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Effect of Grain Crushing and Bedding Plane Inclination on Ras en-Naqab Natural Sand Behavior

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ABSTRACT
This paper presents an experimental investigation for inherent anisotropy and particle breakage for natural Ras en-Naqab sand southern Jordan. The natural sand specimens were subjected to one dimensional compression to induce breakage. The grain size distributions of the specimens were reported before and after the application of the stresses. Thereafter, the sand shear strength parameters were assessed using direct shear box tests. Examining the obtained results revealed that the amount of breakage due to one dimensional compression is of order higher than the amount occurring during direct shear test. Peak shear strength parameters have little or no change with increasing particles breakage. However, dilatancy component of shear strength diminishes with increasing the amount of particles breakage. Moreover, examining the effect of angle of deposition shown a considerable amount of dilation occurs on the higher deposition angle regardless the extent of breakage reported.

KEYWORDS: natural sand, granular materials, crushing, breakage, anisotropy, fabric, shear strength, dilatancy, direct shear.

INTRODUCTION
The mechanics of particle crushing, or particle breakage, is one of the most intractable problems in geosciences. The topic is of interest to many research disciplines including powder technology, minerals and mining engineering, geology, geophysics and geomechanics (Einav, 2007). Grain crushing is one of the micro-mechanisms that govern the stress–strain behavior of a granular material, and also its permeability by altering the grain size distribution (Markotos and Bolton, 2007).

The description of the mechanical behavior of granular materials, such as sands, clays, and powders is important to many fields of science and engineering. Granular assemblies are intriguing systems rich with unusual properties such as dilatancy, arching, instability, and thixotropy. These properties conspire to create a complex system with numerous instabilities.
Examples include liquefaction failures, density waves in hopper flows, and stick-slip motion in shear flows.

Thus, the behavior of granular materials is very complicated, and presently not well understood, behaving neither like solids nor like viscous fluids. Stresses inside the granular medium are composed by multiple of stress chains, which can lead to local high-stress concentrations within the system. Such high stress concentration may lead to crushing of single particle even under relatively low stresses. If granules are broken into smaller particles due to the application of external force, physical and mechanical properties of the granular matter will undergo significant change. Therefore, the original engineering properties with which a structure was designed will change during its engineering life. Examples of these structures which will suffer from such changes are pavements, highway embankments, earth dams’ embankment, rock fill dams, and etc. Changes in the original engineering properties could put the stability of such structures in jeopardy and make it unsafe during their life of operation. Therefore, understanding the crushing in granular materials and its evolution during the process of compression and shearing is of highly demands.

Literature is depleted in many experimental and numerical studies to thoroughly understand the particle crushing phenomenon and to be able to figure out quantitatively its impact on the engineering properties of granular materials. Lobo-Guerrero and Vallejo (2005, 2006) examined the effect of particle crushing on the capacity of driven piles. Their results indicated that the particles crushing negatively affect the capacity of piles. Okada et al. (2004) reported that grain crushing was in onset for triggering a landslide. An investigation of excess pore water pressure generation of a weathered granitic sand, taken from the source area of a typical landslide caused as a result of liquefaction, indicated that grain crushing within the failure zone is the key phenomenon of rapid long-runout motion of landslides. Moreover, Fragaszy and Voss (1986) reported that particle breakage will cause settlements and reduction in hydraulic conductivity.

Experimental works on the crushing of the granular materials point out many key factors associated with the occurrence of particle crushing. It has been established that grain crushing is influenced by soil particle strength, topology such as angularity, granular materials physical properties such as gradation, porosity, moisture content, and induced stresses level and anisotropy (Lee and Farhoomand 1967; Hardin 1985; Hagerty et al. 1993; Lade et al. 1996; McDowell and Bolton 1998; Takei et al. 2001; Coop et al. 2004; Tarantino and Hyde, 2005; and Lobo-Guerrero and Vallejo, 2005). Moreover, previous research has indicated that the angle of shearing resistance of granular materials undergoing crushing decreases as a consequence of particle crushing (Bolton, 1986; Feda, 2002). Coop et al. (2004) conducted ring shear tests on carbonate sand and reported that crushing of particles occurred without a loss of residual angle of internal friction. In this regards, the reported results give the impression that crushable granular materials experience a reduction in the internal friction angle as a consequence of particle breakage prior to achieving a constant value of residual strength.

According to Lee and Farhoomand (1967), one of the most important factors influencing the crushing of a mass of granular materials is the crushing resistance of the grains. Coarse granitic sand particles with an average diameter of 2.8 mm experienced breakage at pressures equal to 2 MPa, while calcareous shells began crushing at 0.05 to 0.2 MPa (Lee and Farhoomand, 1967). Angular particles of freshly quarried materials undergo fragmentation under ordinary pressures (about 0.98 MPa) due to breakdown of sharp angularities (Ramamurthy, 1974). When a granular
mass is subjected to a compressive load, the particles resist the load through a series of contacts between the grains in the shearing zone as pointed out by Oda et al. (2005), (Fig. 1).

As shown in Fig. 1, particles do not share equally in the bearing of the applied load. Some particles carry more load than others. In fact, some particles can actually be removed without affecting the mechanical equilibrium of the packing. The particles with highly loaded contacts are usually aligned in chains (Cundall and Strack, 1979). Crushing starts when these highly loaded particles fail and break into smaller pieces that move into the voids of the original material. These load chains change in intensity and direction as the crushing develops in the particle assemblage. On crushing, fine grains are produced and the grain size distribution curve becomes less steep. Consequently, with continuing crushing, the soil becomes less permeable and more resistant to crushing. Therefore, the grain size distribution is a suitable measure of extent of crushing material (Hardin, 1985; Lade et al. 1996; Tarantino and Hyde, 2005; and Einav, 2007).

Lade et al. (1996) found that if uniform sand is crushed, the resulting grain size distribution approaches that of a well-graded soil for a large compressive load. However, before reaching a well-graded particle distribution, the granular assemblage will experience gradual changes in particle size depending on the level of progressive load being applied.

Tarantino and Hyde (2005) performed simple direct shear tests on carbonate sand to demonstrate the affect of crushing on shear strength properties. The shear tests have been carried out on mono-granular and fractal grain size distributions of crushable carbonate sand at vertical stresses ranging from 0.2 MPa to 1.4 MPa and horizontal displacements from 0.5 mm to 8 mm. In order to compare particle breakage of specimens of different particle sizes, specimens were...
prepared with a sample height of about 20D50. Grain size distributions were measured before and after shearing. They established a link between grain crushing, shear strength and general mechanical behavior of sands. They found that the apparent critical state friction angle has been shown to contain both frictional and elastic components. They concluded that the apparent critical state angle of friction increases as the rate of particle crushing normalized with respect to the normal force, increases.

Moreover, with progression of particle breakage due to applied load, the void space between large particles filled with crushed material. Due to this process, the hydraulic conductivity for the material is reduced. For instance, for asphalt pavement crushing of granular material can occur during installation and placement, compaction, and through daily vehicular traffic. Most serious problems are caused to asphalt pavements when their granular bases are unable to remove the water that enters the pavement (Al-Qadi et al., 2004). Hence crushed material is full of voids in which water flows; as a result, an excess pore water pressure will develop and produce failure in the granular base as well as in the pavement.

The motivation of this work is the fact that the strength and stress characteristics of sands as determined from conventional testing such as triaxial compression are a function of their initial fabric. The initial fabric of sand specimen is a function of the method of sample preparation as pointed by Zlatovic and Ishihara (1997). Moreover, with altering initial (inherent) fabric, which is a function of bedding plane inclination (i.e., depositional angle of sand particles) at a fixed void ratio and confining stress, Oda (1972) showed that the initial stiffness, peak strength, and volume dilation are varied.
The main focus of this study is to separate the effect of particle breakage and depositional angle in the shear strength parameters for granular material subjected to direct shear tests. Up to the knowledge of the authors, this is the first time such an effort is being reported. The results from direct shear tests conducted on Ras en-Naqab sand will be presented and analyzed.

**REGIONAL GEOLOGY**

The material used for the tests was natural sand from Ras en-Naqab area southern Jordan. Huge amount of silica sand resources of early Ordovician are found in this area south of the Ras en-Naqab escarpment (70 km north of Ras en-Naqab) (Fig. 2). The exposures are extended over an area of more than 150km² with a thickness of about 265-350 m.

**MATERIALS**

In this study, Twenty fresh representative raw silica sand channel samples were collected from Ras en-Naqab area. The Chemical composition of the used samples are listed in Table 1 (NRA, 2006). Ras en-Naqab silica sand composed mainly of SiO₂ >98.72%, with very little contaminant oxide contents (i.e., Al₂O₃, TiO₂, CaO, and Fe₂O₃) and heavy minerals of < 0.1%.

| Table 1: Chemical analysis of sand samples from Ras en-Naqab area (NRA 2006). |
|---------------------------------|-----|
| Major Oxides                  | %   |
| SiO₂                          | 98.7 |
| Al₂O₃                         | 0.52 |
| Fe₂O₃                         | 0.04 |
| TiO₂                          | 0.09 |
| CaO+ MgO                      | 0.08 |
| Na₂O+K₂O                      | 0.11 |

Mineralogical investigation of Ras en-Naqab raw sands and size fraction indicated that they are consist mainly of quartz as a major mineral with minor amounts of kaolin, where as mineralogical investigation of fine fraction (<63 micron) reveals that the fine fractions of the glass sand consist mainly of Kaolin, Feldspar and quartz as a major minerals with traces of heavy minerals such as rutile, illmenite (NRA, 2006). The specific gravity of Ras en-Naqab sand was determined and evaluated by Al Dwairi (1995). The specific gravity of Ras en-Naqab sand is 2.63. Determmation of particles shape was carried out by calculating sphericity. Sphericity was calculated by Hydraulic sphericity and automatic image analyzer (Al Dwairi, 1995), the calculated sphericity by using the two methods ranges between 0.87 - 0.90. Thus, the particles shapes are subrounded in shape. The grain size distribution of Ras en-Naqab sand indicates that it contains more than 98% of sandy fraction. The grain size diameters D10, D30 and D60 are 0.922mm, 1.135mm and 1.579mm respectively. The coefficient of curvature is 0.88 while the coefficient of uniformity is 1.7. Therefore, Ras en-Naqab sand is classified as poorly graded sand, SP according to the Unified Soil Classification System (USCS). Moreover, the maximum and the minimum void ratios were found to be 0.78 and 0.54.
EQUIPMENT AND PROCEDURES

The natural sand samples were prepared as follows. The sand was rained from specific height to a standard compaction test mold of the size 1/30ft $^3$. Thereafter the sand was subjected to one dimensional compression using a hydraulic jack to the desired pressure. The sand specimen is then sieved. These specimens were then subjected to direct shear tests using a standard laboratory shear box apparatus with an initial sample cross-section of 60 mm x 50 mm. Followed Tarantino and Hyde (2005) the sample height in all testing was kept above 28 D50. This is due to the fact that experimental results reported by Finno et al. (1997) revealed that the thickness of the shear zone lies between 10 and 25 times D50.

The sand samples were prepared by sieving a predetermined mass of sand over an open box-shaped metal grid into the shear box, and then slowly raising the grid. This technique assures that there is no segregation of the particle sizes during the deposition process. Moreover, to achieve different bedding angles, the shear box was placed in adjustable plate connected with pin rotating around the horizontal plane through 90 degrees (Fig. 3).

![Figure 3: Sample preparation techniques to achieve well-graded samples in given depositional angle, $\theta$](image)

A series of shear tests was carried out, each at a constant vertical effective stress $\sigma_v$, with values of 55, 110, and 165 kPa and total horizontal displacement of 12 mm. Other sets of tests were also conducted after applying one dimensional compression in order to quantify the amount of grain crushing due to vertical compression and horizontal shearing. This made it possible to differentiate crushing occurring during the horizontal shearing stage. Table 2 summarizes all tests performed, including void ratios after one dimensional compression, and after pluviation before direct shear tests.
### Table 2: Test Summary

<table>
<thead>
<tr>
<th>One dimensional compression (MPa)</th>
<th>Initial Voids Ratio, e</th>
<th>Voids Ratio, e (after compression)</th>
<th>Deposition Angle, θ (°)</th>
<th>Vertical Stress, σ_v: kPa</th>
<th>Horizontal Displacement, x: mm</th>
<th>Voids Ratio, e (after pluviation)</th>
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**Figure 4: (a)**

![Horizontal Displacement vs. Shear Stress](image)
**Figure 4:** Direct shear test on natural Ras en-Naqab sand (a) shear stresses (b) vertical displacement, legend values are $\sigma_n$ in kPa

**EXPERIMENTAL RESULTS**

Fig. 4 shows the results of direct shear tests on the sand sample without prior to one-dimensional compression. The figure clearly shows that the shear stress on the sand specimens increases gradually to the peak value and then gradual softening to the residual value, Fig. 4ae. On the other hand, the volume change increases until a displacement of 7 mm has been reached, after which it becomes asymptotic to horizontal.
Figure 5: Influence of bedding plane orientation on sand behavior under direct shear test on natural Ras en-Naqab sand, (a) shear stresses (b) vertical displacement, $\sigma_n=55\text{kPa}$
Figure 6: Influence of bedding plane orientation on sand behavior under direct shear test on natural Ras en-Naqab sand, (a) shear stresses (b) vertical displacement, $\sigma_n=110\text{kPa}$

The corresponding peak and residual shear stresses as a function of the applied vertical stresses is shown in Fig. 8a and 8b. It is clearly shown that the bedding plane affects the response of the sand specimen to shearing in all reported range of vertical stresses. The specimens of a deposition angle of 30° with respect to the horizontal plane (i.e., parallel to the shearing plane) show the lowest values of shear stresses. Moreover, the same specimens show the higher amount
of initial compression and the lowest amount of dilation. However, specimens of a deposition angle of 60° and 45° show the higher values of shear stress response. Similar results were reported by Oda (1972) and Tatsuoka (1990) for sand tested on conventional triaxial tests. Furthermore, it is noticed that after the constant volume has been reached, the stress strain curve start to depart away from this condition after a displacement of 6 mm (see Fig. 4 and Fig. 5). This mainly due to the fact that in direct shear tester, non-uniform shearing caused non-horizontal sliding, therefore, it prevents constant-volume conditions to be stabilized as clarified by Tarantino and Hyde (2005).

Figure 7: Influence of bedding plane orientation on sand behavior under direct shear test on natural Ras en-Naqab sand, (a) shear stresses (b) vertical displacement, σn=165 kPa
Figure 8: (a) Peak (b) Residual horizontal (shear) stresses versus vertical stresses for different bedding plane angles, $\theta$. 
The effect of one dimensional compression on grain size distribution is shown in Figure 9e. The initial and final grain size distribution after compression is shown. It is obvious as the vertical stress increases the amount of particle breakage increases.

The amounts of particles crushing (breakage) were evaluated based on the modified Hardin (1985) formula by Einav (2007). Einav (2007) postulates that the grain size distribution will start from an initial grading and ultimately reaches a final grading due to shearing and compression. The relative breakage index, Br, is defined as an area ratio

$$Br = \frac{B_t}{B_p}$$ (1)

where $B_t$ and $B_p$ are shown in Figure 10.

In this figure, $B_p$, the 'breakage potential', is defined by integrating the entire area confined between the initial and final grain size distribution whilst $B_t$ is the area between the current (at given compression stresses), and the initial one, when there is no applied shear or compression stresses. The relative breakage index evolution as a function of compression stresses is shown in Fig. 11. It is obvious from this figure that there is an asymptotic value for fragmentation of sand particles upon increasing the compression pressure applied to the sand particles. Similar results were also deduced by Einav (2007).

![Figure 9: Final grain size curve of samples after vertical one-dimensional compression.](image-url)
Figure 10: Einav (2007) modification definition of Hardin’s breakage index $B_r$.

Figure 11: Evolution of The relative breakage index in one dimensional compression.
The response of stress strain curve at relative breakage index, Br=0.74 for different bedding plane under normal stresses of $\sigma_n=55\text{kPa}$, $110\text{kPa}$ and $165\text{kPa}$ are shown in Figs. 12, 13 and 14. It is clearly shown from these figures that in case the bedding plane is horizontal ($\theta=0^{\circ}$) and parallel to the direction of shearing, the sand has the larger peak strength and the higher volumetric dilation. Hence, the bedding plane being parallel to the horizontal implies simply more contacts normals are oriented horizontally so that the specimen appears to be strong in this direction. Therefore, there is less potential for volume changes to occur. On the other hand, if the bedding plane ($\theta=60^{\circ}$) most contact normals are vertical and then the materials appears to be overly weak.

The grain size distribution for the sand specimen before and after shearing at Br=0.74 is shown in Fig. 15. It is obvious that the amount of particle breakage for this sand under direct shear condition is insignificant; the change in Br is less than 1.5%. This is because the quartz and feldspars are generally hard particles which resist disintegration during shear process. Therefore, crushing of this sand under conventional applied shear stress is in consequential. Similar trends were also observed for the other reported values of Br.
Figure 12: (a) Stress ratio $\tau/\sigma_n$ (b) vertical displacement at $Br=0.74$ for different bedding plane, Normal stress=55 kPa
Figure 13: (a) Stress ratio $\tau/\sigma_n$ (b) vertical displacement at $Br=0.74$ for different bedding plane, Normal stress=110 kPa
Figure 14: (a) Stress ratio $\tau/\sigma_n$ (b) vertical displacement at $Br=0.74$ for different bedding plane, Normal stress=165 kPa
Figure 15: Contributions to shear resistance of granular materials (Guo and So (2007)).

Effect of Sand Breakage on the Shear Strength Parameters

For soil sheared in a direct shear box, Taylor (1948) derived a simple soil model based on energy considerations. In this model, the peak internal friction angle is given as

$$\tan \phi_{\text{max}} = \tan \phi_{\text{residual}} + \tan \psi$$  \hspace{1cm} (2)$$

where

$$\tan \phi_{\text{max}} = \tan \phi_{\text{peak}} = \frac{\tau_{\text{maximum}}}{\sigma_n}$$  \hspace{1cm} (2a)$$

in which $\tau$ and $\sigma_n$ are the applied maximum shear and normal stresses;

$$\tan \phi_{\text{residual}} = \tan \phi_{\text{cv}} = \frac{\tau_{\text{residual}}}{\sigma_n}$$  \hspace{1cm} (2b)$$

$\phi_{\text{residual}}$, residual internal friction angle and $\phi_{\text{cv}}$, internal friction angle at constant volume; $\tau_{\text{residual}}$, the residual shear stresses or the shear stresses at constant volume;

$$\tan \psi = \frac{-d\varepsilon}{d\gamma}$$  \hspace{1cm} (2c)$$

in which $d\varepsilon$ is the increment of normal stress and $d\gamma$ is the increment of shear strain.
In order to evaluate the effect of particles breakage on the shear strength parameters, the peak and residual internal friction angles were evaluated for different direct shear stress tests preceded with one dimensional compression tests. Fig. 16 shows the difference between the maximum internal friction angle and the residual friction angle measured in the direct shear box. This figure clearly shows that as the one dimensional compression stress increases the difference between the peak and residual angles decreases. On other words, the dilatancy component of the shear strength suppressed (i.e., the dilatancy angle diminishes with increasing one dimensional compression). Moreover, at Br=0.49 the measured values of dilatancy angles were decreased then started to increase again at Br=0.74. This behavior is due to the fact that with the increases in crushing stresses, the asperities of the sand grains were flattened, however, with increases in the compressive crushing stresses new asperities were developed due to the fracture of sand grain, which in turn increases the interlocking energy due to the rearrangement of the soil particles. Furthermore, at depositional angle of \( \theta=30^\circ \), the amount of difference between the peak and residual frictional angles is the lowest regardless the amount of grains breakage.

**CONCLUSIONS**

Inherent anisotropy and particle breakage for natural Ras en-Naqab sand were investigated experimentally. The natural sand specimens were subjected to one dimensional compression to induce breakage. The grain size distributions of the specimens were reported before and after the application of the stresses. Thereafter, the sand shear strength parameters were assessed using direct simple shear. Examining the obtained results revealed that the peak shear strength parameters have little or no change. However, inspection of the residual shear strength parameters, ie., the apparent critical state angle of friction, showed an increase as the amount of particle crushing increases, regardless of the level of the applied normal stresses. Moreover,
examining the effect of angle of deposition, it shows a considerable amount of the dilation on the higher deposition angle regardless the extent of breakage reported

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