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Engineering geological parameters of sandstone hosting future highway tunnels, an example from Hungary

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Abstract

Quartz cemented sandstone is the prevailing lithology of the planned northwestern section of the M0 highway near Budapest (Hungary). For the design of future tunnels, core drillings were made to explore the engineering geological conditions of the missing highway section. The lithotypes of the core drillings shows similarities to outcrops in the Buda Hills. They represent the Oligocene shallow marine to lithoral sandstone series that belongs to the Hárshegy Sandstone Formation. Laboratory tests were made from drill cores using standard test methods to assess their properties. These included measuring different physical parameters such as bulk density, ultrasonic wave velocity, uniaxial compressive strength and indirect tensile strength (Brazilian test). Lithological descriptions helped to identify the various lithotypes ranging from fine-grained to coarse-grained varieties. The current paper presents a statistical analysis of the physical parameters, taking into account the lithological variations. The obtained relationships can be used for describing the rock mechanical parameters of sandstones from other regions. The results can help in the design of the supporting system of tunnels, since the calculated equations provide relationships between parameters and can be used as a reference for other construction projects in a similar rock environment.

Keywords

Sandstone, Grain-size, Bulk density, Ultrasonic wave velocity, Uniaxial compressive strength.

1 Introduction

The M0 highway, which encircles Budapest, is designed to relieve traffic congestion in the broader area of the capital of Hungary. However, its northwestern and western sections have not been constructed yet. According to current plans, two tunnels are proposed for the northwestern section, and the alignment of the second tunnel would predominantly pass through rock masses belonging to the Oligocene Hárshegy Sandstone Formation. This area is strongly tectonized, which significantly reduces the quality of the sandstone despite its otherwise favourable strength parameters. The objective of our study was to analyse the consequences of this structural geological effect, as well as to investigate whether variations in grain size of the sandstone have a measurable impact on the rock mechanical parameters.

2 Geological background

The Oligocene Hárshegy Sandstone Formation is predominantly a coarse-grained sandstone, intermittently interbedded with fine- and medium-grained sandstone layers with a few conglomeratic intercalations. It is of shallow marine, nearshore origin. The thickness of the formation is variable, but it generally decreases in a NW–SE direction, from approximately 230 meters in the Dorog Basin to around 25 meters near Solymár. The Hárshegy Sandstone can essentially be regarded as the transgressive basal formation of the Kiscell Clay Formation (Báldi et al. 1976). The coarsest-grained parts and the conglomeratic intercalations are typically found along the Buda Line (5–20 km wide tectonic zone). The study area is located near the settlement of Üröm, marked with a circle on Fig 1.

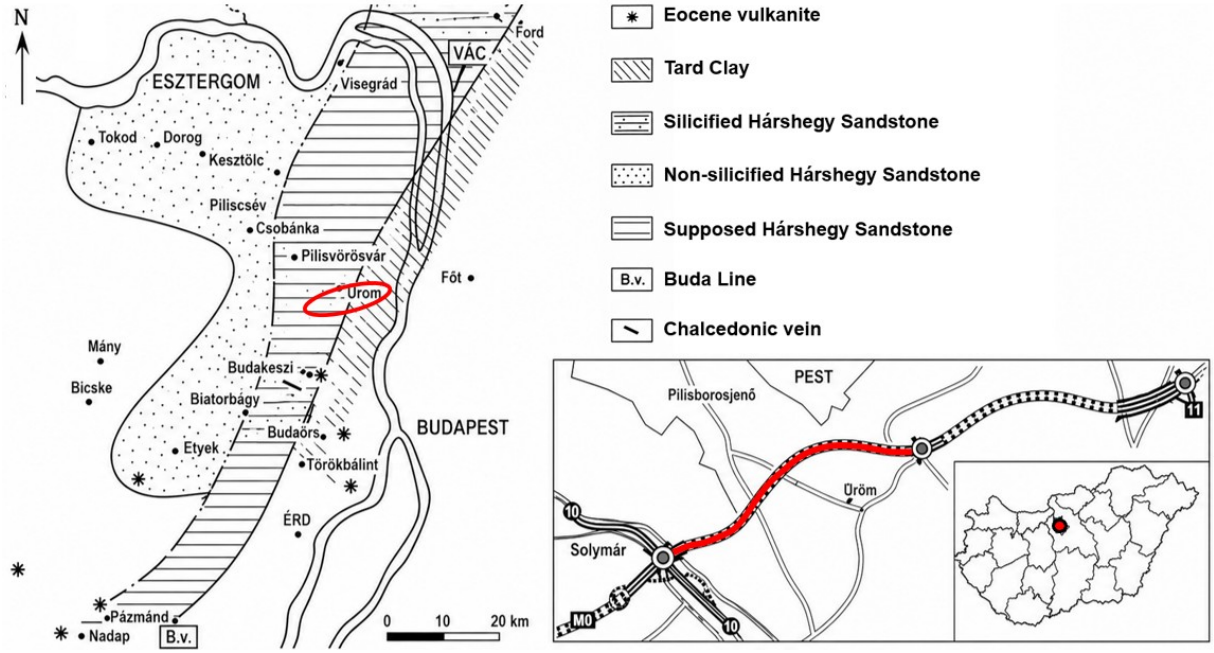


Fig. 1 The location of the "B" tunnel and the geological conditions of its surroundings (Fodor et al. 1994, NIF).

The area is strongly tectonized, mostly characterized by NW-SE and NE-SW-oriented faults. The NW-SE normal faults were formed during the Cretaceous period and reactivated in the Pleistocene (Fodor et al. 1994). Solymár Valley, which is located near the western exit of the planned tunnel, provides an example of this structural geological evolution, since this valley was formed along a major fault.The NE-SW normal faults were formed in the Miocene. This type of fracture is found between Üröm and the Solymár Valley. These fractures give the rocks here secondary porosity. Due to this, the sandstone here has medium permeability (Wein 1977).

The sandstone is strongly silicified due to hydrothermal activity along the Buda Line, and its carbonate content is minimal. The degree of silicification is variable and may be more pronounced along fractures (Báldi 1983). The sandstone is composed almost entirely of quartz, with minor amounts of feldspar and muscovite. In the lower parts of the sequence, conglomerates are found containing the clasts exclusively derived from the underlying carbonate formations, such as Triassic limestone or dolomite (Báldi et al. 1976). The rock mass exhibits considerable variability in fracturing. Certain portions of the sandstone can be described as compact and strong; however, in some intervals,

particularly at the planned tunnel depth in several boreholes, it is highly fractured. At some places, nearly vertical fractures with dips of approximately 75–80° were also observed.

3 Materialsand methods

Rock units assigned to the Oligocene Hárshegy Sandstone Formation were explored in 11 boreholes of Tunnel "B". Their colour is predominantly grey to greyish yellow, although strongly limonitized zones may exhibit a reddish-brown hue. The grain size of the sandstone is highly variable: both fine-grained, well-sorted intervals and coarse-grained, poorly sorted lithotypes were found (Fig 2.). The coarse-grained sandstones often contain slightly rounded pebbles, predominantly composed of white quartz and grey chert, with subordinate occurrences of black lydite pebbles. Silicification (siliceous cement) predominates. Quartz cementation plays a fundamental role in controlling the petrophysical and mechanical properties of sandstones. As summarized by McBride (1989), the extent of quartz cementation is influenced by factors such as temperature, burial depth, pore fluid chemistry, and the availability of silica, and it significantly reduces porosity while improving rock consolidation. Although grain size is primarily discussed in terms of its control on cementation through its influence on specific surface area, its effect on mechanical behaviour can also be outlined. Smaller grain sizes provide a larger surface area for quartz overgrowth and allow the formation of more extensive cement, leading to stronger bonds between grains and filling intergranular pores. Previous studies (Wasantha et al. 2014; Sun et al. 2017) have also demonstrated that grain size directly affects the mechanical properties of sandstones. Namely, fine-grained sandstones generally exhibit higher strength and stiffness due to increased grain contact density. Therefore, the mechanical behaviour of quartz-cemented sandstones is governed by the combined effects of diagenetic processes and microstructural characteristics, including grain size and cement distribution.



Fig. 2 Fine-grained sandstone from 51.7 m (borehole 830/2) and coarse-grained sandstone from 50.18 m (borehole 831).

Three representative images obtained by polarizing microscopy are presented, illustrating a fine-grained, a medium-grained, and a coarse-grained sandstone (Fig. 3). Based on microscopic observations, the siliceous cement fills the pores and provides strong bonds between grains. Larger grains also occur, but near these grains, small pores were found. These larger grains are more prone to fracturing as it was observed under the microscope: micro-fractures passing through grains.

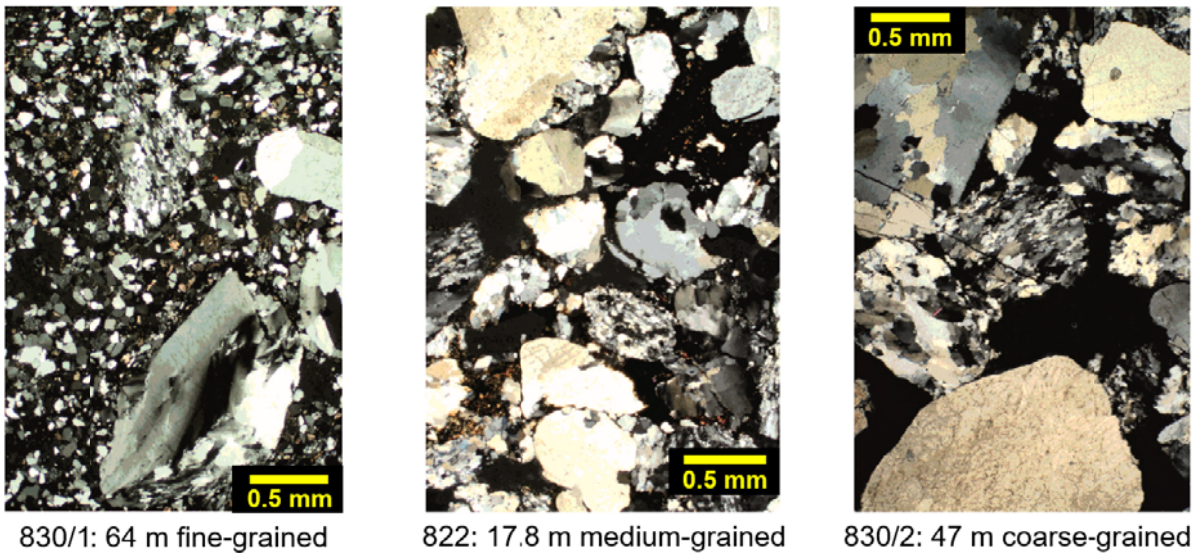


Fig. 3 The polarizing microscope images of three different types of sandstone.

During the laboratory tests, both non-destructive and destructive test methods were used. Tests included the measurement of bulk density and ultrasonic wave velocity. Two types of strength tests were also performed: uniaxial compressive strength (UCS) and indirect tensile strength tests (BTS). The tests were carried out according to the ISRM Suggested Methods (ISRM 2007). Table 1 summarizes the test specimens representing various lithologies. To compare the mechanical behaviour of intact and fractured rocks samples were also taken from highly fractured zones.

Table 1. The available samples grouped by grain size.

Borehole ID	fine-grained	medium-grained	coarse-grained	conglomerate	SUM
817	-	1	6		7
822	-	4	-	1	5
825	2	5	-	2	9
827	2	10	-	3	15
828	2	3	3	-	8
830/1	4	2	13	3	22
830/2	5	4	7	15	31
831	8	4	22	-	34
838	-	-	7	-	7

4 Results and discussion

The test results of bulk density, ultrasonic wave velocity, uniaxial compressive strength (UCS) and indirect tensile strength (BTS) tests and the ranges of obtained values are presented in Fig. 4. The smallest range of values of physical parameters was found at measured values of ultrasonic wave velocity, since the studied four lithotypes have fairly similar mean values. The highest UCS value was found in fine-grained sandstone. However, based on the study, the conglomerate also has similar strength values. The medium-grained sandstone exhibited the lowest BTS values, whereas the coarse-grained sandstone yielded the highest average BTS among the investigated lithologies. It seems that siliceous cementation has a greater influence than grain size.

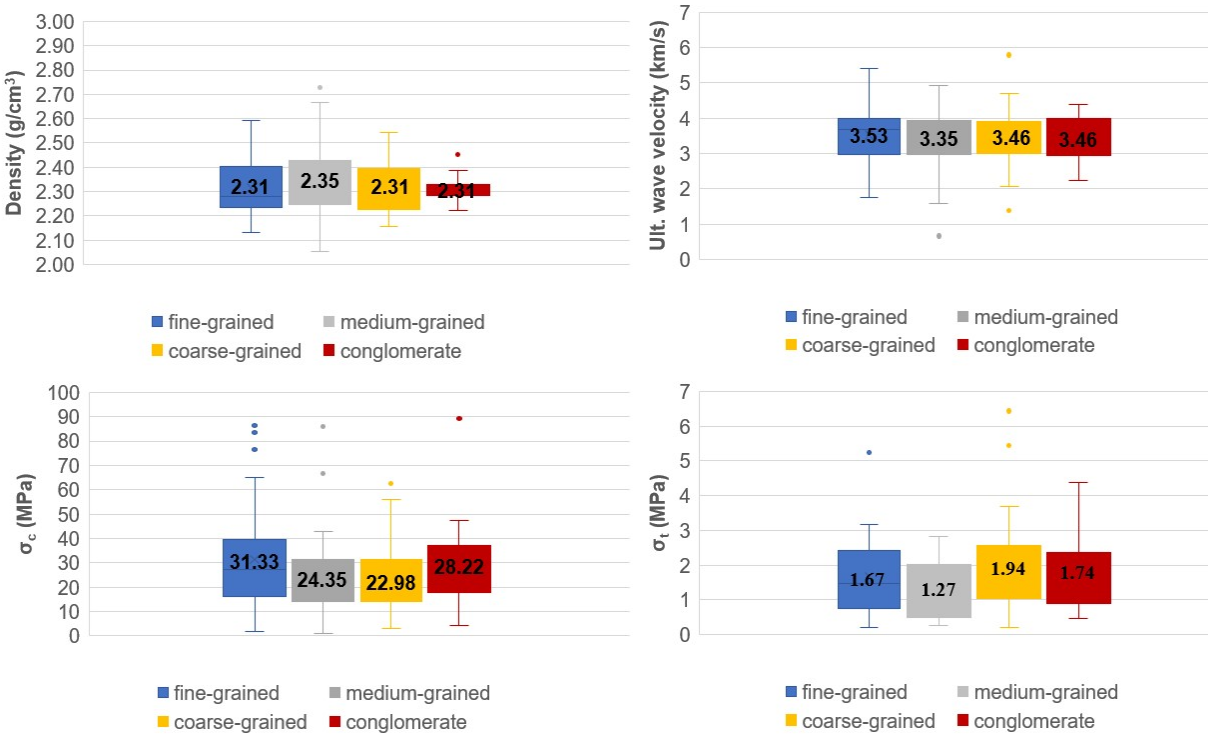


Fig. 4 Bulk density, ultrasonic wave velocity, UCS (σ_c), BTS (σ_t) parameters of the different types of Hárshegy Sandstone.

The relationship between the ultrasonic wave velocity and uniaxial compressive strength was also outlined for different grain-size types. According to our results, there is no major difference between the various lithotypes as a function of grain size (Fig. 5). The results rather suggest that UCS values depend on porosity. The bulk density measurements do not correlate well with the ultrasonic pulse velocity measurements nor with UCS values.

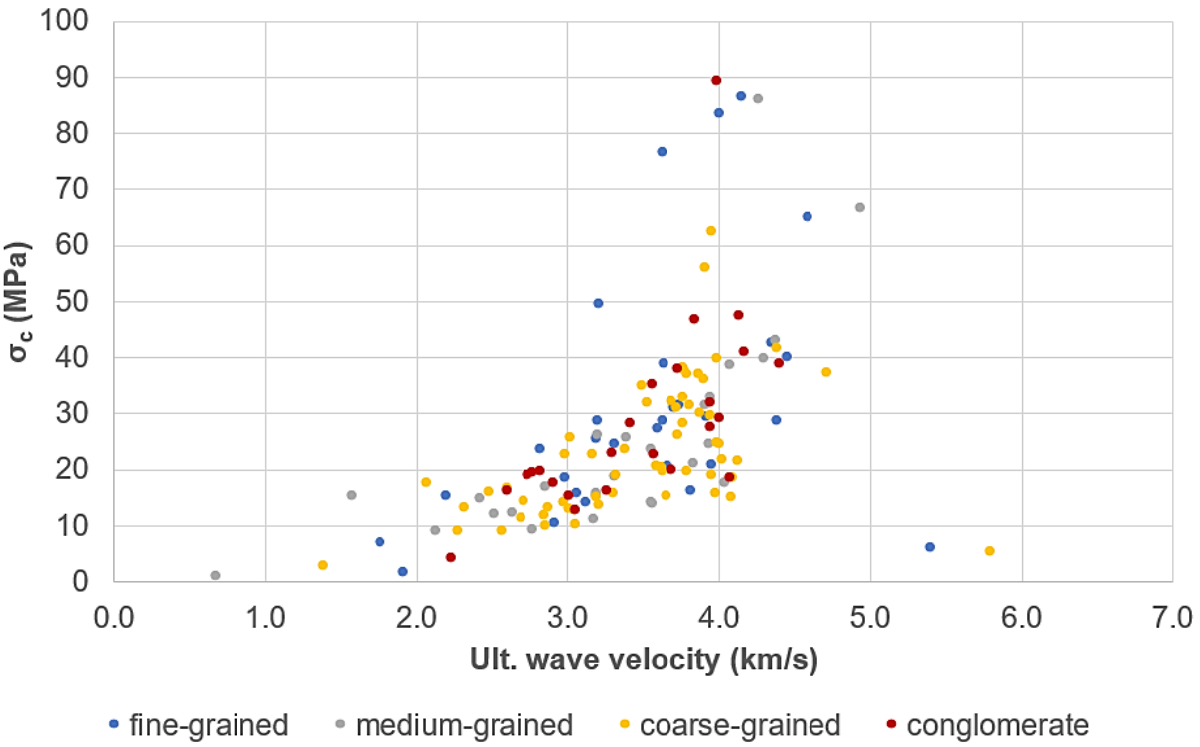


Fig. 5 The relationship between ultrasonic wave velocity and UCS (σ_c) parameters for sandstones of different grain sizes.

This theory is also supported by the data presented in a graphic form (Fig. 6). The geomechanical properties of the intact coarse-grained sandstone samples were also compared with those of nine coarse-grained sandstone samples collected from fractured zones. The left graphics of Fig. 6 show the UCS as a function of the ultrasonic wave velocity. It is not possible to distinguish between samples from intact and fractured parts; in both cases, the growth trend is clearly visible. The right side of Figure 6 illustrates the cohesion (c) and internal friction angle (φ) of intact and fractured coarse-grained sandstone specimens. A substantial reduction in cohesion is observed in the fractured samples relative to the intact specimens, indicating that the presence of fractures markedly decreases the cohesive component of shear strength. Conversely, the average internal friction angle values show only minor differences between the two groups.

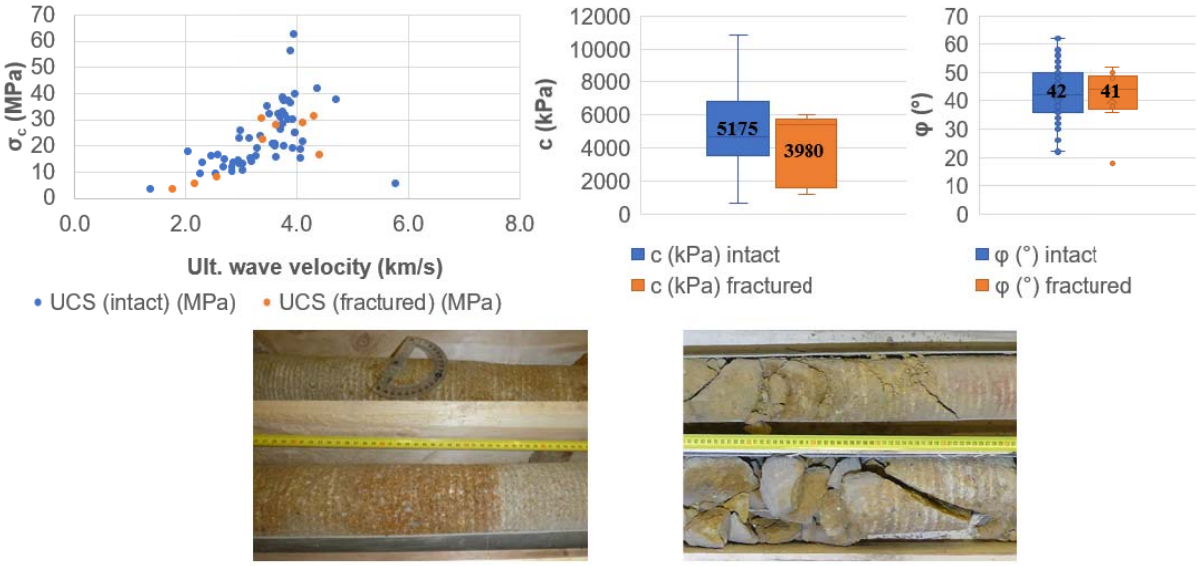


Fig. 6 The relationship between ultrasonic wave velocity -uniaxial compressive strength (σ_c) and friction angle (φ),cohesion (c) parameters for intact and fractured coarse-grained sandstones.

It has been suggested that quartz-cemented sandstones have higher strength and are more durable than carbonate-cemented ones (McBride 1989). However, other studies refer to the influence of grain size on the strength of sandstone, providing a strong hint that finer-grained sandstones are more durable (Wasantha et al. 2015). The role of mineralogy and cement types in sandstone behaviour was also characterised by Cook et al. (2015) and Sun et al. (2017). Our study implies that tectonic stress can

often override these primary depositional and diagenetic factors, and micro-cracking caused by intense tectonic activity can significantly reduce the cohesion of the studied sandstones.

5 Conclusion

In this study, four different types of lithologies, including sandstone with varying grain sizes and conglomerate, were investigated. Based on laboratory test results, only minor differences were observed in bulk density, ultrasonic wave velocity, and uniaxial compressive strength values of samples with different grain sizes. It is suggested that strength parameters are controlled not by grain size, but by strong siliceous cementation for the studied lithologies. This cementation appears as a pore-filling network in microscopic images.

Siliceous cementation significantly improves the strength parameters of the sandstone; nevertheless, the average uniaxial compressive strength values ranged between 20 and 30 MPa. This is likely due to secondary porosity developed in the sandstone. Samples of relatively less fractured sandstone core logs were compared with samples obtained from more fractured zones. When comparing the values of ultrasonic wave velocity and uniaxial compressive strength, the samples from the fractured zone fit well into the general trend, suggesting that at the sample level, the fracture system does not influence the strength significantly, but at the rock mass level, it has to be considered.

6 Acknowledgment

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