DOI: https://doi.org/10.68732/5d824487fa0a77c5

ISBN: 978-9989-2053-6-1

Planetary Rock Mechanics and Future Prospects

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Abstract

There is recently an increasing interest to explore the ways to find out the characteristics of other planets and possibility of exploiting their mineral resources. Images from Mars particularly show the striking similarities between rocks on Earth and those of Mars. One can easily notice layered rock masses, jointing, weathering effects and some slope stability issues such as plane and wedge sliding, block and flexural toppling type failures.

The dynamics issues in Mars, Moon and Venus and other planetary objects remain to be the similar to those on Earth. Although mankind has no direct access to Mars yet, the exploration rovers, Mars Reconnaissance Orbiter and InSight Lander provided very valuable data so that some dynamics issues should be recognized.

Low gravity planetary bodies such as comets and asteroids have been great interest to mankind since early times. Attempts to bring materials from several asteroids were recently successful and they may provide important information on the characteristics and how to mine the asteroids. Furthermore, some familiar phenomena of slope failures, sinkholes, debris flow and boulder toppling under low gravitational environment are observed at these low gravity bodies.

This keynote lecture covers thoughts of the author on the aspects of planetary rock mechanics and rock engineering deducted from the images sent to the earth from Mars, Moon and Venus by exploration rovers and from comets and asteroids from spacecrafts. Particularly the images from Mars are spectacular to imagine and infer many aspects planetary rock mechanics and resemblances of rocks and their weathering, discontinuity formations, slope stability problems and natural caves lead to mankind contemplate possible mechanics and material behavior of rocks and their related scientific and engineering aspects.

Keywords

Planetary mechanics, Exploitation, Rock slopes, Sinkholes, Quakes.

1 Introduction

USA and Russia (formerlyUnion of Soviet Socialist Republic (USSR)) initiated space programs and sent several spacecrafts to Moon, Venus and Mars and some of them landed on Moon, Venus and Mars to find out the characteristics of other planets and possibility of exploiting their mineral resources. Some of most impressive images from the Apollo Program of NASA were the man from Earth

standing next to lunar rock mass and a geologist from Earth is hitting lunar rock by a geologist hammer. USA and Russia (former Union of Soviet Socialist Republic (USSR)) initiated space programs and sent several spacecrafts to Moon, Venus and Mars and some of them landed on Moon, Venus and Mars to find out the characteristics of other planets and possibility of exploiting their mineral resources. Some of most impressive images from the Apollo Program of NASA were the man from Earth standing next to lunar rock mass and a geologist from Earth is hitting lunar rock by a geologist hammer. The images from recent Mars exploration rovers such as Opportunity, Spirit, Curiosity and Perseverance (NASA 2019b, 2022) showed striking similarities between rocks on Earth and those of Mars. One can easily notice layered rock masses, jointing, weathering effects and some toppling type rock slope stability problems as well as sinkholes (skylights) related to the collapse of underground openings.

Mankind has been exploring space objects since very old times. For example, Sumerians, who established a great civilization in the Mesopotamia during a period between 4000 to 2000 BC, laid out the foundations of the modern astronomy. Indian, Chinese, Persian, Arabian and Turkish astronomers fundamentally are similar to those of Sumers. Figure 1 shows the symbols of universe according to Sumerians and Oz Tamga (symbol) of proto-Turks on basaltic rock surface at Saymalıtaş (Kyrgyzstan) (e.g., E. Herzfeld, 1930; Cığ, 2020; Somuncoğlu, 2010, 2011).



(a) Sumerian bowl symbolizing universe (4000BC)

(b) Oz Tamga (Symbol) (Saymalıtaş, older than 5000 BC, likely to be 10000 BC).

Fig. 1 Some artifacts symbolizing universe from Sumers and proto-Turks.

The author felt the necessity to teach about the Planetary Rock Mechanics during his Rock Mechanics Classes at Tokai University since 2010 and the University of the Ryukyus since 2014. Since then, the author has been actively doing research in the topic and published many articles about Mechanics and Engineering of rocks of planetary bodies together with emphasis on those from Earth as a planetary body and discussed the future directions of studies and implications.

In this article, some thoughts of the author on the aspects of planetary rock mechanics and rock engineering deducted from the images sent to the earth from Mars, Moon, Mercury and Venus by exploration rovers and from comets and asteroids from spacecrafts are described. Particularly the images from Mars and Moon are spectacular to contemplate and infer many aspects planetary rock mechanics and resemblances of rocks and their weathering, discontinuity formations, slope stability problems and natural caves lead to mankind contemplate possible mechanics and material behaviour of rocks and their related scientific and engineering aspects.

2 Solar System and Terrestrial Planetary Bodies

As well-known, the solar system consists of eight planets, namely, Mercury, Venus, Earth, Mars, Saturn, Jupiter, Uranus, Neptune. On the basis of computations, the existence of a planet between Mars and Jupiter was estimated. However, at the estimated location, an asteroid belt exists. This asteroid belt might have corresponded to the missing planet. Initially, Pluto was found in 1930 and it was considered to be the 9th planet until 2006. On the basis of definition of planets of our solar system, it was not assumed to be the 9th planet any more. The density of planets differs as a function of distance from the Sun and it decreases as the distance increases. Terrestrial planets such as Mercury, Venus, Earth and Mars (Figure 2) are considered to be quite similar to each other in many

aspects while they are different from each other in terms of size and geology. Mercury and Venus have no natural satellites while the Earth has Moon as a natural satellite. Mars has two natural satellites called as Deimos and Phobos.

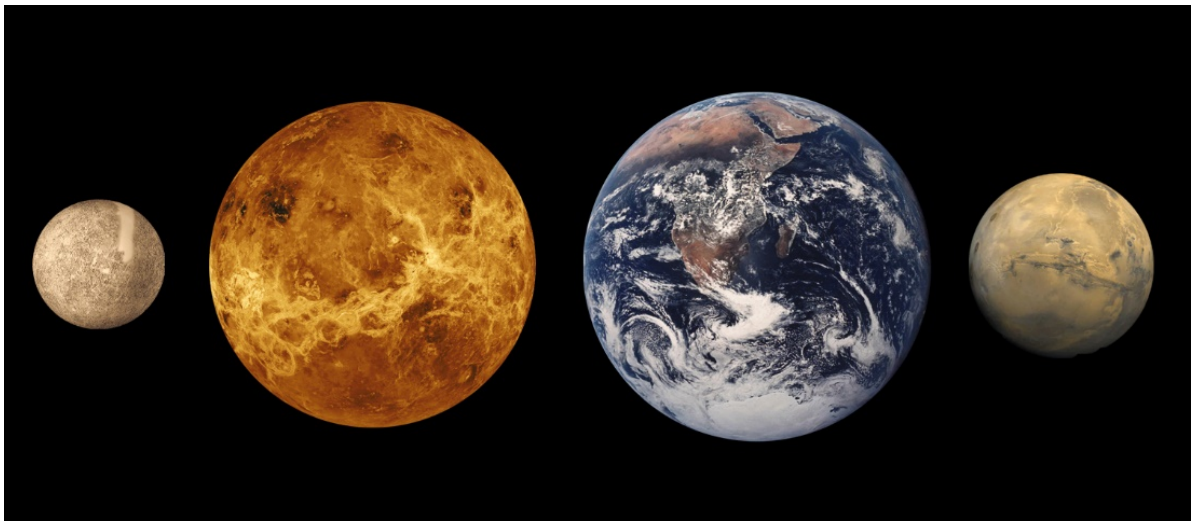


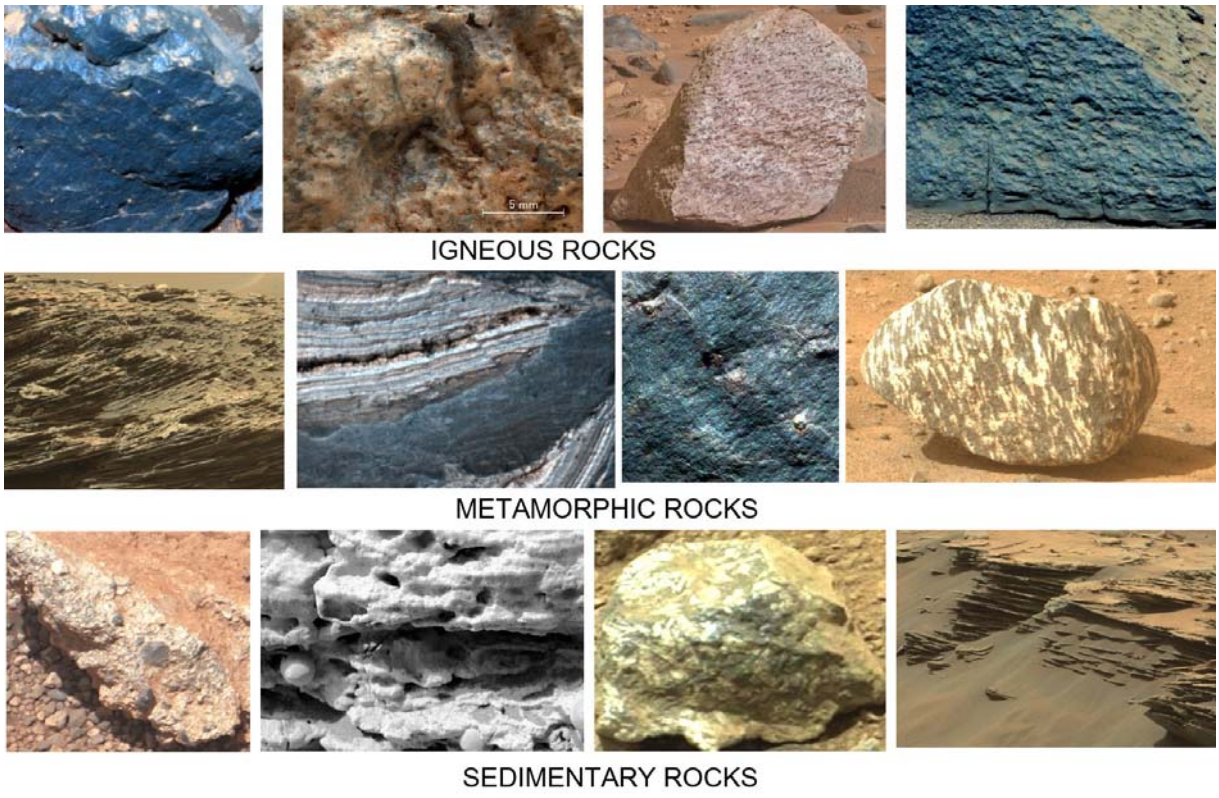
Fig. 2 Planetary bodies: Mercury, Venus, Earth and Mars (from NASA).

3 Rocks, Discontinuities and Weathering of Planetary Bodies

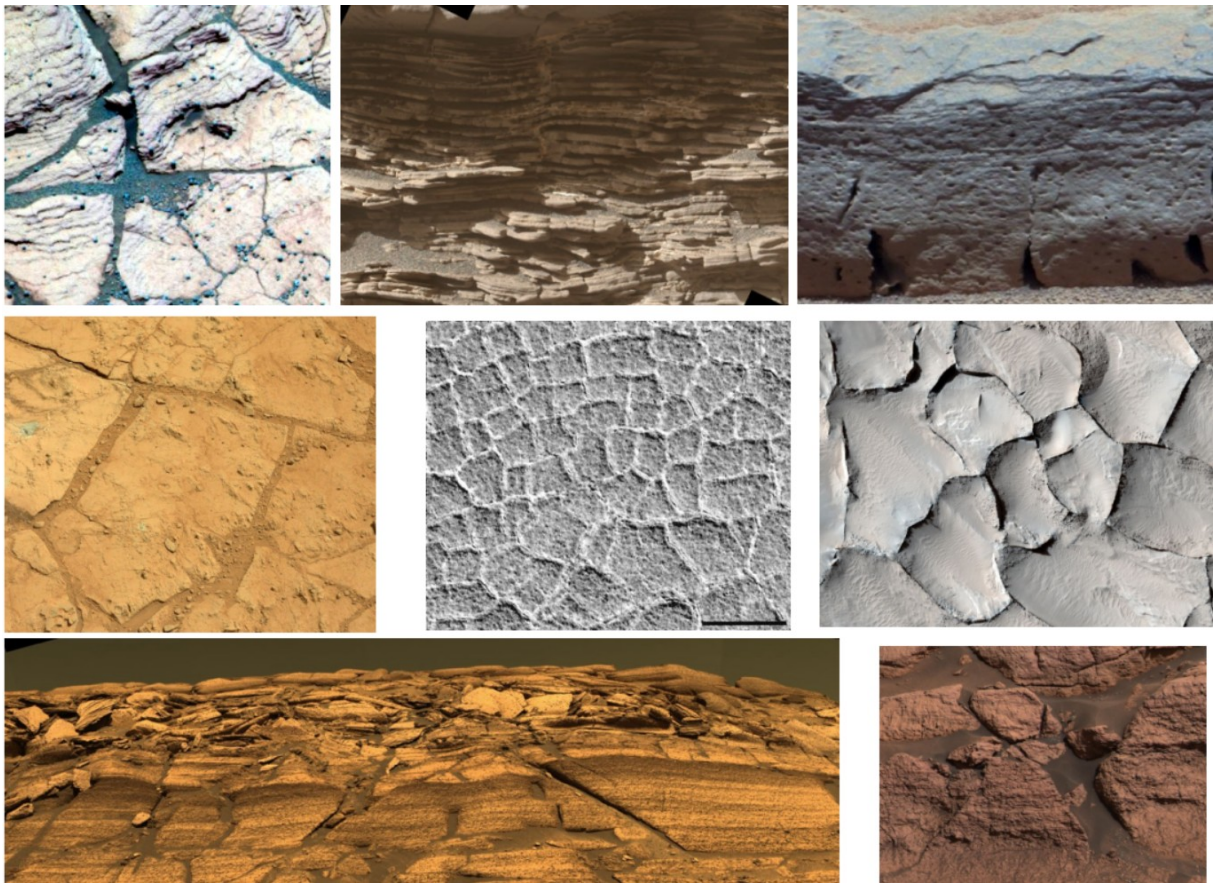
The information on the rocks of other planetary bodies besides those of the Earth are available from meteorites fallen on Earth, explorations using the unmanned and manned explorers on Moon, Mars and Venus as well as optical and electro-magnetic exploration rovers. In addition, some, unmanned space probes sent to several asteroids provided additional information on their constituting substances. It is very likely that the rocks of planetary bodies would be quite close to those of Earth. For examples, the classification of rocks is igneous, metamorphic and sedimentary on the bases of the images, drilling, cores and their chemical analyses performed on various sites on Mars as well as on Moon. Although it still needs some clarifications whether rocks seen in Earth fully exist on Mars. However, the sedimentary rocks (such as conglomerate, sandstone, siltstone, mudstone, sulphate deposits), metamorphic rocks such as phyllite, shale and serpentine and extrusive rocks (basalt, andesite-like (silicate bearing basalt), breccia) of Mars clearly similar to those of Earth (Figure 3a,b).

Flow planes, bedding planes and schistosity planes, which are intrinsic to each rock class, are distinctly observed. In addition, some discordant sedimentation of sandstone layers was also distinctly observed. There are various causes for the formation of discontinuities in rocks. The causes can be grouped into a) tension discontinuities due to cooling, drying, freezing, bending, flexural slip, uplifting, faulting, and stress relaxation associated with erosion or retreating glacier, b) Shear discontinuities due to folding, and faulting, c) Discontinuities due to intrinsic properties of rocks (sedimentation, metamorphism, magma flow). Without any exception, discontinuities in rocks/rock masses of Mars are fundamentally similar to those observed in Earth as seen in Figure 4.

The surface morphology and filling situations rock discontinuities are quite similar to those seen in Earth. Although the striation of shear discontinuities could not be confirmed from the images taken by the Mars Exploration Rovers, they should be quite similar to those observed on Earth. The chemical analyses of the filling material so far showed that they are generally consisted of calcium sulphate (anhydrite) or calcium carbonate (calcite). Sometimes they included boron minerals, which are probably associated with dissolved substances when the planet was wet environment in the past.



(a)



(b)

Fig. 3 Views of (a) of rocks, (b) discontinuities observed in Mars (images from NASA).

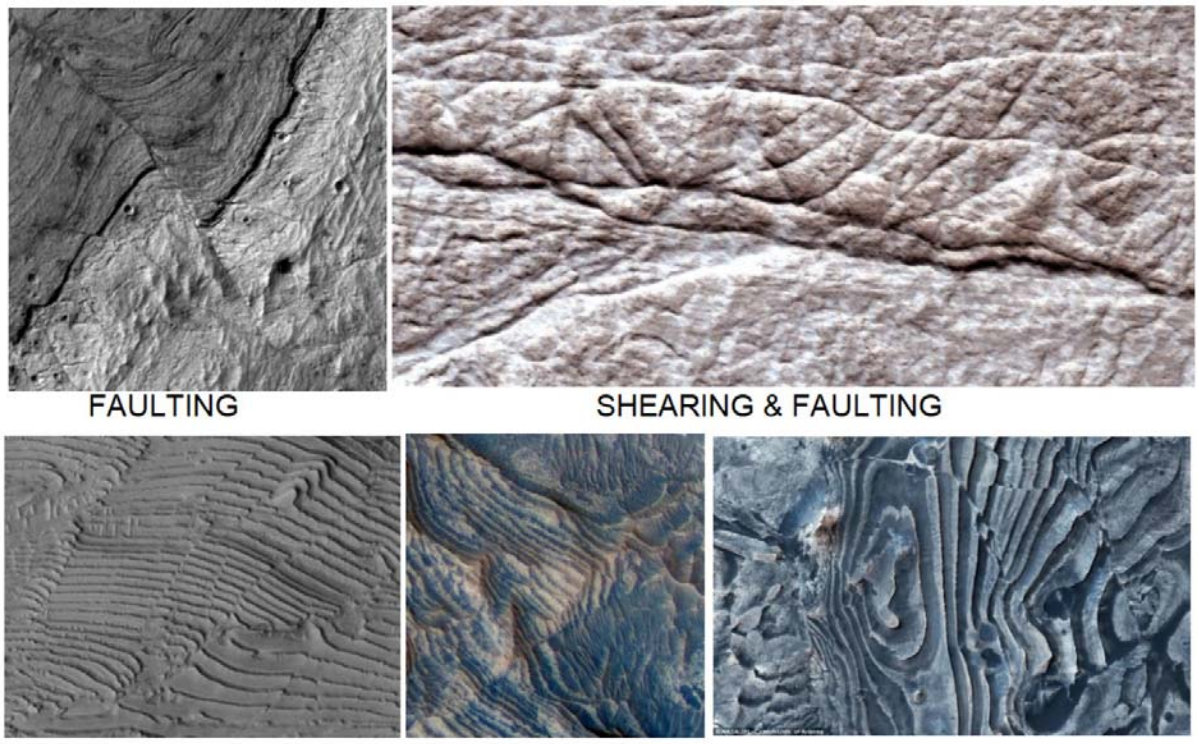


Fig. 4 Views of large scalediscontinuities observed in Mars.

4 Stress Sates of Planetary Bodies

Stress state is one of the most important items when rock mechanics and rock engineering to be utilized in moon and other planets. Particularly, the engineering design requires data on in-situ stress state as well as quake related topics. Figure 5 shows the density, gravity and hydrostatic pressure distributions with depth in Venus and Mars together with those of Earth.

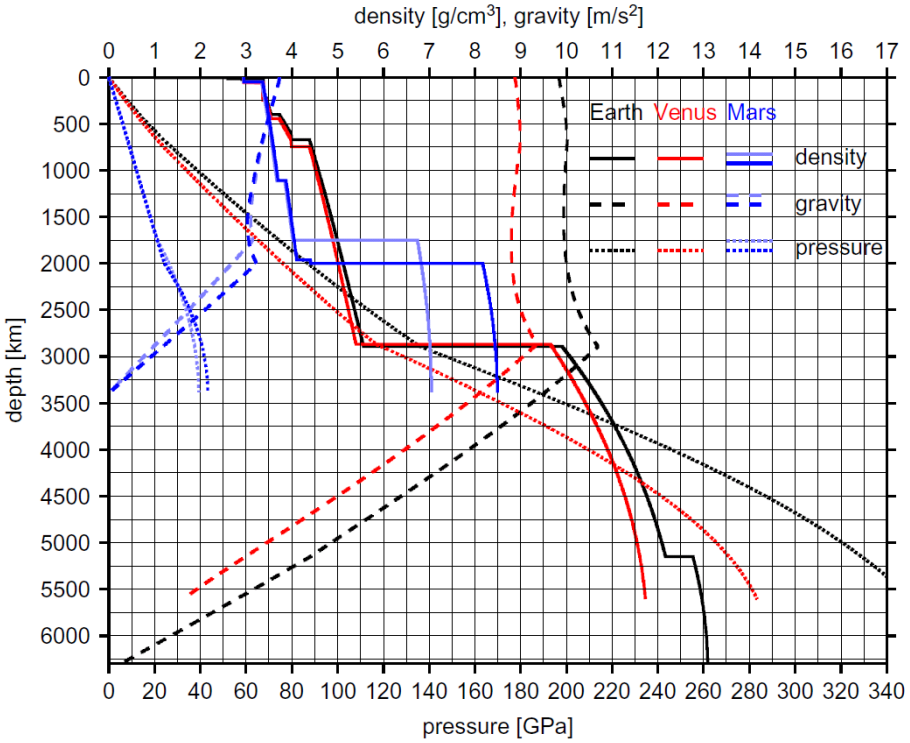


Fig. 5 Comparison of the density, gravity and hydrostatic pressure distributions with depth in Venus and Mars together with those of Earth (from Steinberger, 2010).

The author analysed the stress state of Moon, Mercury, Venus as well as Earth by considering the following cases:

CASE 1: Planetary bodies are in liquid state (hydrostatic)

CASE 2: the crust and mantle are elastic solids and the core is in liquid state (non-hydrostatic)

CASE 3: the crust and mantle are elasto-plastic solids and the core is in liquid state (isothermic: room temperature)

CASE 4: the crust and mantle are thermo-elasto-plastic solids and the core is in liquid state (non-isothermic)

Parameters b_1, b_2, S_o, S_∞ of the yield criterion were chosen as 0.2 GPa^{-1}, 0.0014 $^oC^{-1}$, 0 MPa, 5GPa, respectively.

Figure6 shows the distributions of radial and tangential stresses in the lithosphere for each case. The elasto-plastic analyses showed that the whole crust and mantle became plastic. Large tangential stresses seen in CASE 2 were dissipated when the plastic behaviour of the crust and mantle was considered. The tangential stresses dissipated in the mantle increased both radial and tangential stresses in the core. The consideration of the thermo-elasto plastic behaviour of the mantle and the crust of the earth further decreased the deviatoric stresses in the mantle and in the crust.

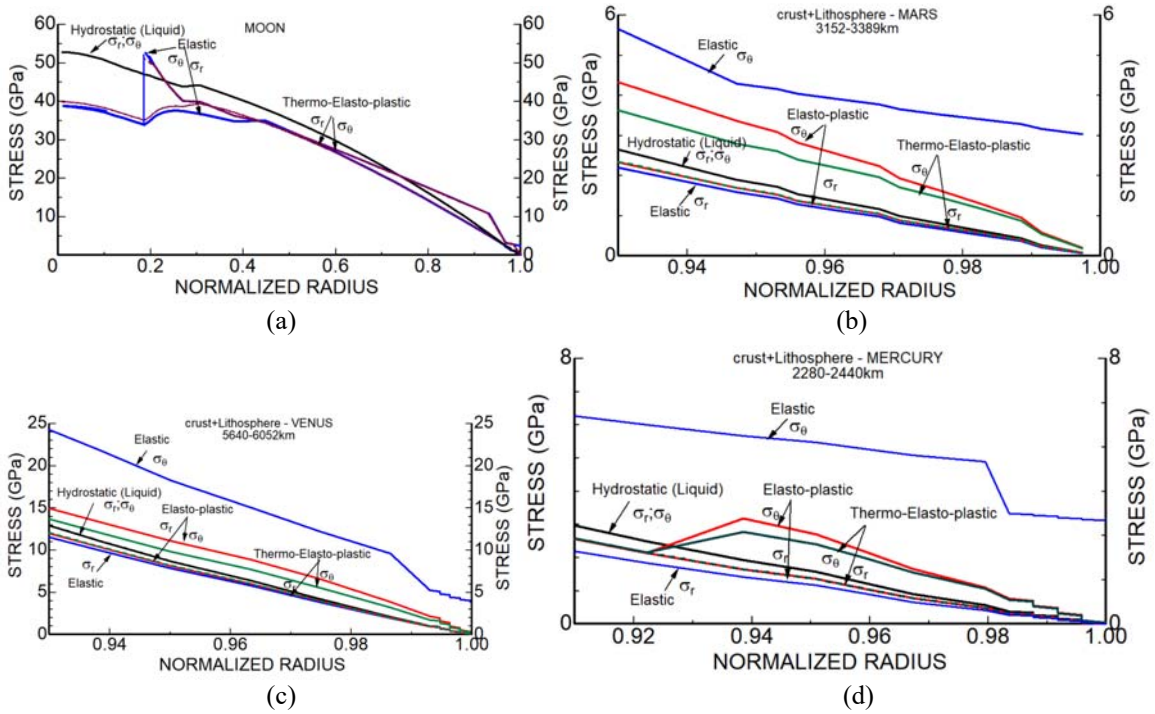


Fig.6 Distribution of stresses (a) throughout Moon, and lithosphere of (b) Mars, (c) Venus and (d) Mercury.

5 Rock Slopes

The images and drilling operations performed by Mars Exploration Rovers (Opportunity, Sprit, Curiosity, Perseverance) on some selected rocks and rock blocks indicated that rocks are quite similar to those of the earth. It still needs some clarifications whether rocks seen in Earth fully exist on Mars. However, the sedimentary rocks (such as conglomerate, sandstone, siltstone, mudstone, sulfate deposits), metamorphic rocks such as phyllite, shale and serpentine and extrusive rocks (basalt, andesite-like (silicate bearing basalt), breccia) of Mars clearly similar to those of Earth. Although the present climatic conditions such as none existence of rainfall and groundwater and large difference of daily temperature, the failures due to gravitation and seismic forces, impacts, differential weathering are likely to occur. Furthermore, it is well understood that the circumstances in the past were quite similar to those of Earth and many paleo rock slope failures should be very similar to those observed on Earth. In this section, rock slope failures in Mars on the bases of the images provided by Mars Rovers of NASA are summarized with the consideration of the following conditions:

a) Slope Failures in Layered Rock Mass

b) Slope Failures in Jointed Rock Mass

c) Actual or Potential Slope Failures in Discontinuous Rock Mass

d) Steep or Overhanging Cliffs in Layered Rock Mass
e) Failures of Overhanging Cliffs in Discontinuous Rock Mass
f) Stability of Precarious Rock Blocks
g) Impact and Vibration Induced Mass Movements.

Aydan (1989) categorized rock slope failures on Earth. Fundamentally rock slope failures involve three categories, specifically, intact rock or rock mass, discontinuities and intact rock and discontinuities. They may be named as shearing or bending failure, combined shearing and sliding, buckling, flexural toppling, planar and/or wedge sliding and columnar toppling. Figure 7 shows some examples of rock slope failures in Mars.

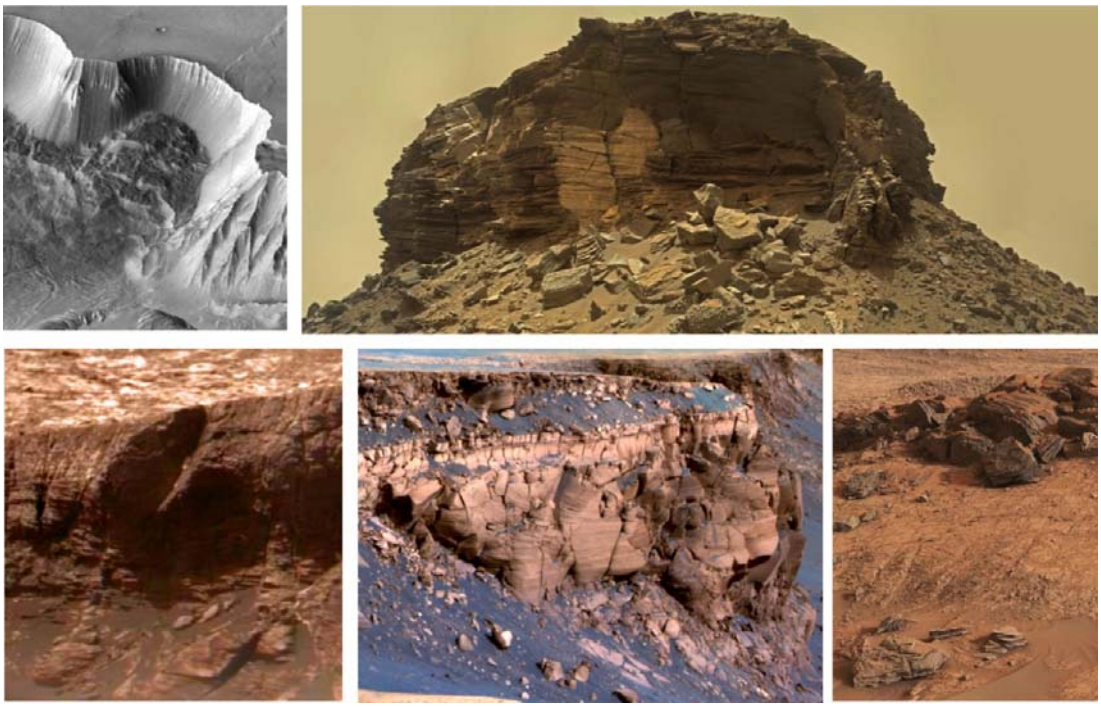


Fig.7 Views of slope failures observed in Mars.

Figure 8 shows an application of the integrated slope stability assessment proposed by Aydan et al. (1991) to rock slopes of Mars. Lines in the figure represent the relations between the bedding plane and lower slope angle for stability of rock slopes for jointed rock mass. The friction angles used in this graph are for those of basaltic rock joints on Earth.

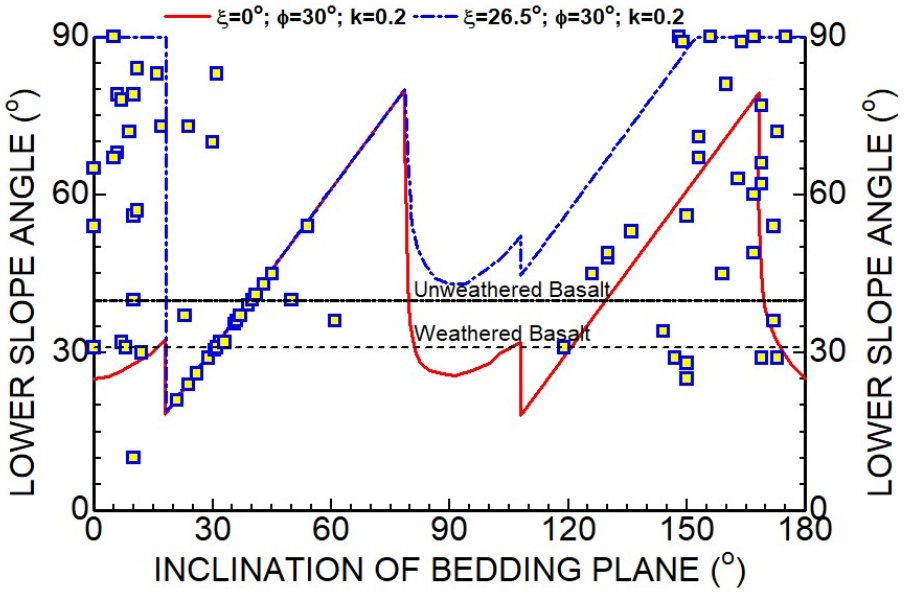


Fig.8 The relation between inclination of bedding plane and lower slope angle for rock slopes on Mars.

6 Underground Openings

The stability issues of underground cavities and sinkhole issues on Earth and other terrestrialbodies. Sinkholes are a severe problem on Earth. This problem has been often observed in karstic terrains, evaporitic formations and volcanic regions on Earth. The images as seen in Figure 9 clearly showed that sinkholes also formed in Mars. These sinkholes have been found in basaltic flow areas. Some of sinkholes may also be formed by impacts of meteorites and/or rifting induced by tectonic movements.

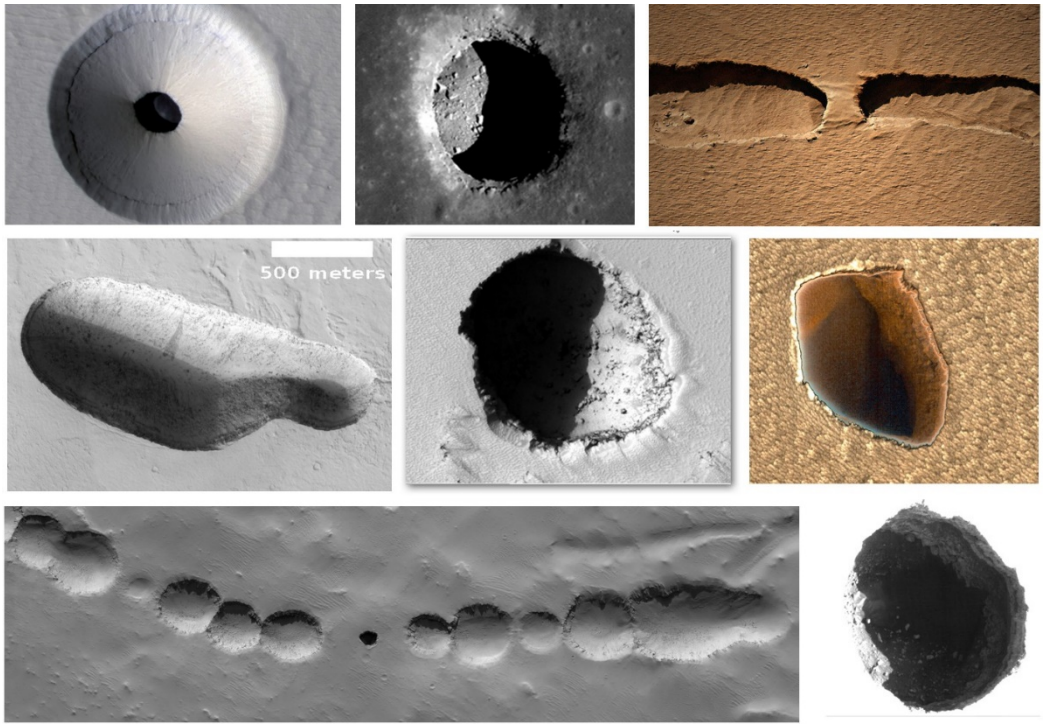


Fig.9 Images of sinkholes in Mars (compiled from the images released by NASA).

As noted from the figure, basalts of Mars are quite porous, which may be called vesicular basalt. It is very likely that the porous structure may lead heavy weathering as well as a decrease of mechanical properties. As there is no experimental data on Martian basalt, the drilling and grinding operations by the rovers on rocks of Mars may be utilized to infer their mechanical properties. As reported by Aydan (2022), the tensile and uniaxial strength of vesicular basalt decreases as a function of porosity (Figure 10). As the basalts of Mars resemble to those of Earth. Therefore, the mechanical properties of the vesicular basalt of Earth may be utilized to evaluate the mechanical properties of Martian vesicular basalts.

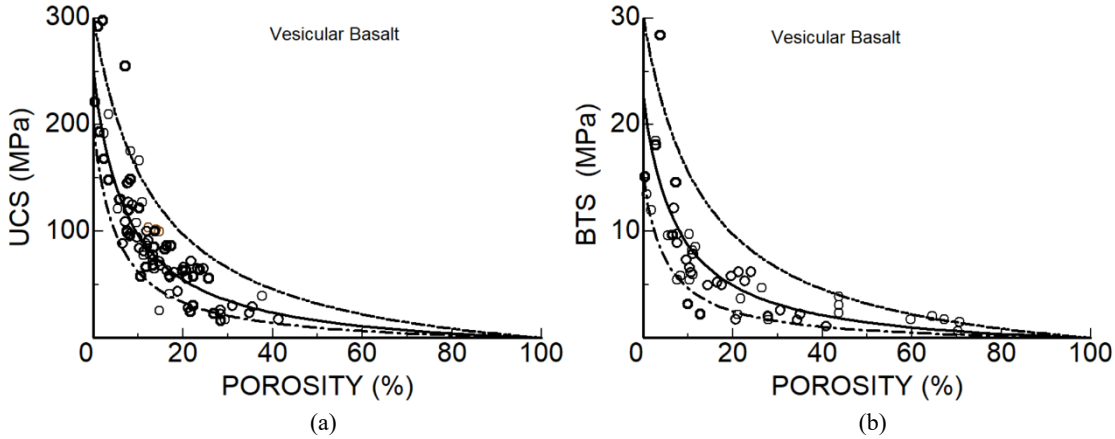
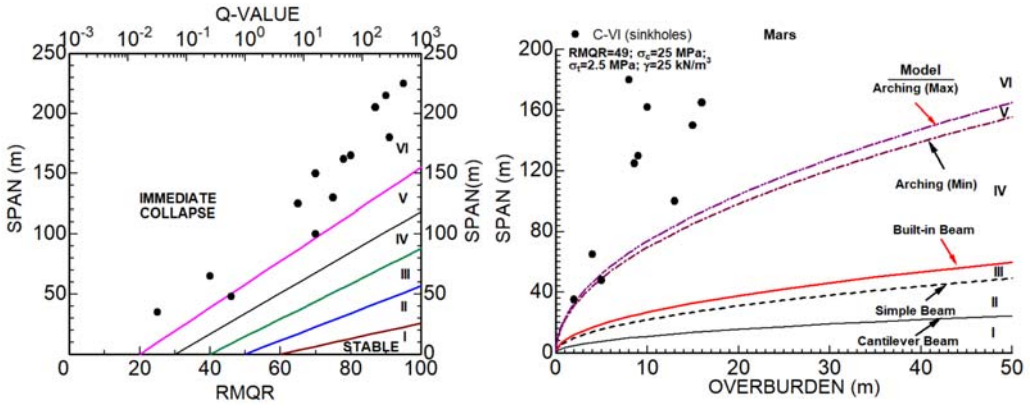


Fig.10 Variation of (a) uniaxial compressive strength and (b) Brazilian tensile strength of basalt from Türkiye and Japan with porosity.

In this sub-section, the applicability of some stability assessment techniques to the sinkholes in Mars are presented. Fundamentally, empirical, analytical and numerical methods can be used described. The methods are not presented herein and the interested readers can consult some publications (e.g.,

Kawamoto and Aydan 1999; Kawamoto et al. 1991; Aydan et al. 1996; Aydan and Tokashiki 2011; Lang 1994). Specifically, empirical and analytical methods are utilized described.

Some attempts have been done to evaluate these two parameters from images on the bases of knowledge available from sinkholes of Earth. Furthermore, that the strength of vesicular basalt is estimated to be about 25 MPa in view of its porosity. As the gravity coefficient of Mars and Moon is 0.387 times that of Earth, the stress induced by the Mars gravity is assumed to be 0.387 times that on Earth, respectively. By considering these facts, the empirical and analytical methods have been used to assess the sinkholes occurrence for Mars. The estimations from empirical and analytical methods are shown and compared with observational data in Figure 11. The overall trend is quite promising despite many data are based on some inferences for similar situations on Earth. Once again it is noted that the analytical methods yield also the bounds to be on the safe side. When observational data is compared with empirical estimations, the overall trends are quite similar and the empirical estimation is on the safe side.



(a) (b)

Fig. 11 Comparison of (a) empirical and (b) analytical stability charts with observation data on Mars.

7 Seismicity and Quakes

It is shown that quakes also occur in planetary bodies and named as Marsquakes and Moonquakes. Furthermore, the possibilities of Venusquakes and Mercuryquakes are contemplated. This issue may be quite important regarding the settlement and exploitations of the planetary bodies by mankind.

Aydan (2017c, 2022a,b, 2023b) stated that possible causes of quakes in planetary bodies are as follow:

a) Impacts by Meteorites

b) Thermal Contraction & Expansion

c) Volcanic Activity

d) Large Scale Mass Movements

e) Plate-tectonic Type Movements

f) Daily Rotation and Annual Solar Motion

It should be noted Earth is well-instrumented while there is very limited instrumentation on Moon and Mars for seismic events. In this chapter, quakes on Earth (e.g. Aydan 2023a, 2017b, 2002, 2003, 2006, 2007, 2009, 2012a; Aydan et al. 2005a,b, 2007a,b; Ulusay et al. 2001, 2003a,b) are considered and available knowledge and information are extended to other terrestrial bodies.

The seismometers installed in Moon recorded moonquakes, which were initially unexpected (Figure 12). The records from the moonquakes revealed inner structure of the moon like that of Earth. It was found that the earthquakes were categorized as deep earthquakes resulting from the tidal force interaction between Earth and Moon, shallow earthquakes due to tectonic forces and thermal stress variations and other earthquakes due the meteorite and lunar module impacts. The magnitude of the shallow earthquakes could be up to 5.5 while the magnitude of the deep earthquakes was much smaller and generally less than 2. The shallow earthquakes may pose a hazard to a lunar habitat and they may last for more than 10 minutes. The deep earthquakes occur at depths of 700 to 1000 km and it occurs periodically at 14 and 206 days, implying the causes of the events are terrestrial and related to solar

tidal forces. It was found that the vibrations caused by impacts can last for more than 1 hour while deeper earthquakes last only 10-20 minutes. The reason for such a long seismic vibration is considered to be due to the existence of a thick elastic crust. As the viscosity of the crust small, the vibrations last longer for surface impacts.

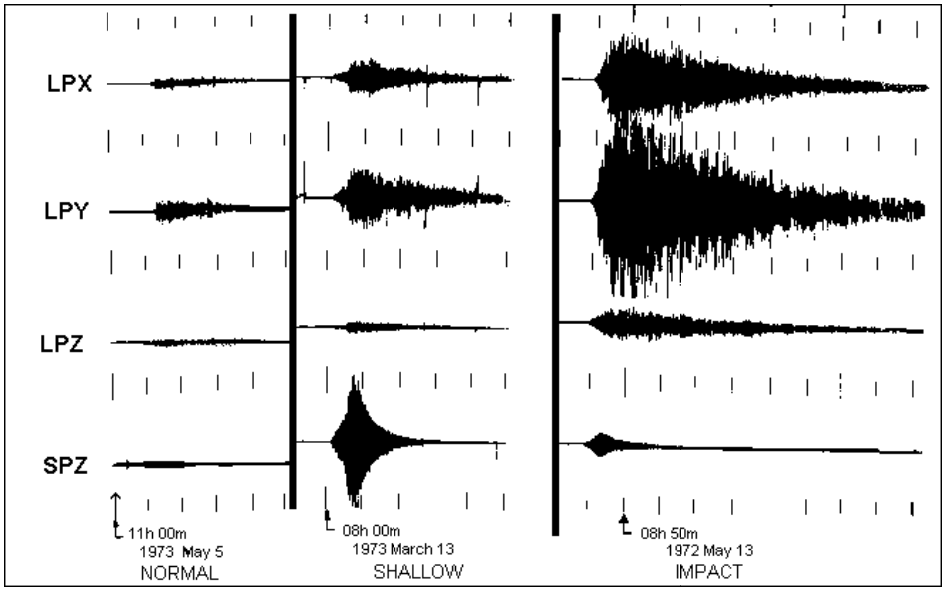


Fig.12 Records of moonquakes and lunar impacts (time marks 10 minutes) (from NASA)

The first seismic observation station, named as InSight Lander was installed on Mars very recently in 2018.The InSight Lander touched down on Mars on November 27, 2018. Until the record of a seismic event on April 6, 2019, the occurrence of Mars quakes was a speculative issue. The first seismic event on April 6, 2019 confirmed the existence of quakes of Mars (Figure 13). The first vibration record obtained from a marsquake by the InSight Lander was quite longer than those observed on Earth and shorter than those on Moon as seen in Figure 12. The seismic monitoring would improve the understanding of the seismicity and the interior structure of Mars and provide essential data on the necessity of quakeproof design of structures to be built in Mars or similar planetary objects.

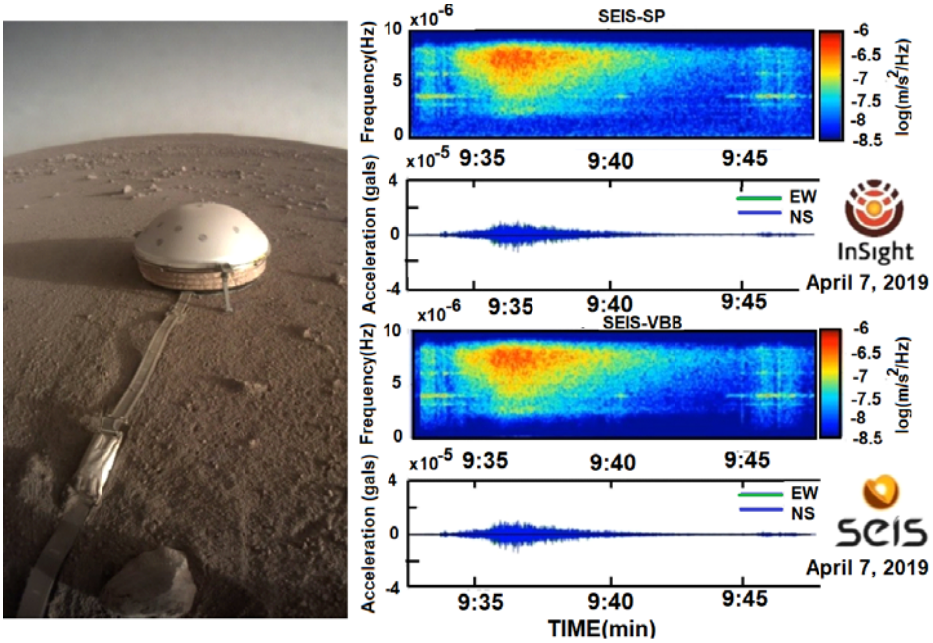


Fig.13 A seismic record by the seismometer of the INSIGHT Mars module of a marsquake occurred on April 24, 2019 (arranged from NASA).

There is no doubt that quakes do occur in Venus in view of volcanic activities and the existence of large-scale fracture zones. The possibility of installing seismometers on the surface of Venus is extremely difficult due to thick clouds and greenhouse effect, surface temperatures of Venus approach 462 °C causing water vaporization. Recently NASA has been exploring to utilize the same technique to monitor the earthquakes in California. Compared to conventional seismographs, there are some

technical issues with balloon equipped with air-pressure sensors for determining the location, magnitude of earthquakes and its focal mechanism, it is probably the only technique available so far.

Mercury is likely to have seismic activities, which may be referred as "mercuryquakes". These quakes are thought to be primarily caused by the shrinkage of the planet. The existence of large fault scarps (up to 1000 km long) suggests significant tectonic activity and potentially strong "quakes" on Mercury. NASA detected smaller scale thrust faults with a length ranging from 1 to 7 km. For such fault lengths, the estimated moment magnitude of earthquakes could range between 4.2 and 5.6 using the empirical relations proposed by Aydan (2012).

8 Characteristics of Planetary Bodies

8.1. Properties of rocks and discontinuities

As discussed in previous sections, rocks from moon and Mars are quite similar to those of Earth. In rock mechanics and rock engineering, numerous experiments on rock, rock discontinuities and rock masses have been carried out and many mechanical and engineering properties have been determined. Nevertheless, it is needless to say that we need to carry out similar experiments for extraterrestrial rocks probably in their environment. During the Apollo program, more than 300 kg rock sample have been brought to Earth. However, no mechanical experiments have been carried out yet. The Mars rovers provided many images of rocks, rock masses and discontinuities. Back analyses of many images may provide some information on the mechanical analyses. Furthermore, the back analyses of failed rock slopes and rock cliffs may further provide on strength properties of rock masses. Some of such analyses are reported by several researchers (e.g. Luccitta (1979); Schultz, 2002; Neuffer & Schultz, 2006). The force and rate of advance during drilling operations by the MERs such as Curiosity may also provide another data on mechanical properties of intact rocks.

8.1.1 Inference of Properties from Rocks broken by MERs

As shown in Figure 14a, a platy rock piece was broken due to bending stress under the weight of the MER through its metallic wheel. This type breakage can be utilized to infer bending (tensile) strength of terrestrial planetary bodies. The bending theory for beams on elastic foundations may be utilized for such purpose. If the loading is somewhat complicated, numerical analyses may be used. The simple technique might be the utilization frame type analyses capable of considering ground reaction.



(a) (b)

Fig.14 (a) Broken or fracture platy rock fragments due to weight of MERs and (b) Views of drilling tailings in Mars and laboratory on Earth.

8.1.2 Inference of Properties from Drilling and Grinding Operations by MERs

The force and rate of advance during drilling operations by the MERs such as Curiosity, Perseverance may also provide another data set on mechanical properties of intact rocks (Aydan 2022b 2023b). Particularly, the utilization of drilling performance and drill-hole tailings shown in Figure 14b and drilling performance may yield additional data on the physico-mechanical properties of rocks. Besides

empirical techniques, numerical methods may be utilized to evaluate drilling performance and back analyses the physico-mechanical properties.

8.2 Utilization of Index Test Techniques

Many index test techniques have been developed in the field of Rock Mechanics and Rock Engineering. Although the utilization of proper testing techniques is always necessary, it is almost impossible to implement them during explorations of rocks and discontinuities in other terrestrial planetary bodies. Therefore, this section addresses this issue and describes some index methods for assessing the physico-mechanical properties of rocks, available in the field of Rock Mechanics and Rock Engineering (e.g., Aydan 2012b; Aydan et al. 2014a; Ulusay et al. 2015, 2025; Aydan and Ulusay 2024), which may be utilized in the next generation exploration rovers. In addition, numerical studies require the evaluation of parameters of constitutive laws and some available techniques for such a purpose have been introduced in this sub-section.

8.2.1 Elastic Wave Velocity

When rocks are assumed to be isotropic, p-wave and s-wave velocities of samples are measured in a single direction. However, they should be measuredperpendicular to bedding (schistosity) and two mutual directions parallel to the bedding plane (schistosity) if the anisotropy is dominant. Such examples are described in literature (e.g., Aydan and Ulusay 2003, 2013; Aydan et al. 1993, 1996b; Sezaki et al. 1990, 1994; Seiki and Aydan 2003)and there are many empirical relations to establish the relations among wave velocities and strength and deformability characteristics. These type measurements may also be done by equipping the explorers with appropriate devices. If mankind gets access the exploration sites, similar devices can also be used in such explorations of the terrestrial planetary bodies.

8.2.2 Schmidt Rebound Number

Schmidt hammer, which is initially developed for concrete of civil and architectural structures, are used in Rock Mechanics and Rock Engineering applications with some modification of the devices (Seiki and Aydan 2003; Aydan and Ulusay 2024). Schmidth hammer can also be used as an index testing device in planetary explorations. Therefore, the present exploration rovers may be equipped with such devices. However, major issue would be the interrelations between the rebound value and strength and deformability properties as the gravitation fields in planetary bodies are different. When this index method is utilized, some consideration on the existence of inclusions in rock matrix should be also given as the rebound values will be different for soft/hard matrix and hard/soft inclusions. In addition, the direction of measurement must be also taken into account.

8.2.3 Needle Penetration Index Tests

The needle penetration device is developed by MARUTO Co. of Japan (Maruto Co., 1999). The device can measure the applied load up to 100 N and the penetration depth is up to 10 mm. The diameter of the needle is 0.82 mm (Ulusay et al., 2014; Aydan, 2012b; Aydan et al., 2014a). The ratio of applied load to penetration depth is called needle penetration index (NPI). The original motivation to develop this device was to assess the properties of squeezing rocks (soft rocks with UCS up to 30 MPa) in tunneling and soft rocks beneath large bridge foundations, as it is often difficult to sample rocks and to test them in laboratory. The damage caused to rock by the needle penetration is also quite negligible and the device can also be effectively used in assessing the state and properties of rocks in archeological remains excavated in/on rock mass, particularly.

Another penetration test device utilizing a low-capacity loading device and a special rod-like loading platen with a flat-end was developed by Aydan et al. (2008). The device is presently used in laboratory conditions. However, it can be easily used in field explorations. The diameter of rod-like platen ranges between 1 to 3 mm. However, experimental results indicates that there are some undesired stress concentrations when the diameter is less than 1mm and the rod-like platen may buckle when high strength rock is tested. For the interpretation of the experimental results, the nominal strain is defined in terms of penetration displacement divided by rod diameter. Furthermore, the applied stress is defined by dividing the applied load by the area of the flat-end. The device is equipped with a load cell and a displacement transducer to record load-displacement responses. In addition, an AE sensor is attached to the sample to monitor the cracking phenomenon. This device has also big potential to be utilized in explorations in terrestrial planetary bodies.

8.2.4 Equotip or Leeb Hardness (Rebound) Tests

Equotip hardness (rebound) test device was originally developed for evaluating the hardness of metals However, since 1990's it is also widely on rocks (e.g. Aydan and Ulusay 2024; Ulusay et al. 2025). The device measures the ratio of a rebound height of a small hardened steel sphere to the original drop height and the ratio is multiplied by 1000. As the test area is very small, it can be utilized in many places and it is very likely to measure also the state of matrix and inclusions in some rocks. It is probably one of suitable techniques for terrestrial explorations as it is small device and data storage should be quite easy with some small technical modifications. It should be noted that some slight damage definitely occurs beneath the impact locations always even in many hard rock samples, and, the Equotip hardness (rebound number) differs even on the same surface and the surface conditions.

8.2.5 Inference of Parameters of Elasto-plastic Constitutive Law

The analytical and numerical methods require the parameters of constitutive laws, which are not strength parameter only. In other words, some researchers mistakenly consider the constitutive laws to be only strength criteria. The determination of fundamental parameters of constitutive laws for rocks constituting terrestrial planetary bodies is almost impossible without actual rock samples. In this sub-section, the procedure for determining some important parameters based on uniaxial compression strength (UCS) is introduced.

The details of the parameters and their utilization have been described in the publications of Aydan et al. (1993, 1996b), which were initially developed for rocks of tunnels subjected to squeezing phenomenon and it was extended to high strength rocks subjected to rockburst conditions. These parameters were utilized to assess the deformation responses of various rock structures on Earth. It is also common not to find many parameters used in analytical and numerical analyses. Even for such cases, simple parameters such as uniaxial compressive strength and/or elastic wave velocity can be utilized. Sometime, elastic-wave velocity is more easily found. The procedure for determining some important parameters based on uniaxial compression strength (UCS) is introduced. Figure 15 shows the idealized strain-stress relations during deformation together with internal fracturing of rocks. As shown in Figure 16, Aydan et al. (1993, 1996b) defined some plastic deformation parameters using the strain levels for post-yielding behaviour.

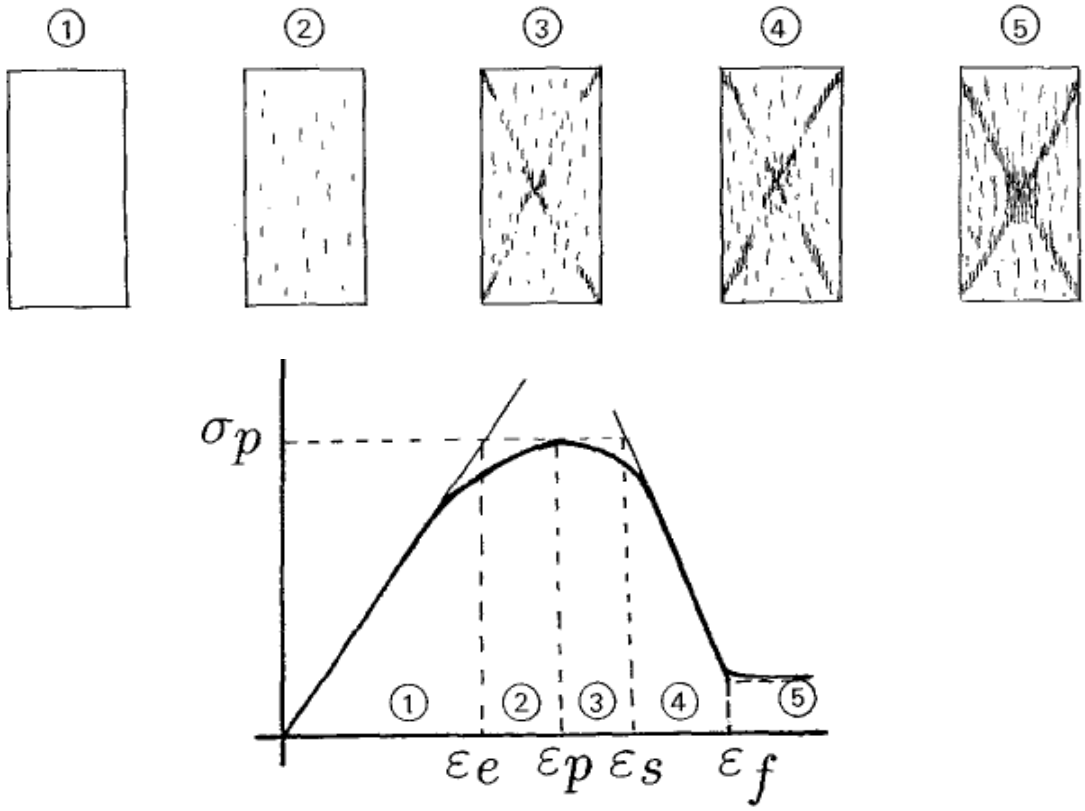


Fig. 15 The idealized strain-stress relations during deformation together with internal fracturing.

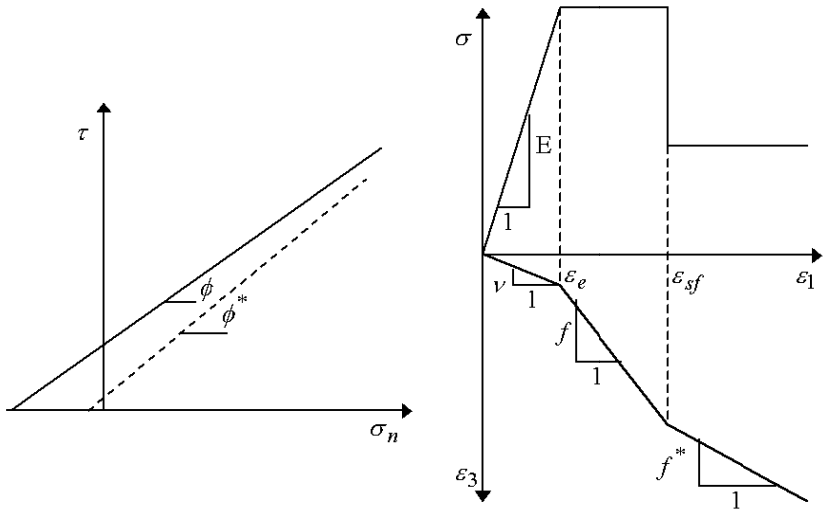


Fig. 16 Illustration of definition of plastic deformation parameters using the strain levels for post-yielding behaviour.

Therefore, the interrelation between elastic wave velocity and uniaxial compressive strength shown in Figure 17 may be utilized if there is no data on uniaxial compressive strength (UCS). However, if the uniaxial compressive strength (UCS) data is available, some of the direct relations established by Aydan et al. (1993, 1996b) and extended to high strength rocks (Aydan et al. 2001; Aydan, 2018a) shown in Figure 18, can be utilized to evaluate the parameters of post-yielding of rocks to assess the response of rock structures in other terrestrial planetary bodies using the analytical and numerical analyses. The same methodology may also be extended to evaluate the visco-elasto-plastic parameters of rock in other planetary bodies using the knowledge gained from rocks of Earth.

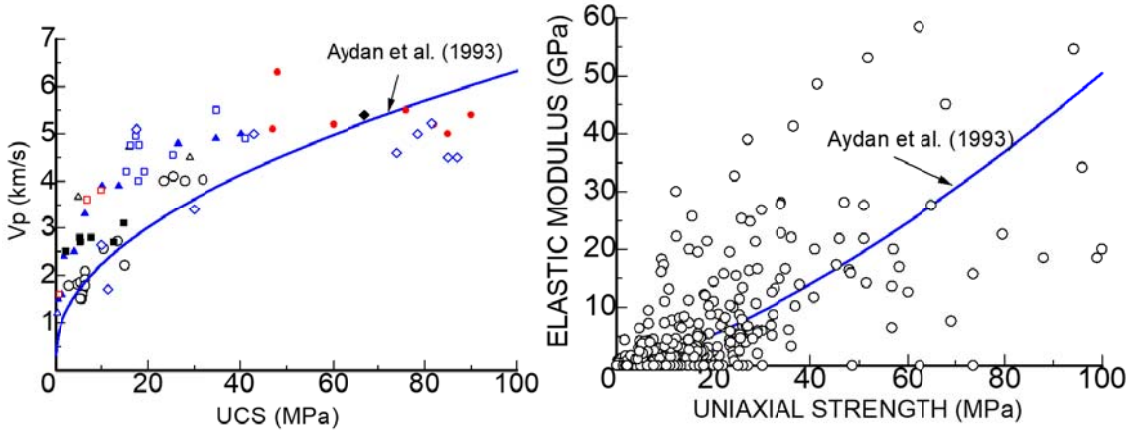


Fig. 17 Interrelations uniaxial compressive strength (UCS) among p-wave velocity and elastic modulus.

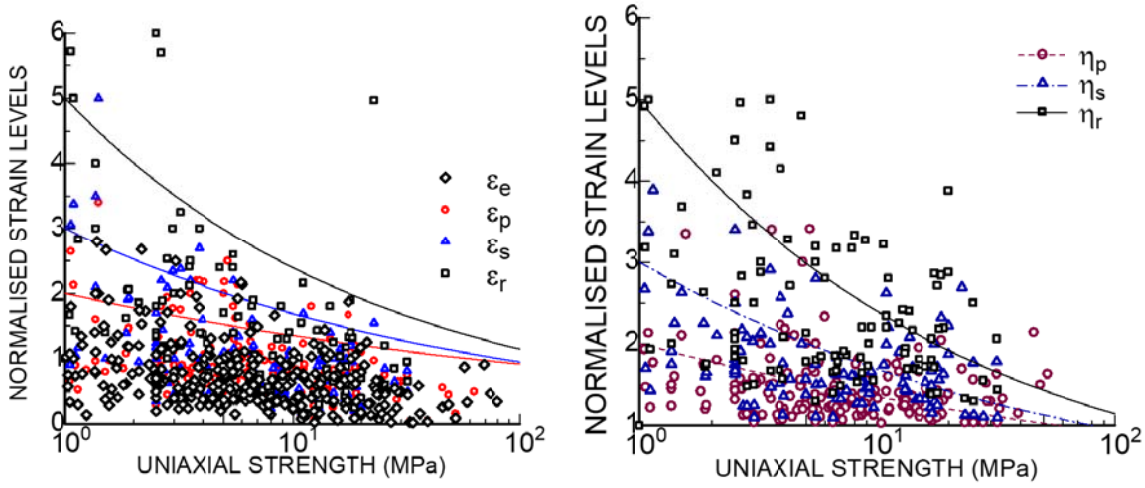


Fig. 18 Interrelations uniaxial compressive strength (UCS) among plastic behaviour parameters.

9 Conclusions

The rock mechanics aspects of Mars are quite similar to those of the Earth. The differences result from gravitational acceleration, climatic conditions (temperature, humidity, winds), thickness of atmosphere and none or limited amount of ground water. The knowledge on the behaviour of rocks, discontinuities and rock masses acquired on the Earth can be easily used in Mars with the consideration of the differences resulting from gravitation acceleration, climatic conditions and fluid in rock masses.

The knowledge on the behaviour of rocks, discontinuities and rock masses acquired on the Earth can be adopted in Mars with the consideration of the differences resulting from gravitation acceleration, climatic conditions and fluids in rock masses. On the basis of knowledge gained from rocks of Earth, the stress state of Mars is studied using an thermo-elasto-plastic behaviour constitutive model and spherical symmetric finite element method four different conditions. Although these results are preliminary, they are expected to provide some bases for future studies. The computational results clearly explain why mountains are higher in Mars compared with those on Earth and why tectonics is less pronounced in Mars.

This study is summarized the techniques to evaluate the stability of natural underground structures and sinkhole formation in Mars on the bases of some information, data and inferences obtained from the natural underground structures in volcanic areas on Earth. The available techniques and mechanical data were utilized by considering the gravitational conditions in Mars. Despite some ambiguities on material properties as well as rock mass conditions in Mars, these preliminary analyses provide some insight view of sinkholes on Mars and their possible stability situations. Undoubtedly more data and more detailed analyses utilizing numerical techniques would provide better information about the stability of caves and conditions of sinkhole formation in Mars. In addition to the conditions considered in this study, the dynamic loading conditions due to marsquakes and impacts by the meteorites will be necessary in future studies.

Acknowledgements

The author gratefully acknowledges NASA and the people involved in the development and operation of Mars exploration programs, Mars rovers, namely, Opportunity, Sprit and Curiosity and earlier rovers, and processing and releasing their images on related web-sites. Thoughts of the author are based on Images of Mars Rovers and mostly obtained from the following web-site: https://mars.nasa.gov/mer/gallery/images.html

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