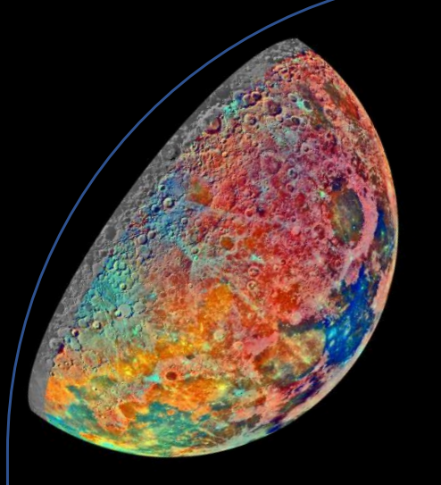
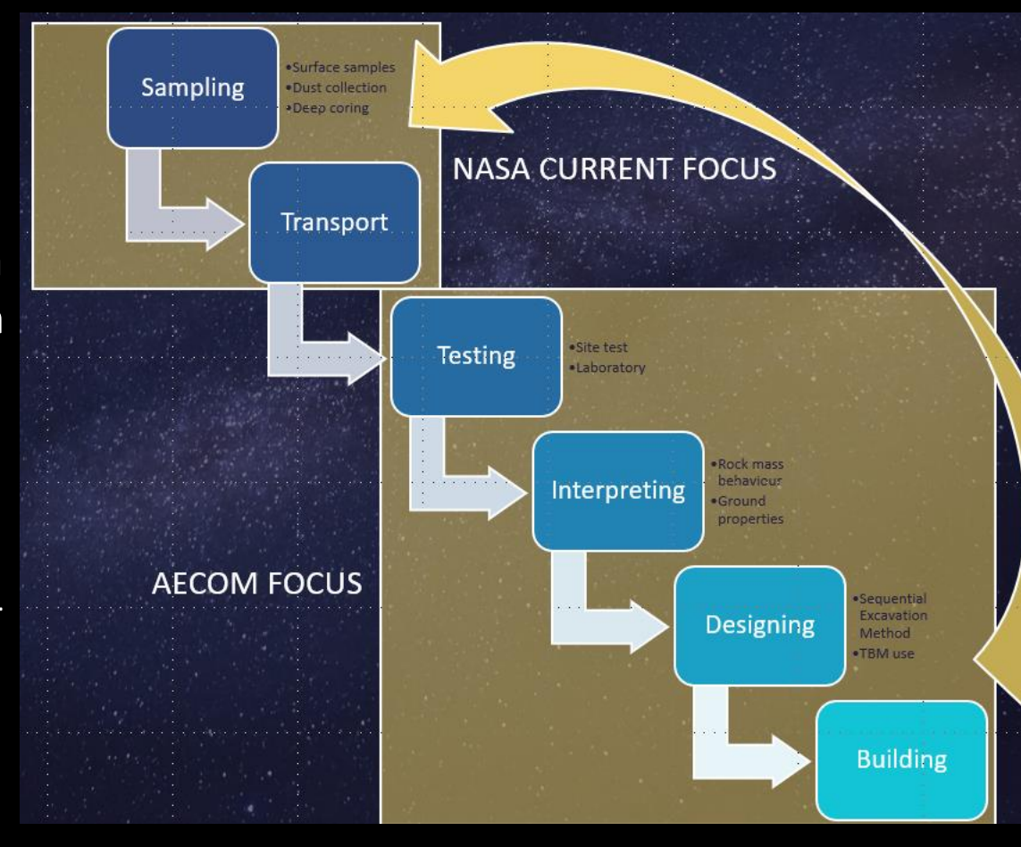
Reviewing of the Existing Knowledge on the Moon Rocks and Tunneling Solutions

Demoraes, R*. and Gaspari, G**
Director of Tunnels – AECOM Canada (roberto.demoraes@aecom.com)
***AVP Tunnel Practice Leader – AECOM Canada (giuseppe.gaspari@aecom.com)*



Motivation

We reviewed the data on the physical and mechanical properties of the lunar rocks such as basalt, anorthosite, and breccia acquired in the direct investigations on the lunar surface carried out in the human-crewed and robotic missions and in the laboratory examination of the lunar samples returned to the Earth. Therefore, due to the lack of a proper procedure for all necessary stages of Site Investigation (SI), we understand that the SI can be broadly integrated to the Moon exploration into the stages shown in the Figure on the right. There are gaps to be filled when you consider the current NASA approach and the four stages necessary to classify a site such as reconnaissance, data and map study, in-depth investigation and laboratory testing. This is the main motivation to propose a different and more reliable investigation program for the Moon exploration.

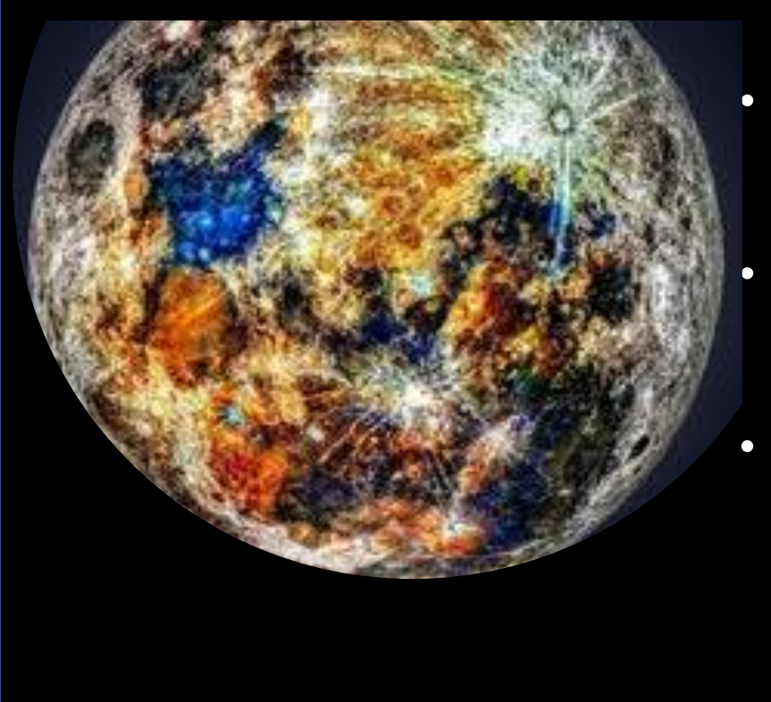


It is important to highlight that the main physical and mechanical properties of the lunar soil, such as the composition, density and porosity, cohesion and adhesion, angle of internal friction, shear strength of loose soil, deformation characteristics (the deformation modulus and Poisson ratio), compressibility, and the bearing capacity, are the main parameters to be considered for the design of underground facilities and excavations. This review brings a new view on the Moon rock's mechanical properties gaps, which are relevant to constructing effects on materials extraction, excavation, processing, and handling.

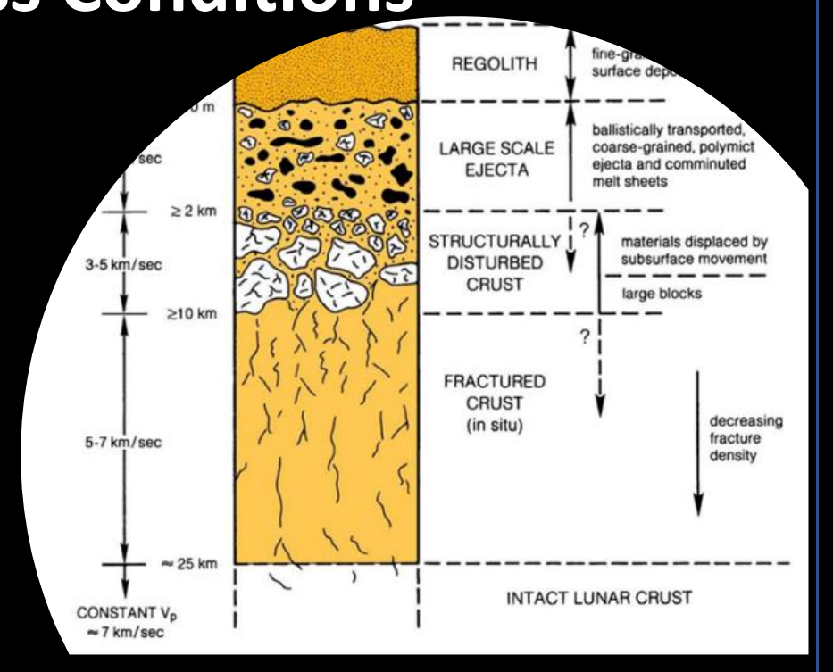
Objectives

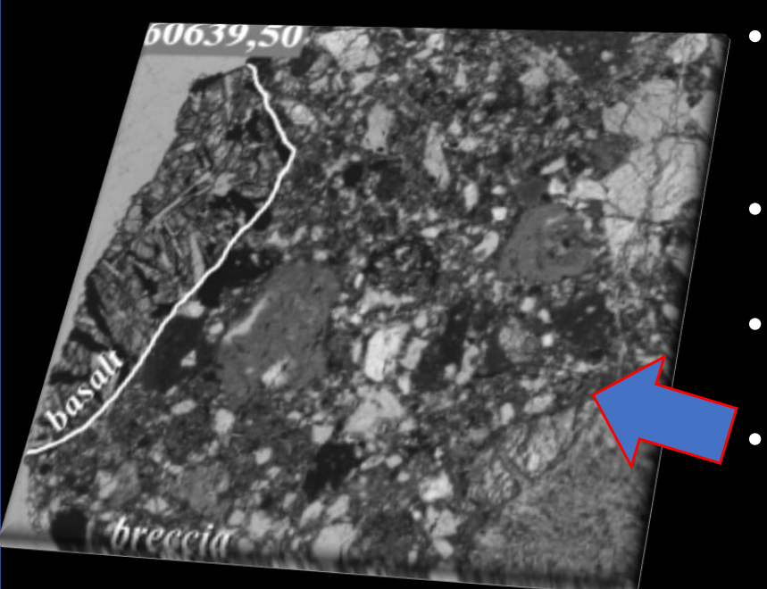
- ➢ Develop and propose method of site investigation tailored to extraterrestrial environments like the Moon that can play a role in constructing necessary infrastructure for underground and surface excavation of human habitats and facilities.
- ➢ Be adaptable to a variety of Moon's environmental conditions.
- ➢ Consider the use of the In—Situ Resources Utilization (ISRU).
- ➢ Adapt and redefine the existing design for geotechnical, structural and geological conditions such as the International Society for Rock Mechanics (ISRM), Eurocode 7, American Society of Civil Engineering (ASCE), AASHTO and others which are critical for define thew minimum design loads for buildings and other structures, review the design and construction codes of Frost-Protected shallow foundation (FPSF), seismicity codes, reviewing of existing specifications and guidelines.
- ➢ Review and adapt the Rock Mass Classifications such as the Rock Mass Rating (RMR), Q-system, Geological Strength Index (GSI) and others related to soil mechanics.

Uncertainties and Lack of Information to the Rock Mass Conditions



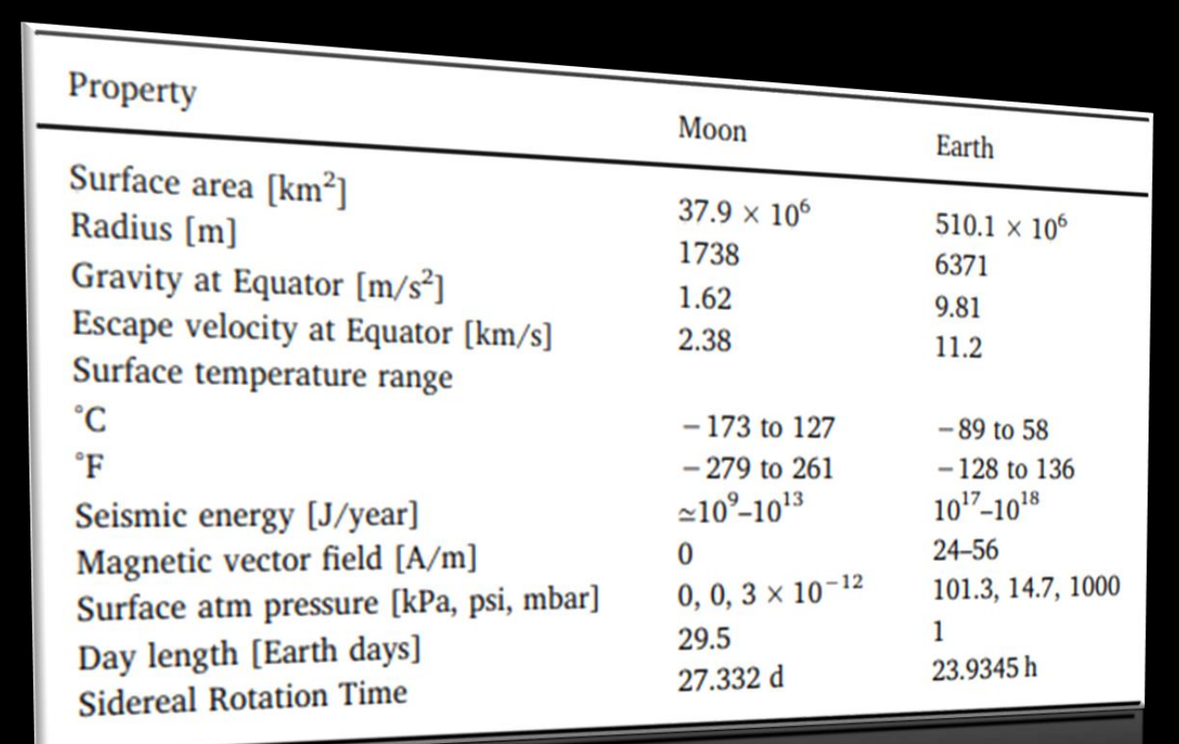
- All direct measurements of physical and chemical properties of lunar material have been made on the samples, both rocks and soils, collected from the regolith.
- Only the regolith layer has been conducted experiments by the astronauts on the Moon and by remotely monitored from the earth.
- Simulating lunar soil and rock is difficult and expensive because its formation mechanism and geotechnical behavior are comprehensively different from those of the terrestrial soil and rocks.





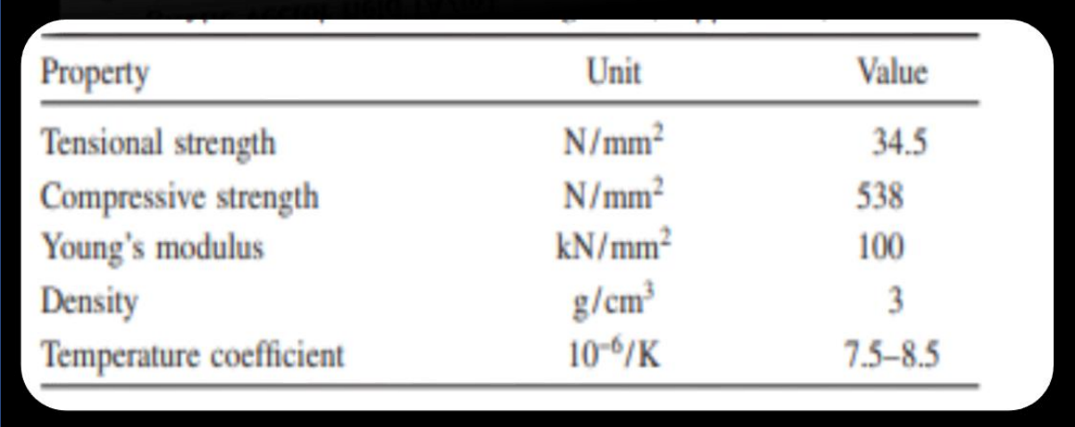
- Geotechnical characterization of lunar soils usually has been presented in terms of shear strength, shear modulus, density, and void ratio. However, no data set has been collected for the rocks and rock masses.
- Various lunar soils simulants have been developed for Earth based lunar soil studies, however, most were made from exotic materials using complex procedures.
- There are no validations for international standardized tests such as ASTM or ISRM rock testing suggestions.
- Most of the lab tests were performed in basalt fragments and basalt clasts from Apollo 16 breccia. No Geotechnical Parameters.

The Earth and Moon Properties



Property	Moon	Earth
Surface area [km^2]	37.9 × 10^6	510.1 × 10^6
Radius [m]	1738	6371
Gravity at Equator [m/s^2]	1.62	9.81
Escape velocity at Equator [km/s]	2.38	11.2
Surface temperature range		
°C	−173 to 127	−89 to 58
°F	−279 to 261	−128 to 136
Seismic energy [J/year]	$\simeq 10^9$–10^{13}	10^{17}–10^{18}
Magnetic vector field [A/m]	0	24–56
Surface atm pressure [kPa, psi, mbar]	0, 0, 3 × 10^{-12}	101.3, 14.7, 1000
Day length [Earth days]	29.5	1
Sidereal Rotation Time	27.332 d	23.9345 h

Cast Regolith (Cast Basalt) Known Parameters



Property	Unit	Value
Tensional strength	N/mm^2	34.5
Compressive strength	N/mm^2	538
Young's modulus	kN/mm^2	100
Density	g/cm^3	3
Temperature coefficient	10^{-6}/K	7.5–8.5

- **Cast basalt** has extremely high compressive and moderate tensile strength. It can easily be cast into structural elements for ready use in prefabricated construction. Feasible shapes include most of the basic structural elements, such as beams, columns, slabs, shells, arch segments, blocks, and cylinders (Table above).

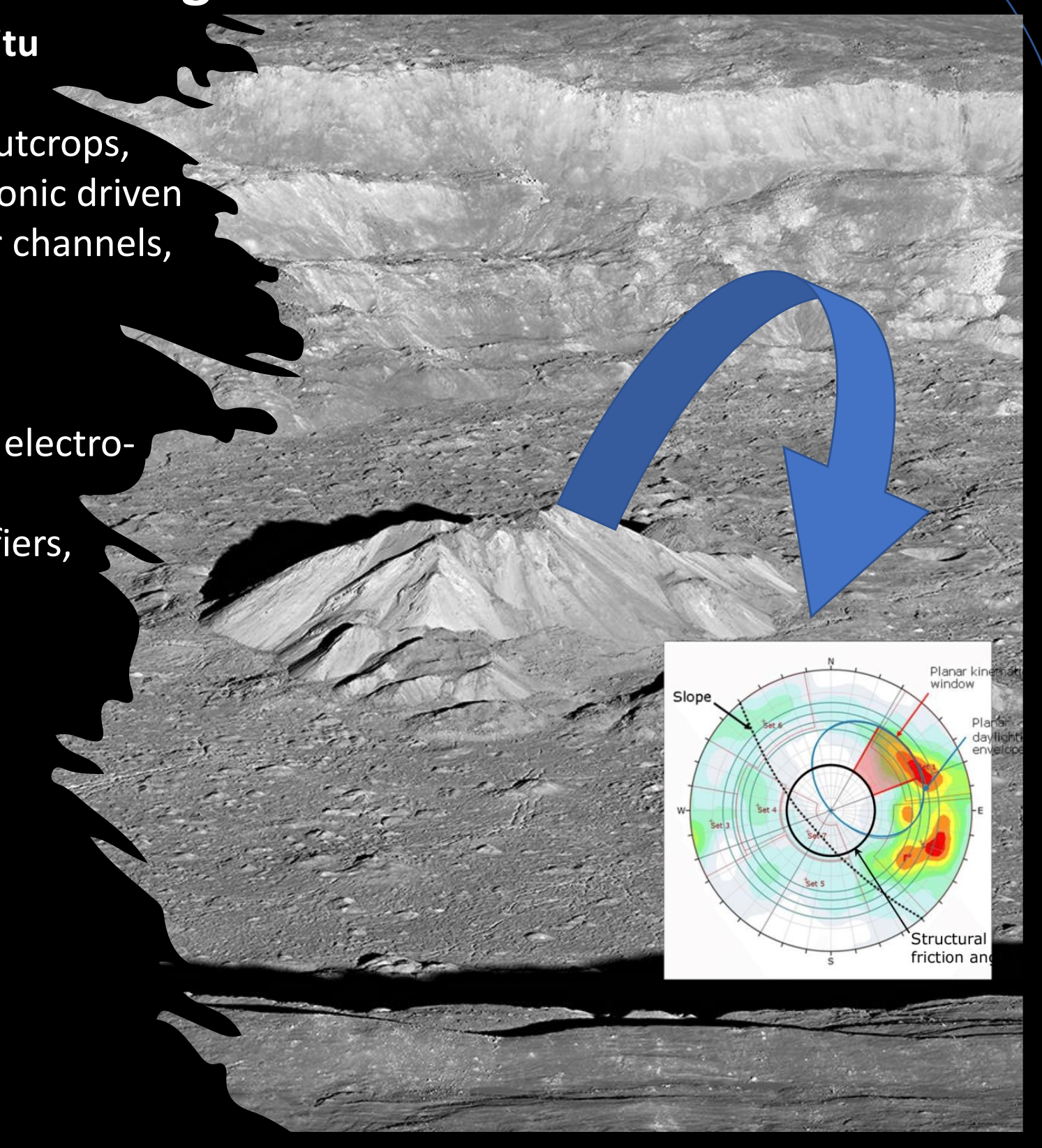
Lunar Environment: Better "Go Underground"

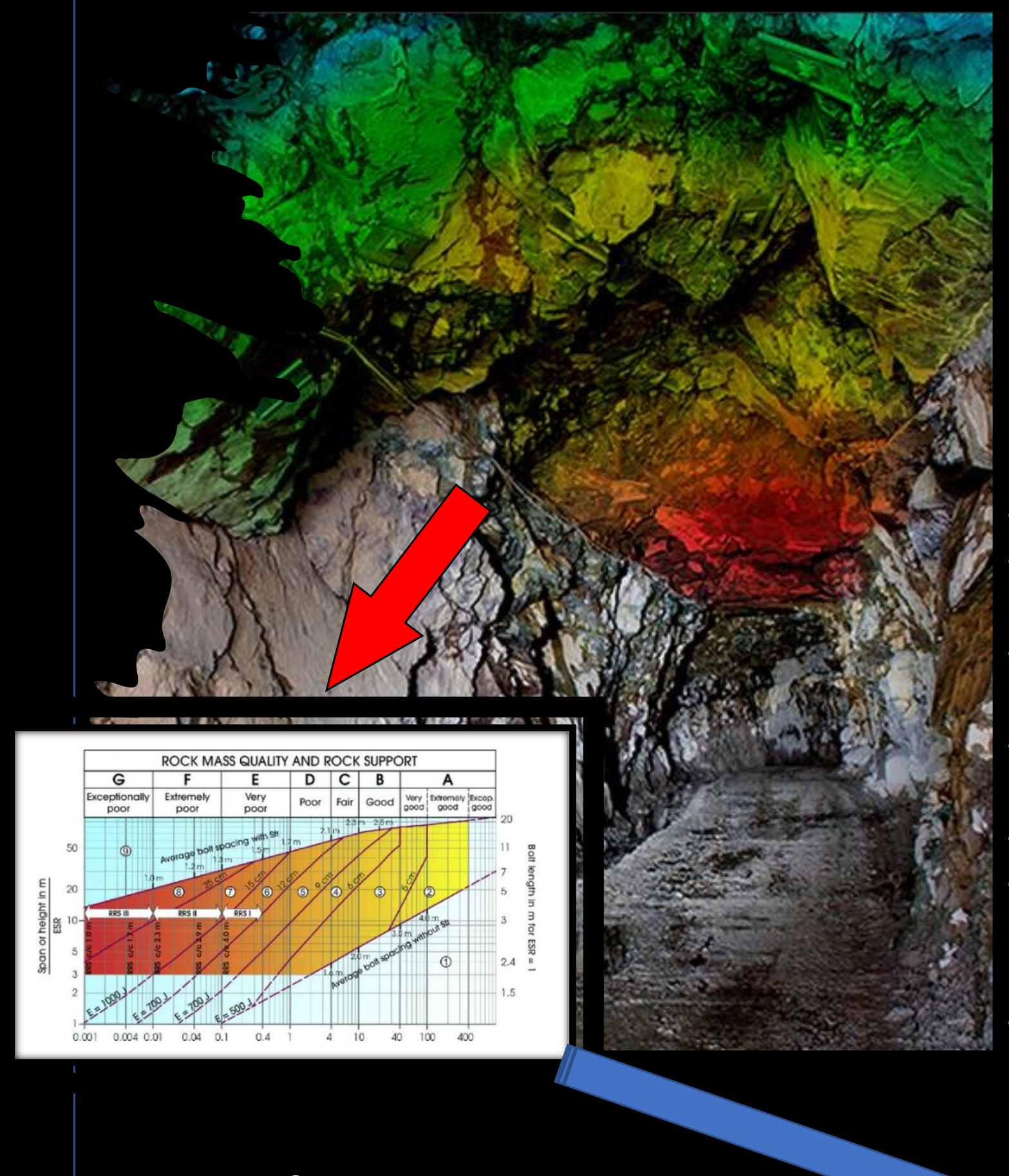
- ➢ **Establishing bases on the moon underground** seems to be a logical choice as they would protect future lunar inhabitants and equipment from the harsh environment at the surface, including the vacuum environment, impact by meteorites, radiation, extreme temperatures, storms, and other unknown conditions integral to long-term activities on the moon.
- ➢ **Developing riles** (ancient lava flows that formed into hollow structures as the outer layers of lava cooled), and lava tubes could create underground spaces to house bases the size of large cities with tunneled interconnections. Lava tubes could also provide skylights to the surface, with special filters to mimic the natural light on the earth.
- ➢ As well as the potential for developing riles and lava tubes, limited exploration has shown that **water ice, carbon dioxide, and several other volatiles** are present in and near the permanently shadowed craters of the lunar north and south poles. Tunneling presents expanded opportunities to access and extract these resources.
- ➢ **Providing atmosphere**: Given that lack of atmosphere means near absolute vacuum on the moon, pressurizing an underground space to 1 bar or 100 kpa pressure and maintaining the temperature and moisture content to near that of the earth could be achieved by using a natural impermeable membrane for maintaining the air pressure.
- ➢ **Thermal stability**: Surface temperature varies from about -190°C to +120°C between day and night at the lunar equator. It is ±3K at 30cm beneath the lunar surface and there is no day/night variation below 700mm. Permafrost may present challenges when excavating through lunar ice.
- ➢ **Radiation shielding**: Radiation from solar flares and galactic cosmic rays is a serious concern and regolith could provide radiation with densely packed regolith more than 4m+ deep at the crown to provide a safe living environment for long term use.
- ➢ **Micrometeorite protection**: The lunar surface is constantly bombarded with meteorites. Covering a lunar habitat with regolith would protect from micrometeorites, while a deeper underground space would protect from larger meteorite impacts.

Uncertainty and Lack of Information Concerning to the Rock Mass

How to characterize the surface and underground rock in-situ conditions?

- Via naturally available access points: surface exposures/outcrops, caves, Valley, tectonic driven exposures (faults/), nontectonic driven features (faults/fractures), lava tubes, underground water channels, craters (meteorite-induced features);
- Engineered: borehole, wells, adits/shaft/tunnels, surface excavation/digging
- Geophysical methods: thermal, seismic, electromagnetic, electro-resistivity, magnetometry
- Geochemical methods: mineralogy, processes, age-identifiers, composition
- Geo-mapping
- Rock Mass classification via RMR, Q-system, GSI
- Remote sensing, LiDAR, InSAR, GPR



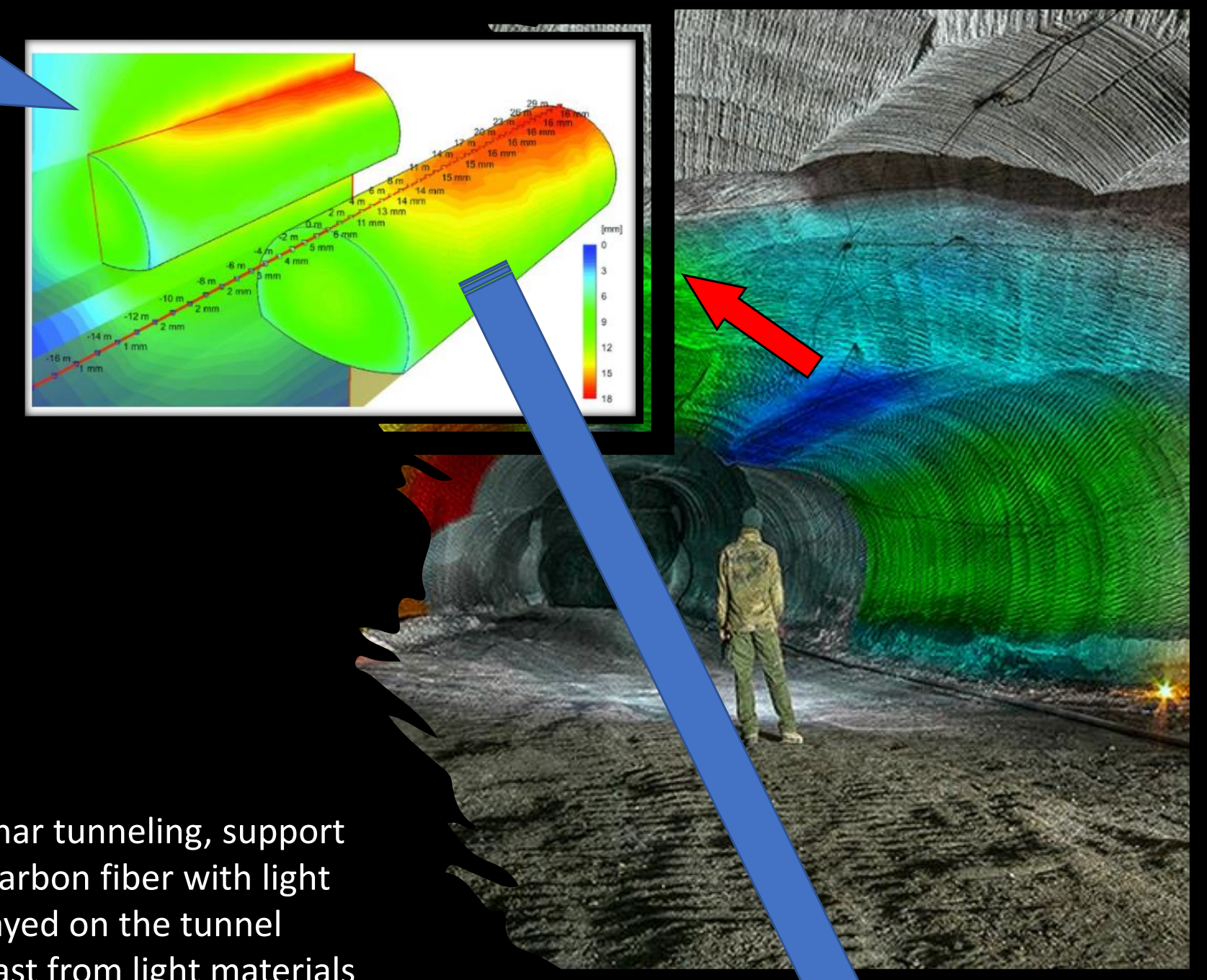


How to fill the gap on underground and surface investigations?

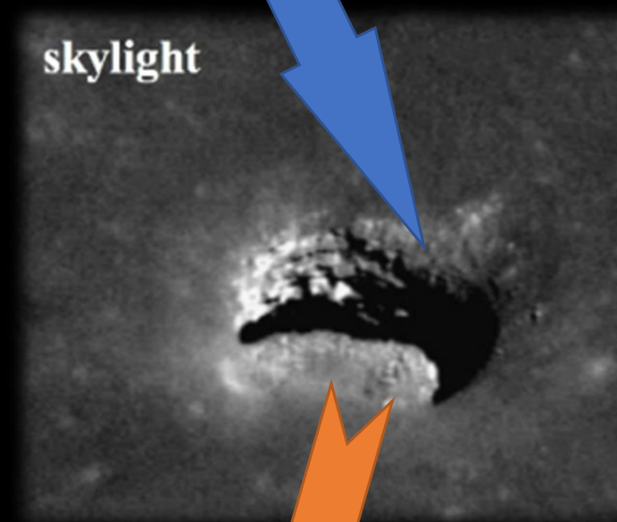
- To Characterize the rock conditions
- To characterize the potential for various failure mechanisms and behavior in its original state.
- Characterize the potential for various failure and behavior in response to engineering activities (matrix response).
- Matrix of interactions: intact rock, discontinuities, construction, stability analyses.
- Minimum knowledge with structural systems (lunar crater base).
- Underground construction. Cavern stability is unknown. No experience available for lunar conditions. Excavation/Tunneling is highly considered.
- Lava tubes: The structure is already there. Of course, no foundations are needed. However, some remediation of the cavern will be needed to provide a safe structure. Stability is not proven.

Lava Tubes

- Lava tubes can present different patterns: a) single tubes, sinuous or rectilinear, b) braided tubes, with bifurcations and conjunctions c) multilevel tubes with different levels connected by lava falls and shafts, d) a combination of braided tubes on different levels;
- This range of morphologic variability is due to different genetic processes controlled mainly by the effusion rate, the slope of the land surface on which the lava flows, the underlying paleo-topography, and the composition and related rheology of the lava;
- Lava tubes formed by shallow inflation are usually characterized by a superficial bulge (due to the inflation) along its development, and by an original horizontal elliptical cross section that can be entrenched by thermal erosion;



- **Ground Stability and Support**: for lunar tunneling, support tools could be made from Kevlar or carbon fiber with light polymer or resin-based cements sprayed on the tunnel surface. Special segments could be cast from light materials such as 3D printed rock powder to form air-tight rings in the same way soft-ground machines easily keep 7-8 bar of water pressure at bay.

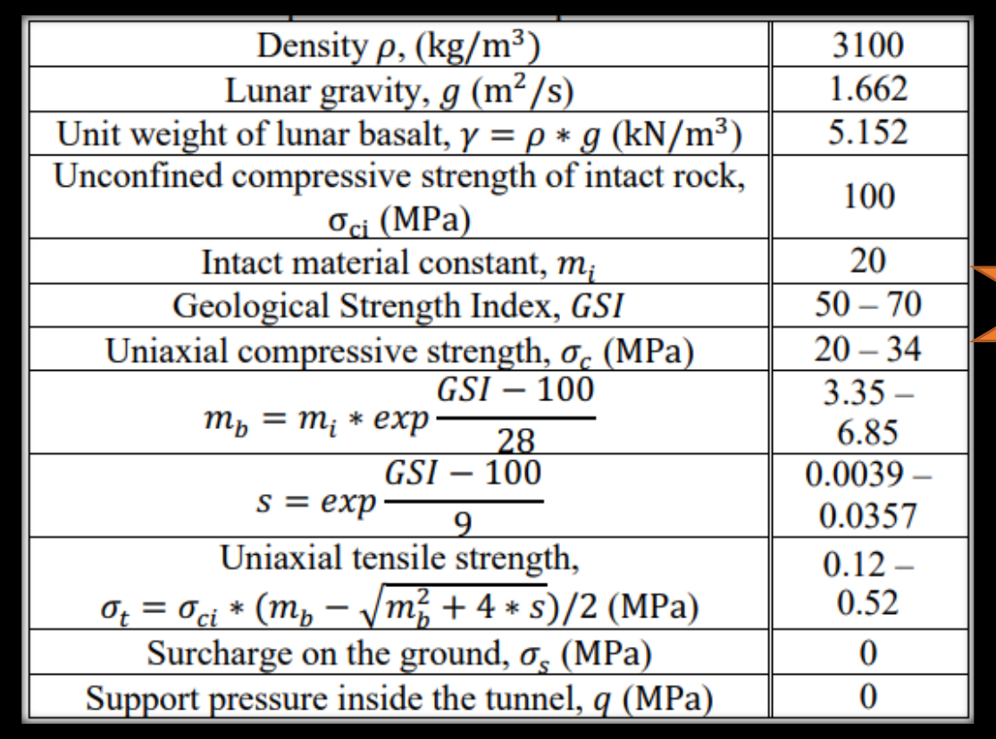


Structural Stability of Lava Tubes

- ➢ The design step of ground management for the lava tubes is associated with input geological and geotechnical data from site investigations, engineering geological mapping and results of laboratory/field tests. Design analysis of an underground excavation is carried out based on ground behavior, failure mechanisms and project conditions, and results in location and project orientation, excavation method, sequential excavation, extraction rate, and selecting ground support systems.

Analysis of a Moon Lava Tube via Limit Equilibrium Method Parameters

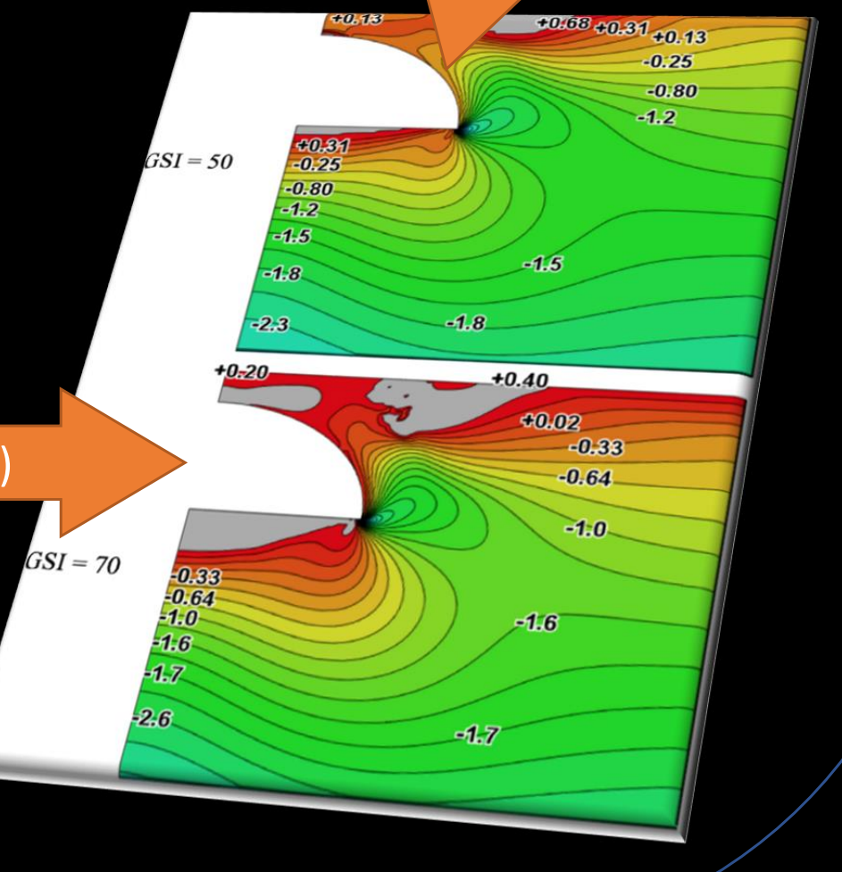
(Purdue University)



Density ρ, (kg/m^3)	3100
Lunar gravity, g (m^2/s)	1.662
Unit weight of lunar basalt, $\gamma = \rho * g$ (kN/m^3)	5.152
Unconfined compressive strength of intact rock, σ_{ci} (MPa)	100
Intact material constant, m_i	20
Geological Strength Index, GSI	50 – 70
Uniaxial compressive strength, σ_c (MPa)	20 – 34
$m_b = m_i * exp\frac{GSI-100}{28}$	3.35 – 6.85
$s = exp\frac{GSI-100}{9}$	0.0039 – 0.0357
Uniaxial tensile strength, $\sigma_t = \sigma_{ci} * (m_b - \sqrt{m_b^2 + 4 * s})/2$ (MPa)	0.12 – 0.52
Surcharge on the ground, σ_s (MPa)	0
Support pressure inside the tunnel, q (MPa)	0

A FEM modelling for a 1000m lava tube with a roof thickness of 100m. Assuming GSI 50 and 70

Principal stresses(MPa)



Underground and Surface Excavations Conditions

Any lunar structure will be designed for and built with the following prime considerations:

- **1/6 g gravity**: In order to maximize the utility of concepts developed for lunar structural design, mass rather than weight-based criteria should be the approach of lunar structural engineers. All of NASA's calculations have been done in "kg-force" rather than newtons. Calculations are always without the gravity component; use kilogram feet per square centimeter as pressure, for example.
- **Foundation design**: In the area of foundation design, most classical analytical approaches are based on the limit-state condition, in which the design is based on the limit of loading on a wall or footing at the point when a total collapse occurs—that is, the plastic limit.
- **Blasting in Vacuum Conditions**: Blasting in a vacuum is another interesting problem to consider. When the explosive in a blast hole is fired, it is transformed into a gas, the pressure of which may sometimes exceed 100,000 terrestrial atmospheres. How this would affect the area around the blast on the Moon and the impact of ejecta resulting from the blast is difficult to predict.
- **Infrastructure:** The grain size distribution of a common regolith, as well as its high density below the top layers, is hardly found in the terrestrial environment. This creates unique problems for excavating, trenching, backfilling, and compacting the soil. These operations, however, are needed to create building foundations; roadbeds; launch pads; buried utilities power, communication!; shelters and covers; open-pit mining; and underground storage facilities.

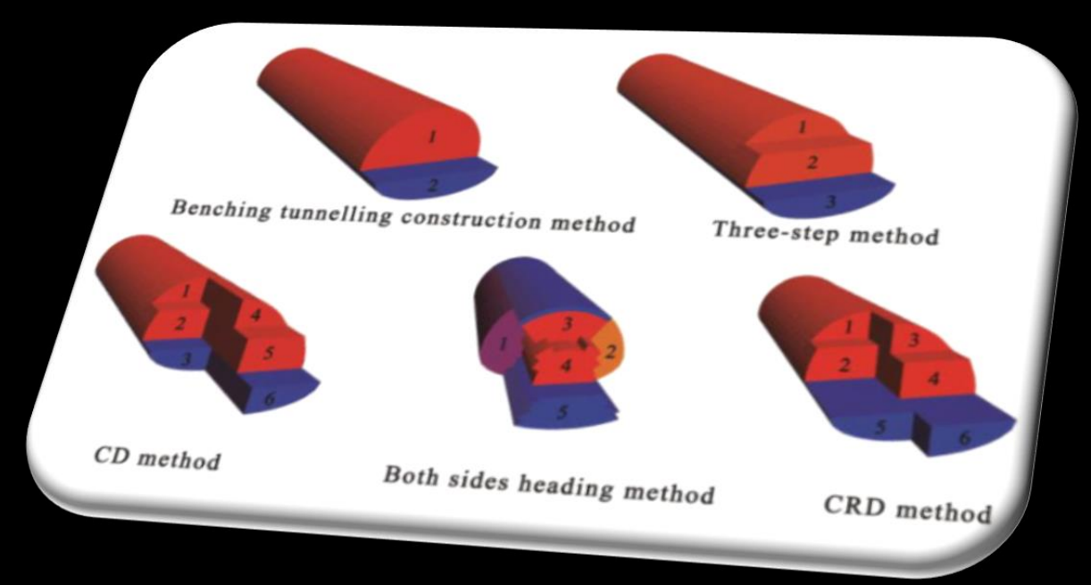
Potential Mining or Tunneling Techniques

Mined tunnel construction, including the use of a TBM, SEM, and other mining techniques, allows for tunnel excavation to occur below the surface without substantially disrupting the surface above. There are three potential excavation methods that could be applied as follows:

- ➢ Mined tunnel construction with a Tunnel Boring Machine (TBM);
- ➢ Mined tunnel construction using Sequential Excavation Method (SEM);
- ➢ Excavation using cut-and-cover construction.

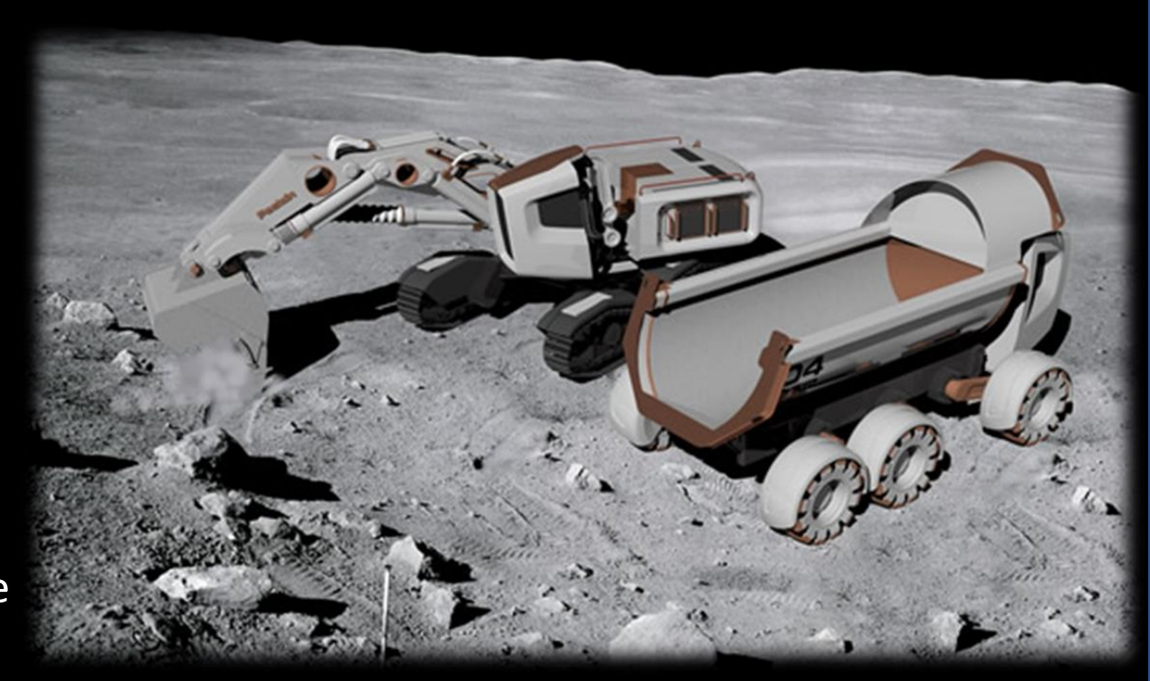
Which Tunneling Technique Would be Suitable for the Moon Environment?

SEM: For shorter tunnel sections (generally less than 2 km), tunnels with variable geometry, and tunnels in mixed ground conditions, SEM provides more cost-effective, flexible, and safe tunneling without the long and costly mobilization process associated with TBM tunneling. In addition, compared to the Cut & Cover construction method, it minimizes the impact on the environment by avoiding surface disruption.



Today, SEM works in any ground with minimal overburden and is therefore well suited for tunnelling in the Moon environments. Because of its flexibility and highly reliable construction schedule, SEM has become widely accepted by clients and contractors alike. However, the excavation method should rely on the process from the ground investigation to the final definition of the ground support system. It can be summarized in three suggested models:

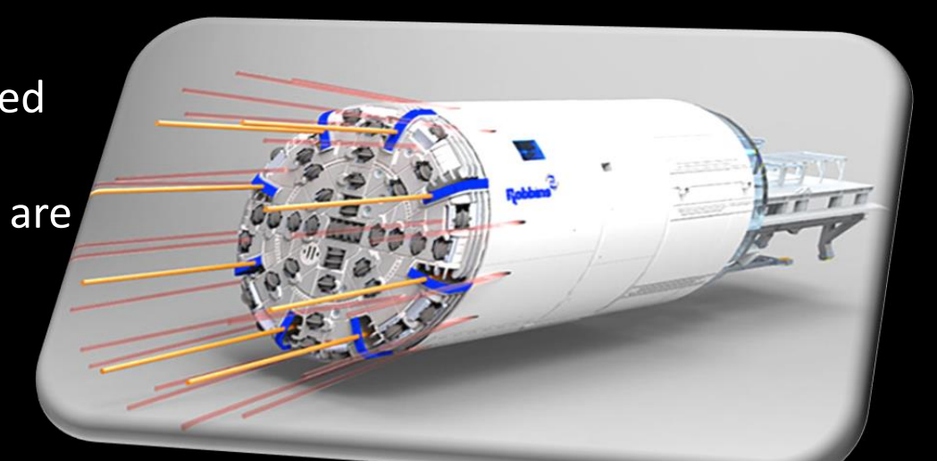
- ➢ Geological Model
- ➢ Geotechnical Model
- ➢ Tunnel Support Model (based on Q-system and RMR)



This concept 55-ton autonomous excavator and dump truck can work together, and they are suitable for moon mining activities.

TBM: There are numerous challenges and limitations associated to the use of Lunar TBMs, which makes this choice inviable. Major constraints:

- ➢ Weight: a typical TBM with back-up system weights a few hundred tons (which is a problem for payloads limits)
- ➢ Power: a typical TBM uses several hundreds kW electrical (Limited available power on the Moon, perhaps in 50-100 kW range)
- ➢ Wear and Abrasivity of the Material: Volcanic rocks and regolith are known to be very abrasive
- ➢ Vacuum, Fluids and Thermal
- ➢ Geological conditions and ground stability



Conclusions

- Considering the need to excavate underground space to establish manned bases on the moon, TBMs seem to be the less promising excavation method. TBMs have a good track record of activities on the earth, are the easiest systems to automate and operate remotely, and are capable of offering high performance. However, it requires a very specific tools for operating such equipment in the lunar environment. Therefore, a combination with SEM and Cut & Cover methods are more appropriated.
- Locating a lunar lava tube may well be one of the first stages of setting up a lunar base site. Lava tubes can provide the most expedient and economical way of starting an indigenous lunar architecture.
- Understanding the geotechnical engineering of the Moon rocks and the stability to the Lava tubes is critical for the development of the moon habitats.
- The use of numerical analyses, geotechnical parameters to assess the structural stability of the lunar lava tubes can help us to understand the behavior of the relationship between roof thicknesses and material strength and how it affects the stability of the lava tubes itself.
- Codes and Standards should be reviewed and adapted for the Moon conditions.
- Mix tunneling techniques can be adapted and used for shallow and deep excavations. The design should be based on the current Earth practice but considering cost-effective solutions due to the major constraints imposed by the Lunar environment.

Authors References

1. **McKay, Mary Fae, David S. McKay, and Michael B. Duke, 1992, Space resources. Volume 4: Social Concerns**
2. **Blair, D M., Chappaz, L, Sood, R, Milbury, C, Bobet, A, Melosh, H. J., Howell, K. C., and Freed, A. M., 2017, "The structural stability of lunar lava tubes." Icarus 282, 47-55.**

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