This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 870377.

Near Earth Object
Modelling And Payloads
for Protection

A physical model for low-velocity penetration into granular media

7th IAA Planetary Defense Conference 2021

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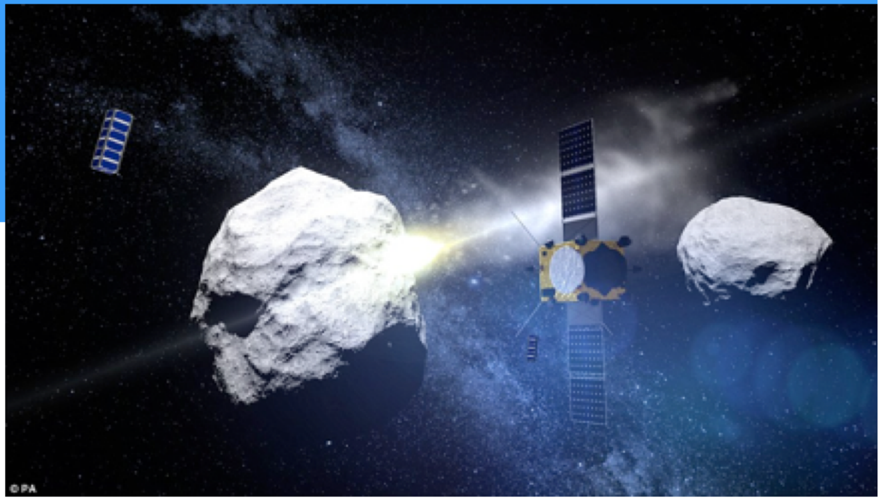
Framework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The H2020 **NEO-MAPP project** (*Near Earth Object Modelling and Payloads for Protection*) aims to provide significant advances in our understanding of the response of NEOs to external forces

- **Planetary defense**
- Investigate the **physics of low-velocity collisions**, and the mechanical properties of the regolith that composes the surface of asteroids
- Better understand the **evolution of small body surfaces**
- **Prepare the design and operations for future space missions**

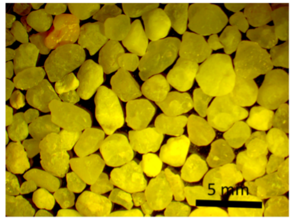
Main aim of our study:

Improve our understanding of landing on small bodies

- **Analyze accelerometer data recorded during low velocity collisions, in both static and low gravity environments**
- **To develop a theoretical framework to describe low velocity collisions into granular material**

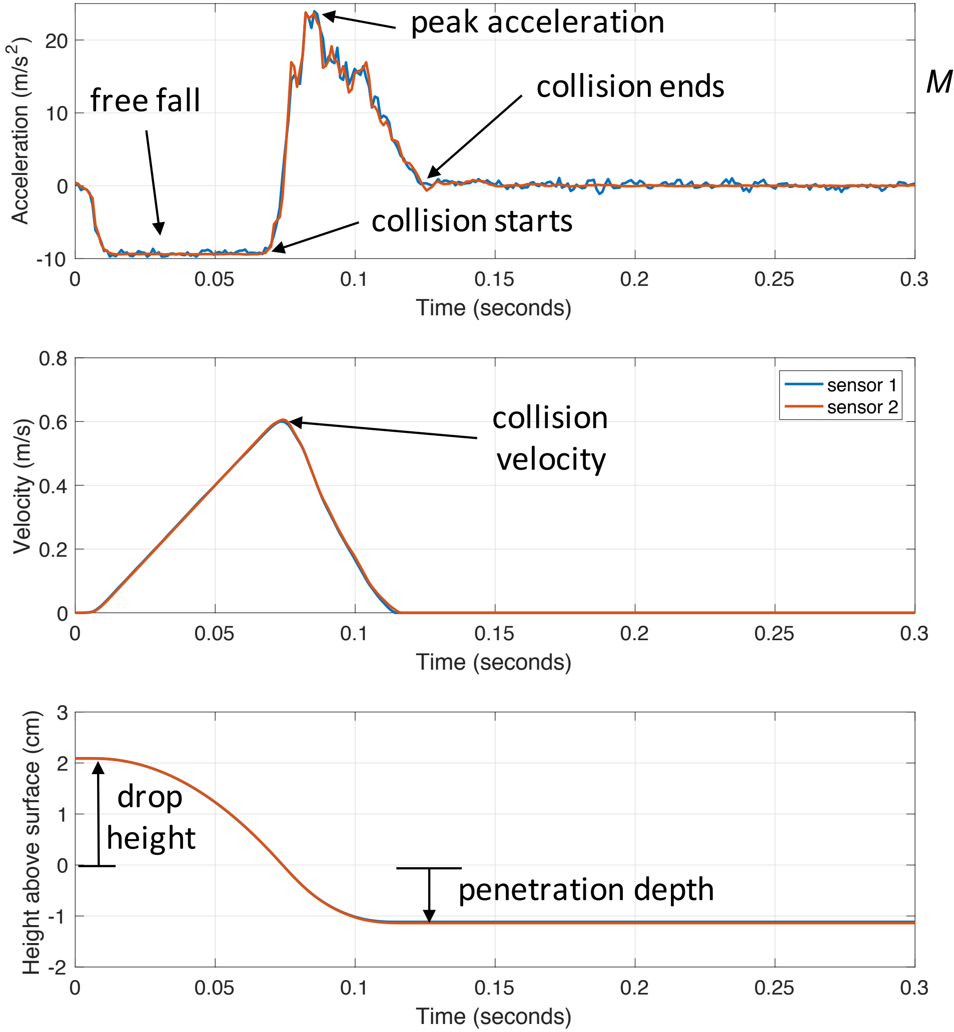
Experiments: example of collision data

- **Terrestrial gravity trial, using a 10 cm diameter aluminium sphere impacting quartz sand:**



- We use **three key collision measurements**:
  - the peak acceleration
  - the collision duration
  - the penetration depth

- Analyses a little more complex for the low gravity trials, but the idea remains the same (see Murdoch et al., 2017 for details)

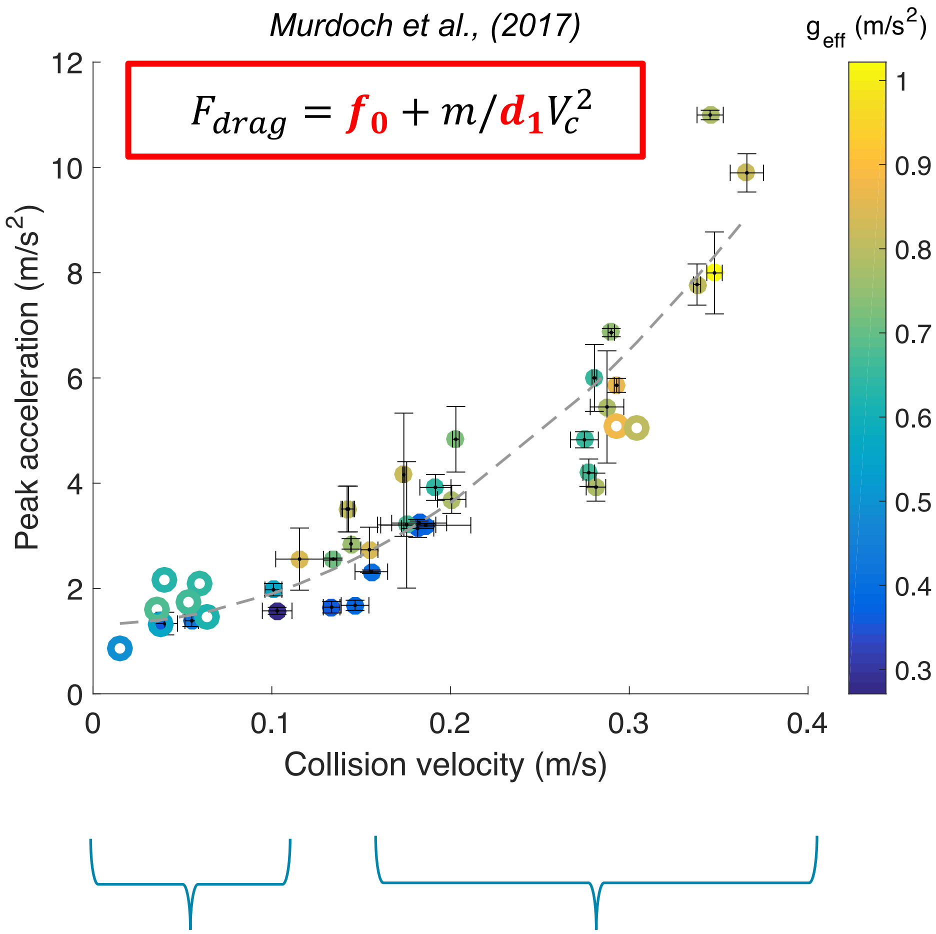


Murdoch et al. (2021)

Accelerometers inside the projectiles measure the in-situ acceleration profile during the impact.

Analytical model

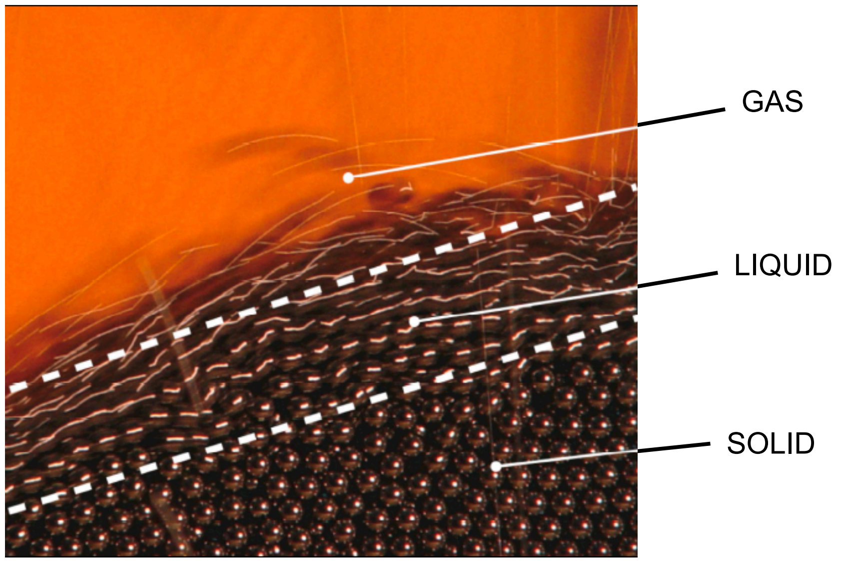
Murdoch et al., (2017)



Quasi-static (frictional) regime (a$_{peak}$ independent of V_c)

Inertial (hydrodynamical) regime (a$_{peak}$∝ V_c^2)

Image: Pouliquen & Forterre



- **Inertial (hydrodynamic) regime**: the grains have become sufficiently fluidised for the system to display inertial, fluid-like drag.
- **Quasi-static (frictional) regime**: the static resistance force dominates (the particles "jam")

Analytical model

Unified force law:

$$ma = mg - f(z) - h(z)v^2$$

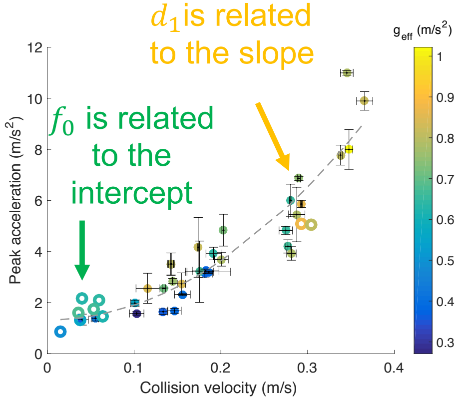
Frictional drag

Inertial drag

Simplification used in Murdoch et al. (2021):

$$ma = mg - f_o - \frac{m}{d_1}v^2$$

Assume drag terms are depth independent



Peak acceleration:

$$a_{\text{peak}} = \frac{f_0}{m} + \frac{V_c^2}{d_1} - g$$

Quadratic fit

$$\rightarrow \frac{dK}{dz} = mg - f_0 - \frac{2}{d_1}K$$

Kinetic energy reformulation (Clark & Behringer, 2013)

Maximum penetration depth:

$$z_{\text{stop}} = \frac{d_1}{2}\ln\left[1 + \frac{mV_c^2}{d_1(f_0 - mg)}\right]$$

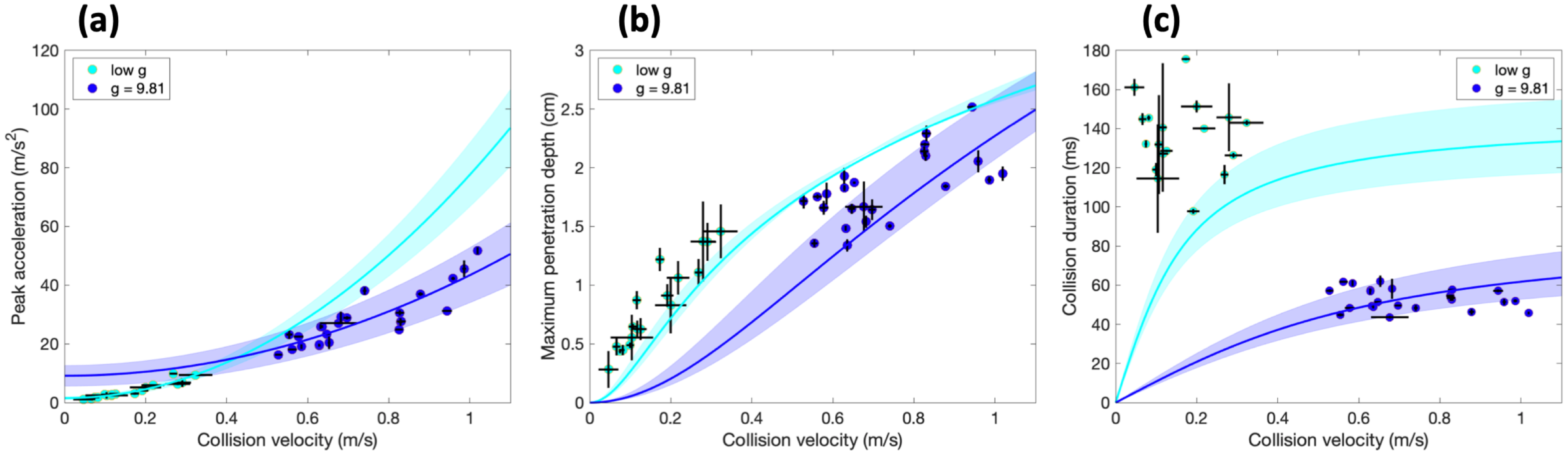
Collision duration:

$$t_{\text{stop}} = \frac{\operatorname{atan}\left[V_c^2\sqrt{\frac{m}{d_1(f_0 - mg)}}\right]}{\sqrt{\frac{1}{d_1}\left(\frac{f_0}{m} - g\right)}}$$

Testing the model: influence of the gravity

Peak accelerations are used to find f0 and d1

The drag force model is then used to predict the maximum penetration depth and collision duration



Peak acceleration

Maximum penetration depth

Collision duration

- The force law model explains well the 1g data
- At low g (0.4 – 1.4 m.s^{-2}), the peak accelerations can be correctly modelled with the proposed theoretical model, and the model provides reasonable predictions for the maximum penetration depth
- The collision duration is significantly underestimated by the current model at low g
- The theoretical model needs to be improved in order to correctly capture the collision durations of the lowest-velocity impacts

Testing the model: influence of the gravity

Material	Effective gravity (m.s^{-2})	Hydrodynamic drag force term $1/d_1$ (m^{-1})	Static resistance force term f_0 (N m)	Transition velocity (m.s^{-1})
Quartz sand	9.81	34 ± 6	19 ± 4	0.75
1.5 mm glass beads	9.81	12 ± 1	15 ± 1	1.12
Quartz sand	0.4 – 1.4	76 ± 10	2.3 ± 0.5	0.17
1.5 mm glass beads	1.15 -1.21	17 ± 7	2.2 ± 0.2	0.36

If g ↘ :

d_1 ↗ and f_0 ↘

- The hydrodynamic and frictional contributions are related to the material frictional properties, the projectile geometry, and the gravity.
- The transition from a frictional to a hydrodynamical drag regime is shown to occur at lower impact velocities in reduced-gravity trials than in terrestrial gravity trials, indicating that **regolith has a more fluid-like behaviour in low-gravity**
- This confirms the previous hypothesis of Murdoch et al. (2017)
- Work in progress considering the theoretical model:
  - add a depth dependence of the drag coefficients
  - take into account the surface of contact

Depth dependence

Unified force law:

$$ma = mg - f(z) - h(z)v^2$$

Frictional drag

Inertial drag

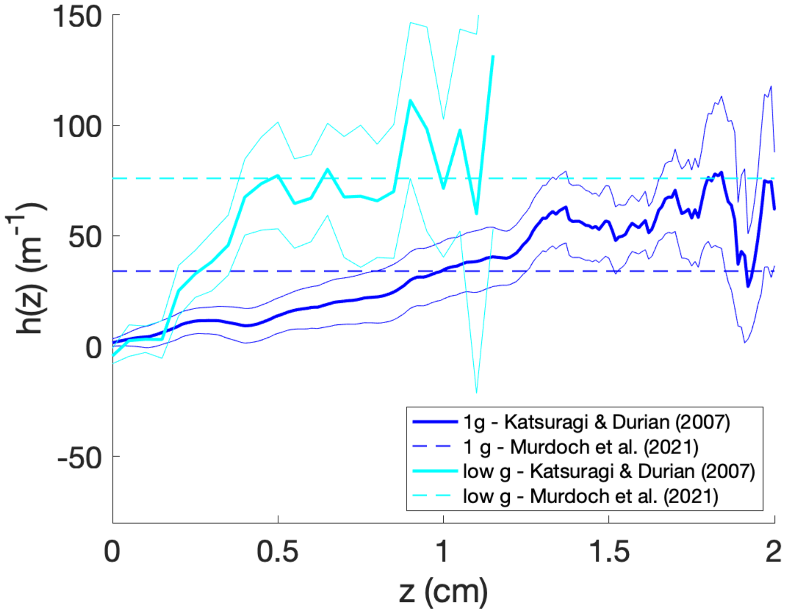
Simplification used in Murdoch et al. (2021):

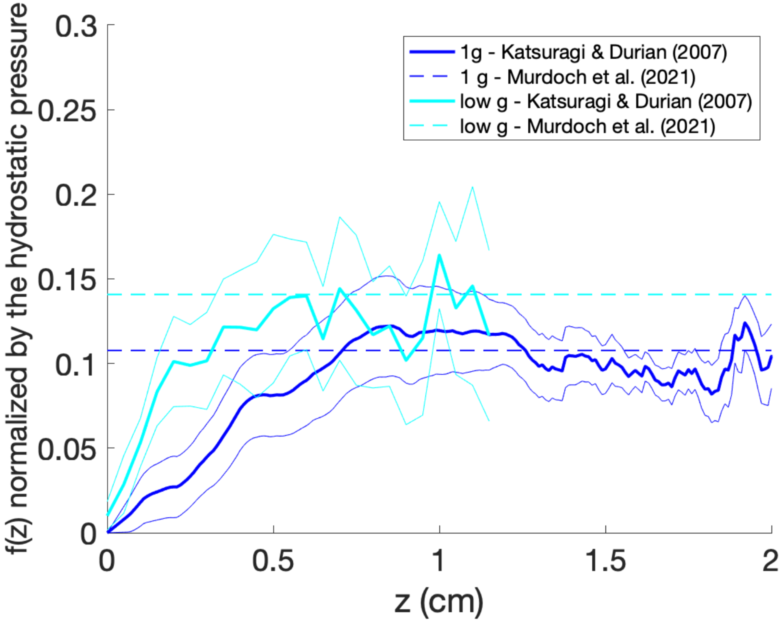
$$ma = mg - f_o - \frac{m}{d_1}v^2$$

Assume drag terms are depth independent

- The work of Murdoch et al. (2021) considers the frictional and hydrodynamical contributions to the drag force model as constants
- We experimentally measure how $f(z)$ and $h(z)$ contributions vary as a function of penetration depth (Katsuragi & Durian, 2007), without providing an assumption about the functional form of these terms

→ The hydrodynamic drag increases with depth, but only over very shallow depths





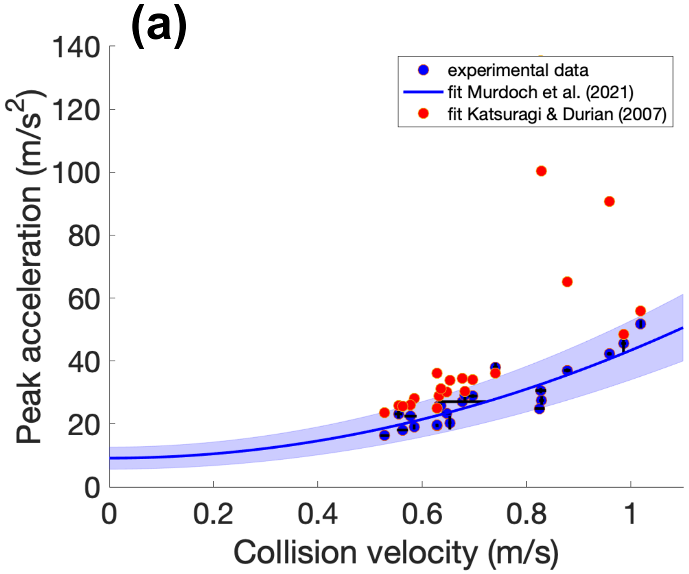
→ The frictional drag varies with gravity, but falls on the same curve when normalised by the hydrostatic pressure

→ $f(z)$ and $h(z)$ can be considered as constants, except at very shallow depths

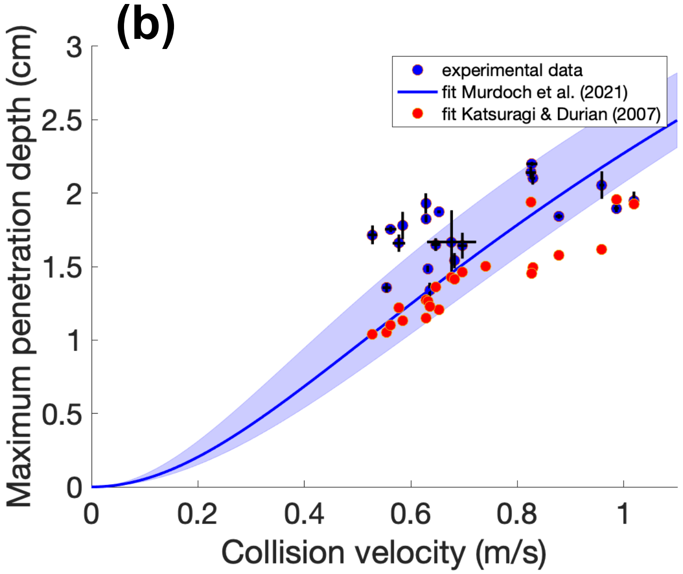
Depth dependence → terrestrial gravity

- For a given maximum penetration depth, we are now able to estimate $f(z)$ and $h(z)$
- By reinjecting these values in the equations of the analytical, models, new values of the peak acceleration, maximum penetration depth, and collision duration, can be estimated (red dots)

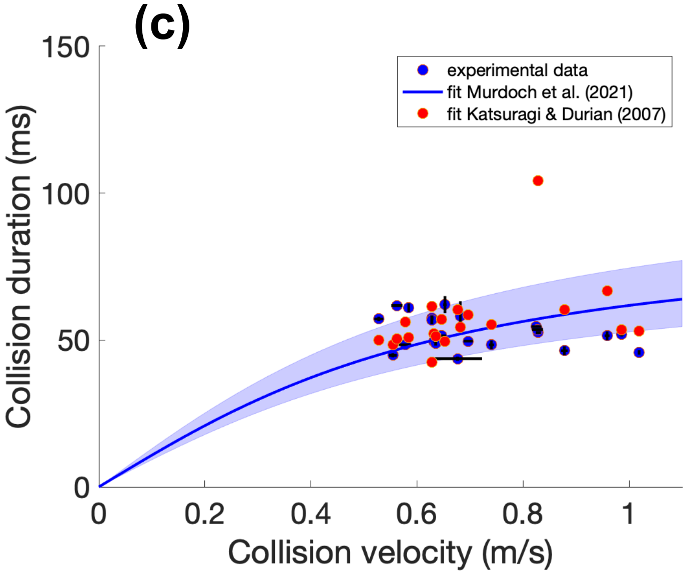
Peak acceleration



Maximum penetration depth

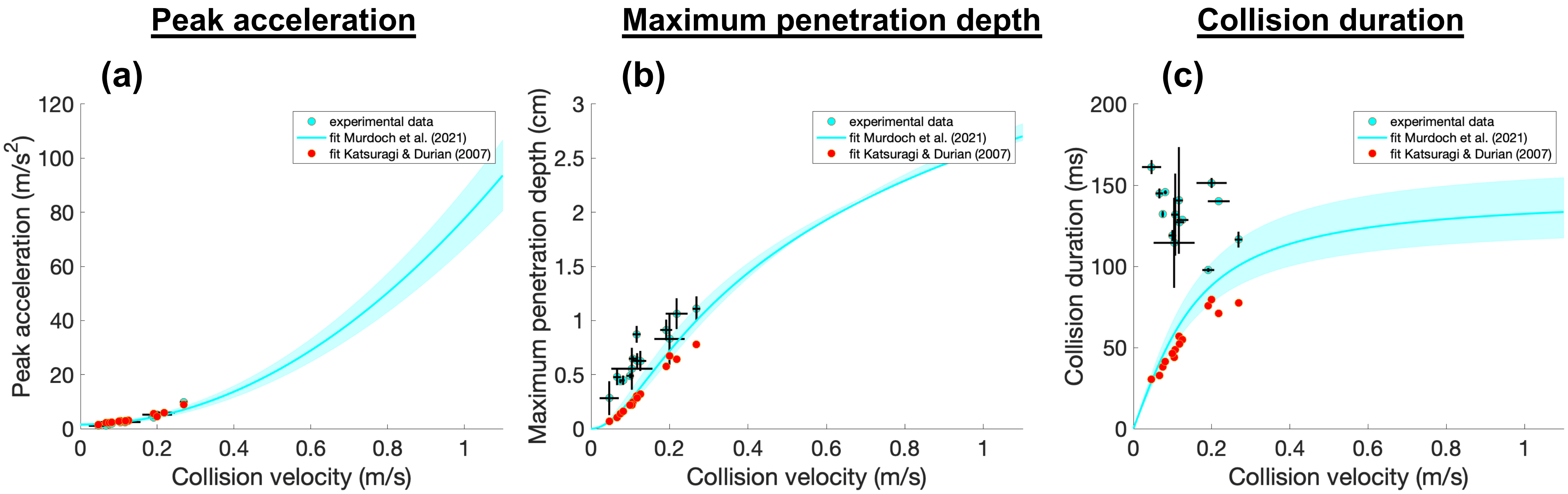


Collision duration



- The new fit from the method of Katsuragi & Durian (2007) lies within the 95% confidence bounds of the fit obtained by Murdoch et al. (2021), except for collision velocity larger than 0.8 m/s.
- Including the depth dependence of $f(z)$ and $h(z)$ does not significantly improve the model predictions

Depth dependence → low gravity



- As for the data recorded under terrestrial gravity, including the depth dependence of $f(z)$ and $h(z)$ does not improve the model predictions

A few conclusions

- To better understand asteroid landing dynamics, we have analyzed data from experiments of low-velocity impacts of projectiles of various shapes into different types of granular material in both normal ($9.8\ m.s^{-2}$) and reduced gravity ($0.4 – 1.4\ m.s^{-2}$)
- The different, more fluid-like, behaviour observed in low-gravity highlights the **importance of understanding the influence of the low gravity environment for correctly interpreting accelerometer measurements**
- In Murdoch et al. (2021), we have developed an **analytical (drag force) model** to explain the observable data: peak acceleration, collision duration, penetration depth
- In an attempt to improve the analytical model for the case of low-gravity experiments, we have derived and accounted for the **depth dependence** of the frictional and hydrodynamical drag terms. However, this does not improve the model predictions for the penetration depth and collision duration.
- **Numerical simulations** (validated via comparison with experiments – Sunday et al., 2020) are being used in parallel to complement the experimental results (can obtain a larger range of collision velocities and gravity levels than are accessible to the experiments)
- More work need to be done in order to better understand the experiment behaviour at low gravity. The current model predicts zero penetration depth and zero collision duration for a null collision velocity, whereas a finite penetration and duration are always observed in the experimental data

HORIZON 2020

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NEO-MAPP

Thank you.

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