Review History for "Effects of Particle Shape on the Shear Wave Velocity and Shear Modulus of 3D Printed Sand Analogs"

Sheikh Sharif Ahmed & Alejandro Martinez ***2022***

Summary

The paper was sent to three reviewers — Prof. Marcos Arroyo (Reviewer A), Prof. Torsten Wichtmann (Reviewer B) and Prof. Jean-Michel Pereira (Reviewer C). The reviewers remained anonymous during the entire review process and the authors were anonymous for the reviewers. After the reviewing process was complete, all reviewers agreed to disclose their identity. In Review Round 1, the reviewers provided a series of comments for the authors and required a revision of the manuscript. In Review Round 2, the reviewers recommended the manuscript for publication. The reviewer C added a short non-mandatory suggestion which was not accepted by the authors. After the Review Round 2 the managing Editor decided to accept the manuscript for publication.

Review Round 1

Reviewer A (Marcos Arroyo)

This is an interesting study that deserves to be published. Still, I have a few remarks that I would like the authors to consider in review.

- Figure 2. To provide some context for the reader, it may be illustrative if you were to add some curves from literature of the contact force-displacement behaviour of, say, quartz sand grains.
- The legend in Figure 10 seems wrong.
- You should present a table with the values of R and R_G of the sands whose data is included in Figure 12.
- The differences with previous trends shown in Figure 3 are remarkable and I feel they are being somewhat glossed over. Apparently you have used some new procedures to establish extreme void ratios (Carey et al 2020) instead of the ASTM procedures that Cho employed. There is a possibility that the different procedural techniques employed might have had an influence on the discrepancy; it will be good if you can reassure the reader that this is not the case (e.g. by obtaining some ASTM measurements of emin & emax for the extreme roundness cases of your material).
- The discussion in 4.2 leads to a kind of general-purpose warning (*"it should be considered how inherent differences caused by the materials and layer deposition process used in 3D printing may affect different aspects of the behavior of*

granular materials"), which is unobjectionable by itself, but appears quite unrelated to the specific tests and observations presented in the paper. Following on my previous point, one wonders if a material that is very lightweight and has a considerable capacity to store elastic energy is well suited to mimic granular soil responses to procedures, such as tamping or pluviation, in which dynamic excitation and inertial forces are meant to play a significant role. I wonder if the authors would be able to comment on this?

- Another significant discrepancy with previous research is that illustrated by figures 11 c and d. There is some hard to follow explanation in a paragraph in page 10 (starting *"Cho et al..."*) that leads the authros to conclude that *"...it is possible that the Cho et al. [2006] equation and Equation 7 highlight similar trends"*. Another possibility is that the range of "beta" explored in the authors experiments is just to narrow to discern any trend in it. Would you care to comment on that?

- This begs the question of why would that "beta" range be so narrow in your experiments? Perhaps the soft contacts of the printed material are diluting any other possible contributing factor, such as shape, to the pressure dependency of Vs? If that is the case the effects of shape detected in your tests may underestimate those in real sands. (By the way, this is also suggested by how the effect of shape narrows down with increased density in Figure 5 or in Figure 7). Perhaps this should lead to a more specific warning?

Reviewer B (Torsten Wichtmann)

The paper presents an experimental study on the shear wave velocity in samples composed of 3D-printed polymeric particles with different shape. The applied 3D printing technique allows to generate particles with prescribed size and shape characteristics. It enables systematic investigations on the influence of the particle characteristics, where a single parameter (size, general shape, roundness of corners) can be varied while the other ones are kept constant. In case of natural sands this can usually only be achieved by huge sieving and mixing effort. The dependencies of the shear wave velocity on void ratio, pressure and shape parameters measured by the authors on samples of the 3D-printed granular materials are consistent with well-known relationships for natural soils. The authors address the effects of certain differences between natural and artificial granular materials, as the lower stiffness and higher surface roughness of the polymeric particles, as well as special features of the 3D-printed grains like an anisotropy of the friction coefficient. Overall, the paper is well written and represents an original contribution to the field of experimental soil dynamics. The described 3D printing technique has high potential to be more frequently applied by researchers in future. Consequently, I recommend the paper for publication with some revisions addressed below. Furthermore, I have added a few typographical corrections into the PDF file.

Recommended revisions:

- Page 2, left column, first paragraph: Could the conflicting observations regarding the dependence of shear wave velocity on particle characteristics found in the literature be partly caused by the chosen base of comparison, i.e. either a constant void ratio or a constant relative density? The latter will also consider changes of the extreme void ratios e_{min} and e_{max} with the varied parameter (e.g. D_{50} or grain shape).

- Figure 1: Which shape parameters were intended to be varied when generating the particles of mixes 3, 6, 7 and 8? It looks like the particles possess a similar roundness of the corners, but a different overall shape.

- Page 4, first paragraph of Section 2.2: I recommend to include definitions of the shape parameters roundness R, circle ratio sphericity S_C, perimeter sphericity S_P, width-to-length ratio sphericity S_{WL} and convexity C in the manuscript. The underlying geometrical properties of the grains could be explained by means of a scheme.

- Page 4, Table 1 and corresponding text: Which methods were applied to take pictures of the grains used as basis for the determination of the grain shape parameters?

- Page 4, Table 2: The tested artificial materials had slightly different mean grain sizes D_{50} (2.5 to 3.2 mm) and uniformity coefficients C_U (1.0 to 1.47). Do the authors expect an influence of these variations on the test results? I recommend to add a figure showing the grain size distribution curves of the tested artificial materials. Is it justified to speak of "sand" analogs, considering that the mean grain sizes of these materials are above 2 mm, i.e. in the range of fine gravels? In Table 2 the unit of D_{50} should be added.

- Page 4, second paragraph of Section 2.2: *"The polyjet 3D printing process results in a large surface roughness, which is greater than that typical of natural soil particles."* If the authors have quantified the surface roughness, typical values of the artificial particles in comparision to those of natural sands should be given here.

- Page 4, Figure 2 and corresponding text: The diameter of the particles used in the particle-particle compression test should be specified.
- Page 4: *"Another important difference between the polyjet particles and natural sand particles is the magnitude and anisotropy of the friction coefficient of the former."* Even if the details are included in another paper it should be briefly described here what the authors understand under an anisotropy of the friction coefficient of the polyjet particles.
- Page 5, Section 2.3: Which method was applied to prepare the samples? Air pluviation using a funnel or loose placement with subsequent compaction? I guess all samples were tested in the dry condition. Respective comments should be added.
- Page 6, Figure 5: It seems that mixes 1, 2 and 4 have not been tested at a pressure $p' = 80$ kPa, which should be mentioned in the test description.
- Page 6: *Analytical relationships for the β-exponents indicate values of 0.167 for a Hertzian contact ..."* A respective reference to the literature should be added.
- Page 6: *"It is noted that the G_{max} values reported are smaller than those typical of natural sands due to the smaller specific gravity of the 3D printed sands."* Can the lower values of shear modulus partly be attributed to the lower stiffness of the polymeric material constituting the artificial particles?
- Page 9: Eqs. (3) to (7): These equations are shown as dashed or dot-dashed lines or curves in Figure 10? At least in case of SAGI this seems not to be the case because a linear relationship is described by Eq. (6), while a curved relationship is shown in Figure 10d. Please add respective remarks to the manuscript.
- Page 10, Figure 11: Which void ratios e_0 or relative densities D_r were used in the tests forming the basis for the equations proposed by Cho et al. (2006) compared with the authors' equations in this figure? This information should be added to the text.
- Page 11, Figure 12: Please specify the ranges of roundness and regularity, D_{50} and C_u, relative density and pressure for the experimental data from the literature included in this figure, e.g. in tabular form. Why data of different studies is used in diagrams (a) and (b), i.e. Liu and Yang (2018) in case of roundness and Liu et al. (2021) in case of regularity?
- Page 11, Figure 12: Can the authors add an explanation why the equations developed based on the tests on the 3D printed particles describe well the v_S data for natural sands, although the polymeric material constituting the artificial particles has a significantly lower stiffness?

Reviewer C (Jean-Michel Pereira)

The manuscript presents the results of an experimental work aiming at characterising the effects of particle shapes on some mechanical properties (Vs and Gmax) of granular materials. The authors use 3D printed grains to distinguish the effects of various shape descriptors on these mechanical properties while working with the same grain material and grain contact properties.

The manuscript is very well written and easy to follow. The research problem is well stated, and properly treated.

The reviewer would like to invite the authors to react to the following points.

- §2.2: Please provide the thickness of printed layers (vertical resolution of the printer used). Commenting on the limitations inherent to the printer (resolution) on the reachable shape descriptors and other grains characteristics (roughness, etc.) would be valuable.
- §2.2: An other difference in the intergranular contact behaviour is probably the ductile behaviour of asperities. Do the authors expect the same brittle behaviour of asperities of printed grains compared to natural sands?
- §3.1: What is the uncertainty associated to beta values obtained from the best fit exercise? Is the variation mentioned at the bottom of p.5 (right) significant with respect to this uncertainty?
- Figs 5 and 7: It is fine not to show the fits but it is suggested that the authors provide (maybe in appendix) a measure of the quality of the fit. This point is actually related to the confidence that we can have on fitted parameters (alpha, beta, A, n...).

- Fig 10 (e-h): It seems that there are two regimes for beta exponent. One for low values of the descriptors and another one for large values of those. This seems to be recongnized by the authors at the bottom of p. 10 (left). What is the reason? Actually, the exact same trend can be observed for n exponent in fig A5.
- §4.2: The authors are invited to print the same grains but rotated to various angles to have layers stacked in other directions with respect to the grains main axes. This could be of some value to estimate this "direction-dependency".

Typos:

- p.2: "capture"
- p.2: "shown" instead of "show"
- p.9: repeated "of" to be removed
- p.10: "in" to be removed after "between"
- p.11: "dependency"

Author Response

We appreciate the opportunity to revise our manuscript in light of the helpful feedback provided by the three reviewers. In this letter, we provide an individual response to each of the reviewers' comments. For reference, the text that has been added or modified is highlighted in blue font in the submitted revised manuscript. We are also submitting a clean version of our revised manuscript. If you should have any additional questions or inquiries about our manuscript, please do not hesitate to contact me at *amart@ucdavis.edu*.

Reviewer A

This is an interesting study that deserves to be published. Still, I have a few remarks that I would like the authors to consider in review.

We appreciate the feedback provided by the reviewer. In this document, we provide responses to each of the reviewer's comments. In the revised manuscript, we have highlighted the text that has been modified or added in blue font for reference.

Figure 2. To provide some context for the reader, it may be illustrative if you were to add some curves from literature of the contact force-displacement behaviour of, say, quartz sand grains

We appreciate the reviewer comment. We have added the results of uniaxial particle-particle compression tests of glass beads and natural sand (the latter obtained from the literature). The figure shows the stiffer response of the glass beads and natural sand particles. In addition, it highlights the fact that the contact behavior of glass beads is mostly Hertzian, the contact behavior of natural sand particles has an initial stage of asperity yielding, and the contact behavior of the 3D printed particles has a considerable amount of asperity yielding. These results are included in the manuscript in the new Figure 4.

We have included additional information in the text to describe this; this reads as follows:

"Figure 4a shows the results of interparticle uniaxial compression tests performed by Ahmed and Martinez (2020) on spherical polyjet particles with diameter of 3.175 mm. The results show that initial increases in force result in a soft contact response due to plastic yielding of the particles' micro-asperities. As the load is increased, the contact becomes stiffer and follows the Hertzian solution more closely. For comparison, Figure 4b presents similar results for a pair of glass spheres with diameter of 3.175 mm, showing the stiffer contact response that closely follows Hertz' solution. Figure 4c shows the results of a single grain crushing test on Leighton Buzzard Sand (LBS), from Cavarretta et al. (2010). The response of LBS also shows an initial softer response due to plastic yielding of microasperities, followed by a stiffer response that conforms well to Hertz theory."

The legend in Figure 10 seems wrong

We understand that there was an error in the caption of this figure. We have now corrected the caption.

You should present a table with the values of R and R_G of the sands whose data is included in Figure 12.

The data used for comparison are shown in newly added Table 3.

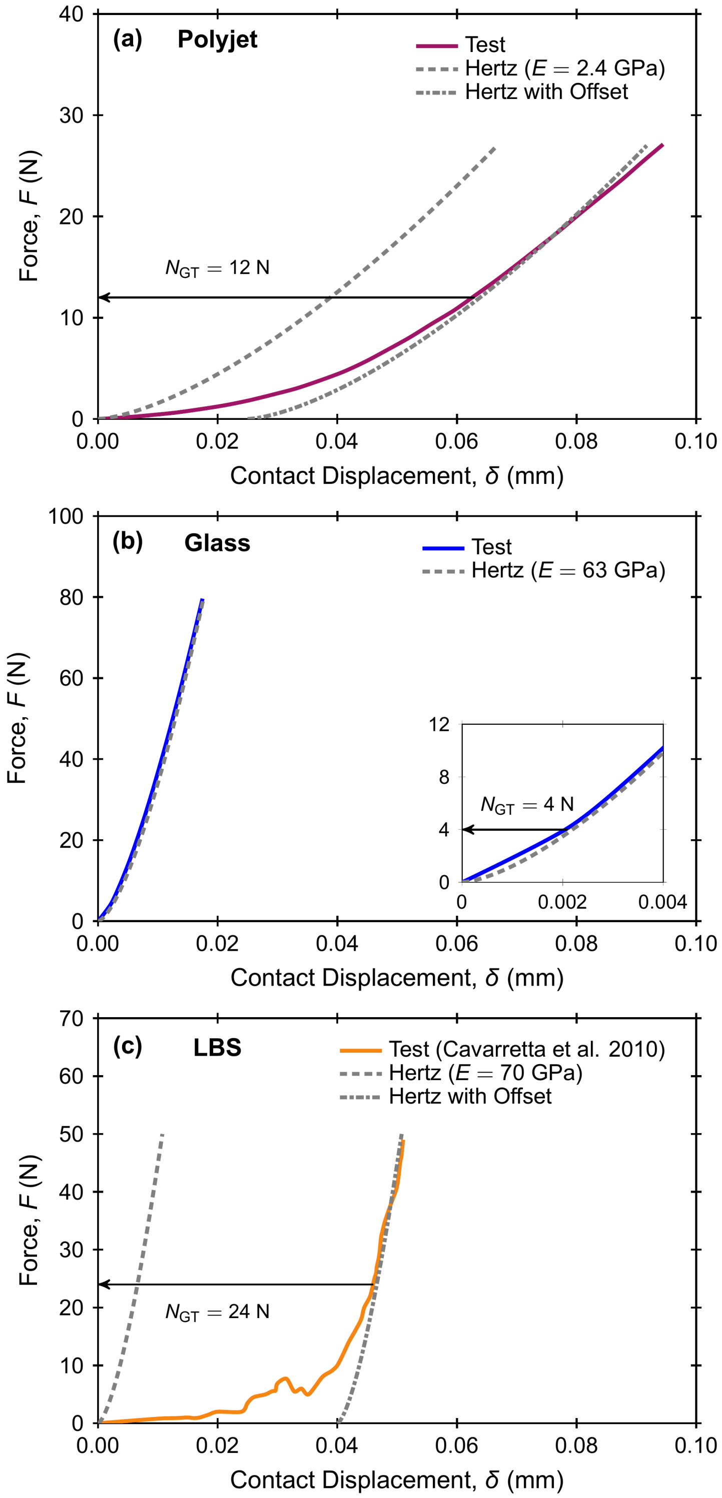


Figure 4: Uniaxial particle-particle compression test results on (a) polyjet 3D printed and (b) glass equal-sized spheres (after Ahmed and Martinez 2020), and (c) single grain crushing test result on Leighton Buzzard Sand (LBS) (after Cavarretta et al. 2010). Note: diameter of the spheres is 3.175 mm, and the diameter of the LBS particle is 1.67 mm

The differences with previous trends shown in Figure 3 are remarkable and I feel they are being somewhat glossed over. Apparently you have used some new procedures to establish extreme void ratios (Carey et al 2020) instead of the ASTM procedures that Cho employed. There is a possibility that the different procedural techniques employed might have had an influence on the discrepancy; it will be good if you can reassure the reader that this is not the case (e.g. by obtaining some ASTM measurements of e_{min} & e_{max} for the extreme roundness cases of your material).

We appreciate this comment as it has allowed us to include further discussion. Unfortunately, we are unable to perform e_{min} measurements following the ASTM standards because we do not have enough material to perform the tests. An additional consideration is that we are unsure whether the e_{min} test, involving the vibratory table and the static weight, may result in damage to the 3D printed particles. The methods used by Carey et al. 2020 use modified ASTM D4254 Method C and Lade's procedures. Carey et al. 2020 presents a comparison of the e_{max} and e_{min} results from a fine sand obtained using the modified methods with those from ASTM 4254 A (funnel test) and ASTM 4253 1D (wet soil, vertically vibrating table). The authors report an average difference of 0.06 in e_{max} and 0.003 in e_{min}. Therefore, we conclude that the reported differences in our results and those by Cho et al. 2006 are likely not due to the different methods used, but are rather a result of the differences in the behavior the materials (i.e. natural sands versus 3D printed soils).

We have modified the related text, which now reads:

"The maximum and minimum void ratios of all the mixes were determined using the methods outlined in Carey et al. (2020), which have been shown to provide maximum and minimum void ratios similar to those provided by the ASTM 4254 and ASTM 4253 methods. The results are shown in Table 2. Figure 5 shows the variation of e_{max} and e_{min} with particle R, S_C, and R_G. These parameters were selected to allow for comparison with published relationships from Youd (1973) and Cho et al. (2006). As shown, the measurements indicate a decrease in e_{max} and e_{min} as roundness, circle ratio sphericity and regularity are increased, which is consistent with the trends from literature. For the relationship with R, the e_{max} and e_{min} measurements fall in between the relationships from Youd (1973) and Cho et al. (2006) (Figure 5a); however, the trends reported by Cho et al. (2006) indicate a steaper decrease as S_C and R_G are increased (Figures 5b and 5c). While further research is required to explain these differences, it is possible that the smaller friction coefficient in relation to those reported for natural sands, as presented by Ahmed and Martinez (2021), may result in the smaller void ratio values reported."

The discussion in 4.2 leads to a kind of general-purpose warning ("it should be considered how inherent differences caused by the materials and layer deposition process used in 3D printing may affect different aspects of the behavior of granular materials"), which is unobjectionable by itself, but appears quite unrelated to the specific tests and observations presented in the paper. Following on my previous point, one wonders if a material that is very lightweight and has a considerable capacity to store elastic energy is well suited to mimic granular soil responses to procedures, such as tamping or pluviation, in which dynamic excitation and inertial forces are meant to play a significant role. I wonder if the authors would be able to comment on this?

We appreciate this comment as it has motivated us to provide a more detailed discussion of the possible effects of the differences between the 3D printed and natural sands, which include the smaller stiffness and density, greater surface roughness, and layered configuration. We have significantly revised Section 4.2, which now reads as follows:

Considerations on the modeling of sand behavior with 3D printed particle analogs

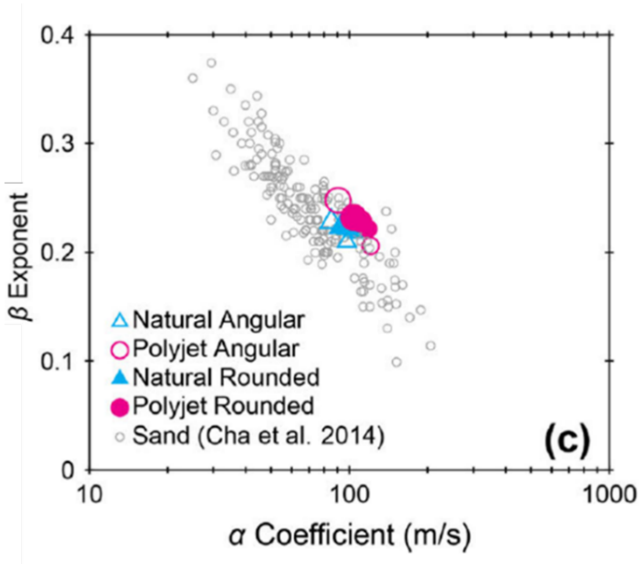
"A significant advantage in using 3D printed soils is the ability to control particle shape while the remaining properties (i.e. particle size, constituent material, surface roughness) are maintained constant, which expand the experimental capabilities available to researchers. A similar procedure can be used to isolate the effects of particle size, as shown by Adamis et al. 2020. Despite this benefit, it is important to consider the possible effects of the differences between the 3D printed and natural sands resulting from their different constituent material properties and genesis. Namely, the polymeric material has a smaller stiffness and specific gravity than natural minerals such as quartz. The smaller stiffness of the polymer results in softer inter-particle contacts which leads to a greater bulk compressibility, while the smaller density can influence behaviors in which dynamic and inertial effects are important such as tamping and pluviation used for specimen preparation. The layer deposition printing process inherently results in an anisotropic configuration. This has been shown by Ahmed and Martinez (2021) to lead to anisotropy in the inter-particle friction coefficient. However, the results presented by Ahmed and Martinez (2020) suggest that the contact normal force-deformation response does not exhibit anisotropy due to the layer deposition orientation. Finally, the printing process can produce a large surface roughness which also leads to softer inter-particle contacts. Because different 3D printing technologies (e.g. stereolithography, selective laser sintering, fused deposition modeling) use different manufacturing processes and are capable of printing different materials, the possible effects of each technology on the response of soil particles should be evaluated and understood. However, it is envisioned that such differences in properties will be addressed as the additive manufacturing technology enables generating objects with a broader suite of materials and processes. Ultimately, comparisons of the measurements on 3D printed analogs with experimental data on natural soils and established relationships can help validate the conclusions drawn from such studies."

Another significant discrepancy with previous research is that illustrated by figures 11 c and d. There is some hard to follow explanation in a paragraph in page 10 (starting "Cho et al. . . ") that leads the authros to conclude that "..it is possible that the Cho et al. [2006] equation and Equation 7 highlight similar trends". Another possibility is that the range of "beta" explored in the authors experiments is just to narrow to discern any trend in it. Would you care to comment on that?

We appreciate this comment, as we realize that our original sentence was unclear. We have revised the text to make the explanation referenced by the reviewer clearer. The revised sentence reads:

"It is possible that the decrease in attainable e_0 values with increases in R and R_G (i.e. as reported by Youd 1973 and Cho et al. 2006 and shown in Figure 5) causes a concomitant decrease in β-exponent. In fact, Patel et al. (2009) provided an equation for V_s that explicitly considers e_{max} and e_{min} in addition to other particle shape and size parameters."

We also agree with the reviewer in that the range of β-exponents from our experiments is smaller than those reported in other papers such as Cho et al. (2006) and Cha et al. (2014) which range from about 0.07 to 0.35, while our values range from about 0.21 to 0.25. However, one key difference between that the data from Cho et al. (2006) and Cha et al. (2014) comes from sands with different mineralogy, particle sizes, and particle shapes, while our experiments virtually isolate the effects of particle shape from those of other variables. In fact, in a previous study (Ahmed and Martinez 2020), we performed V_s measurements at different confining pressures on rounded and angular natural sands and on 3D printed sands generated from X-ray CT scans of the corresponding natural particles to faithfully reproduce the particle shape. The results show a similar range in β-exponents for both natural and 3D printed sands, with values between 0.20 and 0.23 for the former and between 0.2 and 0.25 for the latter (see figure below from the original publication).



We have added the discussion to Section 3.1 that reflects this, which reads:

"It is noted that the range of β-exponent values reported by Cho et all. 2006 and Cha et al. 2014 range from 0.07 to 0.36, while those from the measurements on the 3D printed sands presented herein ranges from 0.21 to 0.25. While it is possible that that the greater compressibility of the polymeric material is responsible for the smaller range of β values, it is likely that the smaller range is due to the isolation of the particle shape effects from those of particle size and mineralogy. In fact, this is suggested by Ahmed and Martinez (2020), who show a similar range of β-exponents (i.e. 0.20 to 0.23) for rounded and angular natural sands with the same mineralogy and particle size and shape as the values (i.e. 0.20 to 0.25) for 3D printed sands obtained from X-ray CT scans of the natural sands."

This begs the question of why would that "beta" range be so narrow in your experiments? Perhaps the soft contacts of the printed material are diluting any other possible contributing factor, such as shape, to the pressure dependency of V_s? If that is the case the effects of shape detected in your tests may underestimate those in real sands. (By the way, this is also suggested by how the effect of shape narrows down with increased density in Figure 5 or in Figure 7). Perhaps this should lead to a more specific warning?

We refer the reviewer to the response of the previous component and the referenced modified text.

Reviewer B

The paper presents an experimental study on the shear wave velocity in samples composed of 3D-printed polymeric particles with different shape. The applied 3D printing technique allows to generate particles with prescribed size and shape characteristics. It enables systematic investigations on the influence of the particle characteristics, where a single parameter (size, general shape, roundness of corners) can be varied while the other ones are kept constant. In case of natural sands this can usually only be achieved by huge sieving and mixing effort. The dependencies of the shear wave velocity on void ratio, pressure and shape parameters measured by the authors on samples of the 3D-printed granular materials are consistent with well-known relationships for natural soils. The authors address the effects of certain differences between natural and artificial granular materials, as the lower stiffness and higher surface roughness of the polymeric particles, as well as special features of the 3D-printed grains like an anisotropy of the friction coefficient. Overall, the paper is well written and represents an original contribution to the field of experimental soil dynamics. The described 3D printing technique has high potential to be more frequently applied by researchers in future. Consequently, I recommend the paper for publication with some revisions addressed below. Furthermore, I have added a few typographical corrections into the PDF file.

We appreciate the feedback provided by the reviewer. In this document, we provide responses to each of the reviewer's comments. In the revised manuscript, we have highlighted the text that has been modified or added in blue font for reference. We have also implemented the typographical corrections provided by the reviewer in the separate PDF file.

Recommended revisions:

Page 2, left column, first paragraph: Could the conflicting observations regarding the dependence of shear wave velocity on particle characteristics found in the literature be partly caused by the chosen base of comparison, i.e. either a constant void ratio or a constant relative density? The latter will also consider changes of the extreme void ratios e_{min} and e_{max} with the varied parameter (e.g. D_{50} or grain shape).

We appreciate this comment, and the reviewer is correct. One of the main challenges in interpreting the research is that different studies can use different basis for controlling state (void ratio vs. relative density vs. state parameter) as well as different parameters for describing particle shape. To make this more explicit, we have added the following text to Section 1:

"Also, different parameters have been used to characterize a given particle property, and it is often unclear which one better captures the aspects of the behavior that govern the property of interest. For example, particle shape can be characterized in terms of roundness, sphericity, and regulatity. Soil state can be captured in terms of the void ratio, relative density, and state parameter, where the latter two are defined in terms of a reference (i.e. extreme void ratios and critical state line, respectively)."

Figure 1: Which shape parameters were intended to be varied when generating the particles of mixes 3, 6, 7 and 8? It looks like the particles possess a similar roundness of the corners, but a different overall shape.

We intended to maximize the range of both roundness (R) and sphericity (S_C) parameters among the seven mixes. Because mixes 1 and 2 have larger R values, we prioritized mixes with smaller R for the remaining ones. For example, mix 8 was designed to have a small R and a large S_C while mix 7 was designed to have small R and S_C. We have modified the text in Section 2.2, which reads:

"These four materials were designed to have a D_{50} of 2.5 mm, C_u of 1.26 (Table 2), R between 0.48 and 0.61, and S_C between 0.53 and 0.84. To extend the range of particle shape parameters considered in this investigation, the three 3D printed mixes used by Ahmed and Martinez (2020, 2021) were also tested. Two of these mixes (mix 2 and 4) were generated from the X-ray CT scans of randomly selected rounded and angular natural sand particles, respectively, as described by Ahmed and Martinez (2020) (Figure 1b, Tables 1 and 2). The D_{50} and C_u of these materials are 3.2 mm and 1.47, respectively. The last mix (mix 1) consisted of equal-sized spheres with a D_{50} of 3.2 mm and a C_u 1.0. These three mixes had greater R values (0.52 to 0.90) than the four mixes generated using spherical harmonics."

Page 4, first paragraph of Section 2.2: I recommend to include definitions of the shape parameters roundness R, circle ratio sphericity S_C, perimeter sphericity S_P, width- to-length ratio sphericity S_{WL} and convexity C in the manuscript. The underlying geometrical properties of the grains could be explained by means of a scheme.

The equations for the shape parameters have been added in Equations 1-5.

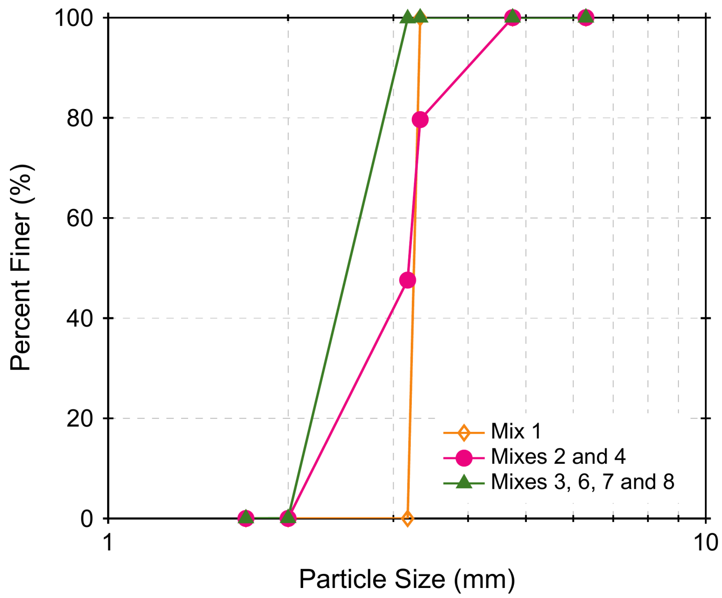


Figure 2: Grain size distribution of all the 3D printed sand mixes

Page 4, Table 1 and corresponding text: Which methods were applied to take pictures of the grains used as basis for the determination of the grain shape parameters?

The pictures were taken using a white light scanner with a resolution of 0.1 μm (VR-3100, Keyence, Osaka, Japan). The following text has been added to the manuscript:

"The particle images were obtained using a white light scanner with a resolution of 0.1 μm (VR-3100, Keyence, Osaka, Japan)."

Page 4, Table 2: The tested artificial materials had slightly different mean grain sizes D_{50} (2.5 to 3.2 mm) and uniformity coefficients C_u (1.0 to 1.47). Do the authors expect an influence of these variations on the test results? I recommend to add a figure showing the grain size distribution curves of the tested artificial materials. Is it justified to speak of "sand" analogs, considering that the mean grain sizes of these materials are above 2 mm, i.e. in the range of fine gravels? In Table 2 the unit of D_{50} should be added.

We have added the grain size distribution plot for all the soil mixes and added the following text to describe the newly added figure as well as to discuss the differences in D_{50} and C_u:

"Figure 2 shows the grain size distributions for all the soil mixes. As shown, mixes 3, 6, 7 and 8 have identical grain size distributions with similar D_{50}, mixes 2 and 4 have a slightly larger D_{50}, and the range of particle sizes in Mix 1 is narrower. According to ASTM D2487 (Unified Soil Classification System) all the soil mixes can be considered sand since more than 50% passes no. 4 sieve. Also, although there are slight differences in both D_{50} and C_u of the soil mixes considered, no significant effect of those on the small strain behavior is expected."

Page 4, second paragraph of Section 2.2:" The polyjet 3D printing process results in a large surface roughness, which is greater than that typical of natural soil particles" If the authors have quantified the surface roughness, typical values of the artificial particles in comparison to those of natural sands should be given here.

Unfortunately, we have not been able to quantify the surface roughness of the 3D printed. However, these differences are readily visible in X-Ray CT scans presented by Ahmed and Martinez (2020). The figure from the original paper is included below, where the top row of images shows the scans of natural particles and the bottom row shows images of the corresponding 3D printed particles.

To address this, we have added a comparison of a few particles in Figure 3. We have also added the following text to describe the newly added figure:

"The polyjet 3D printing process results in a large surface roughness, which is greater than that typical of natural soil par-

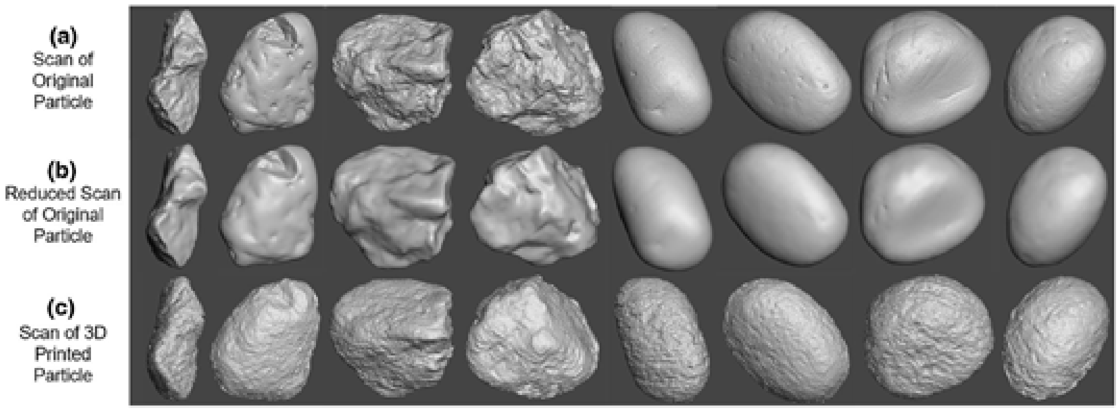


Fig. 6 Comparison of X-ray CT scans of **a** natural particles, **b** reduced scans for 3D printing, and **c** of additive manufactured particle analogs

ticles, as shown in the comparison of X-ray CT scans presented in Figure 3 and further described in Ahmed and Martinez (2020, 2021)."

The new figure is included below for reference.

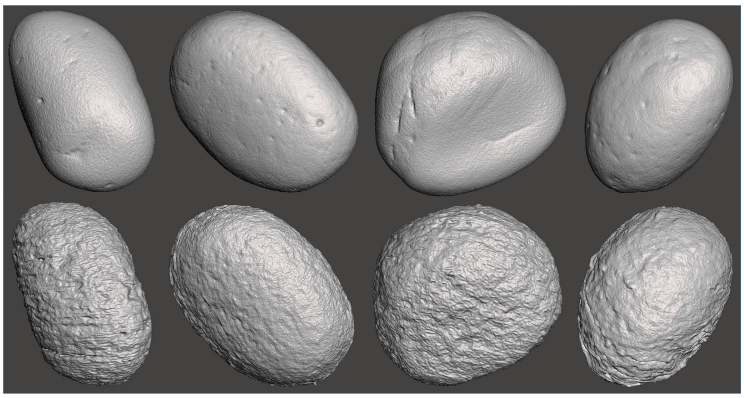


Figure 3: Comparison of X-ray CT scans of natural (top row) and 3D printed particles (bottom row) of mix 2

Page 4, Figure 2 and corresponding text: The diameter of the particles used in the particle-particle compression test should be specified.

We appreciate this comment. The diameter of the polyjet and glass spherical particles was 3.175 mm. We have added this in the caption of Figure 4 (previous Fig 2) as well as in the text. The text reads:

"Figure 4 shows the results of interparticle uniaxial compression tests performed by Ahmed and Martinez (2020) on spherical polyjet particles with diameter of 3.175 mm."

The caption of Figure 4 is:

Figure 4: Uniaxial particle-particle compression test results on (a) glass and (b) polyjet 3D printed equal-sized spheres, and (c) Single grain crushing test result on Leighton Buzzard Sand (LBS) (after Cavarretta et al. 2010). Note: diameter of the spheres is 3.175 mm, and the diameter of the LBS particle is 1.67 mm.

Page 4: "Another important difference between the polyjet particles and natural sand particles is the magnitude and anisotropy of the friction coefficient of the former." Even if the details are included in another paper it should be briefly described here what the authors understand under an anisotropy of the friction coefficient of the polyjet particles.

We appreciate this comment. To address it, we have added the following text to Section 2.2:

"Namely, the friction coefficient measured perpendicular to the printing direction (0.11 – 0.19) was considerably smaller than that measured along the printing direction (0.38 – 0.50) (Ahmed and Martinez 2021). The friction coefficients measured perpendicular to the printing direction are also considerably smaller than measurements on natural sand particles, which range between 0.17 and 0.36."

Page 5, Section 2.3: Which method was applied to prepare the samples? Air pluviation using a funnel or loose placement with subsequent compaction? I guess all samples were tested in the dry condition. Respective comments should be added.

We have added the following description of the specimen preparation to the manuscript:

"The specimens were prepared inside split molds in five lifts, which were poured using a funnel. After pouring of each lift, the mold side was tapped with a rubber mallet to densify the specimen to the target void ratio."

Page 6, Figure 5: It seems that mixes 1, 2 and 4 have not been tested at a pressure of 80 kPa, which should be mentioned in the test description.

We have added the following sentence in Section 2.3 to address this:

"However, it is noted that mixes 1, 2, and 4 were tested at p' from 10 to 70 kPa due to a leak in the membrane that developed at greater p' values."

Page 6: "Analytical relationships for the β-exponents indicate values of 0.167 for a Hertzian contact . . . " A respective reference to the literature should be added.

We have added a reference to Cascante and Santamarina (1996) to the sentence referenced by the reviewer.

Page 6: "It is noted that the G_{max} values reported are smaller than those typical of natural sands due to the smaller specific gravity of the 3D printed sands" Can the lower values of shear modulus partly be attributed to the lower stiffness of the polymeric material constituting the artificial particles?

The reviewer is correct. We have modified the referenced sentence to reflect the reviewer suggestion. The revised text reads:

"It is noted that the G_{max} values reported are smaller than those typical of natural sands due to the smaller specific gravity of the 3D printed sands (1.18 compared to 2.65 to 2.7 for silica sands) and the smaller stiffness of the polymeric constituent material (Young's modulus of 2.4 GPa compared to about 76 GPa for silica sands)."

Page 9: Eqs. (3) to (7): These equations are shown as dashed or dot-dashed lines or curves in Figure 10? At least in case of SAGI this seems not to be the case because a linear relationship is described by Eq. (6), while a curved relationship is shown in Figure 10d. Please add respective remarks to the manuscript.

We realize that our original submission was unclear in this respect; we try to further clarify the differences between Figure 12 (previous Fig. 10) and Equations 8 to 12 (previous 3 to 7).

In Figure 12, we plot the alpha and beta parameters as a function of roundness, regularity, overall regularity, and SAGI, but we do not take into consideration the effect of initial void ratio. In contrast, to obtain Equations 8 to 12 we used multivariate linear regression to consider the effects of the shape parameters as well as of void ratio. However, the reviewer is correct in that it would be more appropriate to fit the relationship between alpha and SAGI in Figure 12d with a line such that the functional form agrees with our linear regression analysis. To address this, we have changed the fit in Figure 12d to a linear function. We have also added a note in section 4.1 that explicitly says that Equations 8 to 12 are different from those provided in Figure 12. This note reads:

"In the regression analysis, V_s (m/s) was defined according to Equation 6, and it is noted that these relationships differ from those presented in Figures 12a to 12h because they include e_0."

Page 10, Figure 11: Which void ratios e_0 or relative densities D_R were used in the tests forming the basis for the equations proposed by Cho et al. (2006) compared with the authors' equations in this figure? This information should be added to the text.

Unfortunately, Cho et al. (2006) did not provide void ratio or relative density values in their dataset. In fact, Cho et al. (2006) did not consider the effect of void ratio or relative density in the development of their relationship. This is the reason why we were not able to include their data in the comparison in Figure 14 (previous Fig. 12). We have noted this in the text in Section 4.1, and reads as follows:

"...While Cho et al. (2006) did not consider the effect of e_0 on α, nor provided e_0 values for their dataset, the predicted values are generally consistent with one another..."

Page 11, Figure 12: Please specify the ranges of roundness and regularity, D_{50} and C_u, relative density and pressure for the experimental data from the literature included in this figure, e.g. in tabular form. Why data of different studies is used in diagrams (a) and (b), i.e. Liu and Yang (2018) in case of roundness and Liu et al. (2021) in case of regularity?

We used different data for parts (a) and (b) of Figure 14 (previous Fig. 12) because not all studies provided measurements of both R and R_G. Namely, Liu and Yang (2018) only provided R, while Liu et al. (2021) only provided R_G values. We also added Table 3 to include the data used for the comparison.

Page 11, Figure 12: Can the authors add an explanation why the equations developed based on the tests on the 3D printed particles describe well the V_s data for natural sands, although the polymeric material constituting the artificial particles has a significantly lower stiffness?

We appreciate this excellent question. We were purposeful in casting the proposed equations 8 to 12 (previous 3 to 7) in terms of the alpha and beta coefficients, rather than in terms of shear wave velocity magnitudes. The match between the V_s predicted by equations 8 to 12 and experimental measurements in natural sands suggests that the aggregated dependency of V_s on particle shape, void ratio, and effective stress (and other influencing parameters) is similar in 3D printed sands and in natural sands. Indeed, more research is required to fully answer this question. However, we can provide some discussion on two possibilities for this. The first possibility is that the granular nature of the soil (i.e. stress, fabric, and particle shape dependency) is the controlling factor. Another option may be that the effect of different parameters or behaviors could offset each other. For example, the effect of the smaller stiffness of the polymeric material could be offset by the effect of the larger inter-particle contacts (i.e. according to Hertz theory, the contact stiffness increases with contact area).

We have added the following discussion to Section 4.1 of the paper:

"This agreement may be unexpected considering the differences in constituent materials between the 3D printed and natural sands. One possibility is that the dependence of V_s on particle shape, void ratio, and effective stress is governed by the particulate nature of soils, which is properly replicated by the 3D printed soils. Another possibility is that while certain parameters or behaviors may have different effects on V_s, these have an aggregated effect that is similar between the 3D printed and natural sands. For example, the effect of the smaller stiffness of the polymeric material could be offset by the effect of the larger inter-particle contacts owing to the greater compressibility. Indeed, further research is required to further understand the mechanisms leading to similarities and differences in the behavior of 3D printed and natural soils."

Reviewer C

The manuscript presents the results of an experimental work aiming at characterising the effects of particle shapes on some mechanical properties (V_s and G_{max}) of granular materials. The authors use 3D printed grains to distinguish the effects of various shape descriptors on these mechanical properties while working with the same grain material and grain contact properties.

The manuscript is very well written and easy to follow. The research problem is well stated, and properly treated.

We appreciate the feedback provided by the reviewer. In this document, we provide responses to each of the reviewer's comments. In the revised manuscript, we have highlighted the text that has been modified or added in blue font for reference.

The reviewer would like to invite the authors to react to the following points.

§2.2: Please provide the thickness of printed layers (vertical resolution of the printer used). Commenting on the limitations inherent to the printer (resolution) on the reachable shape descriptors and other grains characteristics (roughness, etc.) would be valuable.

We appreciate this comment. The thickness of the printed layers was 30 μm. This information has been added to Section 2.1.

In two previous studies, we investigated the ability of the polyjet printer to reproduce the particle shape of natural soils. This was done by printing particles based on X-ray CT scans of natural sand particles. The shape parameters of the 3D printed and natural particles were then compared. The original figure from Ahmed and Martinez (2020) is shown below, which shows that there is no significant difference in the shape parameters of the 3D printed and natural particles.

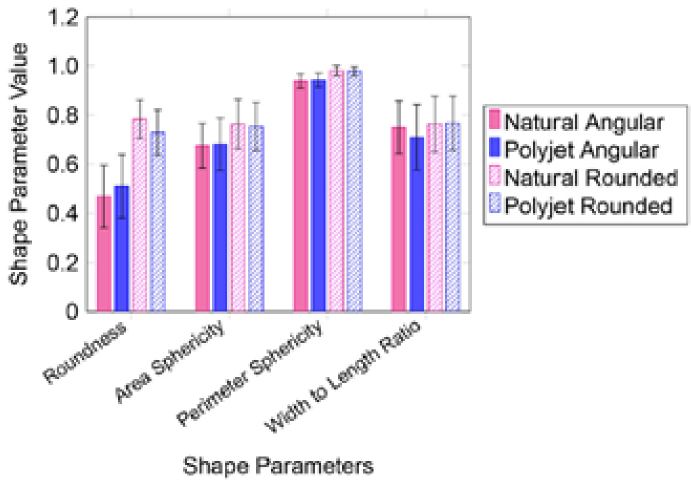


Fig. 7 Comparison of shape parameters for natural and additive manufactured particles (*Note*: standard deviation shown by error bars)

We have added a sentence to Section 2.1 that reflects this.

"As previously shown by Ahmed and Martinez (2020, 2021), the polyjet printer is able to create 3D printed particles that successfully reproduce the shape of natural sand particles, as evidenced by the negligible differences in the shape parameters reported in their study."

However, the printing process results in a greater surface roughness as that of natural soil particles. This is readily visible in X-ray CT scans. We have added a new figure (Figure 3) to include a comparison of printed and natural sands to highlight this point. The figure and associated text are included below:

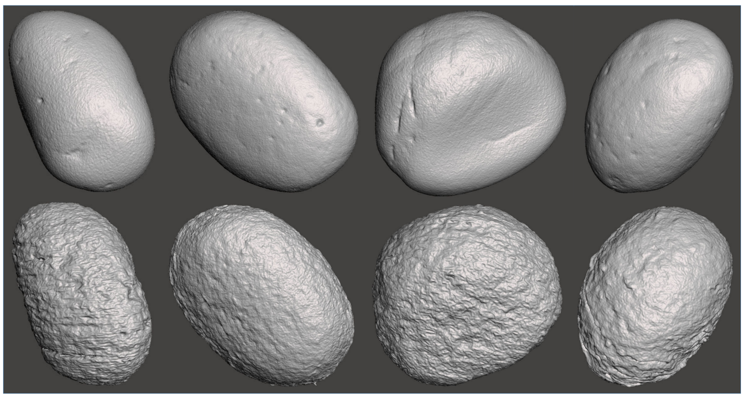


Figure 3: Comparison of X-ray CT scans of natural (top row) and 3D printed particles (bottom row) of mix 2

"The polyjet 3D printing process results in a large surface roughness, which is greater than that typical of natural soil particles, as shown in the comparison of X-ray CT scans presented in Figure 3 and further described in Ahmed and Martinez (2020, 2021)."

§2.2: Another difference in the intergranular contact behaviour is probably the ductile behaviour of asperities. Do the authors expect the same brittle behaviour of asperities of printed grains compared to natural sands?

The reviewer is correct. We have added the results of uniaxial particle-particle compression tests of glass beads and natural sand (the latter obtained from the literature). The figure shows the stiffer response of the glass beads and natural sand particles. In addition, it highlights the fact that the contact behavior of glass beads is mostly Hertzian, the contact behavior of natural sand particles has an initial stage of asperity yielding, and the contact behavior of the 3D printed particles has a considerable amount of asperity yielding. These results are included in the manuscript in the new Figure 4.

We have included additional information in the text to describe this; this reads as follows:

"Figure 4a shows the results of inter-particle uniaxial compression tests performed by Ahmed and Martinez (2020) on spherical polyjet particles with diameter of 3.175 mm. The results show that initial increases in force result in a soft contact response due to plastic yielding of the particles' micro-asperities. As the load is increased, the contact becomes stiffer and follows the Hertzian solution more closely. For comparison, Figure 4b presents similar results for a pair of glass spheres with diameter of 3.175 mm, showing the stiffer contact response that closely follows Hertz' solution. Figure 4c shows the results of a single grain crushing test on Leighton Buzzard Sand (LBS), from Cavarretta et al. (2010). The response of LBS also shows an initial softer response due to plastic yielding of micro-asperities, followed by a stiffer response that conforms well to Hertz theory."

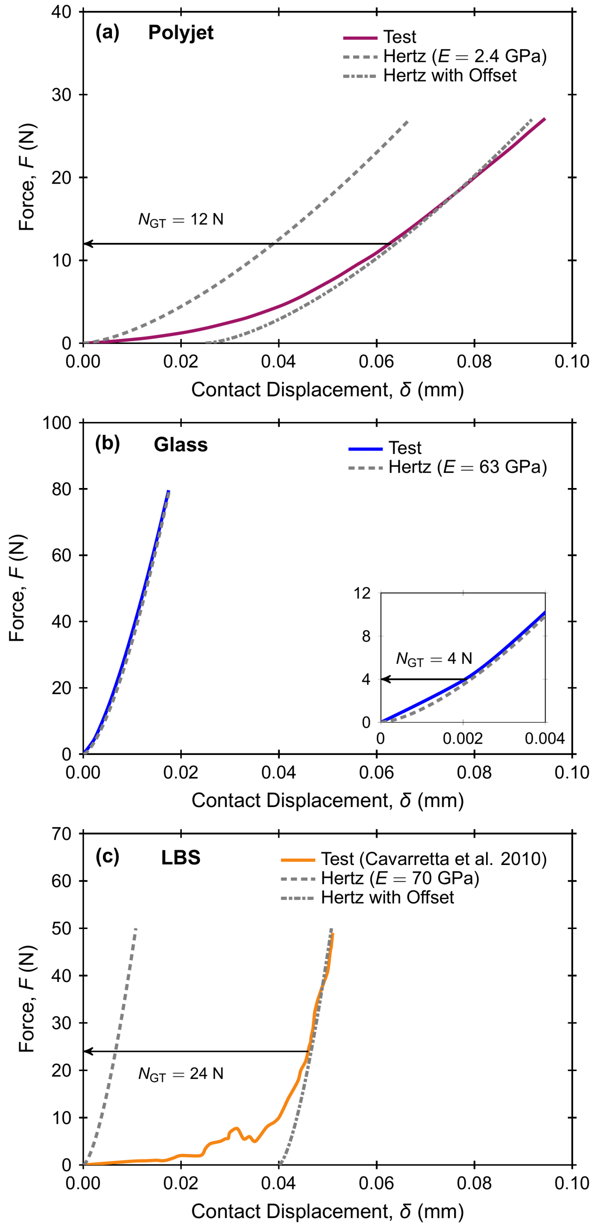


Figure 4: Uniaxial particle-particle compression test results on (a) polyjet 3D printed and (b) glass equal-sized spheres (after Ahmed and Martinez 2020), and (c) single grain crushing test result on Leighton Buzzard Sand (LBS) (after Cavarretta et al. 2010). Note: diameter of the spheres is 3.175 mm, and the diameter of the LBS particle is 1.67 mm

Please note that we have grouped this comment with the following one to answer both simultaneously.

What is the uncertainty associated to beta values obtained from the best fit exercise? Is the variation mentioned at the bottom of p.5 (right) significant with respect to this uncertainty?

Figs 5 and 7: It is fine not to show the fits but it is suggested that the authors provide (maybe in appendix) a measure of the quality of the fit. This point is actually related to the confidence that we can have on fitted parameters (alpha, beta, A, n...).

We appreciate this comment. We have added the power-law fits in Figures 7 and 9 (previous Figs. 5 and 7) to show the quality of the fit; in addition, we have added the R^2 values for each mix in the legend. As shown, the quality of the fit is high, as evidenced by the high R^2 values. In addition, since each power-law relationship was fitted to either seven or eight data points, we feel like the uncertainty of the fitting exercise is relatively low. However, there is the possibility of uncertainty due to experimental factors, such as unintentional differences in void ratio stemming from the uncertainty of volume measurements in the laboratory. While we have made efforts to quantify these uncertainties (void ratio measurements had a variability of plus or minus 0.02 across our entire investigation), there is always the possibility of an experimental measurement to have some associated error/uncertainty. To address this, we have added a short sentence to Section 3.1 in addition to the aforementioned changes in Figures 7 and 9.

Fig 10 (e-h): It seems that there are two regimes for beta exponent. One for low values of the descriptors and another one for large values of those. This seems to be recognized by the authors at the bottom of p. 10 (left). What is the reason? Actually, the exact same trend can be observed for n exponent in fig A5.

The reviewer raises an interesting point. One interpretation of the data is that, as mentioned by the reviewer, there are two regimes for the beta exponent as a function of the shape parameters. Alternatively, it is possible that shape parameters are a poor predictor of the beta exponent for the 3D printed sands. Ultimately, we chose the second option as the more likely one, because we expect any possible relationship between the beta exponent and the shape descriptors to not have discontinuities, i.e. beta to change smoothly as the shape descriptors are changed. We employed the same logic in describing the relationship between the n exponent and the shape descriptors. Please note that the Fig. 10 is now Fig. 12.

We have added the following sentence in Section 3.2 to reflect this discussion:

"This suggests that for the 3D printed soils, the shape parameters are poor predictors for β and that β depends only on e_0."

§4.2: The authors are invited to print the same grains but rotated to various angles to have layers stacked in other directions with respect to the grains main axes. This could be of some value to estimate this "direction-dependency".

We sincerely appreciate this recommendation by the reviewer and we agree in that this would be important for understanding the anisotropy in the behavior of 3D printed soils. However, at this point it is not possible for us to print new particles and perform tests on them. We can provide some additional discussion on this that we hope can illustrate, at least qualitatively, our understanding of this direction-dependency.

As mentioned in Section 2.2, the friction coefficient of 3D printed parts does have a direction-dependency. We expanded this discussion per the request in comment #8 of Reviewer B. The associated text reads:

"Namely, the friction coefficient measured perpendicular to the printing direction (0.11 – 0.19) was considerably smaller than that measured along the printing direction (0.38 – 0.50) (Ahmed and Martinez 2021). The friction coefficients measured perpendicular to the printing direction are also considerably smaller than measurements on natural sand particles, which range between 0.17 and 0.36."

In the study presented in Ahmed and Martinez (2020), we performed uniaxial particle-particle compression tests. We performed over 10 experiments, where we were intentional in compressing the particles in different orientations with respect to the printing direction. In these experiments, we did not observe any systematic relationship between the contact compression behavior and the orientation of loading relative to the printing directions. This leads us to conclude that while the friction coefficient has a strong dependency on the printing direction, the normal contact force-displacement behavior does not.

We have significantly expanded the discussion in Section 4.2 to reflect these points along with others raised by Reviewers A and B. The revised Section 4.2 reads as follows:

Considerations on the modeling of sand behavior with 3D printed particle analogs

"A significant advantage in using 3D printed soils is the ability to control particle shape while the remaining properties (i.e. particle size, constituent material, surface roughness) are maintained constant, which expand the experimental capabilities available to researchers. A similar procedure can be used to isolate the effects of particle size, as shown by Adamidis et al. (2020). Despite this benefit, it is important to consider the possible effects of the differences between the 3D printed and natural sands resulting from their different constituent material properties and genesis. Namely, the polymeric material has a smaller stiffness and specific gravity than natural minerals such as quartz. The smaller stiffness of the results in softer inter-particle contacts which leads to a greater bulk compressibility, while the smaller density can influence behaviors in which dynamic and inertial effects are important such as tamping and pluviation used for specimen preparation. The layer deposition printing process inherently results in an anisotropic configuration. This has been shown by Ahmed and Martinez (2021) to lead to anisotropy in the inter-particle friction coefficient. However, the results presented by Ahmed and Martinez (2020) suggest that the contact normal force-deformation response does not exhibit anisotropy due to the layer deposition orientation. Finally, the printing process can produce a large surface roughness which also leads to softer inter-particle contacts. Because different 3D printing technologies (e.g. stereolithography, selective laser sintering, fused deposition modeling) use different manufacturing processes and are capable of printing different materials, the possible effects of each technology on the response of soil particles should be evaluated and understood. However, it is envisioned that such differences in properties will be addressed as the additive manufacturing technology enables generating objects with a broader suite of materials and processes. Ultimately, comparisons of the measurements on 3D printed analogs with experimental data on natural soils and established relationships can help validate the conclusions drawn from such studies."

Typos:

- p.2: "capture"

- p.2: "shown" instead of "show"

- p.9: repeated "of" to be removed

- p.10: "in" to be removed after "between"

- p.11: "dependency"

Thank you. We have corrected these typos.

Review Round 2

Reviewer A (Marcos Arroyo)

Recommendation: Accept Submission

Reviewer B (Torsten Wichtmann)

Recommendation: Accept Submission

Reviewer C (Jean-Michel Pereira)

The authors have carefully addressed my comments in the revised version of their manuscript.

I simply have a final comment, which might appear as a bit too formal but I prefer putting it here as a suggestion.

The authors refer to the ”anisotropy in the inter-particle friction coefficient”. I'm wondering if anisotropy is appropriate here. Indeed, the printing process clearly leads to anisotropy of bulk (average) properties like stiffness. However, here, the authors are comparing frictional properties at different locations around the grains (which correspond to different directions around the grains, but not at the same material point). This behaviour seems to be better described by ”heterogeneity” than by ”anisotropy”.

Author Response

Thank you very much for your message and for the opportunity to address this final point.

We would prefer not to make changes to the paper based on the reviewer's suggestion for two reasons: 1) consistency with our previously published paper, and 2) the fact that there is difference in friction in different regions of the grains but also at the same point depending on the direction of slippage between grains.