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A comprehensive review of lunar lava tube base construction and field research on a potential Earth test site

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ABSTRACT

The Moon, as the closest celestial body to the Earth, plays a pivotal role in the progression of deep space exploration, and the establishment of research outposts on its surface represents a crucial step in this mission. Lunar lava tubes are special underground caves formed by volcanic eruptions and are considered as ideal natural shelters and scientific laboratories for lunar base construction. This paper begins with an in-depth overview of the geological origins, exploration history, and distribution locations of lunar lava tubes. Subsequently, it delves into the presentation of four distinctive advantages and typical concepts for constructing bases within lava tubes, summarizing the ground-based attempts made thus far in lunar lava tube base construction. Field studies conducted on a lava tube in Hainan revealed rock compositions similar to those found during the Apollo missions and clear lava tube structures, making it a promising analog site. Lastly, the challenges and opportunities encountered in the field of geotechnical engineering regarding the establishment of lunar lava tube bases are discussed, encompassing cave exploration technologies, in-situ testing methods, geomechanical properties under lunar extreme environments, base design and structural stability assessment, excavation and reinforcement techniques, and simulated Earth-based lava tube base.

1. Introduction

The Moon, being the closest celestial body to the Earth, serves as a primary site for resource exploration, scientific and technological experiments, and an outpost for deep space exploration [1–4]. The imperative to establish a lunar base has grown significantly for scientific exploration. Throughout history, humans have sought shelter in caves to resist external influences, and similarly, natural caves on extraterrestrial planets can provide initial shelters for humans [5]. In recent years, with the rapid advancement of observation technologies, research on planetary caves has experienced substantial growth, and the exploration and utilization of extraterrestrial caves are in a golden age of scientific discovery [6–8].

Lunar lava tubes are naturally occurring underground spaces on the Moon and are considered as ideal natural shelters and scientific laboratories for building lunar bases, offering unique environmental advantages such as a relatively stable temperature environment, low radiation levels and large internal volume. Over the past few decades, a series of discoveries relating to lunar lava tube skylights and gravity gradients features have fueled enthusiasm for lunar base construction [9–11]. Scientists have consistently advocated for the establishment of lunar bases using lunar lava tube, considering it the optimal location for human construction of research bases on the Moon [5,12–14].

More than 50 years ago, Halliday [15] speculated on the existence of lunar lava tubes and proposed the concept of using them as human habitats. In 2018, Gibney [16] suggested in *Nature* that lava tubes could provide natural barriers, offering protection for shelters and their inhabitants from potential hazards of charged particle radiation and meteorite impacts. In recent years, some inflatable human habitat modules have been proposed, which can be adapted for the construction of lunar lava tube bases [17,18]. Additionally, both domestic and foreign research institutions are conducting technical verification work on Earth to accumulate experience for future lunar lava tube exploration and construction [19–21].

This study aims to comprehensively present the latest advancements in the establishment of lunar lava tube bases, offering an in-depth review of their formation mechanisms, exploration history, distinct advantages, and conceptual frameworks. The paper is structured as follows: it begins by introducing the geological ori-

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gins, exploration history and evidence, and distribution locations of lunar lava tubes. Subsequently, it elaborates on the four unique advantages of selecting lunar lava tubes to build bases and reviews current domestic and foreign concepts for lunar lava tube base construction. Then, the Earth analog sites of lunar lava tube bases and the field research of Haikou lava tube in China are presented. Lastly, it provides a summary of the challenges and opportunities pertaining to geomechanics in the construction of lunar lava tube bases.

2. Lunar lava tubes

2.1. Geological origins

Lava tubes, also referred to as pyroducts [22], form as a result of volcanic eruptions in celestial bodies and represent a specific type of subterranean cavity created by the flow and subsequent solidification of lava [23]. Thermal and mechanical erosion are significant factors contributing to the widening and reinforcement of lava tubes [24]. During volcanic eruptions, the lava in motion exhibits an extremely high temperature while the surrounding environment remains comparatively cooler. The temperature difference between the flowing lava and the atmosphere causes the outer, less viscous lava to cool and solidify as it moves, resulting in the formation of a sturdy, insulating shell [25,26]. This insulating shell reduces the cooling rate of the internal lava, maintaining its high fluidity in a state of elevated temperature, allowing it to flow over significant distances until the supply of lava from its source diminishes. Through successive lava overflows or the cooling and solidifying of the outer layers of lava, the thickness of the lava walls gradually increases, thereby stabilizing the entire structure and forming a hollow conduit [27]. The schematic diagram of the formation mechanism of a lava tube is shown in Fig. 1.

The solidification mechanisms of lunar lava tubes generally encompass two types: (a) the development of a roof over exposed lava channels; and (b) the underground enlargement of internal channels [28,29]. The formation of a lava tube's roof primarily occurs as the surface of the lava flow cools and solidifies. This process is accompanied by the merging of lava blocks that are transported along the flow's surface. Together, these elements form a thermal-insulating layer encasing the exterior of the flow that helps to retain the heat within, allowing the lava beneath to continue flowing smoothly and unimpeded. Occasionally, previously solidified crustal shells may loosen, fracture, and flow downstream with the lava, subsequently shaping the roof of the downstream channel [28,30,31]. The expansion mechanism of the lava tube typically occurs in sluggish, low-viscosity pahoehoe lava flows characterized by a slow speed and a ropey appearance [32]. The expansion of pahoehoe lava causes the crust to rupture, generating crustal fragments that help support the outer shell of the lava tube, ultimately resulting in the formation of a hollow conduit [28]. In this mechanism, the outer shell of the lava tube essentially cools and solidifies in situ.

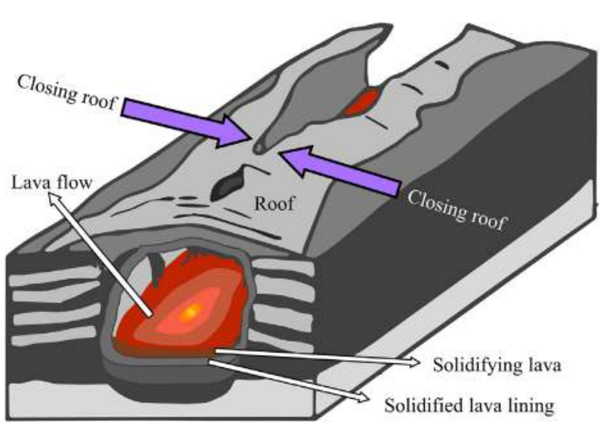


Fig. 1. Schematic diagram of the formation process of a lava tube.

Although the mechanisms behind the formation of lava tubes on both Earth and extraterrestrial bodies are similar, there are significant differences in the volume and length of lava tubes on extraterrestrial bodies due to environmental factors such as gravitational strength, temperature, and atmospheric conditions. The Moon's surface gravity is approximately 1/6 that of Earth, while Mars' gravity is around 1/3 of Earth's, resulting in a more favorable environment for the development of large lava tubes. While lava tube diameters on Earth typically vary from a few meters to tens of meters [31], those found on the Moon exhibit a broader range, may spanning from hundreds to thousands of meters [33,34].

2.2. Exploration history and evidence of lunar lava tubes

2.2.1. Sinuous rilles and skylight

Lava tubes commonly display surface features such as pits, chains of pits, and skylights [27]. These features have become crucial indicators for locating subterranean lava tubes on the lunar surface. A skylight, illustrated in Fig. 2, refers to an aperture at the apex of a cave or lava tube, usually a circular or elliptical orifice with steep edges, serving as a visual cue of the presence of underground voids. The identification of skylights substantially enhances the probability of substantial subterranean cavities and holds substantial exploration value [35].

The exploration of lunar lava tubes commenced during the Apollo program in the 1970s. Ronald Greeley, utilizing lunar remote sensing images, geomorphology, and comparisons with Earth's lava tubes, postulated that the rilles in the lunar mare are indeed lava tubes [13]. Nonetheless, the absence of direct low-altitude image evidence at that time led to skepticism regarding the presence of lunar lava tubes. Subsequently, numerous geologists, including Greeley, advocated for establishing an Apollo landing site in the Marius Hills region to enable direct exploration of lava tubes, ultimately yielding conclusive evidence [37]. The Apollo 15 mission, aided by the lunar rover, approached Hadley Rille, capturing valuable images portrayed in Fig. 3a. This remains the closest photographic documentation of a potential lunar lava tube to date. Nevertheless, these morphological features alone were inadequate to confirm the existence of complete lava tubes on the Moon.

Significant advancements in the exploration of lava tubes were hampered for several decades due to technological limitations, until the breakthrough of lunar spacecraft and cameras. In 2009, Haruyama et al. [10] from the Institute of Space and Astronautical Science (ISAS) in Japan captured high-definition images of lunar lava tubes for the first time using the Terrain Camera on the SELENE (SELenological and ENgineering Explorer) lunar orbiter. The image had a resolution of 10 m per pixel, as shown in Fig. 3b. They identified a vertically oriented circular hole measuring approximately 65 m in diameter, which seemed to serve as a skylight for a lava tube. This feature was found within a winding rille in the Marius Hills region of the Moon. This discovery carries great scientific significance and has consequently emerged as a prominent objective for future exploration missions.

After the discovery of the Marius Hills Hole (MHH) in 2010, Haruyama et al. [38] utilized data from the SELENE mission to identify two additional pits in the Mare Tranquillitatis and Mare Ingenii regions. Subsequently, NASA's Lunar Reconnaissance Orbiter (LRO) equipped with two narrow-angle cameras (NAC) with a res-

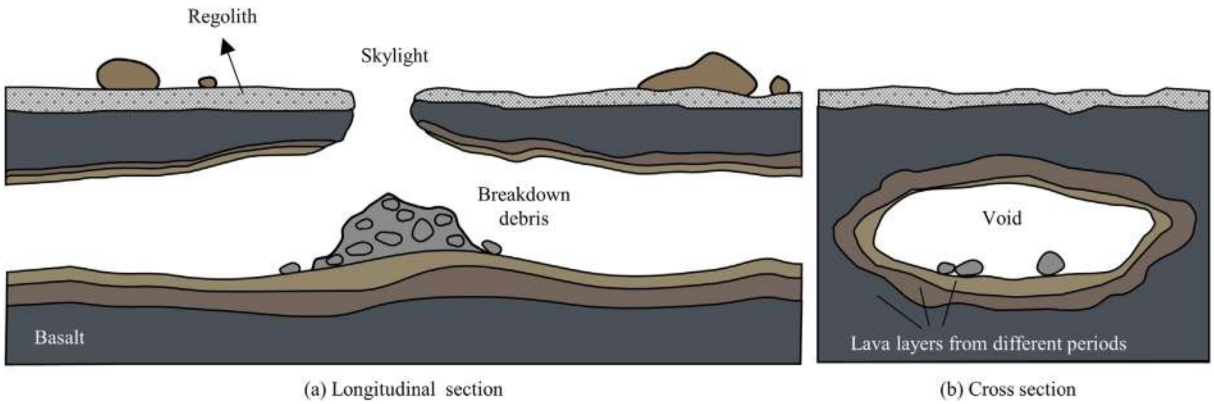


Fig. 2. A typical longitudinal and cross-section profile of a lava tube (modified from [36]).

olution of 0.5 m per pixel, conducted more detailed observations of these pits identified by Haruyama et al., revealing the presence of 228 previously unknown pits with diameters ranging from 5 to 900 m [35,39]. High-resolution oblique views of these pits indicated that, in several cases, the cavities beneath the pits were wider than the surface openings [40]. Additionally, the exploration efforts led to the research of skylights and sinuous rupture models [41]. The LRO's NAC captured an image of the Marius Hills pit, marking the highest resolution image of the pit to date, as shown in Fig. 3c. This pit is believed to potentially serve as a skylight for a lava tube located in the Marius Hills region. Through subsequent analysis of multiple Lunar Reconnaissance Orbiter Camera (LROC) images captured at later instances with higher solar elevations than the initial observation, the Marius Hills pit was determined to be approximately 58 m in diameter and 49 m in width, with a depth of 40 m.

In 2011, India's Chandrayaan-1 orbiter carried the Terrain mapping camera (TMC) with a spatial resolution of 5 m and 3D visualization capabilities. This mission provided evidence suggesting the possible existence of an uncollapsed, approximately horizontal, and intact lava tube in the Oceanus Procellarum area of the Moon [33]. Fig. 3d is a contour map of the study area, within the red box is the rille of the lava tube and the uncollapsed portion, approximately 360 m wide and 1.7 km long.

According to the latest data available, over 300 pits have been identified on the Moon as of 2019. It is worth noting that a substantial number of these pits are located within lunar impact melts and exhibit a wide range of morphologies. While only a small portion of these pits are associated with sinuous rilles or collapse chains on the lunar surface [42], the remaining pits hold comparable value to collapse pits in terms of their potential for lunar habitation.

2.2.2. Gravity

Although these images reveal numerous surface defects on the Moon, such as sinuous rilles and skylights, relying solely on these images is insufficient for accurately determining the size and shape of underground lava tubes [31,43]. Gravity measurements, on the other hand, can provide valuable information about both surface and subsurface features. In 2013, NASA conducted the Gravity Recovery and Interior Laboratory (GRAIL) mission, which enabled high-resolution monitoring of the lunar gravity field and unveiled previously unseen lunar features [44]. Building upon this mission, Chappaz et al. [43] analyzed the gradient measurement data from GRAIL and identified a 4 km-wide lava tube in Rima Sharp. In subsequent years, they further examined GRAIL data from various lunar regions, including the vicinity of MHH, and discovered extensive mass deficits around MHH, indicating the presence of large cavities beneath the lunar surface [9]. By constructing a lava tube model based on this information, they obtained a gravitational map of the subsurface cavities, which revealed several strong candidate lava tubes. This finding holds valuable implications for lunar lava tubes research, despite some discrepancies found in the analysis and results of the GRAIL team across some aspects. More recently, in 2023, Zhu et al. [45] analyzed the lunar gravity field model derived from the GRAIL mission data and identified a negative density anomaly near MHH. Through forward modeling, they estimated the dimensions of this lava tube to be approximately 60 km in length, 9 km in width, 605 m in depth, and with a height of about 55 m, featuring a skylight on the east side serving as an entrance.

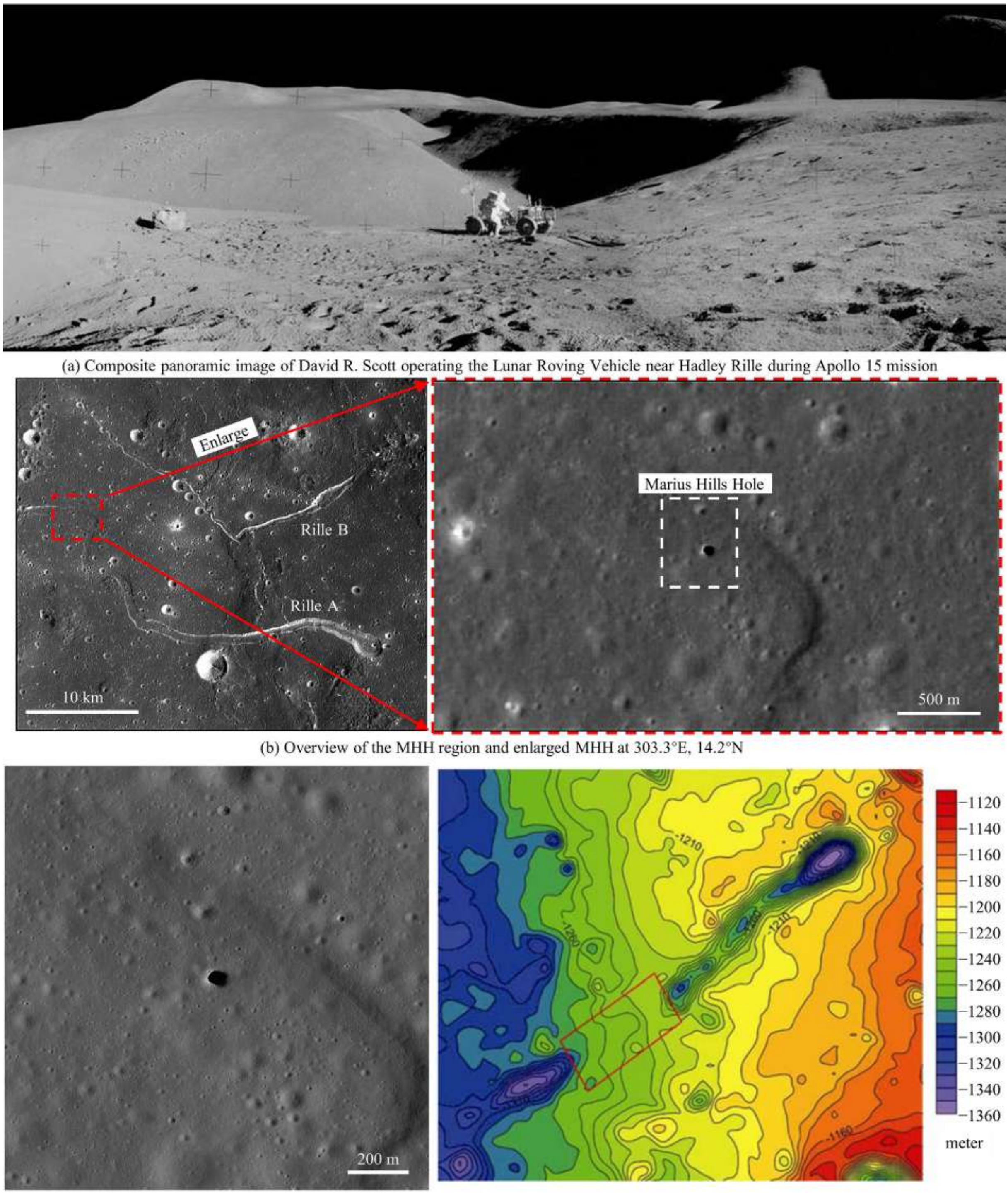
2.2.3. Ground penetrating radar

Ground penetrating radar (GPR) is indeed an effective method for detecting lunar lava tubes. By analyzing the electromagnetic characteristics of radar echoes and underground structural information, GPR can provide valuable insights into the location, physical morphology, and size of lava tubes [46–48]. In a study by Kaku et al. [11], the Lunar radar sounder (LRS) results from the SELENE mission were analyzed, and underground void echoes were identified around MHH at multiple locations. Many of these void locations aligned with the mass deficits observed in the GRAIL data. Based on the findings from the GRAIL and LRS data, there is a high probability that an intact lava tube exists in the Marius Hills region, though its precise dimensions remain uncertain. Additionally, Ding et al. [49] reported the detection of a buried underground cavity structure about 3.1 m below the Chang'e-3 landing area on the Moon using GPR on the Chang'e-3 lander. This finding provides further evidence of the usefulness of GPR in identifying subsurface structures on the Moon.

2.3. Distribution location

There have been various speculations regarding the potential locations of lunar lava tubes. The presence of lava tubes can be inferred through the observation of sinuous rilles, skylights, gravity deficits, and GPR echo features. The initial speculations about lava tube locations were made by Coombs and Hawke [12], who primarily conducted qualitative observations of Apollo satellite images and Lunar Orbiter images at that time to identify sinuous channels and skylights. They ultimately identified 67 candidate lava tube locations, some of which had lengths exceeding 10 km and widths of up to 1 km.

Table 1 provides detailed information on some typical lunar lava tube candidate locations. Among the studied regions, the Marius Hills region has received the most attention, and the existence



(a) Composite panoramic image of David R. Scott operating the Lunar Roving Vehicle near Hadley Rille during Apollo 15 mission

(b) Overview of the MHH region and enlarged MHH at 303.3°E, 14.2°N

(c) Marius Hills pit

(d) Contour map of the rille and the uncollapsed portion of the lava tube

Fig. 3. Some landmarks in the exploration of lunar lava tubes. Note: Diagram (a) is taken from the web page (https://www.nasa.gov/history/50-years-ago-apollo-15-on-the-moon-at-hadley-apennine/). Diagram (b) is modified from [10]. The Marius Hills pit is a possible skylight in a lava tube in an ancient volcanic region of the Marius Hills and Diagram (c) is derived from LROC NAC image M114328462R. Image credit: NASA/GSFC/Arizona State University. The rectangle in diagram (d) shows the rille of the lava tube and the uncollapsed part, modified from Ref. [33].

of lava tubes has been confirmed through imagery, radar, and gravitational analyses [9–11,31,45]. High-precision camera images from spacecraft have been instrumental in discovering numerous pits on the Moon [40,50,51], which could potentially be skylights of lava tubes. This information is crucial for narrowing down the investigation range of lava tubes. However, determining the precise size and morphology of lava tubes based solely on imagery and radar data is challenging. For obtaining quantitative dimensions, analyzing gravity loss data is a key analytical method. Gravity measurements provide valuable insights into the size and shape of lunar lava tubes and are an important complement to other detection techniques.

Table 1
Typical lunar lava tube candidate locations.

Location	Latitude	Longitude	Diameter	Depth	Data source (basis for identification)	Reference
Marius Hills Region	14.2°N	303.3°E	Minimum width: 370 m		SELENE Terrain Camera and Multi-band Imager (Image analysis)	[10]
	13.00–15.00°N	301.85–304.01°E			SELENE-LRS data (Radar analysis)	[11]
	13.096°N 13.603°N	57.056°W 58.047°W			SELENE / LRO-NAC / LRO LOLA DTMs (Image analysis)	[31]
	14°N	302°E	Width: 400 m; Length: 60 km	200–300 m	GRAIL mission data (Gravity analysis)	[9]
	14.3°N	57.5°W	Width: 9 km; Height: 55 m; Length: 60 km	605 m		[45]
Ziwei Crater	44.121°N	19.512°W	Height: 3.1 m		Chang'e-3 LPR data by Yutu Rover (Radar analysis)	[49]
Rima Sharp	35–40°N	311–316°E	Witdth: 2 km; Length: 75 km	600 m	GRAIL mission data (Gravity analysis)	[43]
South of Rima Sharp and west of Rima Mairan	36°N	314°E	Witdth: 3.5 km; Height: 550 m			[9]
Aristarchus Plateau	27°N	313°E	Witdth: 3.75 km; Height: 600 m; Length: 60 km			
Gruithuisen Hyginus Rill Tectonic	34.618°N 8.384°N	43.467°W 5.630°E			SELENE / LRO-NAC / LRO LOLA DTMs (Image analysis)	[31]

Note: LOLA: lunar orbiter laser altimeter; NAC: narrow-angle camera; DTMs: digital terrain models; and LPR: lunar penetrating radar.

3. Lunar lava tube base

In building lunar bases, the effects of the Moon's unique external environment, such as temperature, radiation, moon dust, and micrometeorite impacts, on the base need to be considered. As opposed to lunar surface habitats, building bases in lava tubes can reduce the complexity and cost of the project by utilizing natural caves, and there are also unique advantages in the internal environment.

3.1. Advantages of establishing a base on the lunar lava tubes

3.1.1. Stable temperature environment

In 2009, the United States launched the LRO, equipped with the Diviner radiometer system, which provided valuable data on the thermal environment of the Moon [52,53]. This instrument measured lunar radiation at various locations and times, subsequently generating a comprehensive lunar temperature distribution map. The average temperature at the lunar equator was determined to be −57.65 °C, with an average temperature of −179.24 °C at the lunar poles [54]. The Apollo project and the later global mapping campaign by Diviner indicate that the diurnal amplitude of the surface temperature is approximately 300 °C near the equator, and varies with latitude and local topography [55]. Based on the observations made by the Diviner, it has been revealed that the thermal conditions on the lunar surface display intricate fluctuations over time and in response to seasonal changes. Consequently, extensive and enduring shadowed regions are formed, surpassing the extent of permanently shadowed regions (PSRs) by a considerable margin [53]. Underneath the lunar surface, covered by a layer of lunar regolith measuring tens of centimeters in thickness, the temperature remains relatively stable, consistently hovering around −20 °C [56]. These substantial temperature variations can induce thermal stress on machinery and construction materials, presenting significant challenges to both equipment performance and the construction of lunar bases.

Relying on data from the Diviner lunar radiometer experiment and thermophysical models, Horvath et al. [57] postulated that the temperature within lunar lava tubes remains relatively constant. They suggested that the environment inside the lava tube near the Mare Tranquillitatis is likely much more desirable than that on the surface, maintaining a stable temperature of 17 °C year-round. While direct measurements of the internal temperature of lunar lava tubes are currently unavailable, Haruyama et al. [58] conducted temperature measurements within illuminated and shadowed areas of collapsed caves, providing insights into temperature variations on the lunar surface and within lava tubes, as shown in Fig. 4a. Lunar surface temperatures were observed to range from −170 to 110 °C, whereas shadowed caves, devoid of direct sunlight, maintained temperatures between −20 and 30 °C. In addition, the latest research shows that although lunar pits and lava tubes may not be the optimal locations for storing water ice in terms of geological time scales, they can still serve as viable options for storing artificial water sources within the time frame of human missions, which is within 100 years [59].

According to the data obtained from Diviner, the thermophysical properties of the lunar regolith demonstrate a remarkable level of consistency on a global scale, demonstrating a high degree of spatial uniformity [60,61]. Notably, both the surface regolith and the subsurface regolith at a depth of 1 m exhibit exceptionally low thermal conductivity, indicating their excellent insulation capabilities [62]. In August 2023, India's Chandrayaan-3 Lander successfully executed a lunar landing and conducted thermophysical experiments on the lunar surface [63]. These experiments involved measuring the temperature distribution of the lunar regolith surrounding the lander. A temperature probe, equipped with 10 independent sensors and a controlled penetration mechanism, reached a depth of 10 cm below the lunar surface. The results of these experiments showed that when the surface temperature reached approximately 50 °C, the temperature at a depth of 8 cm below the surface dropped to −10 °C, as shown in Fig. 4b. This discovery highlights the thermal-insulating properties of the 8-centimeter-thick lunar regolith, which effectively mitigates temperature changes of up to 60 °C.

3.1.2. Excellent radiation protection

The lunar surface is continuously exposed to long-term galactic cosmic rays (GCRs) and sporadic solar particle events (SPEs) [64]. Due to the absence of a magnetosphere and atmosphere, galactic and solar system, particles are not attenuated when they reach the lunar surface, rendering particle radiation a significant risk factor for human activities on the Moon [65]. This radiation field interacts with the lunar regolith, generating neutrons and gamma rays. GCRs comprise charged particles with exceptionally high

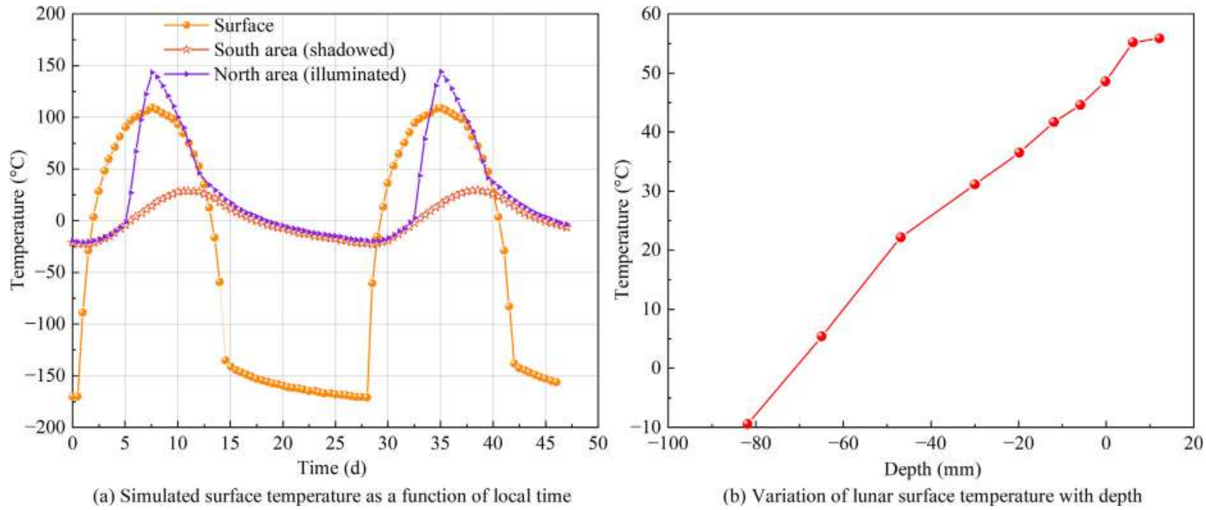


Fig. 4. Temperature conditions on the surface of the Moon. Note: Data from [58] and Indian Space Research Organisation (ISRO).

energy and extremely low flux, resulting in inevitable but relatively low radiation doses. In contrast, SPEs occur less frequently and release substantial quantities of high-energy particles during active solar events such as coronal mass ejections or solar flares. Prolonged exposure to GCRs and SPEs can have detrimental effects on astronauts' health, potentially leading to cataracts, cancer, or degenerative diseases of the nervous system [66,67]. Hence, the consideration of radiation protection performance is paramount when establishing a lunar base.

Numerous existing assessments of lunar surface radiation doses rely on theoretical models and simulation estimates, involving the inversion of lunar surface data based on environmental measurements acquired in lunar orbit. However, these simulations yield markedly different results across various models [68,69]. It wasn't until 2019, with the successful touchdown of China's Chang'e-4 lander on the lunar surface, that direct measurements of particle radiation doses and neutron radiation on the Moon were obtained. These measurements were conducted as part of the Lunar Lander Neutron and Dosimetry (LND) mission. By combining LND data with information from the DOSIS 3D DOSTEL instrument [67,70], it was determined that the daily GCRs dose equivalent measured on the lunar surface exceeded that recorded inside the International Space Station (ISS) by a factor of 2.6, amounting to 1369 and 523 μSv, respectively. Notably, no SPEs were observed during this measurement period, which coincided with a period of minimal solar activity [71]. Therefore, the measured GCRs dose serves as a reference upper limit.

Concerning the impact of radiation dose on the human body, NASA has established equivalent dose limits (EDL) based on a maximum 3% lifetime excess risk of cancer mortality [72], accounting for age and gender, as depicted below:

$$\mathrm{EDL}_{\max} = \begin{cases} 2000 + 75 \times (a - 30), \text{ for males} \\ 2000 + 75 \times (a - 38), \text{ for females} \end{cases} \tag{1}$$

where a is the age of the astronaut.

To calculate the theoretical maximum duration of radiation exposure for an astronaut on the lunar surface, we can employ the following equation:

$$t_{\max} = \frac{\mathrm{EDL}_{\max}}{H} \tag{2}$$

where H represents the equivalent daily dose measured on the lunar surface during the LND test. Using this method, we can determine the maximum exposure durations for astronauts of varying genders and ages in the radiation environment, as presented in Table 2. It is evident that a 35-year-old male can withstand the lunar surface for a maximum of 1826 d without radiation protection, while a female in the same circumstances can only endure 1278 d. This illustrates the significant threat posed by lunar surface radiation to both human survival and productivity. It is worth noting that the calculation of these values does not consider the shielding effect of the extravehicular activity (EVA) suit, habitat, or lander on radiation.

Recent research conducted by scholars has substantiated the exceptional radiation resistance properties of lunar regolith. Simulation results indicate that when regolith attains a thickness between 1 and 6 m, the detrimental radiation effects of SPEs and GCRs on the human body become negligible [64], as shown in Fig. 5. Consequently, taking into account available data regarding the dimensions and upper thickness of lava tubes [12,40,51], it becomes evident that there is no imperative need for additional radiation protection equipment in the establishment of human habitats within these lava tubes.

3.1.3. Few lunar dust and meteorite impact effects

The absence of atmospheric protection on the lunar surface facilitates the formation of charged lunar dust from fine materials under the influence of the solar wind. During lunar sunrise and sunset, an electric field drives substantial movement of negatively charged lunar dust from shadowed regions to positively charged areas in the light [10].

The Apollo program demonstrated that lunar dust yields 9 primary effects on lunar landings, including vision obscuration, false instrument readings, dust coating and contamination, loss of traction, clogging of mechanisms, abrasion, thermal control problems, seal failures, and inhalation and irritation [73]. Astronaut Gene Cernan, a member of Apollo 17, also noted the adhesion of lunar dust to skin, equipment, and spacesuits, which significantly limited lunar surface exploration. Moreover, the presence of lunar dust considerably hampers the operation of various mechanical exploration equipment, leading to clogs, wear and tear, and reduced heat dissipation [73].

In stark contrast, the permanently shadowed regions of lunar lava tubes, shielded from the solar wind, experience minimal micrometeorite impacts and consequently contain very low levels of lunar dust. Mandeville and Bariteau [74] conducted research

Table 2
Radiation exposure limits and theoretical maximum exposure times for astronauts on the lunar surface.

Gender	Age	Radiation exposure limits (mSv) [72]	Theoretical maximum exposure time (d)
Male	25	1500	1096
	35	2500	1826
	45	3250	2374
	55	4000	2922
Female	25	1000	730
	35	1750	1278
	45	2500	1826
	55	3000	2191

revealing that cosmic micrometeorites pose a substantial impact risk to human exploration, with an 8% probability of penetrating spacesuits and a 30% probability of penetrating 1 cm-thick aluminum plates exposed on the lunar surface for one year. Conversely, the lunar regolith and rocks found at the tops of lava tubes provide robust protection against micrometeorite impacts within these subterranean passages [58].

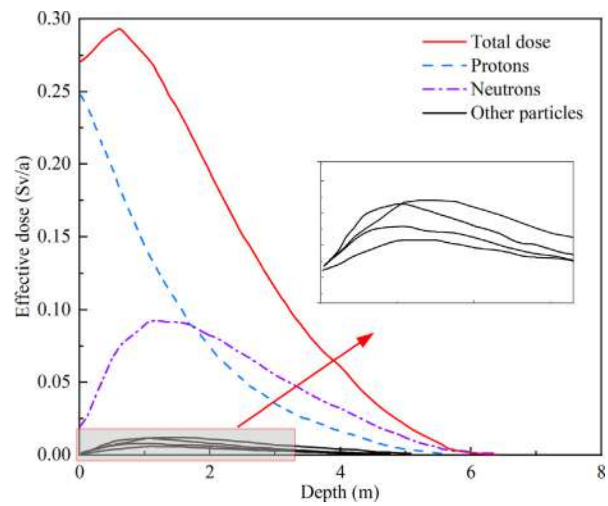


Fig. 5. Effective dose from GCRs with depth (other particles including electrons, positrons, photons, pions, muons, kaons, deuterons, etc., modified from [64]).

3.1.4. Suitable size and stable structure

The lower gravitational acceleration and higher lava flow velocity on the Moon are favorable for the formation of large-sized lunar lava tubes [75,76]. The findings in Table 1 based on remote sensing data indicate that the width and depth of lunar lava tubes reach significant dimensions, measuring hundreds of meters. The simulation results also support the idea that lunar lava tubes would be much larger than their terrestrial counterparts.

The size and stability of lunar lava tubes have been the subject of scholarly speculation using stability structural theory. Many scholars have utilized finite element models and plane strain assumptions to study lunar lava tube size and stability based on assumed parameters of lunar rock samples. Blair et al. [34] suggested that a lava tube with a roof thickness of 500 m could remain stable even with a 5 km width, but this overlooks the lower tensile strength of the rock compared to its compressive strength. Modiriasari et al. [77] demonstrated that the cross-sectional shape of the lava tube affects its structural stability, highlighting that circular or elliptical shapes in the vertical long axis direction are more stable. Theinat et al. [76] conducted stability assessments of lunar lava tubes with varying widths and roof thicknesses through analytical and numerical simulations, as depicted in Fig. 6. Additionally, the weakening effect of thermal stress during lava tube formation must be taken into consideration. Based on the analysis of 41 lunar mare impact craters, Du et al. [78] proposed that the thickness of lunar basalt ranges from 35 to 455 m, with a median value of 105 m. The studies mentioned above contribute to validating the GRAIL observations and demonstrate the presence and structural integrity of large lunar lava tubes.

3.2. Lava tube based lunar base concepts

Lava tubes are indeed being considered as preferred or prioritized areas for lunar bases due to their unique advantages. NASA first proposed the idea of establishing a lunar base within a lava tube as early as 1985 [5]. In recent years, various conceptual lunar lava tube bases have been developed. For instance, Grandl [79] proposed the "Green" habitat to be built in the Mare Tranquillitatis Pit, which can accommodate 100 residents. Fig. 7a shows the basic design. The initial workstation is constructed on the lunar surface near the cave entrance and then extends vertically through modules to the bottom of the cave, where the entire structure is completed. The cave entrance can be sealed with a transparent dome and filled with air to create a habitable environment for humans. Inflatable structures can be utilized for insulation and farming within the cave. Building upon this design concept, Martin and Benaroya [80] have developed a 2D model to investigate the structural stability of the lava tube under pressurized air conditions using finite element techniques.

Mizuguchi and Ikeda [18] proposed a concept for a long-term lunar base known as the "Swarm Habitat" designed to adapt to the lunar gravity and irregular terrain. Their focus was on the interior design and architectural scale, achieving the final base structure by combining 100 truncated octahedron modules (Fig. 7b). In low gravity conditions, these modules can collaborate like a swarm, smoothly moving and sliding into the lava tube within complex terrain.

Kalita et al. [50] presented a conceptual model for a lunar lava tube base, as illustrated in Fig. 7c. The entire base spans across a skylight and an underground lava tube, primarily comprising living spaces, control and communication systems, power systems, life support systems, and storage facilities. Vock and Nilsson [81], in collaboration with the European Space Agency (ESA), put forward a lava tube base concept capable of adapting to rough terrains near the lunar poles through in-situ resource utilization (ISRU) and 3D printing technology.

In 2023, a team from the Harbin Institute of Technology in China proposed a lunar base construction plan based on lunar lava tubes [82]. The specific steps of the plan are as follows: (i) Radar exploration will be used to locate the approximate position of the lunar lava tubes and a 3D scanning robot will then be deployed to reconstruct the internal structure of the lava tubes in 3D. (ii) Once the accurate location and internal structure of the lava tubes are determined, a drilling projectile will be fired from the space station to enlarge the skylight entrance. Robots will be utilized to reinforce the skylight entrance and clean the interior ground. (iii) The core module will be landed in the skylight, and the premade skeletal structure of the workspace will be expanded. The support module will be inflated inside the cabin, and the lunar soil mixture will be poured and used to lay lunar soil bricks, creating a living chamber. The plant chamber will also be inflated, forming a complete underground living area. (iv) To further develop the lunar base, the shelter module's double-layer gas film will be expanded. Robots will collect lunar soil and use it to construct lunar surface infrastructure. (v) Finally, a fully functional lunar lava tube base will be formed, allowing astronauts to enter and inhabit the base, as shown in Fig. 7d. Overall, this plan aims to utilize the potential of lunar lava tubes for creating a sustainable and habitable lunar base.

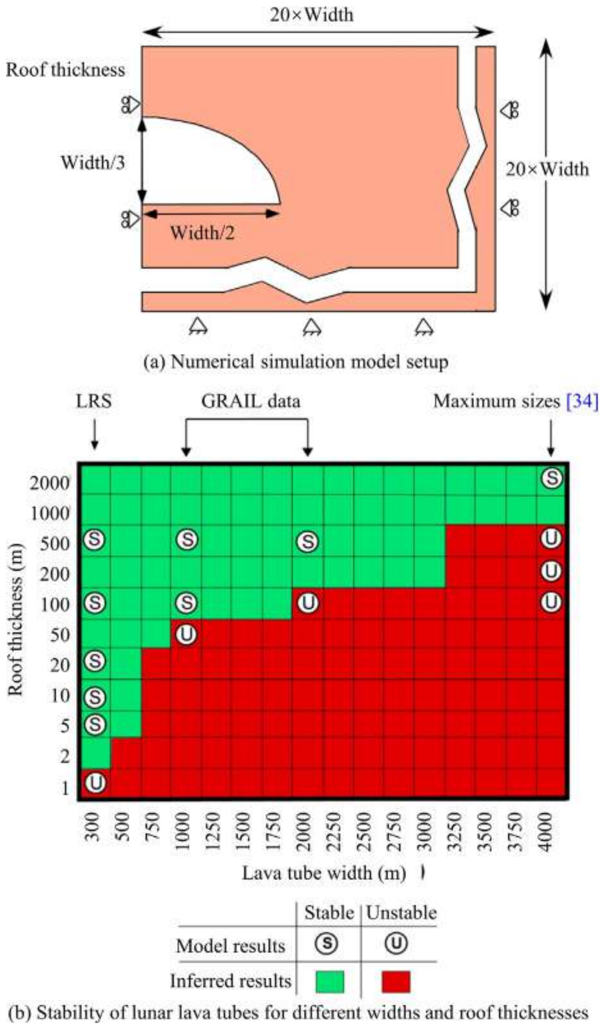


Fig. 6. Structural stability analysis of lava tubes (modified from [76]).

4. Analog sites of lunar lava tubes

4.1. Terrestrial attempts

The accumulation of experience in position detection, base construction, and personnel training for lunar lava tubes, based on existing conditions on the Earth, is crucial [28,31]. Simulating equipment, operations, and procedures used in space missions at a suitable location on the Earth can help mitigate the risk of mission failure. Such a simulation site can serve as a research platform for simulating the challenges encountered in future lunar lava tube construction. Several countries have already made progress in this field. For instance, Bell et al. [28] correlated the magnetic anomalies generated by lava tubes with their location and geomorphology. They conducted field tests at the Lava Beds National Monument in California, USA, with the aim of applying the magnetic anomaly model established there to lunar lava tube exploration.

In 2021, the CHILL-ICE mission took place at the 10th entrance of the Stefánshellir lava tube in Iceland, with the participation of young professionals and students from 16 countries (Fig. 8a and b). The primary objective of the mission was to deploy an inflatable tubular habitat and its systems inside a simulated lunar lava tube [21,83]. The mission successfully tested emergency equipment necessary for astronauts' initial arrival on extraterrestrial bodies, as well as a lunar rover, and conducted a series of sampling and exploration simulations. Researchers collected samples from lava tubes on the island of Lanzarote in the Canary Islands and utilized a Mars rover to navigate inside, thereby preparing for future lunar exploration, as illustrated in Fig. 8c.

Ding et al. [19] proposed the use of karst caves on the Earth (Fig. 8d) as simulation sites for lunar lava tubes, demonstrating the feasibility from both structural and environmental perspectives by utilizing Wulong's karst caves as an example. The laboratory structure platform they envisioned, which includes daylight system, control equipment, automated construction laboratory, and ecological laboratories, is shown in Fig. 8e.

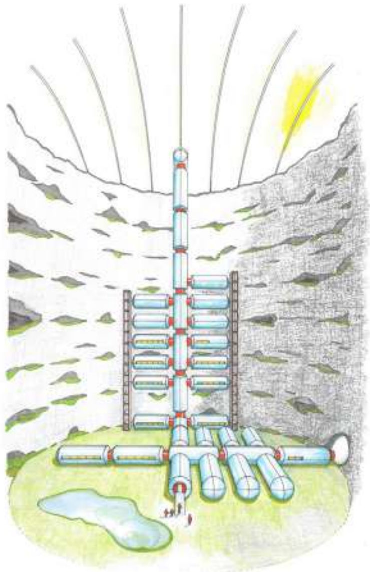
Simulating the internal environment of lunar lava tubes in caves on Earth allows for testing relevant detection, construction, and survival methods. This approach can significantly reduce the consumption of energy, transportation costs, and trial and error expenses associated with space missions. Furthermore, it provides an opportunity to enhance the success rate of space missions and improve related technological equipment and methods. The rapid development of robotics, 3D printing technology, and the utilization of space resources necessitates a series of Earth-based experiments to support their application on the Moon.

4.2. Field mapping and laboratory testing of lava tubes in Haikou

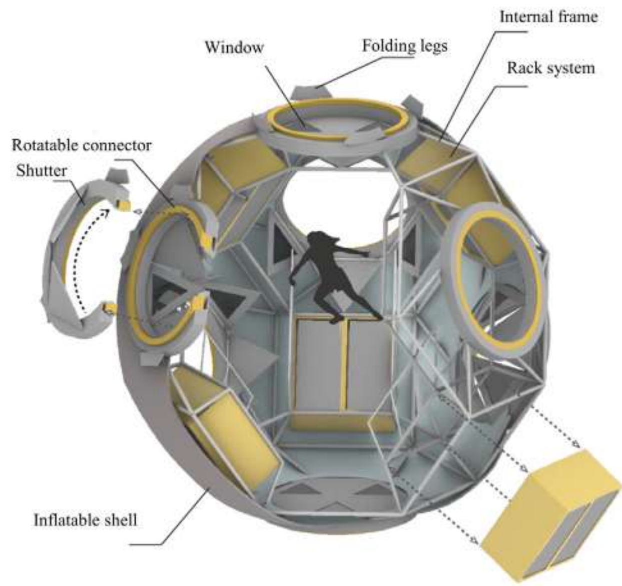
To broaden the potential sites for simulating lunar lava tubes on Earth, a field survey of a lava tube in Haikou, China was conducted, along with laboratory experiments using rock samples. The surveyed lava tunnel, known as "Seventy-Two Caves", is situated in the Shishan volcanic group in Haikou, Hainan Province, China (19.925°N, 110.219°E). The Shishan volcanic group is in the northern part of Hainan Island, at the southeastern edge of the Eurasian Plate. It is influenced by the combined effects of the Philippine Plate, Indian Plate movement, and the expansion of the South China Sea basin, resulting in significant tectonic, volcanic, and seismic activity. The Shishan volcanic group is one of the few dormant volcanic groups in China that exhibited volcanic eruption activity in the Holocene period, approximately 10000 years ago. It comprises 40 volcanoes of various types arranged in a northwest direction and over 30 lava tubes. The "Seventy-Two Caves" lava tube surveyed in this study has a total length of over 780 m, with a main passage height of 3–4 m and a width of approximately 20 m. It is named after being divided into dozens of lava tube segments due to multiple collapses inside the tunnel.

The "Seventy-Two Caves" lava tube contains several collapsed sections and is surrounded by dense vegetation, which hinders normal passage. Consequently, a partially intact section of the "Seventy-Two Caves" lava tube was surveyed from west to east, and a topographic map was created (Fig. 9). The entrance has a large diameter and a height of approximately 2–4 m, as shown in Fig. 10a. The inner walls of the lava tube exhibit distinct grooves and scratches (Fig. 10b, d, and f), suggesting the occurrence of previous lava flow impacts. Further exploration revealed a prominent skylight in which the mixture of collapsed rocks and soil on the ground fostered plant growth at the collapse site (Fig. 10c and e). The top of the lava tube is densely populated with trees, and their roots extend along the basalt fractures, compromising the stability of the lava tube. Moreover, the warm and humid climate in Haikou fosters the growth and reproduction of animals and plants, as evidenced by the presence of bats inside the lava tube.

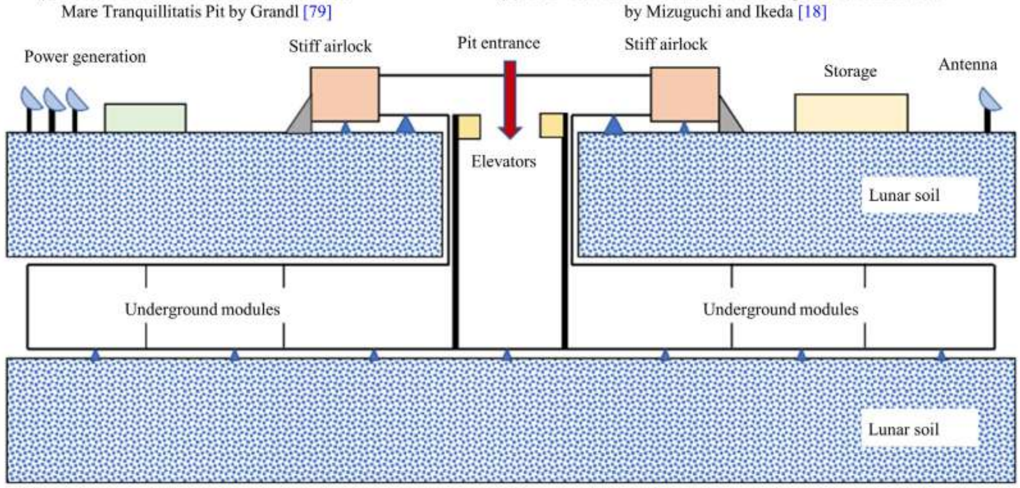
To analyze the structural stability of the "Seventy-Two Caves" lava tube, a sampling of the basalt inside the tunnel was conducted, and laboratory tests were performed to determine its basic physical and mechanical properties. The density of the basalt ranged from 2.152 to 2.680 g/cm^3, with a Poisson's ratio of 0.22 to 0.3. X-ray fluorescence (XRF) spectrometer testing of the basalt sam-



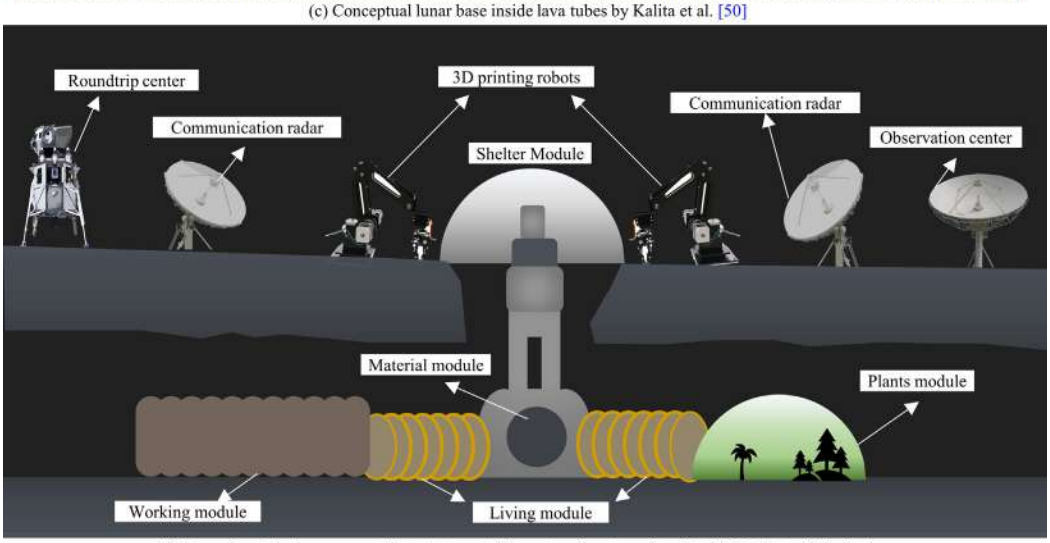
(a) "Green" habitat for 100 inhabitants inside Mare Tranquillitatis Pit by Grandl [79]



(b) A 3D view of the modules that make up the "Swarm Habitat" by Mizuguchi and Ikeda [18]



(c) Conceptual lunar base inside lava tubes by Kalita et al. [50]



(d) Lunar lava tube base concept by extraterrestrial construction team from Harbin Institute of Technology

Fig. 7. Some representative lava tube base design concepts (Modified from [18,50,79]).

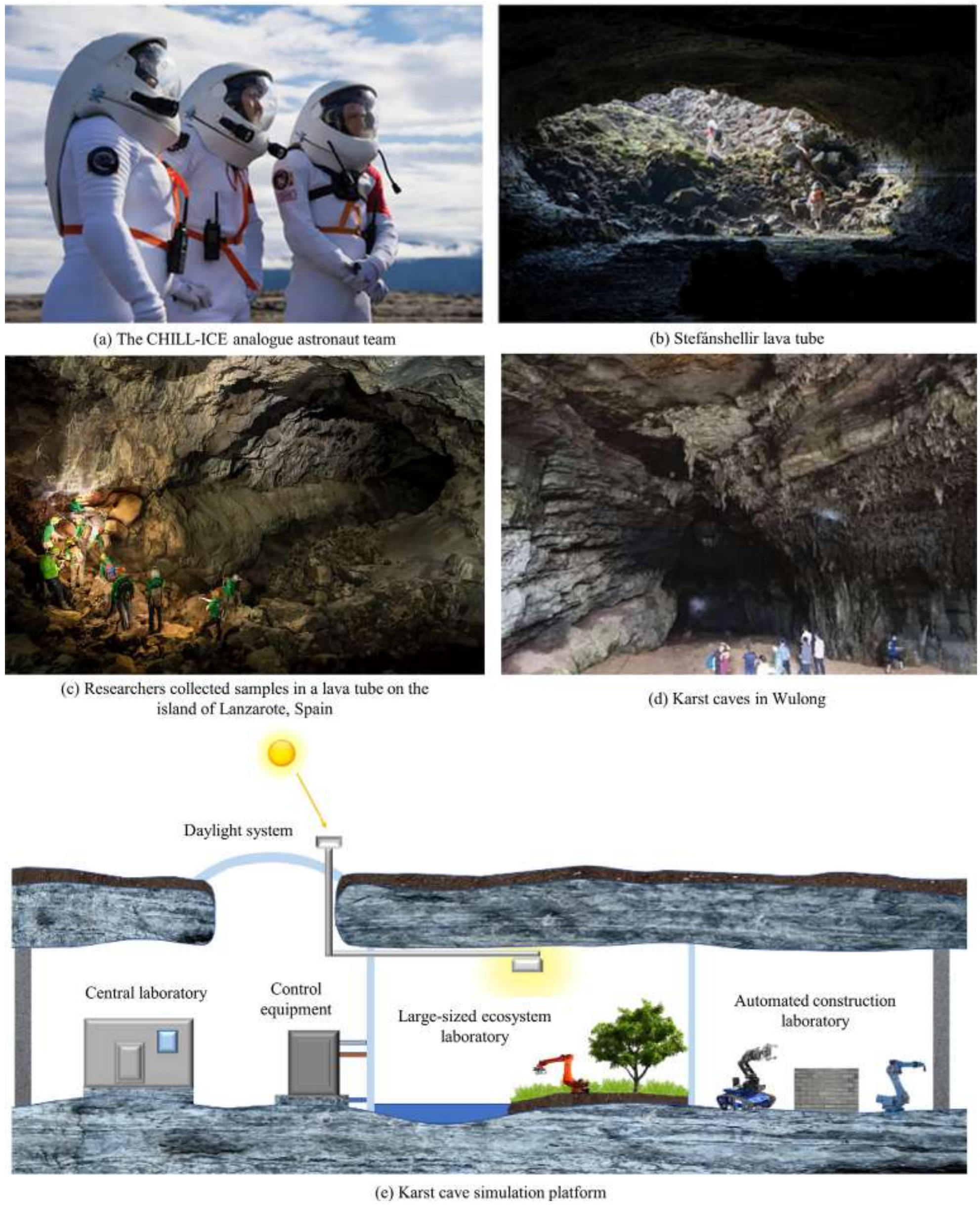


Fig. 8. Some representative terrestrial attempts. Note: Diagram (b) is modified from [21]. Diagram (c) is taken from the web page (https://www.inverse.com/science/underground-caves-on-the-moon-could-offer-refuge-for-future-astronauts). Diagram (e) is modified from [19].

ples revealed that they mainly consisted of elements such as SiO_2, Al_2O_3, FeO, and CaO (Fig. 11a). The composition proportions of Haikou basalt were highly similar to those of the lunar regolith samples collected by the Apollo 14 mission, indicating that the particle size distribution could be adjusted based on this basalt composition to simulate lunar regolith [84].

The retrieved basalt samples contain a significant number of vesicles, primarily formed due to the release of volatile gases during the lava flow process. The presence of vesicles indicates the presence of moisture during lava flow overflow in the area. Six rectangular specimens were created using dense and porous basalt, each with dimensions of 50 mm × 30 mm × 100 mm. The stress-strain curves under uniaxial compression for these specimens are presented in Fig. 11b. Specimens B1–B3 represent dense basalt, while specimens B4–B6 represent porous basalt. The average compressive strength of dense basalt is 76.40 MPa, with an average elastic modulus of 26.98 GPa. The average compressive strength of porous basalt is 63.25 MPa, with an average elastic modulus of 22.75 GPa. It can be observed that the presence of vesicles weakened the strength and elastic modulus of the basalt [85]. Morphology of dense and porous basalt and the corresponding maximum principal strain contour at peak load are depicted in Fig. 11c. The maximum principal strain contour at peak load reveals that dense basalt exhibited a tensile failure mode, while porous basalt experienced local failure at weak locations due to the presence of vesicles, resulting in a shear failure mode.

Therefore, based on the field survey and laboratory tests conducted on the "Seventy-Two Caves" lava tube, there are several reasons to consider it as a potential site for simulating lunar lava tubes on Earth. Firstly, according to the compositional analysis comparison presented in Fig. 11a, it is evident that the basalt found within this lava tube shares a remarkable similarity in major

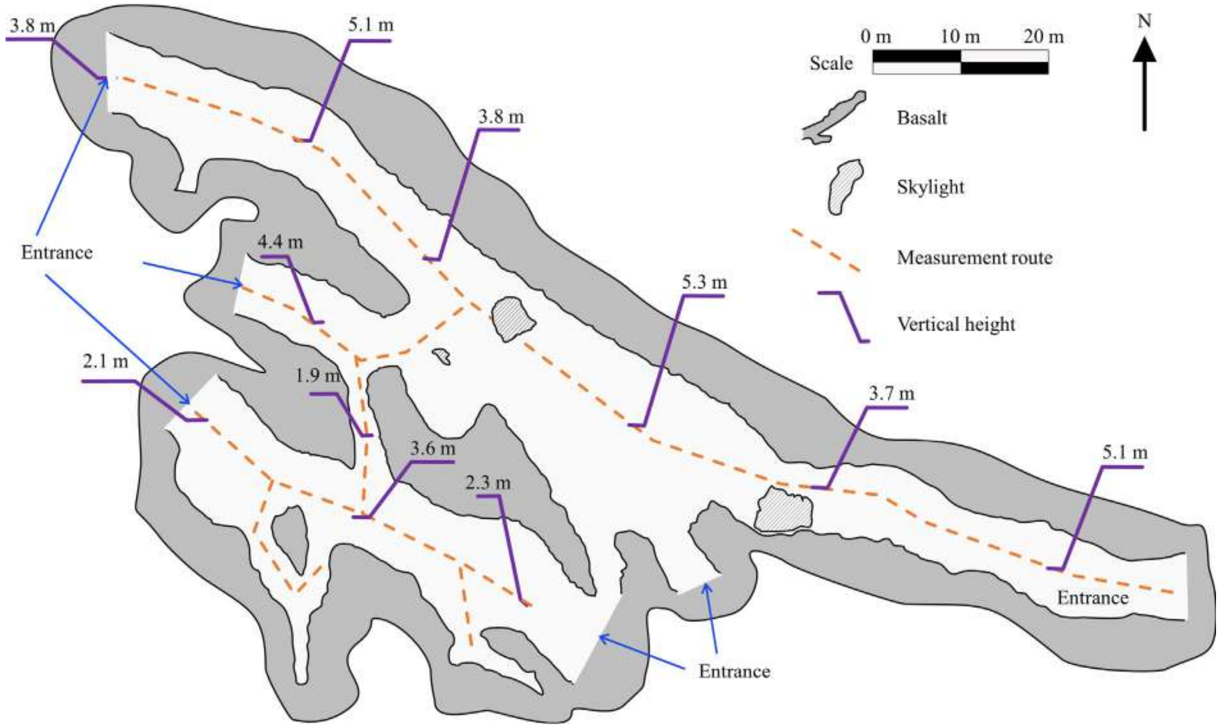


Fig. 9. Topographical map of the "Seventy-Two Caves" lava tube.

element composition with the lunar regolith collected during the Apollo 14 mission. This resemblance holds considerable advantages when it comes to simulating the authentic physical and mechanical characteristics of lunar regolith. Additionally, the Haikou area benefits from convenient transportation, with a well-developed transportation network and airports, facilitating the travel of researchers and transportation of materials. Lastly, while many lava tubes have been developed into tourist attractions, the "Seventy-Two Caves" lava tube remains relatively untouched, with less human interference and fewer nearby residents, making it suitable for scientific research purposes.

5. Challenges and opportunities for geotechnical engineering

Due to the unique geographical location and numerous construction advantages of lava tubes, the concept of a lunar lava tube base has gained international recognition. However, the design and construction of these bases still face several technical challenges, necessitating interdisciplinary collaboration. Geotechnical engineering encompasses a multitude of challenges and opportunities.

Cave exploration devices and methods. The current selection of lava tube sites for exploration primarily relies on remote sensing data, but the accuracy is somewhat insufficient [46]. To address this challenge, it is essential to design a detection device that can obtain as much scientific information as possible within limited scientific payloads. Before designing a lunar lava tube base, on-site exploration of the internal structure of the lava tube using rovers and robotic vehicles equipped with detection equipment is necessary [86]. Robotic rovers or spacecraft equipped with high-resolution cameras, multi-spectral microscopic imagers, and 3D laser scanners can capture images, mineral features, and cave morphology models within lava tubes [87]. However, the design and development of these rovers need to consider the extreme lunar environment and long-distance communication challenges. Achieving precise localization and traversing capabilities within almost pitch-black and enclosed caves poses significant challenges for the rovers [88,89]. Additionally, microseismic data has proven to be suitable for cave detection, and the ESA has already collected microseismic information in the lava tubes of the Corona volcanic region, providing valuable references for planetary cave exploration [90,91].

In-situ drilling, sampling, and testing techniques. The physical and mechanical properties of lunar regolith and rocks surrounding the lava tube are essential for base design. However, existing information on lunar or Martian soil and rock is limited to surface and shallow samples [92,93]. Obtaining deeper geological information is crucial for establishing a base, but it poses implementation difficulties. Potential missions to lunar pits (e.g., Moon Diver, Daedelus, etc.) aim to obtain comprehensive information about the environment, mineralogy, and elemental composition of these features [87,89]. Moreover, they seek to provide insights into the formation of the lunar secondary crust. However, considering the construction of a lava tube base, numerous geotechnical parameters specific to rock and soil engineering are required. Conducting in-situ testing in geotechnical engineering proves to be the most efficient and ideal approach for acquiring these parameters, but it presents challenges [94,95]. Drilling technology is a practical application of geotechnical engineering in space exploration, including base construction, drilling and sampling [96], anchor installation [97] and underground tunnel construction [98]. However, the unique atmospheric environment, microgravity, and extreme temperatures on the Moon severely affect the application of existing ground drilling, sampling, and testing techniques [99]. The interaction mechanism between drilling and sampling equipment and lunar regolith or rocks in extreme environments is a challenge, and the development of in-situ testing technology suitable for space environments is crucial [100,101].

Soil/rock material properties under lunar extreme environments. To construct a base on the Moon, it is necessary to minimize dependence on Earth-based supplies and obtain water and

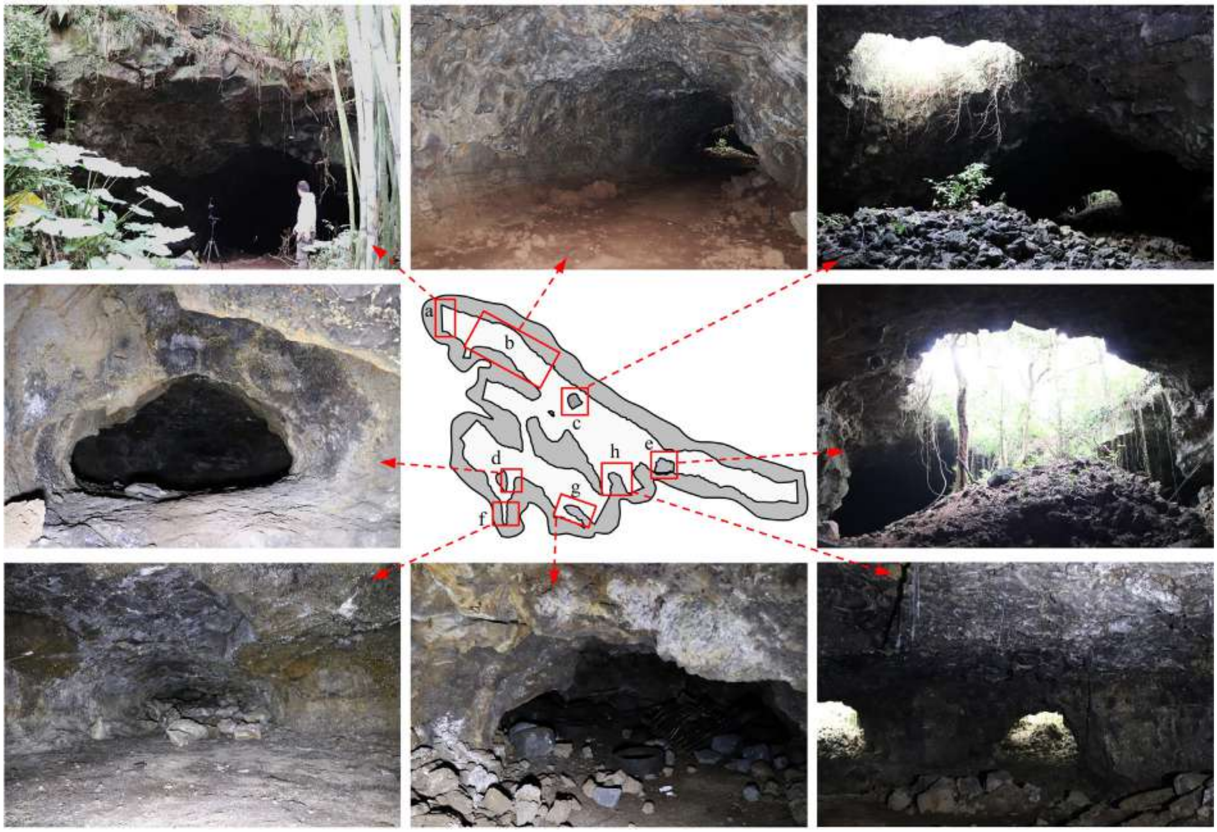


Fig. 10. The typical morphological features of the "Seventy-Two Caves" lava tube.

building materials from lunar rocks. A comprehensive study of lunar rock properties is necessary to achieve potential ISRU under harsh space conditions [102]. The unique extreme environment on the Moon leads to significant differences in the physical and mechanical properties of soil and rock samples compared to those on Earth under vacuum, microgravity, and extreme temperature conditions [101,103,104]. In extreme temperature environments, certain findings on Earth have already demonstrated that rocks exhibit varying degrees of degradation [105,106]. In low-gravity environments, granular materials often exhibit distinct mechanical properties such as high friction angles and significant expansion [107,108]. However, existing strength criteria for granular materials struggle to accurately characterize these unique behaviors. Due to the scarcity and preciousness of lunar soil and rock samples obtained through space missions, simulated lunar soil and rock materials and lunar extreme environment simulation systems must be developed on Earth [84,109,110]. This research helps analyze the mechanical behavior of rocks on the lunar surface and in lava tubes, evaluate the impact of extreme environments on material properties, and develop methods for extracting and manufacturing construction materials from lunar soil/rock [111].

Design and stability assessment. Design and stability assessment of lava tube bases can be carried out based on 3D models obtained from cave scanning modeling and the physical and mechanical properties of lava tube wall rocks [31,112]. However, considering the unique environmental constraints on the Moon, the applicability of existing methods for rock structure classification and structural design theory is questionable. Furthermore, there is a need to reconstruct the method for evaluating the structural performance of lava tubes. The design of a lava tube base must not only ensure structural stability but also effectively integrate life support systems [113]. It is necessary to analyze the influence of load-bearing strength, disturbance, and moonquakes on structural stability, as well as the time-dependent deformation characteristics. Model tests using simulated lunar regolith and numerical simulations can provide optimized design solutions and stability assessment methods for lava tube bases.

Excavation and reinforcement technology. The only entrance to a lunar lava tube is located at its skylight, so the stability and reinforcement of the entrance must be considered early on [114]. During the base construction phase, the impact of low gravity excavation must be carefully studied, and exploration techniques suitable for lunar lava tube exploration and construction are required. Model tests using simulated lunar regolith materials can be conducted to evaluate the excavation efficiency of various schemes such as mechanical drilling, melting, and laser melting [115,116]. Dust and excavation debris are significant issues during the construction process. Developing cave lining materials based on lunar soil/rock materials has engineering significance and can help propose reasonable skylight and lava tube wall reinforcement solutions.

Simulated Earth-based lava tube bases. Conducting simulated construction of lava tube bases on Earth can verify technical solutions in advance, reduce risks in actual lunar construction, help assess base construction costs and resource requirements, identify potential failures, and accumulate valuable experience for lunar surface operations. However, replicating the true lunar lava tube environment in Earth's caves is a challenging task, requiring the

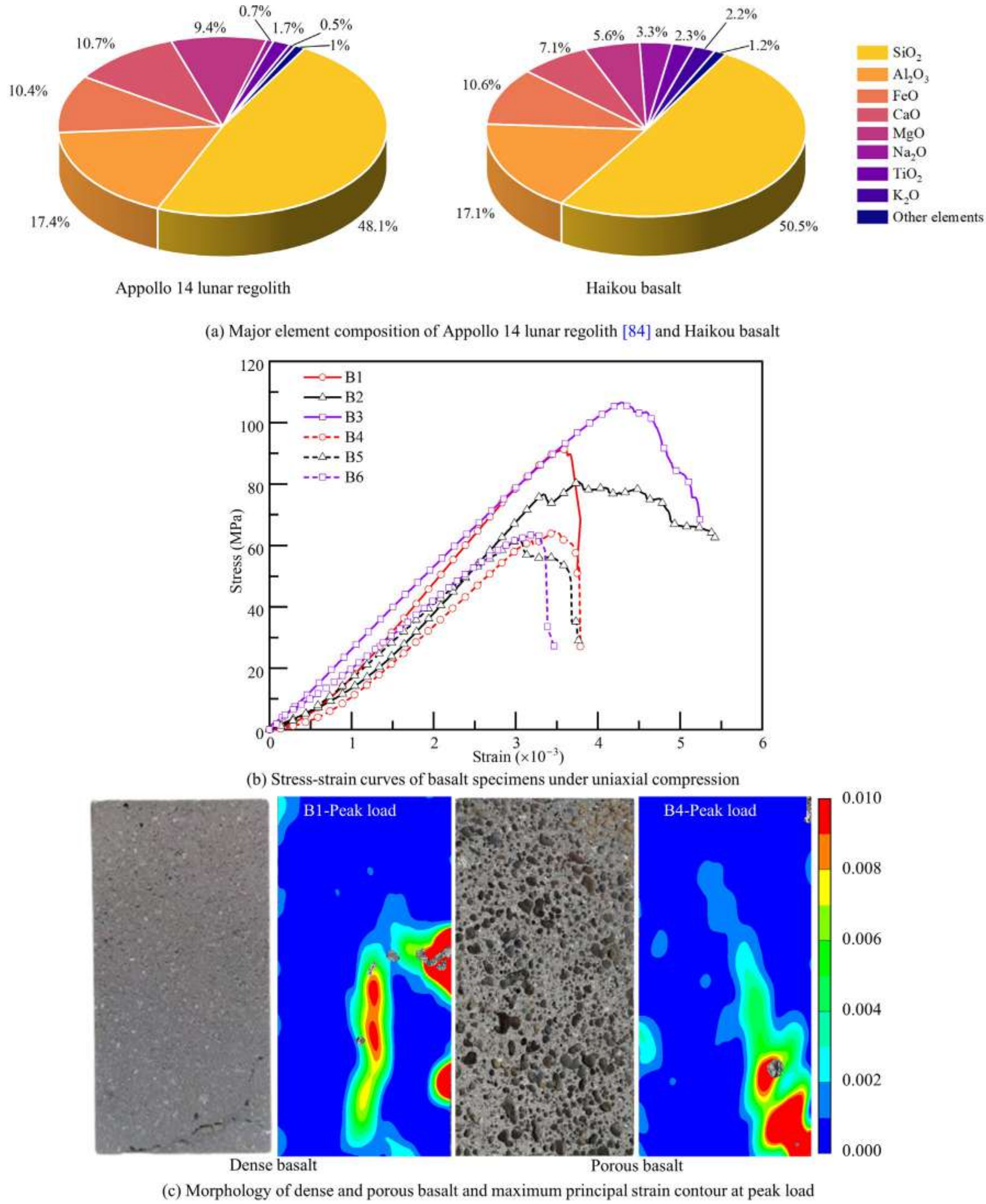


Fig. 11. Chemical composition and mechanical results of Haikou basalt. Note: The major element composition of the Appollo 14 lunar regolith is derived from [84]. B1–B3 and B4–B6 in diagram (b) represent dense basalt and porous basalt, respectively.

selection of suitable lava tube simulation sites and attempting to replicate the difficulties that may be encountered on the Moon's surface.

6. Conclusions

This article presents a systematic review of the geological formation, exploration history, and geographic distribution of lunar lava tubes, while elucidating their benefits and potential uses for constructing lunar bases. Lunar lava tubes offer a protective barrier and a stable internal environment, which are advantageous for shielding against external hazards and minimizing the need for extensive surface structures. Recent technological advancements have enhanced our understanding of these tubes' geographical and geological features, prompting developments in simulation experiments and related technological fields. Field investigations of the Haikou lava tube, combined with laboratory studies and on-site mapping, have established its suitability as a terrestrial analogue for lunar conditions.

However, the exploration and construction within lunar lava tubes present numerous engineering, technical, and scientific challenges, particularly those associated with the Moon's harsh environmental conditions. Therefore, interdisciplinary cooperation is imperative. The combined efforts of scientists specializing in geotechnical engineering, geology, mining, mechanics, materials, and astronauts are critical to solving these intricate problems. Collaborative endeavors encompass various areas such as advancing cave exploration methods, developing in-situ drilling and sampling methods, understanding the properties of lunar soil and rock materials in extreme lunar environments, enhancing excavation and reinforcement technologies, and simulating Earth-based lava tube habitats. The utilization of lunar lava tubes in base construction not only appears feasible but also offers distinct advantages. Embracing this innovative approach to base construction has the potential to expedite lunar exploration and marks a significant stride toward the goal of sustained human presence and activity in space. Consequently, we advocate for greater involvement of geotechnical engineering professionals in the research and development of lunar lava tube bases, thereby contributing to the groundwork for humanity's extraterrestrial aspirations.

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