Experimental and numerical investigation on bearing capacity of granular soil affected by particle roundness

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Main objective of this study is investigation effect of roundness of particles on ultimate bearing capacity (UBC) of soil. A strip footing was modeled and UBC has been gained at three roundness groups of angular, rounded and well-rounded soil. Two other factors of size and relative density were added to tests for better understanding of soil behavior at different conditions. Tests have been done at 3 roundness groups, 6 size groups from 0.30mm to 4.75mm and 3 relative densities of 30%, 50% and 70%. On next step direct shear tests done at all 54 different conditions. Values from shear box test were compared with experimental results. Comparison showed acceptable relations between theory and experimental results. UBC decreased by increasing roundness of particles. Changing angular soil to well-rounded shape decreased the UBC about 33% at relative density of 30%. This decrease was about 40% at Dr=50%. Ultimate bearing capacity of well-rounded sample was 45% less than angular samples at Dr=70%. It means effect of roundness on UBC was more considerable at bigger relative densities. Same behavior was seen at bigger sizes. Finally changing shape of particles from angular to rounded soil had more effect on decreasing UBC than changing rounded to well-rounded soil.

[Keywords: Granular Soil, Ultimate Bearing Capacity, Particle Roundness, Strip Footing]

Introduction

Ultimate bearing capacity of granular materials is a classic issue in civil and geotechnical engineering1. Lots of studies have reported by researchers by using different materials such as calcareous2. Reinforcement of fill can improve both ultimate bearing capacity and settlement of the foundation3-9. On the other hand particles shape is an important factor on shear behaviors of granular materials10-12. There are some researches that studied effect of particles shape or size on soils behavior.

On the study of shear strength behavior of composite soils affected by grain size distribution and particle size has been investigated13. Two different samples of fine (clay and silt) and natural coarse (river sand and crushed gravels) have been prepared and direct shear box test has been done on samples at this study. Terms that used to describe particles shape can be named as texture, sphericity, roughness and roundness14, 15. Recent researches have showed that increasing angularity of materials cause increase in minimum and maximum void ratio ($e_{\text{max}}$ and $e_{\text{min}}$) and so increasing roundness of particles will lead to a decrease on maximum and minimum void ratio15-18.

Holtz and Gibbs19 research showed that increasing angularity of a mixture and angular materials have much higher shear strength than sub-angular or sub-rounded materials. From previous researches it is clear that many of investigation has been done on effect of particle shape on granular soils properties like sands, but experimental investigation about particles shape and size distribution on granular materials are rare, even if they are most frequent geo-materials in engineering13. By using different image analysis techniques, many investigations have been done on relationships between particle shapes or grain-size distributions and mechanical properties of geo-engineering materials20,21,22. Many studies have been done on bearing capacity of strip footing on different kinds of soils such as normal or reinforced sands, clay, silt or other soils. Load-settlement behavior of a shallow
foundation on iron ore tailings has been investigated on other study. At the same time different studies have been done on different kinds of footings or columns on different foundations. Cascone and Casablanca have been studied on dynamic bearing capacity of shallow foundations. Ultimate bearing capacity (UBC) of strip footing has been analyzed on reinforced soil by Chen and Abu-Farsakh. At that study, an analytical solution has been developed for estimating UBC of strip footing on reinforced soil. Results showed that underlying unreinforced soil and relative density of reinforced soil layer has effect on punching shear failure zone.

Cicek et al. studied effect of reinforcement length on strip footing behavior. At this study some laboratory tests has been done on unreinforced and reinforced soils. Geogrid has been used for reinforcing the soil and different types and number of reinforcements has been investigated to find if these parameters had effect on optimum reinforcement or not. Results showed that for achieving optimum reinforcing, length of reinforcement was needed.

Cure et al. were generated both model and analytical tests on strip footing near a sandy slope. Effect of ultimate load has been investigated at this study on both centrally and eccentrically loaded surface. Results showed that by increasing eccentricity ultimate load decreased. Amount of decreasing of ultimate capacity increased by increasing eccentricity.

Arasan et al. has been studied on Balast, Calcareous, abrasive and bearing balls. By considering roundness values of particles they classified tested soils to 6 roundness classes. For this purpose, the shape properties of particles were calculated and the effect of particle shape on the geotechnical properties of aggregate was investigated by analyzing images of basalt, calcareous and steel balls (abrasive and bearing balls). Calcareous has been changed from angular calcareous to well-rounded calcareous by using Los Angeles machine at specified revolution.

Although there are lots of studies on strip footing and granular materials at different conditions but there are rare studies about particle roundness or shape and their effect on mechanical properties and behavior of aggregate. Effect of size and relative density of soil can be founded at literature, but effect of roundness of particles on bearing capacity of soils was not founded. The originality of this study is that, roundness of particle has been added to two other parameters of size and relative density, and effect of combination of these three parameters on shear strength and UBC of granular soil have been studied. At present experimental study, a strip footing has been modeled at three kinds of angular, rounded and well-rounded soil, 6 size groups and three different relative densities and effect of these parameters has been studied on shear strength and ultimate bearing capacity.

Materials and Methods
Granular crashed Calcareous has been used at this study. It has been gained from Ergunler Company in Erzurum, Turkey. According to ASTM D 854-14, the specific gravity of soil determined 2.7. Soil has been washed and dried at laboratory temperature and sieved. Size of soil was from 0.30mm to 4.75mm and it has been divided to 6 different size groups. Sieves used for soil division were 0.30mm, 1.18mm, 1.40mm, 2.36mm, 2.80mm, 3.35mm and 4.75mm. Totally 18 kinds of samples have been prepared and tested at 3 different roundness classes of angular (AC), rounded (RC) and well-rounded calcareous (WRC) and 6 size groups. Each kind of samples has been tested at three different relative densities of 30%, 50% and 70%. So altogether there were 54 different tested conditions. According to unified soil classification system, ASTM D 2487-11, samples were classified as SP. Grain size distribution gained according ASTM D 6913-04 has been shown at Fig 1.

![Fig.1- Grain Size Distribution of Soil](AC: Angular Calcareous, RC: Rounded Calcareous and WRC: Well Rounded Calcareous)

Roundness value of soil determined using Cox equation and Power chart. By calculating this value, the soil gotten from Ergunler Company was classified as angular soil. Roundness values and shape of particles by Cox has been shown on Fig.2.
Los Angles Rattler Machine without balls has been used for changing angular calcareous (AC) to rounded calcareous (RC) and well-rounded (WRC) that explained in Arasan. Angular soil has been rounded for 50000 and 100000 of revolution on Los Angles machine for changing to the shape to rounded and well-rounded soil respectively. After rounding angular soil to rounded and well-rounded, they have been washed, dried and sieved at mentioned size groups. Roundness values and groups of soil have been shown at Table 1.

Table 1- Roundness Values and Classification of Soils

<table>
<thead>
<tr>
<th>Sample</th>
<th>Roundness Value</th>
<th>Roundness Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angular Calcareous (AC)</td>
<td>0.693-0.744</td>
<td>Angular-Sub Angular</td>
</tr>
<tr>
<td>Rounded Calcareous (RC)</td>
<td>0.786-0.803</td>
<td>Rounded-Well Rounded</td>
</tr>
<tr>
<td>Well-Rounded Calcareous</td>
<td>0.834-0.854</td>
<td>Well-Rounded</td>
</tr>
</tbody>
</table>

Shape of calcareous at three different roundness classes has been showed on Fig.3. As seen at this picture roundness of particles increased by going from angular calcareous toward well-rounded calcareous and it is even visible by eye.

This study involves series of tests done at laboratory in a model tank. A tank with dimension of 1mx1mx0.10m has been used for modeling a strip footing. A Plexiglas plate has been used in front of tank to see the soil and footing. Strip footing used at this study was made of Polyamide with the dimension of 9.8cm length, 5cm width and 4cm of height. It was rigid enough that footing acted as rigid foundation. At this study the length of model footing was almost equal to the width of the tank in order to maintain plane strain conditions. A hydraulic jack has used for loading the footing. It has been fixed to a strong horizontal beam of the frame that could carry thrust developed by hydraulic jack without any deformation. Loading was applied in small incensement so speed of displacement was 2<mm/min. A load-cell with capacity of 50kN was placed between the footing and hydraulic jack for measuring applied load. A shaft has been used that transferred the load to footing. It has been placed between load-cell and footing. Single point load has been applied to footing by use of ball bearing that has been placed between shaft and footing. As rigid footing has been used at this study, uniform load has been applied to soil. For preventing contact between walls of tank and footing a 1mm wide gap has been placed between them. At the same time two sides of footing and walls of tank were coated with petroleum jelly for minimizing end friction effects. Two linear variable displacement transducers (LVDT) were used at two cross corners of footing for measuring vertical settlement of footing. Average of these two LVDSs has been considered as footing settlement. Picture and schematic draw of test box have been shown on Fig. 4 and Fig. 5 respectively. Load cell and LVDTs connected to a data logger for transferring data to computer.
Samples have been classified to 3 roundness groups of angular, rounded and well-rounded shape. Each roundness group has been divided to 6 different size groups too. Tests have been done at three relative densities of 30%, 50% and 70% (Dr=30%, 50% and 70%) for each roundness and size groups. Altogether there were 54 different types of tests done. Each test has been done at least three times for ensuring the results. Tests program has been showed at Table 2. Minimum and maximum void ratio ($e_{\text{min}}$ and $e_{\text{max}}$) of each sample has been found according to ASTM D4253-16 and ASTM D4254-16 and weight of soil for each tested sample has been calculated and placed in tank at three relative densities by considering soil physical characteristics and tank volume.

### Table 2- All 54 Different Conditions of Tests

<table>
<thead>
<tr>
<th>Dimension (mm)</th>
<th>Roundness Class</th>
<th>Relative Density (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.30–1.18</td>
<td>Angular, Rounded, Well-Rounded</td>
<td>30 – 50 - 70</td>
</tr>
<tr>
<td>1.18–1.40</td>
<td>Angular, Rounded, Well-Rounded</td>
<td>30 – 50 - 70</td>
</tr>
<tr>
<td>1.40–2.36</td>
<td>Angular, Rounded, Well-Rounded</td>
<td>30 – 50 - 70</td>
</tr>
<tr>
<td>2.36–2.80</td>
<td>Angular, Rounded, Well-Rounded</td>
<td>30 – 50 - 70</td>
</tr>
<tr>
<td>2.80–3.35</td>
<td>Angular, Rounded, Well-Rounded</td>
<td>30 – 50 - 70</td>
</tr>
<tr>
<td>3.35–4.75</td>
<td>Angular, Rounded, Well-Rounded</td>
<td>30 – 50 - 70</td>
</tr>
</tbody>
</table>

### Results and Discussion

After filling the tank, strip footing has been placed on the soil and loaded. Data have been transferred to computer. Average of settlements at two cross corners of footing has been considered as settlement of footing. Bearing capacity has been gained by dividing load to area of footing. Load-Settlement graphs have been drawn and ultimate bearing capacity has been gained from these graphs.

Ultimate bearing capacity (UBC) of strip footing at three roundness classes (Angular, Rounded and Well Rounded Calcareous) founded and compared together at three different relative densities of 30%, 50% and 70%. Results have been shown at Fig. 6, Fig. 7 and Fig. 8. UBC has been decreased by increasing roundness of samples. Effect of particles roundness on bearing capacity is more considerable at size or bigger relative densities. By changing angular soil to well-rounded shape, ultimate bearing capacity decreased about 33% at relative density of 30%. This decrease affected by roundness of particles was about 40% at relative density of 50%. Ultimate bearing capacity of well-rounded samples was 45% less than angular samples at Dr=70%.
By looking to results it found that, changing angular soil to rounded soil has more effect on ultimate bearing capacity than changing rounded to well-rounded soil. On the other word differences on ultimate bearing capacity while angular soil changed to rounded soil is more than differences on UBC while rounded soil changed to well-rounded. Changing angular to rounded soil caused an average decrease more than 40% on ultimate bearing capacity at relative density of 70%. While rounded soil changed to well-rounded this value was less than 20%. This decrease on ultimate bearing capacity is more considerable at bigger relative densities. For example at relative density of 70%, changing angular soil to rounded shape caused at least 40% of decrease on ultimate bearing capacity that this value at Dr=30% was less than 20%.

There was an increase on bearing capacity by increasing the size of soil from 0.30mm to 4.75mm too. This increase was 2.3, 2.5 and 2 times on angular, rounded and well-rounded soils respectively while relative density of samples was 30%. At relative density of 50% (Dr=50%) increasing value was 2.9, 3.2, and 2 times for three kinds of angular, rounded and well-rounded samples. Finally effect of increasing of roundness and size of particles from 0.30 to 4.75mm was, 1.8, 2.2 and 2.2 times on angular, rounded and well-rounded soils at Dr=70%.

Fig. 9 shows ultimate bearing capacity of soil at all 54 different conditions of tests at three different roundness groups and relative densities. As seen at this figure, ultimate bearing capacity of soil decreased by changing shape of particles from angular to rounded and well rounded. Roundness of particles and less friction of soil on well rounded samples are the reasons of this decreasing. Changes on bearing capacity at a same roundness class are more considerable on bigger sizes than smaller.

**Fig. 8- Ultimate Bearing Capacity of Strip Footing at Three Roundness Groups (Dr=70%)**

By looking on Load-Settlement graphs it found that at relative densities of 30%, 50% and 70%, soil had punching, local and general shear failure respectively. As an example it has been shown for angular calcareous soil with size of 1.40 to 2.36mm at Fig. 10. Samples showed to some extent same behavior at all angular, rounded and well-rounded classes. Soil failure mechanisms on failing moment have been shown below on Fig. 11, Fig.12 and Fig.13.

**Fig. 9- Ultimate Bearing Capacity at Three Roundness Classes and Relative Densities**

**Fig. 10- Load-Settlement Graphs at 3 Different Relative Densities for angular Calcareous for material with Dimension of 1.40 to 2.36mm**
There was an increasing on ultimate bearing capacity by increasing dimension or relative density of aggregate. Increasing of bearing capacity because of increasing size, has been shown for well rounded calcareous (WRC) at relative density of 30%, 50% and 70% on Fig.14, Fig.15 and Fig.16 respectively. As seen at these graphs, increasing size from 0.30 mm to 4.75 mm caused an increase of 2 times on ultimate bearing capacity. Approximately 3 times of increase has been happened while relative density increased from 30% to 70%.
Direct shear strength tests have been done on all samples and friction angle of soil at three roundness groups and different sizes and relative densities have been calculated. Shear tests have been done according to ASTM D3080M – 11 and results have been shown at Fig. 17. As seen at this figure by increasing roundness of particles, shear strength of soil has been decreased. In opposite increasing relative density or size of soil increased the shear strength of samples.

![Fig.17- Friction angle of Soil at different Roundness Groups and dimensions](image)

Smallest value of friction angle gained at well-rounded samples with size of 0.30-1.18mm at Dr=30% that was 28 degree and biggest value of 48 degree belongs to angular calcareous at size of 3.35-4.75mm and relative density of 70%. Like ultimate bearing capacity, difference on shear strength of samples was more between angular and rounded soil than differences between rounded and well-rounded soil. It means difference on shear strength is more considerable while angular soil changes to rounded.

Theory results of ultimate bearing capacity can be gained from Terzaghi formula (Formula. 1) that used for strip footings.

\[
 q_u = C N_c + \gamma D_f N_q + 0.5 \gamma B N_f
\]

As soil was sandy soil so the value of cohesion waws equal to zero (C=0). Footing spaced on the soil surface then \( D_f = 0 \). Value of \( N_q \) depended on friction angle of soil. By calculating values for \( N_q \) considering \( \gamma \) (Unit Weight) at different conditions of tests and knowing amount of \( B \) (Footing width), ultimate bearing capacity of soil can be calculated. Results gotten from theory and experimental tests have been shown at Table. 3. As seen at this table results are near and are in acceptable range. On experimental shear tests, there can be an acceptable tolerance of 2 degrees on getting and calculating friction angle (\( \phi \) of soil. Changing in \( \phi \) will change the value of \( N_q \) and so the result for ultimate bearing capacity will change. By considering this tolerance some bigger differences on theory and experimental results of ultimate bearing capacity will be in acceptable rang too.

### Table 3- Comparison between Theory and Experimental Result of Ultimate Bearing Capacity

<table>
<thead>
<tr>
<th>Size (mm)</th>
<th>Dr</th>
<th>AC (Theory)</th>
<th>AC (Test)</th>
<th>RC (Theory)</th>
<th>RC (Test)</th>
<th>WRC (Theory)</th>
<th>WRC (Test)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.30-1.18</td>
<td>30%</td>
<td>11.6</td>
<td>15.0</td>
<td>6.2</td>
<td>12.0</td>
<td>5.4</td>
<td>10.0</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>24.6</td>
<td>40.0</td>
<td>12.6</td>
<td>28.0</td>
<td>12.9</td>
<td>25.0</td>
</tr>
<tr>
<td></td>
<td>70%</td>
<td>55.4</td>
<td>130.0</td>
<td>26.4</td>
<td>55.0</td>
<td>22.4</td>
<td>44.0</td>
</tr>
<tr>
<td>1.18-1.40</td>
<td>30%</td>
<td>23.2</td>
<td>18.0</td>
<td>13.9</td>
<td>13.0</td>
<td>11.9</td>
<td>12.0</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>42.4</td>
<td>45.0</td>
<td>24.6</td>
<td>34.0</td>
<td>17.6</td>
<td>28.0</td>
</tr>
<tr>
<td></td>
<td>70%</td>
<td>80.4</td>
<td>130.0</td>
<td>45.3</td>
<td>80.0</td>
<td>38.2</td>
<td>72.0</td>
</tr>
<tr>
<td>1.40-2.36</td>
<td>30%</td>
<td>27.9</td>
<td>20.0</td>
<td>19.8</td>
<td>15.0</td>
<td>17.3</td>
<td>13.0</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>52.0</td>
<td>50.0</td>
<td>43.8</td>
<td>42.0</td>
<td>30.9</td>
<td>30.0</td>
</tr>
<tr>
<td></td>
<td>70%</td>
<td>100.1</td>
<td>135.0</td>
<td>67.9</td>
<td>85.0</td>
<td>56.9</td>
<td>80.0</td>
</tr>
<tr>
<td>2.36-2.80</td>
<td>30%</td>
<td>41.2</td>
<td>24.0</td>
<td>29.1</td>
<td>22.0</td>
<td>17.3</td>
<td>16.0</td>
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<tr>
<td></td>
<td>50%</td>
<td>96.8</td>
<td>70.0</td>
<td>53.7</td>
<td>44.0</td>
<td>45.3</td>
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<tr>
<td></td>
<td>70%</td>
<td>156.7</td>
<td>155.0</td>
<td>84.1</td>
<td>88.0</td>
<td>85.7</td>
<td>86.0</td>
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<td>2.80-3.35</td>
<td>30%</td>
<td>50.2</td>
<td>30.0</td>
<td>42.7</td>
<td>25.0</td>
<td>20.8</td>
<td>18.0</td>
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<tr>
<td></td>
<td>50%</td>
<td>96.8</td>
<td>75.0</td>
<td>66.2</td>
<td>55.0</td>
<td>45.8</td>
<td>44.0</td>
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<tr>
<td></td>
<td>70%</td>
<td>156.7</td>
<td>168.0</td>
<td>104.6</td>
<td>100.0</td>
<td>86.7</td>
<td>96.0</td>
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<tr>
<td>3.35-4.75</td>
<td>30%</td>
<td>61.5</td>
<td>35.0</td>
<td>52.7</td>
<td>30.0</td>
<td>30.1</td>
<td>20.0</td>
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<td></td>
<td>50%</td>
<td>121.2</td>
<td>115.0</td>
<td>82.0</td>
<td>64.0</td>
<td>55.5</td>
<td>50.0</td>
</tr>
<tr>
<td></td>
<td>70%</td>
<td>252.1</td>
<td>250.0</td>
<td>130.9</td>
<td>120.0</td>
<td>107.3</td>
<td>100.0</td>
</tr>
</tbody>
</table>
Conclusion

Increasing each parameters of angularity, size or relative density of aggregate will increase shear strength and UBC of soil. Changes on shape of angular soil are more considerable than rounded or well-rounded soils. This effect is more considerable at bigger sizes or relative densities. By increasing particles size or relative density, UBC showed more increase on angular soils than rounded or well-rounded soils. Effect of increasing size and relative density is more considerable at angular soils than rounded or well-rounded soil. Changes on shape of angular soils especially at dense or bigger soils should be studied carefully.

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