PRESSURE-SINKAGE TESTING OF LUNAR REGOLITH SIMULANTS IN AMBIENT PRESSURE AND VACUUM

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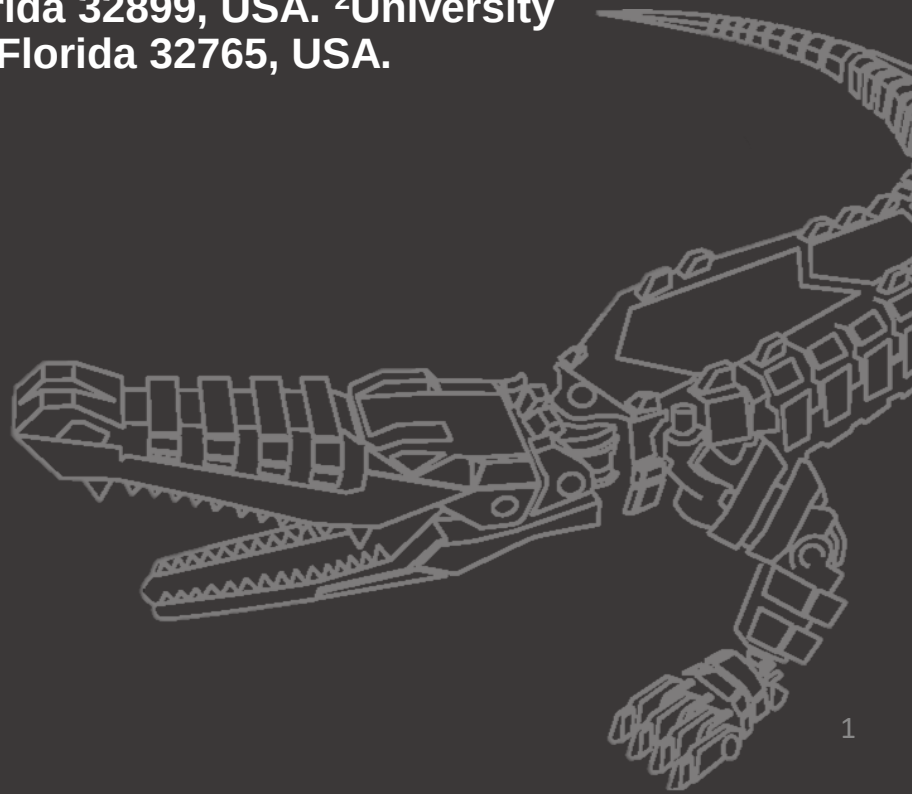


Tommy Gold (1920-2004)

- Professor of at Astronomy at Harvard and Cornell University
- In the 1950s, he suggested that the lunar surface was coated with a deep layer of fine rock powder, warning that astronauts and landers would sink out of sight.
- While Tommy Gold's remote sensing analysis was correct – the Moon has a "fluffy" low density surface, it rapidly increases in bulk density after 2-3 cm.
- The theory was opposed by many planetary scientists, but in part because of Gold's reputation, NASA sent unmanned missions to test the strength of the lunar surface.
- When the manned Apollo craft landed safely, it was said to have debunked Mr. Gold's theory. However, the scientist said lunar samples proved him correct, that "in one area as they walked along, they sank in between five and eight inches." Further, he held that they would have sunk more except they weighed one-sixth of what they did on Earth.

wikipedia

https://www.astronomy.com/science/thomas-gold-19201502004/

https://www.washingtonpost.com/wp-dyn/articles/A1122-2004Jun23.html

NASA Lunar Ranger

Rangers were designed to relay pictures and other data as they approached the Moon and finally crash-landed into its surface.

The Ranger Program

Spacecraft	Launch Date	Purpose	Results
Ranger 1	Aug 23, 1961	Lunar Prototype	Unsuccessful
Ranger 2	Nov 18, 1961	Lunar Prototype	Unsuccessful
Ranger 3	Jan 26, 1962	Impact Probe	Unsuccessful
Ranger 4	Apr 23, 1962	Impact Probe	Unsuccessful
Ranger 5	Oct 18, 1962	Impact Probe	Unsuccessful
Ranger 6	Jan 30, 1964	Impact Probe	Unsuccessful
Ranger 7	Jul 28, 1964	Impact Probe	Successful
Ranger 8	Feb 17, 1965	Impact Probe	Successful
Ranger 9	Mar 21, 1965	Impact Probe	Successful

https://science.nasa.gov/mission/lunar-rangers-and-surveyors/#:~:text=The%20first%20image%20from%20Surveyor,region%2C%20out%20to%20the%20horizon.

NASA Lunar Surveyor

- The Surveyors were designed for lunar soft landings.
- “The first image from Surveyor 1 showed its own landing foot firmly planted upon lunar soil, mute proof that landing was possible.”

The Surveyor Program

Spacecraft	Launch Date	Purpose	Results
Surveyor 1	May 30, 1966	Lunar Lander	Successful
Surveyor 2	Sep 20, 1966	Lunar Lander	Unsuccessful
Surveyor 3	Apr 17, 1967	Lunar Lander	Successful
Surveyor 4	Jul 14, 1967	Lunar Lander	Unsuccessful
Surveyor 5	Sep 8, 1967	Lunar Lander	Successful
Surveyor 6	Nov 7, 1967	Lunar Lander	Successful
Surveyor 7	Jan 7, 1968	Lunar Lander	Successful

https://science.nasa.gov/mission/lunar-rangers-and-surveyors/#:~:text=The%20first%20image%20from%20Surveyor,region%2C%20out%20to%20the%20horizon.

Surveyor 1 Landing Foot

Technical Memorandum 33-443

Basic and Mechanical Properties of the Lunar Soil Estimated From Surveyor Touchdown Data

F. B. Sperling

landing parameters; i.e., a 45-deg beveled footpad with an 8-in. baseplate radius (see Fig. 1), impacting with a velocity of approximately 12 to 13 ft/s.

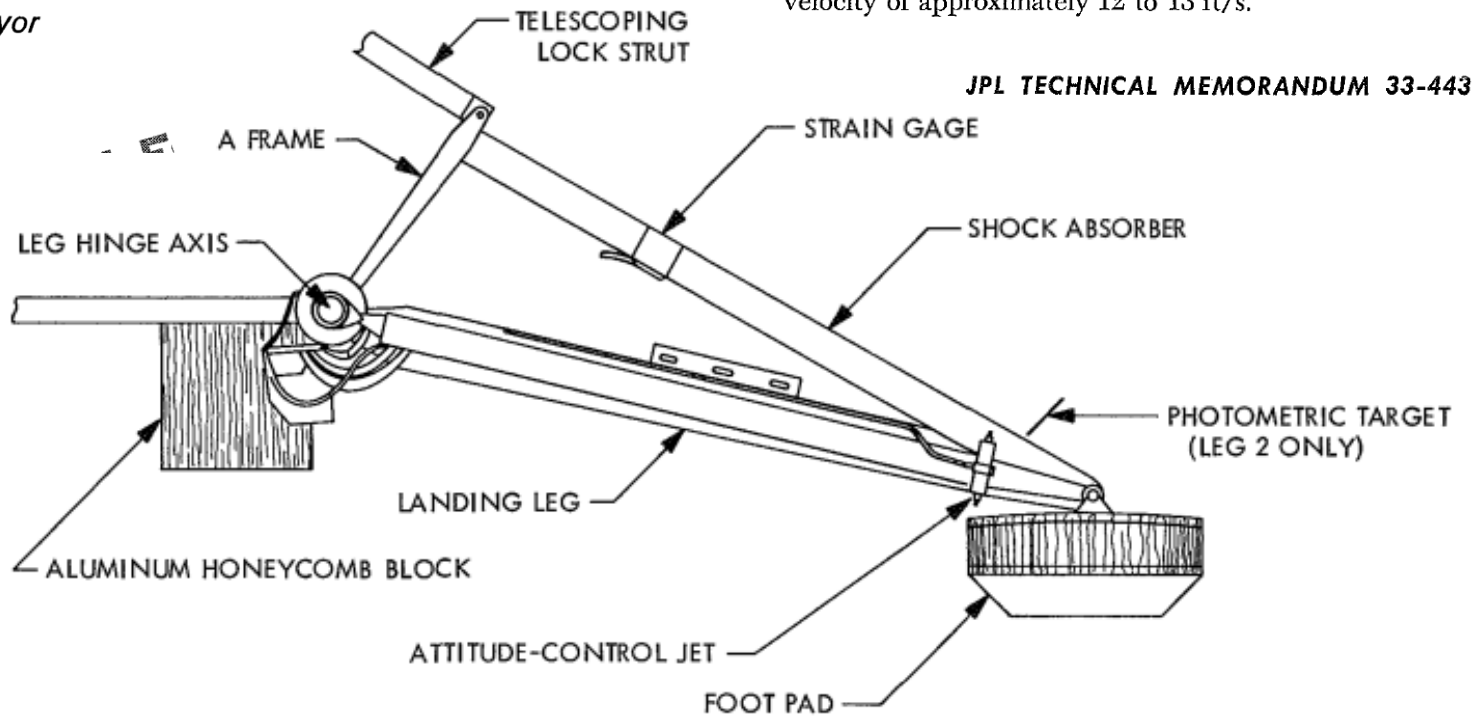


Fig. 1. *Surveyor* landing gear in extended position

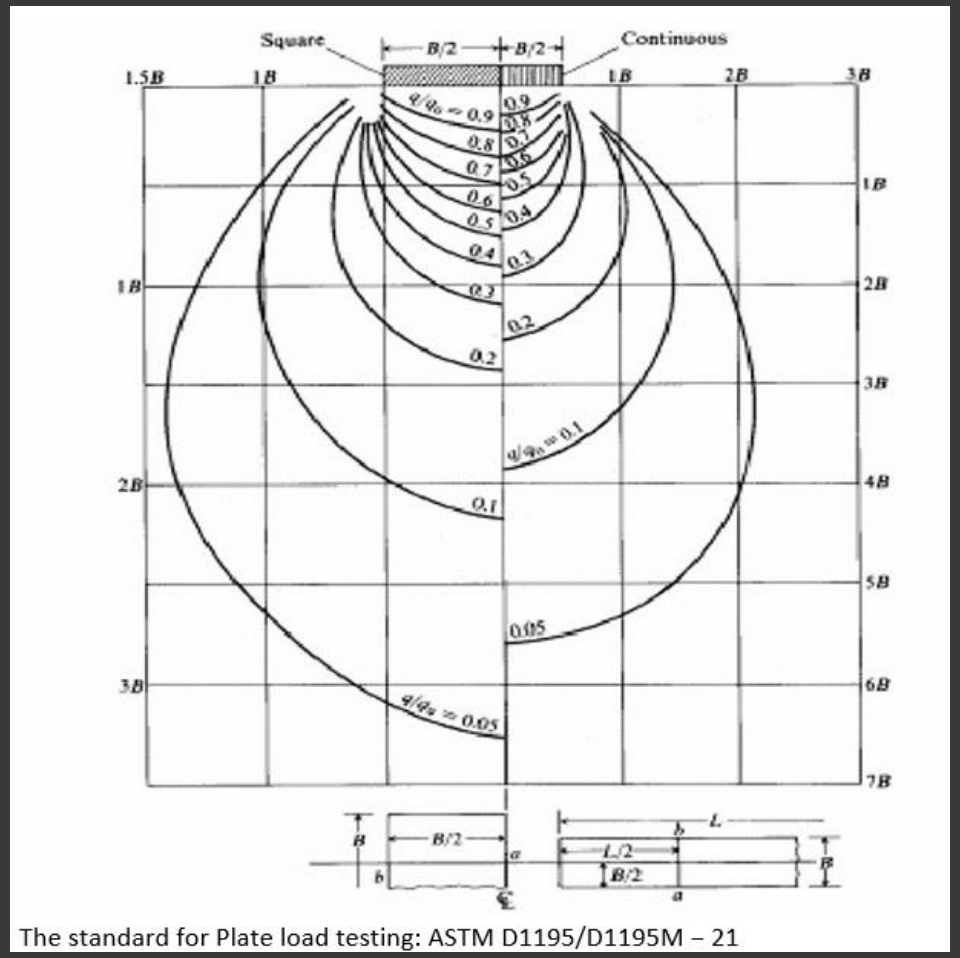
Upper part of the foot is made of honeycomb structure with a crushing strength of 20 pounds per square inch (138 kPa) . Lower part crushes at 10 psi (69 kPa)

https://www.lpi.usra.edu/resources/mapcatalog/Surveyor/press_releases/surveyor_I/

KSC Pressure Sinkage (P-S) Test Rig

Bins (x4): 30.5 cm x 30.5 cm x 35 cm tall
Plates Used: 5.08 cm x 5.08 cm (2” x 2”)
5.08 cm x 10.16 cm (2” x 4”)
Vacuum Levels: ~ 1x 10^{-3} Torr - 1x 10^{-5} Torr

KSC P-S Test Rig



The standard for Plate load testing: ASTM D1195/D1195M – 21

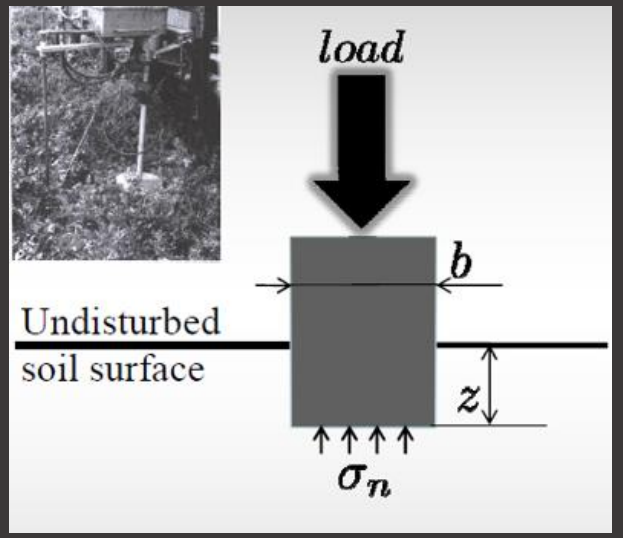
Bowles, J. (1988). Foundation Analysis and Design, McGraw-Hill, New York

The original Bernstein-Goriatchkin model is an empirical pressure-sinkage single-parameter equation:

- Pressure-sinkage relationship for geomaterials

$$\sigma = kz^n$$

  - σ is normal pressure
  - *k* is empirical constant
  - *z* is sinkage from free surface



P-S Test Matrix

Regolith Simulant	Bulk Density (g/cm^3)	Plate Size (mm x mm)	Ambient Pressure (101.3 kPa)	Vacuum ($1x\ 10^{-3}$ Torr)
LHS-1E	1.42	Plate 1: (50.8 x 50.8) Plate 2: (50.8 x 101.6)	4 tests	4 tests
	1.65	Plate 1: (50.8 x 50.8) Plate 2: (50.8 x 101.6)	4 tests	4 tests
	1.86	Plate 1: (50.8 x 50.8) Plate 2: (50.8 x 101.6)	4 tests	4 tests
BP-1	1.42	Plate 1: (50.8 x 50.8) Plate 2: (50.8 x 101.6)	4 tests	4 tests
	1.65	Plate 1: (50.8 x 50.8) Plate 2: (50.8 x 101.6)	4 tests	4 tests
	1.86	Plate 1: (50.8 x 50.8) Plate 2: (50.8 x 101.6)	4 tests	4 tests
LHT-1G	1.42	Plate 1: (50.8 x 50.8) Plate 2: (50.8 x 101.6)	4 tests	4 tests
	1.65	Plate 1: (50.8 x 50.8) Plate 2: (50.8 x 101.6)	4 tests	4 tests
	1.86	Plate 1: (50.8 x 50.8) Plate 2: (50.8 x 101.6)	4 tests	4 tests
MGS	1.42	Plate 1: (50.8 x 50.8) Plate 2: (50.8 x 101.6)	4 tests	4 tests
	1.65	Plate 1: (50.8 x 50.8) Plate 2: (50.8 x 101.6)	4 tests	4 tests
	1.86	Plate 1: (50.8 x 50.8) Plate 2: (50.8 x 101.6)	4 tests	4 tests

96 tests in this KSC regolith simulant testing Campaign

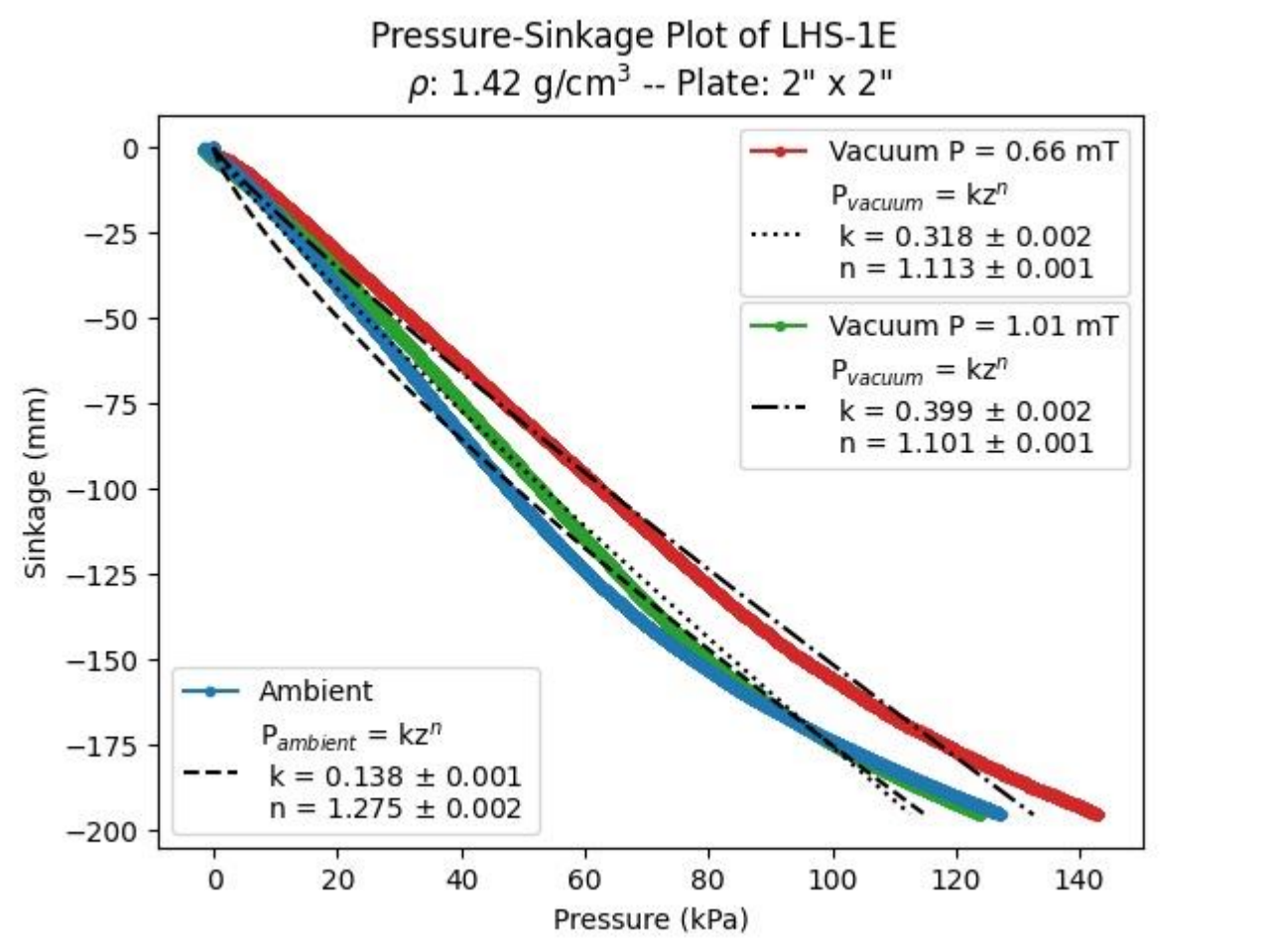
LHS-1E:
Lunar Highlands Simulant

BP-1:
Lunar Mare Black Point -1

LHT-1G:
Lunar Highlands Type

MGS:
Mars Global Simulant

P-S LHS Test Results

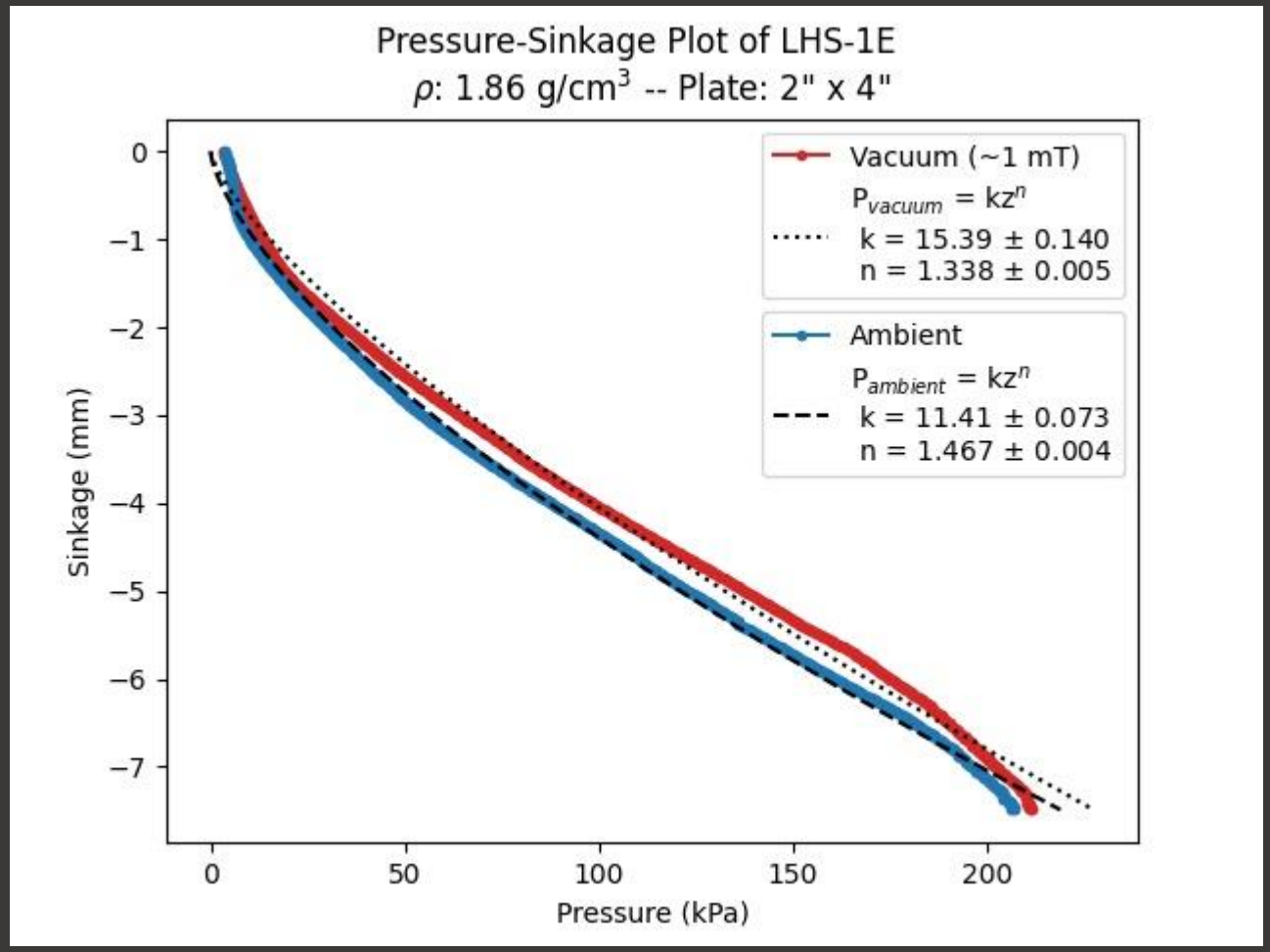


Selective preliminary test results only shown here

Observations:

- Deep Sinkage at low bulk densities
- Small plate (50.8 mm x 50.8 mm) Mimics one wheel contact patch on a small rover
- Higher vacuum levels show a trend of less sinkage for a given pressure vs an ambient baseline
- ***High lunar vacuum (1x 10^{-12} Torr) may have lower sinkage in actual lunar regolith on the Moon than in ambient terrestrial testing***

P-S LHS Test Results - KSC

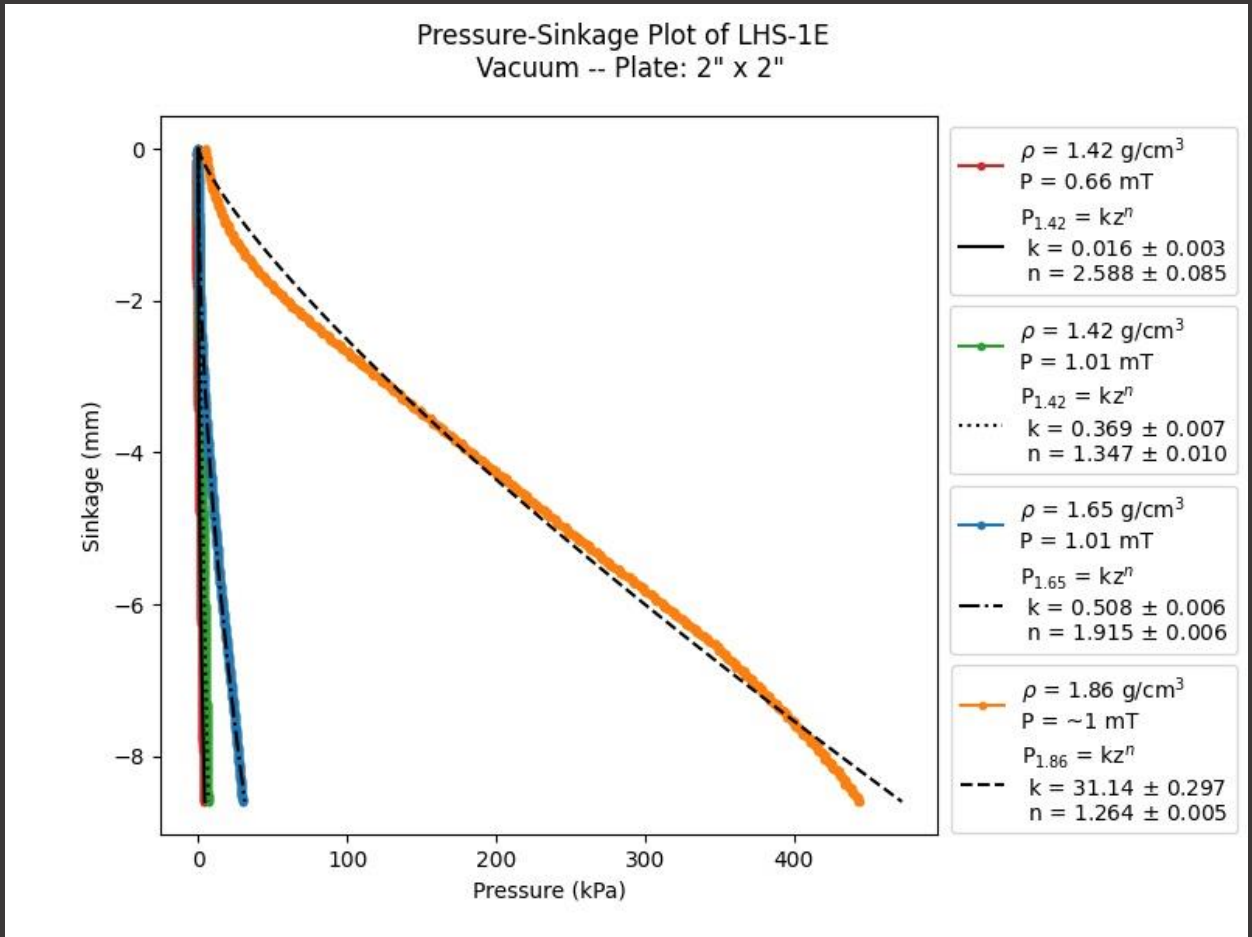


Selective preliminary test results only shown here

Observations:

- Very shallow sinkage at high bulk densities
- An order of magnitude less sinkage than at low relative density (mm's vs cm's)
- Small plate (50.8 mm x 101.6 mm) mimics one wheel contact patch on a small rover
- Higher vacuum levels show a trend of less sinkage for a given pressure vs an ambient baseline

P-S LHS Test Results - KSC



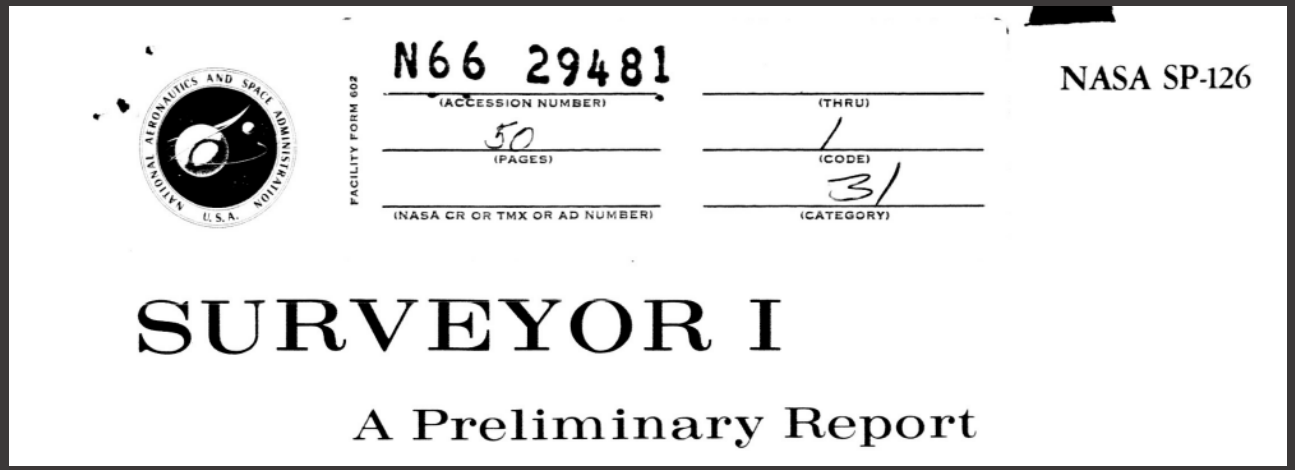
Selective preliminary test results only shown here

Observations:

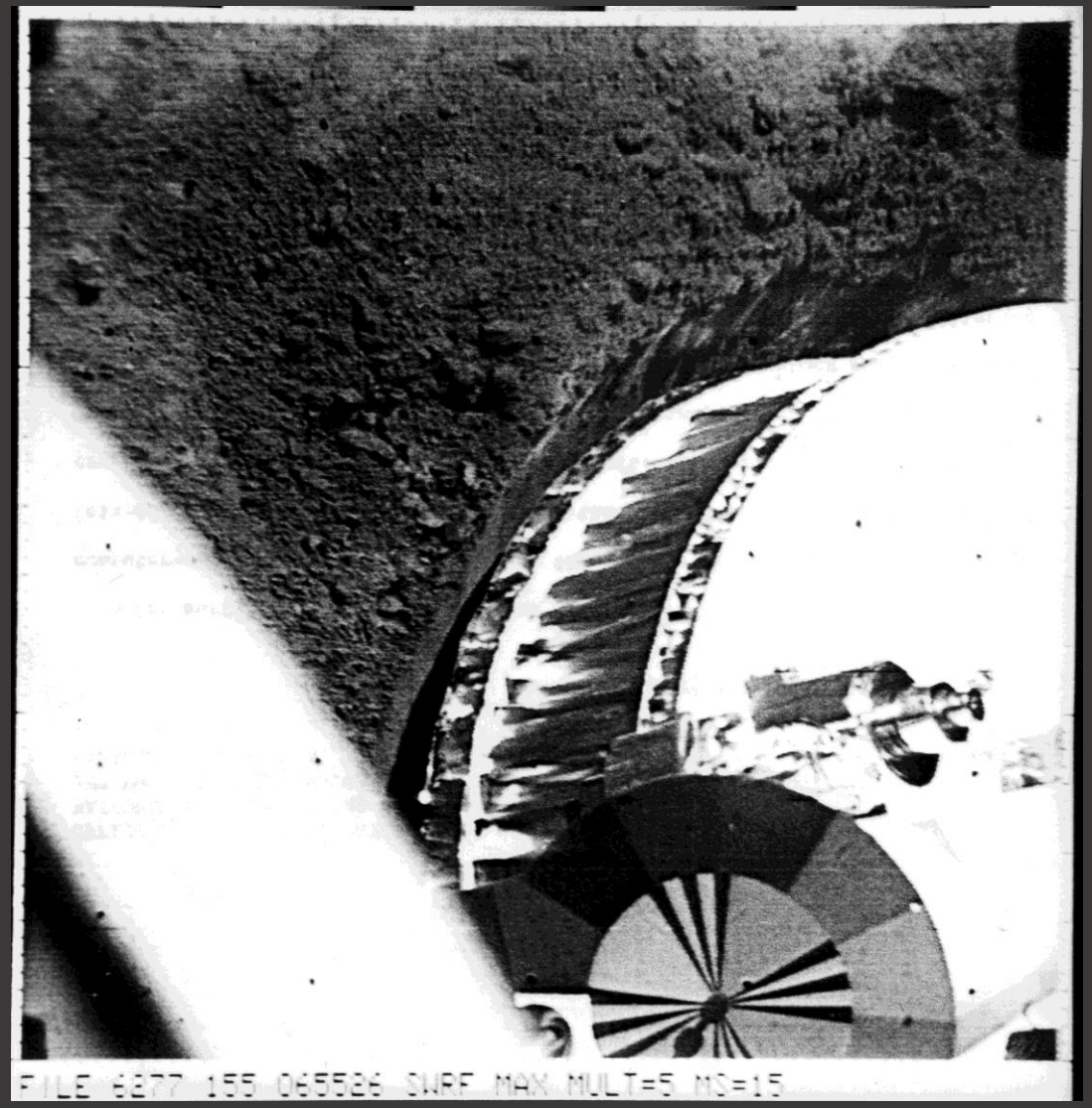
- For a given sinkage – much higher pressures are required at high bulk densities
- Two orders of magnitude higher pressure required for a given sinkage depth than at low relative density (mm's vs cm's)
- More data is required to establish a mathematical relationship
- More testing is ongoing at KSC and will gather the required data
- Higher vacuum < 10^{-5} Torr is desirable

Surveyor 1 Landing Foot

- The first images from Surveyor 1 showed its own landing foot.
- The landing foot pads of the pre-Apollo Surveyor spacecraft had a static bearing pressure of ~4.5 kPa (0.65 psi) each, assuming even loading.
- The observed landing sinkage was 20-40 mm and dynamic landing loads per leg were ~2,000 N or ~61.7 kPa (8.94 psi) indicating a medium–low relative density of regolith at the landing sites. Note that the 10 psi (69 kPa) strength honeycomb was not crushed.



https://www.lpi.usra.edu/resources/mapcatalog/Surveyor/press_releases/surveyor_I/



Lunar Surveyor footprint

Apollo Astronaut Footprint

- The pressure from an Apollo overboot print was 7 kPa*

* Apollo Soil Mechanics Experiment S-200

The observed sinkage on the Moon z= 4.3 mm to 8.8 mm

Swamp Works LHT prediction:

1.42 g/cm^3 1.01 mTorr
$P= 0.399z^{1.101}$ => $z= (P/0.399)^{1/1.101}$

z= 13.5 mm

1.65 g/cm^3 1.01 mTorr
$P= 0.508z^{1.915}$ => $z= (P/0.508)^{1/1.915}$

z= 3.9 mm

Swamp Works LHT prediction is approximately correct but needs higher vacuum levels and intermediate bulk density (~1.55 g/cm^3) for improved fidelity

Rover Wheel Sinkage

Apollo Lunar Rover Vehicle (LRV) with Crew
wheel pressure: 26 kPa

Apollo Reported Wheel Sinkage: 12.5 mm
Maximum: 50-70 mm

Swamp Works Prediction:
1.42 g/cm^3 1.01 mTorr
$P = 0.399z^{1.101}$ => $z = (P/0.399)^{1/1.101}$

<u>z= 44 mm (soft regolith)</u>

Astrobotic Cube rover
wheel pressure
(assuming 1”x 1” contact): 4.4 kPa

Swamp Works Prediction:
1.42 g/cm^3 1.01 mTorr
$P = 0.399z^{1.101}$ => $z = (P/0.399)^{1/1.101}$

<u>z= 9 mm (soft regolith)</u>

Costes, Nicholas C., John E. Farmer, and Edwin B. George. *Mobility performance of the lunar roving vehicle: terrestrial studies, apollo 15 results*. Vol. 401. NASA, 1972.

LHS PS Testing Conclusions

- Regolith Bulk Density has a significant effect on Pressure-Sinkage: ~ one order of magnitude (mm – cm) sinkage difference between 33% RD and 99% RD
- Soft regolith at 1.42 g/cm^3 (33 % Relative Density (RD)) shows considerable sinkage: ~150 mm at 100kPa in ~ 1x10^{-3} Torr vacuum
- Dense regolith at 1.86 g/cm^3 (99 % RD) shows very little sinkage: ~4 mm at 100 kPa in ~ 1x10^{-3} Torr vacuum
- Chamber pressure < 1x10^{-3} Torr showed a P-S trend of less regolith sinkage at higher vacuum levels
- All regolith simulant was dried and this showed a difference compared to undried regolith simulant ambient testing
- Future tests require a better vacuum: ~ 10^{-5} Torr is achievable at KSC Swamp Works