Response to the reviewers: Computational Sedimentation Modelling Calibration: a tool to measure the settling velocity at different gravity conditions, By N. J. Kuhn and F. Trudu

Dear Susan,

We resubmit our manuscript with some changes and corrections, as suggested by the Referees.

Below are the changes in response to Referee #1 and Referee #2

Response to Referee #1

<u>Specific comments:</u>

Abstract

1. ***The first sentence of the abstract (L10) is very general. There is no explanation (here or in the introduction) why it is essential.***
   "*Research in zero or reduced gravity is essential to prepare and support planetary sciences and space exploration*." With this sentence we want to emphasize the importance of conducting studies in environments where gravity is significantly reduced. We have added a sentence in the introduction that helps explain why these experiments are critically important:
   Conducting research in zero or reduced gravity helps simulate the conditions experienced in outer space. This is crucial for understanding how various phenomena, materials, and biological processes change under the influence of gravitational acceleration different from Earth's. For example, with reduced gravitational force, fluid flow dynamics and other physical quantities relevant to the morphology of planets and moons in our solar system, change. One of these physical quantities is the settling velocity of solid particles.
2. ***"models" (L20) is not defined here and therefore the sentence is unclear. There are many types of models. Please specify you mean the Ferguson and Church relation.***
3. ***"underestimate" (L21), by reading the rest of the manuscript I understand this follows from the data and previous experiments, however, without context I would think terrestrial inputs leads to overestimation of settling (because gravity might not be correctly included), not underestimation. This thought process should be explained or previous experiments should be referenced.***
   We have modified the abstract accordingly:
   Research in zero or reduced gravity is essential to prepare and support planetary sciences and space exploration. In this study, an instrument specifically designed to measure the settling velocity of sediment particles under normal, hyper-, and reduced gravity conditions is presented. The lower gravity on Mars potentially reduces drag on particles settling in water, which in turn may affect the texture of sedimentary rocks forming in a standing or moving body of water with settling particles. To assess the potential impact, an instrument was designed to simulate sediment settling at gravities different from Earth during parabolic flights. The trajectories of particles settling in water were recorded during the ascending part of a parabola (about 1.8 g), under reduced gravity conditions (Martian and lunar) and on Earth. The data were used to compute the terminal settling velocity of isolated and small groups of particles and compared to the results calculated using a semi theoretical formula derived in 2004 by Ferguson and Church (Ferguson & Church, 2004). The experimental data confirm the trend already highlighted in a series of previous experiments (Kuhn, 2014), namely that models, such as Ferguson and Church's, whose parameters were calibrated with data collected using Earth's gravity, underestimate settling velocities in reduced-gravity environments. More specifically, the values predicted using models calibrated with data collected at terrestrial gravity underestimate settling velocity on Mars. The results also demonstrate that the instrument is operational, providing a Martian gravity analogue for sedimentation studies on Earth.

Introduction

1. ***"Drag depends on the size, density and velocity of the particle," (L33) And shape, right? This seems to be the case according to Ferguson and Church (2004).***
   Absolutely true. We added the word 'shape' in the text.
2. ***Similar to the abstract, specify that with "models" (L56) you refer to the Ferguson and Church relation. Just "models" is too broad***.
   The term "models" is intentionally broad, because we are not referring only to the Ferguson and Church model, but to generic models that depend on a set of adjustable parameters. While it is an advantage to have so many models that allow us to calculate physical quantities, such as terminal velocity or drag coefficients, with high accuracy and precision, the great number of adjustable parameters introduces new challenges related to the non-uniqueness of model solutions.
3. ***Similar to the abstract, I do not understand why you assume a potential for "underestimation of sedimentation velocity on Mars" (L57). I have trouble following your thought process without having read about the previous experiments or results.*** **Lower settling velocity for Mars due to lower gravity, like Ferguson and Church predict, makes sense to me. Please explain why you think it could have been an underestimation. Without context, the opposite would make more sense to me. If you calibrate everything on Earth, you might underestimate the gravity effect, so overestimate the settling velocity.**
4. ***Same issue, "underprediction" (L64), underprediction by? Feguson and Church? Compared to Earth?***
5. ***"Drag values derived on Earth" (L65). Do you mean using the same drag value for Earth and Mars does not work? Or is the predicted drag based on Mars gravity by Furguson and Church does not work?***
   I see your point. We have added a clarifying sentence in the text:
   The calculation of the terminal velocity of a solid particle in free fall in a stationary fluid depends on the force of gravity, the buoyancy force, and the drag force. While the first two forces do not depend on the velocity, the drag force depends on the drag coefficient and the velocity of the particle. The parameters of Ferguson and Church's formula were calibrated based on Earth's gravity. If the drag force has terrestrial parameters, it could be greater than it should be under reduced gravity, theoretically slowing the particle down in free fall more than under reduced gravity.
6.

Materials and methods

1.
2. ***Figure 2: The figure is quite clear. But I do not understand why it was not made to scale, which seems like it would be an improvement. Or would that make certain elements too small?***
   Some elements would have been too small.
3. ***Table 2: the caption of Table 2 is very unclear as it refers to Chamber number, but the reader has no information about which experiments was performed in which chamber. There is mention of a 1 particle lunar experiment and a 3-particle experiment, which are not mentioned in Table 1. The naming in the left column of the Table is in my opinion also unclear.***
   Table 1 has been modified and has the required information: chamber number, experiment, and indication for Table 2.
4. ***Table 2: I am missing the data of reference experiments on Earth. This seems valuable information and an extra data point in terms of gravity and certainly in terms of validation.***
   The same experiments conducted during the parabolic flight were conducted in Earth gravity. The data for comparison can be found in the Supplementary Information, Supplementary Table 1. We refer to these data and this Table in the text of the manuscript.

Results and discussion

1. **"Some samples got stuck as they moved from the upper valve to the lower ball valve" (L171). Did this not happen during your tests with Earth gravity?**
   No, it didn't happen.
2. ***Parts of the result section should be transferred to the methods section. L171-188 in section 3.1 and L214-223 section 3.2 was not measured or discovered by the authors. I am also unsure if the error determination should be in the result/discussion section. This could also be methodology or separate discussion.***
   The parts indicated serve for the discussion of the results and provide continuity to the discussion, we would prefer not to move them, as well as the determination of the error.
3. ***"a group of three particles (Sample 1 and Sample 1/3 to 3/3) has been detected." (L189-190). Clarify that this was due to a problem in the experiments. Also, clarify what you mean with Sample 1, 1/3 and 3/3. These names were not defined. Is it related to number of particles, sample number or something else? Consider naming your experiments or samples 1 to 12 and indicate their planned and measured particles to avoid confusion.***
   Table 1 has been changed, as well as the description of the experiments, now numbered and an explanation of the meaning of Sample 1, etc…
4. ***In my opinion it is valuable to create a graph of settling velocity (terminal fall velocity) over gravity which includes all data points of individual particles, uncertainties, and Earth experiments. In this case the reader can decide for themselves if the uncertainty is good or bad. This graph can also contain the prediction by Ferguson and Church.***
   This manuscript focuses on planetary landscapes, landforms, and their analogues. We believe that the required data would be given for another manuscript. The purpose of this manuscript is to present the experimental equipment and the results that show that this equipment, which includes video analysis, works, and can also be used by other scientists who wish to do these kinds of experiments.
5. ***"Uncertainty of the position data" (L201). Despite that I think the uncertainties are reasonable, one aspect of uncertainty was not mentioned. Due to the viewing angle of the gopro and the distance between the particle and the ruler, the particle can appear in a different location. If the particle is close to the ruler the uncertainty is smaller than when the particle is closer to the gopro. The distance travelled might look larger than in reality due to the viewing angle. This could lead to overestimation of the calculated settling velocity.***
   We checked where the particles hit the bottom of the chamber. This deviation from the straight line from the release valve is small, less than a centimeter, so can be ignored. For future experiments, two cameras will be used to establish a 3d track of the particle.
6. ***"It is plausible to hypothesize that there was a slowdown, due to particle interaction" (L234-235) Earlier you argue this is not the case.***
   We referred to the hindered settling phenomenon, which is plausible to be present also in such a low gravity environment condition. In this paper, we just present the instrument. More tests will allow a systematic study of the relevance of hindered settling.
7. ***L237: Can you further expand on why you argue that fluid status is the cause of the difference between predicted and measured values? Why is it not and how should it be included in the Ferguson and Church relation?***
   It is explained in the Introduction. We did not want to expand the text on more basic flow hydraulics.
8. ***I think it would be a good idea to also vary particle size in the future. I think it is more important information than tests with 1, 5 or 10 particles, which is in all cases likely to few particles for significant hindering to occur anyway.***
   Thank you for the suggestion, this is what we intent.
9. ***Section 3.2: I am really interested to see if your tests on the ground with Earth gravity compare 100% with the predictions. If you cannot show this, it seems impossible to me to prove that the chosen values for C1 and C2 were inaccurate. These are calibration parameters. For glass spheres the difference***

should be minimal, but still, it is worth showing you can reproduce the predicted values with your experiments.

This is the point. Of course, there are some differences between our results and the predicted values, that's why a more fundamental modelling approach is required. In addition, similar standards for settling experiments should be used, e.g., identical glass spheres, e.g., with regards to roughness and coating, which affect the skin roughness of particles. The experiments only highlighted the limitation of using models that depends on empirical parameters. We are already using different and more fundamental methods, such the Lattice Boltzmann method. This latter is a computational fluid dynamics technique, that does not depend on any empirical parameters.

Conclusions

1. ***L251-252, see previous comment, I am not convinced there is no distortion. The curvature due to the lens might be removed, but the issue of the viewing angle remains. If the particle is far away from the ruler and closer to the camera, it might appear to be at a different height then in reality. I am not sure, but I think this distortion is increased by the air-water transition.***
   We have checked the effect of the distortion by mapping settling velocities on Earth. If there was a distortion, we would see a systematic change of settling velocity along the settling path from the top of the chamber to the middle and then again back to the values observed at the top when the particle approaches the bottom. We do not observe such changes and take this as evidence for a limited, if none, effect of distortion.

<u>Technical corrections:</u>

Abstract

1. ***"Once operational, it will be …" (L12) Is it not operational now? This sentence should not be future tense.***
2. ***"… with settling particles forming a sediment" (L15) Particles are sediment. This part of the sentence should be rephrased or removed.***
3. ***Remove "that" (L20)***
   Sentence has been changed according to your previous comment (Abstract, point 2, and 3.)

Introduction

1. ***References should be merged to 1 set of brackets (L30): (Yin & Koch, 2007; Hagemeier et al., 2021). This should be corrected throughout the paper.***
   References are merged.
2. ***"(see equations (1) and (2))" (L45) Brackets in brackets here are unnecessary.***
   Brackets removed.

Materials and Methods

1. **"is" (L108) replace by "was"**
   Done.
2. **"while density" (L136) replace by for example "with densities ranging".**
   Done.
3. **"planned measurements" (L141). Past tense, probably a remnant of a research proposal. Replace by for example "the experiments". If the planned and executed experiments are different, please specify.**
   Done.
4. **Punctuation problem at L167**
   Done.
5. **Figure 5: I only see 4 particles.**

There are five particles, one is close to the top of the chambers, the other four are in the middle of the chamber.

Results and Discussion

1. ***Capitalise "discussion" in section title.***
   Done.

Response to Referee #2

Particles with irregular shapes are certainly more difficult to deal with, so the shape factor must be considered. It is certainly possible to carry out similar experiments. The most difficult part is the analysis of the trajectories and considering the moment of inertia of the irregular particles and identifying the correct functions for the description of the shape. Our idea is to use carry out some experiments these and use the results to numerically simulate their trajectories based on computational fluid-dynamics techniques. Ideally, we would use a technique that is as free as possible from empiric parameters, for example Lattice Boltzmann equations that are widely used in geoscience and have the characteristics needed to deal with these kinds of problems. Once this model has been developed, it can be used for particles with a wide range of sizes and shapes.

We thank you very much for your precious revisions.

Kind regards,

Federica Trudu and Nikolaus Kuhn.