Stability analyses of underground structures cut into porous limestone

Contrôle de la stabilité des cavités souterraines réalisées dans le calcaire grossier

Görög P., Hangodi Á., Török Á.
Department of Construction Materials and Engineering Geology, BUTE, Hungary

ABSTRACT: Porous limestones are easy to cut and work with, therefore these stones were widely quarried and used as construction materials worldwide. One typical occurrence is in Central Europe, Austria, Hungary, Slovakia and Czech Republic, where surface and subsurface quarrying were very intense from the Roman period to the end of 19th century. In the present paper the porous limestone occurrences in Hungary and especially in Budapest and its region were studied. The limestones there were exploited from underground quarries. These subsurface tunnels and galleries are now found beneath the city. The underground openings cause several problems, due to the collapse or deformation of the walls and pillars. The present paper gives an overview of the various cellar types and the most important parameters that are used for stability modelling of these structures. As input parameters dry and water saturated physical properties, rock mass parameters such as joint system and the geometries of the structures were used. The underground spaces were modelled by using different FEM softwares. The limestone is very porous with open pore spaces of 24 to 36%. It is very sensitive to water, since water saturation decreases its strength by nearly 30-40%. It is considered as a soft rock/hard soil. In the models different soil covers and building loads were compared, as well as dry and water saturated conditions were assessed. These obtained results can be generalized and used in the design of buildings and other engineering structures that are cut into or built over various types of porous limestones occurring in other countries, too.

RÉSUMÉ : Grâce à l'exploitation simple et la mise en œuvre facile du calcaire grossier, cette roche est largement utilisée et préférée comme matériau de construction. En partant des temps de l'empire romain jusqu'au XIX^{e} siècle, le calcaire a gagné du terrain en Europe centrale. Il a été exploite surtout en Autriche, Hongrie, Slovaquie et en Rép. Tschéque sous forme d'exploitation en surface et en souterrain. L'objet de l'étude est de donner un aperçu général sur la présence et l'étendue du calcaire grossier en Hongrie et, tout spécialement, aux environs de Budapest. Dans ces régions on a favorisé l'exploitation souterraine, les tunnels et cavités qui en témoignent, se trouvent déjà, dans nos jours, sous la capitale. Les éboulements des cavités et des tunnels sont à l'origine des nombreux problèmes et difficultés. L'article a essayé de récapituler les divers types de cave et les plus importants paramètres nécessaires aux calculs de stabilité des parois, piliers, et des voûtes. Une attention particulière a été portée sur les problèmes liés aux caractéristiques physiques en état sec et saturé de la roche, on a également étudié les paramètres de la structure et de la fracturation générale du massif, tout en tenant compte de la géométrie des caves. En ce qui concerna la modélisation des cavités souterraines, on s'est servi des softwars d'éléments finis. Le calcaire grossier est un matériau poreux. Sa porosité apparente varie de 24 %à 36 %, sa résistance à la rupture en état saturation peut diminuer de 30 % à 40 %. Vu ces pertes de résistance, le calcaire peut être caractérisé soit comme roche faible, soit comme sol dur. Les échantillons soumis aux essais étaient prélevés des profondeurs différentes, faisant varier l'état sec et saturé. Les résultats obtenus permettent de les généraliser et peuvent être utilisés à l'étude des immeubles fondés sur ce calcaire et à celle des autres structures souterraines.

KEYWORDS: limestone, porosity, cellars, FEM analysis

1 INTRODUCTION

Stability of subsurface openings such as galleries or tunnels cut into limestones are often endangered by the collapse of roofs and side walls similarly to natural sinkholes (Waltham and Fookes 2003, Xeidakis et al. 2004, Török et al. 2006, Farrant and Cooper 2008).

Parise and Lollino (2011) demonstrated that for studying the stability of man-made caverns cut into porous limestone both field observations and numerical simulations can be used. In the present paper rock mechanical data obtained from field sampling and laboratory testing is used as input parameter for the modeling of underground structures. Geometry of cellars were also documented during the field survey and used for the modeling. For the numerical simulations 4 different FEM software ere used to evaluate the advantages and limitations of the usage of computer codes in stability analyses of limestone openings.

2 GEOLOGY

Cellars were cut into porous limestone of Miocene age. The origin of the subsurface cellar system is related to quarrying, since the stone has been used as a dimension and ornamental stone for centuries in Budapest region. The porous limestone is yellowish-white colour when it is freshly quarried. The quarries still exist but most of them were operated during the second half of the 19th century when construction activity was intense and rapid development of the city was marked by construction of public buildings.

Three main limestone types have been identified (Török 2002) and widely used in the buildings and monuments of Budapest. The three lithologies are i) fine-grained limestone; ii) medium-grained oolitic limestone and iii) bioclastic macro-porous limestone. No significant difference of mineralogical composition was found in the quarry samples, since the main mineral is calcite (92-97%) in all lithotypes (Török 2003). Minor amount of quartz and sand-sized lithic clasts are also present according to XRD analyses. The biggest amount of noncarbonate components was found in medium-grained oolitic limestone with maximum values of 8%, which is mostly given by quartz and subordinately by feldspar.

3 METHODS

3.1 *Sampling, core drilling and laboratory analyses*

Samples were obtained from underground structures and surface quarries. Additionally where it was avilable core drillings were made.

For the laboratory analyses samples were drilled and cut from porous limestone blocks or core drillings were processed. Cylindrical test specimens were used and the following rock mechanical tests were made according to European Norms: bulk and material density (EN 1936), ultrasonic pulse velocity (EN 14579), water absorption (EN 13755) uniaxial compressive strength (EN 1926), indirect tensile strength.

3.2 *Numerical modelling*

Different FEM codes were use to modell the cellars cut into porous limestone such as Plaxis v8, Geo4 Tunnel module, Phase2, Examine3D.

The first three codes use the same calculation methods but they are able to use different material models. The Plaxis v8 and the Geo4 are developed for modeling soils while the Phase^2 is for modeling rocky environment. In spite of it the Plaxis and Geo4 can be also used for rocks but the Phase^2 has some specific material model for rock masses for example the Hoek-Brown model, and it is able to calculate with the anisotropy of the rock masses.

The porous limestone can be described as soft rock or hard soil, therefore all of these codes can be used for modeling its behaviour. The rock mass of the porous limestone is usually can be considered as intact rock or blocky according to the chart of Marinos & Hoek (2000). The joint system of the limestone is characterized by faults or bedding. The Phase^2 has a good tool for modeling the joints.

The geometry of the cellars sometimes very different, in the area of Budapest can be found individual cellars, but sometimes huge cellar systems as well. The cross-sectional area of them is varies from 2 m^2 to more than 100 m^2 and there are cellar systems which is above each other. The modeling of a cellar system with such complicated geometry is not easy, sometimes it is necessary to use 3D tools for example Examine3D. This software is easy to use, but it is not able to consider different layers and joints.

4 RESULTS

The paper provides three different cases on cellar system cut into porous limestone. The first one is a more than a hunderd years old individual cellar that was cut under a road and a railway (Fig.1). There is a plan to enlarge the cross-section to use the system as an access footpath to a huge cellar system. The small cover above the tunnel is the major risk.

The second case is the study of the interaction of two cellar systems, which are above each other.

The third case study deals with a cellar that is located just 3 metres below the surface. According to plans a new house is to be built above.

4.1 *Tunnel enlargement*

The area of the first and the second case study is located very close to each other, namely the planed tunnel goes into the cellar system of the second case. Thus the differences between them are the vertical placements of the cellars. The base level of the tunnel is at 102.8 m Asl., while the base level of the second one is about 106.5 m Asl. The geological set-up of the area of the tunnel is showed in the table 1.

Figure 1. The road and the railway above the tunnel

Table 1. Layers and its parameters used for modeling

Layer	bulk density (kg/m^3)	friction angle (degree)	cohesion (kPa)	rock mass modulus (MPa)
sandy clay fill	1800	25	0	5
clayey rubble	1950	18	40	8
porous limestone rubble	1650	47	17	80
porous limestone	1650	49	174	248

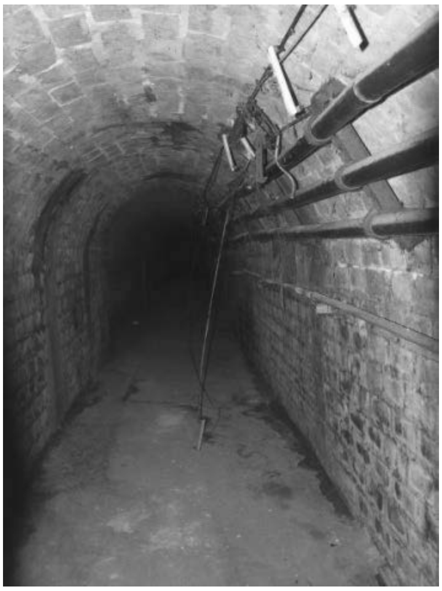

Figure 2. The tunnel with the concrete masonry support system

The cover of the tunnel is 1.3 m, and it has a concrete masonry linning system (Fig.2).

Above the tunnel the clayey rubble layer is found, and behind the tunnel lining the porous limestone rubble, while the intact porous limestone only occurs under the base level of the tunnel. The enlargement of it can be built by reducing the base level of the tunnel. According to the drilling results behind the concrete block masonry the void between the porous limestone blocks are very high. Therefore the rock mass behind the linning should be grouted. Fig.3 shows the stresses in the grouting zone obtained by using Plaxis 8.2.

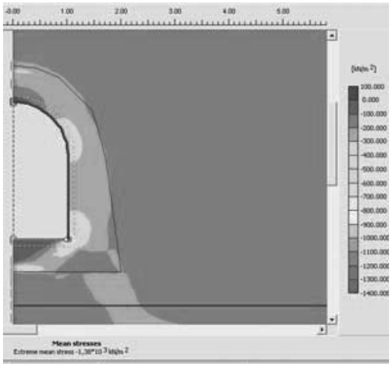

Figure 3. The calculated stresses in the grouting zone

After the grouting, the enlarged cross-section of the tunnel was examined with Geo4 Tunnel module. The safety factor of the calculations is 1.69 (Fig. 4).

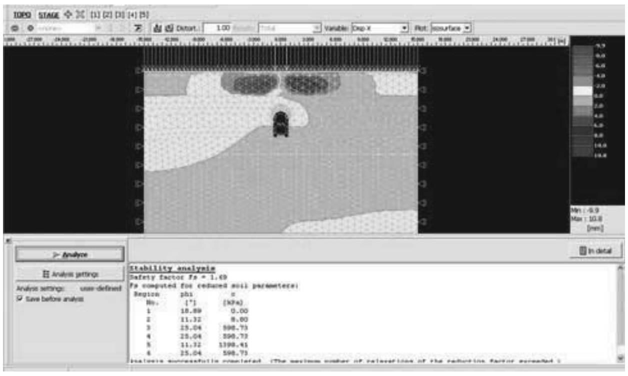

Figure 4. The safety factor of the enlarged section using Geo4

The results of this stability calculations suggest that the enlargement of the cross-section of the tunnel can be made only after grouting of the area behind the present linning structure. The head of the tunnel can be excavated gradually at its base. After the excavation of a short span, the linning should be closed immediately.

4.2 *Interaction of different cellar systems*

There is a network of cellar systems in this area. They were cut more than a hundred year before to explore limestone. It was not known that they are so close to each other. Later on they were used as wine cellars and now an underground "wine city" is planned in them. Thus the two different cellar system planed to be connected, and the safety of them has to be investigated.

The layers of the second cellar system is showed in the table 2. Under the upper silty clay layer the porous limestone is very thick (about 15 meters), and in it there are some thin (about 0,5 meters) bentonite layers. The main geotechnical properties of them are also shown in table 2.

Table 2. Layers of the second cellar system

Layers	density (kg/m3)	sig c (MPa)	sig t (MPa)	E (MPa)	ν (-)
silty clay	1900	-	-	-	-
porous limestone	1510	1.60	0.41	226	0.25

The silty clay layer is not important from the point of view of the stability of the cellars because it is the thin cover soil layer of the porous limestone. Therefore it is not analysed.

In the studied cross-section the cellars are above each other (Fig. 5). The height of the vaults at the right side of the Fig. 5 is 5 meters, and here the thickness of the cover is enough for developing the arch effect above the vaults as it can be see on Fig. 5.

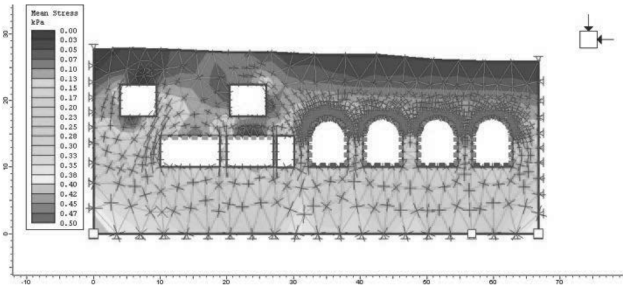

Figure 5. The stress distribution around the interacting cellars calculated using Phase^2 software

This calculation is a simplification of a 3 dimensional problem. The geometry of the cellars is not planed and there is no exact assesment available. Thus the three dimensional modeling of the cellar system was not possible. The safety factor of this cross-section was n=1.5 taking into consideration the load of a huge wine barrel with volume of 30.000 l.

This is not a final result because the 3D model is also needed and has to be calculated, therefore for the investigation the real safety of this cellar the exact assessment of the geometry is needed.

4.3 *Effect of surface loading on the stability of a cellar system*

A building is planed above a cellar system cut into porous limestone. The site plan of the buildig and bellow the cellars are showed on Fig. 6. The yellow part of the figure shows the pillars beetween the cellars. Black colour indicates the footing of the planned house and dark grey sign the pillars which are under the footing. As it can be seen on Fig 6. the cellars cover about 70% of the area under the planned building.

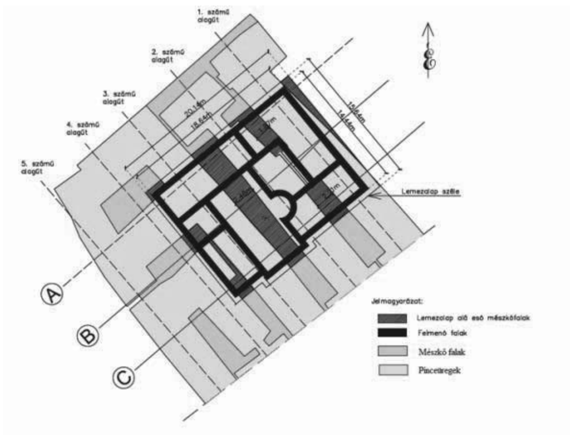

Figure 6. Site plan of the footing and the cellars

The geological section consists of 0.3 m thick soil layer, under it there is 0.8 m moderatly jointed porous limestone. Under this layer the intact porous limestone is found with the cut cellars.

In the intact porous limestone there is a 0.4 m thin bentonite layer, which is located under the shoulder of the vaults of the cellars. The cover of the cellar system is only 2.7 meters.