENON IN SANDS.

In this paper the influence of shear rate in the Bromhead Ring shear apparatus is studied with tests executed at the Soil Mechanics and Foundation Engineering Laboratory of the Department of Civil Engineering at the Demokritos University of Thrace. A new series of tests was executed with variable shear rates and progressive shear displacements by using three types of sand, silica, calcareous and quartzitic and applying the same Normal stress. The purpose was to determine if the shear displacement rate variance, (faster vs slower) influences the grain crushing phenomenon.

We know by the bibliography that as long as a drained behavior is achieved "within reasonable limits, then, the rate at which a cohesionless soil is sheared is not important" [14]. Nevertheless at the same source, Lambe, we find at the triaxial testing for cohesionless soils section that "Tests on one type of dry sand indicated only a 10% increase in strength when the elapsed time from the start of loading to the time of maximum compressive stress was decreased from 1000 seconds to 0.01 second". So it is recognized that when the time of loading is decreased substantially, thus the shearing speed is increased, there is a noticeable increase in strength. Shear strength or resistance is the fraction τ/σ so for the fraction to increase, by keeping the normal stress σ constant, τ increases. In triaxial testing the displacements are minimal when compared to those achieved in the Ring Shear apparatus, thus a small increase may alter significantly the end result in large deformations.

The first study found from our bibliographical research to point differences in shear stress when different shear speeds are applied to the Ring Shear apparatus was Fukuoka et al [15]. As can be seen in Figure 1 and Figure 2 differences in shear speed caused differences in shear stresses, although grain crushing percentages were not considered changed.

On the contrary a more recent paper by Okada, Sassa, Fukuoka of 2004 [16] as can be seen on Figure 3 reports an increased grain crushing percentage in sands in relation to the increased shear stress caused when high shear speeds are applied to Ring Shear tests.

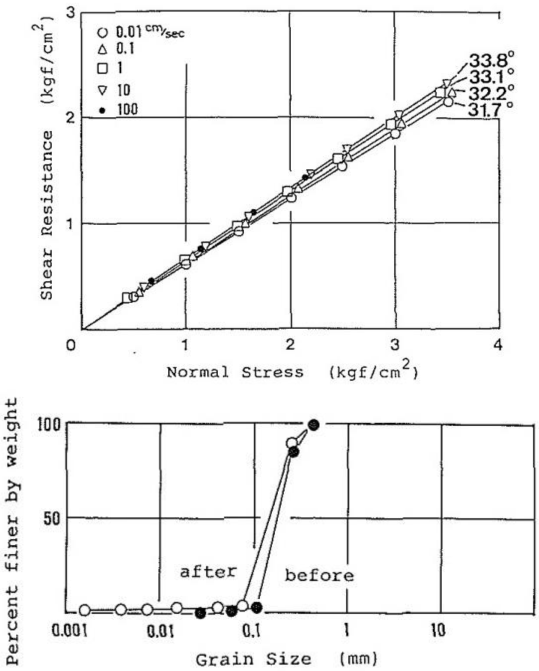

Figure 1. When Ring Shear tests for Toyoura sand executed with different shear rates are compared, it seems that the shear stress increases with the increase of the shear speed, the granulometry was not found, to differ among the various speeds [15]

The increase in shear stress may very well alter the grain crushing phenomenon as "Grain crushing depends, in addition to the load and time, on the stress path if exposed to more intensive gradient of shearing, the extent of crushing increases" [17] Another paper [18] mentions that "Under relatively high shear velocity conditions (i.e., >100 mm/sec), the grain crushing effect is more significant and results in rapid mass movements" strengthening the hypothesis that higher shear speeds may mean higher grain crushing percentages.

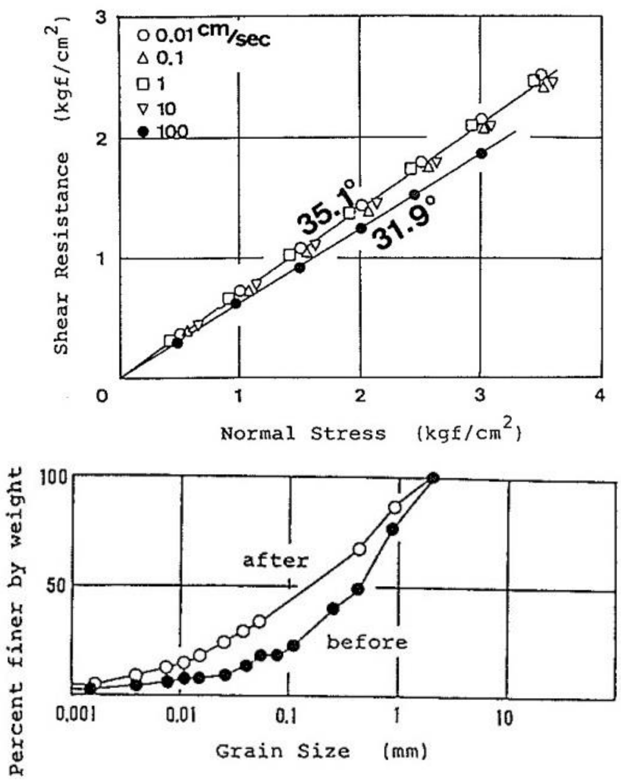

Figure 2. On the other hand when Ring Shear tests with plain tennis court sands executed with different shear rates are compared, the faster ones seem to present slightly lower shear stress. In both comparisons of Figure 2 and 3 the grain crushing phenomenon is reported as constant

Other researchers agree on the fact that changes in shear speed lead to changes in the shear strength but disagree on the effect that the increase in shear strength has on grain crushing "Shear strength is a function of shear velocity and normal stress. Generally, shear strength increases with increasing shear velocity", [19]" but then proceed to find different results as illustrated in Figure 4. In fact Jiang et al measure higher grain crushing percentages for lower shear rates which attribute to "greater time available for particle crushing during the slower tests", [19] among other factors.

The fact of the matter is that a paper that studies the influence of shear displacement rates on grain crushing in cohesionless soils for the Bromhead apparatus was not found in the bibliography available. As changes in grain crushing due to changes in the shear rate are probably not very intense, such an influence may not be predicted easily as results from studies can be controversial.

Test no.	Sample	σ_0 (kPa)	e_0	B_D	Shear speed (mm/s)	Sample preparation	Drainage condition
S_1	Silica sand no. 8	50	1.13	0.95	56	NC	Naturally drained
S_2		198	1.09	0.95	56	NC	
S_3		472	0.96	0.96	58	NC	
S_4		471	0.97	0.96	3	NC	
S_5		472	0.97	0.96	5	NC	
S_6		473	0.97	0.96	100	NC	

Table 1. Test identification numbers and specimen characteristics [16]

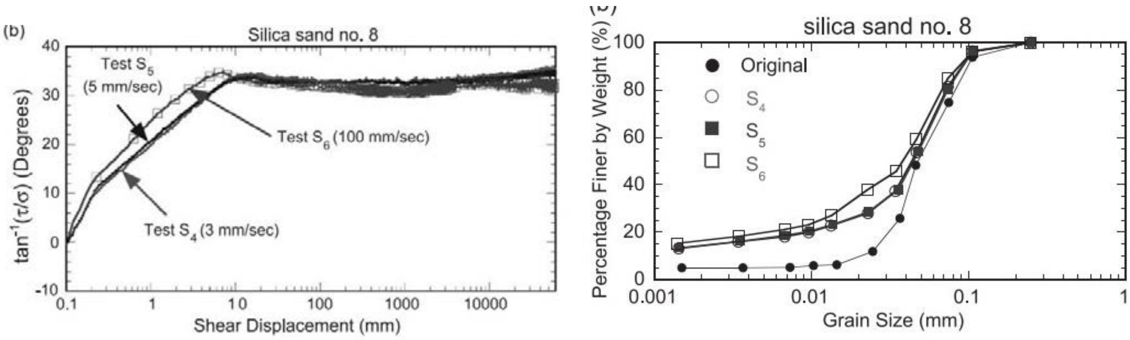

Figure 3. Here a comparison of similar tests executed with different speeds is reported, the test executed with the higher shear rate displacement seems to present greater shear stress values at the initial stage of the test and the same test seems to present a greater grain crushing percentage. The other two tests with similar shear speeds presented same shear stress values and same grain crushing percentages [16]

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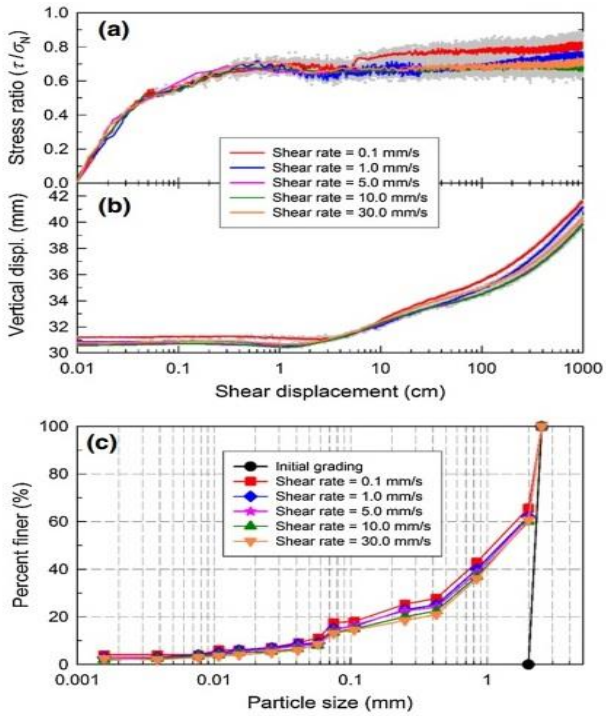

Figure 4. In the study of Jiang et al, the slower the shear speed the higher the shear stress and the grain crushing phenomenon, it can be seen that researchers who study different shear speeds in Ring Shear tests find different results [19]

3 NEW TESTS EXECUTED ON SILICA SAND WITH VARIABLE SHEAR RATES

In order to study accurately the phenomenon of grain crushing in relation to shear speed, a series of new tests was executed using silica sand, a material already used in the past in research, known to present grain crushing when tested, quite easily. The initial granulometry of this material was between 300-150 μm, a granulometry that allowed for the grain crushing phenomenon to develop freely by forming a shear zone to the relatively shallow Bromhead cell [13] and [20] but at the same time it allowed for the phenomenon to be clearly monitored and measured by sieving the remaining sample material.

The densities of the samples in all the tests executed for this study were in the range of 1,60-1,65 gr/cm^3. The densities were achieved as uniformly as possible by following this procedure: initially the sample was placed in the cell with a small spoon, then the ring shape cap was placed appropriately above the cell and 40 kg of dead weight were applied on the loading pin of the apparatus. This weight on the loading pin is equivalent to 1200 KPa of pressure. After that, there enough time was left for the sample to compact, and that was controlled by the vertical displacement gauge. When the vertical displacement gauge stopped moving, the weight of 40 kg was put down. After the loading pin was released, 2 kg of dead weight, equivalent to 75 KPa of pressure, were loaded to the pin. The sample was again left to consolidate and then the tests could begin. The parameters of the tests apart the shear rate, mainly the compaction process, the vertical stress σN and the initial granulometry, were chosen so as to achieve reliable results for the maximum shear displacement possible in the Bromhead apparatus [13].

The time scale used on the recorder was that of the Logarithmic type because it offers more measurements at the initial part of the test when the shear stress increases where the differences in shear stress may or may not affect the shear stress-strain response. Later on, when the shear stress reaches a constant value as can be expected by the bibliography, the need for many measurements becomes less important. The tests were stopped when the proper shear displacement was reached according to the program established earlier, as shown in Table 2. The rotation was converted to linear displacement according to the formula mentioned in the Bromhead apparatus manual [21]. Practically degrees per minute are multiplied by 0.742 to be converted in mm/min and then as shear speed is constant it is easy to calculate the duration of the tests by dividing shear displacement with time.

When the tests reached the proper shear displacements, the apparatus was stopped, the cell emptied, the content was dried and the granulometries taken. Then results were reported to picture 6 so as to establish a timeline of the grain crushing phenomenon for each shear rate applied.

As can be seen in Figure 5 all tests arrived at the same shear stress value after shear displacement arrived at 0.01 meters and remained almost constant until the end of the tests. At the initial stages of the tests though, the shear stress-stress responses differ somewhat. Before analyzing the differences of the stress-strain responses, the different number of values taken for the different tests especially at the initial stages of the tests, must be taken into account and justified. In fact the logarithmic scale model measures the majority of values during the initial stages of a test, that is why it is used in this paper. Since differences among tests occur at the initial stages, then measurements need to be more precise, but the time needed for the tests to be finished differs vastly. Thus in order for the fastest test of 60 deg/min to arrive at 1 meter of shear displacement it takes 22.5 min to be completed, for the slowest of 1.80 deg/min it takes 750 min (that is 12.5 hours!). So it is obvious that as the tests become faster less values are reported at the initial stage, something that may alter somewhat the natural curve of the stress-strain response until it reaches constant values. Unfortunately the instruments at our disposal do not predict a faster measuring protocol than the logarithmic one used.

Nevertheless it can be seen that the slower test of 1.8 deg/min arrives at the constant values by a path that reports smaller values, that is less steep than all the others. On the contrary one of the faster tests executed at 30 deg/min not only arrives much more steeply but is also presenting a pseudo dense behavior with a small peak at the shear stress-strain response graph. There is reason to believe of course that the shear stress-strain response of the test executed at 60 deg/min is steep as the one executed at 30 deg/min, but the recorder measured the second value when the test had already reached the constant shear stress status, thus no curve is represented but rather a line.

Name	Type of sand	Moisture %	Density in gr/cm3	Type of shear behavior	Speed of shear in deg/min	Shear Displacement in m
S1	Silica	10	1.61	Drained	1.8	0.3
S2	Silica	12	1.65	Drained	1.8	0.5
S3	Silica	11	1.6	Drained	1.8	0.7
S4	Silica	9	1.62	Drained	1.8	1
S5	Silica	11	1.63	Drained	6	0.3
S6	Silica	12	1.65	Drained	6	0.5
S7	Silica	10	1.64	Drained	6	0.7
S8	Silica	10	1.63	Drained	6	1
S9	Silica	9	1.64	Drained	15	0.3
S10	Silica	12	1.62	Drained	15	0.5
S11	Silica	11	1.61	Drained	15	0.7
S12	Silica	10	1.61	Drained	15	1
S13	Silica	12	1.65	Drained	30	0.3
S14	Silica	9	1.6	Drained	30	0.5
S15	Silica	11	1.65	Drained	30	0.7
S16	Silica	11	1.64	Drained	30	1
S17	Silica	10	1.63	Drained	60	0.3
S18	Silica	9	1.64	Drained	60	0.5
S19	Silica	11	1.62	Drained	60	0.7
S20	Silica	12	1.61	Drained	60	1

Table 2. The principal parameters of the tests. All the samples had the same initial granulometry of 300-150 μm so as to achieve clear objective measurements of the grain crushing phenomenon as it evolved. The tests also were subjected to vertical stress σN 75 KPa which was found by previous research at the Soil Mechanics and Foundation Engineering Laboratory of the Department of Civil Engineering at the Demokritos University of Thrace enough to provoke grain crushing but also help to maintain a stable shear stress path for a maximum of 1 meter of shear displacement

In Figure 6 there is the comparison of the grain crushing percentages measured after the tests were finished. Naturally by the compaction process a certain percentage of grain crushing already occurs and for the parameters used in these tests it was found to be 4,83%. This percentage was subtracted by the final grain crushing percentages measured. Obviously since only the compaction process was responsible for this percentage, thus no shear movement had happened yet, it was the same for all tests executed.

It can be seen a noticeable difference in the grain crushing for the two faster tests, the series executed at 60 deg/min and 30 deg/min while no distinct difference was found for the other tests.

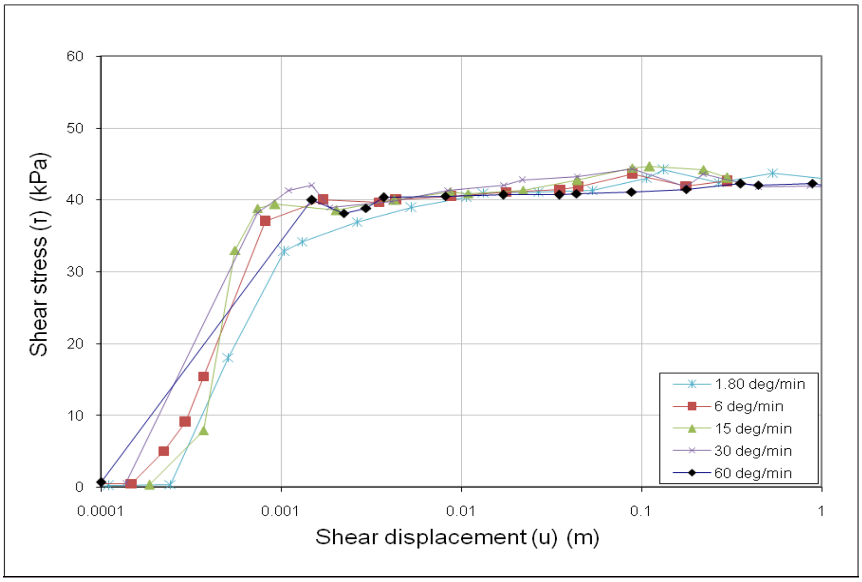

Figure 5. Results from Silica sand tests that arrived up to 1 meter of shear displacement, i.e. S4, S8, S12, S16, S20. Similar graphs could be made for tests that arrived shear displacements of 0.3 m, 0.5 m, 0.7 m but it seemed superfluous as this graph is representative of the others

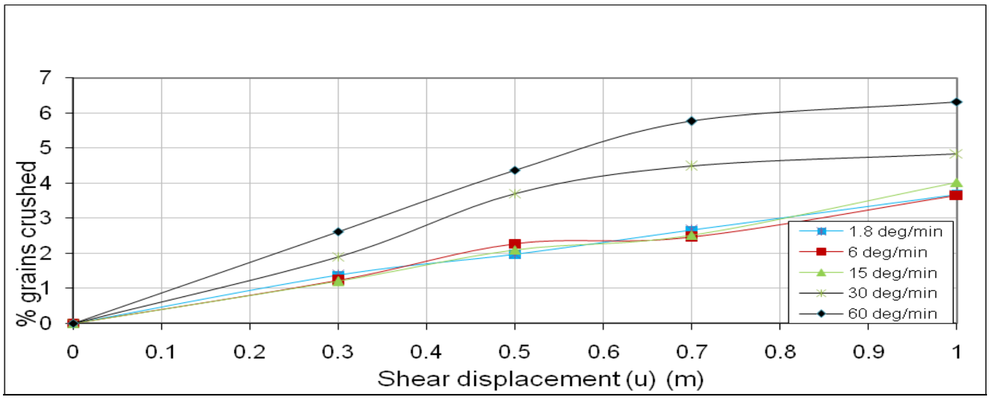

Figure 6. Percentages of the crushed grains in relation to the shear displacement and the shear rates used for the execution of the tests. The two series of tests executed faster i.e. with 60 deg/min and 30 deg/min present larger percentages of crushed grains in relation to the slower ones executed with 15, 6 and 1.8 deg/min of shear rate. The three slower ones in fact seem to not present considerable differences in crushed grains

4 NEW TESTS EXECUTED ON CALCAREOUS SAND WITH VARIABLE SHEAR RATES

The methodology of examining Calcareous sand was identical with the one previously used to examine Silica sand. The initial granulometry was kept between 300-150 μm, the densities of the samples were in the range of 1.60-1.65 gr/cm3 achieved by following the preloading procedure as described previously, the Normal pressure applied during the tests was 75 KPa, and the shear rates and displacements were kept the same so as to make comparisons easier. The test parameters are shown in more detail in Table 3.

Name	Type of sand	Moisture %	Density in gr/cm3	Type of shear behavior	Speed of shear in deg/min	Shear Displacement in m
C1	Calcareous	11	1.63	Drained	1.8	0.3
C2	Calcareous	10	1.62	Drained	1.8	0.5
C3	Calcareous	10	1.61	Drained	1.8	0.7
C4	Calcareous	10	1.61	Drained	1.8	1
C5	Calcareous	11	1.6	Drained	6	0.3
C6	Calcareous	12	1.64	Drained	6	0.5
C7	Calcareous	11	1.65	Drained	6	0.7
C8	Calcareous	10	1.6	Drained	6	1
C9	Calcareous	12	1.61	Drained	15	0.3
C10	Calcareous	11	1.62	Drained	15	0.5
C11	Calcareous	11	1.63	Drained	15	0.7
C12	Calcareous	10	1.61	Drained	15	1
C13	Calcareous	9	1.64	Drained	30	0.3
C14	Calcareous	10	1.62	Drained	30	0.5
C15	Calcareous	9	1.64	Drained	30	0.7
C16	Calcareous	10	1.63	Drained	30	1
C17	Calcareous	10	1.62	Drained	60	0.3
C18	Calcareous	10	1.61	Drained	60	0.5
C19	Calcareous	12	1.63	Drained	60	0.7
C20	Calcareous	11	1.6	Drained	60	1

Table 3. Main parameters of the Calcareous sand tests as executed in the Bromhead apparatus. The initial granulometry of all the samples was 300-150 μm, while the vertical stress applied was 75 KPa for reasons explained previously

In Figure 7 are reported the shear stresse-stress responses of the Ring Shear tests that were left to arrive up to 1 meter of shear displacement. It can be seen that five shear rates were used, starting from the slowest, 1,80 deg/min, up to the fastest that the Bromhead apparatus may permit, 60 deg/min. It can be noticed that although the residual stresses are nearly the same in all shear speeds, the stress-strain responses at the initial phases of the tests differ somewhat. The slower tests present an increase at the shear stress in smaller shear displacements, although the shear stress strains response measured is less steep. It is rather interesting that the initial values of the shear stresses present themselves in order from the slower to the fastest and on the graph there is a clear distinction.

The shear stress-strain responses as reported on Figure 7 show certain differences that concern not only the initial phase of the tests but also the constant shear stress phase. It can be noticed that the initial phases of the tests differ in relation to the shear rate used. The slower the test, the shear test shows increases for smaller displacements. On the other hand the faster tests present the same residual shear stresses for larger shear displacements and their shear stress-strain response is much steeper but it reaches constant shear stress phase in lower displacements when compared to the slower tests. For example the 60 deg/min test reaches constant shear stress at 0,002 m while the 1,8 deg/min at more than 0,01 m of shear displacement, thus more than five times the shear displacement of the faster test.

The constant shear stress phase of the tests also seems related to the shear rate as can be seen at the graph in Figure 7. In fact the faster tests seem to present slightly higher shear stresses than the slower ones, a behavior also found bibliographically [15], [19].

On Figure 8 are reported the percentages of the crushed grains caused only by the Ring Shear tests as the initial quantity of crushed grains caused by the compaction process on the samples (the preloading as previously reported) which was found to be 7.56%, was subtracted.

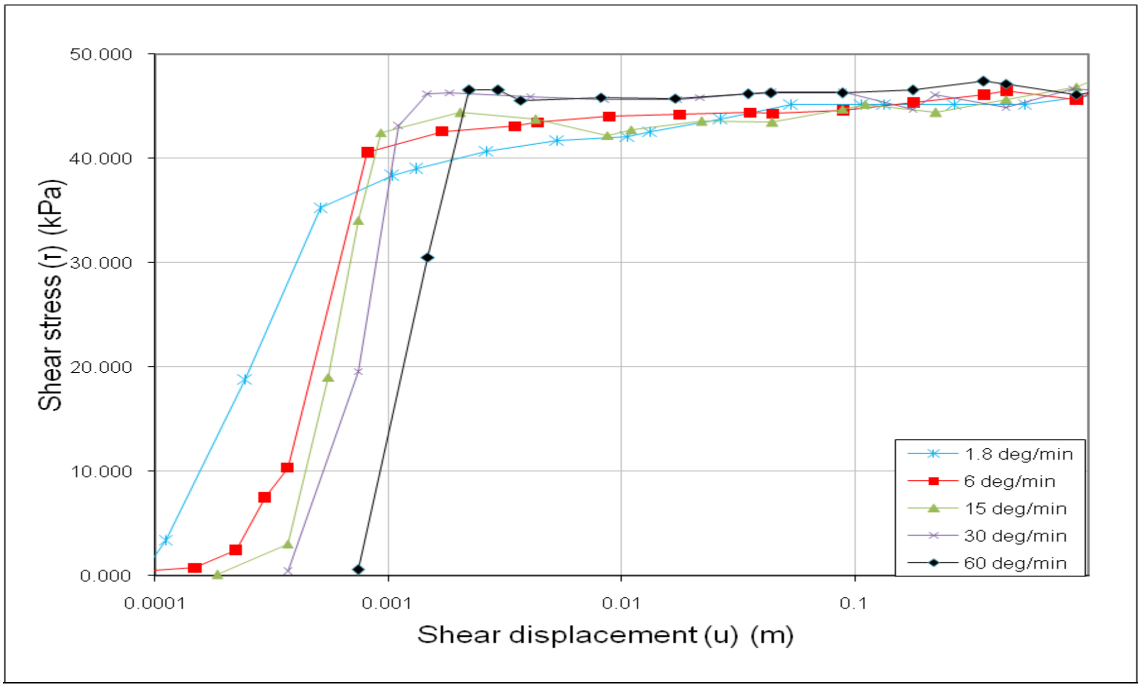

Figure 7. . Results from Rings Shear tests on the Bromhead apparatus that arrived up to 1 meter of shear displacement, i.e. C4, C8, C12, C16, C20. It can be seen that the shear rate plays a certain role to the initial shear stress path of the tests, in fact the slower tests present an increase in shear stress for shorter shear displacements

As can be seen in this series of tests, the fastest test of 60 deg/min presented a rather smaller percentage of crushed grains for the final displacement of 1 meter. The other tests although present grain crushing differences at the progression of the shear displacement, their final percentages of grain crushing share nearly the same values. It is to be noticed though that despite the minor differences in grain crushing at the final displacements, the order of shear rates correlates negatively to the grain crushing percentage, that is, the faster the test, the lower the grain crushing percentage. As far as the progression of the grain crushing phenomenon is concerned, the slower shear rates had slightly larger grain crushing percentages which decreased with the increase of shear speed.

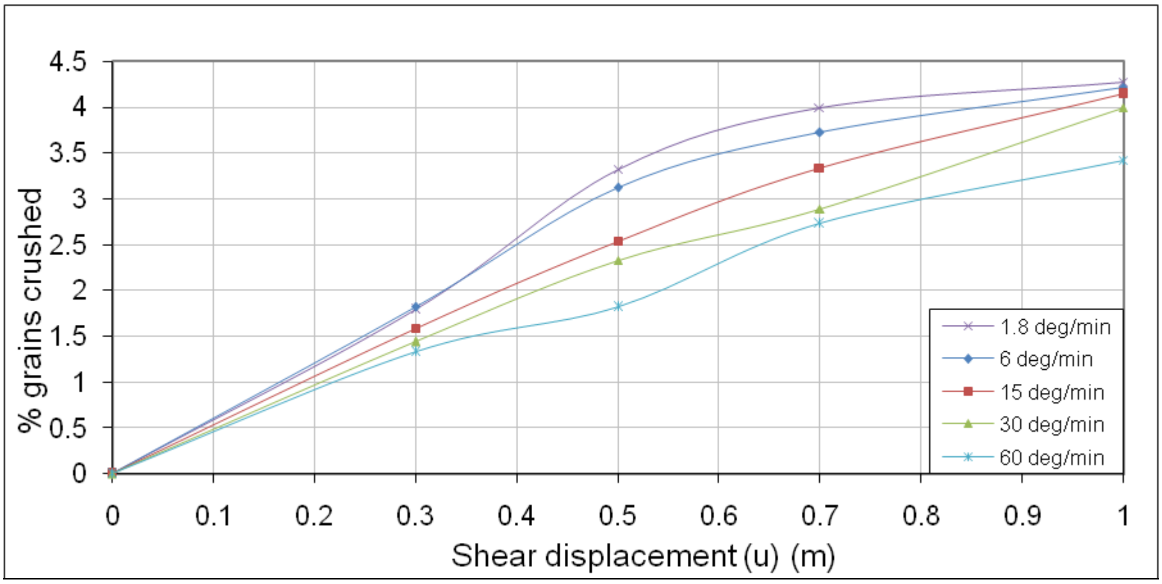

Figure 8. Percentages of the crushed grains of Calcareous sand after the Ring Shear tests executed in relation to the shear displacement and the shear rates used for the execution of the tests. The series of tests executed faster i.e. with 60 deg/min present a smaller percentage of crushed grains in relation to the slower ones executed with 30, 15, 6 and 1.8 deg/min of shear rate. The trend though for the Calcareous Sand used in these tests at the Bromhead Ring Shear apparatus was that the slower the test the more increased the grain crushing percentage

5 NEW TESTS EXECUTED ON QUARTZITIC SAND WITH VARIABLE SHEAR RATES

A series of Ring Shear tests on the Bromhead apparatus was executed using Quartzitic sand. This sand has the characteristic that presents very limited grain crushing as measured by similar experiments [22] and [13]. Six tests were executed ending at 1 m of shear displacement by using the same test parameters as previously, granulometry of 300-150 µm, 10% of moisture, 75 Kpa of normal stress, density of 1,60-1,65 gr/cm^3 and variable shear rates of 60, 30, 15, 6 and 1,8 deg/min. Test parameters can be seen on Table 4.

The compaction process was as reported previously and the initial grain crushing percentage caused solely by the compaction process was found to be 1,85%. This percentage was subtracted by the final granulometries found at the end of the tests. In this way only the grain crushing percentages caused by the rotational movement of the Ring Shear Apparatus were reported in Figure 10.

On Figure 9 are reported the shear stresses in relation to the shear displacements for the six shear rates used. As can be seen the faster shear rates follow a steeper path towards the residual stress values which remain constant. On the other hand the shear stresses begin to increase for smaller displacements as the shear rates are slower. All shear stress paths begin the residual shear stress phase for nearly the same shear displacement as can be seen on Figure 9.

Name	Type of sand	Moisture %	Density in gr/cm3	Type of shear behavior	Speed of shear in deg/min	Shear Displacement in m
Q1	Quartzitic	10	1.61	Drained	1.8	1
Q2	Quartzitic	11	1.61	Drained	6	1
Q3	Quartzitic	10	1.60	Drained	15	1
Q4	Quartzitic	10	1.63	Drained	30	1
Q5	Quartzitic	11	1.61	Drained	60	1

Table 4. Main parameters of the Quartzitic sand tests as executed in the Bromhead apparatus. The initial granulometry of all the samples was 300-150 μm, while the vertical stress applied was 75 KPa

The residual stresses remain constant but the two slower tests, (1,8 and 6 deg/min) present slightly lower values in shear stress than the others. The two slower tests and the three faster tests present among themselves no noticeable difference in values.

Grain crushing percentage as expected is lower than the other two sands tested. There seems to be a negative correlation between shear rate and grain crushing percentage i.e. the faster tests seem to cause lower grain crushing and as the tests become slower the grain crushing increases.

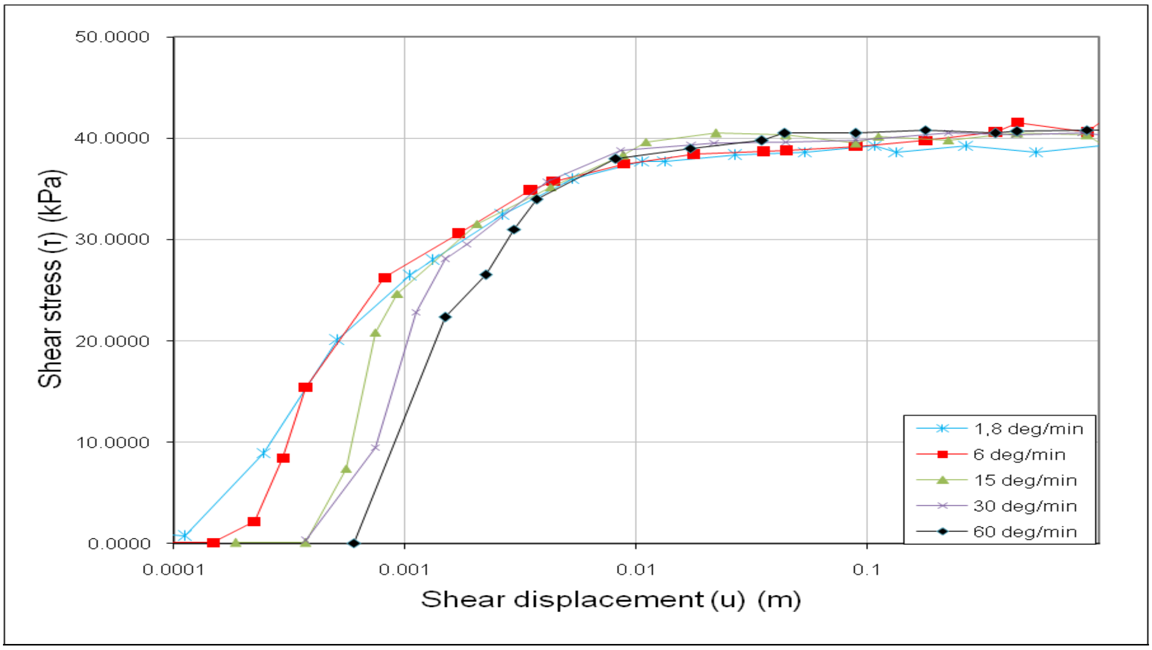

Figure 9. Results from the tests executed on the Bromhead apparatus with quartzitic sand that arrived up to 1 meter of shear displacement, i.e. Q1, Q2, Q3, Q4, Q5. In the case of quartzitic sand It can also be seen how the shear rate plays a certain role to the initial shear stress path of the tests. In fact the slower tests present an increase in shear stress for shorter shear displacements and their path is less steep

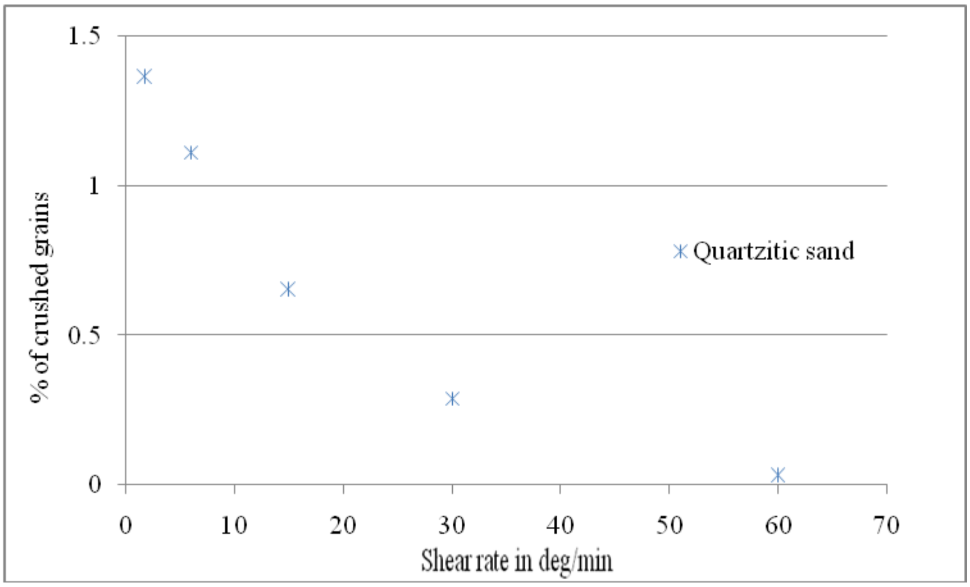

Figure 10. Percentages of the crushed grains of Quartzitic sand in relation to the shear displacement and the shear rates used. The series of tests executed faster i.e. with 60 deg/min present a smaller percentage of crushed grains in relation to the slower ones executed with 30, 15, 6 and 1.8 deg/min of shear rate

6 COMPARISONS BETWEEN THE THREE SANDS TESTED ON THE BROMHEAD APPARATUS

Testing three different types of sand by using the same test parameters permits us to evaluate the element of material diversity to the results of the Ring Shear tests at the Bromhead apparatus. As can be seen on Figure 11 where shear stress paths are reported for same test parameters, different sand types present similar shear stress paths, but do show some differences.

For this comparison the shear speed of the 15 deg/min was chosen as it is in the middle of the shear rates used and provides a fairly representative picture of the whole phenomenon. Quartzitic sand presents lower values of shear stress throughout the entire test when compared to Silica and Calcareous and its initial phase is less steep. Silica Sand presents higher constant shear stress values when compared to Calcareous and Quartzitic. Silica and Calcareous sand arrive at the constant shear stress values rather abruptly when compared to quartzitic and at nearly the same displacements in relation to quartzitic.

The main differences of sand material diversity to the Bromhead Ring Shear tests though seem to lie on the effect it has on the grain crushing phenomenon. As can be seen in Figures 12, 13, 14 higher shear rates lead to higher grain percentages for Silica sand, while the inverse happens for Calcareous and Quartzitic sands. On Figures 12, 13, 14 are reported the grain crushing percentages measured at 1 meter of shear displacements and the formulas that emerge from the graphs that relate shear rate to grain crushing percentage. The different crushing percentages seem to correlate to the variance of shear rates when all other test parameters are kept the same. Correlation, negative and positive between shear rates and grain crushing is mentioned in the relative literature as already mentioned.

In order to determine why diverse shear rates have the inverse effect on grain crushing in relation to the sand type, the diverse breaking propensity of sands to normal and shear stress must be considered. On table 4 the percentages of the crushed grains caused by the compaction process i.e. normal stress, the ring shear test process i.e. shear stress, and their fraction which delimit the importance of one over the other. In Calcareous and Quartzitic sand where the fraction of percentage of crushed grains caused by Normal stress, divided by the percentage of crushed grains caused by shear stress is superior to the unit, the slower tests present more intense grain crushing. Thus when the vertical stress is more influential than the shear stress to the totality of the grain crushing phenomenon, time under normal stress plays a key role to higher grain crushing percentages. On the other hand when the aforementioned fraction is below the unit, such as in Silica sand, higher shear rates cause higher grain crushing percentages.

Type of sand	% of crushed grains caused by compaction	% of crushed grains caused by Ring Shear Test	Fraction of compaction/Ring shear test
Silica	4.83	6.3	0.77
Calcareous	7.56	4.5	1.68
Quartzitic	1.85	1.4	1.32

Table 5. Main parameters of the Quartzitic sand tests as executed in the Bromhead apparatus. The initial granulometry of all the samples was 300-150 μm, while the vertical stress applied was 75 KPa

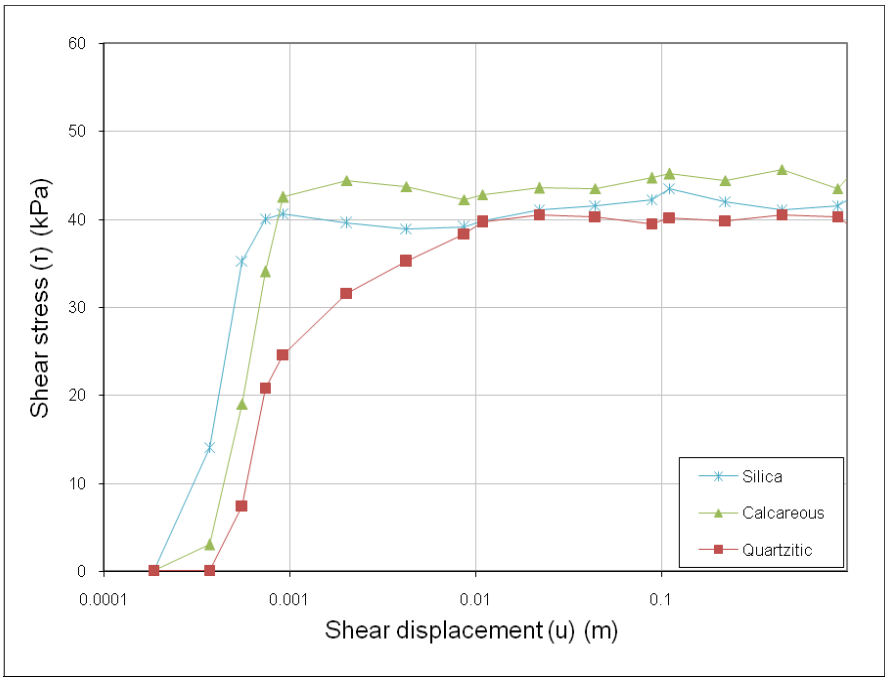

Figure 11. Shear stress-strain responses of the three sands tested on the Bromhead apparatus for 1 m and 15 deg/min of shear speed. The differences at the initial phase of the tests and at the constant phase of residual shear stress are noticeable

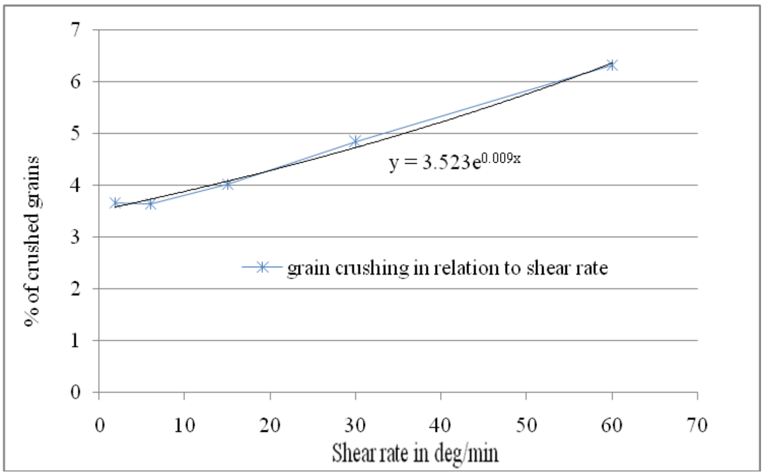

Figure 12. Percentages of the crushed grains of Silica sand in relation to the shear displacement. It can be seen that there although the relation extracted is an exponential function the graph is almost linear between the grain crushing percentage and the shear speed of the tests

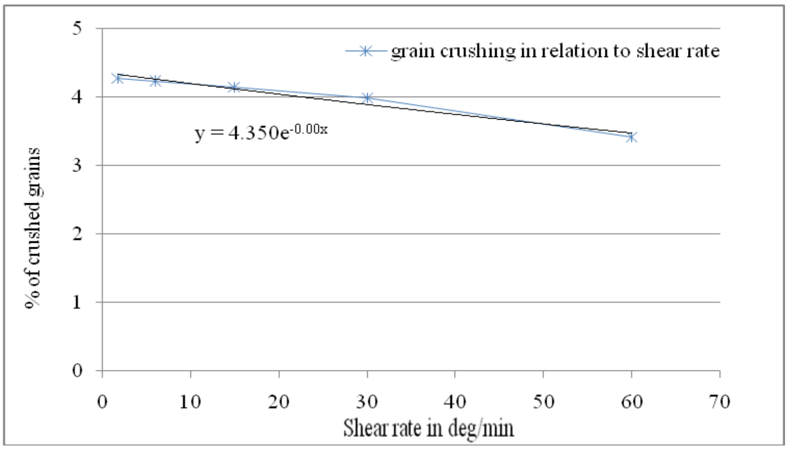

Figure 13. Percentages of the crushed grains of Calcareous sand in relation to the shear displacement, the polyonimic function extracted by the values measured lead to an exponential function. Of course the limits are because of the non negative values and the limits to shear speed

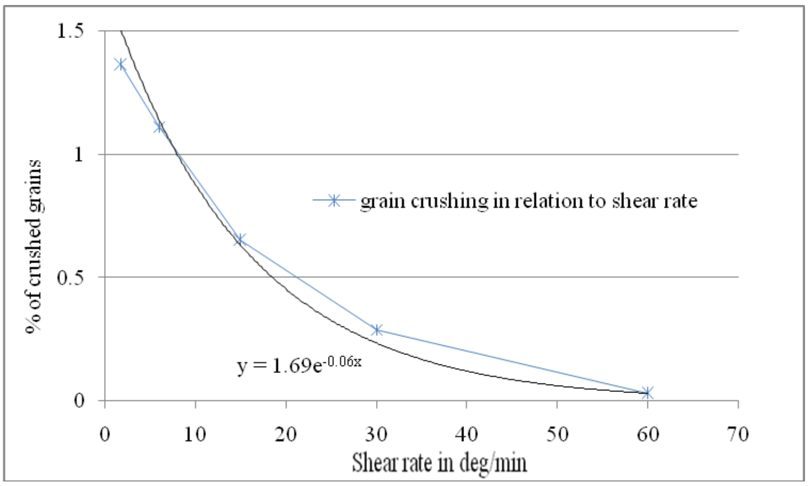

Figure 14. Percentages of the crushed grains of Quartzitic sand in relation to the shear displacement lead to an exponential function

7 CONCLUSIONS – PROPOSALS FOR FUTURE STUDY

In order to determine the effect variation of shear rates plays over the grain crushing phenomenon of sands over large shear displacements, three series of new tests were executed on three different types of sand. The tests were executed on the Bromhead apparatus of the Soil Mechanics and Foundation Engineering Laboratory of the Department of Civil Engineering at the Demokritos University of Thrace. The parameters of these tests i.e. the initial granulometry, the compaction process, moisture contained, vertical stress applied and the lengths of shear displacements were determined at previous papers and taken so as to ensure reliable results. [13] and [20]

Conclusions over differences of the shear stress paths measured in relation to the shear rates are in general agreement to bibliographical references. Grain crushing percentages seem to correlate with shear rates, positively when shear stresses cause more grain crushing than normal stresses, negatively when the inverse happens. In fact when Normal stress is more important than shear stress for the grain crushing phenomenon, (at least for the parameters tested in this paper) then time under load is of paramount importance for the grain crushing phenomenon.

The grain crushing phenomenon is rather complex and needs to be studied further as it proves quite important to landslide behavior. A future research could involve the study of grain crushing in relation to different normal stresses. It is found that higher normal stresses accentuate the grain crushing phenomenon but the phenomenon should be studied further to see if it is possible to extract any relative formulas.

The grain crushing phenomenon could be studied for different fractions of moisture from air dry to saturated, and by using diverse types of sand or mixtures of the sand types already used. Also it would be interesting to see how different granulometries of sands, after the Bromhead apparatus has been validated to ensure reliable results for such granulometries, affect the grain crushing phenomenon.

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