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ESTIMATION OF THE NEEDED REGOLITH FOR COVERING LUNAR HABITAT BY PROTECTIVE LAYER

Petr KONEČNÝ[1], Jacek KATZER[2], Janusz KOBAKA[2], Karol SEWERYN[3]

[1] Faculty of Civil Engineering, VSB – Technical University of Ostrava,
Ostrava, Czech Republic
[2] Faculty of Geoengineering, University of Warmia and Mazury in Olsztyn,
Olsztyn, Poland
[3] Centrum Badań Kosmicznych Polskiej Akademii Nauk (CBK PAN),
Warsaw, Poland

e-mails: petr.konecny@vsb.cz, jacek.katzer@uwm.edu.pl,
janusz.kobaka@uwm.edu.pl, kseweryn@cbk.waw.pl

ABSTRACT. The article deals with estimation of the amount of regolith to be mined with respect to the preparation of lunar habitat. Estimation of the size of the pit is related to the overlay of regolith for habitat made of a composite concrete-like structure. The evaluation is based on the number of inhabitants, necessary floor area, and the considered structure that is made of three segments. The first segment is a linear vault with a half cylinder cross section ending with a half sphere on both sides of the vault. Elementary formulas for the computation of volume of cylinder and sphere are applied.

Keywords: space exploration, transportation; identification, modeling, lunar habitat, pit size

1. INTRODUCTION

The civilization has progressed, and current technology seems to be capable of allowing us to colonize our space neighbors. Permanent human presence on the Moon will be associated with significant construction efforts (Kobaka, Katzer and Zarzycki, 2019). Therefore, preparation for such a construction process including evaluation of structural concepts and *in situ* resource utilization (ISRU) has to be worked on. Some aspects of such a construction process have been already developed (Ruess, Schaenzlin and Benaroya, 2006; Benaroya and Bernold, 2008; Faierson et al., 2010), but a lot of key issues are still waiting to be addressed. One of the problems which is still waiting for thorough consideration is the volume of needed regolith for the creation of initial lunar habitat, its beneficiation, and mining procedures (Hadler et al., 2020). Due to radiation (solar and gamma), meteoroid impacts, and significant temperature fluctuations on the lunar surface (from −183 °C to +106 °C), vast majority of proposed construction solutions of future bases are associated with lunar soil used as a cover. In some cases, initial lunar base is foreseen as an inflatable composite structure covered with lunar soil (Cadogan, Stein and Grahne, 1999). Other research teams forecast harnessing of natural lunar caves and lava tubes (Wynne, Titus and Diaz, 2008; Gibney, 2018). Such locations could provide shelter for future colonists, but using the lunar soil for creation, some parts of cover would also be needed. It is sometimes predicted that creation of 3D-printed building blocks will be needed for such covers (Cesaretti et al., 2014). During previous research tasks, the research team conceptualized about 3D-printed Voronoi egg-shaped habitat for permanent lunar outpost (Juračka et al., 2023). Such a base would also require to be fully covered by lunar soils. The volume of regolith needed for construction effort will influence the size of the pit for regolith mining and, subsequently, the technology of mining itself. The size of the mine depends, besides other aspects, on the size of the habitat. Some recommendations regarding the needed cubature of the habitat and the floor area per person are given in literature. Ruess, Schaenzlin and Benaroya (2006) recommend 34 m^2 per person, as well as higher height of a storey (in comparison to Earth standards) due to lower gravity. Rues at al. suggest a storey of 4 m (including 50 cm related to the heating/ventilation, etc.). Based on the number of people in the habitat, the size and the dimensions of the structure shall be derived. The dimensions of the habitat determine the needs of structural performance and the selection of the structural concepts.

There are a lot of strategies to tackle the issue of lunar habitat structural concept. Benaroya and Bernold (2008) thoroughly summarize the available concepts. For example, one of the strategies given by Faierson et al. (2010) is based on a dome-like structure (voussoir arc). The structure is foreseen to be erected using precast bricks and lost formwork created by the air-filled airtight membrane. Ruess, Schaenzlin and Benaroya (2006) proposed a lightweight aluminum vault transported from the Earth and assembled on the Moon with the regolith overlay. Another approach, preliminary evaluated with respect to structural performance by Konecny and Katzer (2021), is focused on concrete-like material with a regolith overlay built also on lost formwork. If the regolith overlay is considered, then the actual procedure of mining the materials available *in situ* needs to be developed. Preparation of the procedures for regolith mining, experimental evaluation of available lunar simulants, and numerical modeling of the behavior of the simulant as well as designing of the pit for mining of the regolith should be considered. Therefore, the volume of needed regolith will influence the size of the pit.

2. LUNAR HABITAT STRUCTURE

2.1. Structural concept

The type of a structure chosen for the analysis is based on a thin concrete shell supported from the inside by air pressure. To counterbalance the air (which wants to fly out the “balloon” of the created habitat), the weight of the structure as well as the protective overlay of lunar soil should be used. Regolith will be used to create a concrete-like composite for the creation of a thin-wall structure of the habitat and for the protective overlay. The overlay will play multiple roles: protection against space radiation, thermal insulation, and a layer absorbing small meteorites (and preventing ricochets). Such a strategy based on the structure made from concrete-like material and regolith overlay was discussed preliminarily in a previous publication (Konecny and Katzer, 2021). The structural performance is related to the dimensions that depend on the size of the habitat. Using the recommendations of Ruess, Schaenzlin and Benaroya (2006), the effective height of the storey of 3.5 m was chosen for further analyses. To limit the height of the habitat, it was decided to adapt the design based on a half sphere (as the ending) and a half cylinder (as the central part). In this way, the size of the habitat can be easily extended (by creating a longer central half cylinder part) without changing its height. In case of traditional dome, the number of people would influence its overall dimensions (including height). From civil engineering point of view, the larger the height, the more complicated the construction process will be.

The conducted computations were divided into two stages: a) half sphere and b) half cylinder. The cylindrical part is a straight part with the cross section defined by a half circle forming a horizontal half cylinder with the radius r and length d. The half sphere is represented by two quarters of a sphere that form the ending segments of the habitat on both ends of the straight part. The sphere has also the radius r. The scheme of the habitat is presented in Fig. 1, while the cross section of the proposed habitat is presented in Fig. 2.

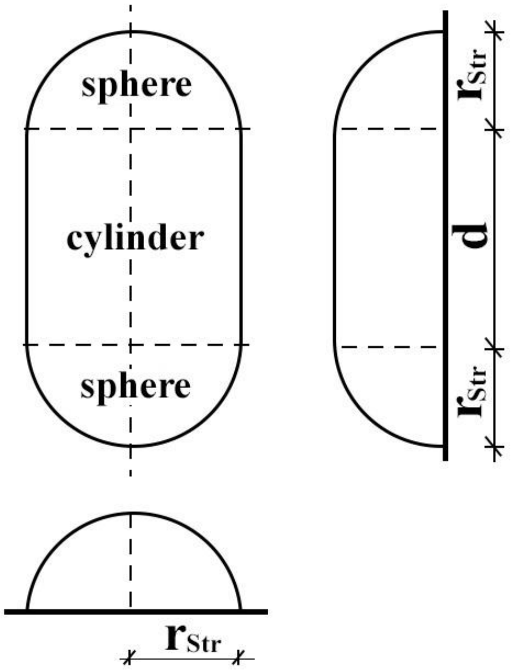

Figure 1. Scheme of the lunar habitat: floor projection, side view, and frontal view

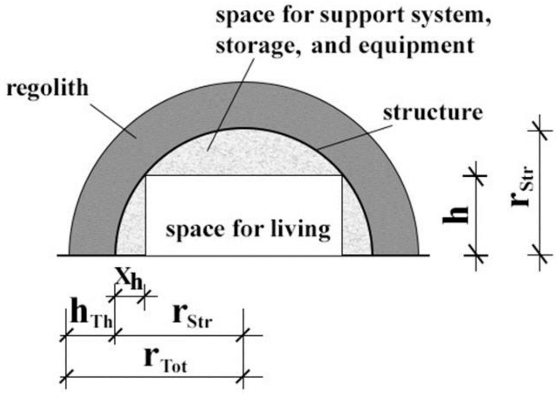

Figure 2. Cross section of the lunar habitat

2.2. Effective floor area

The effective floor area is computed first. It is based on the known radius of the spherical part r_{Str} and considered effective height of the habitat storey h. The effective usable area of the spherical cupola is computed based on the formula of the y coordinate (center line of the structure, see Fig. 1):

$$y = \sqrt{2r_{Str}x - x^2}, \tag{1}$$

which shall be larger than the limiting value of the storey height h. This is fulfilled for $x > x_h$ as follows:

$$x_h = \frac{2r_{Str} - \sqrt{4r_{Str}^2 - 4h^2}}{2}, \tag{2}$$

which is the second solution of quadratic formula.

The floor area is computed for the cylindrical part and the spherical parts separately. Therefore, the sum of floor areas is computed as follows:

$$S_E = S_{E,d} + S_{E,c}, \tag{3}$$

where the area of the rectangular floor projection of the cylinder is $S_{E,d}$:

$$S_{E,d} = 2d(r_{Str} - x_h) \tag{4}$$

and the area under the circular floor projection of the cupola is computed from the projections of two quarters of the sphere $S_{E,c}$ yielding:

$$S_{E,c} = \pi(r_{Str} - x_h)^2. \tag{5}$$

The volume of the habitat's living space $V_{Str,E}$ can be computed from the floor area S_E by multiplication by height h as follows:

$$V_{Str,E} = S_E \cdot h. \tag{6}$$

The suitable number of inhabitants np is derived based on eq. (3) from the necessary floor area for one inhabitant S_n:

$$n_p = \frac{S_E}{S_n}. \tag{7}$$

If the desired number of inhabitants np and the radius of the structure *r* are given, then the above-mentioned computations shall be repeated iteratively with a variable length of the straight part *d* until satisfactory result is achieved.

2.3. Estimation of regolith volume

The regolith volume V_{Rl} is obtained as a computation of the total volume of the habitat, including the regolith cover, V_{Tot}, without the volume of the structure itself V_{Str}:

$$V_{Rl} = V_{Tot} - V_{Str}. \tag{8}$$

The cylindrical part and the spherical parts are computed separately in a manner similar to that of floor area. Therefore, the sum of volumes, either for the structure or the total volume, is computed as follows:

$$V_{Rl} = V_d + V_c, \tag{9}$$

where the volume of the half cylinder is V_d:

$$V_d = \frac{\pi r^2}{2} \cdot d \tag{10}$$

and the volume of the cupola formed from two-quarters of the sphere V_c is

$$V_c = \frac{2\pi r^3}{3}. \tag{11}$$

It is worth mentioning that the radius of the cupola or the cylinder stands for r_{Str} in case of V_{Str} computation or for r_{Tot} in case of V_{Tot} computation, as shown in in equations (10) and (11).

The volume of regolith is computed as follows:

$$V_{Rl} = \frac{\pi(2rh_{Th} + h_{Th}^2)}{2} \cdot d + \frac{2\pi(3r^2 h_{Th} + 3rh_{Th}^2 + h_{Th}^3)}{3}. \tag{12}$$

The last parameter to be computed is the volume of the supporting systems, storage, and equipment V_{Supp}, that is:

$$V_{\text{Supp}} = V_{Str} - V_{Str,E}. \tag{13}$$

2.4. Results

Computations were based on the input parameters given in Table 1. Output parameters of the calculated model of habitat are given in Table 2. The necessary volume of the regolith depending on the thickness of the cover to be excavated for the lunar habitat V_{Rl} occupied by four inhabitants is presented in Table 3.

Table 1. Input parameters related to the assumed habitat dimensions

Parameter	Symbol	Value	Unit
Radius of the structure	r_{Str}	5	(m)
Thickness of the regolith	h_{Th}	0.3–3	(m)
Length of the straight part	d	14	(m)
Height of the storey	h	3.5	(m)
Square area per person	S_n	34.4	(m^2)

Table 2. Output parameters of the calculated model of habitat

Parameter	Symbol	Value	Unit
Persons	n_p	4.1	(-)
Sufficient floor height coordinate	x_h	1.43	(m)
Floor area	S_E	140	(m^2)
Habitat's volume	V_{Str}	812	(m^3)
Habitat's living space	$V_{Str,E}$	490	(m^3)
Supporting space *)	V_{Supp}	321	(m^3)

*) Including space for equipment, storage, and life supporting systems.

Table 3. Volume of lunar regolith

Thickness of the regolith cover	Unit	Volume	Unit
0.3	(m)	118	(m^3)
0.5	(m)	202	(m^3)
1	(m)	432	(m^3)
2	(m)	984	(m^3)
3	(m)	1668	(m^3)

3. DISCUSSION AND CONCLUSIONS

The size of the pit related to the building of a lunar habitat is approximated based on the amount of the regolith necessary to be used as a protective shielding of the habitat made from concrete-like material.

The effective living space of the habitat is computed, as well as the space of the supporting systems such as heat, air conditioning, storage, and equipment.

The sample computation is based on the consideration of four inhabitants, considering 34.4 m^2 per person and 3.5 m as the living space habitat's storey effective height.

The circular arch is considered as a shape of the vault-like structure that consists of cylindrical and spherical parts. Therefore, analytical formulas were used. If more complicated geometry is applied, a numerical solution of the computation of the regolith volume is necessary.

The shape of the regolith cover is considered to be circular as well as the shape of the habitat structure. The actual shape of the cover depends on the angle of repose and/or the structure supporting the regolith shape.

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