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Geotechnical Investigation and Risk Assessment at Budapest Metro Line 4

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ABSTRACT: The construction of the structure of Phase1 of Budapest Metro has been completed. The geotechnical investigations carried out on the basis of the Geotechnical Base Line Report (GBR) and Risk Assessment have considerably decreased geotechnical risks. The comparison of the amount of investigations carried out before the tender and in the construction phase reflects well the efforts to ensuring a safe and economical tunnel construction process. Budapest Metro was built in a "soft ground" geotechnical environment, where the ratio between the boring lengths and the tunnel lengths was equivalent with 1.2, a number accepted and applied in practice internationally. Conscientious preparatory work and site investigations in compliance with design needs have ensured that no considerable geotechnics-based events and claims have occurred during the construction phase.

1 Introduction

Unexpected subsurface conditions are the primary causes of disputes and litigations arising from contracts for underground construction. The risk of unknown sub-surface conditions is a primary concern of contractors. More importantly, effective pre-construction contract investigation of the geotechnical conditions is essential, not only to locate risks but also to reduce them with the help of monitoring and risk assessment meetings.

It is obvious that there is a close correlation between the level of geotechnical investigations and risk-assessment carried out, and the level of risks.

It is difficult to define, from the aspects of both the investor, designer and constructor, the amount of required geotechnical investigations. For further reading please see references: [1],[2],[3],[4] and [5].

The tunnel construction works of Budapest Metro Line 4 have been successfully completed without major geotechnical claims. See (Figure 1).

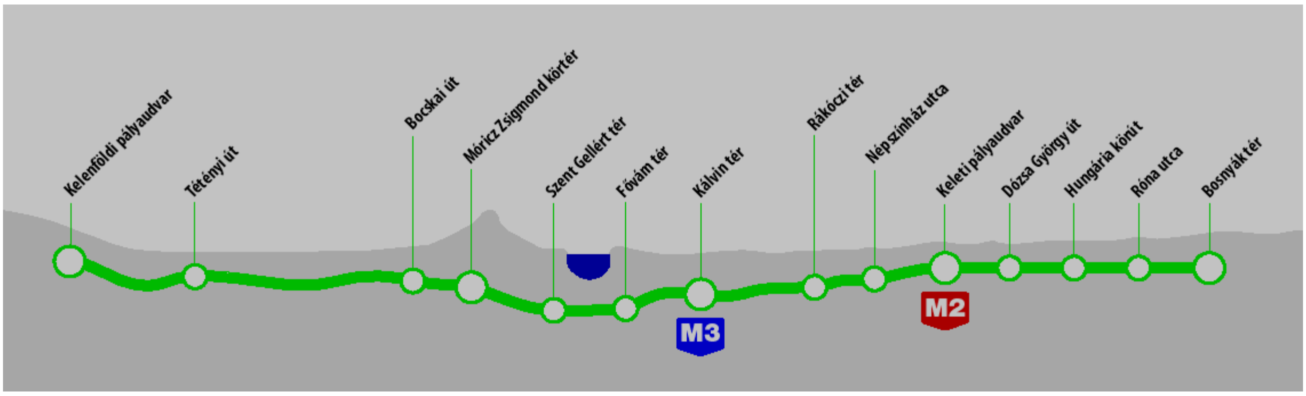

Figure 1. Main features of Budapest Metro 4, sections

A geotechnical risk analysis has been carried out due to the geotechnical investigation and was reported in the tender documentation.

The route proceeds at a relatively shallow depth, at a rail-top level of 16-22 metres below the surface on average, increasing to a depth of 32-34 metres under the Danube, passing beneath an almost entirely built-up area and through extremely varied geological strata.

In our paper we are going to demonstrate whether the data from the engineering-geological investigation carried out for the completed metro-construction works in Budapest were sufficient for ensuring a proper level of risk assessment and a safe tunnel construction process.

2 Engineering-geological profile along the line

The geological and engineering-geological profile of the neighbouring areas along the line has been described in numerous publications, therefore the typical conditions are specified only shortly. On the basis of the engineering-geological profile, the route of the metro line is broken up to three specific engineering-geological units in terms of tunnel construction, as follows:

Buda-side: marly clay, clay

Crossing beneath the riverbed of Danube: marly clay, clay

Pest-side: clay with bentonite, loose sand, clay

2.1 *Short engineering-geological description of Buda-side*

Beneath the surface there are 4-8m thick layers of plastic silt and fine-grain sand developed from the Pleistocene deposits of the Ancient-Danube (sand, gravelly sand), and from regolith, in which strata open-surface groundwaters are stored and flowing.

Beneath these young sediments, clay marl and marl from the Tertiary period (Oligocene) is found in a thickness of several hundred meters. The tunnels were built in this layer which can be described by uniform, less variegated parameters. (Figure 2) shows the typical engineering-geological longitudinal section.

Special and frequently occurring problems were caused by the highly detrital character of the Oligocene surface and its lithoclases of non-tectonic origin, due to which influxes of partly groundwater and partly of karstic water caused difficulties in the construction process and damages to buildings.

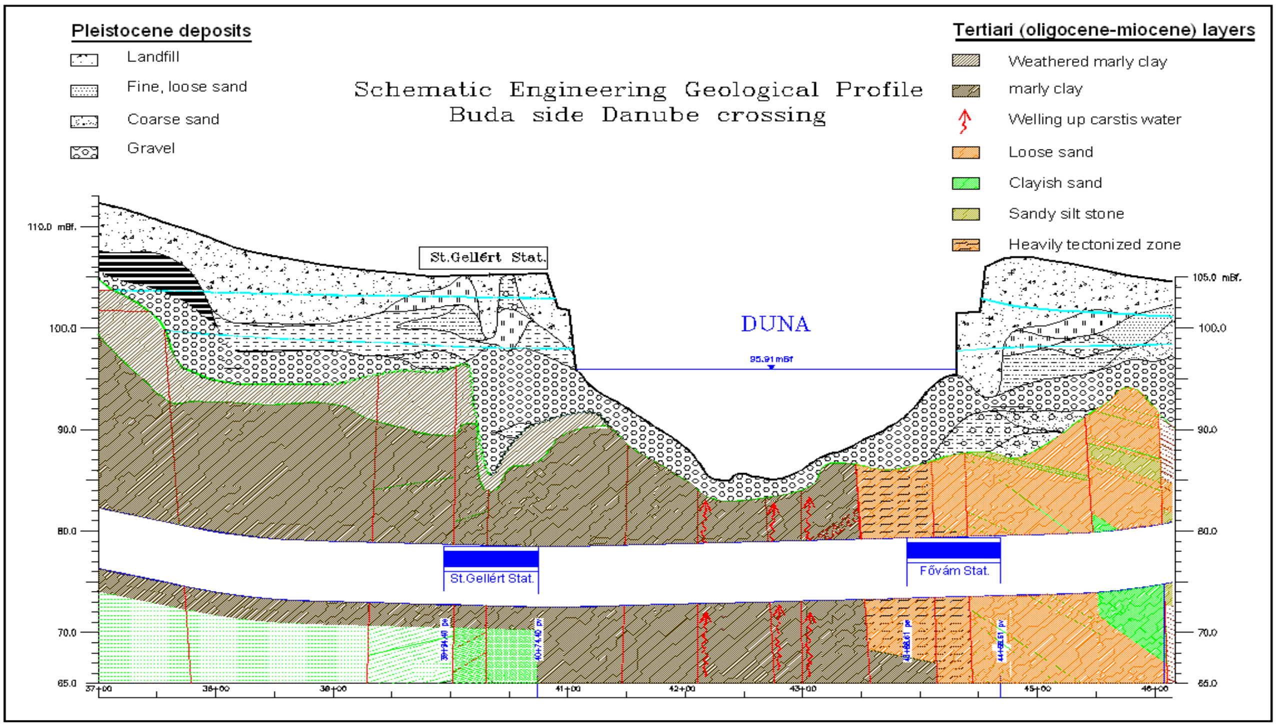

Figure 2. Schematic engineering-geological profile, Buda-side and Danube-crossing

2.2 *Short engineering geological description of the crossing section beneath the riverbed of Danube*

This is one of the most exciting sections of the completed metro line, in which the line tunnels were built under a very thin (1-2 m) clay cover. The protection of thermal springs, considered as national treasures, represented a special task for engineers and for environmentalists. Extensive geophysical investigations were carried out to ensure the protection of thermal springs. On the basis of these investigations, the spatial situation of the thermal water reservoir could be well delineated. During the construction works it was required to provide a full-scale protection for thermal springs and to ensure their intactness. We have shown the schematic engineering-geological profile above, in (Figure 2).

As usually, the two TBM drives were driven sequentially using the same team to avoid unnecessary risks during the crossing phase. The construction of both tunnels went generally well with the exception of a short stoppage of the TBM on the occasion of the first crossing, caused by a blocking of the face at 2/3 of the way across the Danube.

2.3 *Short engineering geological description of Pest-side*

The geological profile, the engineering-geological characteristics, and the geotechnical parameters of Pest-side displayed a high variousnes. Beneath the surface, there are 10-16 m thick, plastic silt and fine-grained sand layers made from Pleistocene deposits of Ancient Danube (sand, gravelly sand) and from regolith, in which open-surface groundwaters are stored and flowing.

Beneath the Pleistocene layers, Tertiary (Miocene) layers are settling, in which the tunnels have been built. These strata have variegated geological profiles and geotechnical parameters. The varied engineering-geological longitudinal section is presented in (Figure 3).

Significant tectonic zones that could have endangered the construction works had not been expectable, and actually have not occurred.

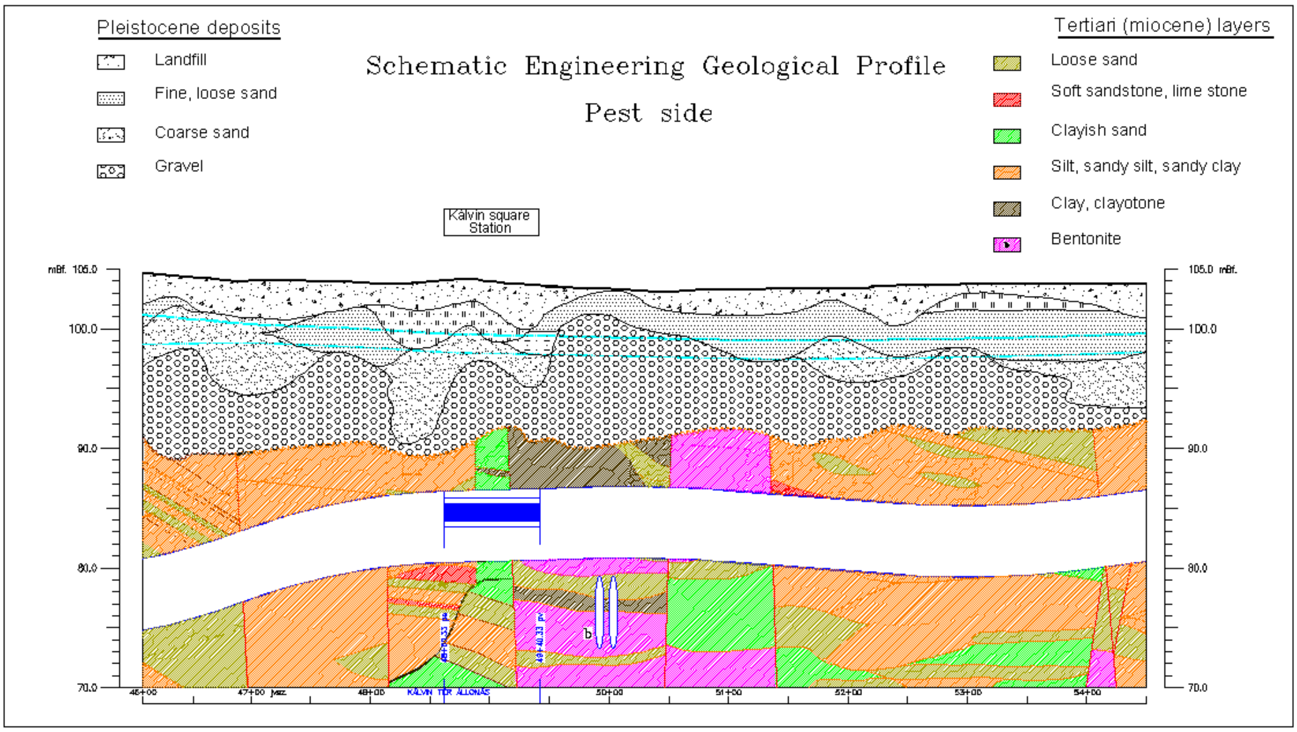

Figure 3. Variegated engineering-geological longitudinal section at Pest-side

3 Site investigations and risk level diminishing

The engineering-geological investigations took place after the preliminary investigations, in the period of 1999 to 2004. The data necessary for the Geotechnical Baseline Report (GBR) made in 2005, for the geotechnical risk assessment and for the invitation of tender were provided by the preliminary investigations. The underground works were awarded in accordance with the FIDIC Plant and Design- Built form of contract. The tender allowed the undertaking of additional investigations to clarify the risks where considered appropriate.

The scope of the engineering-geological investigations pertaining to the various sections for the pre-tender phase and for the construction works phase is shown by Figure 4. After the completion of additional borings, investigations and monitoring systems, the risk severity and the risk index could be reduced significantly. Only those boring investigations are included in this figure, where a modern, 3-wall, Wire Line system was used. It can be established from the figures that a considerable number of exploratory borings and investigations were carried out at Buda-side and Pest-side prior to the drawing up of GBR, and these were relatively few for the section under the Danube.

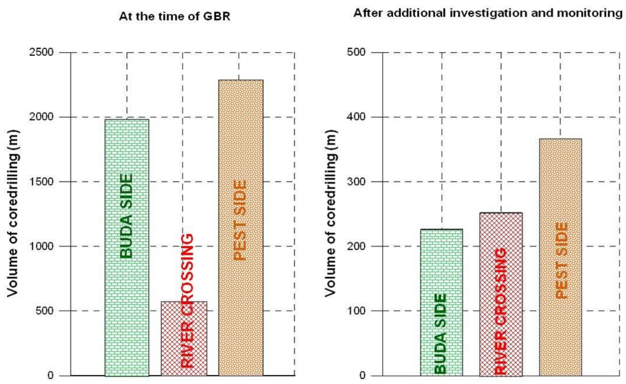

Figure 4. Volume of site investigations (SI)

The applied methodology of risk assessment is shown by Figure 5, schematically. After the completion of additional borings, investigations and monitoring systems, the risk severity and the risk index could be reduced significantly.

Risk Severity/ Likelihood	1 - Catastrophic	2 - High	3 - Significant	4 - Low
1 - Frequent	1	2	3	4
2 - Likely	2	4	6	8
3 - Occasional	3	6	9	12
4 - Unlikely	4	8	12	16
5 - Improbable	5	10	15	20

Figure 5. Applied Risk Assessment Classification Matrix

Table 1. Risk Index, Classification and Marking

Risk Index (R)	Risk classification	Marking
1 - 4	Very high	V (Very high)
5 - 9	High	H (High)
10 - 14	Medium	M (Medium)
15 - 29	Low	L (Low)

After determining likelihood and severity of the risk we determined the risk index by means of the assessment matrix.

Risk index = Likelihood of occurrence x Severity of risk

RI = L x S

The risk index has been calculated for the „starting/initial" Cases and the cases yet remaining despite the efforts made to alleviate of the risk involved.

The pre-construction geotechnical risk assessment, based on GBR, indicated the prospective risks and the level of required monitoring with sufficient thoroughness. The volume of additional investigation that had to be carried out during the fulfillment of the Design – Built form of contract served rather the purpose of security and basically did not reveal new and essential engineering-geological information and risks.

Also as a result of exploratory borings, a significant decrease of the risk index took place at Buda-side. (Figure. 6).

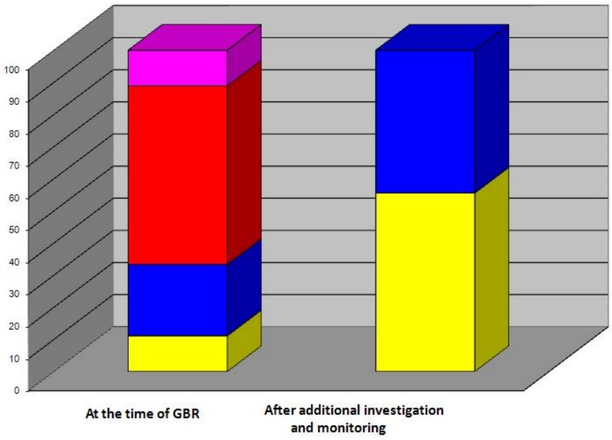

Figure 6. Buda side, Decreasing of Risk Classification due to site investigations *(SI)*

No significant delays and extra costs due to geotechnical reasons/conditions occurred at Buda-side, in spite of the fact that the medium-level residual risk was high. It can be traced back partly to the TBM tunnel construction method, and partly to the low variation index of the geological/geotechnical conditions, as well as to the proper amount of site investigations.

In the Danube-crossing section – which represents an environment characterized by high geological risks and major geological/hydrogeological variations – the length of exploratory borings was 750 running metres. In this section extensive hydrogeological investigations were carried out, which provided further, more accurate data on the geotechnical and hydrogeological condition of this section, and reduced the risk index presented by (Figure 7).

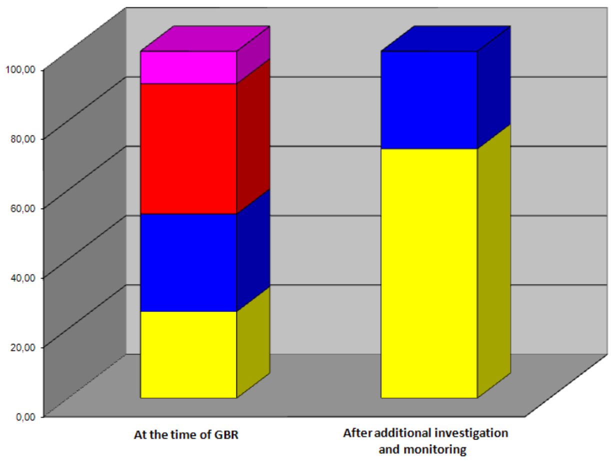

Figure 7. Danube river crossing, Decreasing of Risk Classification according to site investigation

It clearly shows that the geotechnical risks have largely decreased after the investigations.

Once, during the tunnel construction works under the Danube, an about two-week long stoppage of the TBM occurred. The stoppage did not jeopardize either the tunnel construction works or the thermal-water reservoir, which is considered as a national treasure. With a situation of a thin covering layer of clay, the tunnels have been built successfully.

In Pest side, the tunnels were built under highly variegated geological and geotechnical conditions. Figure 4 shows that the volume of additional site investigation was the highest in the section of the highly variated Pest side. A TBM-process being in compliance with the geotechnical conditions, as well as the additional investigations decreased significantly the very high risk levels (Figure 8.).

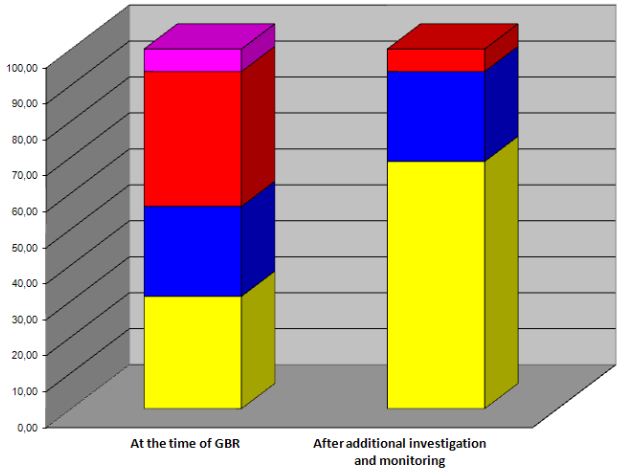

Figure 8. Pest side, Decreasing of Risk Classification due to the site investigations (SI)

No significant delays or extra costs due to geotechnical reasons occurred during the tunnel construction work. The built-up environment was in security during the tunnel construction works.

In the case of tunnels built in shallow and soft ground, in an urban environment, one of the indices characteristic of the costs/volume of site investigation is the ratio between the boring lengths and the tunnel lengths. According to recommendations, this ratio should be between 1.2 and 2.0. Using this simple ratio as the basis for investigations seems to be a bravery for the first thought, but there were numerous examples to support the applicability of this ratio as an initial and minimum condition for a safe and cost-effective tunnel construction.

(Figure 9). shows the ratio between the core-drilling and boring lengths and the tunnel lengths in the case of the Budapest metro-construction. It shows that the ratio 1.2 was used in the case of the SCL tunnel construction method, and 2.0 in the TBM tunnel construction method for the metro in Budapest.

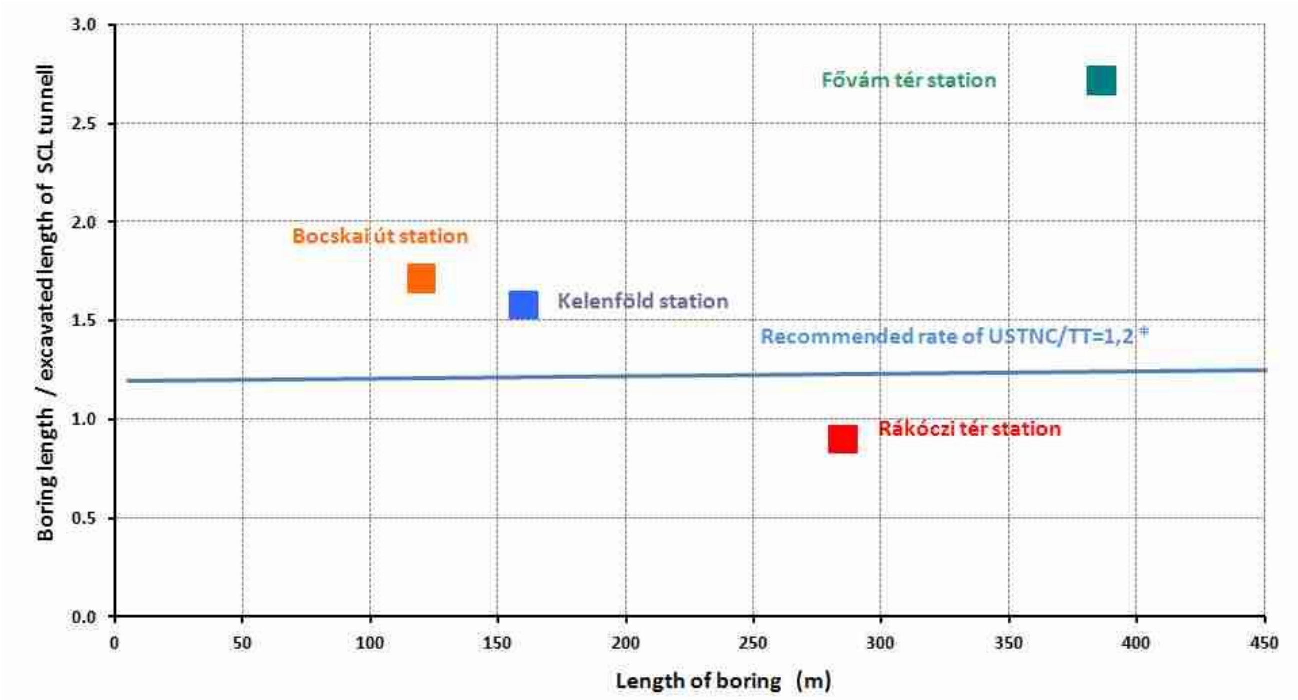

Figure 9. Length of boring versus length of tunnel

Using an appropriate volume of exploratory borings was one of the key factors in ensuring the successful and safe construction of Section 1 of Budapest Metro Line 4, like in any other tunnel construction project.

For the cynics who believe in the laws of diminishing return for the site investigation of underground projects there is a new fact and example that attempts to quantify the benefits. Similarly for those whose yard stick is that site investigations rate should be reduced – trusting in the technology- please read it again.

REFERENCES

1. KNIGHTS M. (1986), " *Site investigation examined as a basis of cost-effective tunnelling"* , Tunnels & Tunnelling, September, pp.30-31
2. PARKER H.W. (2004)," *Planning and Site Investigation in Tunnelling*", 1º Congresso Brasilero de Túneis e Estruturas Subterráneas, Seminárió Internacional South American Tunnelling
3. ESKENSEN S. D., TENBORG P.,KAMPMANN J.,Veicherts T.H. (2004)" *Guidelines for tunnelling risk management"*, International Tunnelling Association, Working Group No.2, Elsevier 2004, pp.217-237
4. Horvath T., (2006) " *Geotechnical Risk Analysis at Budapest Metro 4, I. section",* Professional Days on Tunnelling and Civil Engineering 2006,Proceedings
5. ZHOU Y.,CAI J. (2007), " *Managing Geological Risks in a Rock Cavern Project without GBR"* Underground Singapur 2007&Workshop on Geotechnical Baseline Reporting, 29-30 November 2007