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Remarks On The Sources Of Error In The Modelling Of Lunar Geotechnical Structures

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Abstract: Scale modelling should be a very useful strategy for the design of lunar structures. Preventing structural damages in the lunar environment is crucial and scale models are helpful to achieve this aim. The size of these models must be scaled to take into account the different gravitational levels. Since the lunar gravity acceleration is about one-sixth of the terrestrial one, it follows that the models on Earth will be very smaller than the prototype to be realized on the Moon. This strategy will represent an opportunity for engineers working on lunar structure design, provided that the errors, both computational and experimental, related to the change of scale are quantified, allowing reliable extension of the physical scale modelling results to the prototype. In this work, a three-dimensional finite element analysis of walls retaining lunar regolith backfill is described and discussed, in order to provide preliminary results, which can guide a future experimental investigation based on physical scale-modelling. In particular, computational errors related to the scale effects are assessed, with respect to a virtual prototype of the lunar geotechnical structure, and compared with errors from other sources of discrepancy, like the adopted constitutive model, the variability of the geotechnical parameters and the calculation section used in the 3D analysis. The results seem to suggest the soundness of this strategy of modelling and are likely to encourage new research, both numerical and experimental, supporting the structure serviceability assessment.

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1 Introduction: How To Model Lunar Structures In A Lab?

The construction of physical scale models becomes a very useful strategy for the design of civil structures on the Moon, such as habitat for crew and roads for rovers. The size of these models must be scaled in order to take into account the different gravity levels. Since the lunar gravity acceleration is about one-sixth of the terrestrial one, it follows that the physical models on Earth will be very smaller than the prototype to be realized on Moon. Further reduction of the model sizes can be achieved by centrifuge testing, although in a much more expensive way (*Table 1*). Another advantage of this strategy of investigation is that no error related to Coriolis effect is expected, since the scaling procedure is purely based on gravity and not based on inertial effect, as in centrifuge testing [1], where the acceleration is generated by rotation (*Table 1*). This strategy will represent a growing opportunity for structural and geotechnical engineers working on lunar structure design, provided that the errors, both computational and experimental, related to the change of scale are quantified, allowing reliable extension of the physical scale-modelling results to the prototype. In this respect, research studies should aim at relating the uncertainty of the experimental results obtained by physical modelling to all the possible sources of errors.

Two basic principles for an accurate physical modelling of geotechnical problems must be considered *[2]*: first, the behavior of the soil in the scaled model must be the same as in the prototype; second, fundamental physical laws, as stress equilibrium, definition of strains and the constitutive relation must be satisfied both in the scale model and the prototype. From a practical point of view, model behavior and prototype behavior cannot be

Table 1: Scaling strategies for simulating the behavior of a lunar structure.

SCALING PATH	INVESTIGATION OUTPUT	ADVANTAGES	PROBLEMS
Microgravity To Terrestrial Gravity	Prototype Behavior	Low Cost; No Coriolis Effect	Fixed Size Reduction; Scale Error deduced by “Virtual Prototype”
Microgravity To Hypergravity	Prototype Behavior	Further Size Reduction; Scale Error measured on Experimental Basis	High Cost; Coriolis Effect; Undesired Shear Stresses

identical; therefore a procedure validaing the modelling should look at the discrepancy between them with a given tolerance.

The validation procedure for the modelling technique should consist, when possible, of a comparison of the experimental results deduced by several models scaled for different gravitational levels *[1] [3]*, which is typical for models subjected to hyper-gravity. Experimental sources of discrepancy can arise from particle size, when using for the model the same granulometry of the prototype: in this case, different acceleration levels should imply an error, although negligible for high ratios of the structure size to the average grain size *[4] [5]*. Since a lunar geotechnical structure would be too large to be tested on either parabolic flight or drop tower, reproducing microgravity conditions, it has to be modelled either under hyper-gravity or under terrestrial gravity (*Table 1*). A “hybrid” validation method is proposed here for physical modelling at *1 g*, based on the following steps:

a) Experiment at *1 g* is carried out with scaled (from *1/6 g*) model representing the lunar structure.
b) Constitutive and numerical models suitable for simulating the behavior of the experiment at *1 g* are identified by numerical simulation of the static problem and of the earth pressure mobilization.
c) The numerical model is employed to generate a “virtual prototype” and to predict its behavior at *1/6 g*.
d) The measures obtained from the experiment carried out at *1 g* are scaled by the well-known laws *[6]* in order to deduce the behavior expected for the prototype at *1/6 g*.
e) The correspondence between the outputs of (c) and (d) is checked and the discrepancy between them, here called “experimental scale uncertainty”, ER_{exp}, will quantify the reliability of the modelling.

This procedure implies that the degree of computational uncertainty of the virtual prototype behavior has to be defined, since it must be taken into account when the “scaled” experimental results are compared with the virtual prototype for assessing the model’s reliability. With this aim, one could compare the numerical outputs related to the virtual prototype (c) to the numerical outputs from the physical model (b) after scaling them for the difference in gravity acceleration: since discrepancy is not theoretically expected, it can only have computational meaning. It is here referred to as “computational scale uncertainty”, ER_{comp}. It should depend, for a given constitutive model, on the adopted calculation code, the numerical integration method and the iteration set-up.
In this approach, the lower ER_{comp} is the more the calculation method should be suitable for an assessment of ER_{exp} in the proposed indirect way. Moreover, in order to judge if ER_{exp} is acceptable for the design, another source of uncertainty must be characterized, related to the setup of the soil in the physical model, that is, the “effect of variability of the geotechnical parameters” (ER_{geot}). The present study attempts to define both ER_{comp} and ER_{geot} for a given geotechnical structure under lunar conditions, while also investigating the incidence on the calculation of two different constitutive models and of two different analyzed sections (i.e. 3D effects), to point out the relative weight of ER_{comp} with respect to other sources of output discrepancies.

More specifically, this study is concerned with the numerical simulation of the behavior of a lunar regolith backfill retained by concrete walls, which ideally could allow a better soil deposition and compaction, in order to make either a cover for a lunar base or a road for rovers. The reason for a regolith layer covering the lunar base is the environment in which it would be built *[7]*: continuous solar and cosmic radiation, extremes in temperature and radiation, meteorites *[8]*, abrasive and adhesive dust. It appears that at least 2.5 m of regolith cover would be required to keep the annual dose of radiation at 5 rem, which is the allowable level for radiation workers *[9]*.

In the following sections, a finite element analysis of the wall–backfill interaction is described and discussed, in order to provide preliminary results, which can then inform the interpretation of the physical modelling results. The relative impact of the investigated factors on the calculated stresses and displacements has been pointed out. This information is crucial for the preliminary assessment of serviceability of the soil-retaining structures and also for the prevention of damages. In the approach adopted in our study, a structure for human habitat has not been implemented in the numerical simulation: it could be realized underground after excavation of the natural soil and thereafter burying it with regolith man-made cover.

2 Computational Setup: Geometrical And Geotechnical Model

Some indications of the needed habitable area for a human habitat on the Moon have been provided in the literature *[10]*. In the present study, four concrete walls of rectangular shape 3.9 m in height, 48 m and 9 m in length, 1.5 m in thickness, retaining a regolith layer as a cover for the habitat, have been conceived (*Figure 1*).

The density of the concrete wall has been assumed to be 1661 kg/m^3 *[11]*, a value measured on the Technical Demonstrator for the non-conventional concrete made of lunar simulant DNA-1 and realized by the new 3D printing technology *[11]*, which could be the way for constructing the moon base. The described structure is founded on a natural regolith layer, which allows settlements of the same structure. The walls can translate and rotate and consequently active earth pressures in the soil can arise.

In order to carry out the numerical simulations, the PLAXIS 3D FEM *[12]* code has been used. The setup for calculation has been characterized by a tolerated error of 0.01 and a maximum number of iterations equal to 60. To generate mesh (*Figure 2*), a coarseness factor of 0.1 for walls and interfaces, 0.25 for backfill and 0.5 for foundation has been imposed, while the average size of each element is equal to 0.46 m for walls and interfaces, 1.15 m for backfill and 2.3 m for foundation respectively. The total amount of clusters is 507,700. Given that the mesh dependence is a crucial problem and the numerical model itself can be a source of error, especially with respect to the effect of model size and number of elements, it must be underlined that the results of the present work refer to a given computational setup.

In this work, two models for the soil behavior have been considered: the linear elastic perfectly plastic model, well-known as Mohr-Coulomb model (*MC*) and the hardening soil model (*HS*) *[13]*. The linear elastic part of the Mohr-Coulomb model is based on Hooke's law of isotropic elasticity. The perfectly plastic part is based on the Mohr-Coulomb failure criterion, formulated in a non-associated plasticity framework. The basic parameters of this kind of model are: (a) Young's modulus (E_0); (b)

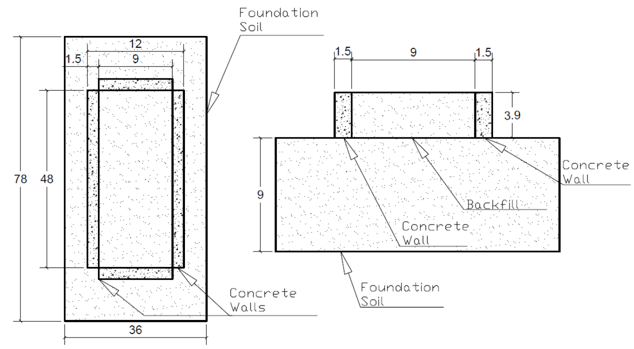


Figure 1: Geometrical model: plan view (left side) and cross section (right side).

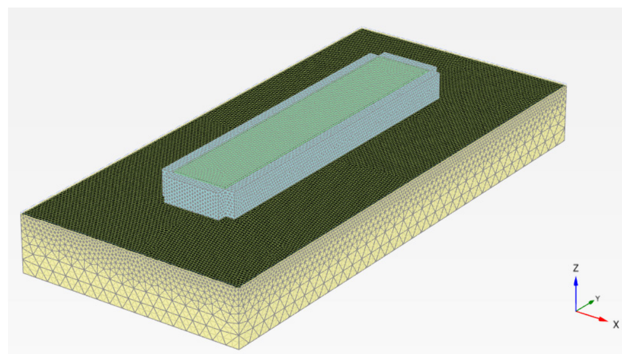


Figure 2: Three-dimensional view of the generated mesh.

Poisson's ratio (ν_0); (c) cohesion (c); (d) shearing resistance angle (ϕ_0); and (e) dilatancy angle (ψ). In contrast to an elastic perfectly plastic model, the yield surface of a hardening plasticity model is not fixed in the principal stress space, but it can expand due to plastic straining. Some parameters of *HS* model coincide with those of the *MC* model. These are c_0, ϕ_0 and ψ. The two models differ with respect to soil stiffness parameters. These are: (a) secant stiffness in standard drained triaxial test (E^{ref}_{50}); (b) tangent stiffness for primary oedometer loading (E^{ref}_{oed}); (c) unloading/reloading stiffness (E^{ref}_{ur}); and (d) power for stress-level dependency of stiffness (m).

Numerical simulations have been carried out implementing the geotechnical parameters of the JSC-1a lunar simulant *[14]*. In particular, for the foundation layer the geotechnical parameters have been fixed and imposed equal to ϕ'=45.5°, ψ=14.3°, E'= 20,400 kPa, whereas for the artificial backfill the parameters employed in the performed analyses have been set as shown in *Tables 2* and *3*.

The interaction between wall and soil has been simulated as implementing interfaces, both at the foundation level and at the contact between wall and backfill. The interaction has been modelled using the

Table 2: Mohr-Coulomb Model Parameters.

Parameter	Unit of Measurement	Backfill	Foundation
ρ	[kg/m³]	1700	1800
E’	[kN/m²]	10900	20400
ν’	[]	0.25	0.25
φ’	[°]	41.8	45.5
δ	[°]	20.9	22.75
R_{inter}	[]	0.427	0.412
ψ	[°]	15.6	14.3

Table 3: Hardening Soil Model Parameters.

Parameter	Unit of Measurement	Backfill	Foundation
ρ	[kg/m³]	1700	1800
E_{50}^{ref}	[kN/m²]	10900	20400
E_{oed}^{ref}	[kN/m²]	10900	20400
E_{ur}^{ref}	[kN/m²]	32700	61200
p^{ref}	[kN/m²]	15	30
m	[]	0.5	0.5
ν_{ur}	[]	0.20	0.20
φ’	[°]	41.8	45.5
δ	[°]	20.9	22.75
R_{inter}	[]	0.427	0.412
ψ	[°]	15.6	14.3

Table 4: Comparison between maximum absolute values for prototype and scaled model.

		Prototype	Scaled Model	N*Scaled Model
|u|	[mm]	3.375	0.541	3.246
σ_{xx}	[kN/m²]	2.488	2.305	2.305

strength reduction factor ($R_{inter} = tan\delta/tan\phi'$, where δ is assumed equal to $\phi'/2$ and represents the wall-soil friction angle), as shown in *Tables 2* and *3*.

3 Computational Errors Related To The Scale Effect

This study was undertaken to simulate a model subjected to terrestrial gravitational conditions (a_g = *1g*). The prototype has the same sizes reported in Section 2, and it has been subjected to lunar gravitational conditions ($a_g = 1/6g$). Therefore, the model has been scaled down to $1/N_l = 6$ with $N_l = 1/N_g = 1/6$ and $N_g = a_{g,model}/a_{g,prototype} = 6$. By the similarity theorem, self-weight-induced stresses and strains do not vary *[15]*. The particle size does not change as the ground size is reduced in the model (the same as in a centrifuge model test) *[15]*. For this comparative analysis, the Mohr-Coulomb model has been chosen. The unit weights of the materials have been scaled in the analyses for the different gravitational levels. The initial stress state of the soil has been defined in Plaxis by using the K_0-procedure.

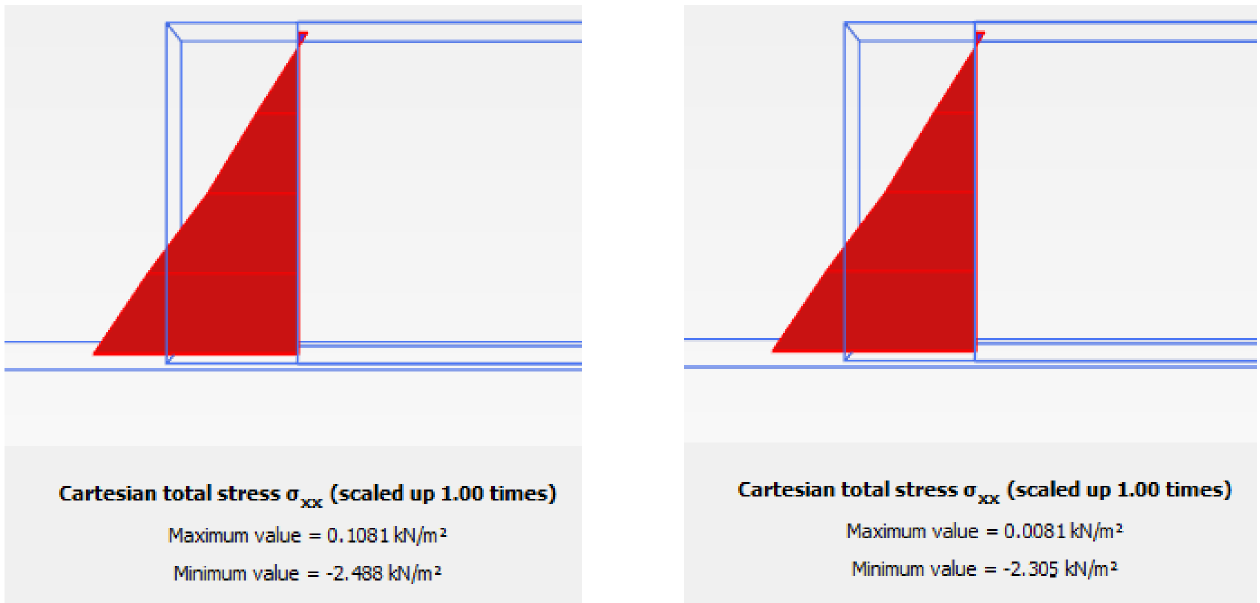
The numerical analysis has given maximum deviatoric strains of about 0.001. The ER_{comp} on the calculation of the maximum (absolute value) displacement and of the maximum horizontal normal stress (*Figure 3*), for the examined problem, can be deduced by comparing the values reported in Table 4: the numerical predictions for the prototype and the corresponding values (“*N * scaled model*” in Table 4) scaled from the numerical predictions for the model (“*scaled model*” in Table 4) are quite similar. ER_{comp} could be defined as the ratio (here called “normalized deviation”) of the deviation of the values pertaining prototype and “*N * scaled model*”, with respect to their average, to the same average. Although other calculation approaches could further reduce these ER_{comp} values, they seem to be quite low (3.8% for the horizontal stress), suggesting that the adopted calculation method is suitable for investigations aimed at defining ER_{exp} in similar problems, as described in the Introduction.

4 Comparison With Other Sources Of Uncertainty

To better assess the calculated computational errors, a comparison with discrepancies from other sources can be useful. In particular, the effect on the predicted prototype behavior of (a) two constitutive models for a given set of geotechnical parameters and (b) the effect of some variability in the geotechnical parameters for a given model are investigated.

Moreover, some 3D effects have been investigated by carrying out calculations along two different vertical sections, i.e. the middle one along the *x*-direction (crossing the longer walls) and the middle one along the *y*-direction.

In Case (a), a comparison between Mohr–Coulomb and hardening soil models is reported, as shown in Figure 3. The results are presented in terms of displacements in



(a) (b)

Figure 3: Total horizontal stress σ_{xx}: (a) Prototype; (b) Scaled model. (Plaxis notation for the sign).

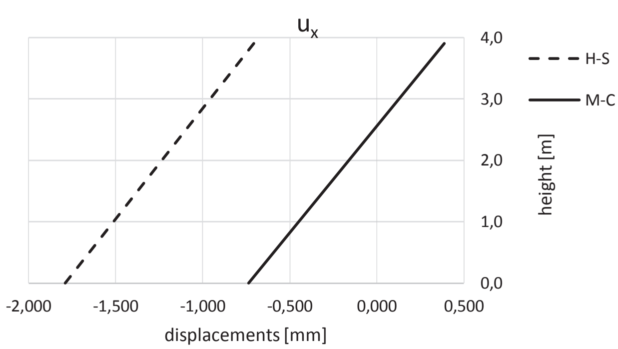


Figure 4: Effect on the predicted prototype behavior of two constitutive models (Mohr-Coulomb and Hardening Soil): results are shown in terms of displacements along *x*-direction (u_x).

Table 5: Comparison between maximum values for M-C and H-S models (Case a).

		H-S	M-C	Ratio
u_x	[mm]	1.799	0.736	2.4
u_z	[mm]	7.464	3.294	2.3
|u|	[mm]	7.678	3.375	2.3
σ_{xx}	[kN/m^2]	3.426	2.488	1.4

x-direction (u_x). The wall rotates toward the backfill in both cases because of the influence of the ground settlements (*Figure 4*).

Table 5 shows the maximum output absolute values obtained for both models, in terms of horizontal, vertical and total displacements and total horizontal stresses. Coefficients of active earth pressure (referring to the maximum values of σ_{xx} at the bottom of the walls) are $K_{a,MC} = 0.229$ and $K_{a,HS} = 0.316$, while the coefficient of earth pressure at rest is $K_0 = 0.333$. Earth pressure distribution seems to be quite consistent with the Rankine's active regime. While horizontal stresses are almost equal for both models, the *HS* model gives greater displacements than the *MC* model. Indeed, the last column of the table is the ratio between *HS* results and *MC* results and it shows that maximum displacements of the *HS* model are about 2.4 times greater than those of the *MC* model.

As regards the Case (b), the variability of the backfill set-up has been chosen in tune with the other factors remaining constants, in order to evaluate the influence of some scatter of the friction angle and the dilatancy angle values on the numerical predictions. This geotechnical variability should depend both on differences in the grain size distribution of the soil and on differences in the soil compaction, due to the effect of relative density on the strength of sands *[16]*. In this parametric analysis, the two aspects have not been distinguished. The Mohr–Coulomb model has been chosen for the analysis. Six combinations have been investigated, as outlined in *Table 6*, in which the values of the abovementioned parameters have been both increased and decreased. The maximum output values

Table 6: Geotechnical parameters used in the analyses (Case b)

Combination	φ' [°]	ψ [°]	E' [kN/m²]	ν' []	δ [°]	R_{inter} []
1	45.50	15.60	20400	0.25	22.75	0.412
2	45.50	20.90	14200	0.25	22.75	0.412
3	45.50	22.60	11200	0.25	22.75	0.412
4	41.80	15.60	10900	0.25	20.90	0.427
5	45.50	15.60	20400	0.25	22.75	0.412
6	49.70	15.60	24400	0.25	24.85	0.393

Table 7: Maximum values obtained for each combination.

		1	2	3	4	5	6
u_x	[mm]	0.795	0.843	0.864	0.736	0.795	0.764
u_z	[mm]	3.016	3.033	3.046	3.294	3.016	3.038
$\|u\|$	[mm]	3.119	3.130	3.166	3.375	3.119	3.133
σ_{xx}	[kN/m²]	1.552	1.840	1.879	2.488	1.552	1.598

Table 8: Comparison between results obtained for *x*-direction and *y*-direction.

		x-direction	y-direction
$\|u\|$	[mm]	3.375	2.901
$\sigma_{xx(yy)}$	[kN/m²]	2.488	1.825

Table 9: Normalized Deviation (with respect to average) of σ_{xx}.

Type of Effect	Normalized Deviation
Scale Effect	3.8%
Constitutive Model Effect	15.9%
ϕ' Variability Effect	32.4%
ψ Variability Effect	11.7%
3D Effect (σ_{xx} vs σ_{yy})	15.4%

obtained for each combination are reported in *Table 7*, in terms of both displacements and horizontal stress.

Comparing the middle section along *x*-direction and *y*-direction, total displacements and horizontal stresses exhibit non-negligible differences, as shown in *Table 8*.

Finally, *Table 9* summarizes the normalized deviation of σ_{xx} for the different options investigated here, with respect to the average value of the outputs for each calculation problem. The assumed variability of the geotechnical parameters seems to affect the calculation outputs much more than the scale effect. Important discrepancies have been obtained also by comparing the two constitutive models and by comparing results pertaining to different sections (i.e. 3D effects). These results need to be enriched by similar analyses for other geotechnical designs and using mechanical parameters of different lunar simulants, in order to generalize the conclusions.

5 Conclusions

The design of civil structures for Moon could benefit from the construction of scale models on Earth. Their behavior must be scaled for the different gravitational levels by lunar prototype and terrestrial models. The methodological and numerical study discussed in this work has provided some results useful to better address such a strategy of investigation and, in this respect, a validation procedure has been proposed. On the basis of numerical results, it seems that the proposed strategy, based on the behavior of a "virtual" prototype, can be used for this aim, since the computational uncertainty related to the numerical modelling is relatively low if compared to other sources of uncertainty that could characterize the physical scale-modelling, such as the composition and relative density of the backfill. Indeed, the variability of the geotechnical parameters, the constitutive model and the 3D effects seem to affect the calculation outputs much more than the computational scale problem. Further investigations, both numerical and experimental, should be carried out in order to better support these preliminary results. In particular, the incidence of the adopted computational setup should be investigated.

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