the borings at depths from the ground surface varying from 7 feet (2 m) to 55 feet (17 m). The water was not always observed during drilling, but sometimes a day after drilling, which is typical of ground water in the mountains. Some water was also observed in the cavities.

As previously discussed the bedrock consisted of the Eagle Valley Evaporite Formation. This bedrock consisted of intermixed and interlaminated anhydrite, shale, sandstone, and limestone seamed and veined with white gypsum. In some areas the gypsum had been eroded from the bedrock by flowing ground water. This resulted in open cavities and cavities filled with very soft soils. The surface of the bedrock was discovered at depths ranging from 19 feet (6 m) to 85 feet (26 m) beneath the ground surface. Cavities ranging in height from 2 feet (1 m) to 13 feet (4 m) were encountered in the borings. The cavities were intercepted by the borings at depths from 25 feet (8 m) to 84 feet (26 m) beneath the ground surface. Based on the investigation it appeared that several long, linear, narrow, chambered solution cavities existed in the evaporite bedrock. These cavities appeared to be geologically old features (created before the end of the ice age) and the solutioning process was dormant or occurring at a slow rate. Based mainly on direct observations made from boring PH-2 of the cavern penetrated by that boring, a geologic profile (Figure 3) and a geologic map (Figure 4) were prepared. The location of the profile and map are shown in Figure 2.

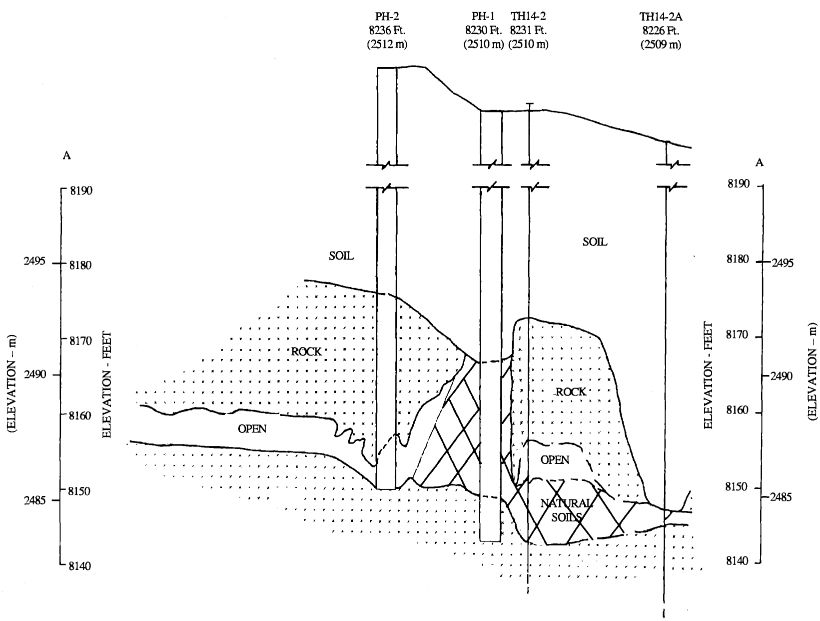

Figure 3. Geologic profile of the cavity complex

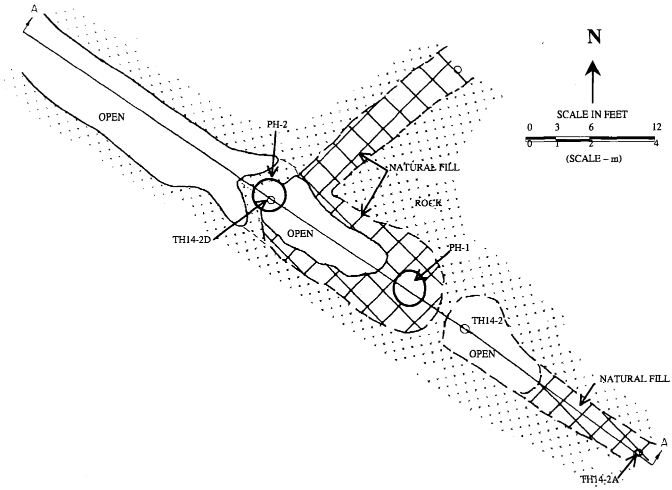

Figure 4. Geologic map of the cavity complex

Foundation System

Shallow and deep foundation systems were considered for this site. The performance of each foundation system was influenced by the cavities beneath the site.

A shallow foundation system, such as spread footing foundations, could support the structures with a low risk of movement if the cavities were filled with grout. Filling the cavities with grout was possible. However, the quantity of grout that would be needed to fill the cavities was unknown. In addition, confirming that all cavities were filled with grout would be difficult. Therefore this foundation system would have an unknown risk of settlement.

Deep foundation systems such as driven piles and drilled caissons were also possible. These systems could support the structures with a low risk of movement provided they were founded in the competent bedrock. Both of these systems would also be influenced by the cavities. Driving pile foundations through the soils would be possible. However, it would be difficult to drive the piles through the bedrock surface and then through cavities to the competent bedrock. It would not be possible to observe the tip of the pile. With the unknown bearing condition, this foundation system would have some risk of movement. Construction of caisson foundations would require drilling a caisson hole through the soil, into the bedrock, through the cavities, and then socket into the competent bedrock. The drilling and bottom of the caisson could be observed. However, the portion of the caisson through the cavity would require forming so that the caisson concrete did not flow into the cavity.

Due to the unknown costs associated with filling the cavities with grout, risk of settlement with a spread footing foundation, construction difficulties with a driven pile foundation, the developer selected a caisson foundation system. However, to contain the concrete when the caisson penetrated through a cavity we recommended installing permanent casing through the cavities. An example of a permanently cased caisson is shown in Figure 5.

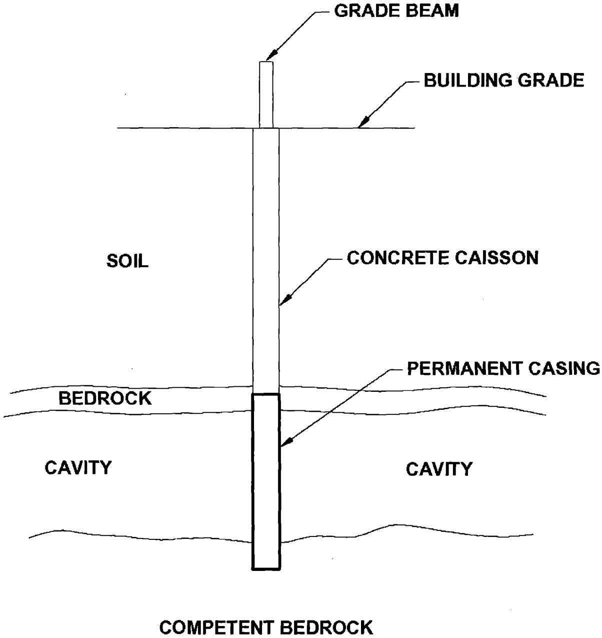

Figure 5. Example of permanently cased hole

Additional Investigation

Upon discussing and reporting our findings with the owner of the lots and the developer, a fourth phase of the investigation was developed. In this phase the caisson foundation system was designed for each of the four buildings. Then KCE investigated the subsurface conditions at each caisson location. The purpose of this phase of the investigation was to evaluate the location and depth of cavities at each caisson location. Access to the site was provided for a truck drill rig by grading level areas where the foundation walls would be constructed. This was performed in June and July 1987, by drilling 103 borings with a 4-inch (10-cm) diameter, continuous flight, power auger. The holes were advanced continuously with the auger without taking samples of the subsurface materials. The plumbness of the drill rig and augers were maintained as the holes were drilled to obtain a vertical straight hole. The subsurface materials were logged based on the behavior of the drill rig, the materials emerging around the auger, and our experience from the previous investigations. Each boring was drilled at least 25 feet (8 m) into the bedrock resulting in the depth of these borings ranging from 40 feet (12 m) to 113 feet (34 m). Based on the results of these borings we recommended the need for permanent casing, the length of casing, and the bottom elevation for each caisson.

Construction

The additional boring information, bottom elevation of each caisson, which caissons required permanent casing, and the length of permanent casing were provided for contractors to bid on the project. Only 2 contractors bid on the foundation construction. The contract was awarded to the low bidder. During construction we observed the drilling of the 103 caissons. Due to the investigation program, the drilling of the caisson foundations occurred as anticipated and the contractor completed caisson construction as scheduled. A photograph of construction of a caisson is shown on Figure 6.

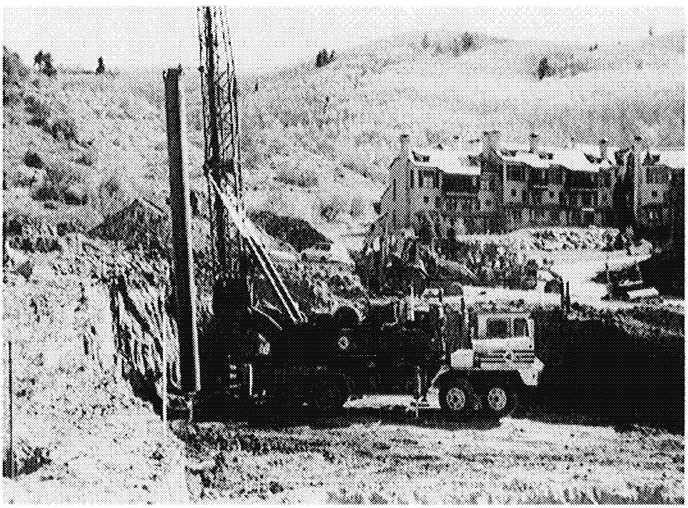

Figure 6. Caisson construction

Conclusions

Even with complex geology beneath this site construction of the buildings was possible. Communication with the developer so that they understood the risks associated with the cavities resulted in their willingness to perform a more detailed subsurface investigation. With the detailed subsurface information for the caisson foundations a bid was obtained from the foundation contractor that had very few contingencies. The selection of this innovative foundation system with permanent casing in the cavity zones resulted in a system that could be constructed with known costs. In addition, the quantity of concrete needed to construct this foundation system was significantly less than pumping grout into the cavities. The buildings have not experienced any movement almost 20 years after construction.

Technology keeps evolving such that other foundation construction techniques continue to be developed. Today another foundation option would be micropiles. Micropiles were not available at the time these buildings were constructed.

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Geotechnical Techniques used in Planetary Exploration

Howard A. Perko, Ph.D., P.E.[1]

[1]Division Manger, CTL|Thompson, Inc., 351 Linden Street, Unit 140, Fort Collins, CO 80525; PH (970) 206-9455; FAX (970) 206-9441; e-mail: hperko@ctlthompson.com

Abstract

During Surveyor and Luna missions, thirteen U.S. and Russian landers and rovers examined the surface of the Moon and evaluated soil mechanics using a variety of penetrometers, soil scoops, and nuclear densiometers. Samples of the lunar regolith were returned to earth via unmanned rocket capsules. During the Apollo Era, the U.S. sent six manned missions to the surface of the Moon. Astronauts incorporated various penetrometers, drills, trench excavations, and other techniques to evaluate soil mechanics. Lunar module footpad penetrations and even astronaut footprints were analyzed to obtain soil mechanics information.

More recently, focus has shifted to exploration of Mars. To date, two Viking landers and three rovers have explored the surface of Mars. Soil mechanics information has been collected by analysis of rover tracks, trench excavations, airbag impacts, back calculation of landslide features, and footpad penetrations. On Earth, geotechnical engineers and geologists employ a number of standard test procedures. It is important to always keep in mind that almost any penetration or interaction with soil and rock can be analyzed to determine useful properties of those materials.

Introduction

A brief history of the exploration of the Moon and Mars is presented. Soil mechanics investigations during various missions are described. The goal of this paper is to expose the reader to a brief account of planetary soil mechanics techniques for the purpose of demonstrating that observations of ordinary interactions with soil and rock can reveal an extraordinary amount of useful information about soil composition, density, and strength.

Pre-Apollo Geotechnical Exploration of the Moon

In 1961 when President John F. Kennedy proposed the manned lunar landing as the focus of the United States' space program, little was known about the properties and composition of the surface of the Moon. The history of lunar space missions is shown in Table 1. Before 1961, the US lunar missions consisted of four Pioneer spacecraft. One of these exploded, two failed to reach escape velocity, and the fourth flew past the Moon on a very distant trajectory and took radiation measurements. Each spacecraft weighed less than 6 kg (13 lb).

Prior to 1961, the USSR lunar space program consisted of two successful lunar flybys and a hard lander. Luna 1 was the first lunar flyby. Luna 2 was the first spacecraft to impact the surface of the Moon, and Luna 3 returned the first image of the Moon's hidden side (Fig. 1). These spacecraft weighed up to 387 kg (853 lb). Clearly, the USSR had a significant head start in the space race.

A number of early theories about the composition lunar surface were derived from laboratory research. One attempt to simulate the formation of igneous rock in vacuum and low gravity resulted in a fiber glass like structure. The work suggested that the surface of the Moon might consist of loose, fibrous material similar to cotton candy in strength and consistency.

A second set of experiments consisted of exposing a granular silicate to ultrahigh vacuum and high temperature for a considerable time period. The resulting product was a type of ceramic. These experiments suggested the surface of the Moon might be extremely hard and cemented.

A third series of experiments consisted of loosely depositing granular silicates in ultrahigh vacuum. The soil formed an extremely porous deposit due to unexplained temporary cohesion. A hypothesis called the "fairy castle theory" suggested that the surface of the Moon was extremely loose and meta-stable.

Yet another research project involved creating iron particles in ultrahigh vacuum. When air containing oxygen entered the chamber, a spark occurred due to oxidation of the metal. It was theorized that opening the Lunar Excursion Module (LEM) could cause spontaneous combustion on the highly reduced iron-rich surface of the Moon.

Still another set of experiments involved depositing dust in vacuum. The dust became electrostatically charged during deposition and adhered in thick layers to all surfaces within the chamber including the underside of wires and equipment. One interpretation of the results was that dust on the surface of the Moon would be so adhesive and pervasive that the LEM and astronauts may be immobilized.

Immediately following President Kennedy's announcement of the lunar agenda, much effort was dedicated to further laboratory testing of soils in low gravity and ultrahigh vacuum. A number of high quality investigations were conducted, too many to list herein. The *Lunar Source Book* (1991) contains many references. An example is found in Perko and Nelson (2000), which describes some of the research at the Illinois Institute of Technology conducted in the 1960s.

To supplement laboratory work, it was imperative to conduct robotic field reconnaissance prior to sending humans to the Moon. Between 1964 and 1965, America sent three successful hard landers to the Moon. These Ranger spacecraft returned close-up photographs of the Moon showing a cratered surface with possible boulders. Meanwhile, the USSR achieved the first successful soft landing on the Moon, Luna 9, which returned several photographs from the surface. Perhaps the most important discovery of the Luna 9 mission was determining that a foreign object would not sink into the lunar dust and that the ground could support a heavy lander.

Table 1. History of Lunar Robotic Missions

Date	Mission	Type	Cntry.	Soil Mechanics Studies
Jan 2, 1959	Luna 1	Flyby	USSR	First Lunar Flyby
Mar 3, 1959	Pioneer 4	Flyby	USA	None
Sept 12, 1959	Luna 2	Hard Lander	USSR	First Lunar Hard Landing
Oct 4, 1959	Luna 3	Flyby	USSR	First Photograph of Far-Side
Apr 23, 1962	Ranger 4	Hard Lander	USA	First US Hard Landing
Oct 18, 1962	Ranger 5	Flyby	USA	Distant Photographs
July 28, 1964	Ranger 7	Hard Lander	USA	Close-Up Photographs
Feb 17, 1965	Ranger 8	Hard Lander	USA	Close-Up Photographs
Mar 21, 1965	Ranger 9	Hard Lander	USA	Close-Up Photographs
Jan 31, 1966	Luna 9	Soft Lander	USSR	First Lunar Soft Landing
1966	Luna 10-12	Orbiter	USSR	Photographs
Apr 30, 1966	Surveyor 1	Soft Lander	USA	Footpad Penetrations, Engine Exhaust Erosion
1966-1967	Lunar Orbiter 1-5	Orbiter	USA	Photographs, Mapping
Dec 21, 1966	Luna 13	Soft Lander	USSR	Penetrometers, Accelerometer
Feb 5, 1967	Surveyor 3	Soft Lander	USA	Trench, Plate Bearing, Footpad Penetrations, Impact Tests, Engine Exhaust Erosion
Jul 19, 1967	Explorer 35	Orbiter	USA	None
Sept 8, 1967	Surveyor 5	Soft Lander	USA	Footpad Penetrations, Engine Exhaust Erosion
Nov. 7, 1967	Surveyor 6	Soft Lander	USA	Footpad Penetrations, Engine Exhaust Erosion
Jan. 7, 1968	Surveyor 7	Soft Lander	USA	Footpad Penetrations, Engine Exhaust Erosion
Apr 7, 1968	Luna 14	Probe	USSR	Photographs
1968-1970	Zond 5-8	Fly-Around	USSR	None
Sept 12, 1970	Luna 16	Soft Lander	USSR	Drill, Sample Return
Nov 10, 1970	Luna 17	Rover	USSR	Penetrator, Densiometer
Sept 28, 1971	Luna 19	Orbiter	USSR	Photographs
Feb 14, 1972	Luna 20	Soft Lander	USSR	Drill, Sample Return
Jan 8, 1973	Luna 21	Rover	USSR	Penetrator, Nuclear Desiometer
May 1974	Luna 22	Orbiter	USSR	Photographs
Aug 9, 1976	Luna 24	Soft Lander	USSR	Drill, Sample Return
Jan 25, 1994	Clementine	Orbiter	USA	Photographs, Mapping, Laser Altimeter
Jan 6, 1998	Lunar Prospector	Orbiter	USA	Spectrometer, Photographs, Mapping
Dec 2002	SMART 1	Orbiter	ESA*	X-Ray Spectrometer, Photographs, Mapping

*European Space Agency

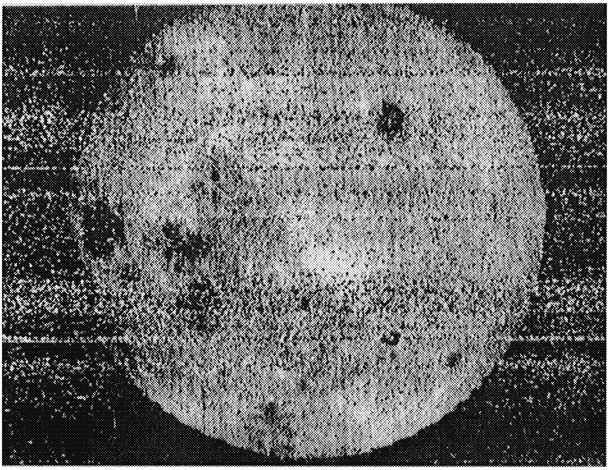

Figure 1. Soviet Image of Lunar Far-Side

In 1966, another USSR soft lander, Luna 13, successfully arrived on the Moon. An accelerometer recorded the landing forces during impact and scientists were able to determine the soil structure down to a depth of 20 to 30 cm (8 to 12 in). In addition, a pair of spring-loaded booms was deployed and titanium-tipped rods were driven into the ground by small explosive charges. The penetrators measured a soil density of roughly 0.8 g/cm^3 (50 lb/ft^3).

Between 1966 and 1968, the U.S. soft landed Surveyor 1, 3, 5, 6, and 7 on the Moon. Surveyor 1 was the first U.S. spacecraft to land safely on the Moon. On all five missions, close-up images of the lunar surface showed that it was safe for manned landings. In all, the Surveyors returned nearly 88,000 high-resolution pictures of the Moon's surface and performed the first soil analysis. The Surveyor 3 lander was equipped with a soil mechanics surface sampler that was designed to dig, scrape, and trench the lunar surface and to transport lunar surface material while being photographed so that the properties of the lunar surface could be determined. The surface sampler performed seven bearing tests, four trench tests, and 13 impact tests. The soil mechanics surface sampler project was administered by Ronald F. Scott, a notable geotechnical engineer from California Institute of Technology. A photograph of the surface sampler and lander footpad on the lunar surface is shown in Fig. 2. Soil mechanics information was also determined from footpad penetrations during landing. Strain gauges on lander legs provided impact force measurements. Photographs showed penetration depths.

Equally important to selecting landing sites, a series of U.S. orbiters, Lunar Orbiter 1-5 (1966-1967), successfully accomplished mapping of 99 % of the surface of the Moon with resolution down to 1 meter (3 ft). Altogether the Orbiters returned 2180 high resolution and 882 medium resolution frames. The micrometeoroid experiments recorded 22 impacts.

The subsequent Apollo manned missions to the Moon were largely successful due to the soil mechanics investigations carried out remotely by landers and extensive mapping from orbiters. Laboratory penetration, direct shear, and density experiments helped to qualify some of the potential processes unique to the lunar environment. Penetrometer data, footpad penetrations, landing forces, soil scoop trench stability, and plate bearing tests were analyzed to estimate soil shear strength, bearing capacity, density, and even gradation. From these data and careful analysis of photographs, a notable geologist, Eugene M. Shoemaker, arrived at the theory that the regolith covering the moon was formed by a weathering process caused by continued meteoroid and micrometeoroid bombardment which, with the decline in meteoroid size and impact frequency over time, has resulted in a gardening effect with finer grained materials at the surface that slowly grade to more course material at depth. This governing theory in lunar geology was formed and the Apollo missions were attempted without soil borings and without cone or split-spoon drive samples.

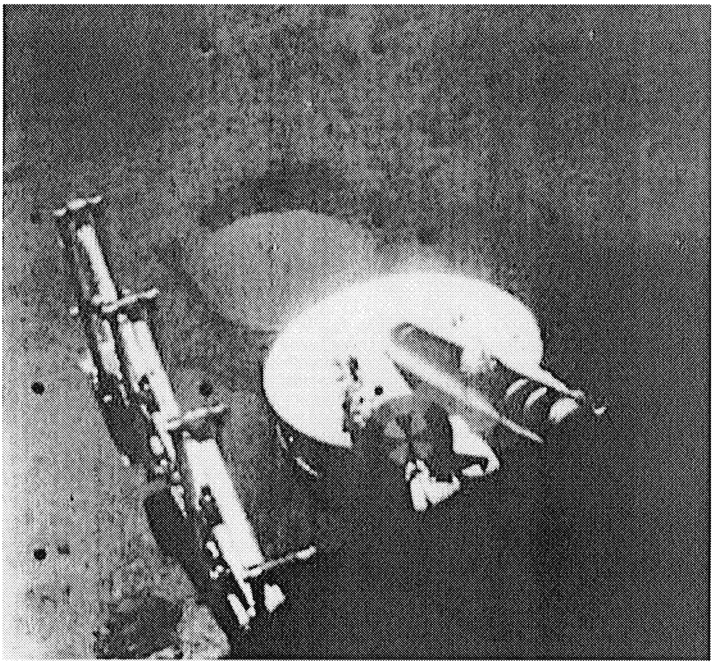

Figure 2. Surveyor Footpad and Soil Mechanics Surface Sampler