SOIL MECHANICS RESULTS OF LUNA 16
AND LUNOKHOD I:
A PRELIMINARY REPORT

by

Stewart W. Johnson

W. David Carrier, III

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INTRODUCTION

The Ninth International Symposium on Space Technology and Science was held in Tokyo, Japan May 17-22, 1971. At this meeting two papers (Ref. 1 and 2) were presented giving results of the Luna 16 and Lunokhod-I experiments. These reports, which were presented by representatives of the Academy of Science of the USSR, concentrated on mechanical and physical properties of the lunar soil. In addition to these two papers, there were two 20-minute films shown on Luna 16 and Lunokhod I. The overall impression was that the USSR has performed a much more extensive soil mechanics investigation on their returned lunar sample and as part of the Lunokhod traverse than has been performed by the U.S. to date in the Apollo program. Apparently the Russian soil mechanics investigations are being conducted with the view that data collected now will be valuable in future exploration of the lunar surface. It was suggested that later versions of Lunokhod would be used to explore the far side of the Moon and would have a data storage capability to use while out of communication with earth.

At the meeting in Tokyo, results were presented for the Lunokhod-I penetrometer and analyses of the interactions between the vehicle wheels and the lunar soil. In addition, data was presented on the compressibility, resistance to penetration, friction characteristics, and shear strength of the returned lunar soil for various bulk densities. Several potentional spacecraft materials have been tested in contact with lunar soil to determine friction and wear characteristics.

GENERAL CONCLUSIONS REACHED BY RUSSIANS

The conclusions reached by the Russians after a study of Lunokhod data are as follows (Ref. 1):

"1. The soil on the route of motion of Lunokhod-1 is fine-grained material possessing some cohesion.

2. The layer of fine-grained soil has a thickness of at least 50 - 100 mm and is uniform in depth. The top layer of the soil is friable, dust-like, easily deformed material.

3. The bearing strength of the soil varies depending on the terrain conditions from 0.2 to 1.0 kg/cm^2 and rotational shear strain from 0.02 to 0.09 kg/cm^2.

   The bearing strength of 0.34 kg/cm^2 and rotational shear strain of 0.048 kg/cm^2 are the most frequently occurring. The mechanical strength of the soil gradually increases with depth.

4. The soil at the site of motion of Lunokhod-1 is characterized by good compacting ability. With the packing of the soil the bearing strength and rotational shear strain considerably increase."

We infer that when they refer to rotational shear "strain" they actually mean rotational shear strength.

ANALYSIS OF LUNOKHOD PENETROMETER RESULTS

In this brief report we will concentrate on the results obtained with the Lunokhod-1 penetrometer. At the time of the meeting in Tokyo (May 1971) it was announced that this unmanned vehicle had completed a 9200 meter closed-loop traverse during 6 months of lunar operations. The penetrometer on Lunokhod-1 has the characteristics shown in Table 1:

TABLE 1

(Modified from NASA photograph S-71-34018)

Main Technical Characteristics of Instrument

Diameter of cone base	5.0 cm
Height of cone	4.4 cm
Angle of cone	60^{o}
Diameter of vanes	7.0 cm
Penetration effort	in excess of 20 kg
Maximum penetration depth	10.0 cm
Angle of turn of vanes	up to 90^{o}

This penetrometer has been used in several different locations on the Lunokhod traverse with results shown in Figure 1 and Table 2 of this report. We have used the data in Figure 1 to develop Tables 3 to 6, which present unit penetration resistance vs. penetration depth for the four surface units described by the Russians.

TABLE 2

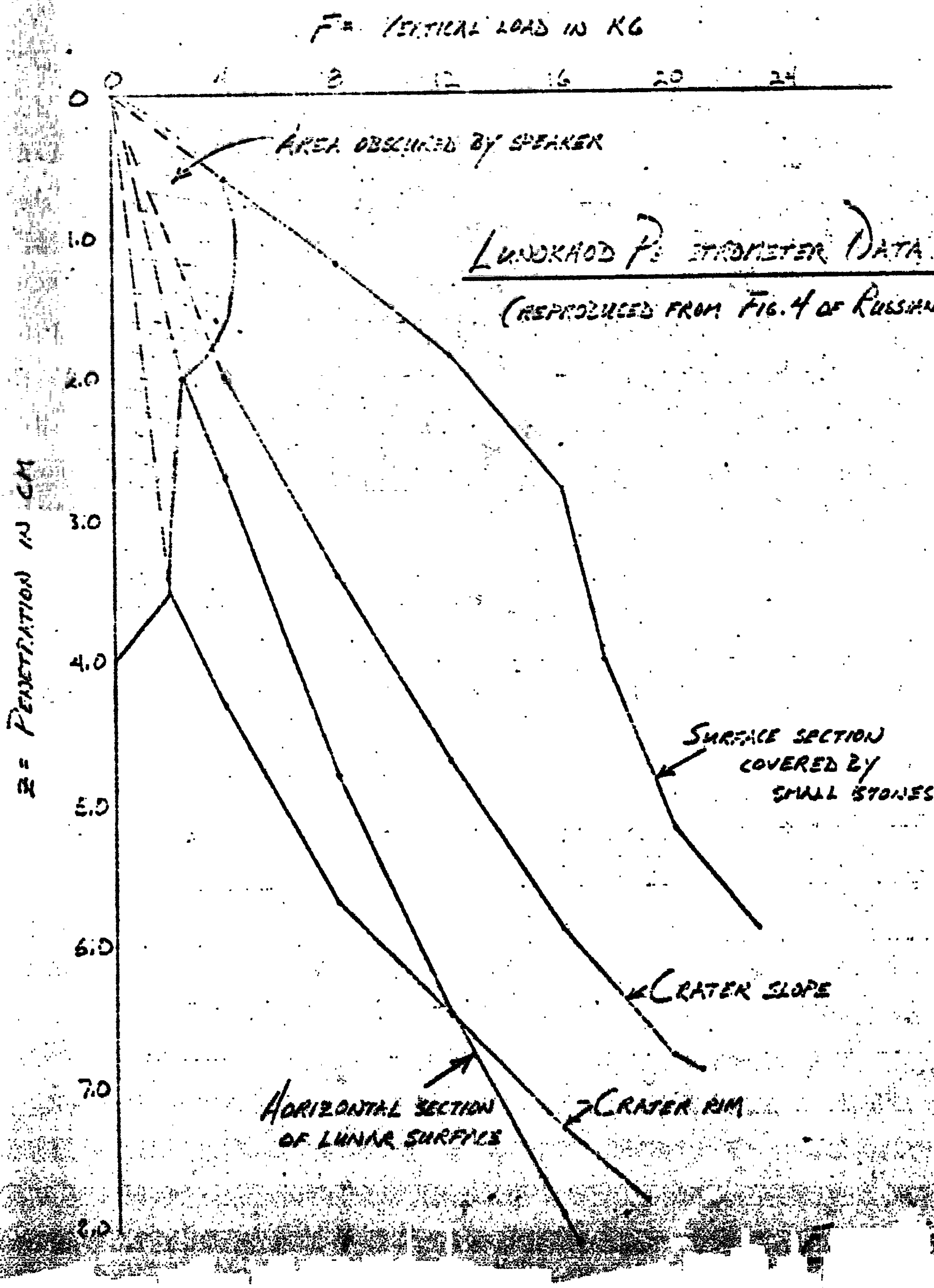
LUNOKHOD PENETROMETER DATA
(extracted from Fig. 4 of Russian paper
and reproduced as Fig. 1 in this report)
NASA Photo No. S-71-34020
F = Vertical load in kg
Z = Penetration in cm

1. Horizontal section of lunar surface	F=0	2.5	4	8	12	16	16.5		
	Z=0*	2.0	2.7	4.8	6.5	7.9	8.1		
2. Crater slope	F=0	4	8	12	16	20	20.5		
	Z=0*	2.0	3.4	4.7	5.9	6.8	6.9		
3. Crater rim	F=0	2	4	8	12	16	19		
	Z=0*	3.5	4.3	5.7	6.5	7.3	7.8		
4. Surface section covered by small stones	F=0	-4	8	12	16	17.5	20	23	
	Z=0*	.6	1.2	1.8	2.8	4.0	5.2	5.9	

*Interpreted from shape of curves: origin obscured by speaker.

LUNOKHOD PENETROMETER DATA

(REPRODUCED FROM FIG. 4 OF RUSSIAN PAPER)



We have made two key assumptions in analyzing the penetrometer data of Figure 1:

1. Assumption:

   Force in kilograms is converted to newtons by multiplying by 9.8 (earth gravity conversion).

   Rationale:

   Maximum force applied is less than 24 kg or 235N; lunar weight of Lunokhod has been estimated to be in excess of 900N. Thus, there is ample reaction force available and it is unlikely that the penetrometer would utilize only 39N (235N ÷ 6) of this reaction force.

2. Assumption:

   Penetration depth is measured with respect to cone tip rather than to cone base.

   Rationale:

   There is no force-intercept at zero penetration (see Fig. 1). If penetration were measured from the cone base, a positive force-intercept would be expected.

TABLE 3.

On horizontal section of lunar surface

F(kg)	F(N)	Z(cm)	$A(cm^2)^a$	$F/A(N/cm^2)$	$Z'(cm)^b$
2.5	24.5	2.0	4.05	6.05	
4	39.2	2.7	7.40	5.30	
8	78.4	4.8	19.65	3.99	.4
12	117.6	6.5	19.65	5.98	2.1
16	156.8	7.9	19.65	7.98	3.5
16.5	161.7	8.1	19.65	8.22	3.7

[a] Area of cone. Height of cone is 4.4 cm and base diameter is 5.0 cm. Area is proportional to square of penetration depth for $Z \leq 4.4$ cm and is constant for $Z \geq 4.4$ cm.

[b] $Z' = Z - 4.4$ cm.

TABLE 4

On crater slope

F(kg)	F(N)	Z(cm)	A(cm^2)	F/A(N/cm^2)	Z'(cm)
4	39.2	2.0	4.05	9.68	
8	78.4	3.4	11.70	6.70	
12	117.6	4.7	19.65	5.98	.3
16	156.8	5.9	19.65	7.98	1.5
20	196	6.8	19.65	9.98	2.4
20.5	201	6.9	19.65	10.23	2.5

TABLE 5

On crater rim

F(kg)	F(N)	Z(cm)	A(cm^2)	F/A(N/cm^2)	Z'(cm)
2	19.6	3.5	12.42	1.58	
4	39.2	4.3	18.73	2.09	
8	78.4	5.7	19.65	3.99	1.3
12	117.6	6.5	19.65	5.98	2.1
16	156.8	7.3	19.65	7.98	2.9
19	186	7.8	19.65	9.47	3.4

TABLE 6

On surface section covered by small stones

F(kg)	F(N)	Z(cm)	A(cm^2)	F/A(N/cm^2)	Z'(cm)
4	39.2	.6	.365	107	
8	78.4	1.2	1.46	53.7	
12	117.6	1.85	3.47	33.9	
16	156.8	2.8	7.94	19.75	
17.5	171.5	4.0	16.25	10.54	
20	196	5	19.65	9.98	.8
23	225	5.9	19.65	11.44	1.5

F/A vs. Z is plotted in Fig. 2.

F/A vs. Z' is plotted in Fig. 3.

F/A vs. Z' for the Lunokhod Penetrometer is compared with similar data for the Apollo 14 ASP (Apollc Simple Penetrometer) in Fig. 4.

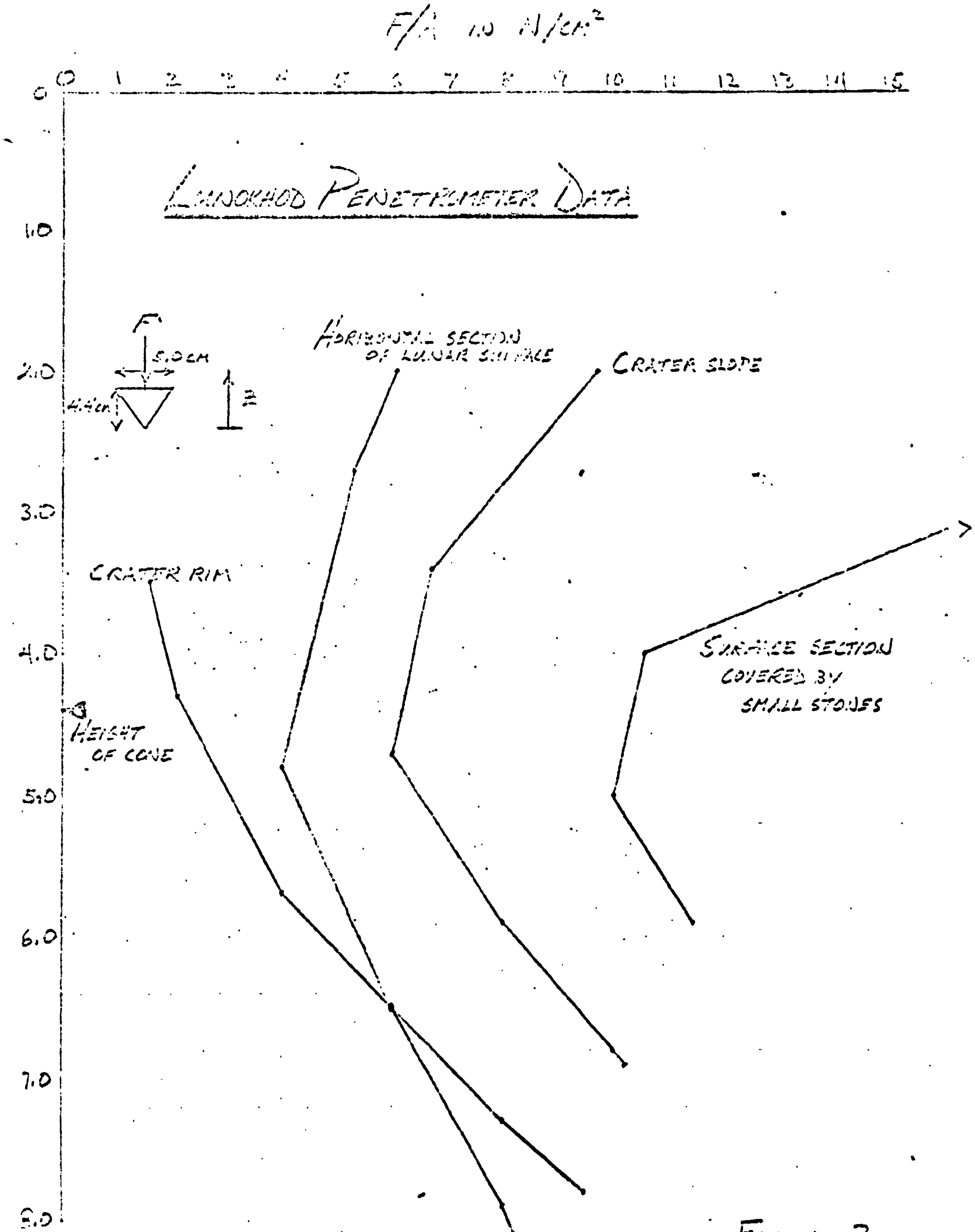
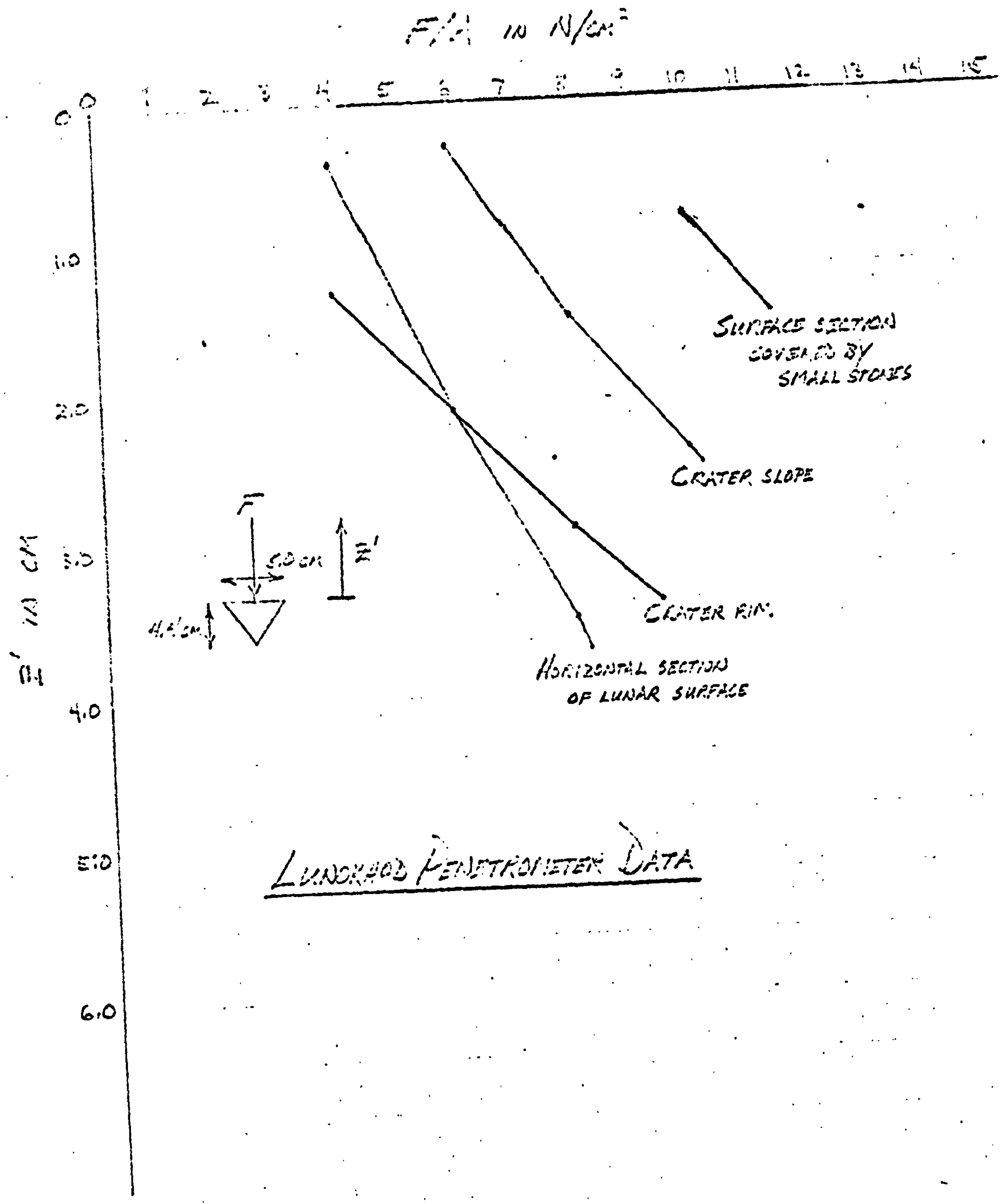

F/A in N/cm²
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
LUNOKHOD PENETROMETER DATA
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
Z IN CM
F
5.0 CM
4.4 cm
HORIZONTAL SECTION OF LUNAR SURFACE
CRATER SLOPE
CRATER RIM
HEIGHT OF CONE
SURFACE SECTION COVERED BY SMALL STONES

FIGURE 2



LUNOKHOD PENETROMETER DATA

FIGURE 3

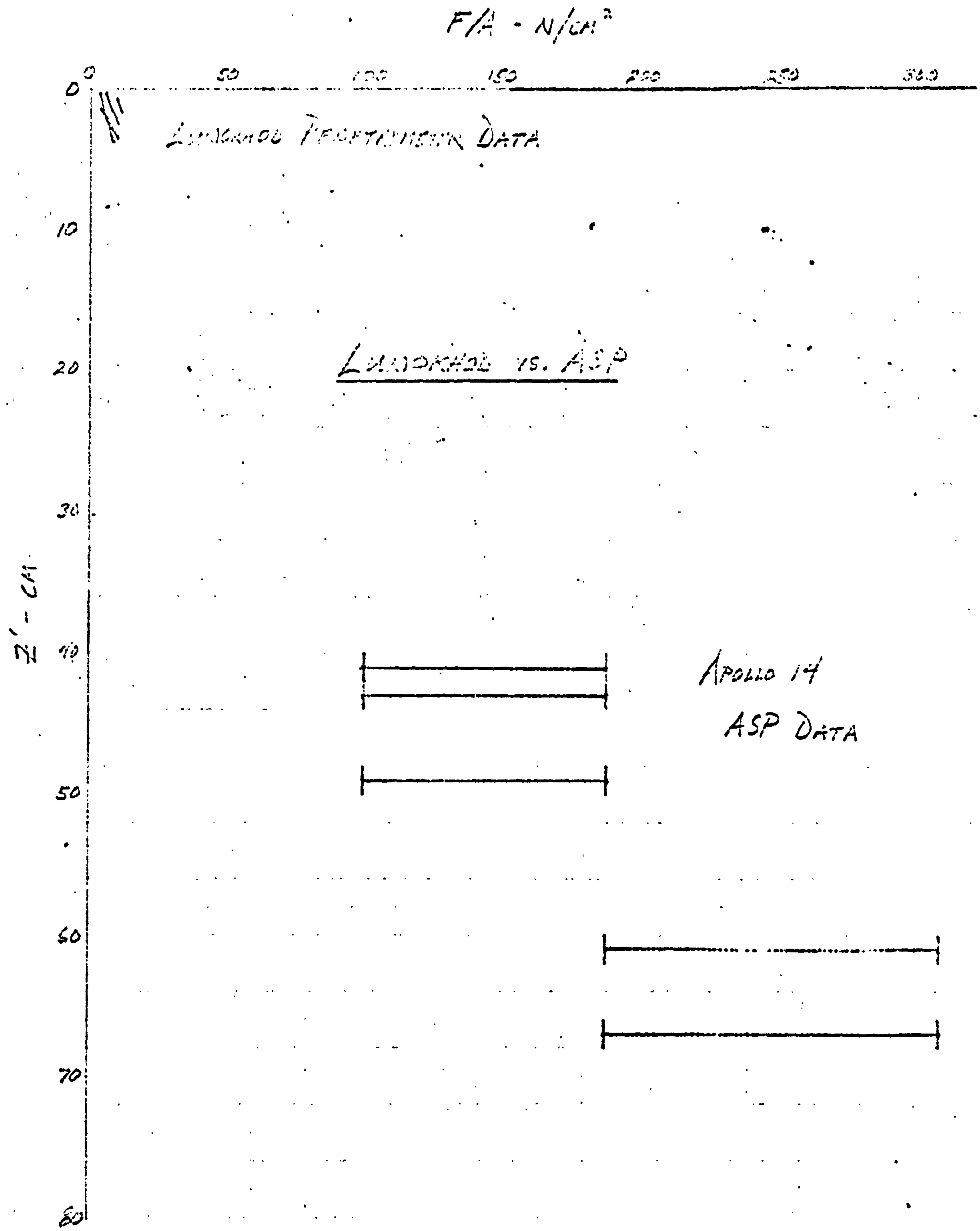

F/A - N/cm²
0
50
100
150
200
250
300
Lunokhod Penetrometer Data
Lunokhod vs. ASP
Apollo 14
ASP Data
z' - cm
10
20
30
40
50
60
70
80

Figure 4

CONCLUSIONS

1. As has been previously observed on the Apollo missions, the rims of craters can be considerably softer than the soil between craters.

2. As has also been previously observed, crater slopes can be considerably stronger than the soil between craters.

3. Small stones on the surface can increase the penetration resistance dramatically.

4. The Lunokhod penetrometer and the ASP measured very different depths in the lunar surface and thus the data cannot be compared directly. However, the two sets of data do permit preparation of a better soil simulant for further testing and analysis.

5. The Russian data permit many calculations to be made concerning settlement, bearing capacity, rover performance, and strength and density parameters for the top 10 cm of the lunar soil. These calculations will be explored in more detail at a later date.

REFERENCES

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2. Cherkasov, I. I., V. V. Gromov, A. K. Leonovich, V. V. Shvarev, and A. A. Silin, "Investigations of the Physical and Mechanical Properties of the Lunar Soil Sample Delivered by Luna-16," Proceedings of the Ninth International Symposium on Space Technology and Science, Tokyo, Japan, May 1971 (in press).