

Underground Houses on Sliding Slopes

Nicoleta M. Ilies^{*1}, Ioana M. Moldovan²

^{1,2} *Technical University of Cluj-Napoca, Faculty of Civil Engineering. 15 C Daicoviciu Str., 400020, Cluj-Napoca, Romania*

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Abstract

The construction of residential buildings on slopes always raises problems regarding the structural and architectural approach. Most of the slopes that have residential development potential, in what concerns adequate sunlight and attractive sights, have also high sliding potential. When the sliding surface is very close to the landscaped terrain, the classical solution that involves securing a backfill and/or an excavation with retaining walls can stabilize, locally, the sliding strip of the slope. In such a solution, it is possible that, in the end, the cost of this extra work might significantly increase the total cost of the building. Burying the structure, together with a viable foundation system, could resolve the stability and the overall costs would be reduced by the simple fact that, the place of the retaining walls would be taken by the actual walls of the house. There are many sites that are perfectly suitable for residential developments, from the architectural and urban planning point of view, but have major geotechnical risks as well. The intentions of this paper are to reveal different structural and architectural solutions that could successfully resolve the problems raised by sites that have potentially sliding surfaces close to the surface.

Rezumat

Construirea de clădiri rezidențiale pe terenuri în pantă întotdeauna ridică probleme în ceea ce privește abordarea structurală și arhitecturală. Majoritatea versanților cu potențial de dezvoltare rezidențială, din punctul de vedere al însoririi corespunzătoare și priveliștilor atractive, au de asemenea și un potențial ridicat de producere a alunecărilor de teren. Atunci când suprafața de alunecare se află la adâncime mică, soluția clasică presupune crearea de rambleuri și debleuri și/sau ziduri de sprijin pentru a stabili local fâșia alunecătoare a versantului. Într-o asemenea situație, este posibil ca prețul lucrărilor suplimentare să crească semnificativ costurile totale de construire. Îngroparea construcției, împreună cu un sistem viabil de fundații ar putea soluționa problema alunecării, iar costurile finale ar fi reduse prin simplul motiv că locul zidurilor de sprijin ar fi luate de către pereții casei. Scopul acestei lucrări este de releva diferitele soluții structurale și arhitecturale care ar putea să răspundă cu succes problemelor ridicate de sit-uri care au suprafețe cu potențial de alunecare aproape de suprafața terenului.

Keywords: sliding slopes; retaining walls; foundations; underground houses.

1. Introduction

Low-rise residential buildings can adapt on almost any type of terrain. However, generally the most efficient solutions are sought in terms of financial effectiveness, namely building the houses on flat

* Corresponding author: Tel.: +40264401511
E-mail address: nicoleta.ilies@dst.utcluj.ro

terrains. In what concerns urban developments, in areas with a different topography than the one of plains, this cannot apply. Also, the hilly areas often raise slope stability problems.

The slopes that fall into the category of the ones that present surfaces with displacement, movement or collapse risk factor are often found in hilly areas. Landslides are part of the natural disasters, although often they are produced involuntarily by men. The reasons that trigger landslides cover a wide range, which includes: loss of stability due to increased load, as well as due to the decrease of the resistance of the earth to shear action; due to the water pressure in pores, as a result of ascending level of the underground water level; excavations or fills on slopes; artificial vibrations; earthquakes, floods caused by prolonged rainfalls or the sudden melting of snow; the erosion of the base of the slope; freeze-thaw phenomenon, etc.

In what regards the classification of landslides, there are a considerable number of criteria by which they can be systematized and the concerning literature catalogued numerous phenomena where natural slopes and embankments lost their stability. Among the most common criteria used for the classification of landslides we find the temporal criterion (active, stabilized, inactive, reactivated landslides); the nature of the rock (rock, debris, earth); depth of the sliding surface (surface, shallow, deep, very deep sliding); by the type of movement (fall, overturning, translational slide, rotational slide, extension, gravitational flow, complex sliding); by the position of the sliding surface to the earth's stratification (curve, flat, angular slide, rolling and collapse); by the sliding speed (extremely fast, very fast, fast, slow, very slow, extremely slow); etc.

2. Architectural approaches regarding building on slopes

The morphology of the terrain, the orientation toward the cardinal points, the presence of prevailing winds, wonderful views, the existence of vegetation, size of the plot, urban or rural location, the stratification of the terrain, the level of the groundwater and so on, are some of the factors to be taken into account when starting the design process of an underground or semi-buried house [1]. Obviously, all these features should be studied before designing any type of home, but in the case of this typology, each element could be extremely influential. Choosing how to approach an underground or semi-buried house can be made only after analysing the topography, the soil, the level of the groundwater and the neighborhoods [2].

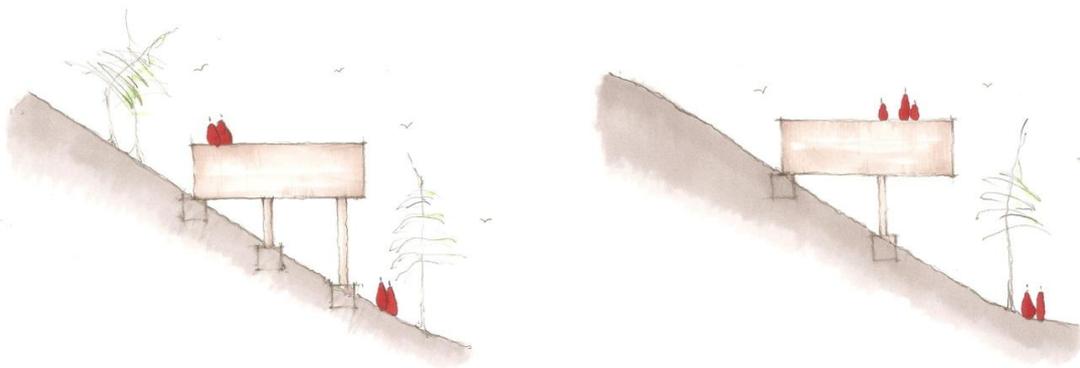


Figure 1. Architectural approach on slope – denying the slope.

Both from the architectural and structural point of view, there is a variety of options in approaching a construction on a slope [3]. Denying the slope and solving the elevation through raising the volume of the construction on stilts, together with the use of cantilevers, has a minimal impact on

the natural terrain. This solution can be applied as well to terrains with very steep slopes (Figure 1). However, due the complexity of the structure, this type of solution may imply higher costs. The direct relation with the terrain, in terms of access, is difficult, but this could be balanced by the views offered from the elevated house.

In what regards the potential risk of sliding slopes, building on stilts will require complex foundation systems, in order to prevent the damage and eventually the collapse of the entire structure.

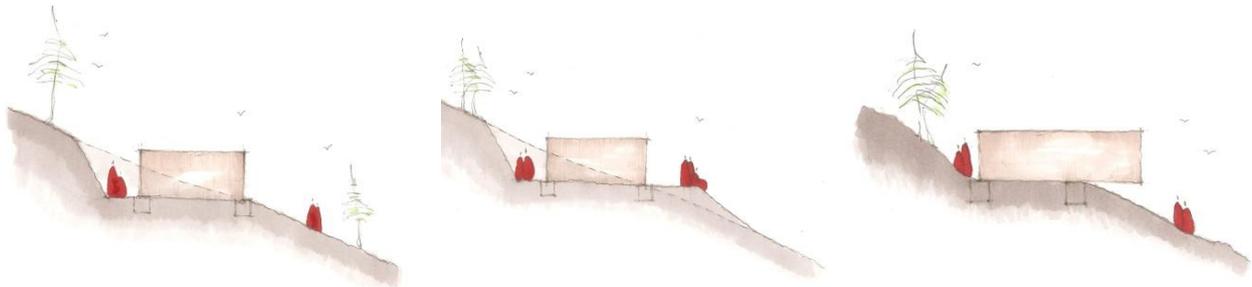


Figure 2. Architectural approach on slope – earthworks.

Creating embankments and cuttings solves some of the problems encountered in the previous solution, by increasing the horizontal surface of the terrain, the house can be accessed from several directions. In this alternative approach of the natural slope of the terrain we are dealing with a different type of the denial of the slope, because even though in this case the house is closer to the ground, it is set by levelling the terrain (Figure 2).

The impact on the natural slope is major and the amount of excavations can raise the cost of the execution. Also, the excavations will more than probably affect the stability of the slope if there is a potential sliding surface. This approach often will require additional interventions in order to ensure the stability of the slope.

Depending on the slope of the terrain, an architectural solution that follows the shape of the slope, where levels (or half-levels) are interlinked and set at different heights can be an interesting option. The volumetric resultant is also called a cascade building (Figure 3). In terms of the impact on the natural terrain, the solution of the cascade house is one that respects the shape of the natural terrain, without interfering too much. The excavation volume is quite small, as well as the embankments and cuttings, the need for horizontal surfaces being satisfied through the terraces resulting from playing with the volumes of the buildings (obviously this implies terrace roofs).

The main disadvantage of this solution, functionally speaking, is the existence of numerous stairs, which must ensure the links between levels. However, if the house sits on a sliding slope, additional attention must be paid to the foundations system.

The encapsulation of the house in the slope comes either from the desire to integrate the house in the natural landscape – in the sense that the visual impact will be smaller – either from the desire to increase the level of the thermal comfort. The advantage of this solution comes with solving the roof as a terrace, in a way that the house can be accessed both from the upper and lower side of the slope (Figure 3).

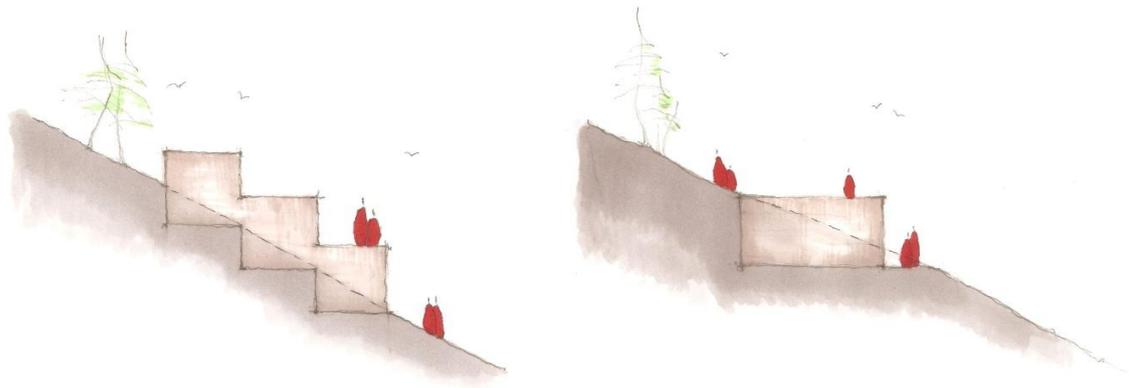


Figure 3. Architectural approach on slope – cascade house (left); embedded house (right).

For this solution as well, the volume of excavations is high, this can increase the price of the investment. The glazing is reduced, at least by half, and the views are diminished as well. If the volume of the house goes below the sliding surface of the slope, this solution might stabilize locally the hill.

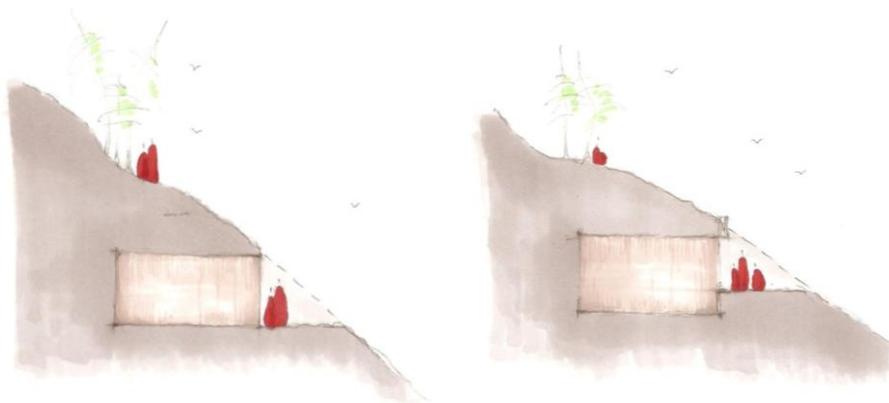


Figure 4. Architectural approach on slope – half-buried and underground houses.

The half-buried house represents a solution which is mainly chosen for the advantages represented by the use of the thermal massiveness of the earth, in order to reduce the energy consumption that results from balancing the interior temperature. This solution embodies the features of the fully recessed, encapsulated house, only this time the glazing is reduced to only one elevation or even less in some cases (Figure 4). The orientation to the cardinal points must necessarily be taken into consideration. However, the advantage of stabilizing a sliding slope is increased, since the volume of the house will pierce deeper into the ground.

In terms of exposed elevations, in general, the solutions do not strictly fall within one category; composed versions are often chosen in order to fully satisfy the desires of the owners and to better respond to the specificity of the terrain.

Regarding the plan of the encapsulated, half-buried and underground houses, in order to have natural lighting and ventilation and to create a comfortable living space by eliminating the

claustrophobic potential, the most effective solutions are presented in the simplest ways, as compact volumes. Thus, the bar-type houses, both linear and curved are the most common. Also, according to the slope typology, solutions that follow the curve or the slope or, on the contrary, deny it, are habitual. In these situations, the plan supports both curved and angular volumes. Seldom, a linear volume is placed perpendicular to the horizontal curve of the slope, setting the house as a cantilever (Figure 5).

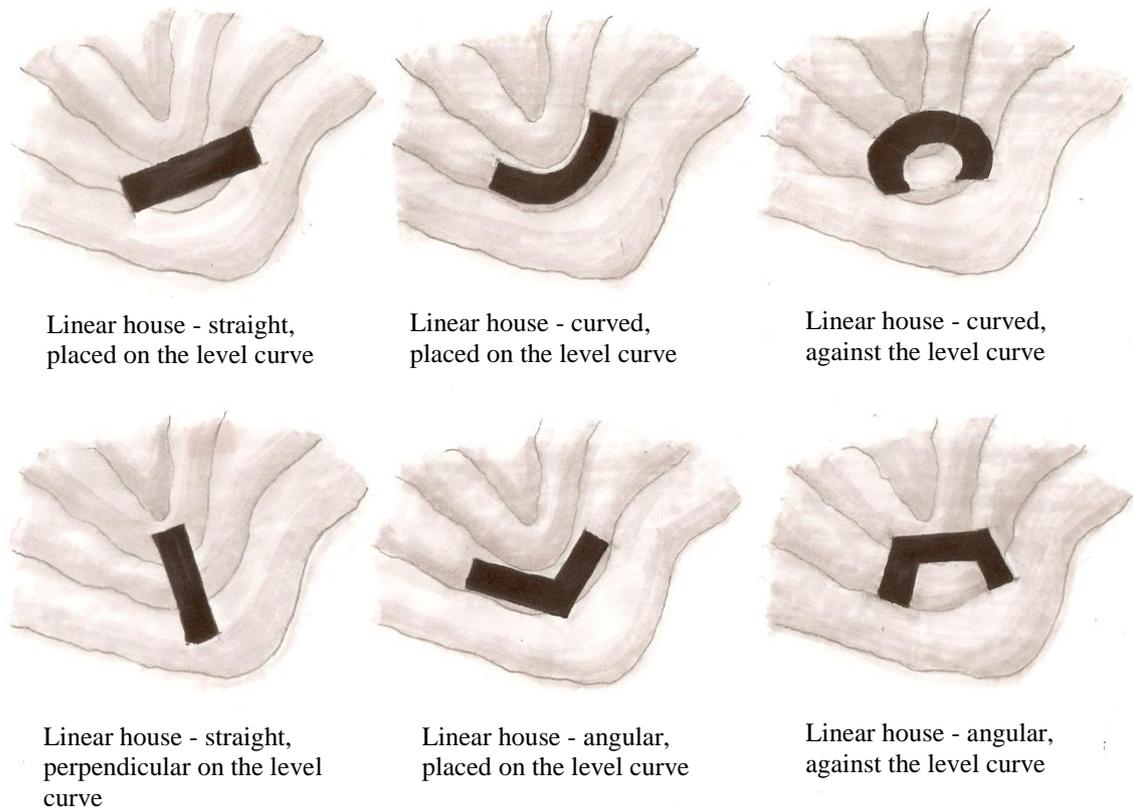


Figure 5. Different approaches for the plan of half-buried and underground houses on slopes.

3. Slope stability case study

The purpose of the slope stability analysis is to determine if the solution proposed by the architectural approach is able to solve the stability problems found on the slope. Also this study's aim is to prove that one of these houses may stabilize the slope.

In order to perform the stability analysis it is considered a slope having 50 m length, 22° inclinations and a succession of soil layers as in Table 1. This considered stratigraphy is characteristic for Transylvanian slopes [4], [5], [6], [7], [8], [9], therefore with small adjustments this study may be used for a regular design.

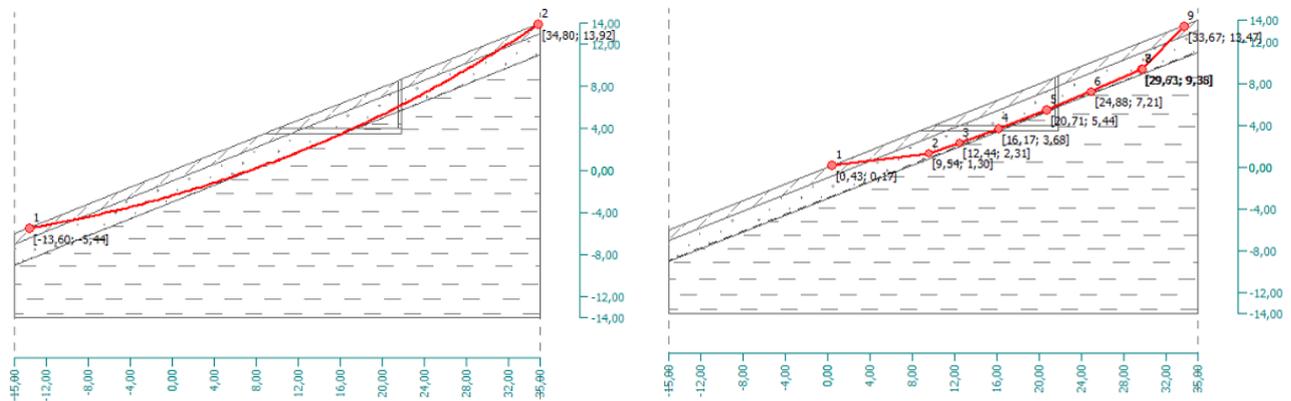
The ground water table is found in the layer of sand, on the inferior part, at - 2.95 m depth from the natural ground level.

Table 1: Soil parameters for mail soil layers

Nr.	Depth	Soil type	γ [kN/m ³]	ϕ [°]	c[kN/m ²]
1	0.00... - 1.00	Silt with soft consistency	21.0	17.0	5
2	- 1.00... - 3.00	Sand with traces of fines	17.0	29.5	0
3	- 3.00...- 8.00	High plasticity clay, very stiff	21.0	15.0	45

Based on the soil stratigraphy and ground water table, the conclusion arising is that the most probable sliding surface will occur in the sandy layer of soil, influenced also by the water table, which modifies the soil parameters.

The analysis in order to find a stable profile was performed using Slope Stability Module of Geo Fine software [10], considering different probable situations. In this case the most suitable analysis uses Sarma method [11], for slopes with probable polygonal sliding surfaces and Fellenius-Petterson [12] method, for slopes with probable circular sliding surface. According to the Romanian and European norms [13], [14], for a slope, in order to be stable, the minimum factor of safety required is $F_s = 1.50$. This case study considers therefore the safety factors approach.



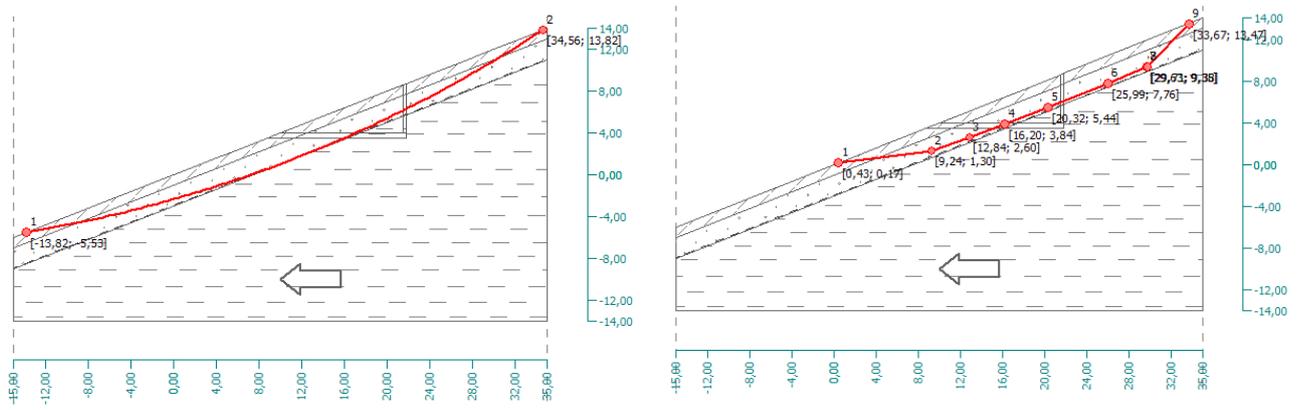
A. Slope stability verification (Fellenius / Petterson method)
 Factor of safety = 1,47 < 1,50
 Slope stability **NOT ACCEPTABLE**

B. Slope stability verification (Sarma method)
 Factor of safety = 1,49 < 1,50
 Slope stability **NOT ACCEPTABLE**

Figure 6. Slope stability analysis considering A. circular sliding surface; B. polygonal sliding surface.

The analysis using Geo5 software proved that the sliding surface with the smallest safety factor occurs in the sandy layer of soil, as in Figure 6.

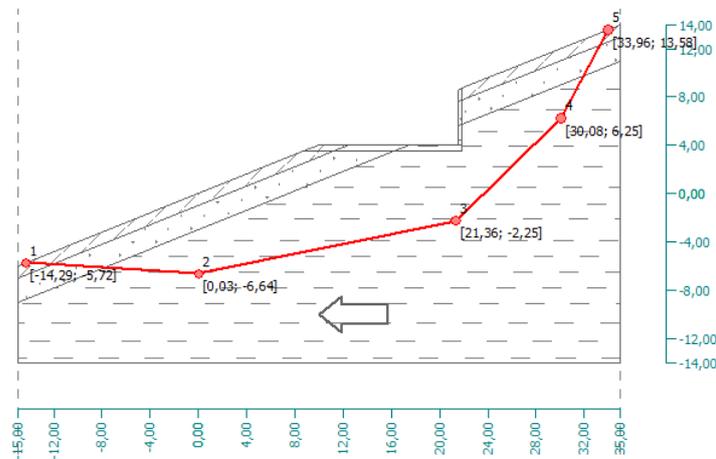
Considering the seismic action, for Transylvanian region, the vertical seismic coefficient $k_v=0.08$, the factor of safety has a significant decrease, as in Figure 7.



A. Slope stability verification (Fellenius / Petterson method)
 Factor of safety = 1,18 < 1,50
 Slope stability **NOT ACCEPTABLE**

B. Slope stability verification (Sarima method)
 Factor of safety = 1,20 < 1,50
 Slope stability **NOT ACCEPTABLE**

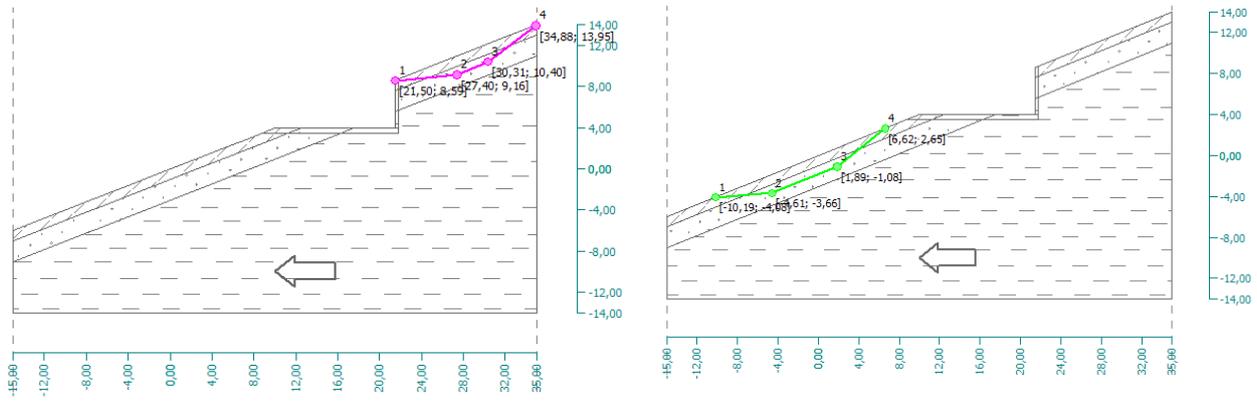
Figure 7. Slope stability analysis considering seismic action A. circular sliding surface; B. polygonal sliding surface.



Slope stability verification (Sarima method)
 Factor of safety = 1,65 > 1,50
 Slope stability **ACCEPTABLE**

Figure 8. Slope stability analysis with the excavation – general stability.

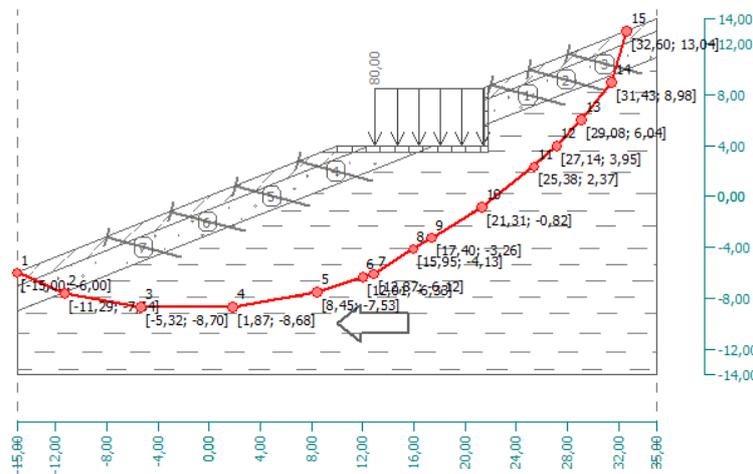
During the excavation, the slope stability changes due to the modification of stresses and strains into the soil massif. The excavation performed has approximately 12 m length and 3.50 m height and is it placed near the centre of the slope. Due to the unloading of the slope, the global stability is ensured, but there exists local stability problems, which have to be taken into consideration, up and down the house, as in Figure 8 and Figure 9.



A. Slope stability verification (Sarma method)
 Factor of safety = 1,33 < 1,50
 Slope stability **NOT ACCEPTABLE**

B. Slope stability verification (Sarma method)
 Factor of safety = 1,28 < 1,50
 Slope stability **NOT ACCEPTABLE**

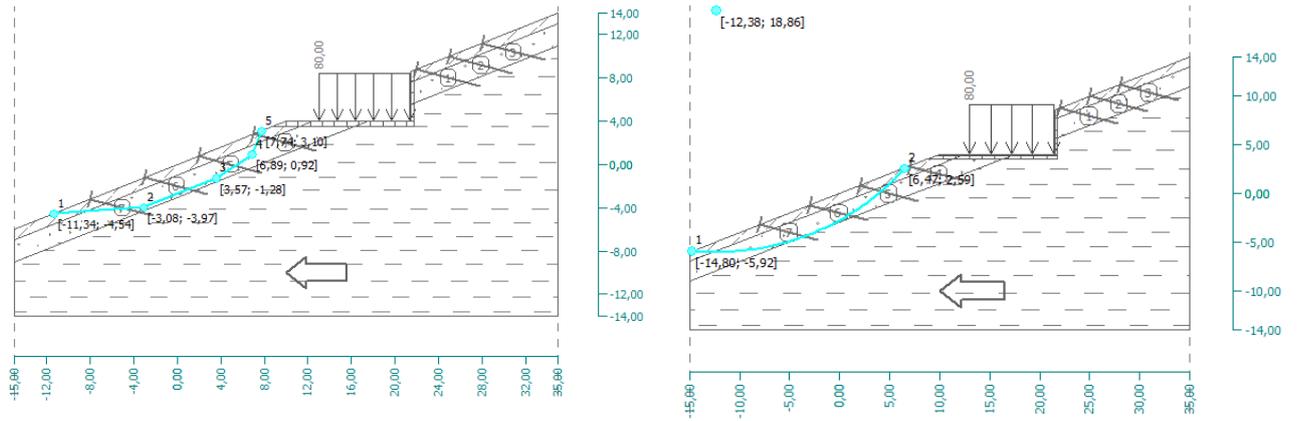
Figure 9. Slope stability analysis with the excavation A. local stability, up the house; B. local stability, down the house.



Slope stability verification (Sarma method)
 Factor of safety = 1,54 > 1,50
 Slope stability **ACCEPTABLE**

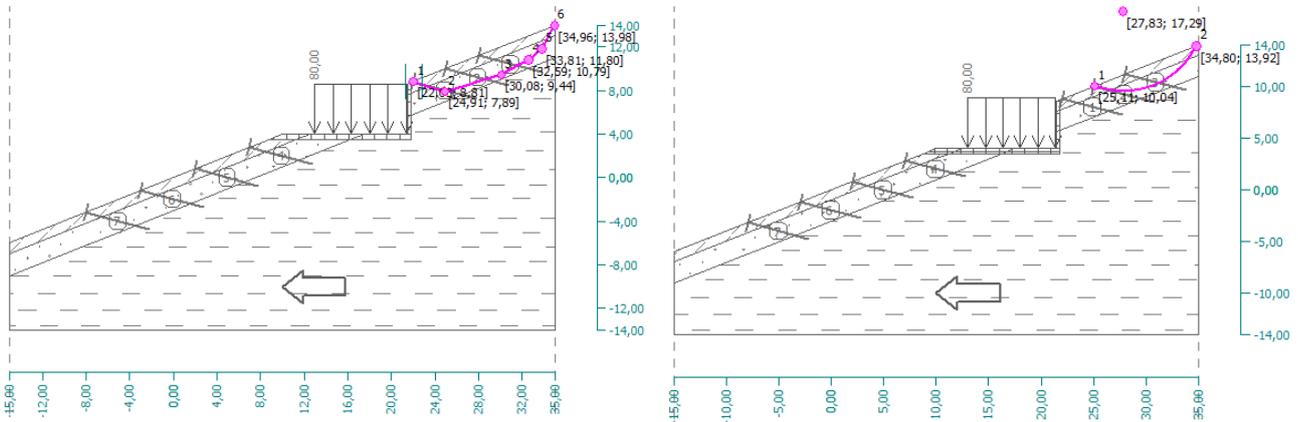
Figure 10. Slope stability analysis with the anchorage system – general stability.

By realizing the house, on a 0.50 m thickness raft foundation and with 0.30 m reinforced concrete diaphragm walls, on direct contact with the soil massif, these diaphragm walls acting like a retaining wall, the entire slope is stabilized, but the local stability is not ensured yet. First of the solutions that come into the engineers mind is to realize some earth cuts and embankments, but this solution will not stabilize the soil, even if the slope is reduced. Therefore, the solution proposed is an anchorage system placed in both unstable areas. The anchorages have 6 m in length and a 15° inclination. The slope stability is ensured, globally and locally, as seen in Figure 10 and Figure 11.



A. Slope stability verification (Sarma method)
 Factor of safety = 1,91 > 1,50
 Slope stability **ACCEPTABLE**

B. Slope stability verification (Fellenius /
 Petterson method)
 Factor of safety = 1,52 > 1,50
 Slope stability **ACCEPTABLE**



C. Slope stability verification (Sarma method)
 Factor of safety = 2,07 > 1,50
 Slope stability **ACCEPTABLE**

D. Slope stability verification (Fellenius /
 Petterson method)
 Factor of safety = 1,67 > 1,50
 Slope stability **ACCEPTABLE**

Figure 11. Slope stability analysis with the anchorage system A. local stability, down the house – polygonal sliding surface; B. local stability, down the house – circular sliding surface; C. local stability, up the house – polygonal sliding surface; D. local stability, up the house – circular sliding surface.

This soil consolidation measures have to be completed with an appropriate drainage system located around the new building. Ground water table may influence significantly soil parameters and respectively soil active pressure and stability conditions.

4. Conclusions

Building on slopes has always been a challenge, both from the architectural and engineering point of view, but in the same time the benefit provided by the landscape or the lower density is indisputable. However, not all the slopes are risk free, many presenting sliding surfaces and

therefore are difficult and/or expensive to exploit. Building half-buried or underground houses, instead of conventional ones, can stabilize the slope and may reduce the overall cost of the investment.

One of the most important stages for this type of construction works is soil investigation. Hydro-geological aspects represent an important issue in predicting the hazards in the constructed area; therefore all the precaution measures need to be accomplished. Underground water has a negative effect on mechanical characteristic of the soil, by reducing them, which is increasing soil instability. Also seismic action may lead to important decrease of safety factors. Starting from the appropriate test methods, for in situ and laboratory tests and continuing with slope stability analysis, all these analysis give an exhaustive image of the site conditions, soil consolidation systems and valuable information about future maintenance of the site.

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