

THE USE OF THE SPECIFIC DRILLING ENERGY FOR ROCK MASS CHARACTERISATION AND TBM DRIVING DURING TUNNEL CONSTRUCTION

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INTRODUCTION

Recording drilling parameters is a useful and economical technique for acquiring geomechanical information of rock mass parameters. Although it is not usually employed at geotechnical boreholes it is systematically used in TBMs.

Drilling equipments at drill rigs and TBMs drilling monitoring devices provides systematically records of the main drilling parameters (thrust, torque,...) from which the specific energy (Se) can be easily derived and expressed in terms of the energy necessary to drill a determined volume of rock (GJ/m^3).

The values of specific energy can be correlated with the main quality indexes as RMR. Also laboratory test have been carried out measuring UCS, Vp an Young Modulus, and have been compared with the specific energy.

This paper shows the obtained correlations using the data coming from a 80 m long pilot borehole as well as from the data recorded while the excavation of the Guadarrama tunnel that have a length of 28.3 km.

DRILLING SPECIFIC ENERGY

The specific energy (Se) can be defined as of the energy necessary to drill a determined volume of rock (GJ/m^3).

Several approaches can be found in the literature but the most accurate and used one is due to Teale (1965) coming from the oil industry and derived from the main parameters that are involved in drilling a rock mass.

Parameters that appear to govern the drilling process may be grouped as follows:

- Parameters related to the equipment such as drilling machine, rod or bit.
- Parameters related to the drilling process: the weight on bit, rotary speed, drilling fluid properties and circulation velocity. These are the three main elements on which the driller can intervene within the limits of possibilities of the equipment.
- Parameters related to the ground response: rate of penetration, rotation torque, drilling fluid pressure, reflected vibration through the drilling rods. For given drilling conditions, these parameters depend on the characteristics of the ground.

The eight parameters usually recorded by the main digital recorders are:

- a. Drilling fluid pressure (Pf).
- b. Rotation torque applied to the string of rods by the head (T).
- c. Thrust applied to the drilling bit (F).
- d. Drilling speed (V).

- e. Rotation speed (N).
- f. Retention force (hold-back) (Fr).
- g. Reflected vibration.
- h. Drilling time for 5 mm penetration (t).

Drilling data varies with drilling equipment and the way it is used, so it is necessary to standardize the testing procedure. While the drilling process is taking place, a relatively constant drilling fluid pressure, rotation speed and thrust on the bit must be provided in order to obtain consistent data.

When drilling parameters are maintained constant, study of rate of penetration allows the detection of changes in lithology and in the rock compactness or the presence of an anomaly such as a cavity or a fracture. It is closely related to the 'hardness' of the strata being drilled, therefore, this parameter is very important and needs to be recorded and interpreted carefully in order to get all significant lithological information.

A relatively constant flow rate (fluid pressure) must be provided to the borehole by a water pump. Ideally, pressure would be measured at the bit. However, because of the impossibility of placing a transducer near the nozzle, the pressure is measured adjacent to the pump at the ground surface.

Thrust on the bit is the main parameter that affects the drilling speed; for a given soil formation, the drilling speed is roughly proportional to the down-thrust.

For this reason it is recommended to keep down-thrust as constant as possible during the drilling process in order to obtain information directly from the drilling speed.

Rotation speed is measured by an electromagnetic proximity sensor. It is usually chosen to suit the drilling conditions. A constant and not very high rotation speed is preferred because higher rates of penetration could mask certain lithological variation that can be reflected by the torque parameter.

Torque is applied and measured in the drilling rod and transmitted to the drilling bit. It should vary nearly instantaneously with rock condition; therefore, torque should be recorded continuously.

Hold-back pressure is necessary to prevent the drilling rod from penetrating too fast in soft ground and to prevent the equipment falling into a hole when a cavity is encountered.

The hold-back pressure has to be subtracted from the down-thrust, in order to obtain the effective net weight on the bit.

Variations in drilling parameters are related to the ground properties. In a given type of soil or rock, the variations of one of the recorded parameters are predominant. However, though this is of great help in the interpretation, it may happen that two different soils have the same dominant parameter. For this reason, it is absolutely necessary to do an initial calibration with the execution of at least one logged destructive borehole near to a cored one, and then compare the parameter values with the lithology obtained in the cored holes. In the absence of the calibration cored borehole it will be more difficult to define the nature of the formation.

Under particularly favourable conditions, it is possible to do a satisfactory soil description with a precision of less than 0.10 m on the depth or thickness of a layer.

This is the first level of interpretation, which is possible from both analogue and digital recorders. However, the main interest for numerical data is that it can be used in computer operations and for combined parameters which are purely empirical or may have a physical meaning.

Several combination of drilling parameters have been used. The most known ones are:

1. Alteration index (Pfister, 1985)

$$A = 1 + (W / W_{max}) - (V / V_{max})$$

W = weight on the bit (thrust – retention force + weights of rods and bit) (kN).

W_{max} = it is the theoretical maximum value of W (kN).

V = it is the instantaneous penetration rate (with maximum value V_{max}) (m/s).

The alteration index, indicative of relative hardness varies from 0 in the softer soils to 2 in the harder ones on a given site. It is very sensitive in medium to low strength soils.

2. Energy used for drilling (Pfister, 1985)

The energy parameter is calculated from the equation:

$$W = T N / V$$

T = is the value of the rotation torque (kN · m).

N = rotation speed (rps).

V = instantaneous penetration rate (m/s).

The drilling energy is very useful in the analysis of hard soils and soft rocks.

3. Resistance to drilling (Somerton, 1959)

$$S_d = W (N / V)^{1/2}$$

W = weight on bit (thrust – retention force + weight of rods and bit) (kN).

N = rotation speed (rps).

V = instantaneous penetration rate (m/s).

4. Γ - hardness parameter (Bingham, 1965)

$$\Gamma\text{-hard} = N F D^2 / V T$$

N = rotation speed (rps).

F = thrust applied on the drilling bit (kN).

D = bit diameter (m).

V = penetration rate (m/s).

T = rotation torque (kN · m).

Γ -hard can be thought of as “hard to drill” and could relate to the difficulty of eroding and transporting soil particles away from the drill bit. For example, a clay might tend to clog the bit and therefore be “hard” to drill, whereas sands may be “easy” to evacuate and quick to drill.

5. Exponent method (Jorden and Shirley, 1966)

$$E = \log (V / N D) / \log (F D / T)$$

V =drilling speed (m/s).

N = rotation speed (rps).

D = bit diameter (m).

F = thrust on bit (kN).

T = rotation torque (kN · m).

Exponent method is related with d-exponent which it is an empirical parameter to track the profile of rock strength in shale.

6. Specific energy (Teale, 1965)

$$E = F / A + 2\pi NT / A V$$

F = thrust on bit (kN).

A = area removed by drill bit (m²).

N = rotation speed (rps).

T = rotation torque (kN · m).

V = drilling speed (m/s).

This parameter is employed to obtain geological and geotechnical information. A more detailed description is given below.

“Specific energy” is defined as the energy required for excavating unit volume of rock. It is a useful parameter that may also be taken as an index of the mechanical efficiency of a rock-working process.

The drilling specific energy is expressed by an equation that calculates the energy as a function of parameters recorded at the selected frequency. It can be expressed as follows:

$$E_s = F/A + 2\pi NT / AV = e_t + e_r$$

Where:

F = thrust on the bit (kN).

A = hole section (m²).

N = rotation speed (rps).

T = rotation torque (kN · m).

V = rate of penetration (m/s).

The first member of the equation represents the contribution of the thrust (thrust component). It is equivalent to the pressure acting over the cross – sectional area of the hole.

The second member is the rotary component of energy.

Specific energy has the same dimensions as pressure or stress. This is because of the fact that if a force F acting on a normal surface (A) moves it through distance ds, the increment of work done, **dW**, is equal to **Fds**. The change in volume effected by the movement, **dV**, is Ads. If Es is the specific energy at any point, then $e = dW/dV = F/A = p$, the pressure at that point.

For a given excavation, A is constant, so et is directly proportional to F. For given A and N, er is proportional to T/V.

Now, the torque/penetration rate curves approximate to a straight line through the origin. The slope of this line is T/V and it is approximately constant.

It follows that for given A, and N, er and therefore e itself should keep a constant value.

Another approach to the above is to put in the equation the term “p” as the penetration per revolution (p=V/N). Then, the equation of rotary component of specific energy can be written as follows:

$$E_r = 2\pi T / Ap \text{ (kN/m}^2\text{)}$$

T is the torque required to remove a layer of rock of depth p in one revolution. Since the amount of energy required for brittle materials like rock is not much affected by the rate at which it is applied, the relationship between T and p may not be significantly affected by changes in rotation speed. The ratio T/p can therefore be a useful index of specific energy.

In Figure 1 it can be seen the relationship between penetration per revolution and specific energy for claystones.

In the er equation it can be observed that specific energy will reach very high values at low thrust.

Below a certain value, the thrust will be inadequate to effect penetration of the bit.

As the thrust increases, the value of specific energy falls until it reaches a value beyond which it continue to decrease so slowly as to remain virtually constant. This can be seen in Figure 2.

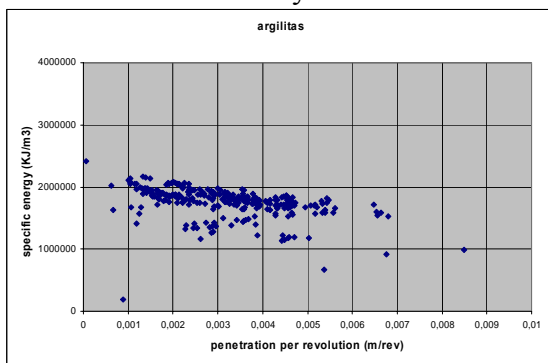


Figure 1 - Relationship between penetration per revolution and specific energy for claystones.

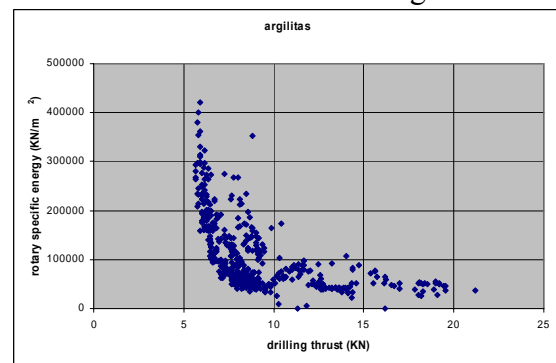


Figure 2 - Relationship between rotation specific energy and drilling thrust in claystones.

Specific energy has a high value at any change in lithology but it falls after that and remains in a constant value.

The lowest value attained is a measure of the maximum mechanical efficiency of the particular tool in the particular operating conditions.

However the fall in specific energy does not continue indefinitely: a stage may be reached when the tool is pushed so heavily into the rock that it becomes overloaded and clogs. The reduction in efficiency will cause the specific energy to rise again.

THE USE OF SPECIFIC ENERGY FOR GEOTECHNICAL SITE CHARACTERIZATION

The first use that can be derived from the drilling specific energy is to correlate it with the main geomechanical rock mass parameters such as RMR (Bieniawski, 1989), UCS, etc. This use provides a cost effective geotechnical tool and can be used either in standard geotechnical boreholes or in open boreholes.

The drilling parameters systematically recorded were depth, rate of penetration (V), weight on bit (F), fluid pressure, torque (T) and rotation speed (N); allowing to obtain the drilling specific energy.

Also a set of lab test were carried out providing the opportunity to make correlations with the basic intact rock parameters.

Drilling parameters and geophysical logging tools were measured at the following boreholes:

- PFM-5, 6, 7 and 8 (20, 11, 13.95, 13 m), for set up purposes.
- BH0 (117 m) at a clayly flysch formation, for set up purposes.
- BH-1 (80 m) at a carboniferous formation.
- BH-2 (227.5 m) at a metamorphic formation.
- BH-3 (210 m) at marls, schist and vulcanites.
- BH-4 (64.2 m) at sandstones, shales and coal seams.

Correlations with rock mass parameters

With the data coming from all the mentioned boreholes, a correlation between specific energy and different rock mass parameters have been investigated.

In the Figure 3 it can be observed the different drilling parameters measured and the specific energy obtained with depth.

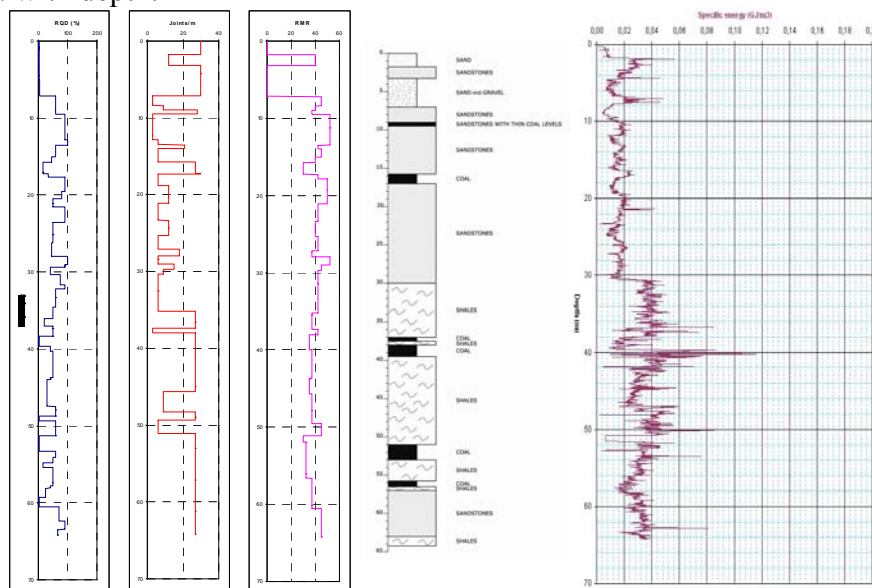


Figure 3 - Rock mass parameters and specific energy obtained with depth (BH-4).

The parameters used for geotechnical purposes are:

- Rock Mass Rating (RMR).
- Number of Joints per metre.
- Rock Mass Uniaxial Compressive Strength (σ_c^m).

Specific Energy (Esp) is the main index related with all drilling parameters. It has been analyzed respect to RMR, Number Joints per metre, Young Modulus (Edyn) and Rock Mass Uniaxial Compressive Strength (σ_c^m), as defined in Kalamaras and Bieniawski (1995). These correlations can be observed below.

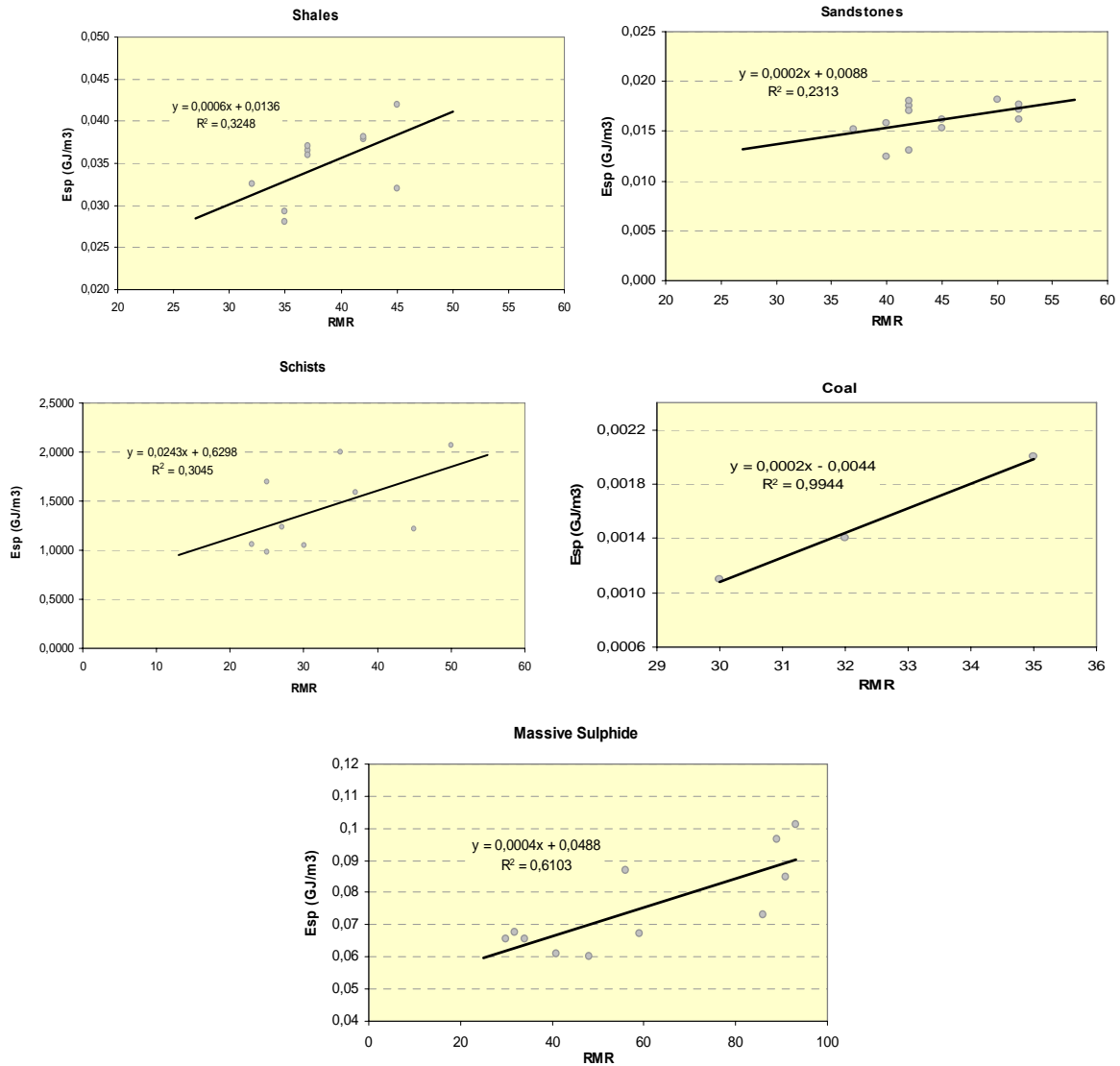


Figure 4 - Correlation between RMR and Esp.

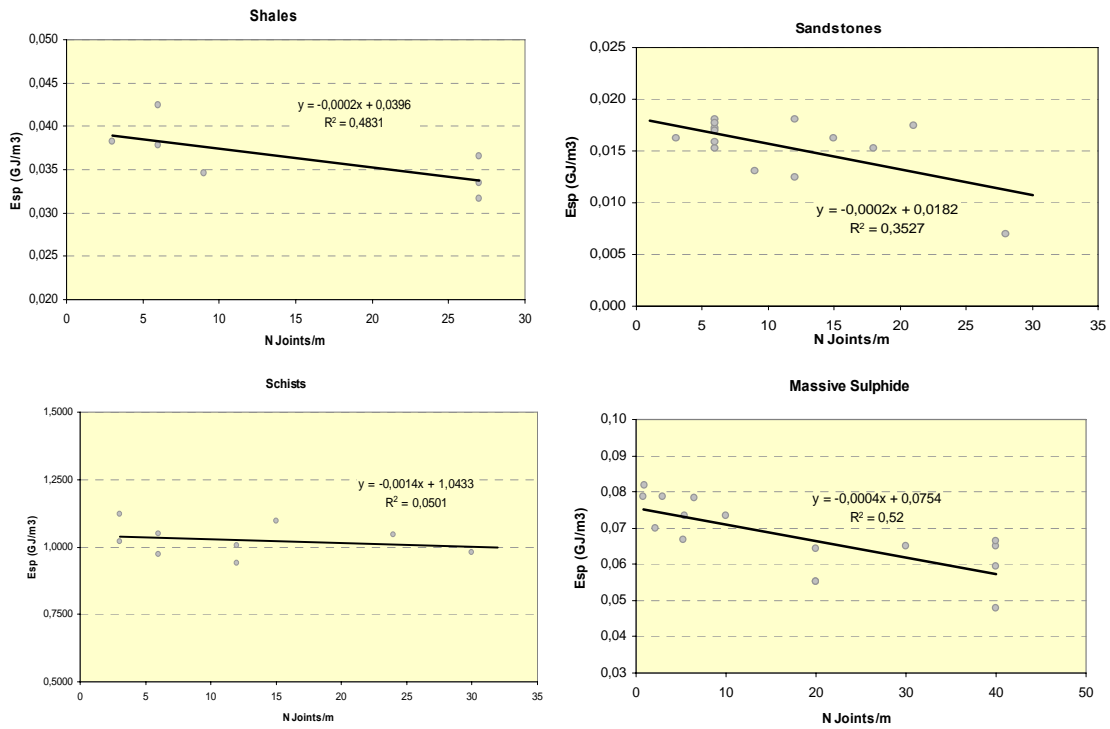


Figure 5 - Correlation between N Joints/m and Esp.

In both cases the Specific Energy shows a relationship respect to the rock mass quality, to greater values of Specific Energy the rock mass quality will be better. It is important to take into account that the number of joints per metre is an important part of the value of RMR, and according the expected results was obtained a logical trend that show the correlations carried out.

Following correlations show Specific Energy (Esp) versus Dynamic Elastic Modulus (Edyn).

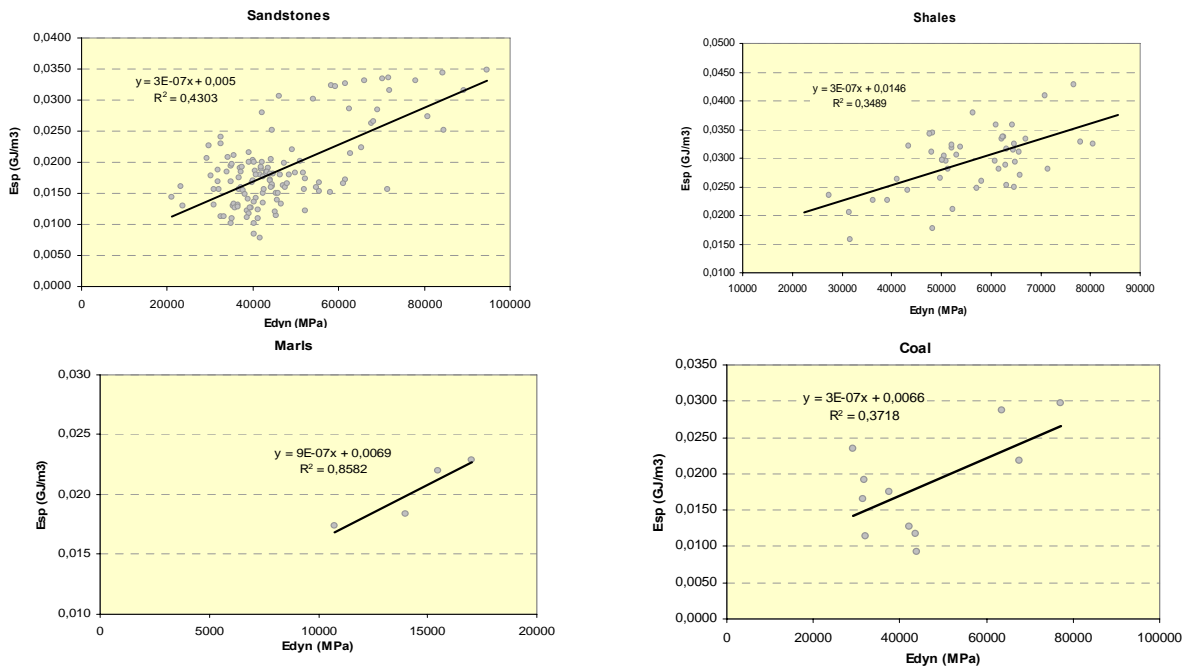


Figure 6 - Correlation between Edyn and Esp.

From Full Wave form Sonic it is obtained P (Vp) and S (Vs) wave velocities, that can be related to elastic deformational parameters of the rock, in this case it is used to obtain the Young Modulus, and in a logical trend, to greater values of this modulus, it is obtain greater values of Specific energy (Esp).

And the last correlation with drilling parameters is between Specific Energy and Rock Mass Uniaxial Compressive Strength (σ_c^m).

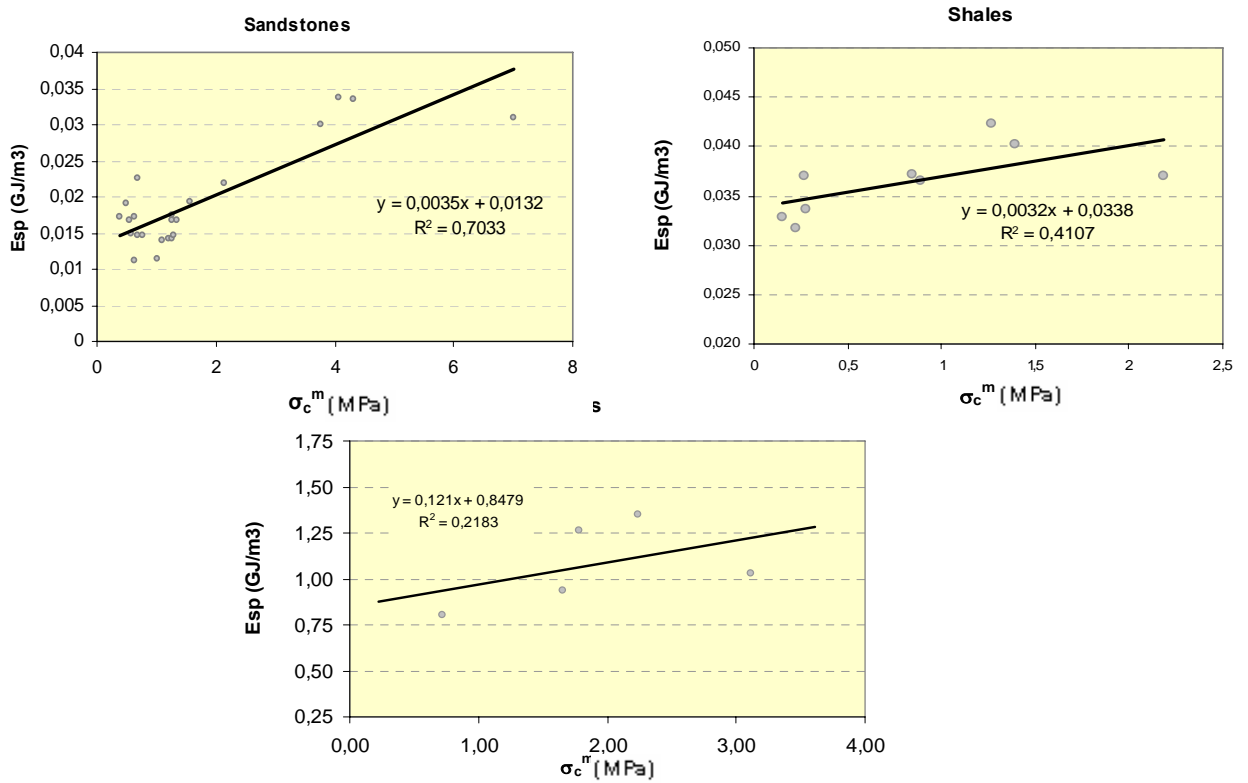


Figure 7 - Correlation between σ_c^m and Esp.

Correlation with intact rock parameters

The laboratory measurements are useful to study the intact rock, the correlations carried out between laboratory tests (UCS and PLT) and field measurements (mainly obtained from full wave form sonic (Vp) and drilling parameters (Esp)) indicate the relation between these parameters.

The results obtained from different lithologies are showed below.

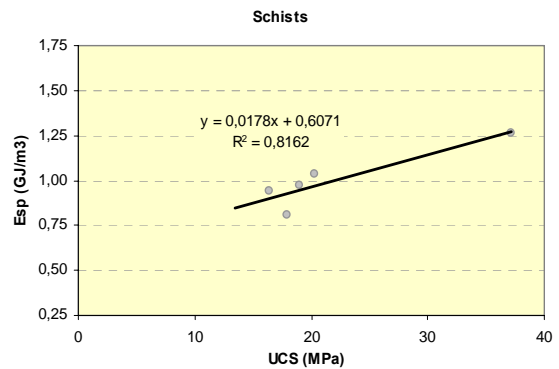
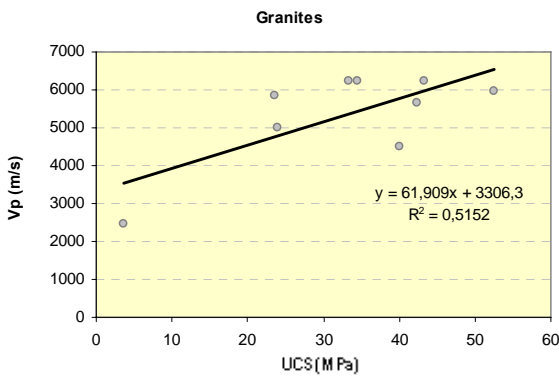
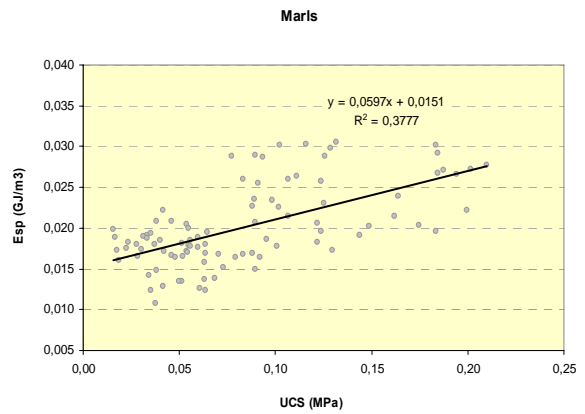
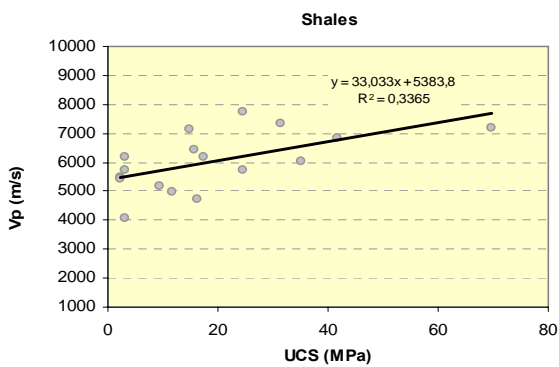
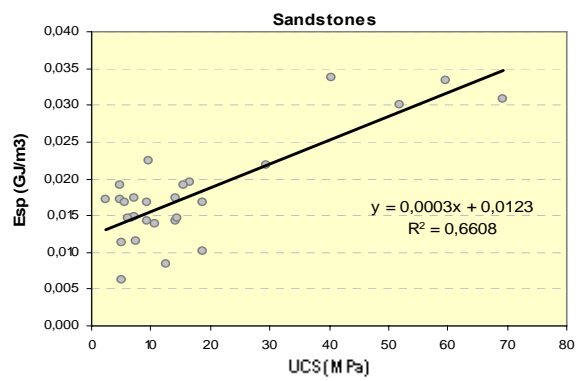
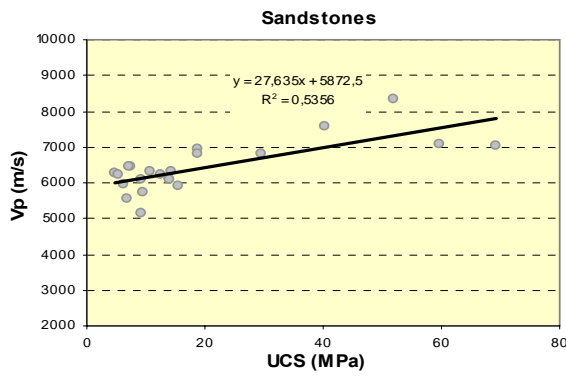


Figure 8 - Correlation between UCS and Vp.

Figure 9 - Correlation between UCS and Esp

In both cases, when UCS increases, Vp and Esp increase in the same way, it is indicative of the rock quality, its geomechanical properties. With the data obtained from Point Load Test (PLT), early studies (Bieniawski, 1979; Broch and Franklin, 1972) found that relationship between UCS and PLT could be expressed as:

$$UCS = (K)Is_{50} = 24Is_{50}$$

Where K is the “conversion factor”, this relationship has been applied to the data obtained with the Point Load Test for the sandstones and shales, with the objective to obtain more data for the correlations.

THE USE OF SPECIFIC ENERGY FOR TBMs DURING TUNNEL CONSTRUCTION

The following TBM drilling parameters are usually systematically recorded:

- Advance rate (ARA)
- Time of excavation
- Weigh of the debris in the belt
- Thrust (total/contact) (F)
- Rotation speed (N)
- Torque (T)

From these data two different interpretations can be done:

- Qualitative
- Quantitative

In the first type the following circumstances have been noticed:

- A significant increase in the rate of advance with a decrease in the geomechanical ground quality.
- An increase in the debris weight with face instability.
- Instantaneous torque increase with face instability.
- The difference between the applied and the contact thrust is equivalent to the TBM friction. If this value increases the TBM can get stocked.

In relation with a quantitative interpretation, the following values have been considered:

- a) Penetration rate (p)

$$p \text{ (mm/r)} = \frac{V \text{ (mm/m)}}{N \text{ (rpm)}} \quad (1)$$

that gives the ground resistance to be excavated.

- b) Penetration index (I_p)

$$I_p = \frac{F_c \text{ (kN)}}{p} \quad (2)$$

that proportionate the thrust per cutter to penetrate 1 mm per revolution.

- c) Specific energy of excavation (E_s)

As defined by Teale (1965)

$$E_s \text{ (kJ/m}^3\text{)} = \frac{F}{A} + \frac{2\pi \cdot N \cdot T}{A \cdot \text{ARA}} \quad (\text{Teale, 1965}) \quad (3)$$

where for TBM machines, E_s = specific energy of excavation (kJ/m^3), F = total cutterhead thrust (kN), A = excavated face area (m^2), N = cutterhead rotation speed (rps), T = applied torque ($\text{kN}\cdot\text{m}$) and ARA = average rate of advance (m/s).

As it can be observed there are two addends, the first one corresponds to the thrust energy (E_{st}) while the second one corresponds to the rotation energy (E_{sr}).

Following it is presented the main results obtained during the excavation of Guadarrama Tunnels and San Pedro Tunnels.

Correlation between I_p vs. E_{sr} .

These data have been systematically recorded during the excavation of Guadarrama Tunnels that consists in two twin tunnels each one of 28.3 km of length, constructed in gneissic and granitic rocks. This results were firstly showed at Tardáguila and Suárez (2005).

Figures 10 and 11 show the existing relation between the penetration index and the specific rotation energy of excavation.

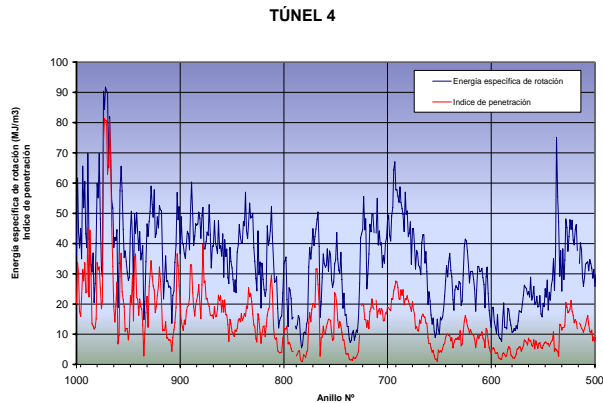


Figure 10. Relationship between I_p and E_{sr} for 500 segments rings

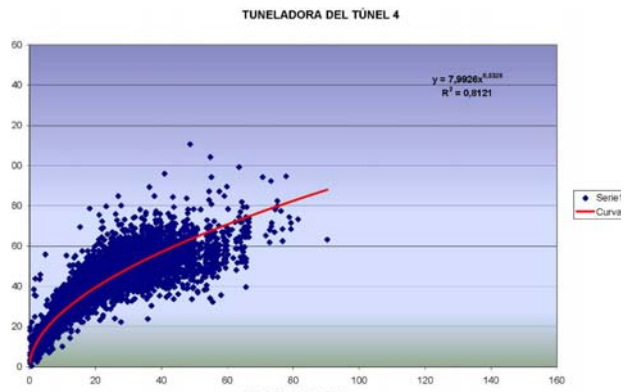
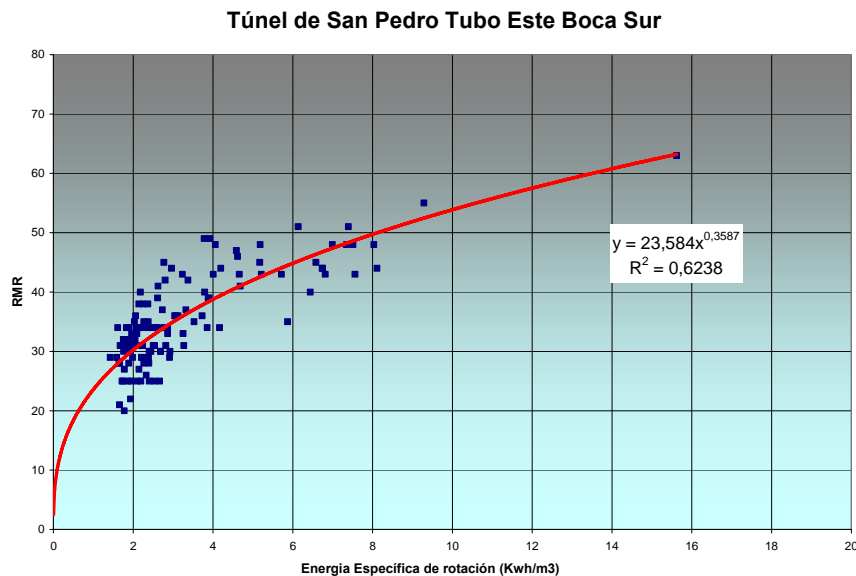


Figure 11. Correlation between E_{sr} and I_p ($E_{sr} = 8 \cdot I_p^{0.52}$).

In the first one it can be observed the direct relation between both parameters considering 500 segment units. From this relation it can be concluded that the rotation specific energy depends on the geomechanical quality of the rock mass as the penetration index does.

Correlation between Specific Energy and RMR

The following figure shows the correlation between the Specific Energy and RMR obtained from the excavation of San Pedro tunnels constructed using an open TBM in gneissic rocks.



CONCLUSIONS

The use of the specific energy in the geotechnical site investigation as well as during tunnel excavation with TBM provides a very interesting geotechnical tool for site characterization.

In relation with geotechnical boreholes, it has been observed that:

- E_{sp} depends strongly on the geomechanical rock mass quality expressed by the RMR and the Number of Joints per metre:

- As higher the RMR is, higher are the values of Esp.
- RQD gives high scatter in relation with Specific Energy.
- It's a good tool for the rock mass characterization. As higher the number of Joints/m are, lower are the values of Esp.
- A clear influence of the lithology in the values of Esp is observed.
- The Dynamic Young Modulus (Edyn), in relation with Esp and RMR, shows good results with the lithologies analyzed.
- The obtained correlation between Vp and specific energy gives an interesting tool for characterization purposes.

In relation with TBM tunnel excavation it can be concluded:

- The rotational specific energy is a very useful tool for the geotechnical control of a tunnel excavated using a TBM.
- The rotation specific energy depends on the geomechanical quality of the rock mass as the penetration index does
- The thrust specific energy represents only 2% of the total specific energy needed to excavate a tunnel with a TBM.

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