PENETRATION TESTING FOR SUBSURFACE REGOLITH PROBES IN MARTIAN ANALOG MATERIAL

A. ELSHAFIE*, V. F. CHEVRIER AND R. ULRICH

[1]Arkansas Center for Space and Planetary Sciences, [2]Department of Chemical Engineering. University of Arkansas, Fayetteville, AR 72701.
e-mail: aelshafi@uark.edu

ABSTRACT

Investigation and characterization of the subsurface of extraterrestrial planetary bodies using penetrometers are of high interest. Because they offer reliable scientific outcomes and due to their mechanical simplicity, this makes them desirable instruments for planetary investigations. Static Penetrometers are deployed using lander/rover where the maximum force of penetration is a direct function of the weight of the lander/rover on their target planetary body. Penetration forces are directly proportional to the bearing capacity factor (N_q) which is related to the regolith density and frication angle. The main objective of this research is to estimate the bearing capacity factor (N_q) experimentally based on forces of penetration for martian analog material (JSC Mars-1). It was found that the bearing capacity factor (N_q) increase with increasing the density of the regolith material. Under a bulk density of 1250 kg m^{-3}, N_q is found to be about 1800. It would require about 600 N to drive a 1.2 cm diameter probe to about 20 cm of the subsurface of JSC Mars-1 under martian gravity. From these results, an estimate of lander/rover weight can be determined for future investigation of the martian subsurface.

1. INTRODUCTION

Regolith mechanical properties of planetary bodies affect both landing of spacecraft and exploring planetary surfaces. Planetary geotechnical parameters are of high importance for scientists and missions designers. Scientists use these parameters to understand the formation and evolution of planetary profiles while mission designers use this information to decide landing sites and target areas of investigations. Likely, most soil mechanical properties are interrelated. Knowledge of one parameter could lead to estimate the rest of the mechanical parameters. Level of compaction, consolidation and others useful information can be known from geotechnical parameters such as density, porosity, void ratio which are indicative of the nature and condition of the surface and subsurface structure. Determination of these parameters will improve future mission success and will provide required information to further understand the history and evolution of planetary surface and subsurface.

On all the surveyor lunar landers, a strain gauge is attached on its three legs to measure the force of penetration into lunar regolith during landing [1].

Their landing velocities ranged from 1.4 to 4.2 m s^{-1} and the penetration depth ranged from 2.1 to 10.5 cm. It was concluded that the force of penetration at the surface is zero and it increase with increasing depth at the rate of 1.87 ± 0.33 MPa m^{-1} [2]. The Soil Mechanics Surface Sampler (SMSS) which was carried on surveyors 3, 4 and 7 indicated that the lunar regolith has a bulk density of about 1.5 g cm^{-3}, an angle of friction range from 35 to 37º and the bearing capacity was about 2.1 N cm^{-2} at a depth of about 3 cm [2]. The Apollo Simple Penetrometer (ASP) on board Apollo 14 was part of the Apollo Lunar Surface Experiment Package (ALSEP) which used to investigate the lunar regolith soil mechanics [3]. ASP was a metal rod 68 cm long and 0.95 cm in diameter with a 30 degree cone angle used in three penetration tests on the Moon by manually pushing it into lunar regolith by astronaut. ASP reached to a depth of 42, 44 and 50 cm and the penetration force was in the range of 70 to 135 N using one hand. A second deployment of ASP reached a depth of 62 cm and required a force of 225 N using both hands [4]. A Self-Recording Penetrometer (SRP) was on board Apollo 15 and 16 missions. This instrument was connected to a recording drum which recorded the force versus depth. At a maximum depth of 76 cm, the Apollo 15 SRP recorded a force of 111 N and the Apollo 16 SRP recorded a maximum force of 215 N [4]. PROP-M (Pribori Ochenki Prokhodimosti-Mars, Martian cross-country capability evaluation instrument) is a tethered walking rover with a mass of 4.5 kg on board Mars 2, 3, 6 and 7 missions to Mars in the period between 1971 to 1973 [5]. PROP-M was designed to make penetrometry and densitometry measurements along its path. The maximum tethered length was 15m; therefore, the rover was programmed to stop and to take measurements every 1.5m [6]. At each measurement point, the penetrometer would be hammered into the regolith and the results would be recorded. Results from Mars 2/3 indicate the surface of Mars had a surface density of 1.2, 1.6 and in some

places up to 3.5 g cm^{-3} [6]. Venera 9 and 10 brought valuable data about Venus. The landers equipped with density meter as one of the soil mechanics instruments. Venera 9 and 10 reported a surface density ranging from 2.7 to 2.9 g cm^{-3} [6]. ACC-E is a piezoelectric force sensor (impact penetroemter) which was part of the Surface Science Package (SSP) onboard the Huygens probe which is used to investigate the subsurface of Saturn's moon Titan [7]. ACC-E, an impact penetrometer, was the first instrument touched down the surface of titan for soil mechanics investigation. The miniature probe (mass of 15 g, 14 mm diameter) has a sensing element of 2mm. The force sensor can measure the force in the range of 0 – 2000 N. The results indicated that the surface had a weak crust and, beneath that, a structure consisted of wet sand and embedded pebbles [8]. Based on the knowledge of the densities of other extraterrestrial planetary bodies, prediction of the forces of penetration as a function of depth can be accomplished.

The downward movement of the penetrometer through regolith is opposed by two reaction forces: the base or cone resistance, which pushes against the cone and sleeve friction, which acts up on the lateral side of the penetrometer [9]. Penetration into regolith materials is directly proportional to the effective unit weight of the regolith (γ), bearing capacity factor (N_q), depth of penetration (D) and friction angle (φ). The main objective of this research is to estimate the bearing capacity factor (N_q) experimentally based on forces of penetration for martian analog material (JSC Mars-1). Our choice of JSC Mars-1 because it is considered as one of the best martian analoge material [14]. From penetration forces as well as the knowledge of some mechanical properties of JSC Mars-1, one can estimate the bearing capacity factor (N_q) under different levels of compaction. (N_q) varies from one type of material to another due to intrinsic regolith properties. Knowledge of (N_q) will help us approximate the force of penetration under different levels of compaction to simulate the conditions on Mars such as density and gravity.

2. EXPERIMENTAL APPARATUS

A specific apparatus was designed and built to measure the penetration forces in unconsolidated materials. A general illustration of the setup is shown in Fig. 1. An automated control system was designed where the whole penetration experiment can be monitored and controlled through a personal computer. Two parameters are being monitored during penetration testing: the penetration force and penetration depth. The results of the penetration experiment are automatically saved in an Excel file. A complete description of the penetration rig and its automated control system can be found in [13].

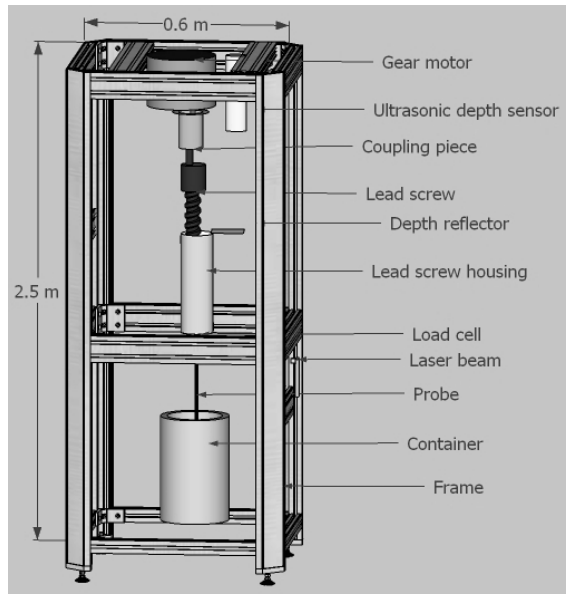


Fig. 1. The penetration testing apparatus.

3. EXPERIMENTAL PROCEDURES

The particle size distribution of JSC Mars-1 was determined by sieving as shown in Fig. 2. The results show that JSC Mars-1 contains 17% medium size particles (>0.5 mm) and 83% fine grained particles (<0.3 mm). Penetration experiments were run at a constant speed of 2 mm s^{-1}. Samples are prepared by filling a 16 cm diameter and 24 cm deep cylindrical bucket with 27.5 kg of dry JSC Mars-1. Then, the bucket is shaken in order to homogenize and compact the regolith to the desired height. All possible care was taken to obtain a uniform density throughout the column regolith. Penetration testing is done only once per sample preparation.

To determine the bearing capacity factor N_q from forces of penetration, a cylindrical container was filled with JSC Mars-1 with a measured bulk density of 1120 kg m^{-3}. Insertion and removals were conducted at this bulk density using 1.2 cm diameter probe. JSC Mars-1 poured out of the container and re-poured in for each penetration test. JSC Mars-1 was adjusted to the same bulk density of 1120 kg m^{-3} for two more penetration testing. The average force of the three penetration testing is calculated and N_q factor is determined at each data point. The average of N_q was determined and implemented in a matlab code to determine the theoretical force of penetration based on the knowledge of bulk density. Table 1 shows symbols used through the paper and their corresponding definition.

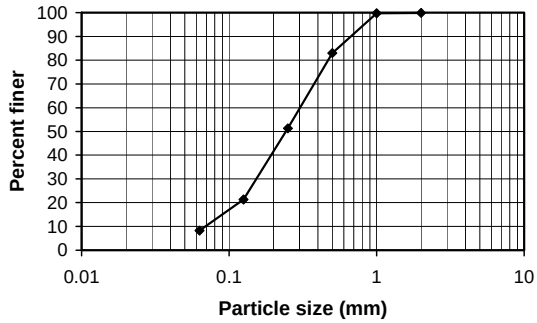


Fig. 2. Particle size distribution for JSC Mars-1.

Table 1
List of symbols used in the paper.

Symbol	Def.
A_c	Area of the cone (m^2)
A_s	Area of the sleeve (m^2)
B	Cone diameter (m)
D	Probe diameter (cm)
D_r	Relative density (dimensionless)
e	Void ratio (dimensionless)
e_{max}	Maximum possible void ratio (loosest condition)
e_{min}	Minimum void ratio (densest condition)
f_s	Sleeve friction (N m^{-2})
F_T	Total resistance force (N)
K	Coefficient of lateral pressure at rest (dimensionless)
K_p	Passive coefficient of lateral stress (dimensionless)
L	Lateral extension of the slip lines (m)
m_s	Mass of JSC Mars-1 (kg)
N_q	Bearing capacity factor (dimensionless)
q_c	Cone resistance (N m^{-2})
V_s	Volume of solid particles (m^3)
V_T	Total volume (m^3)
V_v	Volume of voids(m^3)
Z	Penetration depth (m)
γ	Effective unit weight of JSC Mars-1 (N m^{-3})
φ	Friction angle of sand (degree)
ρ_p	Particle density of JSC Mars-1 (kg m^{-3})
ρ_b	Bulk density of JSC Mars-1 (kg m^{-3})

Table 2 shows test probes used throughout the research. Two different probe diameters (1.2 and 2 cm) are used to certify and ensure the validity of the model.

Table 2
List of probes and their experimental parameters.

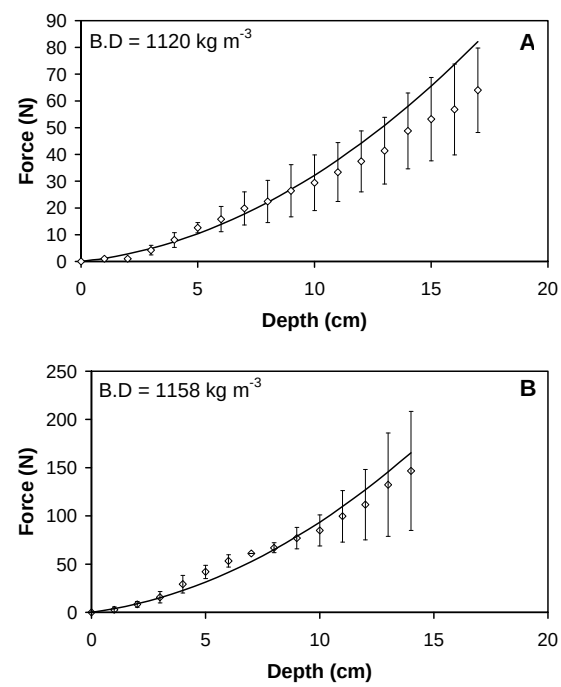
Probe	Diameter (cm)	Length (cm)	Tip Length (cm)	Tip Angle (º)
1	1.2	23	1	30
2	2	23.5	1.5	30

4. EXPERIMENTAL RESULTS

Penetration force is a strong function of the density of regolith materials [10] and increase with increasing bulk density [13].

Five different levels of compaction were prepared to achieve a bulk density of 1120, 1158, 1167, 1184 and 1241 kg m^{-3}. Fig. 3. shows the forces of penetration as a function of depth under different bulk densities. Solid line represents the theoretical force of penetration based on the knowledge of the bearing capacity factor N_q and bulk density. Penetration forces increase with increasing the compaction level.

Fig. 3 F shows the penetration force versus depth using a 1.9 cm diameter probe under a bulk density of 1184 kg m^{-3}. The N_q factor used for the theoretical force is the same as determined by 1.2 cm diameter probe (Fig. 3 D). Theoretical penetration curve is in agreement with the experimental data which supports the validity of the N_q factor under the same bulk density for different diameter probes.



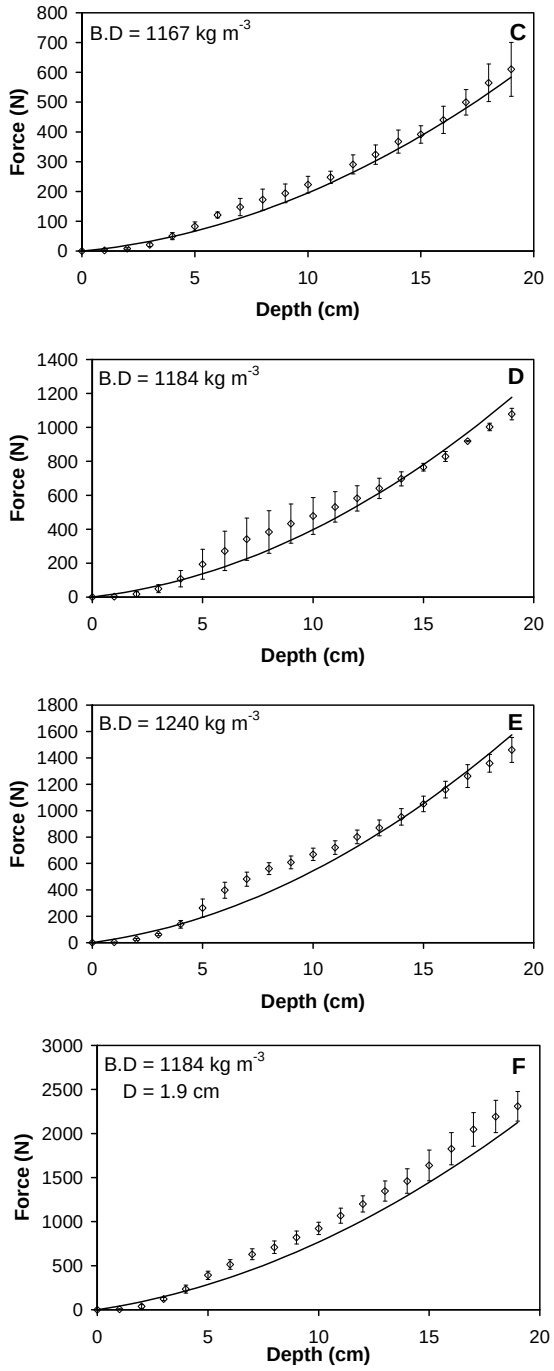


Fig. 3. Penetration forces as a function of depth for different bulk density (D = 1.2 cm for A, B, C, D, and E, T.A = 60º) (For F, D = 1.9, T.A = 60º).

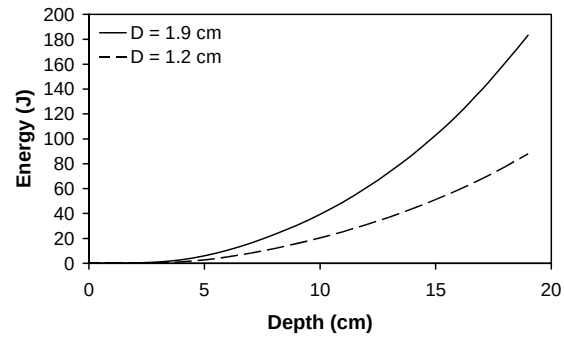


Fig. 6. Penetration energy as a function of depth for two different diameter probes under the same bulk density (B.D = 1184 kg m^{-3}).

Penetration energy is determined using two different diameter probes (D = 1.2 and 1.9 cm) under the same level of compaction (B.D = 1184) (Fig. 6). Penetration energy is determined by integrating the area under the curve for the experimental penetration forces. To reach to about 20 cm depth, a 1.2 cm probe requires about 90 J while the 1.9 cm probe needs about 180 J. Increasing the area by about a factor of two correspond to doubling the penetration energy.

5. DISCUSSION

Terzaghi [19], Meyerhof [20], Hansen [21] and Vesic [9] developed the bearing capacity theory. Some of them added depth and shape factors while others added the effect of unit weight. The bearing capacity factors are affected by the level of compaction as well as regolith friction angle [18]. Estimating the force of penetration using the current bearing capacity factors with JSC Mars-1 regolith material did not show good agreement between the experimental and theoretical values. Therefore, determination of the bearing capacity factor N_q for JSC Mars-1 was essential from forces of penetration.

Bearing capacity theory can be used to explain the movement of the penetrometer through regolith materials. The total penetration force (F_T) during probe insertion into the subsurface is the sum of two forces; the cone resistance (q_c) and the sleeve friction (f_s):

$$F_T = q_C A_C + f_S A_S \tag{1}$$

Where A_c is the area of the cone, A_s is the buried area of the sleeve. The cone resistance can be calculated from [11]:

$$q_C = \gamma \times Z \times N_q \left(1 + \left(K \times \sin\varphi \times \frac{Z}{L}\right)\right) \tag{2}$$

Where γ is the effective unit weight of sand (N m^{-3}), Z is the penetration depth (m), N_q is the bearing capacity factor (dimensionless), K is the coefficient of lateral pressure at rest (dimensionless), φ is the friction angle (degree) and L is the lateral extension of the slip lines (m). The friction angle is defined as [12]

$$\varphi = 25 + (0.15 \times D_r) \quad (3)$$

Where D_r is the relative density. The coefficient of lateral pressure is defined as [12]

$$K = 1 - \sin\varphi \quad (4)$$

Finally, the lateral extension of the slip lines L is defined as [11]:

$$L = B \times e^{(\frac{\pi}{2} \times \tan\varphi)} \times \tan(\frac{\pi}{4} + \frac{\varphi}{2}) \quad (5)$$

Where B is the cone diameter (m). From the knowledge of particle density of JSC Mars-1, the volume of solid particles can be calculated from:

$$V_s = \frac{m_s}{\rho_p} \quad (6)$$

Where V_s is the volume of solid particles (m^3), m_s is the mass of JSC Mars-1 (kg) and ρ_p is the particle density of JSC Mars-1 (kg m^{-3}). The particle density (ρ_s) determination for JSC Mars-1 is carried out by filling a beaker with water to a specific volume, pouring a weighted amount of JSC Mars-1 into the beaker and measure the change in volume. The resulting JSC Mars-1 particle density is ρ_p = 1900 kg m^{-3} and the values of e_{max} and e_{min} are found to be 1.16 and 0.53, respectively. Table 3 shows the particle density, bulk density and void ratio for JSC Mars-1 compared with [14] and [15].

Table 3
JSC Mars-1 regolith properties.

Author	ρ_p (kg m^{-3})	ρ_b (kg m^{-3})		e	
		A	B	e_{max}	e_{min}
[14]	1910	870	1070	1.19	0.78
[15]	1920	900	1160	1.13	0.65
*	1900	879	1240	1.16	0.53

* This paper
A un-compacted regolith
B compacted regolith

Based on Fig.3. a relation between bearing capacity factor N_q and bulk density can be extrapolated for JSC Mars-1 regolith material. Fig. 7. shows the average of the bearing capacity factor N_q and bulk density for JSC Mars-1. The bearing capacity factor N_q varies under each level of compaction which increases with increasing the bulk density of the prepared samples. The error in the caption of the bulk density measurement is about 1% which smaller than the symbol.

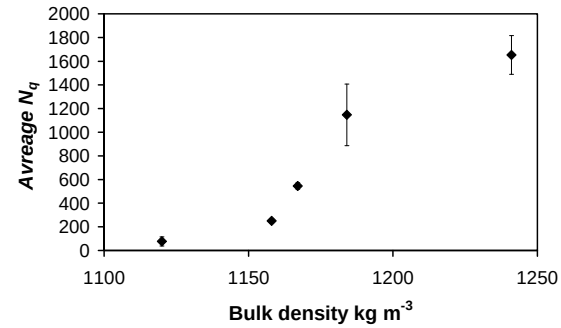


Fig. 7. Average bearing capacity factor N_q as a function of bulk density.

Determination the force of penetration is highly important for trafficability of lander/rover and feasibility of subsurface investigations. Viking lander 1 estimated Mars regolith bulk density of 1000 – 1600 kg m^{-3} while Viking lander 2 estimated a bulk density of 1100, 1480 and 2600 kg m^{-3} [16]. Sojourner, the Mars Pathfinder rover investigated Mars regolith material. The rover used its wheels to do a number of turns and to determine some regolith mechanical properties. The rover applied different turns and reached to different depths. The maximum depth reached by the rover wheels is 6 cm with 1.5 turn. The regolith bulk density is estimated to be 1520 kg m^{-3} [17]. Based on the knowledge of bearing capacity factor N_q and the corresponding bulk density, fig 8 shows the penetration force as a function of depth under Martian gravity for two different bulk densities (B.D = 1160 and 1250 kg m^{-3}).

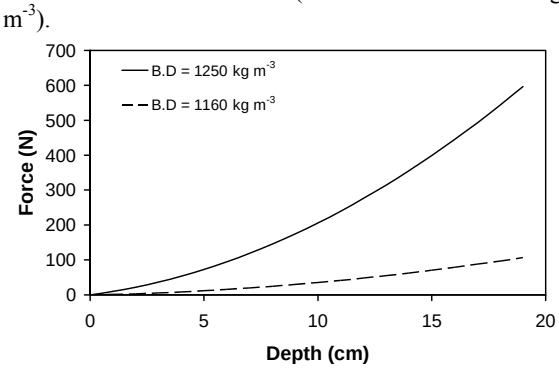


Fig. 8. Penetration testing under martian gravity under bulk density of 1160 and 1250 kg m^{-3}.

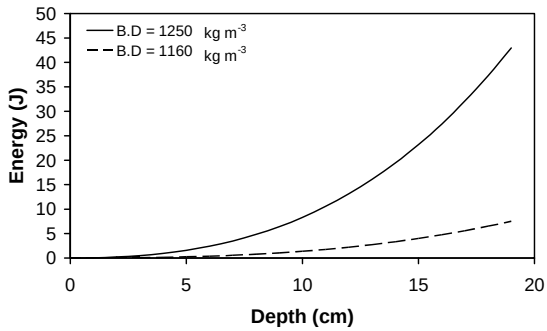


Fig. 9. Energy of penetration as a function of depth based on penetration forces under martian gravity for bulk density of 1160 and 1250 kg m^{-3}.

Regarding the penetration power, Spirit and Opportunity each can generate a peak of about 150 W of solar power. Over an average sol with fairly clean panels, they can produce about 600 W-hrs of power, which is equal to 2.2 MJ. MSL will produce 125 W continuously from its radio-isotropic thermal generator, giving up to 3000 W-hrs/sol or 10.8 MJ. The energy of penetration under martian gravity is shown in fig. 9. Our measurements in compacted JSC Mars-1 simulant (B.D = 1250 kg m^{-3}) with probe diameter of 1.2 cm indicate a requirement of 45 J to achieve about 20 cm. The peak rate of required power for probe insertion will be only about 1.2 W (600 N time's 0.002 m s^{-1}).

5. CONCLUSIONS

Bearing capacity equation is used to estimate the force of penetration of regolith materials. Using bearing capacity factor N_q from previous theories did not show agreement between experimental data and theoretical model. Therefore, there was a need to determine this factor in order to best estimate the force of penetration on extraterrestrial planetary bodies. Different penetration forces under different levels of compaction were carried out in order to determine the bearing capacity factor directly from experimental data.

The results of this investigation showed that the bearing capacity factor N_q vary under each level of compaction which increase with increasing the bulk density of the prepared samples. Knowledge of regolith mechanical properties determined from previous mission such as bulk density on Mars were used and applied in a theoretical model for estimating the force of penetration under martian conditions. Under martian gravity and a bulk density of 1250 kg m^{-3}, 600 N of force are enough to drive a 1.2 cm diameter probe to about 20 cm of the subsurface on Mars with about 1.2 W of power. Estimating the force of penetration would enhance future landing and subsurface planetary investigation which is a success to the whole mission.

6. RFERENCES

[1] Ball, A. J. and R. D. Lorenz. Penetrometry of extraterrestrial surfaces: A historical overview. Penetrometry in the solar system, Austrian Academy of Sciences, 3 – 23, 2001.

[2] Scott, R. F. and F. I. Robertson. Soil mechanics surface sampler. NSAS technical report TR 32-1265, Jet Propulsion Laboratory, 195-207, 1968.

[3] Mitchell, J. K., et al. Soil mechanics experiment. In; Apollo 14 preliminary science report. *NASA SP*. NASA SP-272, 87-108, 1971.

[4] Mitchell, J. K., et al. Apollo soil mechanics experiment S-200. Final report, NASA Contract NAS 9-11266, Space Science Laboratory Series 15, Issue 7, Uni. California, Berkeley, 1974.

[5] Ball, J. and R. D. Lorenz. Penetrometry of extraterrestrial surfaces: A historical overview. Penetrometry in the solar system II. Proceedings of the International Workshop held in Graz, Austria, October 18–20, 1999. Vienna: Austrian Academy of Sciences Press, 1999.

[6] Harvey, B. Russian planetary exploration: history, development, legacy and prospects. Praxis publishing Ltd, Chichester, UK, 134-135, 2007.

[7] Lorenz, D. R., et al. An impact penetrometer for a landing spacecraft. Measurement Science and Technology 5, 1033– 1041, 1994.

[8] Zarnecki, J. C., et al. A soft solid surface on Titan as revealed by the Huygens surface science package. Nature 438, 792–795, 2005.

[9] Vesic, B. A. Bearing capacity of deep foundations in sand. High way research record No39, 112-153, 1963.

[10] Lunne, T., et al. Cone Penetration Testing in Geotechnical Practice, first ed. Blackie Academic and Professional, London, 1997.

[11] Puech, A., and P. Foray. Refined model for interpreting shallow penetration CPTs in sands, Offshore Technology Conference, 6 -9 May 2002, Houston, Texas, 2002.

[12] Harr, M. E. Mechanics of particulate media, 260, McGraw-Hill. 1977

[13] ElShafie, A. et al. Penetration testing for the Optical Probe for Regolith Analysis (OPRA). Adv. Space Res, doi: 10.1016/j.asr.2010.03.017.

[14] Allen, C. C. et al. Martian regolith simulant JSC Mars-1. Lunar and Planetary Science XXIX, 1998.

[15] Perko, H. A. et al. Mars soil mechanics properties and suitability of Mars soil simulants. J. Aerospace engineering, 2006.

[16] Moore, H. J. et al. Surface materials of the Viking landing sites. JGR, 82, 4497, 1977.

[17] Hviid, S. F. et al. Characterization of the Martian surface deposits by the Mars Pathfinder rover, Sojourner. Science, 278, 1768, 1997.

[18] Murthy, V. N. S. Geotechnical Engineering: Principles and Practices of Soil Mechanics and Foundation Engineering (Civil and Environmental Engineering).CRC, 2002.
[19] Terzaghi, K. Theoretical soil mechanics, John Wiley, New York, 1943.
[20] Meyerhof, G.G. Some recent research on the bearing capacity of foundations. Canadian Geotechnical Journal, 1: 16–31, 1963.
[21] Hansen, J.B. A revised and extended formula for bearing capacity. Danish Geotechnical Institute, Bulletin 28, pp. 5–11, 1970.