Study on the volume of landslides in lunar impact craters

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Abstract. The lunar exploration project is of great significance, among which the statistics and measurement of lunar landslide are an important part of lunar exploration. With the help of Google Earth software, lunar image data were obtained, and the volume calculation and analysis of landslides in 14 meteorite impact craters on the Moon were performed using the Alfred S. McEwen formula. It is found by calculation and observation that the diameter of the crater is proportional to the volume of the landslide in most of the meteorite impact craters on the moon.

Keywords: lunar landslide; moon; Lunar craters; Landslide volume.

1. Introduction

The moon is the brightest object that we can see clearly at night. As the only natural satellite of the Earth, the average distance between the Moon and the Earth is about 238,855 miles (384,400 kilometers), according to NASA [1]. When the Moon reaches its shortest distance to the Earth or perigee, it is about 226,000 miles (363,300 km) away. When the Moon is at its farthest distance from Earth, known as apogee, it is about 251,000 miles (405,500 km). There are different theories and hypotheses about the Moon's origin, the leading theory being that a Mars-sized object collided with Earth about 4.5 billion years ago, and the resulting accumulation of Earth debris and impactors formed a natural satellite [2]. But the newly formed satellites are molten. Over the course of about 100 million years, most of the moon's magma crystallized, and less dense rocks began to float upward, eventually forming the lunar crust .

In 1609, Galileo created the telescope; he first discovered the Moon's uneven surface and drew the first map of the Moon [3]. Later, with the progress of modern science and technology, people began to explore the moon with more advanced equipment. With the shocking launch of Sputnik 1 in October 1957, the moon changed from a distant silver disk in the sky to a real place, a probable destination for probes and people. The Soviets struck first, flying Luna 1 by the moon in January 1959. They followed this success with a number of other robotic probes, culminating later the same year with Luna 3, which photographed the far side of the moon, never visible from Earth. [4] In 1968, Apollo 8 took humans out of Earth's orbit for the first time to the moon, where they orbited for nearly a day. It was the first time humans had observed the moon's topography from orbit. In 1970, the former Soviet Union's Lunar probe 16 was the first human probe to achieve automatic sampling on the moon and send it back to the Earth. It soft-landed in the rich sea on the lunar surface and collected 120 grams of lunar rock samples with the drill for the first time and brought them back to the Earth. The exploration of the moon has never stopped, and even if we never find a new habitation there, the exploration of the moon has profound and important implications for our understanding of the history of the Earth and even the universe.

Like the Earth, the moon has a shell, mantle, core and other layered structures. The Moon is a spherical rocky body, probably with a small metallic core, revolving around Earth in a slightly eccentric orbit at a mean distance about 384,000 km (238,600 miles). Its equatorial radius is 1,738 km (1,080 miles), and its shape is slightly flattened in a such a way that it bulges a little in the direction of Earth. The Moon has no global magnetic field like that of Earth, but some of its surface rocks have remanent magnetism, which indicates one or more periods of magnetic activity in the past [5].

Lunar craters are annular craters on the surface of planets, moons, asteroids, or other celestial bodies created by meteorite impacts. As meteorites hit the moon's surface, they create craters of different sizes and widths. The current results of crater detection indicate that they are mostly circular structures, and some older craters are oval or kidney shaped due to the influence of tectonic movement. The main signs of lunar craters are annular crater rim, meteorite fragments and other remnants, crack cone and so on. Data shows that there are at least 1.3 million craters larger than 1 km in diameter, of these 83,000 are greater than 5 km in diameter, and 6,972 are greater than 20 km in diameter [6].

Lunar landslide are not as pronounced as those on Earth or Mars, and most occur in impact craters. In addition, the landslide proved that the moon is not a geologically inactive body. A map created by researchers of the Max-Planck-Institute in Göttingen, Germany, and the Swiss Federal Institute of Technology in Zurich shows at least 136,610 landslides or rockfall boulders dotting the lunar landscape [7]. On the Earth as we know it, landslides are caused by rainfall, river erosion, groundwater activity, earthquakes, volcanic eruptions, or other factors that destabilize slopes, as well as by artificial slope cutting and other human actions. But on the moon, there's no weather, and most landslides are caused by meteorite impacts.

A landslide usually includes a landslide body, that is, the whole sliding part of the landslide, a sliding slope (slide belt), a landslide bed, a landslide step, a secondary step, a trailing margin pool, a landslide perimeter, a landslide wall, a landslide crack, a landslide house, a landslide foot, a landslide toe, and a landslide hump [8]. When the landslide is identified by the naked eye, we can identify whether the terrain constitutes a landslide through these components of the landslide.

This paper includes the introduction of moon, information of landform and landslides on moon, visual identification of landslides in lunar impact craters, calculate the volume of landslides in lunar impact craters, the relationship between the landslides volume and crater dimeter, and the conclusion part.

2. Geological overview of the lunar

In 1610, Galileo observed the moon with a telescope and first pointed out the existence of dark and light areas on the lunar surface. The uneven and complex topography of the lunar surface is formed by a variety of processes, especially impact craters and volcanism play an important role in the characteristics and distribution of the lunar surface topography. The Moon is a differentiated celestial body with a crust, mantle and core. The topographic features of the lunar surface can be roughly divided into three categories, namely lunar-ocean impact craters, lunar land and volcanic terrain. Among them, lunar land and lunar sea are the two most prominent surface topographic features on the moon, and they account for about 4/5 of the entire lunar surface.

Scientists at the Institute of Geochemistry of the Chinese Academy of Sciences have created a detailed geological map of the moon at a scale of 1:250 million. The new lunar map shows 12,341 craters, 81 impact basins of 14 rocks, and 17 different types of structures [9].

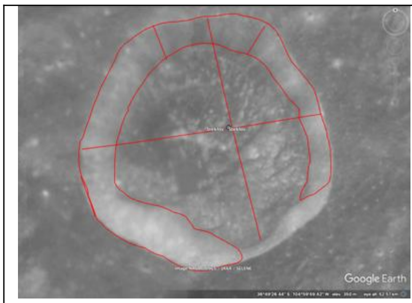
There are a large number of impact craters on the moon, which are circular pits formed on the surface of planets, satellites and other celestial bodies by meteorite impact. These craters have different depths and diameters. Asteroid bombardment over billions of years has left the lunar surface covered in craters of various sizes and covered in solidified lava, rubble and dust. These massive and ancient impacts, estimated to have occurred about 380 to 400 million years ago, likely brought deposits of olivine material to the surface [10]. The hallmarks of meteorite impact craters on the moon usually include circular structures, annular rim, or lip, fracture cones, negative gravity anomalies in the rock at the bottom, and remnants of meteorite fragments or iron and nickel pellets inside the crater.

3. Recognition of landslides in lunar impact craters

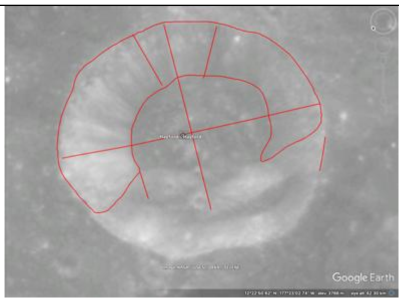
In this section, we collected 14 landslides data from the article Large rock slides in impact craters on the Moon and Mercury [11] . This section briefly make a census of the location and diameter of the landslide . The locations of the analyzed lunar landslide are shown in Table 1 and Figure 1.

Table 1 Location of lunar landslide

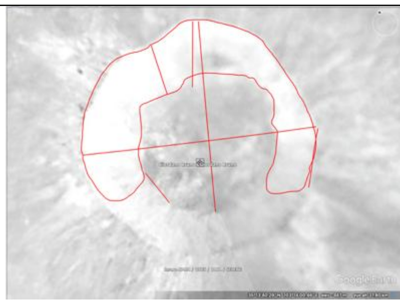
Landslide	Location		Crater	
	Longitude (°)	Latitude (°)	Name	Diameter (km)
1	104.53W	36.41S	Steklov	34.06
2	176.24W	12.41N	Hayford	28.04
3	102.47E	35.54N	Giordano bruno	21.05
4	76.30E	2.35S	Geissler	16.44
5	4.36W	67.31N	Epigenes	52.65
6	48.59E	40.57N	Drebbel	29.02
7	91.48W	38.29S	Crude	20.46
8	76.58E	60.23N	Cleostratus	50.12
9	101.17W	52.41S	Chadwick	27.23
10	59.10E	40.42N	Cassini A	14.75
11	26.42E	10.41N	Carrel	14.28
12	48.11E	12.24S	Bellot	17.37
13	80.05E	5.11N	Banachiewicz	12.18
14	102.42E	59.50S	Unnamed	22.90

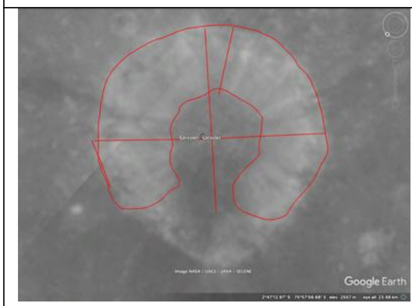


Steklov 36°41’S 104°53’W

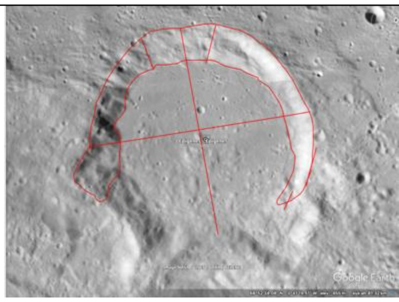


Hayford12°41’N 176°24’W

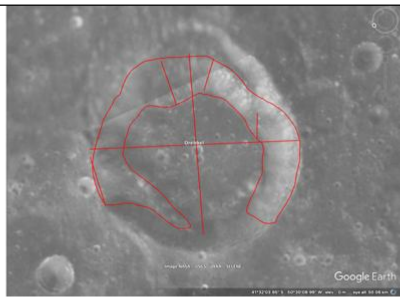

Giordano bruno35°54’N 102°47’E



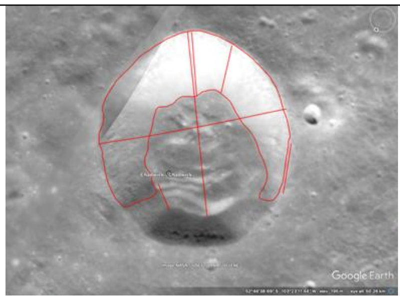
Geissler 2°35’S 76°30’E



Epigenes 67°31’N 4°36’W



Drebbel 40°57’N 48°59’E



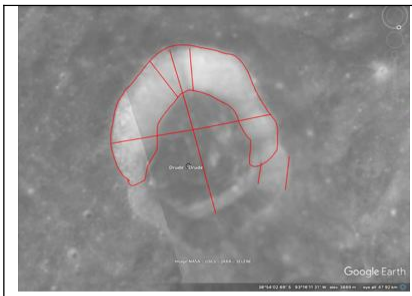
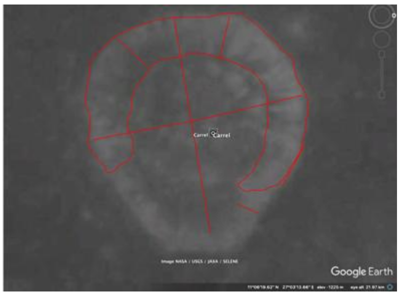
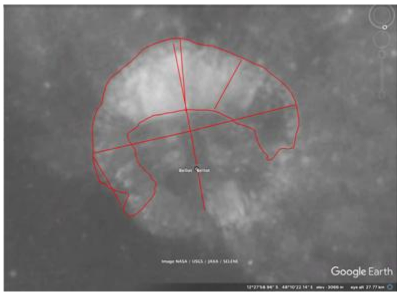
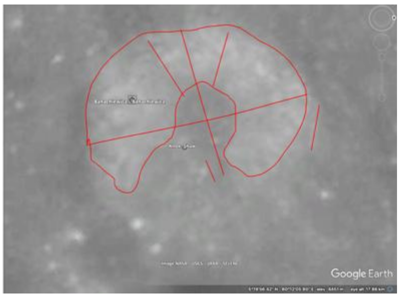
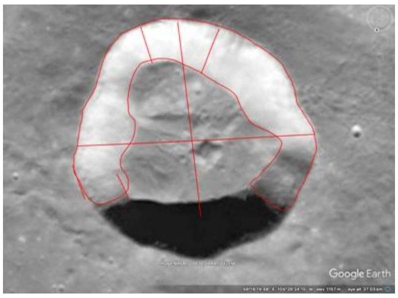
 Crude 38°29’S 91°48’W	Cleostratus 60°23’N 76°58’E	Chadwick 52°41’S 101°17’W
 Cassini A 40°42’N 59°10’E	 Carrel 10°41’N 26°42’E	 Bellot 12°24’N 48°11’E
 Banachiewicz 5°11’N 80°05’E	 Unnamed 59°50’S 102°42’E	

Figure 1 30 lunar landslide

3.1 Volume of landslides in lunar impact craters

3.1.1Methodology

Many different scale landslides have been observed in lunar impact craters. Alfred S. McEwen studied the landslide in Valls Marineris using image data of Valls Marineris, and obtained the landslide volume calculation formula above. In this paper, the formula is used to calculate the volume of meteorite impact craters on the lunar surface:

$$V=ZA+0.5WZ^{2}[\tan(90-\theta_1)-\tan(90-\theta_2)]$$

In this formula:

V is the volume of the slope (km^3);

Z is the height difference (m) between the highest point before sliding and the lowest point after sliding;

A is the area (km^2) projected on the plane before sliding.

W is the width of the slope before sliding (km);

θ1 is the Angle (°) between the slope and the horizontal ground before sliding.

θ2 is the Angle (°) between the slide and the horizontal ground [12].

Where, the formula for calculating the area A projected on the plane before sliding is A = 0.5 × landslide wall area defined by Google Earth × cosθ2. An illustration of the calculation method for landslide volume is shown in Figure 2.

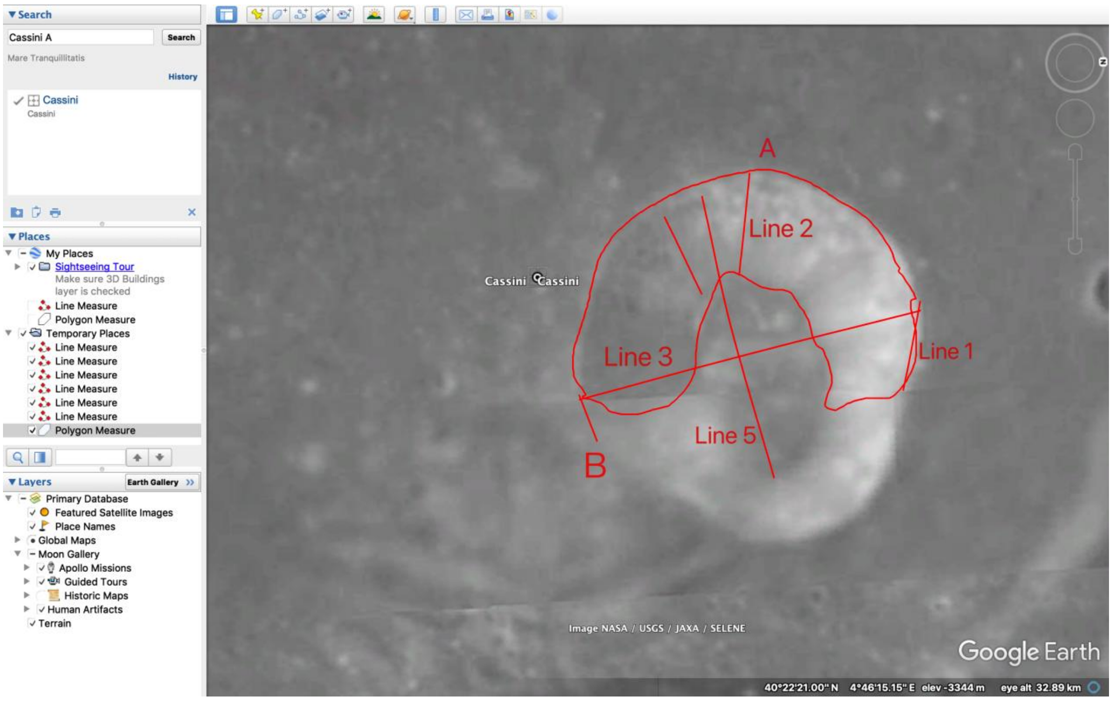


Figure 2 Illustration of the calculation method for landslide volume

3.2 Case study

In this section, the landslide in Cassini A meteorite impact crater of the Moon at 40°42 'north latitude and 59°10' east longitude is taken as an example, and its volume is calculated using Alfred S. McEwen formula. The calculation procedure is shown as follows and the results are presented in Table 2.

Step1

Calculate the height difference Z between the highest point before sliding and the lowest point after sliding. According to the observation of elevation changes by Google Earth, the highest point of the landslide before sliding is A point at the top of the landslide wall, with an elevation about 4.50km. The elevation of point B is about -2.22km. Then, Z=4.50-(-2.22)=6.72km.

Step2

Line 1 is used to calculate the $\theta 1$. Looking around the landslide, line 1 is relatively close to the original terrain, so the Angle between line 1 and the horizontal plane is approximately substituted for $\theta 1$. The length of Line 1 is 4.09km measured in Google Earth software, and the height difference between the beginning and end of Line 1 is 1.04km. Therefore, $\sin\theta 1 = 1.04/4.09=0.254$. It was calculated that $\theta 1 = 14.713°$.

Step3

Line 2 indicates the maximum slope direction of the landslide wall and is used to calculate $\theta 2$ in the formula. The landslide wall is the part that does not slip in the landslide process, so the Angle between the landslide body and the horizontal plane can be approximated by line 2. As measured by Google Earth, Line 2 has a length of 4.83km and a height difference of 2.39km. The calculation method is the same as that of $\theta 1$, $\sin\theta 2 = 2.39/4.83=0.495$, $\theta 2 = 26.670°$.

Step4

Line 3 represents the width W before the slide. The length of line 3 measured by Google Earth is 15.75km, that is, W=15.75km.

Step5

Line 4 is used to calculate the sliding distance of the slope. The measured length of line 4 is 13.26km, and the height difference between the beginning and end of line 4 is 3.88km. Therefore, the sliding distance L of the landslide is $L=\sqrt{(13.26)^2 - (3.88)^2}=12.680$km.

Step6

The area A projected on the plane before sliding is half of the area of the landslide wall multiplied by cosθ2. After the landslide wall is delimit, the area can be directly read in Google Earth software, and its area is about 102.77km^2. Therefore, the area projected by the landslide body on the plane before sliding is A=0.5*102.77*cos(26.670°)=45.918km^2.

Step7

By substituting the calculated parameters into Alfred S. McEwen formula, the landslide volume is V=ZA+ 0.5WZ ^2 [tan(90-θ1) - tan(90 - θ2)] =954.735km^3

Table 2 Volume for the analyzed lunar landslide

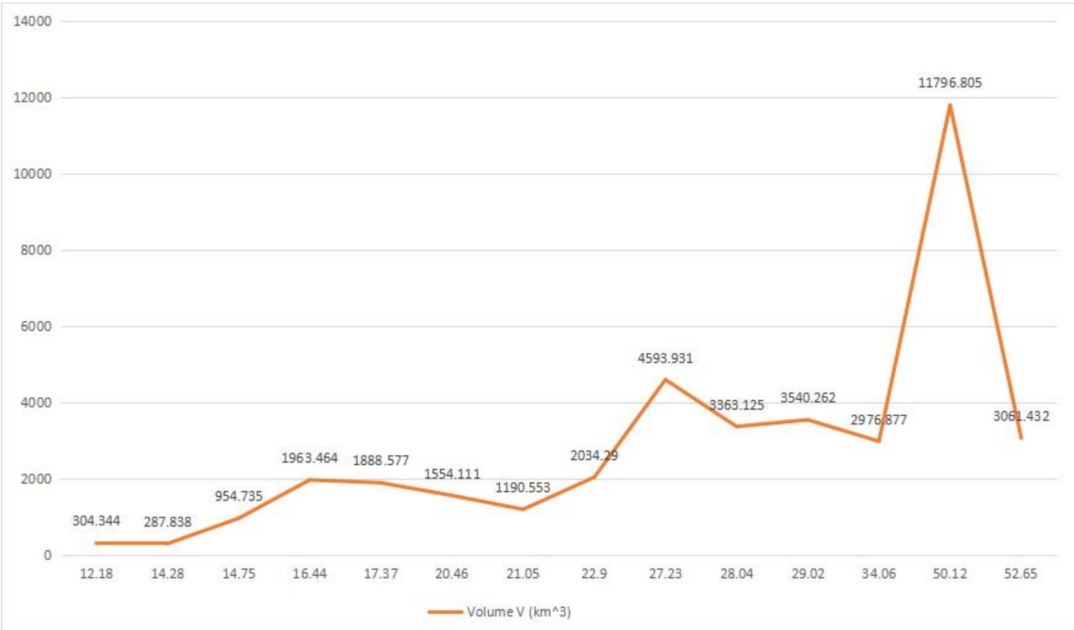
Crater#	Diameter D (km)	Landslide area (km^2)	Landslide wall area (km^2)	Volume V (km^3)
1	34.06	1040.86	198.64	2976.877
2	28.04	589.07	249.02	3363.125
3	21.05	360.47	144.76	1190.553
4	16.44	226.64	150.39	1963.464
5	52.65	2340.48	230.44	3061.432
6	29.02	815.69	350.04	3540.262
7	20.46	454.34	177.67	1554.111
8	50.12	2226.24	648.26	11796.805
9	27.23	667.35	315.64	4593.931
10	14.75	200.78	102.77	954.735
11	14.28	189.26	77	287.838
12	17.37	225.22	111.69	1888.577
13	12.18	148.00	79.03	304.344
14	22.90	481.44	199.29	2034.290

4. Relationship between the landslide volume and crater diameter

By calculating the volume of the landslide in the impact crater of the lunar meteorite and comparing the diameter of the crater, it is found that the larger the diameter of the crater, the larger the volume of the landslide in the crater. As shown in the table 3 and figure 3, by randomly comparing the landslides in Cassini A, Bellot, Banachiewicz, Chadwick and Cleostratus, it can be found that the diameter of the crater is roughly in direct proportion to the volume of the landslide in the crater. Then, crater Hayford and Giordano bruno are randomly selected. The diameter of crater Hayford is 28.04km and the volume of landslide is 3363.125km^3, while that of Giordano bruno is 21.05km and the volume of landslide is 1190.553km^3. Through statistics and calculation, it is found that the volume of the landslide body in most meteorite impact craters is in direct proportion to the diameter of the crater, that is, the larger the diameter of the crater, the larger the volume of the landslide body, which is speculated to be related to the impact energy. But not all craters follow this pattern. It has been observed that the diameter of some craters is relatively short, but the volume of the landslide in the craters is large. For example, the crater Chadwick in the table, whose diameter is 27.23km, is much smaller than that of Epigenes crater, whose diameter is 52.65km. However, the volume of Chadwick's slope is 4593.931km^3, which is much larger than Epigenes' slope at 3061.432km^3. The landslide wall area of Chadwick is 315.64km^2, while that of Epigenes is only 230.44km^2. Comparing with other groups of landslides whose diameter is not proportional to the volume of the landslide body, it is also found that the volume of the landslide with the landslide wall area is larger. The landslide wall is a wall-like interface exposed to the outside after the rear edge of the landslide body is separated from the stationary mountain. The large area of the landslide wall means that the sliding body is large and the sliding part is large, which is obviously proportional to its volume. Therefore, in lunar meteorite impact craters, the larger the diameter of most craters, the larger the landslide volume. However, because there are many factors affecting the landslide, including the landslide wall area, slope Angle and so on, the law that the crater diameter is proportional to the landslide volume only accords with most landslides, but not all landslides.

Table 3 Relationship between the landslide volume and diameter of craters on the moon

Crater#	Crater name	Diameter D (km)	Volume V (km^3)
1	Steklov	34.06	2976.877
2	Hayford	28.04	3363.125
3	Giordano bruno	21.05	1190.553
4	Geissler	16.44	1963.464
5	Epigenes	52.65	3061.432
6	Drebbel	29.02	3540.262
7	Crude	20.46	1554.111
8	Cleostratus	50.12	11796.805
9	Chadwick	27.23	4593.931
10	Cassini A	14.75	954.735
11	Carrel	14.28	287.838
12	Bellot	17.37	1888.577
13	Banachiewicz	12.18	304.344
14	Unnamed	22.90	2034.290



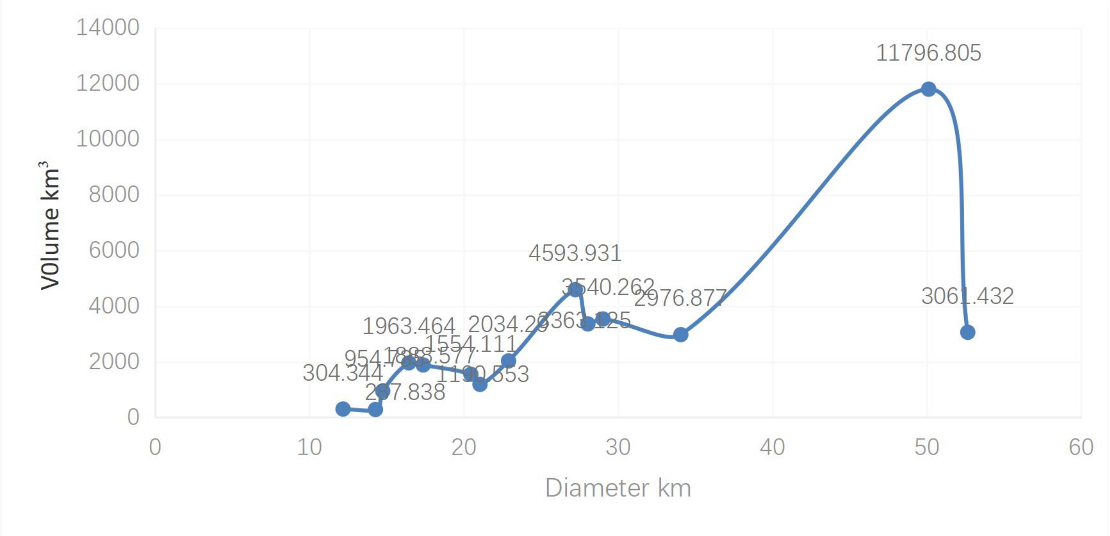


Figure 3 Relationship between the landslide volume and diameter of craters on the moon

5. Conclusion

In this paper, Google Earth software is used to obtain lunar image data, and Alfred S. McEwen formula method is used to calculate the volume of slope in 14 typical craters in Valles Marineris, and compare it with the diameter of the corresponding meteorite impact crater. The main conclusions are as follows: Through measurement and calculation, the relationship between the diameter of lunar crater and the volume of slope in corresponding crater is investigated. The observation shows that in most lunar craters, the diameter of the crater is proportional to the volume of the landslide in the crater, that is, the larger the diameter of the crater, the larger the volume of the landslide in the crater. Even in the process of comparison, the volume of landslide in some craters with smaller diameters is larger than that in some craters with larger diameters, but in general, the volume of landslide in craters with larger diameters is larger. In the comparative observation, some landslides do not fully conform to the rule that the diameter of the crater is proportional to the volume of the slope in the crater, which indicates that the volume of the slope is also influenced by many other factors. But in this study, overall, the larger diameter crater, the larger volume of the landslide.

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