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Tunnelling in urban areas by EPB machines: technical evaluation of the system

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ABSTRACT

The paper refers to the methods adopted for building a high-speed railway tunnel system between Bologna and Firenze (Italy), focusing attention on the Bologna node which represents the heart of the system, connecting the high speed network's main lines. The project includes 9 tunnels, accounting for 73 km of the 78 km route crossing below the Apennines. The paper pays attention to the main aspects to be taken into consideration for correctly choosing the tunnel boring machinery (TBM) to be used in urban areas. The fundamental point in analysing technical aspects regarding an earth pressure balance (EPB) machine concerned storing the main excavation parameter values; having collected and organised such data, statistical methods were used for processing it, the instantaneous velocities attained were empirically estimated and idle times were evaluated. The evaluation was made by calculating excavation specific energies (during different excavation phases) to find a satisfactory correlation with the type of ground crossed. Interesting results have been found by comparison with other excavation parameters; in particular, a better understanding of an earth pressure balance shield's working phases has been reached thanks to an experimental study conducted during the construction of tunnels for a high-speed railway system in Italy. The paper contains details collected regarding the operation of two different EPB machines.

Keywords: earth pressure balance (EPB), specific energy, excavation parameter, tunnel, tunnelling.

RESUMEN

Este artículo se refiere a los métodos utilizados para la construcción de túneles para un sistema de trenes de alta velocidad entre Bologna y Firenze (Italia), el punto de interés está sobre el nodo de Bologna, como el corazón de sistema, conectando las líneas principales de la red de alta velocidad. El proyecto incluye nueve túneles, con 73 de los 78 km cruzando por debajo de los Apeninos. Este artículo presenta los principales aspectos a tener en consideración para la correcta selección de máquinas tuneladoras (TBM) utilizadas en las áreas urbanas. El fundamento en el análisis de los aspectos técnicos consiste en un balance de presión de tierra (EPB) de la máquina relacionado a los principales parámetros en la excavación; una vez recogido y organizado los datos, se realizaron análisis estadísticos, se estimaron las velocidades empíricamente y evaluaron los tiempos de espera. La evaluación fue realizada para el cálculo de las energías específicas de excavación (en diferentes fases de perforación) para encontrar una correlación satisfactoria con el tipo de terreno atravesado. Los resultados obtenidos son interesantes en comparación con parámetros de otras excavaciones; en particular, una mejor compresión en el balance de la presión de tierra en cada fase de trabajo, ha sido descrita gracias a un estudio experimental realizado durante la construcción de túneles para un sistema de trenes de alta velocidad en Italia. Este artículo contiene información detallada recogida de la operación de dos maquinas EPB diferentes.

Palabras clave: balance presión tierra (EPB), energía especifica, parámetro excavación, túnel.

Record

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Introduction

Research instruments' evolution in the field of tunnel construction has contributed towards the improvement of excavation technologies and planning management, almost during the last 30 years.

Excavation techniques' evolution has also been stimulated by growing urbanisation and the assimilation of the "underground" concept as a space resource, becoming more and more exploitable from various points of view.

One of developed countries' major needs nowadays concerns mobility. Many projects have been promoted during recent years to improve interconnections between European countries. This has involved the problem of tunnelling a great part of the work (Barla G., 1994). The best European example highlighting such need has been the *Eurotunnel* project which involved constructing three underwater tunnels linking France and the UK. Another important project which is still in execution is the *High Speed Railway System*; it will

provide a more efficient and faster connection amongst European countries. A critical point has to be resolved when carrying out this work as rail layouts have to cross heavily urbanised areas (Barla G., 2000; Bilotta E. *et al.*, 2002).

Mechanised shields offer a series of advantages and work can be carried out without having to support the roof. The equipment's technical characteristics do not represent a basis for effective evaluation because two mechanically identical machines can behave in completely different ways, depending on soil characteristics. It is thus very difficult to make a reliable and unambiguous evaluation of one machine's best performance compared to that of another (Bebendererde S., 1995; Bovetti B., 2003). The only way to resolve this point is to evaluate the equipment's working parameters during excavation. The most important parameter concerns excavation specific energy which is often used for determining a machine's performance (Altindag R., 2003; Copur H. *et al.*, 2003; Cardu M. *et al.*, 2006; Tardaguila I. *et al.*, 2007; Acaroglu O. *et al.*, 2008; Exadaktylos G. *et al.*, 2008).

Defining the excavation specific energy concept

Excavation specific energy (E_S) represents the amount of energy (expressed in MJ) needed to excavate a unit volume of ground (Rostami J.,Ozdemir L., 1993; Friant J.E., Ozdemir L., 1993). This may be given by:

$$E_s = \frac{W_{tot} \cdot t}{V} \tag{1}$$

where W_{tot} is total power, t is excavation time and V is excavated volume.

The shield's feed motion and the head's rotation speed must be taken into account when evaluating energy consumption due to the excavation of a unit volume of ground. The general formula for calculating total excavation specific energy is given by the sum of these two contributions.

Feed motion contribution

The parameters for calculating a machine's feed motion are:

- The thrust exerted by hydraulic jacks S
- A machine's advancing speed v
- Excavation time t.

Tunnel diameter must be known, as this is used to calculate a tunnel's cross-section. The power needed for a machine's advance (W_{adv}) can then be obtained by using the following expression:

$$W_{adv} = S \cdot v \tag{2}$$

The rate of excavated volume per time unit is:

$$V = A \cdot (v \cdot t) \tag{3}$$

where A is a tunnel's cross-section and product $v \cdot t$ represents advance mad in time t. Equation (1) can thus be written for feed motion specific energy contribution ($E_{S\,adv}$), as:

$$E_{S\,adv} = \frac{W_{adv} \cdot t}{V} = \frac{S \cdot v \cdot t}{A \cdot v \cdot t} = \frac{S}{A} \tag{4}$$

Rotation specific energy

The data needed for calculating rotation are:

- The torque necessary to rotate head C
- The head's rotation speed ω
- TBM advance speed v.

Rotation power (W_{rot}) is given by:

$$W_{rot} = C \cdot \omega \tag{5}$$

Excavation specific energy consumed by head rotation ($E_{S\,rot}$) is thus:

$$E_{S\,rot} = \frac{W_{rot} \cdot t}{V} = \frac{C \cdot \omega \cdot t}{A \cdot v \cdot t} = \frac{C \cdot \omega}{A \cdot v} \tag{6}$$

Total specific energy

This represents a machine's behaviour in terms of non-uniform progression.

Equation (7) is obtained by substituting (1) in equations (4) and (6) (Teale R., 1965):

$$E_{S\,tot.} = E_{S\,adv.} + E_{S\,rot.} = \frac{S}{A} + \frac{C \cdot \omega}{A \cdot v} \tag{7}$$

It should be noticed that total excavation specific energy is expressed by a formula which does not include time as a variable; it can thus be considered a feature characterising excavation in the stretch which has been calculated from the machine's parameters. Moreover, it can be observed that energy, as would be expected, grows with thrust, torque and rotation speed; excavation difficulty increases as these three factors also increase. Excavation specific energy obviously decreases as progression speed increases.

Analysis of field performance data and Discussion

The following considerations were based on data collected when high-speed tunnels in the Bologna node excavation were being cut by two identical EPB TBMs (Cicala T., 2003; Guidarelli D., 2005). Table 1 gives the machines' main characteristics.

The first machine (EPB1) worked at advanced chainage (about 1,500 m) compared to the other one (EPB2). It is very important when analysing data to take into account the kind of ground in which work is being done. Excavation specific energy shown in the following graphs has been represented as a function of route chainage to facilitate correlation with different types of ground identified by geological characterisation.

EPB1 E_s is represented in Figure 1; it varies from a minimum value of around 15 MJ/m^3 to a maximum of 40 MJ/m^3.

Several types of ground are present in this range, particularly:

- Clay, from 1,500 m to 1,800 m chainage
- Moist sand, from 1,800 m to 2,100 m
- Dry sand, from 2,100 m to 2,400 m
- Dry gravel, from 2,400 m to 2,700 m.

A negative E_s gradient was envisaged from 1,500 m to 2,100 m because of a machine's progressive adaptation to local ground conditions. Crossing from clay to sand around 1,800 m chainage was confirmed by decreasing E_s (a machine's adaptation to lithological crossing). Sands were initially on the crown and their presence increased as excavation progressed, making excavation conditions become worse, thereby stressing the need for a machine to become suitable to different kinds of ground. This was not observed on contact between

moist and dry sands (around 2,100 m chainage) where a clear increase in E_s was envisaged. Dry sands, being more compact than moist sands, would require a greater effort to be removed.

Sampling was not regular from 2,100 m to 2,350 m chainage due to some of the machine's sensors malfunctioning; only a net increase in energy was identifiable (but it was impossible to establish whether such evaluation was completely reliable). Sampling worked regularly again from 2,350 m. This stretch crossed gravels and contact was not abrupt.

Table 1: Specifications for the EPB Lovat RME370SE used in the Bologna node

Excavation diameter	9.4 m
EPB length + back-up	180 m
EPB weight + back-up	~990 t
Theoretical maximum progression speed	8 cm/min
Minimum bend radius	250 m
Total thrust capacity	10,197 t
Total power	5,100 kW
Torque (standard conditions)	1,022 t·m at 1.97 rpm
Maximum torque	2,043 t·m at 0.98 rpm
Peak torque	2,452 t·m
Standard cutting power	2,700 kW

Analogous considerations could be made for EPB2 excavation. Figure 2 shows that E_s values were lower than those for EPB1; this clearly stood out by comparing both machines' performances at the same chainage (Figure 3). Unfortunately, the data for EPB2 was only available for chainage between 1,500 m and 2,050 m.

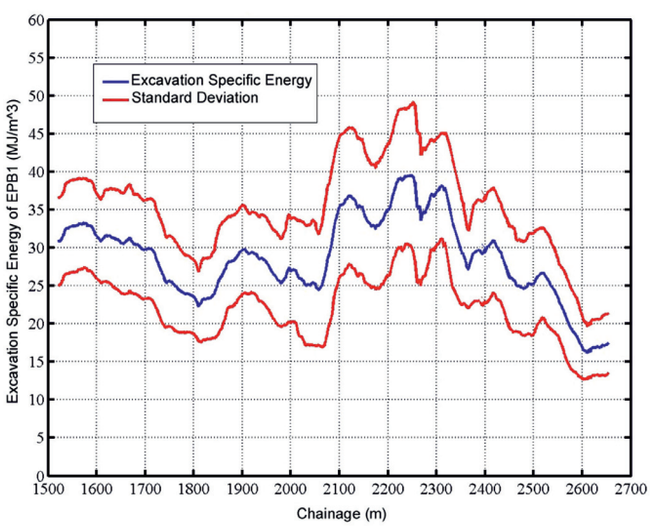

Figure 1. EPB1 excavation specific energy

The phenomenon could have been due to stress release in the ground; the first tunnel (cut by EPB1) was excavated between gravels and sands, leading to gradual adaptation by the machine, confirmed by a negative E_s gradient.

The original stress distribution of the ground was modified as the second tunnel (cut by EPB2) was excavated in close proximity to the first one (less than one diameter), resulting in reduced E_s. The decrease in E_s was evaluated as being about 30%.

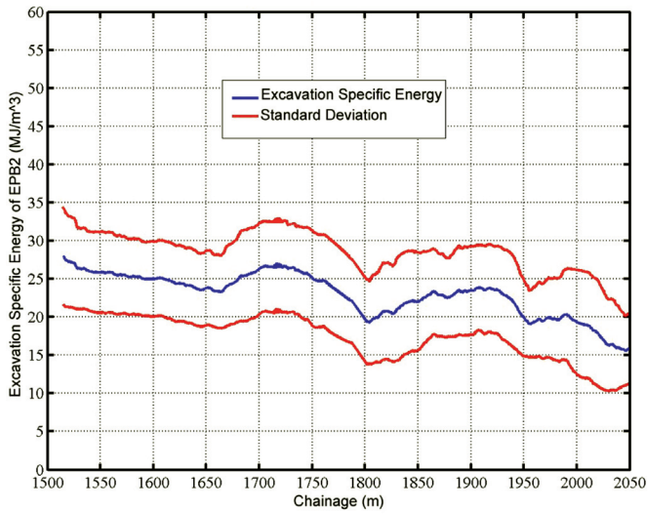

Figure 2. EPB2 excavation specific energy

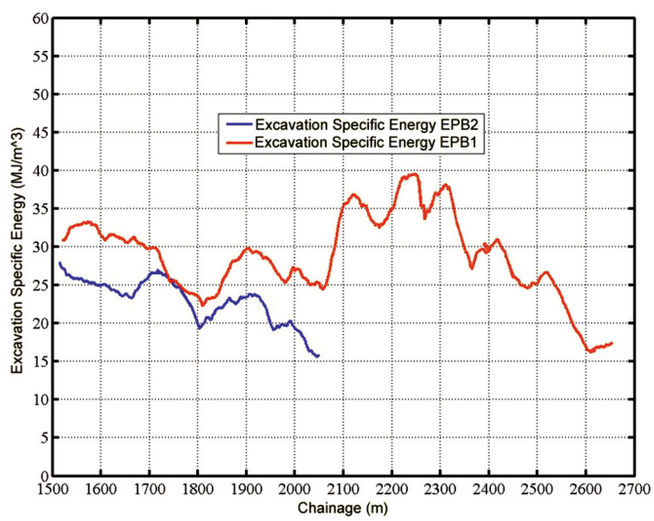

Figure 3. Comparing EPB1 and EPB2excavation specific energies

This result could also have been related to reduced ground strength due to EPB1 tunnel excavation; however, no data was available regarding the mechanical characteristics of the ground measured on site during the excavation to confirm this hypothesis.

Table 2 shows the main ranges of Es values obtained in different kinds of ground for both EPB1 and EPB2.

Table 2. Ranges of excavation specific energy values in different kinds of soil

Type of soil	Excavation specific energy (MJ/m^3)
Clay	25-35
Moist sand	25-30
Dry sand	32-38
Dry gravel	15-25

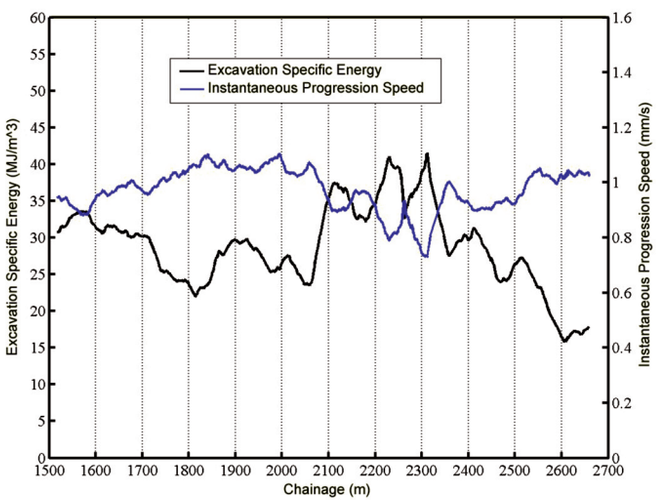

Figure 4. Comparing EPB1 excavation specific energies with instantaneous progression speed

Excavation specific energy compared to progression speed

Progression speed is one of the most important parameters when analysing the excavation cycle (Innaurato N., 1990; Kovàri K., 2002).

Figure 4 compares the E_s with EPB1 instantaneous progression speed at different chainages. According to equation (7), progression speed was inversely related to E_s, which was made evident by the plot (increased velocity coincided with decreased E_s). This was fully in line with the pertinent literature (Graham P.C., 1976; Nielsen B., Odzemir L., 1993; O'Rourke J.E. *et al.*, 1994; Rostami J., 1997; Thuro K., Plinninger R.J., 2003; Gong Q.M., Zhao J., 2009).

The two graphs' normalised gradients were similar, apart from the opposite sign. This was expected because the change in speed obtained from the pushing jacks' extension represented the effect of lithological variation (Lovat R. *et al.*, 2001).

Increased energy and decreased speed indicated greater resistance to excavation by the ground.

Excavation specific energy compared to torque

Figure 5 compares E_s to torque at different chainages for EPB1. A direct correlation was apparent, as expected from equation (7), where the term directly proportional to torque prevailed. The correlation was confirmed by the plot and the gradient was similar for both variables. Since E_{Stot} was mostly dependent on rotational specific energy (specific energy due to thrust is smaller

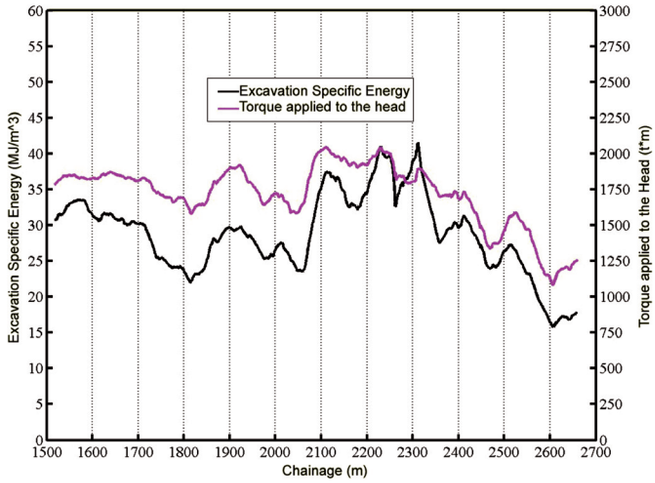

Figure 5. Comparing EPB1 excavation specific energies to torque

and is usually ignored) and torque was a function of the cutting force acting on the cutting tools, then such direct correlation would be expected (Nielsen B., Odzemir L., 1993; US Army Corps of Engineers, 1997; Boniface A., 2000; Gong Q.M. *et al.*, 2007).

Excavation specific energy compared to rotation speed

Figure 6 shows the roughly constant value for rotation speed at different chainages compared to E_s variations for EPB1. Rotation speed and torque were roughly proportional to E_s and, as rotation speed was kept practically constant, energy was only affected by torque changes during excavation.

E_s variation associated with rotation speed constancy showed that the latter was the externally controlled variable. An operator could set a constant level of rotation speed to maintain constant tool wear, while torque would change to cope with resistance to excavation produced by ground changes. On the other hand, if rotation speed were increased, then instantaneous penetration would decrease, and thus both the cutting force acting on the tools and torque would decrease.

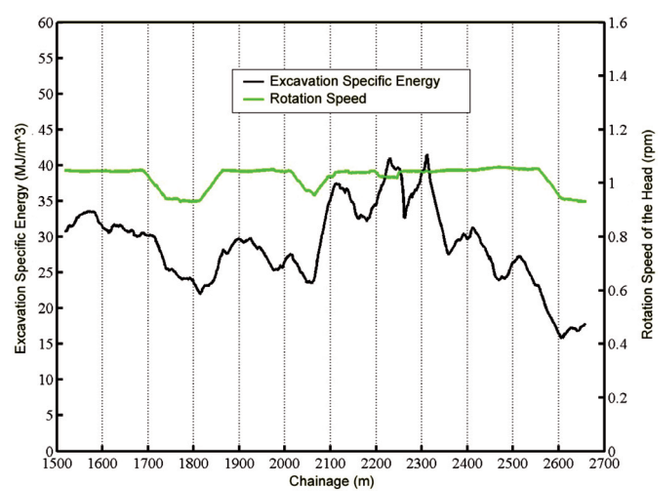

Figure 6. Comparing excavation specific energies and rotation speed

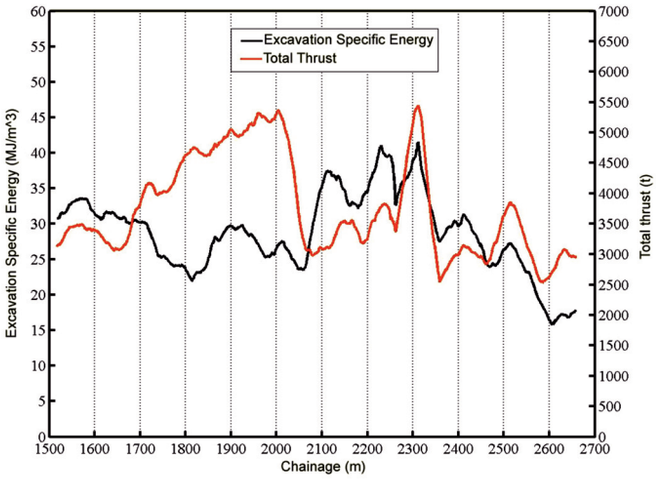

Figure 7. Comparing EPB1 excavation specific energies to thrust

Excavation specific energy compared to total thrust

Figure 7 compares E_s to thrust at different chainages for EPB1. According to equation (7), total specific thrust (thrust per unit cross-section) coincided with specific advance energy and was added to specific rotation energy, to give total E_s

Thrust (as rotation speed) could be controlled by an operator and total thrust plot was scarcely correlated to total E_s plot, apart from some excavation specific energy peak having some counterpart in thrust peaks, probably representing attempts by an operator to raise progression speed in difficult ground (Lovat R. *et al*., 2001; Mair N., 1997).

Figure 8 gives specific thrust energy, specific rotation energy and total E_s (thrust energy was a small fraction of total energy).

Energy values were calculated statistically by the moving average method, assuming 60 m progression steps.

Figure 8 shows that rotation specific energy was comparable to total E_s throughout the chainage. Only rotation specific energies' contribution would thus be considered in the following.

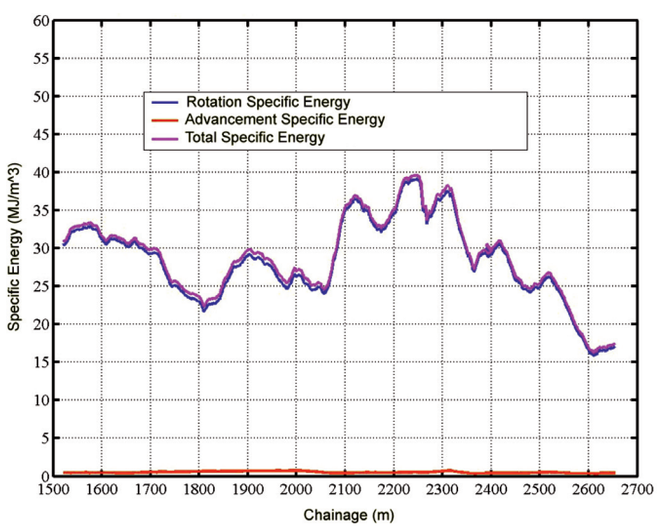

Figure 8. Comparing EPB1excavation specific energies separately due to rotation and progression speeds

Suggested evaluation methodology

Rotation speed (as shown in Figure 6) made a very low contribution since it was kept almost constant by the operator. The most important parameters to be considered when calculating excavation specific energies were thus torque (which is a function of rotation speed, as in equation (5)) and progression speed (Marcheselli P.P. *et al*., 1995; Schmalzbauer S., 1984).

Knowledge of progression speed is determinant during mechanised full-section tunnel excavation to evaluate a machine's performance in real time or at the end of a shift and to improve (if necessary) its performance regarding operator intervention related to inspectable parameters.

Obviously, if progression speeds were known (at least regarding a meaningful sample of excavated length), it would become possible to optimise a machine's work and increase overall excavation time.

It has been previously stated how little influence jack thrust has on evaluating total E_s. Equation (7) can thus be simplified as:

$$E_s \cong \frac{C \cdot \omega}{A \cdot v} \tag{8}$$

Equation (8) shows that energy mainly depended on two parameters (torque and progression speed) by assuming constant rotation speed ω.

The following equation was obtained by multiplying excavation specific energy by tunnel cross-section A:

$$E_s \cdot A \cong \frac{C \cdot \omega}{v} = \alpha \tag{9}$$

α was expressed in MJ/m. Equation (9) showed good correlation between E_s and coefficient α.

The example in the graph shown in Figure 9 referred to a 35 MJ/m^3 E_s value, supplying a 2,360 MJ/m α coefficient.

Therefore, if:

$$\alpha = \frac{C \cdot \omega}{v} = \cos t \tag{9'}$$

then:

$$C \cdot \omega = \alpha \cdot v \tag{10}$$

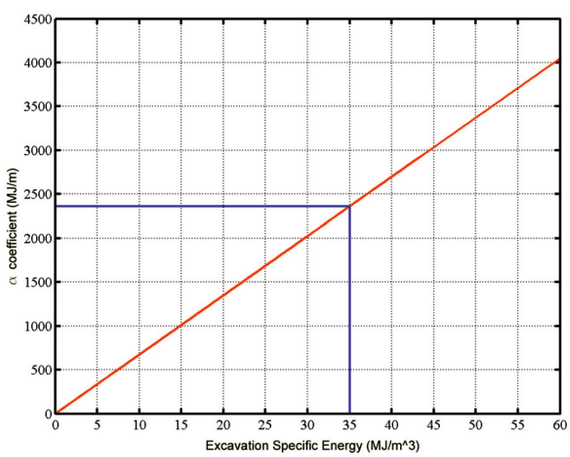

Figure 9. Correlation between excavation specific energy and á coefficient

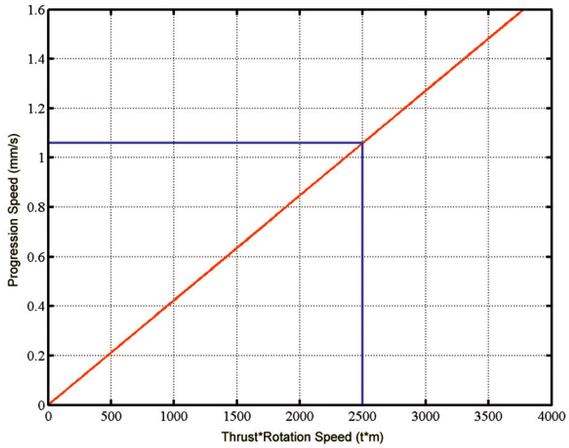

Figure 10. Correlation between torque and progression speed

Hence:

$$v = \frac{C \cdot \omega}{\alpha} \tag{11}$$

Equation (11) shows that torque and progression speed were proportional dimensions, if rotation speed were considered as a constant.

Maximum torque is the most important parameter to be considered when making a decision during tunnel design stage for evaluating the most suitable type of machine. Maximum torque data was provided by the TBM manufacturer.

The graph in Figure 10 gives an example of progression speed evaluated from torque data for EPB1. Assuming 2,500 t·m average torque at TBM cutter head and 1 rpm rotation speed, then a 1.05 mm/s net progression speed would be obtained as a reliable average value.

Analysis of a machine's work performance can be gone into in more depth, leading to obtaining more accurate predictions. TBM work cyclically, through a sequence of well-defined elementary steps, requiring precisely known time intervals.

Each cycle consists of an excavation stage (with a machine advancing through the thrust of the jacks), a support erection stage (where a new lining ring is installed) and idle time devoted to maintenance.

The sum of lining erection times and maintenance time represents the inactive time between successive ring installations and is repeated at each ring.

At the end of a shift, therefore, elapsed excavation time is much shorter than total elapsed time. The ratio between the actual excavation time and total time, given by:

$$\eta = \frac{T_{exc}}{T_{total}} \tag{12}$$

represents a machine's exploitation coefficient (machine utilisation time).

When η and instantaneous progression speed are known, a machine's daily (24 hours) progression can be calculated as:

$$v_{day} = \eta \cdot T_{total} \cdot v_{inst} \cdot 3.6 \tag{13}$$

where v_{day} is daily advance rate (m/d), T_{total} is total working time (hours/day) and v_{inst} is the net advance rate (mm/s).

Exploitation (machine utilisation time) coefficient η is obviously not known *a priori*. In the given example this has been calculated by solving the equation for η, daily progression speed being known as it can be obtained from measured daily advance. However, this only gives a machine's utilisation time factor; every contractor should predict this factor based on experience, a particular project site and conditions prior to construction activity.

Instantaneous progression speed can be obtained by averaging the data stored in a machine's databank files for the 24-hour period being considered. This would then give:

$$\eta = \frac{v_{day}}{T_{total} \cdot v_{inst} \cdot 3.6} \tag{14}$$

The average progression speed calculated for both EPB1 and EPB2 was 0.99 mm/s; a 0.157 exploitation coefficient was then found from these values, meaning that 15.7% of total 24 hours/day working time had been spent in pure excavation.

Total time was assumed to be 24 hours and, from the exploitation coefficient, a 3.8 hours/day excavation time was thus calculated. Total inactive time thus amounted to 20.2 hours/day; this was a very high value, showing the need for optimising working stages.

By dividing the 20.2 hours by the number of rings, it was found that the time elapsed was 2.2 hours between the end of the erection of a ring and the start of the erection of the next one. Part of this time was spent on assembling the ring, which takes about 40 min, and the remaining part was consumed in ordinary maintenance, including time spent waiting for the hardening of the mortar that connects the segments of the ring and maybe some other breakdowns.

The results are shown in Table 3.

Table 3. Mean daily advancement rate values obtained with 9 rings/day for EPB1

Mean daily progression, m	13.5
Mean instantaneous speed, mm/s	0.99
Working hours in a day	24
Exploitation coefficient ç	0.157
Pure excavation time, hours	3.8
Total inactive time, hours	20.2
Time to assemble a ring, min	40
Maintenance time, hours	14.2
Mean maintenance time/ring, hours	1.58

Conclusions

Comparing the most important excavation parameters led to interesting results for better understanding of earth pressure balance shields' working phases.

In particular, the following considerations should be highlighted:

- Excavation specific energy E_s did not appreciably depend upon thrust; rotation velocity too, being constant during drive, did not seem to substantially influence evaluation of excavation specific energy;
- Excavation specific energy E_s was directly correlated to torque;

- Ground stress release appreciably modified excavation specific energy values. In this case, this was the excavation of a second tunnel by machine EPB2 at a distance of less than one diameter from the first tunnel which had already been built by EPB1, occurring with a 30% Es reduction;
- Excavation specific energy E_s varied widely with ground characteristics: a large variation in excavation specific energy ranges was in fact observed as a function of the subsoil encountered, from 25-35 MJ/m^3 for clay, to 15-25 MJ/m^3 for dry gravel, to 32-38 MJ/m^3 for dry sand; and
- Exploitation coefficient η was low and varied from 0.10 to 0.20 for the project being analysed.

Progression speed was one of the main parameters to be considered during excavation. Regarding this point, an interesting method could be suggested, namely automatic continuous diagraphy (DAC).

Through an appropriate scale factor it enables estimating a given machine's daily progression speed (progression speed having already been defined) to establish the necessary torque C to be applied by a tunnelling machine.

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