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PROMOTION OF TUNNELING PERFORMANCE IN LOCALLY SEMI-HARD TO HARD CONGLOMERATE LENSES, CASE OF ESFAHAN HISTORICAL CITY SUBWAY PROJECT

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ABSTRACT

The highly inhomogeneous nature of the river deposits in central Esfahan induced unforeseen problems for tunneling of 2×5 km long of middle section of the Esfahan Subway Project. A noticeable phenomenon in these course grained fluvial (river) deposits is the locally cementation of the soil particles by a calcium carbonate binder and formation of some semi-hard to hard conglomerate lenses. This unique phenomenon is named locally as “Sovord” rock and could be seen just in semi-aired regions as central Iran. Two 6.89 m diameter EPBTBM machines were employed to excavate shallow tunnels in the vicinity of fragile structures of the old city. The main unwanted impacts of this highly cohesive pseudo-rock were noticed as high vibration, temperature raising, tunnel face instability, low rate of machine’s advance, early tools damage and finally great cutter-head damage after the first major collision with this unpredicted phenomenon. We analyzed geotechnical characteristics of this material and the corresponding effects on face supporting pressure, foaming agents, soil conditioning process and operational policy. Lowering the cylinder thrust force, ≤9000KN, improving the cutting wheel rotation speed, ≥2.5RPM, using some anti-abrasive foaming agents, ABR2 lubricants, and periodic tools inspection schedule was considered as solution for the indicated problem.

INTRODUCTION

Esfahan is one of the most popular historical cities in central Iran with high degree of tourist attraction and too many famous monuments including; Naghshe-Jahan Square, Chahar-bagh Boulevard and Chahar-Bagh School, Si-O-Se-Pol Bridge upon the Zayandeh-Rud River (Fig. 1). In the Esfahan city, the growth of car population and the high average age of these cars have led to ever increasing pollution and congestion. In order to alleviate the worsening traffic conditions, the Esfahan Regional Metro Company (ERMC) was founded in 1991. This company was taken with the task of investigating a suitable mass transit system in Esfahan City and the region. This company was taken over then by the Esfahan Urban Railway Organization (EURO) in 2000 and the constructional works of the project were started in 2001.
As the construction and operation of the Esfahan subway has been feared to interact with fragile structure of the old city, sufficient cares were taken in design and execution of the tunnels and stations, in order to minimize the project impact on the adjacent buildings and structures (Taheri and Haghi, 2011).
From the feasibility studies, Light Rail Transit (LRT) system were suggested for carrying passengers through selected alignments which are in sympathy with the high heritage quality of the city and its regions.
The intercity network of this project consists of 2 perpendicular lines; north to south line (Line1) and east to west line (Line2). The priority line for the City recommended as a result of the feasibility studies is the north-south line from Kaveh intercity bus terminal to the Soffeh intercity bus terminal. North to South Line has been separated into five sections and the most sensitive section, middle section, generally follows the alignment of the wide Boulevard of Chahar-Bagh. Middle section (section 3), starts at Keveh Avenue on the opposite of Baboldasht bus terminal and ends in Shariaty station (Fig. 1). To fulfill a construction method with least possible impact on the surface structures in middle section, two EPBTBM machines were ordered in 2001.
The subsurface stratigraphy of the middle section mainly consists of some river deposits with coarse-grained Fluvial and/or fine grained Flood-Plain sediments. These deposits are very permeable and water bearing.

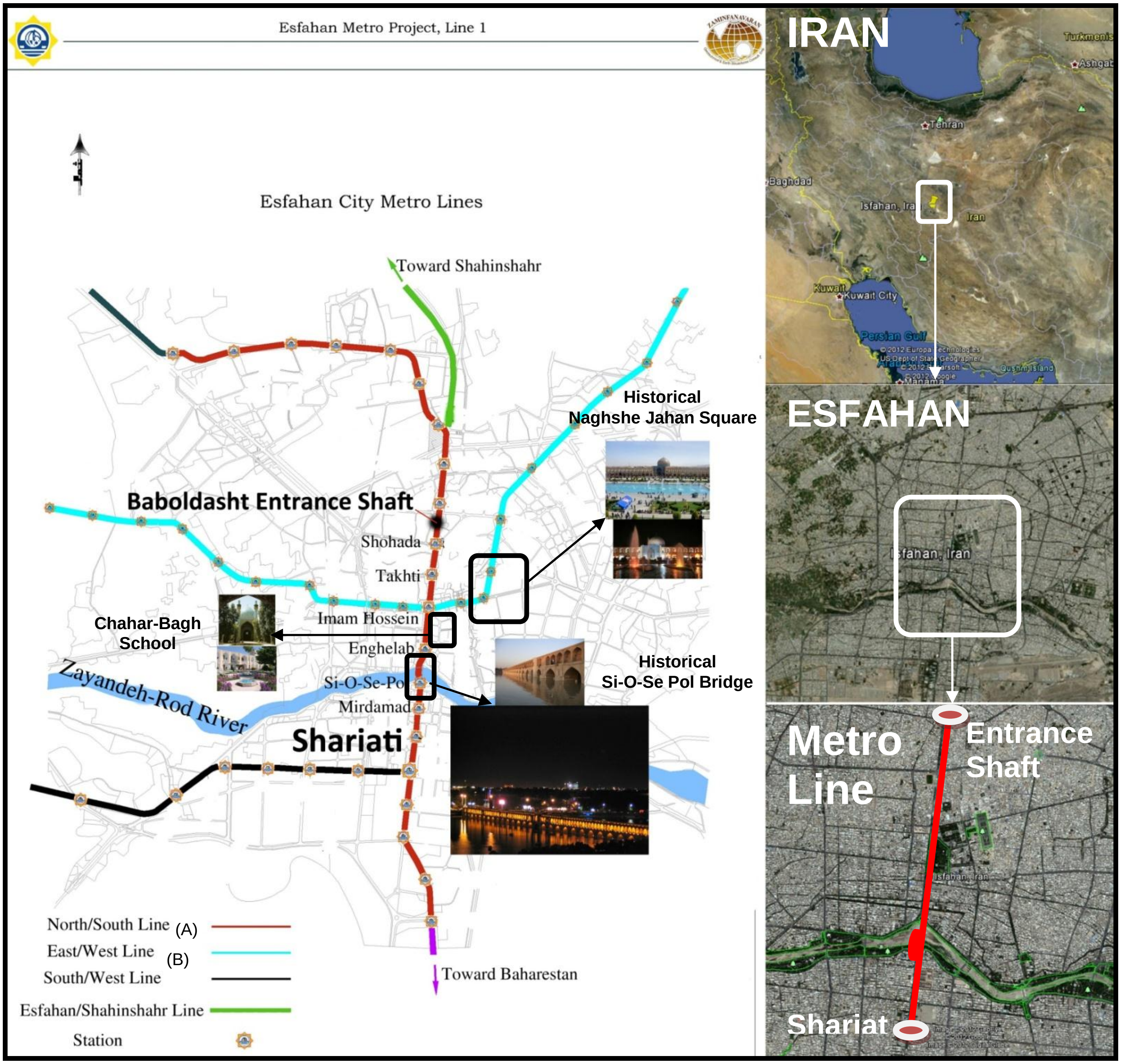

Fig.1 Intercity network of Esfahn subway project

Among the Fluvial deposits, some lenses of uniform sand, fine grained deposits and hard conglomerate have been observed. According to the geotechnical characterization of the river deposits, two EPB shields tunneling machine with the outside diameter equal to 6.89 m were ordered in order to construct approx. 2×5.5 Km tunnels with diameter equal to 6 m under the water table (Fig. 2, Taheri and haghi, 2010). The cutter head tools design of the EPB machines selected mainly from scraper knife tools with carbide bits (Fig. 3). Normally, these types of tools are inconsistent for digging and crashing unpredicted hard rocky materials and are suitable just for soils. In general, the effect of hard abrasive materials at the tunnel face could obviously noticed through EPBTBM tunneling parameters including; advance time, cylinder thrust force, foam injection ratio, cutting wheel rotation speed, temperatures, etc. Moreover, during the operational phase when TBM components are exposed to the unpredicted hard material, the contractor should prepare an agreed plan for scheduled inspections and maintenance. However, presence of high water flow rate under the river and historical structure in adjacent for Esfahan subway project, make cutter head interventions more complicated and time consuming. Furthermore, if primary wear remains undetected and the carbide inserts on knife bits or the disk cutter ring steel and hub body of these tools fitted to the face of the cutter head become excessively worn, subsequently secondary wear on the cutter head structure itself can develop rapidly.

Fig. 2. EPBTBM employed for Esfahan subway project

Fig. 3. Cutting Knife bits with carbide inserts

GEOLOGICAL SUMMERY OF ESFAHAN

The subsurface stratigraphy of the project area which has been presented by the geotechnical longitudinal section of the proposed metro line is as follows (Fig. 4, Haghi et al, 2012).

✓ Bedrock

The lower Jurassic (Lias) deposits, comprising shale and sandstone alternation, are formed the bedrock of the project area. This formation, which is named Shemshak series in Iran, is exposed at southern parts of the City and is overlain by Quaternary aged Alluvial Fan and Zayande-Rud River deposits at most parts of the City area. The bedrock depth increases towards the north of the city and goes much deeper than the proposed metro tunneling depth.

✓ Alluvial fan deposits

These deposits which overlie the bedrock at the southern parts of the City consist mainly of very silty/clayey, sandy gravel, with sub-angular particles. These deposits are mostly heterogeneous and slightly cemented in place. Among the Alluvial Fan Deposits, there are some stiff to hard fine-grained soil lenses with different percentages of sand and gravel.

✓ River deposits

The river deposits consist of coarse-grained Fluvial and/or fine grained Flood-Plain sediments, which overlie the Alluvial Fan Deposits at southern part of the river.

a) Coarse Grained Fluvial Deposits

These deposits comprise dominantly of clean, well graded or poorly graded (gap graded) sandy gravel and/or gravelly sand layers, where, the soil grains are mostly rounded with maximum size of 60 mm. These deposits are very permeable and water bearing. Among the Fluvial deposits, there are some lenses of uniform sand and fine grained deposits. A noticeable phenomenon in these deposits is the locally cementation of the soil particles by a calcium carbonate binder and formation of some semi-hard to hard conglomerate lenses.

b) Fine Grained Flood Plain Deposits

The Flood-Plain deposits comprise of silt and clay with some sand particles (up to 20%). These deposits are mostly homogeneous and firm in place. Among the fine-grained Flood-Plain sediments there are some lenses of coarse grained Fluvial Deposits.

✓ Fills

The natural deposits are covered by fills with variable thicknesses in the City area. These materials are comprised mostly of the local soils with different percentages of building wastes.

There are two shallow aquifers in the City area that impacts the underground works of the proposed project. The most important aquifer in the area is and aquifer exists in the coarse-grained river deposits. This is mostly an unconfined aquifer, whose base is defined by the lower fine-grained soils of the Flood-Plain deposits. In some parts of the City this aquifer is confined between the upper and lower fine grained deposits, i.e. the aquifer are running with an artesian head. The thickness of this aquifer lies in the range of 9.3 to 26.5 m., along the proposed N-S line.

The second shallow aquifer in the project area is an unconfined aquifer intersecting the Alluvial Fan deposits at southern parts of the City. The base of this aquifer is the lower Jurassic bedrock (alternation of the shale and sandstone) which its upper levels contribute to this aquifer, due to relatively high permeability associated with open fractures and surface weathering. According to well pumping test results carried out along the proposed metro line, the horizontal coefficient of permeability (k) of the coarse grained water bearing river deposits lies in the range of 1.2*10-3 to 2*10-3 m/s. Therefore, by taking the average value of the coefficient of permeability of these deposits as 1.6*10-3 m/s and the predominant thickness (t) of the aquifer around 20 m, the aquifer transmissivity is found about 3.2*10-2 m^2/s.

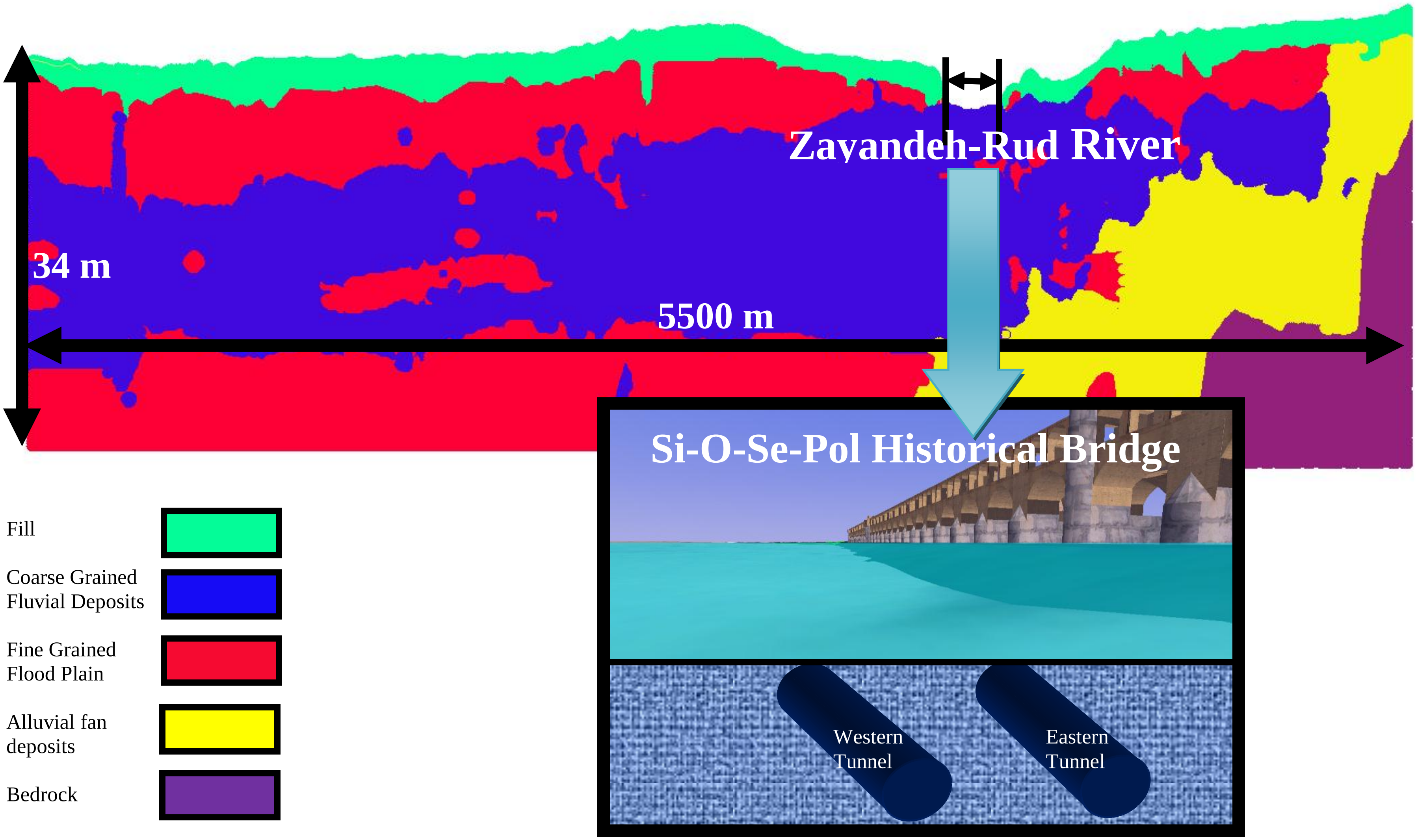

Fig. 4. Geological profile of Esfahan subway project, middle section and the location of tunnels under the Zayande-Rud River at the adjacent of well-known historical Si-O-Se-Pol Bridge

ENGINEERING FAILURE DEALING WITH “SOVORD ROCK”

Throughout arid and semi-arid regions, deposition of secondary calcium carbonates is a widespread phenomenon that is generally named Caliche. Although all such deposits are chemically similar (dominantly calcite) the physical properties, distribution, and degree of development vary due to different modes of formation. In general, the engineering properties of caliche depend on the type and also on the age of caliche that affects degree of development. Commonly, caliche is deposited as part of soil-forming process in arid and semi-arid regions (Gile et al. 1966). Such pedogenetic caliche is formed bellow the topographic surface. It begins as surface coatings on pebbles and cobbles and as stringers and nodules within the unconsolidated sediments. With time, the calcium carbonate fills the pore spaces within the sediment and becomes a continuous layer.

A noticeable phenomenon in the river deposits (fluvial) of central Esfahan is the locally cementation of the soil particles by calcium carbonate binder and formation of some semi-hard to hard conglomerate lenses. This unique rocky material which named locally as “Sovord Rock” classified as pedogenetic caliche for semi-arid region of central Iran (Fig. 5).

The possible origin is from evaporation of subsurface water trapped in broad, shallow topographic pores (lattman, 1973). In some locations with further calcium carbonate deposition, the Sovord horizons become very hard and not slake in water. These horizons vary in thickness from a few centimeters to several meters. Very thick horizons may be of accretional origins (Brown, 1956) which are the result of a slow increase of land along the Zayandeh-rood River. However, the thickness, degree of development and occurrence of this semi-rock material in Esfahan is a function of several parameters and do not follow any simple rule. Hence, it was difficult to predict them across the tunnel lines of Esfahan subway project.

Near the Si-o-Se-Pol historical bridge at the central Esfahan, the first tunnel drives to pass the river at 40 m upstream of the bridge, in order to eliminate any probable disturbance of the tunneling on the bridge structure. As the first major collision with this highly cohesive and unpredicted material, machine encountered with high vibration, temperature raising, tunnel face instability, low rate of advance and plugging. Based on the highly susceptible location under the river and close to the historical bridge, tools inspection under hyperbaric condition was not suggested and machine keeps moving for 400 m. This caused a highly damage of the machine cutter-head (Fig. 6).

Fig. 5. Sovord Rock

Fig. 6. Cutter Head damage, Esfahan Subway Project, Eastern Tunnel

Excavatability is a general term used in underground construction to describe the influence of a number of parameters on excavation performance and the tool wear (Thuro and Plinninger, 2003). For EPBTBM tunneling, the interactions of the main factors involved in tool wear are summarized in Fig. 7.

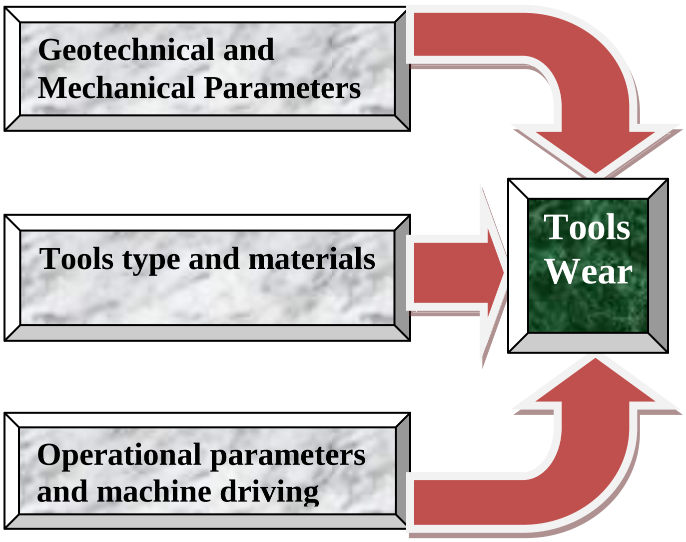

Fig. 7. Overveiwe of three main parameters influencing tools damage in EPBTBM

In the first interaction, the tools wear and cutterhead damage is influenced by the geotechnical and mechanical parameters. Although there are about 200 hardness test for rock characterization (Atkinson, 1993; West, 1989; Brook, 1993; Nelson, 1993), much of them have been introduced for a special purpose and have not been developed further. Only few have gained international attention such as the Cerchar Abrasivity Index CAI (Plinninger, et al., 2003). The Cerchar Abrasivity Test has been introduced in the 70s by the Centre d'Etudes et Recherches des Charbonages (CERCHAR) de France for abrasivity testing in coal bearing rocks (Käsling and Thuro, 2010). The Cerchar-Abrasivity-Index is used as a key parameter in prediction models for TBM tunneling (Gehring, 2005, Rostami, 2005). Modifications of the test setup (Al-Ameen & Waller 1993, West 1989), who are partly not in familiar with the French standard headed to a multitude of testing variations and highly differing testing results all over the world. To analyze the abrasivity of the Sovord under the river, we conduct an analysis to find the Cerchar Abrasivity Index. The result (Fig.8) shows that the samples from the river portion are mainly classified as very to extremely abrasive material (CAI>2). Additionally, we find the uniaxial compressive strength (UCS) of samples between 47 to 57 MPa. Base on ISRM standard this UCS corresponds to medium strong to strong rock.

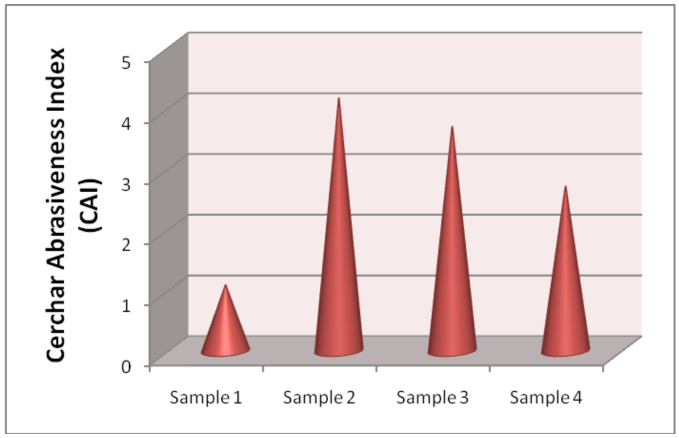

Fig. 8. Cerchar Abrasiveness Index for Sovord samples

It is clear that the abrasivity of a rock type is a result of the amount of abrasive minerals with respect to the tool material. Quartz represents the most common abrasive mineral. Accordingly, the percentage of the SiO2 within the rock mass is a common representation of the rock abrasivity. From chemical analysis of the Sovord samples below the Zayandeh-rood River, the percentage of SiO2 ranges from 48.78 to 51.9 %. In addition to mineral composition, textural features however also impudence on tools wear, such as: grain size distribution (Thuro et al. 2006). Pie diagram illustrated in Fig. 9 represents the grain size distribution for the portion of the reviver.

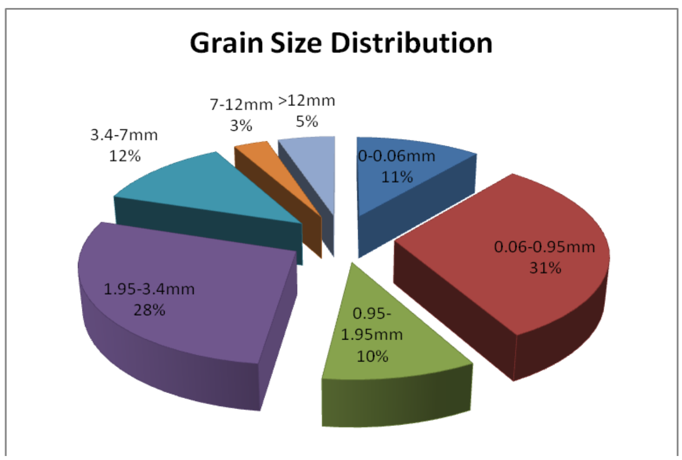

Fig. 9. Grain size distribution pie diagram for the soil materials under the river

In addition to unified abrasion classification for the Cerchar Abrasivity Index, the LCPC Abrasivity Coefficient (LAC) could be used to approximate the abrasivity of Sovord of the central Esfahan. Recently, the LCPC abrasivity test becomes more and more common for rock and soil testing. The common rock samples, the LCPC Abrasivity-Coefficient varies between 0 and 2000 g/t. However, there is a close linear varies between 0 and 2000 g/t. However, there is a close linear correlation between the LAC and the CAI for the tested rock samples (Thuro & Käsling 2009). Base on the data from chemical analysis and grain size distribution diagrams, the LAC represents the wear potential of the river deposites as illustrated in Fig. 10.

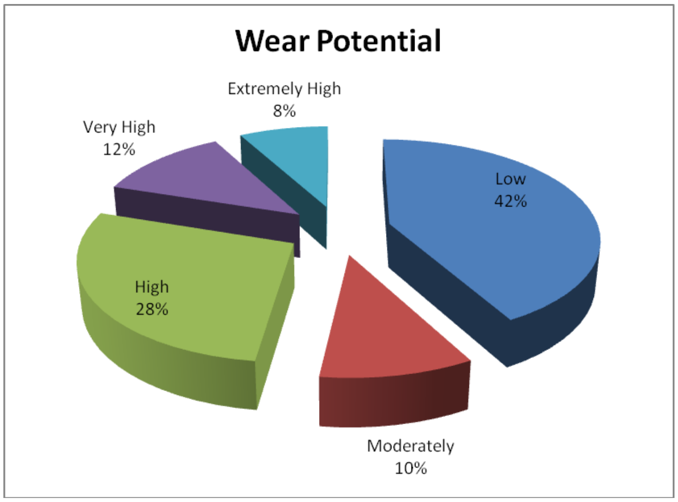

Fig. 10. Wear potential from LAC method for the river section

The result of LCPC Abrasivity-Coefficient, LAC, confirms the presence of 20% of very high to extremely high abrasive material within the fluvial deposits under the river, which is in agreement with Cerchar Abrasivity Index.

In the second interaction, the tools wear and cutterhead damage is influenced by the tools type and material. Normally, hard facing cutter discs have the most efficient advantage while facing hard abrasive materials. As the tunnels of the middle section of Esfahan Subway project mainly interact with fluvial deposits, just 5 cutter discs have been designed by the machine manufacture. It means that the accidentally presence of locally abrasive Sovord material has been ignored. This failure intensified at the portion of the river while the machines must worked continuously for 400 m without any tools inspection. Facing the first major mass of highly abrasive Sovord under the river, the knife bits gets inefficient and wear very soon. Both geotechnical and tools type parameters was unchangeable and out of control at the middle time of the job. The question was "What should be done for the rest of the project?" According to Fig. 7 in the third interaction, the tools wear and cutterhead damage has been influenced by the operational parameters and machine driving. To investigate the effects of the highly abrasive Sovord material under the river, sensitive operational parameters with abrasivity such as cutterhead rotation speed (Fig. 11), cylinder thrust forces (Fig. 12) and foam injection ratio (Fig. 13) were analyzed. As it is illustrated, at middle section of the river cutting wheel rotation speed decreased while the thrust force increased dramatically. These fluctuations represent the presence of a hard material with high coheision in front of the machine.

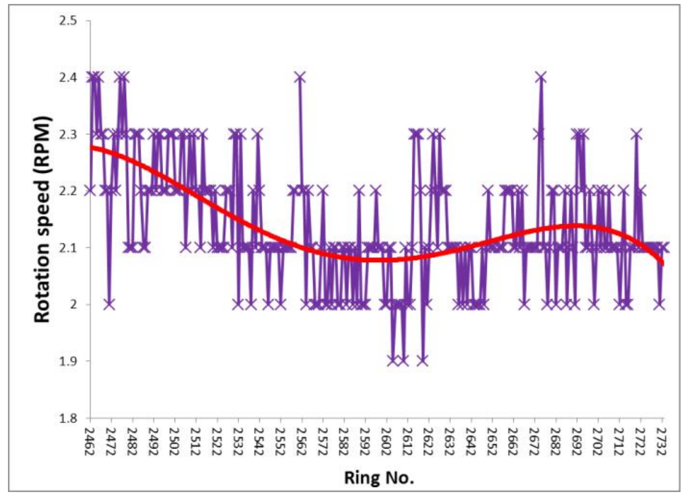

Fig. 11. Rotation speed ver. ring number for the river section

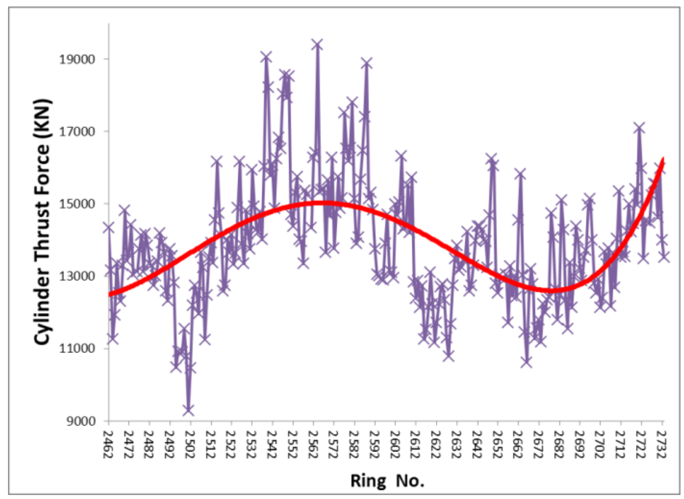

Fig. 12. Thrust forcees ver. ring number for the river section

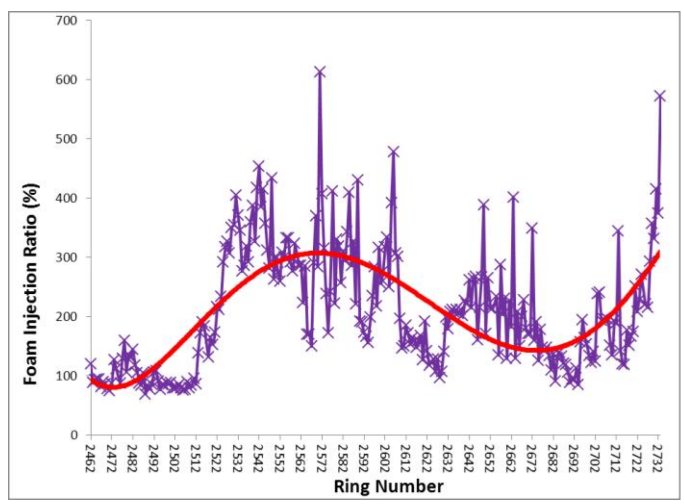

Fig. 13. FIR ver. ring number for the river section

The reaction of the machine operator could be investigates by increasing the foam injection ratio (Fig. 13) to facilitate the machine advancement and increase the advance rate. It is well known that the decrease in friction between the machine tools and hard abrasive materials at the tunnel face, the thrust force will be decreased and rotation speed increased. On the other hand, despite the higher thrust force and consequently the lower rotation speed helped in enhancement of the machine advance rate while facing with Sovord it caused a high rate of tools wear by increasing the friction. Our site investigations show that lowering the cylinder thrust force below 9000KN and improving the cutting wheel rotation speed more 2.5RPM yield the maximum duration for tools wear and the tools inspection base on machine qualifications. Furthermore, injecting anti abrasive ABR2 lubricant (produced by BASF Ltd.) with the FIR equal to 60-90 % increased the tools wear period up to 200%. Some alternatives like injection of pressurized bentonite slurry into the chamber as lubricant was not accepted due to difficulties in bentonite recovery, muck conditioning and time/cost management.

Generally, lowering the face support pressure of EPBTBM ameliorates the tunneling performance with respect to advance time while intensified the tunnel face instability facing with mixed tunnel face problem. Accordingly a sensibility analysis is conducted for Sovord thickness at the tunnel face using finite element numerical methods. As it is illustrated in Fig. 14 for a section of the river, the earth pressure does not change significantly for 3 m Sovord thickness at the mix face condition. It means that lowering the face supporting pressure to facilitate the machine advance could not admitted for the Esfahan Subway Project as the thickness of the Sovord does not exceed 2-3 m at the tunnel face.

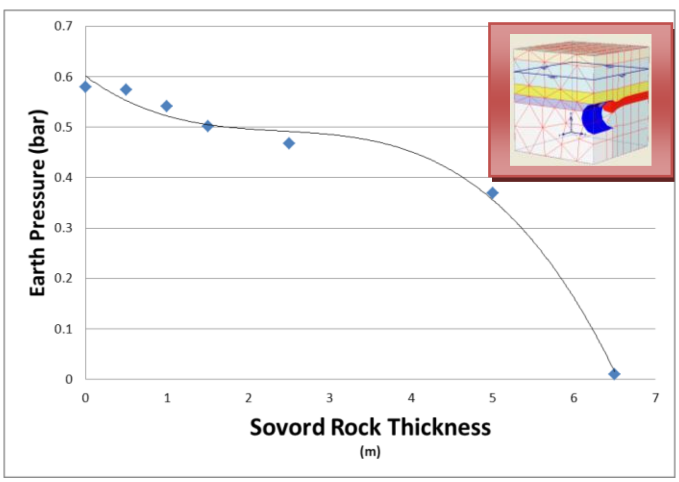

Fig. 14. Sensibility analysis of face support pressure with Sovord thickness

The presented strategies helped us to promote the tunneling performance for more than 3 Km of Esfahan Subway tunnels after the river into difficult geological condition of Sovord rocks alternating with fluvial deposits under the water table and both machines succeed in their competition with accidentally presence of highly abrasive SOVORD rocks (Fig. 15).

Fig. 15. Breakthrough of the machine of Esfahan Subway Project

CONCLUSIONS

After all the experimental results, it is clear, that neither laboratory, geology and field testing alone, nor equipment design and operation expertise can lead to the point where tools wear is anything like a clearly defined formula. Firstly, with the discovered mechanical and geotechnical properties, it should be possible to predict tool wear for the examined rock type in a satisfactory manner. However, beside geotechnical properties and tool design, the main problem is the confident operational process and machine driving for EPBTBM by controlling the executive parameters into the designed limits. Herein, an analysis is conducted to define the reason of the major cutting wheel damage of the Esfahan Subway Project under the Zayandeh-rood River. The problem finds to be related to a pedogenetic caliche for semi-arid region, which locally named SOVORD. Samples of Sovord rock from the river portion was mainly classified as

Very abrasive to extremely abrasive material (CAI>2) based on Cerchar Abrasivity Index.

Medium strong to strong rock (UCS between 47 to 57 MPa) based on ISRM standard

Very high to extremely high abrasive material based on LCPC Abrasivity Coefficient

The following items have suggested while interacting with Sovord rock as machine driving instructions;

- lowering the cylinder thrust force below 9000KN
- improving the cutting wheel rotation speed above 2.5RPM
- injecting anti abrasive ABR2 lubricant with the FIR equal to 60-90 %

Besides, lowering the face supporting pressure and bentonite slurry injection was not admitted due to the limited thickness of Sovord and machine specifications, respectively.

REFERENCES

Al-Ameen & Waller [1993]. “The influence of rock strength and abrasive mineral content on the Cerchar Abrasive Index”. J. *Eng. Geology* 36: pp 293-301.

Atkinson, H., [1993]. “Hardness tests for rock characterization” In: Hudson, J. (ed), Comprehensive rock engineering. Principles, practice & projects. Vol. 3, Pergamon, Oxford, pp. 105-117.

Brook, N., [1993]. “The measurement and estimation of basic rock strength”. In: Hudson, J. (ed), Comprehensive rock engineering. Principles, practice & projects. Vol. 3, Pergamon, Oxford, pp. 41-48

Brown, C.N., [1956]. “The origin of caliche on the north-east Liano Estacado, Texas” J. of Geology, V. 64, pp. 1-15

Finkl, C.W. (ed.)(1984), “the Encyclopedia of applied geology”, Van Nostrand Reinhold Co. Inc.

Gehring, K.-H. [2005]. “Leistungs und Verschleißprognosen im maschinellen Tunnelbau”. *Felsbau* 16 (6):pp 439-448.

Gile, L.H., Peterson, F.F., Grossman, R.B., [1966]. “Morphological and genetic sequences of carbonate accumulation in desert soilds”, J. Soil Science, 100; pp. 347-360

Haghi, A.H., Taheri, A., Mohkam, M., [2012] "Evaluation of the Heading Confinement Pressure Effect on ground settlement For EPBTBM Using 3D Numerical Analysis" , J. of Tunneling and Underground spaces tech., , (In Press)

Käsling, H., Thuro, K., [2010]. “Determining abrasivity of rock and soil in the laboratory”, geological Active, Proceeding of the 11th IAGE Congress, ISBN 978-0-415-60034-7

Lattman, L.H., [1973]. “Calcium carbonate cementation of alluvial fans in southern Nevada”, geological society of America bulletin, v. 84, p.3013-3028

Nelson, P.P., [1993]. “TBM performance analysis with reference to rock engineering”, In: Hudson, J. (ed), Comprehensive rock engineering. Principles, practice & projects. Vol. 4, Pergamon, Oxford, 261-291

Plinninger, R.J., Käsling, H., Thuro, K., Spaun, G., [2003]. “Testing conditions and Geomechanical properties influencing the CERCHAR abrasiveness index (CAI) value”. Int. J., Rock Mech, & Min, Sci. 40: 259-263

Rostami, J. [2005]. “CAI testing and its implications”. *Tunnels & Tunnelling International*, 37 (10): 43-46

Taheri, A., Haghi, A.H., [2010]. “Comparison between real and calculated values of ground settlement corresponding to EPBM tunneling for Esfahan Subway Project”,4th International conf. of soil mechanic and Geotechnical engineering,

Taheri, A., Haghi, A.H., [2011]. “Process Controlling of TBM of Esfahan Metro For Safety of Heritage Structures”, 14th Asian Regional Conference for ISSMGE, ATC19 special session, Hong Kong

Thuro, K., Plinninger, R.J., [2003]. “Hard rock tunnel boring, cutting, drilling and blasting :rock parameters for excavatability” ISRM 2003 Technology readmap for rock mechanics, South African Institute of Mining and Metallurgy

Thuro, K., Singer, J., Käsling, H. [2006]. “Abrasivität suntersuchungen an Lockergesteinen im Hinblick auf die Gebirgslösung.” Proc. Baugrundtagung 2006 in Bremen (Germany), VGE-Verlag, Essen, 283–290

Thuro, K. & Käsling, H. [2009]. “Classification of the abrasiveness of soil and rock”. J. *Geomechanics & Tunnelling* 2: 179188.

West, G., [1989]. “Rock abrasiveness testing for tunneling”. *Int. J. Rock Mech. Min Sci. & Geomech. Abstr.* 26: 321-327.