Summary

Soil particle characteristics like mineralogy, particle shape and size have a significant impact on the soil mechanical behavior of the soil mass. In cases of high stress loading (deep compaction, cone penetration testing, high energy cyclic loading, etc.), crushing can occur, impacting particle shape and grain size distribution (GSD), and therefore changing the behavior of the soil mass.

Soils consisting of weaker particles (like calcareous materials) are more prone to this type of modifications. However, most soil mechanical relations have been established using silica materials and therefore do not reflect the possible impact of crushing.

For the reasons mentioned above, this study presents laboratory test results from 3D particle measurement tests, direct shear tests and triaxial compression tests with bender element measurements to determine the effects of particle characteristics and GSD on the mechanical behavior of calcareous sand. The calcareous sand is taken from two different locations on an artificial island in Abu Dhabi, United Arab Emirates, whereas the commonly used silica sand is obtained from Mol in Antwerpen, Belgium. To study the effect of particle shape, a modification of the original material is performed by crushing to have finer and crushed particles. Afterward, the original calcareous sand is matched with similar sizes of particles and gradations as the silica sand and the crushed calcareous sand. Based on these laboratory results, five main contributions are mentioned:

- The first part of the study mainly describes the process of equipment construction for the experiments. This is the first step to accomplish the scientific goals. A testing system including the cyclic tri-axial apparatus with the bender element device is built in the Geotechnics Laboratory of the Ghent University. For the bender element tests, the system works very well using the

stacking technique recommended for the determination of the travel time. For cyclic loading tests, the system works well until a frequency of 1 (Hz) since the program cannot calibrate itself fast enough to make a balance between the input and the output signals at higher frequencies. This is considered as a limitation of the system in this study.

- The second part of the study focuses on the measurements of the size and shape of the particles of the calcareous sand, silica sand and crushed calcareous sand in different fractions of the GSD. Based on the results of the 3D analysis (3DA), the particles of the calcareous sand are found less spherical than those of the silica sand and the crushed calcareous sand. Next, a relationship between particle shape and size is established for the calcareous sand and the crushed calcareous sand. The average sphericity (SPH) of the particles holds an inverse relationship to the particle size. This finding is consistent with the test results of the maximum and minimum void ratios (e_{max} and e_{min}) since e_{max} and e_{min} decrease with increasing SPH. Further, the 3DA shows smaller particle sizes than the sieve analysis (SA). This is due to particle interlocking caused by the various particle shapes, especially for the calcareous sand. It is concluded that the particle shape is the main factor affecting the SA results.

- Thirdly, the effects of particle characteristics and gradation on shear properties (shear strength and friction angle) are looked upon using the results of the direct shear tests with emphasis again on the difference between the silica sand and the calcareous sand. The results prove that particle shape and composition are the main factors causing the differences between the calcareous sand and the silica sand. Although the calcareous sand forms a higher void ratio, it gives higher peak and residual shear properties than the silica sand. During shearing, the calcareous sand reaches a lower shear strength at a small shear strain in the early state of shearing and shows a lower dilation at the end of testing than the silica sand especially in the dense samples. The main reason is that the variety of particle shapes increases the particle interlocking and the number of inter-particle contacts and thus increases the shear properties of the calcareous sand. For the calcareous sand, the initial relative densities of the samples still have an influence on the shear strength and friction angle at the residual state ($\gamma = 10\%$). This suggests that to reach a critical state, the direct shear tests should be performed to a higher shear strain (e. g, γ = 15% or 20%). Additionally, for calcareous sand, the particle size D_{50} or uniformity coefficient C_u increases the shear properties at the residual state. Looking to the effect of D_{50}, the compression and dilation phase of the calcareous sand are affected strongly by the normal stress. Under the normal stress of 50 kPa, the sample with larger particles shows much more dilation than the sample with smaller particles. However, this trend starts to divert under the higher normal stress of 100 kPa, and finally, the completely opposite tendency is observed under 200 kPa where the sample with larger particles shows more contraction. The particle shape expressed via D_{50} is also correlated to the shear properties of the calcareous sand. Since the well-graded calcareous sands have better packing densities than the uniform calcareous sands, the packing density gives higher contributions to the shear properties than the particle shape. Therefore, the description of particle shape via C_u does not correlate with the shear properties and D_{50} is chosen for correlation purposes.

- The fourth part of the study concentrates on the results of the bender element tests. First, these results indicate that shear wave velocity (V_s) and thus small strain shear modulus (G_0) is strongly affected by particle shape. Less dynamic stiffness is found for particles owning more sphericity and less angularity. The G_0 of the calcareous sand is much higher than that of the silica sand at similar stress level and void ratio. This is because, at the same particle size, the calcareous sand with various particle shapes produces a better fabric for shear wave propagation compared with the silica sand. In addition, the increase of uniformity coefficient C_u and the presence of finer particles (at low C_u) have negative impacts on G_0. Finally, a correlation for G_0 is established for the calcareous sands with different C_u. The study also shows that predicting G_0 for calcareous sands using existing empirical equations gives very large relative errors. In short, not only the uniformity coefficient (C_u) but also the particle characteristics including particle shape, size and stiffness are very important to G_0 of soils.

- Finally, cyclic triaxial tests and bender element tests are performed to investigate the effect of the particle characteristics of the calcareous and silica sands on the correlation between cyclic resistance ratio (CRR) and shear wave velocity (V_{s1}). The cyclic test results show that although the calcareous sand has a higher void ratio, it gives much higher cyclic resistance than the silica sand. The increase is due to the variety of grain shape producing more particles interlocking in the calcareous sand. This property causes a distinctness not only in the progress of pore pressure generation but also in the development of axial strain under cyclic loading as found in the literature. In addition, the study indicates that the CRR–V_{s1} correlation depends on particle characteristics. This result confirms results of previous studies on the same calcareous sands. This study also indicates that the existing CRR-V_{s1} correlations, which underestimate or overestimate liquefaction resistance for calcareous sands, can be used for the initial primary estimation of liquefaction potential. For soils with different particle characteristics, however, further tests for cyclic resistance should be performed.

In conclusion, the effects of particle characteristics commonly not taken into account for estimating G_0 and liquefaction potential and completely ignored in looking at the difference between calcareous sand and silica sand are the main interests in this study. So based on the aforementioned conclusions, the following considerations should be taken into account. First, sampling reconstruction of calcareous sands, which is unavoidable in the laboratory, will affect test results. However, this has a similar influence on all the test samples and thus can be considered to cause comparable changes. Therefore, the tendency of the results may not be influenced and this effect should only be considered when evaluating the exact behavior of the calcareous sand in the field. Secondly, the above conclusions are given within the limit range of gradation and particle shape of the tested material and in the narrow range of effective confining pressures (25 - 300 kPa) that does not cause particle crushing.