Just at the beginning of the first section, 5 discs were replaced, and it can be assumed that the situation on the first day corresponded to the excavation with all new cutter discs. On the 16th day, another 5 cutter discs had to be replaced (which is almost 1/2 of the number of cutter discs mounted on the cutter wheel).

Figure 13 (right) shows the number of cutter discs changed each day. To advance the 61 m, 11 cutters were changed with a consumption of 0.180 cutters/m (equivalent to 0.0450 cutters/m^3). However, there is a difference in the specific consumption, as in the first section 5 discs are consumed and 35 m are advanced (0.143 cutters/m) while in the second section 6 discs are also changed to advance 26 m (0.231 cutters/m). At the beginning of the next section, 8 more discs had to be replaced.

The drop in performance in the first section could be associated with the fact that not enough cutter discs were changed to maintain the performance.

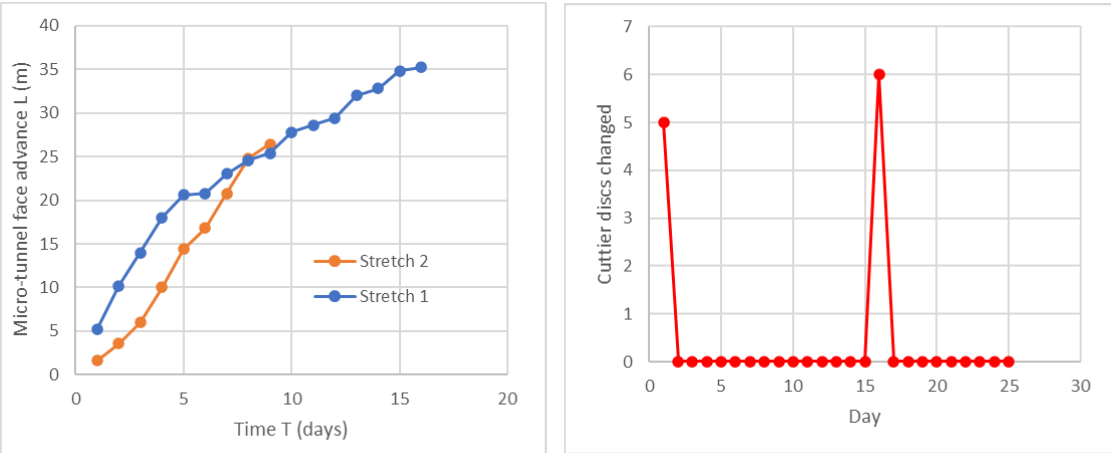

Fig. 13: Number of cutter discs changed a day (left) and accumulated (right)

Fig. 14 Difference between a cutter without wear and a cutter with heavy wear

4.4 Economic analysis

Figure 15 (left) shows the average accumulated advancing rate as a function of time. Up to day 16, the performance decreases steadily and only starts to increase after the replacement of new cutters.

Figure 15 (right) shows the accumulated advance performance as a function of the length of tunnel excavated. Figure 15 shows how in the best conditions of cutter wear, i.e., when practically all cutters are new, the throughput is close to 5.0 m/day; however, in normal advance conditions (i.e., with cutter wearing-replacement process) the cutting performance tends to be around 2.0 m/day.

Therefore, the abrasiveness of the rock means that the throughput drops from 5.0 m/day to 2.0 m/day with a consequent longer duration of the work. To this must be added the replacement time of the cutters, which is 1 day (practically independent of the number of discs that are changed).

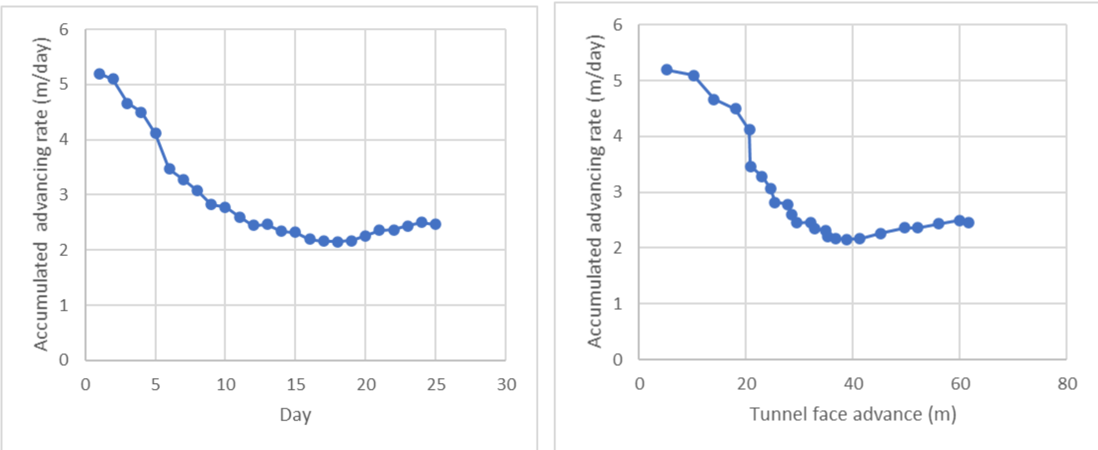

Fig. 15: Accumulated advancing rate as a function of time (left) and length (right)

A similar economic analysis can now be carried out as before. Following the same procedure, the first step is to quantify the economic cost of acquiring the cutter discs. In this case, it is a bit more complex because there are double and single (cheaper) cutter discs. The prize of the set of 13 cutters of the cutter head is of about 36,000 €. To simplify the problem, we do not distinguish between cutters and we will assume an average unit cost of 2,700 € per cutter disc.

The advancing rate, specific cutter consumption and replacement rate of cutters determined from the experience were 2.2 m/day-0.143 cutters/m-0.31 cutters/day in the first section and 2.9 m/day-0.231 cutters/m-0.67 cutters/day.

By a simple extrapolation, we arrive at a specific cutter consumption of 0.119 cutters/m and a replacement rate of 0.24 cutters/day for the 2.0 m/day throughput, while for the 5.0 m/day throughput it would be 0.495 cutters/m and 2.48 cutters/day.

The results are shown in Table 7. When the daily advance drops from 5 to 2 m/day, the cutter consumption and lineal cost will also diminish from 0.495 to 0.119 cutters/m and from 1,328 to 310 €/m respectively.

However, it should be borne in mind here that the days of stoppage contemplated in the real experience would be 2 to change a total of 10 discs. And the performance of

5 m/day would require at least 5 days of downtime. Therefore, when calculating the fixed costs for the 5 m/day performance, 3 additional days must be added.

On the other hand, in the case of excavation using the pipe jacking technique with a micro-tunnelling machine, the fixed costs are in the order of € 6,000/day. Calculations are summarized in Table 8.

Table 7: Lineal cost related to the purchasing of cutter discs

Legnth (m)	Advancing rate (m/day)	Cutters consumption (cutters/m)	Cutters replacement (cutters/day)	Number of cutters	Cost of cutters (€)	Lineal cost of cutters (€/m)
61	5	0.495	2.48	30	81,000	1,328
61	2	0.119	0.24	7	18,900	310

Table 8: Lineal cost related to fixed costs

Legnth (m)	Advancing rate (m/day)	Duration of the work (days)	Downtime cutter change (days)	Fixed costs (€)	Lineal cost (€/m)
61	5	12	3	90,000	1.180
61	2	31	0	186,000	3.049

The effect of abrasiveness on this stretch of granite could be quantified as follows. Progressing with the hypothetical maximum throughput of 5 m/day, the costs relating to cutters and fixed costs would be 171,000 € (2,803 €/m) while progressing with the average throughput of 2.0 m/day the costs analysed would amount to 204,900 € (3,359 €/m). In other words, in this case, abrasiveness represents an extra cost of around €556/m.

It is important to note that, when excavating in highly abrasive rocks with a significant consumption of cutter discs, the cost of excavation is increased not only by the cost of the cutters but also by the decrease in the advance performance. And in the case analysed, the savings from hypothetical increased performance (1,869 €/m) would be greater than the expenditure on cutters to maintain that performance (1,018 €/m).

As it can be inferred from above analysis, there are two differences between the work with large diameter TBM and very small diameter micro-TBM. The first is the fact that the replacement of cutter discs is more complex in the case of micro-TBM; this makes the cutter replacement downtime be bigger in this case. On the other hand, the relationship between fixed costs and cutter disc prize is 10 in the case of TBM and 3 for micro-TBM, and it must be taken in mind that the economic balance is better when this relationship is bigger.

5. CONCLUSIONS

• In the case of hard rock tunnelling with TBM, the wearing or destruction of cutter discs has a major influence. First, because the cutter discs are expensive tools and second, because the cutter wearing makes the TBM performance to diminish and consequently makes the costs to increase.
• In this work, an attempt to analyze how cutter wear influences the TBM's advancing rate and costs, independently of other parameters is carried out. The possibility that performance and cutter consumption are not independent is also analyzed. This means that an increase in performance leads to a higher cutter consumption, but conversely, a higher frequency of cutter replacement will lead to a higher performance. This approach is also introduced in cost analysis.
• Two sections of two tunnels were analyzed. One related to a tunnel of 10 m in diameter excavated with TBM and another related to a tunnel of 2.26 m in diameter excavated with micro-TBM.
• It is inferred that, under certain circumstances, it may be worth considering the possibility of increasing the number of cutter changes if this represents an increase in digging performance. This is because the cost of increased cutter consumption may be less than the savings due to reduced working time.
• As the increase/decrease in performance may be due to other conditioning factors, the results of these two sections studied are neither conclusive nor can they be generalized, but they do illustrate the relationship between these two variables and show a line of research that we believe could be interesting.

REFERENCES

Abascal Aznar, A. (2009), “Herramientas de corte en TBM para roca dura. Consumo de cortadores por formación geológica”, in *Pando, L., López Fernández, C. y De la Rubia Mir, L. (eds.), Jornadas Técnicas de la Variante de Pajares*, ADIF - Universidad de Oviedo, Oviedo, 173-179.
Arlandi Rodríguez, M., Domínguez González, M.L. and Peláez González, M. (2009), “Génesis del proyecto de Pajares. Estudios previos, Proyecto Básico y Proyectos constructivos”, ADIF (ed.), Túnel de Pajares, Madrid, 35-50.
Bieniawski Z.T., Celada C.B., Galera J.M. and Tardaguila I.G. (2009), “Prediction of cutter wear using RME”, *ITA-AITES World Tunnel Congress*, Budapest.
Bruland, A. (1998), “Hard Rock Tunnel Boring”, Dissertation, Norwegian University of Science and Technology (NTNU), Trondheim, Norway.
Dahl E., Grov E. and Breivik T. (2007), “Development of a new direct test method for estimating cutter life based on the Sievers’ J miniature drill test”, *Tunn Undergr Space Technol,*no 22, pp.106–116, doi: 10.1016/j.tust.2006.03.001
Ewendt G. (1992), “Erfassung der Gesteinsabrasivita¨t und Prognose des Werkzeugverschleißes beim maschinellen Tunnelvortrieb mit Diskenmeißeln”, *Kurzberichte aus der Bauforschung* 33(9):821–822 (in German)
Fernández, L. and Garcia, T. (2009), “Seguimiento de la Geología durante la perforación de los túneles de la Variante de Pajares”. in *Jornadas Técnicas Variante*

de Pajares, Eds: Pando, López y de la Rubia, ADIF y Universidad de Oviedo, Oviedo, pp 53-60.

Ferreras, F. and Ferrero, J. (2009), "Características y operativa de funcionamiento de la TBM Pajares 3 UTE". in *Jornadas Técnicas Variante de Pajares*, Eds: Pando, López y de la Rubia, ADIF y Universidad de Oviedo, Oviedo, pp 137-144.

Frenzel, C. (2011), "Disc cutter wear phenomenology and their implications on disc cutter consumption for TBM", in *45th American Rock Mechanics/Geomechanics Symposium*, San Francisco, USA

Frenzel, C. (2012), "Modeling uncertainty in cutter wear prediction for tunnel boring machines", *GeoCongress 2012: State of the Art and Practice in Geotechnical Engineering*, pp 3239–3247

Gallo, J. and Pérez Acebo, H. (2017), "Modelo de rendimiento de microtuneladoras (MTBM)", *Informes de la Construcción*, vol. 69, no. 546

Gehring, K. (1995), "Prognosis of advance rates and wear for underground mechanized excavations", *Felsbau* **13**(6):439–448 (in German)

Geng, Q., Bruland, A. and Macias, F.J. (2017), "Analysis on the Relationship Between Layout and Consumption of Face Cutters on Hard Rock Tunnel Boring Machines (TBMs)", *Rock Mechanics and Rock Engineering*, Vol. 51, Issue 1, 279-297.

Hassanpour, J., Rostami, J., Azali S.T. and Zhao, J. (2014), "Introduction of an empirical TBM cutter wear prediction model for pyroclastic and mafic igneous rocks; a case history of Karaj water conveyance tunnel, Iran", *Tunn Undergr Space Technol*, 43:222–231. doi: 10.1016/j.tust.2014.05.007

Hassanpour, J. (2018), "Development of an empirical model to estimate disc cutter wear for sedimentary and low to medium grade metamorphic rocks", *Tunnelling and Underground Space Technology* no. 75, pp. 90–99.

Hoyo Rodríguez, J. and Romana García, M. (2015), "Guía para la selección del método constructivo en hincas", *Ingeo Túneles*, no. 22, Madrid

Laín, C., Llamas, B., Pous, J. and Laín, R. (2018), "New empirical methodology for TBM cutter wear estimation", *Informes de la Construcción*, Vol. 70, 549, e242, enero-marzo 2018, pp. 1-10.

Liu, Q., Liu, J., Pan, Y., Zhang, X., Peng, X., Gong, Q. and Du, L. (2017), "A wear rule and cutter life prediction model of a 20-in. TBM cutter for granite: a case study of a water conveyance tunnel in China". *Rock Mech. Rock Eng.,* **50** (5), 1303–1320.

Maidl, B., Schmidz, L., Ritz, W. and Herrenknecht, M. (2008), "Hard rock tunnel boring machines", *Wiley*, New York.

Mendaña Saavedra, F. (2013), "Hincas de gran longitud en rocas duras", in *Jornadas técnicas sobre túneles de pequeño y mediano diámetro en ambiente urbano, nuevas tecnologías sin zanja*, Madrid

Nelson, P.P., Al-Jalil, Y.A. and Laughton, C. (1994), "Tunnel boring project data bases and construction simulation", *Geotechnical engineering report GR94-4*, University of Texas at Austin

Proyfe, S.L. (2010), "Anejo Geología y Geotecnia. Colectores Generales del Río Miño en Lugo, España". Tramo N-VI (2ª Fase)"

Rodríguez Ortiz, J.M. (2009), "La Geotecnia de los túneles de Pajares", ADIF (ed.), Túnel de Pajares. Madrid, 75-126.

Rostami, J. (1997), "Development of a force estimation model for rock fragmentation with disc cutters through theoretical modeling and physical measurement of crushed zone pressure" Dissertation, Colorado School of Mines

Toyos, J.M., Suárez, M.A., Rodríguez, L.R. and Serrano, L. (2009), "Perfil geológico a lo largo del trazado de los túneles de la Variante de Pajares", in *Jornadas Técnicas Variante de Pajares*, Eds: Pando, López y de la Rubia, ADIF y Universidad de Oviedo, Oviedo, pp 41-52.

Turtscher, M. (2012), "Analyse von Penetration und Vortriebsgeschwindigkeit bei maschinellen Vortrieben in Festgestein", Dissertation Thesis, Leopold-Franzens-Universität Innsbruck, 392 pp.; Innsbruck.

Wang, L.H., Kang, Y.L., Cai, Z.X., Zhang, Q., Zhao, Y., Zhao, H.F. and Su, P.C. (2012), "The energy method to predict disc cutter wear extent for hard rock TBMs", *Tunn Undergr Space Technol*, 28:183–191. doi: 10.1016/j.tust.2011.11.001

Wijk, G. (1992), "A model of tunnel boring machine performance", *Geotech Geol Eng*,10:19–40. doi:10.1007/BF00881969.

Yang, Y.D., Chen, K., Li, F.Y. and Zhou, J.J. (2015), "Wear prediction model of disc cutter", *J China Coal Soc,* **40**(6):1290–1296. doi: 10.13225/j.cnki.jccs.2014.3037 (in Chinese)

Yang, J.H., Zhang, X.P., Ji, P.Q., Liu, Q.S., Lu, X.J., Wei, J.P., Qi, S.H., Fang, H.G., Fang, J.N. and Geng, Y.J. (2019), "Analysis of disc cutter damage and consumption of TBM1 section on water conveyance tunnel at Lanzhou water source construction engineering", *Tunnelling and Underground Space Technology* 85 (2019) 67–75.

Young, T. and Seungwon, S. (2020), "Efect of Rock Abrasiveness on Wear of Shield Tunnelling in Bukit Timah Granite", *Appl. Sci*., **10**, 3231; doi:10.3390/app10093231.