Comparative analysis of slope stability: seismic loading and engineering geology; examples from Croatia and Hungary

Usporedna analiza stabilnosti kosina na primjerima iz Hrvatske i Mađarske: seizmičko opterećenje i inženjerska geologija

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Abstract

The paper compares the engineering geological parameters of Croatian flysch deposits and Hungarian marls with respect to slope stability. Eocene flysch deposits are widespread sediments in Central Dalmatia. They form gentle to steep slopes in the countryside and in urban areas, with risks of slope instability. Especially weathered and long-time exposed open cuts are endangered. The rock mechanical parameters vary significantly: uniaxial compressive strength from 5 MPa (clayey marl) to 80 MPa (sandstone). In Hungary Eocene marl is common lithology in the broader area of Budapest. The mean UCS of clayey layers is 4-5 MPa, but calcareous marl has a UCS up to 45 MPa. Slope instability is pronounced by small-scale landslide in un-vegetated slopes and also on covered slopes of weathered marls. Besides laboratory analyses of rock mechanical parameters shake table tests are also possible to assess the seismic behaviour of these materials. Large scale laboratory tests can be used to analyse slope stability on small scale model.

Keywords: slope stability, flysch, marl, uniaxial compressive strength

Sažetak


Ključne riječi: stabilnost kosina, fliš, lapor, jednoosna tlačna čvrstoća

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Introduction

Steep and gentle slopes of marls and alternating layers of clay and sandstone represent special landslide hazards since the behavior of such highly heterogeneous material packages are still not fully understood. However, in the past years several studies dealt with the problem of heterogeneous rock masses (Marinos and Hoek 2001, Hoek et al. 2005). It has been demonstrated that the behavior of such rock types strongly depend on the sedimentological characteristics, such as thickness of beds and alternations of harder and less consolidated beds, mineralogy and grade of weathering.

The present study provides a short outlook to the problem comparing two lithologies of heterogeneous rock masses: flysch and marl. The given examples are from Croatia and Hungary. The paper focuses on the properties of these rocks providing information on the laboratory test results. It also outlines the differences in the seismic behavior of both flysch and marl with regard to the different seismicity of Croatia and Hungary.

Geological background

The heterogeneous rock geological formations are common both in Croatia and Hungary, and are found not only in the higher mountainous areas, but also at low lying lands, hills and in coastal zones.

The most common lithotype responsible for landslides in Croatia are Eocene flysch deposits covering large areas in coastal part of Central Dalmatia (Fig. 1).

While flysch deposits are common in Croatia (Vlastelica, 2015), Eocene marls have the same importance in terms of landslide hazard in Hungary (Görög and Török 2007). The calcareous marls are mostly located in Central part of Hungary and forms a part of the Priabonian transgressive system (Fig 2).

Figure 1. Geological map showing the occurrence of flysch deposits in Dalmatian region (after Mostecak et al. 2018).

Figure 2. Distribution of the Eocene depositional systems in Hungary. Buda marl is found within the Priabonian transgression system marked by circled pattern (after Haas 2013).

Eocene marl (Buda Marl Formation) is at the surface especially Buda side of Budapest and in small zones of North Hungarian Mountains. Thus landslide affected areas are mostly found in Buda Hills region. Not only the Eocene marl but also the overlying Oligocene clay (Görög 2007a) is prone to landslides at this part of Hungary.

Figure 3. Distribution of earthquakes in the Carpathian basin and its surroundings (red dots represent earthquake epicentres, and the size of the circle is proportional to magnitude, while the boundary of Hungary is marked in blue) (after Török 2007, data from Gerner et al. 1999).

The seismic activity in the two countries is different. Hungary belongs to the moderately active segment of the Carpathian basin (Fig 3.), while Croatia is...
considered a more active part of the Carpatho-Dinaric region (Fig 4.).

Figure 4. Distribution of earthquakes in the Croatia from BC to 2008. (Herak et al 1996, updated by the Department of Geophysics, University of Zagreb).

Methods

Samples were collected from Eocene flysch deposits of Croatia and of Eocene Buda Marl of Hungary. Rock mechanical parameters were measured under laboratory conditions on cylindrical specimens. The cylinders were either drilled from larger rock blocks or were cut from rotary drill cores. The laboratory tests were performed according to European Norms, and also by following ISRM guidelines. Bulk and material densities, ultrasonic pulse velocity, water absorption, uniaxial compressive strength and tensile strength were measured. Modulus of elasticity was also calculated. Air dry and water saturated specimens were prepared in order to model environmental conditions. Strength parameters were calculated by using Rocscience RockLab software.

Materials

Dalmatian marls found in flysch strata are usually of bright yellow, grey, brown or bluish colour, while their stratification varies from a few centimeters to several meters (Fig. 5). Marl in Dalmatia is usually considered as a rock containing between 15 and 85% of clay, and 15 and 85% carbonate (CaCO3), and it can usually be found in Central Dalmatia in ranges of 40-80% CaCO3 (Vlastelica et al, 2018).

Figure 5. Dalmatian flysch (Vlastelica, 2015).

The major part of the calcite in Dalmatian marl is of chemical origin, i.e. developed by the extraction from the sea or lake water, and the small part is clastic. The studied Hungarian marl forms a part of Eocene Buda Marl Formation. It is light grey predominantly calcareous marl (Fig. 6), which becomes yellowish at the surface due to weathering. It is thick-bedded to laminated. The carbonate content show some variations, but usually more than 40 % (Báldi 1983). Small amount of fine sand can be also detected in the marl sequence. Thus the lithologies can have a wide range from calcareous marl to clay marl.

In some layers pyrite can occur, which than transforms to limonite-goethite at the surface. This transformation also contribute to the colour change of the marl and thus at the surface and close to the surface in the weathered zone most marls are yellowish brown (Fig. 7). The differences in lithologies...
are also reflected in the physical properties as it was pointed out earlier (Görög 2007b).

Results and discussion

The physical properties of the Croatian Eocene marls found in flysch can vary significantly (Table 1) and it reflects the variations in the lithologies. Most typical occurring are marls in range 45-65% CaCO₃ variations in the lithologies. Most typical significantly (Table 1) and it reflects the Eocene marls found in flysch can vary (Vlastelica et al., 2016).

Comparing the physical properties of the Croatian flysch and the Hungarian marls, it is clear that there are significant differences within one Formation. There are some lithological overlaps between the Croatian flysch and the Hungarian marl. Namely: in both formations marly layers are found. According to the test result all the measured properties (density, US pulse velocity, UCS, Young’s modulus) of the marl from Dalmatia is between the Hungarian calcareous and clayey marl (Table 1 and Table 2). The average value of the Young’s modulus of the Dalmatian marl is less than half of the Hungarian calcareous marl, but more than two times higher than the clayey marl. The test results reflect the differences in lithologies. The higher the carbonate content of the Hungarian marl, the higher the strength of the marl.

The physical properties of the Hungarian Eocene marl reflect the variations in the lithologies. Calcareous marl has much higher strength than the clayey marl (Table 2). Namely the mean uniaxial compressive strength of the calcareous marl is more than eight times higher than that of the clayey marl. The differences in strength are also reflected in the indirect tensile strength, but the difference is only triple in that case. The differences in strength of various marl lithologies were also documented earlier (Görög 2007). Ultrasonic pulse velocity data of calcareous marl and clayey marl do not differ that much.

Table 1. Physical properties of Dalmatian flysch (range, in general, Šestanović, 1989) and typical Dalmatian marls (typical values in 45-65% CaCO₃ range).

<table>
<thead>
<tr>
<th>Property</th>
<th>Flysch (in general)</th>
<th>Marl</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Density [kg/m³]</strong></td>
<td>2000-2800</td>
<td>2300</td>
</tr>
<tr>
<td><strong>US pulse velocity [km/s]</strong></td>
<td>0.5-4.0</td>
<td>2.0</td>
</tr>
<tr>
<td><strong>Uniaxial Comp. Str [MPa]</strong></td>
<td>6.2 – 79.5</td>
<td>15</td>
</tr>
<tr>
<td><strong>Modulus of elasticity [GPa]</strong></td>
<td>2-5</td>
<td>3</td>
</tr>
<tr>
<td><strong>Tensile strenght [MPa]</strong></td>
<td>0.8-6.5</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 2. Physical properties of Hungarian Eocene marl lithologies: calcareous marl and clayey marl (mean values) (partly based on Görög 2007b and Török 2007).

<table>
<thead>
<tr>
<th>Property</th>
<th>Calcareous marl</th>
<th>Clayey marl</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Density [kg/m³]</strong></td>
<td>2475</td>
<td>2289</td>
</tr>
<tr>
<td><strong>US pulse velocity [km/s]</strong></td>
<td>2.60</td>
<td>1.65</td>
</tr>
<tr>
<td><strong>Uniaxial Comp. Str [MPa]</strong></td>
<td>44.3</td>
<td>5.5</td>
</tr>
<tr>
<td><strong>Modulus of elasticity [GPa]</strong></td>
<td>7.38</td>
<td>0.52</td>
</tr>
<tr>
<td><strong>Tensile strenght [MPa]</strong></td>
<td>4.4</td>
<td>14</td>
</tr>
</tbody>
</table>

The shake-table can achieve maximal acceleration of up to 5 g, and maximal displacement of approximately 150 mm. The shake-table can achieve maximal acceleration of up to 5 g, and maximal displacement of approximately 150 mm. The shake-table can achieve maximal acceleration of up to 5 g, and maximal displacement of approximately 150 mm. The shake-table can achieve maximal acceleration of up to 5 g, and maximal displacement of approximately 150 mm. The shake-table can achieve maximal acceleration of up to 5 g, and maximal displacement of approximately 150 mm. The shake-table can achieve maximal acceleration of up to 5 g, and maximal displacement of approximately 150 mm. The shake-table can achieve maximal acceleration of up to 5 g, and maximal displacement of approximately 150 mm. The shake-table can achieve maximal acceleration of up to 5 g, and maximal displacement of approximately 150 mm. The shake-table can achieve maximal acceleration of up to 5 g, and maximal displacement of approximately 150 mm. The shake-table can achieve maximal acceleration of up to 5 g, and maximal displacement of approximately 150 mm.
when the highly cemented lithologies are fractured and tectonically deformed. The rock fall hazard of such slopes can be assessed by using physical properties (Crosta & Agliardi 2003) or by modelling of the trajectories of falling blocks (Samodra et al. 2016). Steeper cliff faces can be formed naturally or by human activity from these lithologies. To assess the seismic stability of these cliff faces additional data is needed: such as slope profile, joint pattern, block size (De Biagi et al. 2017).

**Shake table - testing possibilities**

Besides laboratory analyses of rock mechanical parameters, actual behaviour and stability of slopes under an earthquake is still insufficiently investigated area and subject of researches (for example Hong et al. 2005, Shinoda et al. 2013). The experimental study on the behaviour and stability of slopes under seismic (earthquake) loading is planned to be conducted within Laboratory for Seismic Testing at University of Split in Croatia. The Laboratory is equipped with a shake-table with layout size of 4 × 4 m and maximal capacity of 20 tons (see Fig 8).

The shake-table can achieve maximal displacement of approximately 150 mm, maximal acceleration of up to 5 g, and frequencies up to 20 Hz (Baloević et al. 2017). The tests are conducted on scaled models, with variation of several parameters, such as: slope height, slope angle, granulometry, earthquake type, peak ground acceleration etc. The results obtained from shake-table tests can be useful tool to access the actual seismic behaviour of slopes in seismic areas.

**Conclusions**

The rock mechanical parameters vary significantly of Croatian flysch and Hungarian marl. In the flysch cemented sandstone layers have the highest uniaxial compressive strength (in range of 80 MPa), while in the marl calcareous marls have the highest UCS values (44 MPa) that is comparable to the flysch sandstone. In the flysch the grain size and cementation, while in the marl the carbonate content are responsible for the high strength. The slope stability of these heterogeneous layers is controlled by the amount of low strength layers (marls in the Croatian flysch and clays in the Hungarian marl). The earthquake related hazards of slopes that are composed of highly cemented high strength lithologies also depend on other parameters besides strength. A few to mention are the joint system, block size and slope geometry. The earthquake hazard of the two countries are different thus in Croatia where high magnitude earthquakes are more common, the potential risk of earthquake triggered slope instability is higher.

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GEOTECHNICAL CHALLENGES IN KARST

References


