Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-0814

Geotechnical behavior of underground house models

Comportement géotechnique des modèles de maisons souterraines

N.M. Ilies, Corresponding author
Faculty of Civil Engineering/Technical University, Cluj-Napoca, Romania

I. M. Moldovan
Faculty of Civil Engineering/Technical University, Cluj-Napoca, Romania

S.V. Moldovan
Faculty of Architecture and Urban Planning/Technical University, Cluj-Napoca, Romania

ABSTRACT: Cities are expanding. It is inevitable. However, expansion has limitation since the urban surface cannot be enlarged without the infrastructure. This translates in higher costs for the urban growth and it seems that increasing the density appears to be the most favored solution. It is fair to say that the residential developments hold the first place in the hierarchy of new buildings. Urban settlements with natural slopes often present areas with sliding potential and for this reason many of them are avoided when houses are planned. The configuration and the structure of underground or semi-buried homes, can have a beneficial influence, locally, on the behavior of slopes having shallow sliding surfaces. The purpose of this study is to present different typologies of underground houses positioned on sliding slopes together with their behavior and influence on the local stability of the terrain. For the analysis of the effect of underground houses and their structures on a slope, a soil stratigraphy, specific for the Transylvanian region, will be considered.

RÉSUMÉ : Les villes sont en expansion. C'est inévitable. Pourtant, l'expansion a été limitée parce que la surface urbaine ne peut pas être élargie sans l'infrastructure. Cela se traduit par des coûts plus élevés pour le développement urbain et la densification semble d'être la solution la plus favorisée. Il est juste de dire que les développements résidentiels occupent la première place dans la hiérarchie des nouveaux bâtiments. Les établissements urbains à pente naturelles présentent souvent des zones avec un potentiel de glissement, c'est pourquoi un grand nombre d'entre elles sont évitées lors de la planification d'habitations. La configuration et la structure des habitations souterraines ou semi-enterrées peuvent avoir une influence bénéfique sur le comportement des pentes qui présentent une surface de glissement superficielle. L'objectif de cette étude est de présenter différentes typologies de maisons souterraines positionnées sur des pentes avec potentiel de glissement, ainsi que leur comportement et leur influence sur la stabilité locale du terrain. L'analyse des effets des maisons souterraines et leur structure sur une pente prendra en compte une stratigraphie de sol spécifique à la région de la Transylvanie.

Keywords: underground house; superficial sliding surface; slope stability; retaining system

1 INTRODUCTION

This article is part of a series of studies regarding underground, semi-buried and earth sheltered houses conducted by the authors (Moldovan 2014; Ilies & Moldovan 2014; Moldovan & Ilies 2014; Ilies, Moldovan & Moldovan 2015). After identifying the reasons and needs for living underground throughout the history of the built environment, the typologies of houses and their relations with the earth that surrounds them and the resulted advantages, several simulations were conducted, in order to better understand their behaviour and to see whether building houses under the ground could be considered an alternative to conventional homes.

One of the advantages that is often disregarded, favouring discussions on the thermal behaviour of underground houses is related to the size of the terrain where such a house will be located. Burying the house into the terrain removes several constraints associated to the site's vicinities since the building itself does not feature many exposed elevations (only one or two) towards the terrain's perimeter. Consequently, the size of the plot can be reduced. In the same time, another advantage is prefigured, the perceived density decreases. Taking these two advantages into consideration, our findings show that underground, semi-buried and earth are suited for urbanized area in the same way the conventional homes are.

Following these ideas, we studied the General Urban Plan of the city of Cluj-Napoca, Transylvania, Romania, and identified the areas where future residential developments were envisaged. As the study advanced, we realized that the identified areas were on natural slopes. Further along we selected only the sites with a favourable orientation towards the sunlight. We observed that all the areas in discussion were characterized by medium to very high instability of the slope.

The first study, where a simple linear underground home was placed on a slope characterized by a superficial sliding surface, concluded that the house, together with its structural system (reinforced concrete walls and raft foundation) can stabilize locally a slope, up to a certain degree.

Subsequently, in this study four other models of underground houses were chosen and placed in a 22º slope that presents sliding risks.

The first model was similar with the one from the previous study, in terms of shape and size, only this time it was rotated 90º and placed perpendicularly on the slope. One third of the building is cantilevered for architectural reasons, because only one of the elevations could otherwise support windows (the smallest one) and this does not satisfy the natural lighting requirements of the residential programme.

In order to acquire more living space, more natural light and natural ventilation, the second model splits the house in two distinct volumes, parallel to the slope level lines. In this example, the two parts of the building are attached and placed at different depths in the slope, resulting a stepped model.

The third model, for the same reasons as the second one, doubles its volume by placing two linear houses, one on top of the other. The result is a linear underground house, two stories high, a solution suitable for steeper slopes.

The fourth model is also an evolution of the second one, where for privacy reasons the house is divided in two volumes, separate and detached. The guest wing and the master wing are placed at different heights on the slope. The two volumes are connected by a third one, underground, which shelters the staircase and possibly the main entrance.

2 SLOPE STABILITY ANALYSIS

The case study presented in this paper demonstrates the effect of different types of underground houses on the local and overall stability of slopes. The study uses Geo Fine Software – Slope Stability module.

The slope stability analysis performed using Romanian standard SR EN 1997 (Eurocode 7) and the national annex of it, SR EN 1997 – NA, verifies if the design effects of the actions, E_d do not exceed the corresponding resistance, $R_{d.}$ (1):

$$E_d \leq R_d \tag{1}$$

In the slope stability analysis, the effect of the actions is the overturning moment, M_{Ed}, which destabilize the slope and the resistance is the resisting moment, the resistance to the effect of the destabilizing moment, M_{Rd} (Bond & Harris 2008). The equation (1), to be verified, became:

$$\frac{E_d}{R_d} = \frac{M_{Ed}}{M_{Rd}} \leq 1 \qquad (2)$$

In the verification according to the theory of limit states, used by Eurocode 7, the value of utilization V_u is calculated and then compared with 100%. The value of utilization is given by the equation (3), where: M_{Ed} is the sliding moment and M_{Rd} is the resisting moment:

$$V_u = \frac{M_{Ed}}{M_{Rd}} \cdot 100 < 100\% \qquad (3)$$

The Romanian standard SR EN 1997 – NA recommends for slope stability analysis to use the design approach 1 combination 2 (DA1-2) and the design approach 3 (DA3). Considering the values of the safety factors, for the analysis DA1-2 and DA3 are identical, therefore the computation is performed for DA1-2.

The slope considered in the analysis is 100m in length, in order to observe the influence of the different building types on the local and overall stability. The slope inclination is 22° and the soil stratification consists of a sequence of layers commonly found on the slopes of Cluj-Napoca, as seen on Table 1.

Table 1. Soil geotechnical characteristics

Layer	Depth/ Thickness	γ [kN/m^3]	φ' [^{0}]	c' [kN/m^2]
1	0.00…-5.00	18.50	28	3
2	-5.00…-20.00	21.00	15	65

Previous studies of the authors (Moldovan 2014; Ilies & Moldovan 2014; Moldovan & Ilies 2014; Ilies, Moldovan & Moldovan 2015) proved that the largest influence of the building on a slope is observed for 22^0 inclination, therefore a comprehensive study was performed for this inclination, for different architectural solutions.

The study considers several stages necessary to be checked when the building is constructed. The stability is checked for every stage, considering a circular and a polygonal sliding surface, using Morgenstern-Price method (Morgenstern 1965). The Morgenstern-Price method used in calculation it is considered the most appropriate, being a rigorous method, in the sense that satisfies all three equilibrium equations - the force equilibrium equation in the horizontal and vertical directions and the moment equation of equilibrium, and, also by assuming non-zero forces between blocks.

The first stage considers the slope in its initial state, without any constructions. The slope was analysed by the paper of the authors Ilies, Moldovan & Moldovan, 2015, proving that it is stable in its initial condition, the stability factor is close to the limit one, but the sliding is improbable.

The second stage refers to the soil excavation, needed all the underground constructions. When excavating the soil layer, the slope is locally destabilized, upstream the excavation (Figure 1, 2, 3, 4), but is still stable downstream the excavation. This is a very common situation when excavating along the slope, but in this case, earth retaining systems must be designed, in order to prevent soil failure.

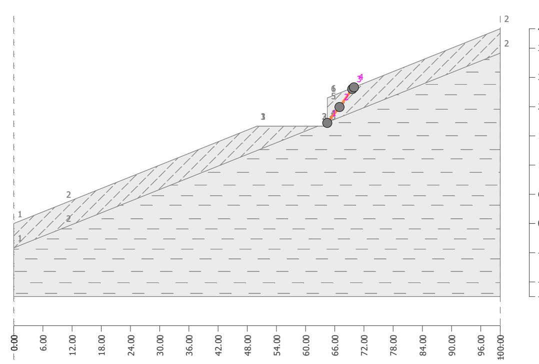

Figure 1. Slope stability analysis for the excavated slope Morgenstern-Price method: V_u=214.9, model 1

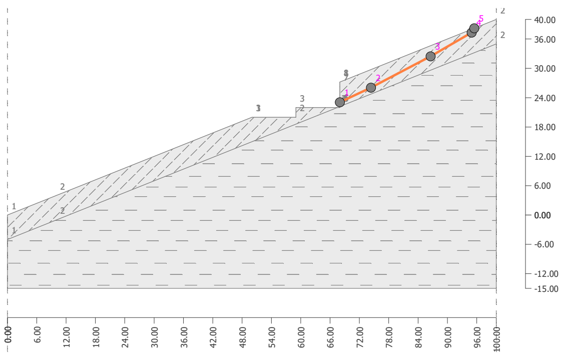

Figure 2. Slope stability analysis for the excavated slope Morgenstern-Price method: V_u=105.5, model 2

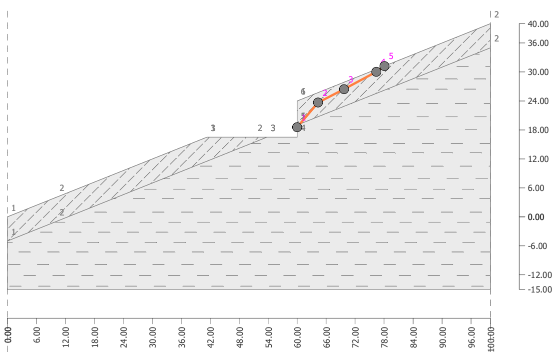

Figure 3. Slope stability analysis for the excavated slope Morgenstern-Price method: V_u=144.9, model 3

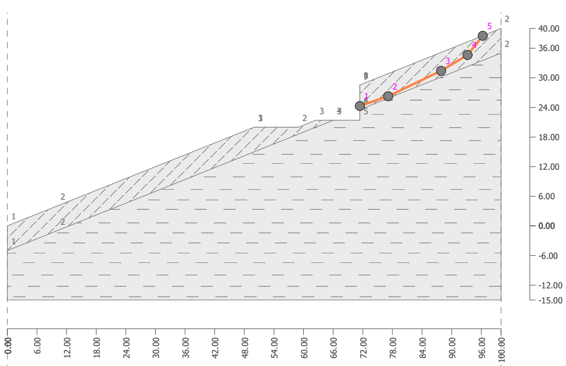

Figure 4. Slope stability analysis for the excavated slope Morgenstern-Price method: V_u=102.3, model 4

The third stage (Figure 5, 6, 7, 8, 9, 10, 11, 12) considers the load of the future underground house acting on the soil and the slope stability analysis also indicates the upstream instability. If a new house is placed on the slope without a retaining system, structural damage, due to the soil failure, might occur.

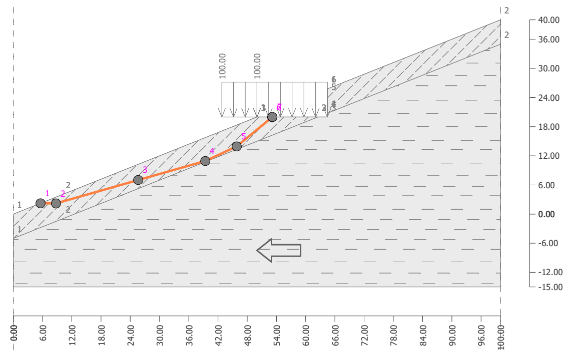

Figure 5. Slope stability analysis for the excavated slope Morgenstern-Price method: V_u=118, model 1, downstream.

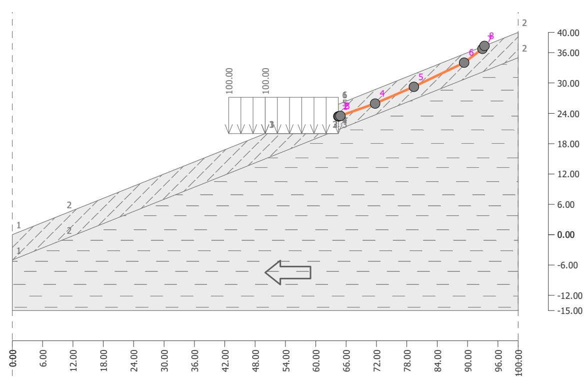

Figure 6. Slope stability analysis for the excavated slope Morgenstern-Price method: V_u=118, model 1, upstream.

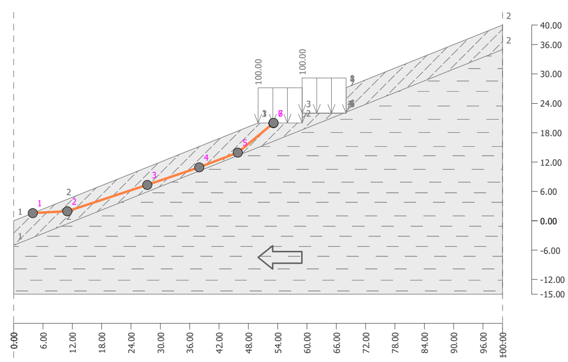

Figure 7. Slope stability analysis for the excavated slope Morgenstern-Price method: V_u=107.5, model 2, downstream.

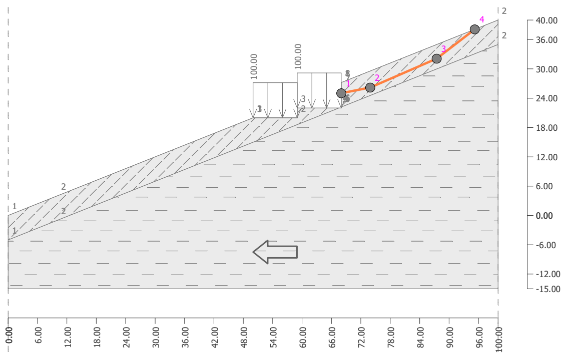

Figure 8. Slope stability analysis for the excavated slope Morgenstern-Price method: V_u=103.5, model 2, upstream.

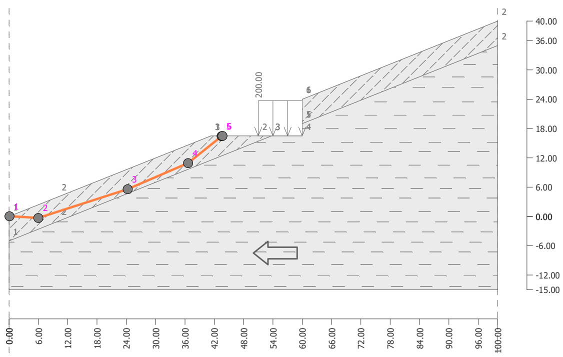

Figure 9. Slope stability analysis for the excavated slope Morgenstern-Price method: V_u=97.9, model 3, downstream.

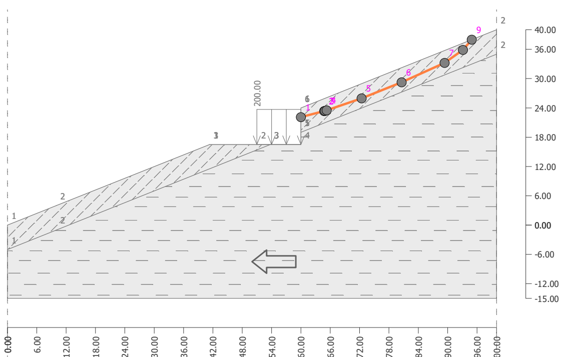

Figure 10. Slope stability analysis for the excavated slope Morgenstern-Price method: V_u=103.5, model 3, upstream.

The fourth stage considers the earthquake action on soil, with a horizontal factor k_v=0.08, corresponding to Transylvanian area. In this case, for almost all the studied underground houses, the slope stability analysis showed that the slope is not stable.

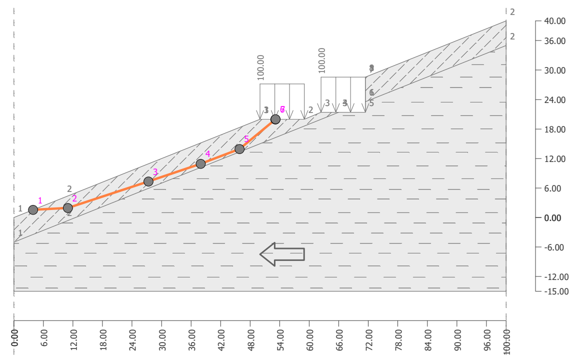

Figure 11. Slope stability analysis for the excavated slope Morgenstern-Price method: V_u=107.5, model 4, downstream.

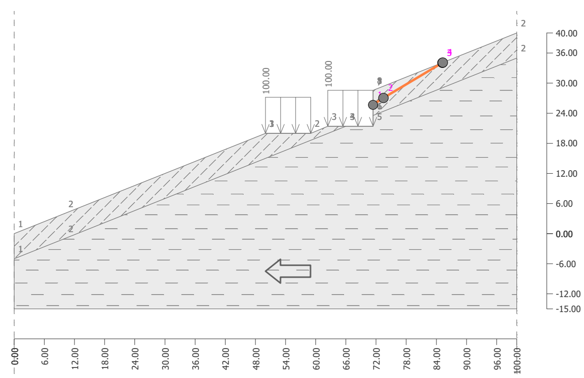

Figure 12. Slope stability analysis for the excavated slope Morgenstern-Price method: V_u=129.7, model 4, upstream.

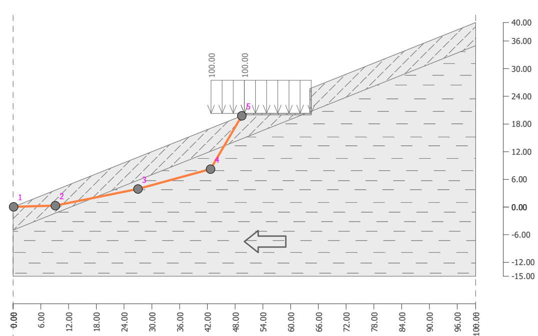

Figure 13. Slope stability analysis for the excavated slope Morgenstern-Price method: V_u=83.7, model 1, downstream.

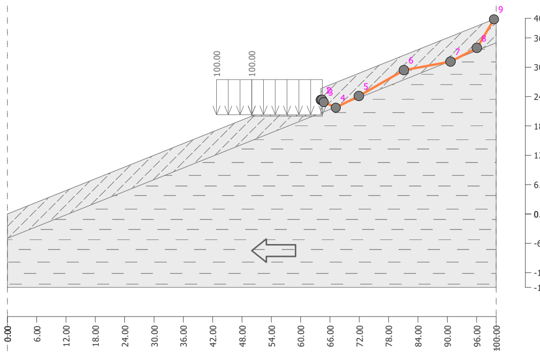

Figure 14. Slope stability analysis for the excavated slope Morgenstern-Price method: V_u=36.9, model 1, upstream.

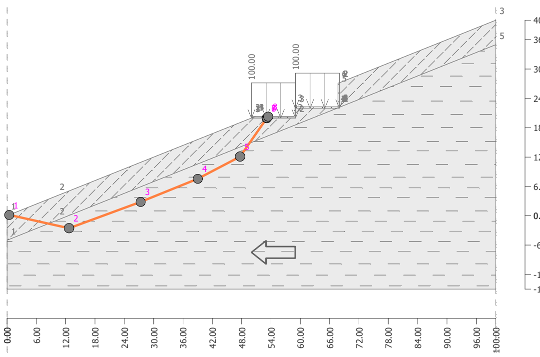

Figure 15. Slope stability analysis for the excavated slope Morgenstern-Price method: V_u=40.2, model 2, downstream.

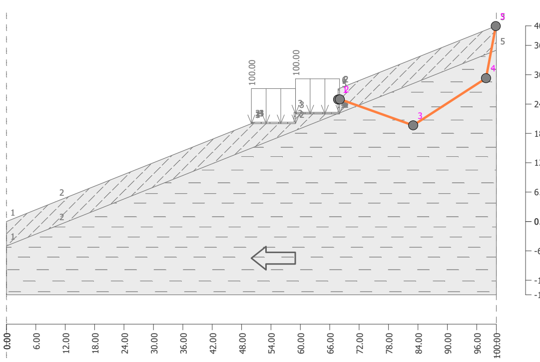

Figure 16. Slope stability analysis for the excavated slope Morgenstern-Price method: V_u=35.1, model 2, upstream.

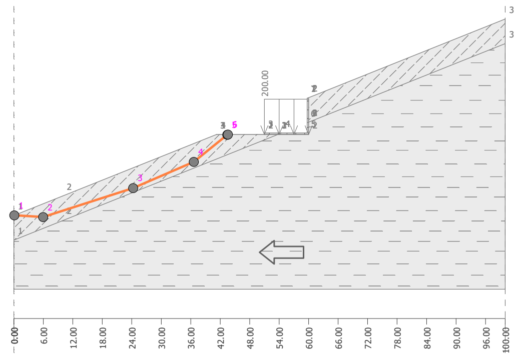

Figure 17. Slope stability analysis for the excavated slope Morgenstern-Price method: V_u=98.1, model 3, downstream.

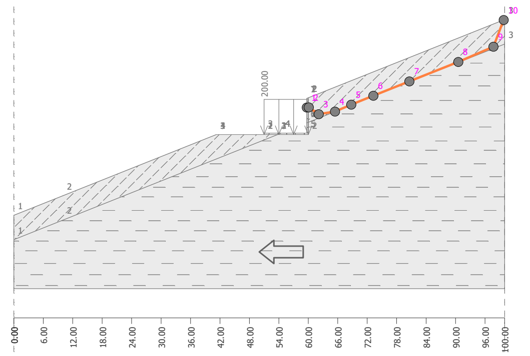

Figure 18. Slope stability analysis for the excavated slope Morgenstern-Price method: V_u=41.7, model 3, upstream.

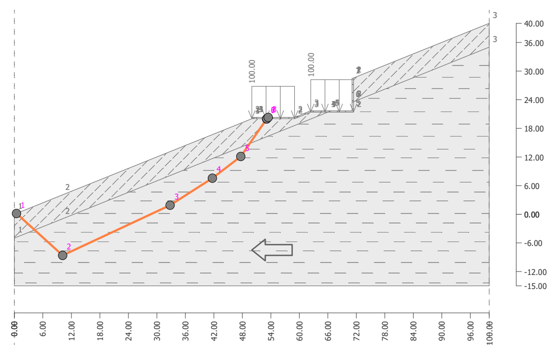

Figure 19. Slope stability analysis for the excavated slope Morgenstern-Price method: V_u=41.3, model 4, downstream.

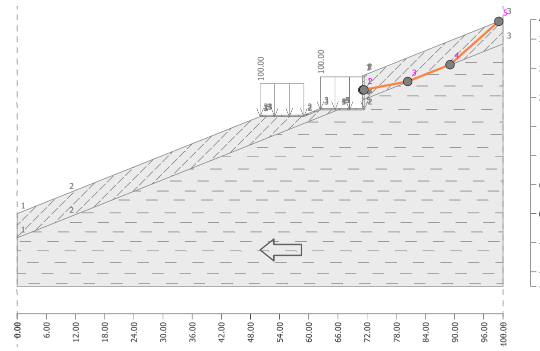

Figure 20. Slope stability analysis for the excavated slope Morgenstern-Price method: V_u=25.5, model 4, upstream.

In the fifth stage, the underground house structural system is introduced in the analysis. The underground house is designed having a 30cm reinforced concrete raft foundation and a superstructure with reinforced concrete diaphragm walls, the ones in contact with the soil having 30cm thickness as well. They are considered as stiff areas in the computation. The analysis performed proved that this structural system has a beneficial effect on slope stability analysis, having the role of a retaining system, the stability upstream the underground house being significantly improved, even with the earthquake action. (Figure 13, 14, 15, 16, 17, 18, 19, 20).

3 CONCLUSIONS

After studying the slope stability for the proposed models of underground houses we can state that they have a beneficial effect on the slope. Even if the construction of the houses might cause local instability, the final structural system increases the slope stability factor.

The positive effect can be observed when the analysis is conducted introducing the earthquake effect as well. The structural system used acts as a retaining system, representing the consolidation system for the slope in the same time.

The results of this study are allowing us to state that different models of underground houses, with an appropriate structural system, might consolidate the slopes with sliding potential. These houses, together with their structural system, can transform sites with low housing potential, caused by the probability of natural hazards occurrence, into buildable areas.

Some of the problems of fast-growing cities in Romanian hilly areas can be solved with the aid of undergrounds semi-buried and earth sheltered houses: the problem of available space and plot size, the problem of slopes stabilization and of course the problem caused by the energy consumption, necessary for indoor heating and cooling systems, etc.

The soil geotechnical parameters used in the slope stability analysis influence the accuracy of the study, therefore, the importance of determining truthful soil parameters must be mentioned.

As a final conclusion, in our opinion, the proposed underground houses, with their corresponding structural system (reinforced concrete walls and a raft foundation), might solve the lack of housing space inside crowded cities, for in this way areas with sliding potential could be suitable for residential developments without requiring very high costs and complex structural solutions. This study offers unconventional solutions for structural engineers and architects, allowing them to make use of the unapproachable sliding sites, improve their stability and control the natural disasters caused by slope sliding in a smart manner.

4 ACKNOWLEDGEMENTS

This research was partially supported by the project 21 PFE in the frame of the programme PDI-PFE-CDI 2018.

Authors are thankful to the software provider Fine Civil Engineering Software.

5 REFERENCES

Geotechnical software suite Geo 5. User's Guide; 2010.

Ilies, N.M & Moldovan, I.M. 2014. Underground houses on sliding slopes, *Acta Technica Napocensis: Civil Engineering & Architecture,* Vol. 57. Number 2. Cluj-Napoca: UTPress.

Ilies, N.M Moldovan, I.M & Moldovan, S.V. 2015, Geotechnical and thermal aspects for underground houses on sliding slopes, *Proceedings of the XVI European Conference on Soil Mechanics and Geotechnical Engineering, ECSMGE 2015*, Vol. 4, 1771-1776

Moldovan, I.M. 2014. Locuinte ingropate (Underground houses). *PhD thesis*, Cluj-Napoca.

Moldovan, I.M & Ilies, N.M. 2014 Stabilization of a potentially sliding slope with the aid of an underground house, *Journal of Applied Engineering Sciences*, Vol. 4 (17) issue 2. Oradea: University of Oradea Publishing House.

Morgenstern, N.R. & Price, V.E. 1965. The analysis of the stability of general slip surfaces. *Géotechnique*, 15(1): 79–93.

SR EN 1997-1. 2006. Eurocode 7: Geotechnical design – Part 1: General rules.

SR EN 1997-1/NB. 2007. Eurocode 7: Geotechnical design – Part 1: General rules. National Annex.

***General Urban Plan of Cluj-Napoca www.primariaclujnapoca.ro/urbanism/regulament-PUG.html, viewed at 28/04/2014.