The Effect of the changing cover thickness on the stability of cellars

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Abstract. The stability of natural and man-made cavities is a very important topic nowadays especially if it is located under new construction areas. There are a lot of residential areas in Budapest and other cities of Europe such as Rome, Paris, and Cracow with stability problems because of cavities. For stability calculations, the geometry of the cavity, strength properties of the rock mass and joints are needed as input parameters, which can be obtained by field and laboratory tests. The FEM software is effective for stability calculations and with them; it is not so difficult to perform parametric analysis. This paper is focusing on the effect of the thickness of the cellar cover on their stability. The investigation site is in Budapest, Hungary, where there are several cellars cut into porous limestone. These cellars are more than 100 years old and nowadays cause difficulties for the building improvements. The geometrical parameters of the cellars and strength properties were measured. The cover of the studied cellar is around 6.0 m, but other cellars in the area have various cover thicknesses from 2.0 to 9.0 m. Therefore, the paper studied the effect of the cover on the stability to find the relation between the depth and the cellar stability. The modelling has been done by Rocscience software (RS2), using a real cross-section that crosses six branches of the cellar system.

1. Introduction

Investigation and stability analysis of cellars and other underground cavities are an important topic, especially when these cavities are under urban areas. Several cities around the world have areas which are undercut by cellars and suffering from stability problems caused by these openings. Well known examples are found in France [1][2], in Spain [3], in Italy [4][5], in China [6], and in Hungary as well in Miskolc [7][8] and in Budapest [9][10]. The cellars and cavities often have historical background and are mainly results of previous quarrying activities. Cellar systems and caverns were established under towns in Hungary form the Middle Age. These were built at a low depth and with thin cover [11]. Nowadays, they are usually abandoned or have different uses, such as wine cellar, mushroom production or storage facility. Most of the above-listed cities, cellars are cut into soft rocks like porous limestone [9], rhyolite tuff [12] or andesite tuff [7]. Because of the need for a new construction area to cover the expansion of the big cities such as Budapest, sometimes the new construction area located above these kinds of cavities; therefore, the stability of these cavities became a serious engineering problem.

There are several different parameters which affect the stability of such cavities such as geometrical parameters including dimensions of the cavity, cover of the cellar, pillar width between branches; strength parameters of the rock mass including joint system, UCS and water resistance of the rock
material, long term behaviour. In this paper, the effect of the cavities cover on the stability is investigated.

2. Description of the studied area
The studied cellar located in the southern part of Budapest – Buda side (Central Europe), it had been cut into Miocene limestone. Above the cellar system, a new construction area is planning to be built, the ground surface is almost flat, the depth of the cellar system around 6 m. The investigated cellar system is consisted of a main corridor and from this corridor; seven cellar branches opened with an average length of 30 metres. The cross-sectional dimensions of the branches are the following: the average width of it is 5 m and the average height of it is 3.5 m. Masonry arches were built in the cellars against local failures.

3. Methodology
Specimens obtained from the cellar, and tested under laboratory conditions. Several rock physical tests were done: the dry and saturated density was calculated according to EN 1936:2007. The uniaxial compressive strength (UCS) test and Brazilian tests for both dry and saturated conditions were performed according to ASTM D7012-14e1 and ASTM D 3967, respectively. Water absorption tests were performed based on EN 13755:2008. The ultra-sonic wave propagation velocity test made following the guidelines given by EN 14579:2005. According to the test result, the following parameters were determined as input parameters for the stability calculations:

\[ \gamma_{\text{dry}} = 1600 \text{ kg/m}^3, \quad \gamma_{\text{sat}} = 1790 \text{ kg/m}^3, \quad \text{UCS}_{\text{dry}} = 7.47 \text{ MPa}, \quad \text{UCS}_{\text{sat}} = 2.85 \text{ MPa}, \quad E_{\text{dry}} = 3.93 \text{ GPa}, \quad E_{\text{sat}} = 1.81 \text{ GPa}. \]

Terrestrial Laser Scanner (TLS) was used to get the geometry of the cellar system. TLS is a useful and effective method for measuring the geometry of buildings [13], rock slopes [14] [15] [16] and 3D geometry of the cellars [16]. The output from this technology is a point cloud in 3D dimension and 2D sections, in a lot of formats like dxf and obj format. The studied cross section is located 21 m distance from the axis of the main corridor; this section is crossing six branches of the seven existing branches of the cellar ‘figure 1’.

![Figure 1. The studied cross-section.](image-url)
For the upper 1.5 m, the UCS reduced by 20% because the rock at this depth is weathered. The generalised Hock-Brown failure criterion was used for the material model. According to the in-situ measurements, there was only one main joint direction with dip direction = 90 deg and dip angle = 74 deg and the joint spacing is about 20 m. The cover above the cellar branches is different therefore the minimum cover ‘figure 2’ modified in the different models later. The cover above the first branch is 5.5 m ‘figure 2’. During the modelling, this cover reduced by 0.5 m in every step until it reaches 2 m and increased by 0.5 m until it reached 7 m, then the covers 8m and 9m also calculated. The modelling has done for surface loads 0.3, 0.4 and 0.5 MN/m², which applied normally to the surface in air dry and water saturated conditions which means the model run 156 times. The modelling built with the RS2 FEM software of the Rocscience software package.

![Figure 2. Cross section A21, the minimum cover.](image)

4. The results

After running the 156 models, the results for maximum displacement and factor of safety in both air dry and water saturated conditions were recorded for different loading conditions table 1, table 2 and table 3.

**Table 1. The result of modelling for load 0.3 MN/m².**

| Cover | 9 | 8 | 7 | 6.5 | 6 | 5.5 | 5 | 4.5 | 4 | 3.5 | 3 | 2.5 | 2 |
|-------|---|---|---|-----|---|-----|---|-----|---|-----|---|-----|---|
| Dry   | 2.4 | 2.38 | 2.41 | 2.26 | 2.23 | 2.32 | 2.24 | 2.39 | 2.34 | 2.34 | 2.21 | 1.69 | 1.16 |
|       | 3.2 | 3.15 | 3.13 | 3.19 | 3.54 | 3.21 | 3.38 | 3.24 | 3.28 | 3.43 | 3.52 | 3.77 | 5.08 |
| Sat   | 1.36 | 1.36 | 1.39 | 1.35 | 1.33 | 1.32 | 1.37 | 1.34 | 1.32 | 1.26 | 0.81 | 0.70 |
|       | 6.21 | 6.1 | 6.02 | 5.99 | 7.12 | 6.89 | 6.72 | 6.26 | 6.27 | 6.64 | 7.22 | 446.00 | 531.00 |

**Table 2. The result of modelling for load 0.4 MN/m².**

| Cover | 9 | 8 | 7 | 6.5 | 6 | 5.5 | 5 | 4.5 | 4 | 3.5 | 3 | 2.5 | 2 |
|-------|---|---|---|-----|---|-----|---|-----|---|-----|---|-----|---|
| Dry   | 2.18 | 2.13 | 2.15 | 1.99 | 1.97 | 2.04 | 1.96 | 2.10 | 2.06 | 2.05 | 1.96 | 1.42 | 1.08 |
|       | 4.07 | 4.02 | 4 | 4.08 | 4.52 | 4.15 | 4.42 | 4.21 | 4.24 | 4.45 | 4.59 | 4.99 | 14.70 |
| Sat   | 1.26 | 1.25 | 1.27 | 1.23 | 1.2 | 1.24 | 1.23 | 1.18 | 0.97 | 0.89 | 0.73 | 0.61 |
|       | 8.07 | 7.97 | 7.86 | 8.11 | 9.12 | 9.11 | 9.13 | 8.70 | 8.92 | 43.70 | 43.70 | 43.70 | 43.70 |
|       | 64.10 | 705.00 | 528.00 |

**Table 3. The result of modelling for load 0.5 MN/m².**

| Cover | 9 | 8 | 7 | 6.5 | 6 | 5.5 | 5 | 4.5 | 4 | 3.5 | 3 | 2.5 | 2 |
|-------|---|---|---|-----|---|-----|---|-----|---|-----|---|-----|---|
| Dry   | 2 | 1.94 | 1.96 | 1.81 | 1.78 | 1.85 | 1.86 | 1.88 | 1.83 | 1.82 | 1.73 | 1.06 | 1.00 |
|       | 4.94 | 4.89 | 4.88 | 4.98 | 5.53 | 5.12 | 5.39 | 5.23 | 5.22 | 5.50 | 5.69 | 6.36 | 60.50 |
| Sat   | 1.18 | 1.19 | 1.18 | 1.13 | 1.12 | 1.12 | 1.15 | 1.16 | 1.10 | 1.01 | 1.00 | 0.67 | 0.57 |
|       | 10 | 9.92 | 10.1 | 10.9 | 14.5 | 19.20 | 21.90 | 18.50 | 41.40 | 55.90 | 118.00 | 727.00 | 1280.00 |

The safety factor is shown in graphs of ‘figure 3’. It shows that the safety factor (strength reduction factor) increases with the increasing cover from 2 m until 4.5 m in both air dry and water saturated conditions.
conditions, from 7 m cover the safety factor started to be constant. From previous results, it’s clear that the cellar system will not affect the ground surface settlement when the cover is equal or greater than 7 m.

The maximum displacement for every cover thickness in every load step is also recorded and drawn in ‘figure 4’. It shows that the maximum displacement didn’t change significantly when the depth is equal or bigger than 2.5 m in dry condition for the three studied loads. While in saturated condition this depth is 3 m for 0.3 MN/m$^2$, 4 m for 0.4 MN/m$^2$ and 7 m for 0.5 MN/m$^2$.

From 4.5 m until 7 m cover, some uncertainty can be seen in safety factor, where the safety factors are increasing and decreasing. The reason for that is the location of the joints is in a high shear strain zone, which is in the pillar between branches. ‘Figure 5-A’ shows this area of shear strain for cover 6 m and load 0.5 MN/m$^2$ in dry condition. It shows very clearly that the joint is located exactly in this shear strain area, which leads to the decreasing safety factor and increasing maximum displacement. After
slight modification of the studied models, by changing the location of the joint to be out of the high shear strain area, the modified example cross section can be seen in ‘figure 5-B’. By moving the joint, the resulted new safety factors are increased and make the graph smooth and fit to the expected value as in ‘figure 5-C’.

![Figure 5. The maximum shear strain area with the joint - 0.5 MN/m²](image)
(a) The original location, (b) Modified location, (c) Original and modified graphs.

5. Conclusion
Around the investigation area, there are thousands of square metres area, which is undercut by similar cellars. The cover of these cellars usually between 3 and 8 metres, it was the reason for this investigation. The modelling results of this study showed obviously that the safety factor increasing and the maximum displacement decreasing with increasing the thickness of cellar’s cover. But we can determine the critical depth of the cellars which has no further effect neither the stability nor the displacement. This critical depth is for safety factor is 3 meters for dry conditions and 4 meters for saturated conditions and for displacements is 3 meters for dry and 6.5 meters for saturated conditions. The surface load cannot be higher than 0.4 MN/m² above the cellars in saturated conditions. Comparing the air dried and water saturated conditions, the reduction in the safety factor was around 50% for the three determined loads. The location of the exciting joints is important in stability point of view if the location of them is not favourable; it reduces the stability of the cellar system.

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