



Payment for tunnel construction by means of the Standard Rate method: Experience on the Bilbao South Metropolitan By-pass

C. Estefanía¹, J.A. Fuldain², J.A. Laguna³, M. Arlandi⁴, ¹ *Diputación Foral de Bizkaia, Bilbao, Spain*; ² *Idom Ingeniería y Consultoría, S.A., Bilbao, Spain*; ³ *Dair Ingenieros, Leioa-Bizkaia, Spain*; ⁴ *Geoconsult Ingenieros Consultores, S.A., Madrid, Spain*

1. INTRODUCTION

This paper contains a summary of the way of contracting and pay we have used in the construction of four stretches of the Bilbao South Metropolitan By-Pass (SMB), especially in those which included tunnels in its alignment. Five double tunnels have been bored within these four contracts, resulting in a total length over 15 Km. of underground work, all of them using the drilling and blasting method

The usual way of payment in Spain of the works performed consists on applying contractual unit prices to the actual bill of quantities of the work, both in common Public Work Contracts and in those which imply an underground work. Tunnel construction is known because of frequent unforeseen events and difficulties that increase the final cost and extend the construction period. The Contractors have usually taken advantage of these circumstances in order to justify the carrying out revisions of the Contract, which will allow them to solve, totally or partially, the economic problems caused by excessively low initial prices.

Being this situation known, at the beginning of the Design stage of SMB we disposed a work group that would analyse the possibilities of contracting the construction of tunnels differently, with some basic principles:

- With some certainty and within a prefixed range, the final price to pay for a subterranean work should be known and fixed.
- Out of the previous range, the modification of the final price should be definitely established.

Summing up, we try to determine a payment system that could not be objected, neither officially, nor technically; apart from the fact that it would be necessary to establish a usual geotechnical parameter (index Q, RMR) continuously, following the tunnel execution. However, **the ultimate aim would be, not only to specify the Index itself, but, above all, to include it within some ranges**, which would limit greatly the possibility of disagreement between the evaluation of the Contractor and the one of the Supervision Team.

2. THE WEIGHTED INDEX

In general, tunnel design means the use of a group of typical cross-sections of support or reinforcement and lining. Using one typical cross-section or another depends on the range in which a specific index is located. In our case, it was decided to use four different cross-sections in the Design regarding the value of Burton's Index Q. Being S₁ the lightest and S₄ the heaviest:

Cross Section	Range of Index Q	Foreseen Percentage	Used length Si	Max. length without support	Number of lengths per unit time
S ₁	Q > 10	P ₁ %	L x P ₁	L ₁ = 4 m	n ₁
S ₂	10 > Q > 1,0	P ₂ %	L x P ₂	L ₂ = 3 m	n ₂
S ₃	1,0 > Q > 0,1	P ₃ %	L x P ₃	L ₃ = 2 m	n ₃
S ₄	0,1 > Q	P ₄ %	L x P ₄	L ₄ = 1 m	n ₄

Table 1. - Typical Cross-Sections

In this way, the precise time needed for the tunnel execution would be given by this formula:

$$T = \sum_i (L \times P_i) / (n_i \times L_i); \text{ that is } T = L \times \sum_i P_i / (n_i \times L_i).$$

Even when the formula gets a bit tricky and longer, as in our case, being the construction foreseen in two stages (heading and bench), it can be displayed, naming $l_s = \sum_i P_i / (n_i \times L_i)$, that $T = L \times l_s$, or, in a more general way:

$$T = A_0 + B_0 \times l_s,$$

Where A_0 and B_0 are constants.

In other words, a tunnel construction period has a linear correlation with a parameter that we name "Weighted Index", and which depends exclusively on the geomechanical characteristics of the bored rock mass, specifically on the percentages in which that rock mass can be classified inside some predetermined ranges of index Q of Burton.

3. COST FRAME OF TUNNEL CONSTRUCTION

It is widely known that the construction cost of a tunnel is, being practical, directly related with its Construction Period. At a first developing phase of the idea, the cost frame of a tunnel construction was studied, with this result:

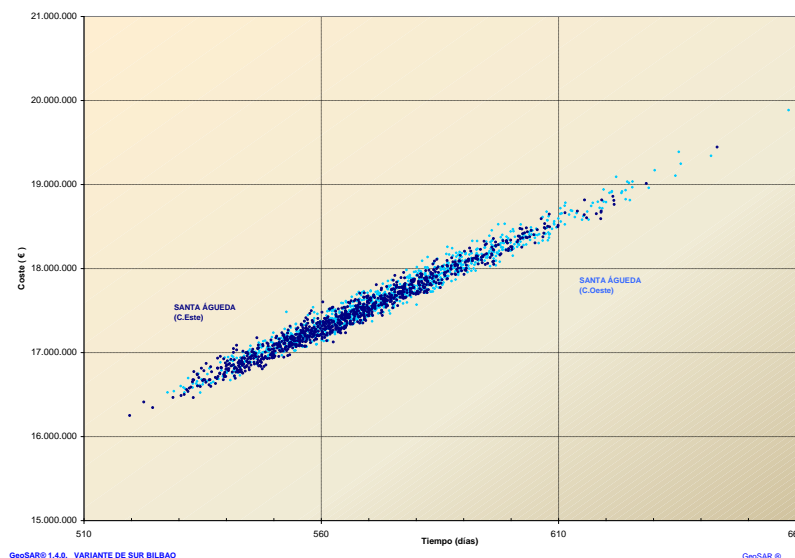


Figure 1. - Simulation of the tunnels of Santa Águeda (time-cost)

- FIXED COSTS, independent from specific circumstances that could affect underground works: start-up costs, power supply and other services, proportional part of the budget assigned to the work superintendent and management... This cost is named FC.

- VARIABLE COSTS, depend on the duration of the construction, such as the hire or recovery of tunnel machinery (jumbo, shotcrete robot, extraction and transport machinery of digging products), hire of equipment of personnel directly assigned on the underground work. In general, there is a linear correlation between this cost, VC, and time. (VC/unit of time for example). Except from small settlements, the Contractor will withstand this cost per unit of time, independent from the real pace of the works.
- COSTS PROPORTIONAL TO THE PRODUCTION, which enclose, above all, material costs of the construction (podwer, shotcrete, bolts, steel arches...). They are fixed costs for a determined typical cross-section. They turn into variable costs depending how much the typical cross-sections do differ from the ones foreseen in the Project. Naming them C_i , that is, cost per unit of length of the typical cross-section i .

Then, the Total Cost of the tunnel will be:

$$TC = FC + VC \times T + L \times \sum_i (C_i \times P_i)$$

4. FIRST APPROXIMATION TO THE COST FUNCTION

From the previous equation, it is inferred that, for a certain tunnel, if the distribution among the different typical cross-sections is considered fixed, then the cost depends linearly on just a variable, that is, construction time T .

Besides, has it has been shown in (2) time is a linear function of the Weighted Index, so we can synthesize the cost function through the equation:

$$TC = A1 + B1 \times Is + L \times \sum_i (C_i \times P_i)$$

Where $A1$ and $B1$ are constants.

Till here, this formulation is exact. In our case, we took a step through in order to simplify the last equation: being linear costs proportional to production higher in the heavier cross-sections, they lower when lighter cross-sections are used, that is, following the growth or the falling of the Weighted Index. Therefore what the matter is about is to consider if a general approximation to the cost like this is accurate enough:

$$TC = A + B \times Is$$

Where A and B are constants.

The quality of this approximation was inferred by a complete simulation work, calculating the exact costs that would be obtained from some "basic tunnels", according to the variation of the distribution of the different typical cross-sections. These exact costs were put into comparison with the ones coming from the "basic budget" and the consideration of a cost function linear with the Weighted Index. This figure shows one of the simulations made.

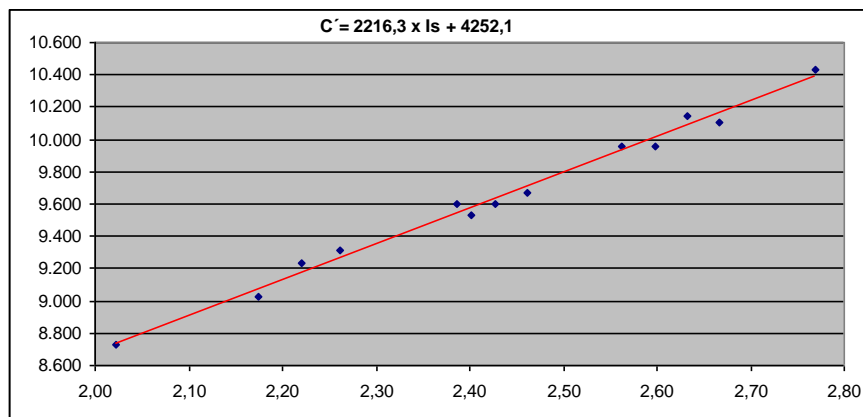


Figure 2. - Example of correlation simulation (WI-Cost)

It was possible to estimate that, for a reasonable variation of the WI, the difference between exact costs and the costs obtained from a correlation with the Weighted Index, were, in absolute value, lower than a 0.7%. In conclusion, we could put into correlation, being accurate enough, tunnel construction costs with the referred Index.

The method to determine this linear function of the cost is simple: locating in a chart the Weighted Index in the axis of abscissas and the Total Cost in the axis of ordinates, the cost line (R_0) would be perfectly determined as a linear function of the Weighted Index. From the Design data it is possible to obtain easily the following values:

- Project Weighted Index (WI_0), deduced from the foreseen distribution of the different typical cross-sections.
- Total construction Cost (TC_0) regarding this Index, that is, the value inferred from the theoretic bill of quantities multiplied by the corresponding unit prices.
- Total Cost (TC_1) that would result in from supposing the typical cross-section distribution different from the foreseen, in other words, associated with a WI_1 Index.
- The Slope of the linear function, which is $B = (TC_1 - TC_0) / (WI_1 - WI_0)$.

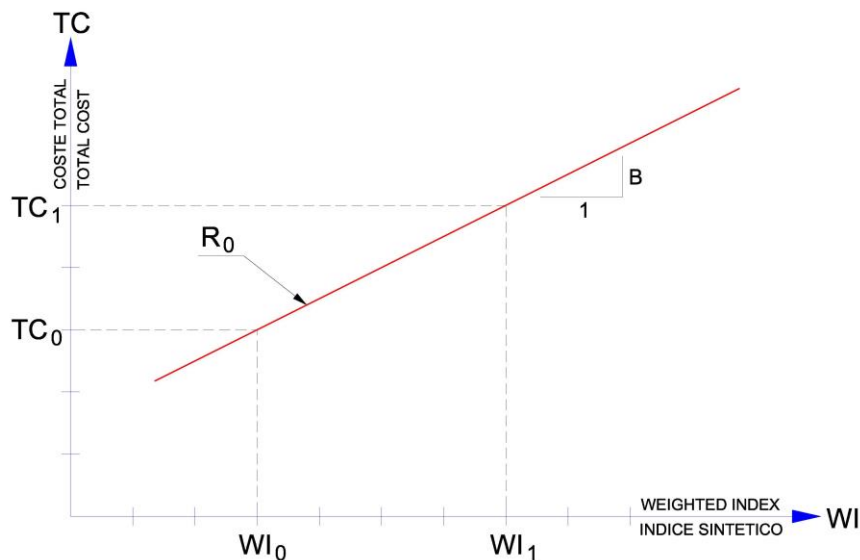


Figure 3.- First approach to the relation WI-TC

5. SECOND APPROXIMATION TO THE COST FUNCTION

The function R_0 defined in the last section would become a very accurate approximation to the cost providing that the whole underground work was performed just applying some predefined typical cross-sections. Nevertheless, a tunnel as a whole makes for other works that were interesting enough to be taken into account, which means to include their costs in our work scheme. There are two kinds of these complementary works:

5.1. Spot Reinforcement

For usual boring conditions, it is enough to use one of the typical cross-sections foreseen in the Design. However there would possibly be founded areas with difficulties in which it would be necessary to complement the use of a typical cross-section with complementary specific measures. For instance: sealing of the excavation face with shotcrete, use of fiberglass bolts, forepoling, punctual construction of invert-vault, use of self-drilling bolts, exhaustion of extraordinary flows, perimeter grouting, filling of holes with concrete or polyurethane...

Summing up, we include in this section those ground reinforcements that are considered to be possibly used, but whose quantity of use or placement cannot be precisely set because of the random nature of the ground.

Their economic estimation is usually considered as a percentage of the civil work budget, provided their random nature. In a common contracting procedure (bill of quantities and unit prices) this estimation would be taken into account as a precaution against eventualities.

To rate the percentage of spot reinforcements proposed in each tunnel, these aspects will be considered:

- Technical difficulty in the tunnel construction.
- Level of knowledge reached in the geotechnical research.
- Past experience in the construction of similar tunnels.

In the five double tunnels constructed in the SMB, there were applied percentages that ranged between a 7 and 15 % of the total cost of the underground work.

To sum up, in order to include this concept in the system we are developing, it is determined for each tunnel an additional cost percentage to apply to the whole of the costs estimated so far, so that we can establish a cost function specific for each tunnel. This function is named R_1 .

5.2. Complementary work previously known

For example, works like the drilling and reinforcement of the tunnel portal, specific works along the first meters of the tunnel (micropiles umbrella, specific reinforcements...) and, even part of the not underground works, like the construction of artificial tunnels and the following fillings to restore the ground to its initial state.

Summing up, it is about a group of works which cost can be known quite accurately. Including this concept in our cost function R_1 is as simple as adding up a constant (ΔTC), that is, turning R_1 into R_2 .

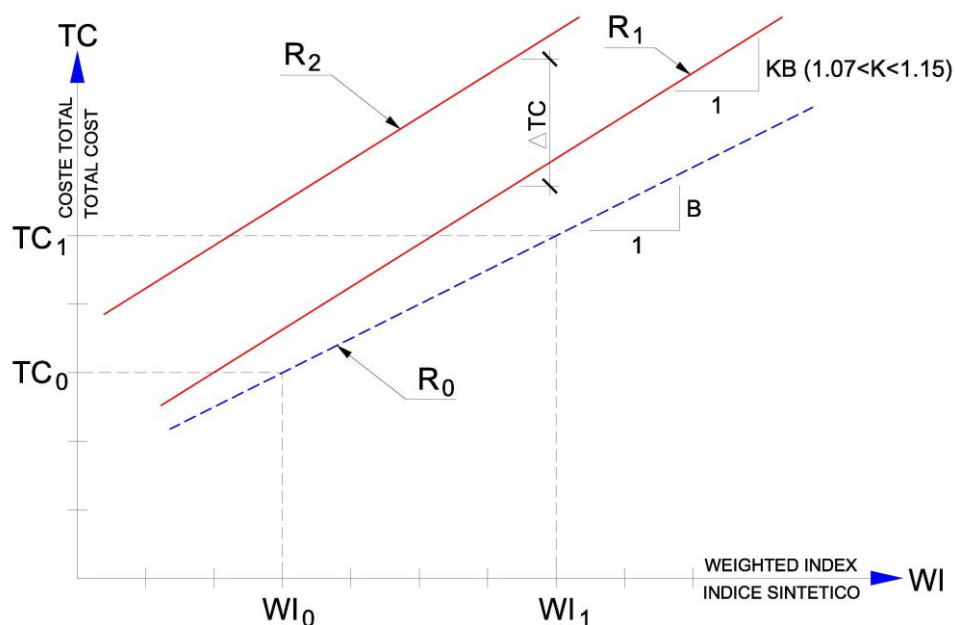


Figure 4.- Definite approach to the relation WI-TC

All in all, we have ended up stating a linear cost function which allows us to establish the final cost of the works, depending on the Weighted Index WI that eventually results in during construction. This estimated cost contains the construction of the underground works, gives a cover against eventualities (up to a reasonable edge) that could appear, and can include as well a certain volume of works related with de underground works that we want to pay by means of the Standard Rate method.

6. OUTLINE OF THE PAYMENT SYSTEM DEVELOPED

Starting from line R₂ already defined that represents the Cost, it is left to define a payment criterion, what was done following this procedure:

6.1. Setting a constant price interval around the Design Weighted Index (WI₀)

It is about setting an interval around the weighted Index. If at the end of the works that Index was located inside the prefixed interval, the total payment to the Contractor would be fixes. The determination of the range of that interval basically depends on level of geotechnical research reached in the Design stage.

In our case, we set the range of this interval (ΔWI) differently in each tunnel after an statistic analysis that would let us assure, with a level of confidence of a 90 %, that the final Index would result inside the interval. This minimum interval could be improved by the tenderers. Once concluded the works, that interval turned out to be too conservative.

The price to pay, if the final Weighted Index was located inside the interval, would be the value deduced from the cost function considering

$$WI = WI_0 + 2/3 \Delta WI$$

6.2. Setting a minimum and maximum price

Being confident that in no case it would go as far as to make the maximum payment, nor the minimum, we set them in an arbitrary way in a 120% and an 85% respectively.

Finally, we have to establish the way of putting together these two limits through a pay-line, with a criterion, that the pay-line would always end up above the estimated cost line.

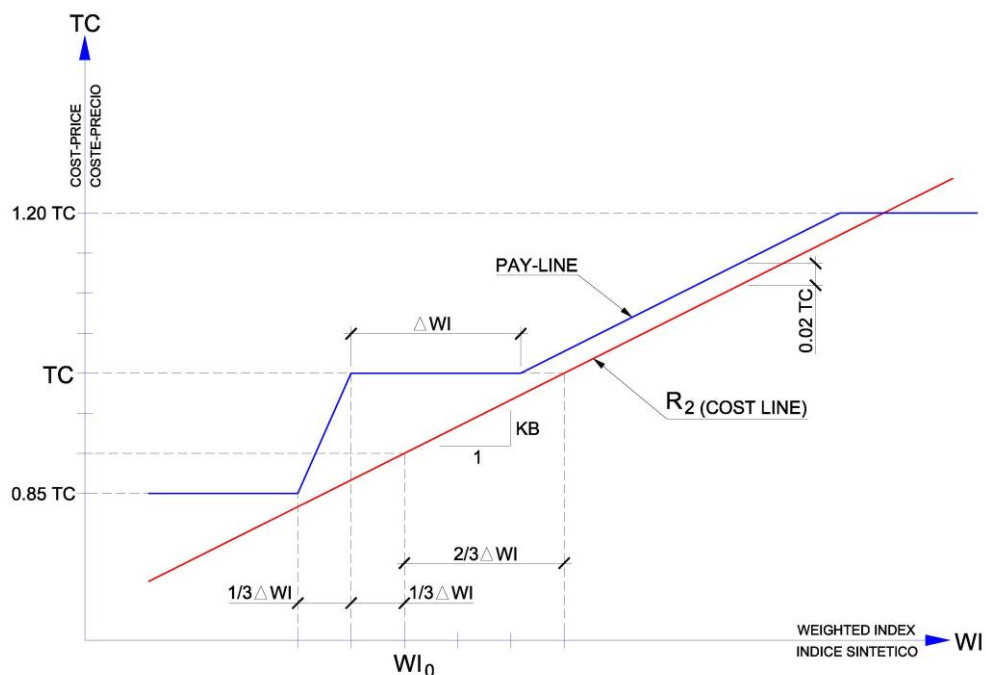


Figure 5.- Cost line and Pay line as a function of WI

In this way we finish setting the pay-line, that resulted to be quite similar to the one showed in the attached figure (Fig. 5).

It is necessary to point out that Cost Line R_2 is based, basically, on two aspects:

- On one hand, it is based on the values of a geomechanical index, index Q of Burton in our case.
- On the other hand, on the supposition of a reasonable efficiency in the construction. It is obvious that as long as the Contractor succeeds in exceeding an average supposed efficiency through a better practice, he will lower his costs without modifying the pay-line, and so, he will increase his regarded benefits.

The system transfers a limited risk level to the Contractor, who expects a higher benefit than usual, above all, up to the extent to which he speeds the construction up. As for the Owner, it has the advantage of letting **know beforehand, with as much certainty as it is required, what the final price to pay would be.** On site, the controversy gets limited to estimate a technical parameter (index R, RMR or Q).

7. OUTLINE OF THE DEVELOPED CONTRACTING PROCEDURE

Besides the scheme explained in the previous sections, it was necessary to develop specific Terms of Reference that would enclose the singularity of the contracting procedure that was set out. As far as we knew, we were not aware of the existence of Contracts performed with a similar system, then, it was required to develop from the beginning the Terms of Reference, both Technical and Official.

Lacking previous experiences on which to base ourselves, it was tried solving and bringing forward all the issues we understand could be important in order to implement a new system, both for the Owner and the Contractor. Among other aspects, there were studied the conditions to solve:

- Possible faults of any kind of the Design. The tenderers ought to study the Project and **assume it as their own explicitly**, or, otherwise, set out the relevant correction as part of their own tender, so that in any case these possible faults could be the cause of a later economic claim.
- The amount of partial payments to the Contractor on site.
- The technical interpretation of the Design, both the initial, or the modified one that could have been proposed by the Contractor in his offer as an alternative.
- The decision taken in each case on the kind of support used, that is, the range in which the index Q is located in each situation.
- The decision on the need or convenience of applying spot reinforcements. System of penalties because of not applying them.
- Corrections on the Contract period caused by differences between the initially supposed Weighted Index and the eventual one.
- Bonus or penalties that would concern for bringing forward the dates or not meeting the deadlines.

8. RESULT OF THE EXPERIENCE

The bidding of the construction works was in the end of 2006, starting the construction in May 2007. When redacting this paper, the construction Contracts are not over. At the moment control and security facilities are being installed. However, all the underground works are accomplished.

The following table shows the group of tunnels executed:

Tunnel	Total length (m)	Initially foreseen index	Range of the Contract*	Final resulting Index	Price of contracts
Argalario - Mesperuza	1.816/1.794 561/ 590	79,15	72,73-91,78	77,60	58,10 M€ 87,15 M.US\$
Santa Agueda	1.964 y 1980	67,72	58,10-89,38	61,36	40,87 M€ 61,30 M.US\$
Arraiz	2.261/2.264 365	76,98	72,27-86,38	72,73	60,65 M€ 90,97 M.US\$
Larraskitu	855/831	83,95	75,55-100,77	86,66	38,44 M€ 57,66 M.US\$

Table 2. - Tunnels Constructed

* Range Offered by the Contractors, usually increasing the minimum foreseen in the Terms of Reference

The Weighted Index has finally resulted in every case inside the interval of the economic offer, and, besides, very close to the values foreseen in the Design. In consequence, the amounts finally paid to the contractor for the underground work construction have been exactly the offered, without any kind of extra cost for the Owner, and, which are the ones shown in the previous table (Table 2). The only quantities paid besides these, which have supposed less than an additional 2%, have been caused by the adjustments (promoted by the Owner) of the civil works contracted to introduce some facilities, and which are related with additional work and not with any kind of economic claim made by the Contractor.

Only when we had some certainty about the geotechnical difficulties that could appear and that were properly enclosed in the design, the system was started. This could no have been done without a very intense geotechnical research campaign. It was just the amount of this campaign that exceeded 3,0 M€ (4,5 M.US \$), being the campaign performed in two stages.

Moreover, the Supervision team that specially focused on the supervision of the underground works, was much more larger than usual. We can add too, that the possible degree of disagreement between the quoted Supervision team and the Contractors have been almost nonexistent as for execution and pay of the underground works, probably caused by the fact that, following the Contract, there were very few issues to argue about.

In consequence, we understand that the contracting and payment system we have presented has allowed to comply with the prefixed objectives of price and deadline of a matter usually as complicated as the construction of underground works.