Experience in Construction in Strong Rock with Roadheader in the Ariz-Basauri section of the Bilbao Metro

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1. INTRODUCTION. DESCRIPTION OF THE WORKS TO BE PERFORMED

The object of the works to be performed is the extension of the Bilbao Metro network (Vizcaya, Basque Region, Spain). The Ariz-Basauri section of line 2 of the Bilbao Metro is being performed by the UTE Ariz-Basauri, a joint venture formed by the companies Exc. Cantábricas S.A., Vda. de Sainz S.A. and Obras Subterráneas S.A. The total length of the section is 2,372 m. of which 2,108 m. are performed in mine tunnel. The section will provide a service to the centre of Basauri with two stations, Ariz station commencing approximately at KP 1+050 and Basauri station at KP 2+105.

Introduction of a new transport infrastructure such as a Metro system in an urban environment has an inevitable impact which must be quantified and, as far as possible, minimized. This impact on the urban environment includes a number of aspects, affecting networks and services, buildings, road traffic and rail traffic, not only influencing the line layout, but also and in particular the construction processes to be applied to ensure a minimum impact on both the existing infrastructure and the population. From the constructor's viewpoint the shallow nature of the work at around 25 m should be highlighted as well as a work plan requiring 3 shifts and involving night work. The decision taken by ETS (Euskal Trenbide Sarea) not to use explosives due to the urban environment in which the Metro is developed is therefore comprehensible.

2. GEOLOGICAL FRAMEWORK

The Basque region is mainly formed of Mesozoic and tertiary materials. Within the Mesozoic Era, the Cretaceous period is particularly notable. In the area in which the line layout is located, a number of units separated from one another by structural accidents of regional importance have been differentiated. In the Basauri area the substrata consists entirely of Cretaceous materials, the following being identified.

Oiz unit (Durango sector). The materials of the Oiz unit in Basauri are grey-blue marls stratified in decimetric banks with intercalated carbonate or pyrite nodules of lower to middle Albian age. These can also be included under the local Bilbao term "*cayuelas*". Within this generic name there are two groups, *Cayuelas*: these are strictly marly, compact, with very dark sections and at times with a nodular appearance; they may occasionally be affected by karstification. *Calcareous cayuelas*: these are marly limestones and limestone marls, dark grey in colour and sporadically nodular in appearance; they commonly show clear signs of karstification when their potential development and lateral continuity is significant.

Yurre unit (**Urgonian complex)**. This unit is formed of metric banks of limestones with rudists and corals in which their lower and higher Aptian fossil content is particularly marked, together with a group of monotonous alternations of mudstones, calcareous mudstones, sandy mudstones and sandstone ranging from the Hauterivian to the lower Aptian inclusive.

3. GEOTECHNICAL DESCRIPTION

The geotechnical study performed for the section project showed that the tunnel would pass through a notable variety of terrains ranging from high geomechanical quality rock to deposits of gravels and calcareous blocks in silt loam matrix. This was confirmed during performance. The rock with the data available prior to commencement of the works is described below.

Oiz unit. As described in the section on Geology, the Oiz Unit consists mainly of a monotonous succession of grey-blue marls stratified in decimetric banks.

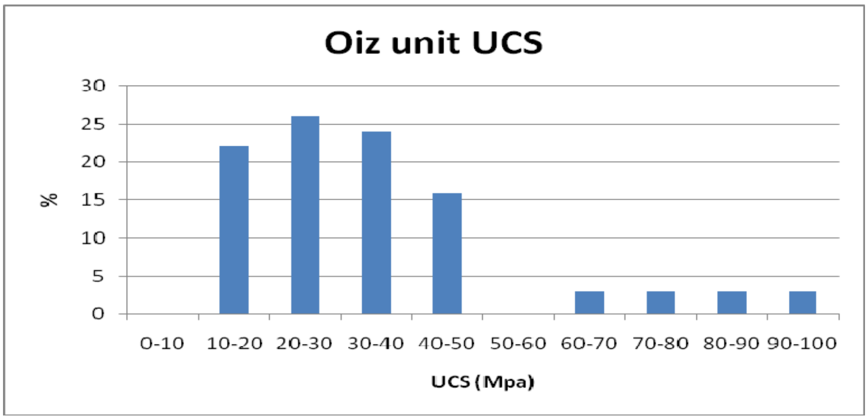


Illustration 1-Histogram of the UCS of the Oiz formation

As can be seen from Illustration 1 – Histogram of the UCS of the Oiz formation, the simple compressive strength values show a marked mode, in the 20-30 M Pa range; the average is 31.4 M Pa and the existence of 14% of values with strengths ranging from 60 to 100 M Pa stands out.
With regards to indirect tensile strength, the Brazilian test shows a highly marked unimodal nature, with dominant type between 4.0 and 6.0 M Pa, the arithmetic average being 5.86 M Pa. Abrasiveness was determined by the Cerchar index and shows a net predominance of the 1.2-2.5 type corresponding to low abrasive rock, although one of the tests showed a highly abrasive rock (4.40).

Yurre unit. To analyse the geotechnical features, a division into three lithotypes was performed:

- Predominance of calcareous mudstones
- Predominance of sandstone and sandy mudstone
- Limestones with rudists and corals

YURRE UNIT – PREDOMINANCE OF CALCAREOUS MUDSTONE - TEST RESULTS				
PARAMETERS		MAXIMUM	MINIMUM	AVERAGE
Dry Density	(t/m3)	3.04	2.52	2.71
Simple c. Strength σc	(kp/cm2)	667.39	230.84	467.61
Brazilian T. Strength	(kp/cm2)	75.79	54.88	65.71
Cerchar Index		2.20	0.60	1.50

As can be seen, the uniaxial compressive strength values show marked homogeneity, mainly grouped in the 40-50 M Pa type. With regards to indirect tensile strength, the Brazilian test shows a bimodal nature with results of around 5.5 and 7.5 MPa, the arithmetic average being 6.57 M Pa. Based on the range of values obtained in the Cerchar index, the rock can be classified as non-abrasive. Values higher than 2, are considered to be anomalous.

YURRE UNIT – PREDOMINANCE OF SANDSTONE AND SANDY MUDSTONE -TEST RESULTS				
PARAMETERS		MAXIMUM	MINIMUM	AVERAGE
Dry Density	(t/m3)	2.74	2.09	2.57
Apparent density	(t/m3)	2.69	2.23	2.46
Simple c. Strength σc	(kp/cm2)	1215.70	4.45	463.26
Brazilian T. Strength	(kp/cm2)	91.80	1.83	59.15
Cerchar Index				1.40
Schimazek Index		0.23	0.06	0.13

In view of the results obtained, simple compressive strength shows a heterogeneous distribution in which over 45% exceed 60 M Pa, 15% are within the 20-60 MPa range, 10% between 10 and 20 M Pa, while the strength of the remaining 30% is less than 10 MPa. Based on the result obtained in the only CERCHAR index analysis performed (1.40) abrasiveness is classified as low. Based on the results obtained when analysing the Schimazek index (0.06-0.23) the rock is cuttable.

YURRE UNIT – LIMESTONES WITH RUDISTS AND CORALS - TEST RESULTS				
PARAMETERS		MAXIMUM	MINIMUM	AVERAGE
Dry Density	(t/m3)	2.76	2.71	2.73
Apparent Density	(t/m3)	2.71	2.66	2.69
Simple c. Strength σc	(kp/cm2)	752.70	252.35	507.45
Brazilian T. Strength	(kp/cm2)	122.30	60.18	91.24
Cerchar Index		1.0	1.0	1.0

Results of the simple compressive strength tests show certain bimodal type homogeneity; so the dominant type corresponds to strengths of 40-50 MPa and the subordinate around 70 M Pa.

3.1. Drillability, abrasiveness, equipment

Rock drillability can be considered to be highly determined by two of its mechanical aspects, strength and toughness. The most commonly recognised rock strength estimator is uniaxial compressive strength. The rock to be excavated in the works is essentially "*cayuela*" with a uniaxial compressive strength of around 30 MPa, a relatively low strength. That is, it is classified as average strength type R3 rock according to the ISRM. To estimate toughness specific tests are required which had not been performed in the project phase (for example fracture energy). In the absence of specific tests, toughness estimators are usually used based on the ratio between tensile strength and the UCS. The ratio would be

Unit	Lithology	UCS	BTS	Ratio 1	Toughness
Oiz	Marl	30.00	5.80	5.17	Very high
Yurre	Calcareous Siltite	46.70	6.57	7.11	High
	Sandy Siltite	46.30	5.90	7.85	High
	Limestone	50.70	9.20	5.51	Very high

The above table confirms that although it is average strength rock it is extremely tough and will therefore need powerful, heavy equipment to achieve good results. This is not new, as other works performed previously by the company found that despite its low strength Bilbao rock is difficult to cut. If we use the values obtained in the CERCHAR index to evaluate the possible behaviour of the rock, we note that most of the findings obtained are in the 1-2 range. This range of values means that we are dealing with moderately abrasive rock with some abrasive samples. Taking into account the client's restrictions, it was essential to perform the works with mechanical excavation. The short length of the sections with constant section and the need to excavate the stations made the use of tunnel boring machines unadvisable.
Therefore, and taking into account the values defined in point 3 it was decided that the suitable machines were high power, low cutting speed roadheaders.

4. PERFORMANCE OF THE WORKS

To perform the works UTE Ariz-Basauri leased two roadheaders from the company Sandvik, models MT-720 of 120 t and 300 kW on the cutter drum.

Bidasoa Mouth, Roadheader MT-720 no. 63: The first of these commenced work in August 2007 in Bidasoa Street, in the centre of Basauri, with very limited space. From commencement of the works in August 2007 to October 2009 the access gallery was performed, the entire Basauri station both the heading and bench excavation phases, the ventilation galleries and shafts and 550 metres of line tunnel. In total around 61,000 m3 were excavated in the medium grain sandstone and mudstone, a high strength lithology at simple compression.

Azbarren Mouth, Roadheader MT-720 no. 20: The tunnel excavation works commenced at the end of October 2007 after deviation of affected services such as demolition of the bridge over the FEVE and Euskotren lines, modification to the FEVE line layout, 1,800 of the water consortium piping, pedestrian crossings, etc.

From commencement of the works at the end of October 2007 until October 2009, 1,050 m of top heading and bench excavation line tunnel were performed of which 200 m were performed under injection umbrellas, full top heading of the Ariz station, the Valencia Street shaft, pumping stations and other auxiliary works, and in parallel and through the same access mouth 700 m of definitive lining were performed. In total 78,000 m3 were excavated.

5. RESULTS OBTAINED

General consideration. The result of the excavation with tunnel miners complied with the client's objectives, although while in some lithologies it worked very well in others many problems arose.

Geological unit	Lithology	K.P.	Roadheader	Performance	Consumption
				M3/h	P/m3
Oiz	Marls Phase I	1+150		49.94	0.07
Oiz	Marls Phase II	1+150		58.87	0.06
Oiz	Marls	1+150	No. 20	54.69	0.06
Yurre	Limestone-Siderite	1+299	No. 20	19.07	2.02
Yurre	Limestones	1+342	No. 20	40.51	0.47
Yurre	Medium grain sandstone and mudstone	1+952	No. 63	24.29	0.43
Yurre	Medium grain sandstone and mudstone	2+070	No. 63	22.21	0.58
Yurre	Medium grain sandstone	2+230	No. 63	18.54	0.36
Yurre	Medium grain sandstone	G.A. 37.5	No. 63	14.50	4.30

As can be seen from the data, excavation of the marls and limestones was satisfactory, while in the rest problems arose which should be evaluated
In the Azbarren mouth, performance was as expected at around 4-6 m/day depending on the support type applied and pick consumption was acceptable. In the Bidasoa mouth performance was much lower than expected and around 50% compared with that obtained in the Azbarren mouth excavated in marls. Pick consumption was 10 times higher.

5.1. Performance problems.

The problems centred on the sandstone in Basauri station. An analysis will therefore be made of the cuttabillity of the medium grain sandstone found in the auxiliary access gallery, the shunting neck and the Bidasoa Shaft.

Predicted / obtained performance. The predicted performance is based on the equipment used, type and power of the miner, head mounted and type of pick (defined by its diameter). Once the equipment had been selected the manufacturer was consulted and based on the project data considered that in the sandstone between 40 and 50 m3/ h could be expected to be reached. The performance obtained in the works performed was 14.7 m3/h.

5.1.1. Possible causes for the difference

Wrong evaluation of the rock. A possible cause for the difference in performance is poor estimation of rock strength. This may be due to the fact that to evaluate drillability of the rock the uniaxial compressive strength of the rock is used with a large weight. Uniaxial compressive strength (UCS) of a rock has great natural dispersion, but also has great dispersion depending on the laboratory where the test is performed. When referring to rock UCS this usually implies that tests should be performed based on a particular standard. In general when testing for calculating the supports to be installed a standard core with a sample slenderness higher than 2 is usually used, ASTM recommends a ratio of between 2 -2,5:1, ISRM suggests 2.5-3:1, but some tests are performed with slenderness 1. The relationship between both tests is well known, but the values obtained in the case in question were different.

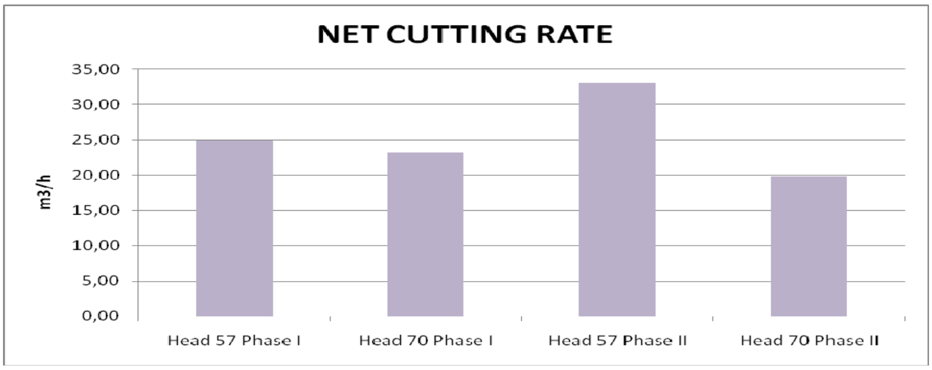
Laboratory	1	2	AVERAGE 1+2	3
Standard	UNE	UNE		ÖNORM B 3124
Slenderness 1	83.47	94.68	89.08	145.75
Slenderness 2	47.68	64.50	56.09	-

The value obtained based on the above table is 2.59 times. But it is noted that the cause for the difference may not only be the concept of slenderness, as with similar slenderness a ratio of 1.6 is obtained. A fourth laboratory was used to analyse this difference and the data obtained on a slightly different lithology are

Laboratory	4	3
Average UCS	92,45	99,77

In the above case the result is a ratio of 1.08 very similar to the data of international bibliographical references. In view of the foregoing data it is considered that it is not only important to select the correct test standard, with its features such as slenderness, load velocity, etc., but that the laboratory methodology should also be taken into account. Laboratory 3 subjects the test samples to a prior evaluation of the fissuration by ultrasound transmission, eliminating those which show signs of fissuration. Laboratory 4 was extremely careful in the visual selection of the test cores to be tested resulting in a behaviour of the values in accordance with bibliographical references. If the laboratory 3 values are used to predict performance, 16 m3/h is expected, which is very similar to the results actually obtained.

Wrong selection of the cutter head. The supplier is very clear on the type of head suitable for each rock, so an attempt was made to improve the results by testing changes of the head model. Firstly a 105-G57 head suitable for rocks with a UCS between 50 and 100 MPa was used, then a 105-G72 head was tested. The results were discouraging as no improvement was achieved.



5.1.2. Comment

The performances recorded are not the performances normally considered by the contractor in terms of m3 excavated per hour worked. Performance is calculated by dividing the volume excavated by the net cutting hours, that is those in which the miner cutting engine is working, but with the difference that it must be consuming more than 100 A (in this case with the 300 kW head).

Machine	No. 63	No. 20	Total	%
Pick change	328.75	44.25	373.00	5.31%
Cleaning	197.25	308.25	505.50	7.20%
Rest of cutting	1978.18	1793.57	3771.75	53.74%
Net cutting	1431.32	936.42	2367.74	33.74%
TOTAL	3935.50	3082.49	7017.99	100.00%

This data indicates that real performance is a third of net performance, although the ratio between the two is extremely variable.

5.2. Pick consumption problems

Predicted / real consumption. To establish predicted consumption, the design project provided CERCHAR (CAI) and Schimazek index values. The usual calculations also take into account rock UCS. Specific pick consumption in transversal cutting head, low speed cutting, high quality pick with inserts of 22 mm in diameter, considering the sandstone with a UCS value of 55 M Pa and CAI of 1.3, was expected to be 0.040 picks / per solid m3 excavated. The consumption actually obtained was 4.48 picks/m3. That is the consumption obtained in the section was 100 times higher.

Possible causes for the difference. Wrong estimation of the rock mass. We should remember that pick wear depends not only on abrasiveness of the formations (essentially related with the mineralogical composition) but also on rock strength. As has already been mentioned, the rock is average strength and given the CERCHAR values obtained it could be expected that the rock would not prove highly abrasive. One of the causes of the difference between the expected and real consumption seems to be related with the norm used in the laboratory test.
If for the forecast of the pick consumption, instead of using the project UCS determinations we use those of laboratory 3 (UCS of 145 M Pa), we find that we should have expected a consumption of 1.3 picks/ m3, much closer to the values obtained.

There is also a difference in determination of the CAI values depending on the laboratory in which they are performed.

Laboratory	1&2	3
No. of Data	6.00	15.00
Average	1.23	2.66
Mode	1.20	2.50
Deviation	0.41	0.30

Using the laboratory 3 values we should have expected pick consumption of 4 picks/ m3, very close to the values actually obtained.

Unsuitability of pick type The study of the possible causes of the high pick consumption, considered the possibility that with an increase in the insertion diameter, the pick consumption would decrease. Different picks were tested with unequal results.

	Pick	No. Picks	Ud/m3	€/m3
Massive A. K.P. 35.2-37.3	d=22	462.00	5.04	68.03
Massive A. K.P. 37.3-38.1	d=22	273.00	7.82	105.53
Massive A. K.P 38.1-42.7	d=25	1,000.00	4.98	84.16
Massive A. K.P. 42.7-45.1	d=22 Betek	500.00	4.77	67.72
A. with fault K.P. 45.1-47.65	d=22	470.00	4.78	64.60
A. with fault K.P. 47.65- 52.70	d=25 special	999.71	4.28	86.81
Massive A. K.P. 60.3-62.3	d=25	466.00	5.38	90.87
Massive A. K.P. 62.3 - 66.25	d=22	380.00	3.26	44.03

The values obtained indicate that no advantage is obtained with an increase in insertion diameter while there is an increase in the cost per unit.

Head change Head change obtained a slight reduction in pick consumption, but so small that this was not advisable due to the decrease in performance.

	Price	No. Picks	Amount	Ud/m3	€/m3
Head 105 G-57+ phase I	13.50	307.00	4,145	0.13	1.81
Head 105 G-72 Phase I	13.50	194.00	2,619	0.11	1.53

6. CONCLUSIONS

The experience of construction of the extension of line 2 of the Bilbao Metro shows that low cutting speed roadheaders are suitable for excavation in competent rock.

To prevent financial setbacks, it should be considered that the uniaxial compressive strength valuations obtained for the support project are not automatically applicable for estimating predicted performance with tunnel miners, as their test standard and the objective, the former focussing on estimating the weakness of the rock and the latter strength, are different.

Evaluation of suitability of the miners for a work should consider a number of factors, not only strength, but also toughness and abrasiveness, all determinations of mechanical properties which show great deviation. This should be considered in contractual relationships.