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Publication date
2023

Document Version
Final published version

Published in
Proceedings of the International Meteor Conference, Proszló, 2022

Citation (APA)
Bettonvil, F., de Vet, S. J., & Netjes, G. J. (2023). Simulating meteorite impacts - an outdoor field experiment. In U. Pajer, A. Kereszturi, & C. Steyaert (Eds.), *Proceedings of the International Meteor Conference, Proszló, 2022* (pp. 62-69). International Meteor Organization . https://ui.adsabs.harvard.edu/abs/2023pimo.conf...68B/abstract

Simulating meteorite impacts - an outdoor field experiment

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We report on the design of a meteorite impact simulator and evaluate the first results. Artificial meteorites were dropped on the ground with realistic terminal velocities. The soil disturbance and impact pit remained recognizable for approximately3 months. These experiments foster our understanding of impact dynamics in soft deformable top soils, and contribute observables to improve the success rate of meteorite search campaigns.

1 Introduction

As of 2022, a modest amount of six meteorites has been recovered in the Netherlands. Historic finds predating WWII were primarily made by eyewitnesses and land workers. Present-day meteorite search and recovery activities are driven by fireball observations in an over-dense camera network with DLSR cameras and the FRIPON/DOERAK and Allsky7 networks, operated by the KNVWS Meteor Section and Dutch Meteor Society. Recent search campaigns in Hoenderloo in 2013, Gaasterland in 2015 (Figure 1), Broek in Waterland in 2017 and Hasselt in 2019, illustrate a roughly 2-year recurrence frequency of possible meteorite falls. However, none of the aforementioned campaigns did successfully recover a new meteorite, despite all efforts of bringing together a group of experts, amateurs, local geologists, involvement of land owners and local inhabitants, and fields searches lasting an extended number of days. The low yield of recovered meteorites during recent search campaigns triggered the question of what it is that we are looking for while walking the fields, which apparently is not a very well-known factor for meteorites and their impacts in various soil types. The idea arose to see if it is feasible to simulate a meteorite fall with an artificial meteorite to study how it penetrates into the ground and understand the soil disturbance it creates. This is the topic of this paper.

We start with describing what we know about Dutch meteorites falls and local soil types (Section 2), continue with the feasibility of an experiment (Section 3), the design of a the apparatus (named *MIS – Meteorite Impact Simulator*) and test results (Section 4 and 5), the field experiment with first results (Section 6 and 7), further work (Section 8) and conclusions (Section 9).

Figure 1 – Line searching during a search campaign in Gaasterland, 2015.

2 Background: Dutch meteorite falls

In the period spanning from 1840 to 2017 six authenticated meteorites have been recovered in the Netherlands; in Uden, Utrecht, Diepenveen, Ellemeet, Glanerbrug and Broek in Waterland. None of them have high-precision orbits associated with them (the latter two fell during day / evening twilight), and the historic falls that impacted soils were only briefly documented[1]. From reports and other studies we have gained

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[1] See for example https://langbrom.home.xs4all.nl/meteorieten/diepnl.html and https://werkgroepmeteoren.nl/nederlandse-meteorieten/ (both in Dutch)

some insight into the impact conditions and soil associated to the falls, as shown Table 1 and 2.

The Netherlands is a flat country with elevations close to sea level (Figure 2a) with a landscape shaped by glacial and fluvial processes, as well as anthropogenic landscape development.

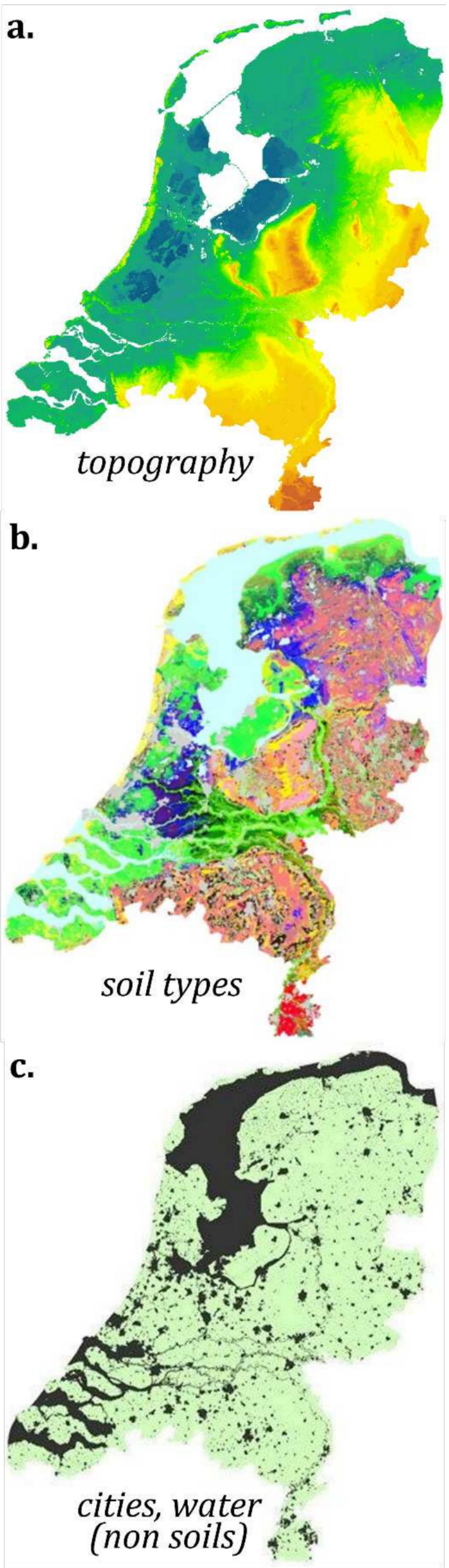

Figure 2 – Overview maps illustrating the terrain in the Netherlands. (a) Topography ranging from -6 to 322 masl.; (b) soil types generalised to peat and peatlands (blues), clay-sandy soils of fluvial origin (greens), loess (red) and sandy terrains (other colours); and (c) areas without soil classification due to infrastructure of urban areas and water bodies. Sources: PDOK, AHN, bodemdata.nl

Table 1 – Properties of Dutch meteorite falls

Meteorite	**Year**	**Type**	**Mass**	**Details**
Uden	1840	LL7	710 g	-
Utrecht	1843	L6	7000 g, 2700 g	aerial break-up into 2 fragments
Ellemeet	1925	DIO	970 g, 500 g	polymict breccia
Diepenveen	1873	CM2-an	68.4 g	surface regolith breccia
Glanerbrug	1990	L/LL5	855 g	polymict breccia
Broek in Waterland	2017	L6	530 g	fusion crusted, secondary crusts

Table 2 – Soil impact characteristics of impacts

Meteorite	**Soil**	**Depth**	**Details**
Uden	sand	~15cm	Circular crater on a dirt road
Utrecht	clay, sand	90 cm	Main mass penetrated clay soil, was stopped on a deeper sandy layer
Ellemeet	clayey sand	~0.5 m,	Main mass broke into 4 fragments during recovery. Second mass impact angle ~70° into the soil.
Diepenveen	sand	~45 cm	Created a pit in a sandy soil
Glanerbrug	roof	-	-
Broek in Waterland	roof	-	If other fragments existed, they disappeared into peat-rich soils or nearby peatlands.

During past glaciations extensive cover sands have been deposited that dominate in the east and south, as well as loamy soils in the Loess Belt in the far south. Subsequent cross-cutting by the Rhine-Meuse Delta and deposition of fluvial sediments has formed a region with sand and clay-rich soils running from east to west and marine influence near the coast. In the coastal zones, formation of extensive peat deposits, with occasional clay layers from marine transgressions, evolved gradually over a period with increasing sea levels. In areas with reclaimed land, soils are mostly consisting of marine clays and are subjected to extensive agricultural reworking. A top-level soil classification identifies 15 soil types, with many subtypes (Figure 2b, www.bodemdata.nl).

The country is densely populated in the western provinces (the ‘Hollands’) and has an intensive agricultural industry. While man-made structures have been key in recovering the last two meteorites in the Netherlands, we expect a larger likelihood for impacts outside densely populated areas due to the limited aerial extent of infrastructure (13%)[2]. Meteorites are thus more likely to penetrate into the ground than impact a roof or road. As the Dutch *soilscape* is a patchwork of various soil types, the corresponding differences in physical properties (e.g. penetration resistance, soil water content, erosion susceptibility) due to textural differences will directly impact the success rate for meteorite recoveries. Key questions to address include the soil penetration of meteorites and associated disturbances as well as the persistence of these impact signatures over time, and under different seasonal conditions.

3 Simulating an impact

Can we simulate an impact? To answer that question we need to get insight in the (free fall) terminal velocity of meteorites. IMO[3] and AMS[4] mention on their websites 100 m/s and 90–80 m/s, respectively. Assuming an equilibrium at the end of the trajectory between a) the free fall of the meteorite due to gravitation acceleration:

$$F = m\,G \qquad (1)$$

with m – mass of the meteorite, and G – gravitational acceleration, and b) drag as encountered by the meteorite during its travel through the atmosphere:

$$F = c_d\,A\,\frac{1}{2}\,\rho\,v^2 \qquad (2)$$

with c_d – drag coefficient, A – front surface meteorite, ρ– density air, v – terminal velocity, one can derive in first approximation a relation between terminal velocity and mass. Figure 3 gives as example the relationship for a perfect spherical meteorite with a density ρ of 2,700 kg/m^3. It results in terminal velocities of 25–75 m/s for meteorite fragments weighing 1–500 g. More accurate estimates can be derived from dark flight modelling, which was done with *PyDaf* [Bettonvil, 2021], see also Section 6, and gave similar results. Achieving such velocities should be feasible using technical means.

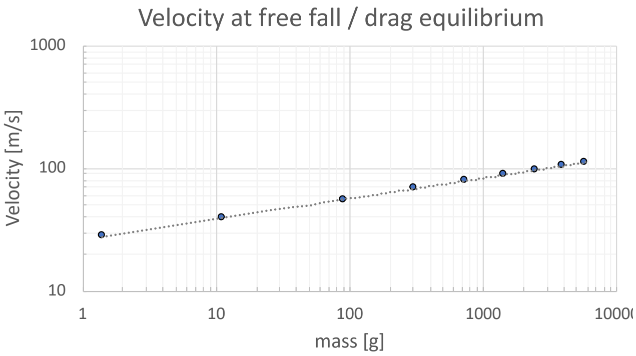

Figure 3 –Terminal velocity for a meteorite with mass m as derived from the equilibrium between free fall and drag for a spherical meteorite (c_d= 0.47, $\rho_{\mathrm{meteorite}}$ = 2700 kg/m^3).

4 Apparatus

We have designed and constructed an apparatus to let an artificial meteorite fall in a controlled way. The design is a cannon using pressurized air (aka *spud gun*), which shoots the meteorite (for safety reasons) vertically downwards into the ground. A technical specification of the device is given in Table 3.

Table 3 – Technical specifications of Meteorite Impact Simulator MIS

Parameter	**unit**	**value**
Mass meteorite	[g]	200 (100–500)
Diameter meteorite	[cm]	7
Max Air pressure	[Pa]	10^6
lengthlaunch pipe	[m]	2.7
Max trust power	[N]	3700
Max exit velocity @ 200g	[m/s]	> 100

The apparatus (Figure 4 and 5) consists of a ~3 m long launch pipe holding the meteorite and is surrounded by a larger diameter pipe that contains the pressurized air. The launch pipe is closed on one side with a valve that vents the pressurized air into the launch pipe. The technical challenge is to get instantly the full pressure on the meteorite. It is done with help of an auxiliary chamber and pilot valve. The

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[2] https://longreads.cbs.nl/the-netherlands-in-numbers-2020/how-do-we-use-our-land/

[3] https://www.imo.net/observations/fireballs/meteorites/

[4] https://www.amsmeteors.org/fireballs/faqf/

apparatus is made of high-pressure PVC piping for practical reasons. Due to the non-trivial design pressure, the apparatus was properly engineered in terms of mechanical stresses and appropriate safety margin applied, leading to wall thicknesses of 6–10 mm. In order to control the launch parameters a manometer was added (Figure 6). A smartphone camera in *slow-motion* mode is used to measure the escape velocity as function of pressure (Figure 7). The apparatus is erected close to a vertical by mounting it on a ladder, as part of a transportable setup, which includes a recoil spring system to deal with the rearward trust (Figure 8).

The artificial meteorites are made of concrete which enables densities of ~2,500 kg/m^3. They are of a cylindrical form and accommodate two foam rings to ensure a tight fit in the tube. These meteorite-simulants are painted black to approximate the colour contrast of soils and fusion-crusted meteorites, see Figure 9.

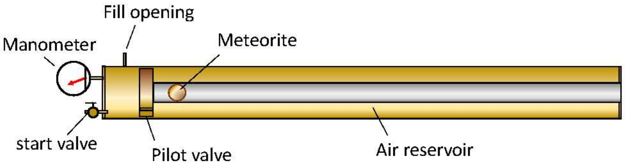

Figure 4 – Design of the simulator. The inner tube is the actual launch tube, which is mounted into a large one, which acts as the reservoir with compressed air.

Figure 5 – Construction of the apparatus. The inner tube is the actual launch tube, which will be mounted into the large one, which acts as the reservoir with compressed air.

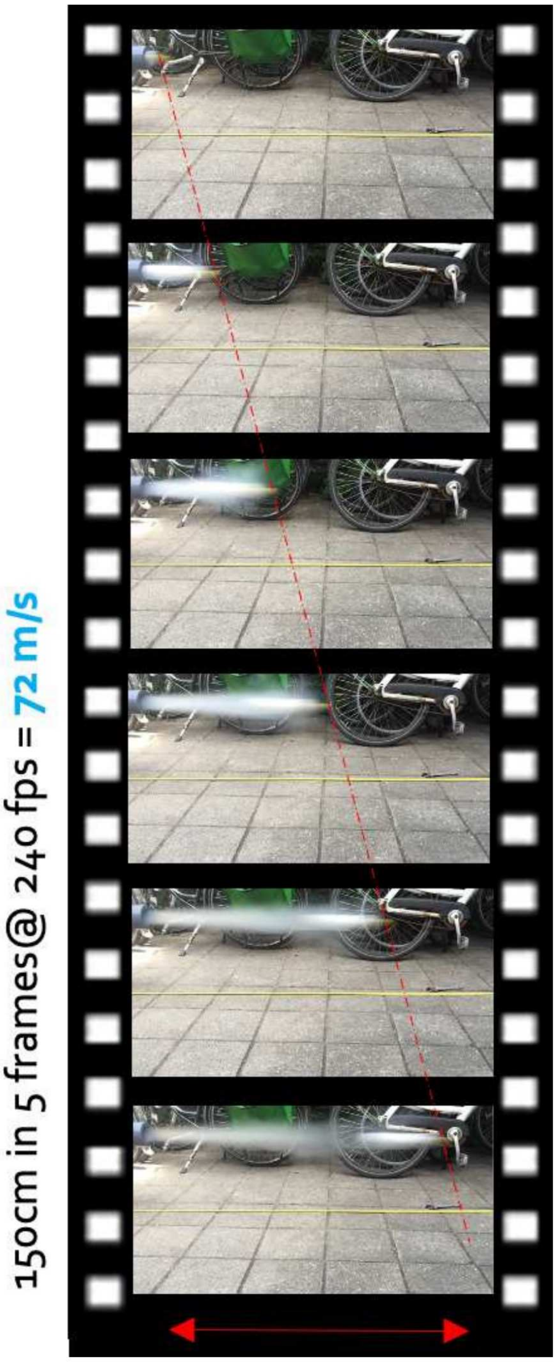

Figure7 – Example of high-speed frame shots, used to verify the exit velocity (here with horizontal setup).

5 Test results

First tests showed that the apparatus works as intended. Exit velocities are matching the computed values quite well. They are slightly lower, likely due to friction of the meteorite in the launch pipe and slight pressure drop in the air supply reservoir.

During one test the meteorite broke into pieces when hitting the ground, producing gram-sized fragments, reproducing surprisingly nicely the ‘real’ size distribution of meteorite fragments (Figure 10). A preliminary test with a 750 g meteorite-simulant showed a penetration depth of 20-30 cm, which is of a similar order of magnitude as that reported for the historical Dutch meteorite falls.

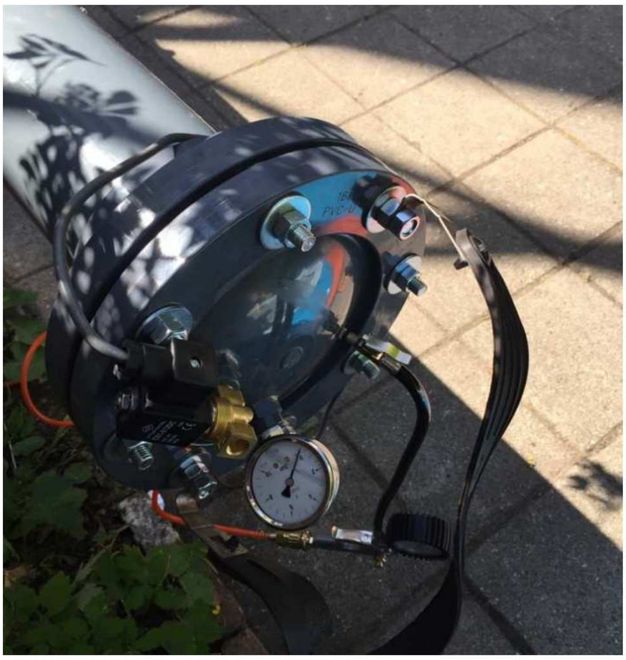

Figure 6 – Backside of the apparatus with manometer, release valve and filling valve.

Figure 8 – Full set up, erected for the ‘fall’ in the botanical garden adjacent to the Old Observatory in Leiden.

Figure 9 – Example of an artificial meteorite, made of concrete, mass ~250 g.

Figure 10 – Produced meteorite fragments after the artificial main body hit a hard underground.

6 Field tests

With the apparatus ready for use, it was brought to locations to conduct the first field tests. The overarching aim of the project is to test on various types of soil to obtain a representative portfolio for impacts in Dutch soils, but for a pilot test campaign we chose three locations in the city of Leiden as part of a science event (Leiden City of Science 2022)[5].

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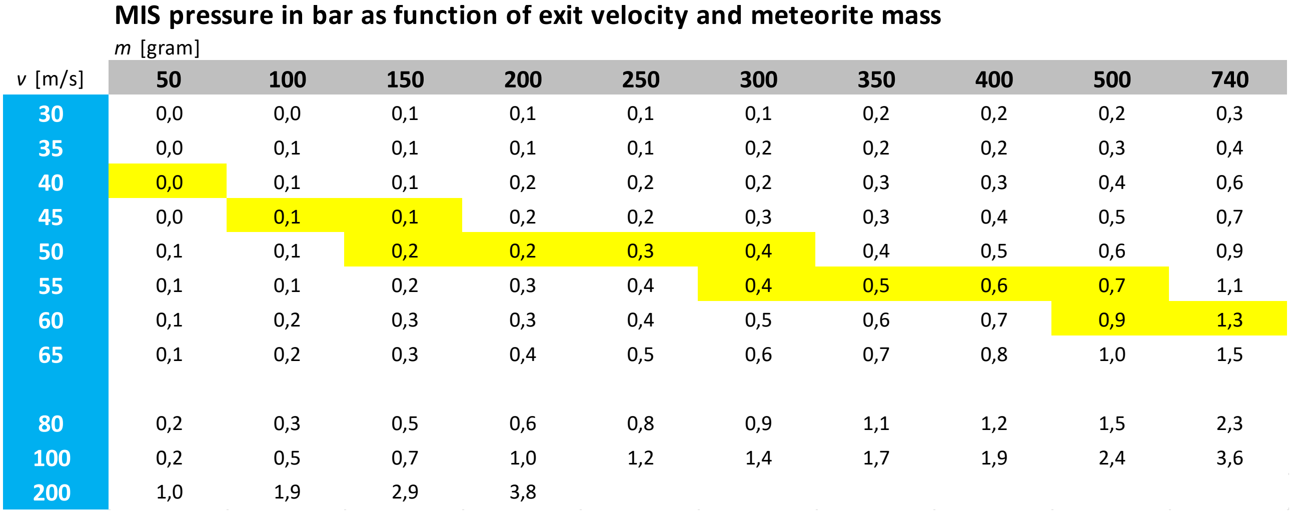
[5] https://leiden2022.nl/en

Table 4 – Relation between mass (horizontal), exit velocity (velocity), and air pressure in the meteorite impact simulator, as well as the expected mass-terminal velocity relationship (indicated in yellow) as derived from *PyDaF*.



MIS pressure in bar as function of exit velocity and meteorite mass

m [gram]

v [m/s]	**50**	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**500**	**740**
30	0,0	0,0	0,1	0,1	0,1	0,1	0,2	0,2	0,2	0,3
35	0,0	0,1	0,1	0,1	0,1	0,2	0,2	0,2	0,3	0,4
40	0,0	0,1	0,1	0,2	0,2	0,2	0,3	0,3	0,4	0,6
45	0,0	0,1	0,1	0,2	0,2	0,3	0,3	0,4	0,5	0,7
50	0,1	0,1	0,2	0,2	0,3	0,4	0,4	0,5	0,6	0,9
55	0,1	0,1	0,2	0,3	0,4	0,4	0,5	0,6	0,7	1,1
60	0,1	0,2	0,3	0,3	0,4	0,5	0,6	0,7	0,9	1,3
65	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	1,0	1,5
80	0,2	0,3	0,5	0,6	0,8	0,9	1,1	1,2	1,5	2,3
100	0,2	0,5	0,7	1,0	1,2	1,4	1,7	1,9	2,4	3,6
200	1,0	1,9	2,9	3,8						

Figure 11 – Soil disturbance of the 'fall' at Old Observatory, image taken directly after the fall.

We report here on those first results. The field experiments were done at public locations near the observatory and botanical garden in Leiden and a school; the latter included the teaching of basic physics in determining the required pressure in the launch pipe and directing to *PyDaF* to learn on the terminal velocities of meteorites (Table4). The pilot campaign served as kick-off of a larger citizen-science plan to tests on many locations, in different seasons, and on a variety of soil types. A participation form has been created online to register a site and upload of photos[6], and promotion material made to attract public attention for the experiment. The project is part of a larger framework on meteorite outreach. With the project we hope to gain better insights into meteorite impacts in soft top soils. Next to gaining insight in the aspects of different Dutch soil types and seasonal effects, we vary the parameter space and the terminal velocity.

7 Results

Figure 11 and 12 show the result of the experiment in the botanical garden and old observatory in Leiden, both on typical garden soils. The experiments were carried out on March 30, early spring. After the fall a small fence was put around the meteorite and landing site and an information panel erected to inform the public on what they see with a request to make photos and send them to us. Other pictures were taken in July 03 and August 19 (Figure 12). In both cases, on July 03 (3 months after the fall), the meteorite was still visible and its crater recognizable. But on August 19 (nearly 5 months later), nothing was visible anymore. While July and August 2022 were very dry, the effect of splash erosion by rainfall and possibly sprinklers of the botanical garden were likely responsible for redistributing soil material and degrading the impact signatures.

Our first results point towards a limited timeframe for starting up search campaigns. Rapid recovery also to avoid meteorite weathering due to prolonged exposure to soil and weather conditions [de Vet, 2015].

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[6] https://werkgroepmeteoren.nl/meteorietinslagtesten/ (In Dutch)

Figure 12 – Result of the ‘fall’ at the botanical garden, directly after the fall on March 30 (top), July 03 (center) and August 19 (bottom).

8 Further work

To quantitatively analyse the impact disturbance, we will study the change in morphometric properties of the impact sites over time. By taking a series of overlapping images from multiple angles, the images can be used for Structure-from-Motion photogrammetry in Agisoft Metashape Pro to generate a 3D model and subsequently a high-resolution Digital Terrain Model (DTM). A first result of this approach is shown in Figure 13 for the impact site in the botanical garden (Figure 12) using images taken a few days after the impact. The photogrammetry approach will allow us to characterise the impact signature and study the small-scale changes in topography to track the degradation of the soil disturbance over time. Creating a time series will better facilitate the correlation of observed physical changes of the soil surface to local weather conditions.

During future field tests we will also collect additional physical soil parameters to assess correlations with local top soils. We foresee documenting properties such as the soil shear stress using a pocket shear vane (Torvane) and soil penetrometer, complemented with descriptions of the soil structure, grain size distribution and texture.

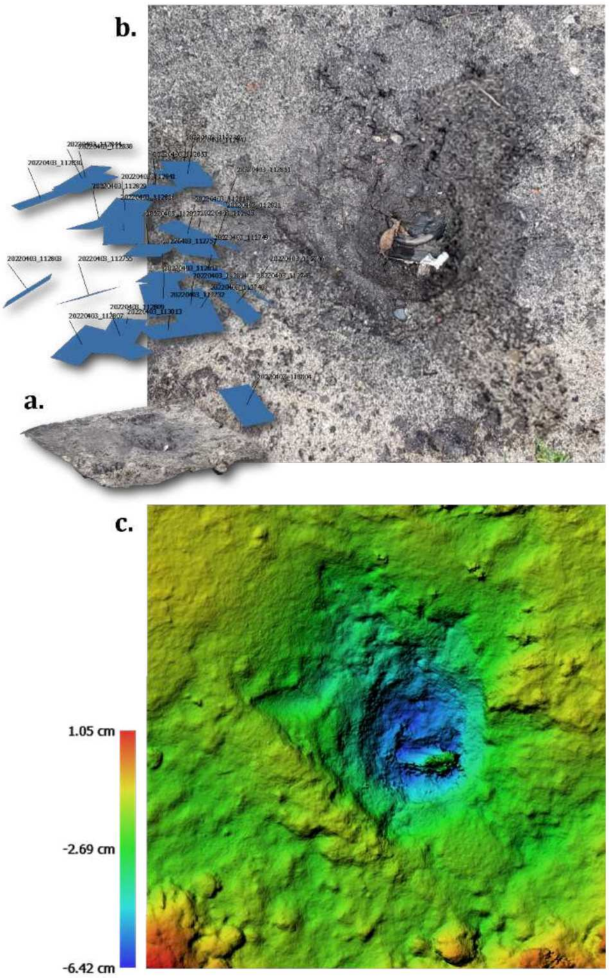

Figure 13 – Photogrammetric reconstruction of an impact site. (a) Multiple images are used to reconstruct the 3D scene of the impact site, which then allows generation of (b) a geometrically corrected orthophoto and (c)Digital Terrain Model that captures the fine-scale topography of the soil disturbance created by the simulated meteorite impact.

9 Conclusions

We succeeded in setting up a realistic experiment to simulate meteorite falls, which informs us about how meteorites impact the Dutch soils. The first tests were completed during a pilot campaign to test the feasibility and functioning of the impact apparatus. We are now planning new campaigns, thinking along the lines of studying a parameter space that is also relevant to predict soil impact signatures from meteorite falls worldwide. From our first tests, under these specific conditions in moderate to coarser-textured soils, we conclude that a 300 g fragments and its impact signature remain visible for ~3 months. While the selected fall speed was on the high side, we should expect that smaller fragments will cause minimal craters, and thus lay on top of the ground, while larger ones make deeper craters. We hope to learn more by expanding the field tests to a larger parameter space with different soil types, in different seasons, weather conditions, and various meteorites sizes (masses), across a range of terminal velocities. This will shed light on impact signatures along a gradient of soil properties. The mobile architecture of the impact apparatus also enables us to perform tests at the beginning of a field search campaign in a strewn field, which can help establish a benchmark for representative impact signatures for the larger masses, which can be illustrative for field campaign participants.

Finally, we also found that in addition to our scientific motivation for the experiments, the approach turned out to be well-suited to involve the public and scholars, and it has been received with enthusiasm.

References

Bettonvil F., Bettonvil D. (2021). “Tests with a basic ablation and dark flight calculator”. *WGN*, **49**, 147-151.

de Vet, S.J., (2015). The 1925 meteorite fall near Ellemeet and Serooskerke, the Netherlands. *Meteoritics and Planetary Science*, **50**(11), E1–E17, doi:10.1111/maps.12554