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Directional Core Drilling as an Approach to Reduce Uncertainty in Tunneling Construction

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Abstract: The definition of a rock mass's characteristics is crucial in underground construction to avoid delays and cost overruns. This study proposes a system to quantify the economic uncertainty related to a lack of knowledge of a rock mass in the tunnel construction stage, either for tunnel boring machines or for drill and blast excavation techniques. Using a back-analysis of three actual tunnels completed in Spain (Burata, Lot 3 of the Pajares variant, and Bolaños), the study assessed the directional core drilling technique (DCD) for this purpose, comparing it with conventional boreholes. In this regard, the DCD approach reduced the uncertainty by between EUR 6.7 and EUR 12.7 for every EUR 1, while the total cost of the drilling campaign remained within a widely accepted proportion of the construction budget. Overall, the uncertainty was reduced by approximately EUR 6000 per meter of the tunnel.

Keywords: tunneling; drill and blast; TBM; directional core drilling; uncertainty

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1. Introduction

The construction of any tunnel or underground work, whether in soil or rock, is associated with a high degree of uncertainty regarding the geomechanical characteristics and stability conditions throughout all of the stages of a tunnel project [1,2]. In this sense, qualitative and quantitative assessment of tunnels has attracted a great deal of interest in recent decades [3], with the idea of integrating the ground conditions into a holistic analysis system for the construction phase of a tunnel. Many case studies have been assessed to define the costs and characteristics of the construction phase of a tunnel [4–12], finding the ground characteristics to be the most relevant factor. Despite the amount of research completed to date, each case has its particularities related to the results and conclusions extracted, due to the uncertainty associated with subsurface excavations, making it difficult to obtain a generalized approach. One of the existing techniques that can provide the most relevant information, and reduce the uncertainty, is to create boreholes that intercept the tunnel route which are used to determine the degree of fracturing, the characteristics of these fractures, the presence of water, and the intact rock features [13].

The information obtained from the subsurface has inspired several authors. For instance, Paraskevopoulou and Benardos [14] presented an approach for determining the cost of a tunnel based on the GSI, while Benardos et al. [2] made an interesting adaptation of the study by Hoek [6] to estimate the costs generated by the excavation and support processes as a function of the ground conditions and excavation diameter. On the other hand, Rostami et al. [12] presented an empirical approach but with an important dispersion due to the geological uncertainty faced in tunneling. Petroutsatou et al. [15,16] indicated that the geotechnical independent parameters that define a tunnel's support requirements, and therefore the associated costs, comprise the GSI, rock mass deformation, depth, and cross-section excavated. However, the traditional approach to determining the relevant parameters for vertical or inclined boreholes only provides knowledge on specific parts of a future tunnel. Such approaches are unable to obtain information on the entire route of a tunnel without incurring excessive costs and impacting a project's viability. This fact creates an important remaining uncertainty that can influence the total cost of a tunnel and the finishing deadline due to low excavation performance [17] or TBM entrapments [18], among other setbacks. It also leads to potential problems in terms of the physical stability of the construction and environmental and safety issues [8,19–23]. Therefore, it is crucial to define a general and flexible system for analyzing costs in the construction phase of a tunnel and, therefore, reduce the uncertainty of the project whenever possible [24].

Directional core drilling (DCD) is a technique that can help to improve the subsurface knowledge in a tunnel construction project. It combines two pre-existing and well-known techniques: drilling with core recovery and directional drilling [25–27]. These techniques have been applied successfully in mine exploration in recent decades [28,29], as well as in recent tunneling projects [30–32]. The techniques permit drilling up to a few kilometers with directional changes [33] and are especially relevant in fault areas and the portals of tunnels. On the other hand, horizontal core drilling (HCD) has also been used for tunnel characterization, and it requires the machine to be placed at the same level of the tunnel as an advanced or parallel tunnel [34–36]; therefore, it requires a previous excavation stage. However, the DCD system allows for testing along the planned tunnel trajectory from the surface or another non-parallel placement, and it is able to characterize the geological and geomechanical properties of the rock mass to be traversed. Thus, it can be used to estimate expected construction costs, along with the associated execution time and the magnitudes of the risks faced by a project.

The goal of this study was to define the benefits of directional core drilling (DCD) for the geological, geotechnical, and hydrogeological characterization of a tunnel project. Defining a methodology for the assessment of DCD vs. conventional boreholes and comparing the levels of uncertainty and their associated costs. Several methods to evaluate tunnels have been developed [37,38] but these focused on some particular issues of tunnel construction. The approach proposed here attempts to reduce uncertainty, or lack of knowledge, about representative parameters of a tunnel project. From the technical point of view of directional core drilling, the system proposed is particularly suitable for analyzing long stretches of shallow tunnels where the entire route can be investigated, and problematic areas of deep tunnels that require detailed information on a stretch.

2. Case Studies

Three actual tunnels from Spain were selected for the analysis: the Burata, Pajares variant Lots 3–4, and Bolaños tunnels. These projects were selected because they are representative of different problems that may arise during the execution of a tunnel due to a lack of information and uncertainties before beginning work. The first was excavated by drill and blast, categorized as low depth and small–medium length. The other two tunnels were excavated by tunnel boring machines (TBM) at low and great depth, respectively. The projects were analyzed based on the information from the project stage and the tunnel excavation stage.

The Burata tunnel was excavated using the drill and blast method, and it has a main tunnel and an additional small parallel tunnel. Its length is approximately 4000 m, and it reaches a maximum depth of approximately 200 m. Its rock mass is composed of granite with differing degrees of alteration. The tunnel was analyzed as a project phase, where the green areas in parts (A) and (B) of Figure 1 correspond to a highly weathered granite residual soil. Part (A) corresponds to the cross-section completed with conventional vertical boreholes, and part (B) shows the real conditions that could be determined using directional core drilling, which detected several additional areas with poor rock mass conditions. The main characteristics and setbacks found in the tunnel have been described by several authors [35,39,40].

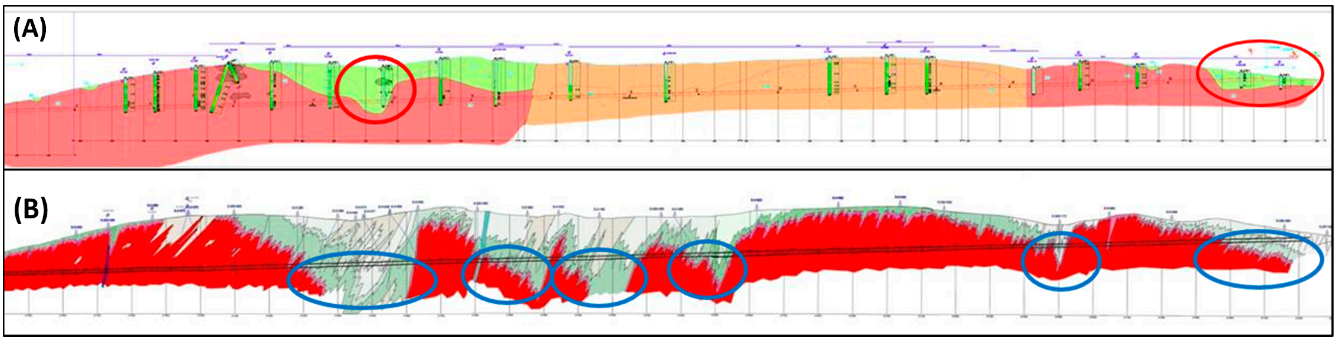

Figure 1. The Burata tunnel's geological cross-sections obtained using conventional vertical drilling (**A**) and directional drilling (**B**).

Lot 3 of the Pajares variant is a single tunnel of 10 km in length that is part of the total infrastructure of a twin tunnel of 23 km in length. A single shield TBM with a 10 m diameter was used for the excavation. The maximum depth is approximately 1000 m, and mainly sedimentary rocks were excavated. This study focused on a stretch with potential squeezing conditions and methane emissions. The tunnel was analyzed as a project phase, using real data from the excavation process. Figure 2 presents the initial geological cross-section (A) and the real cross-section once the tunnel was complete (B). As can be seen, there was a formation not detected through the initial vertical drilling campaign. The geology of the Pajares variant tunnels was well-described by Alonso and Rubio [41], who analyzed the area marked in Figure 2. This particular stretch of the tunnel, called the San Emiliano formation, presented singular stability problems [42,43].

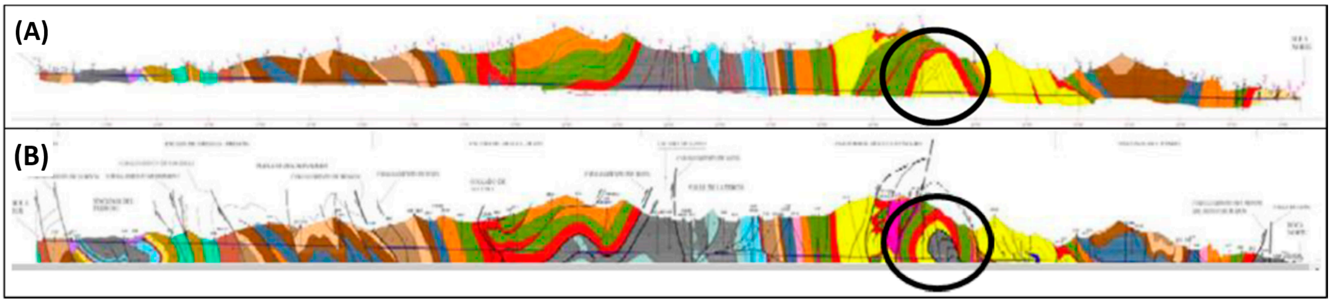

Figure 2. Geological cross-section of the Pajares variant Lot 3 tunnel.

The Bolaños tunnel has a 10 m diameter and is a twin tunnel, though we analyzed only one of them in this study. The analyzed tunnel was excavated using a single-shield TBM. The length of the tunnel is approximately 7000 m, and it has a depth of approximately 200 m. The rock mass consists of slates, quartzites, and sandstones (Figure 3). The study was focused on an area with faults and special requirements for waste management, which can affect the advancement and management of the excavation process.

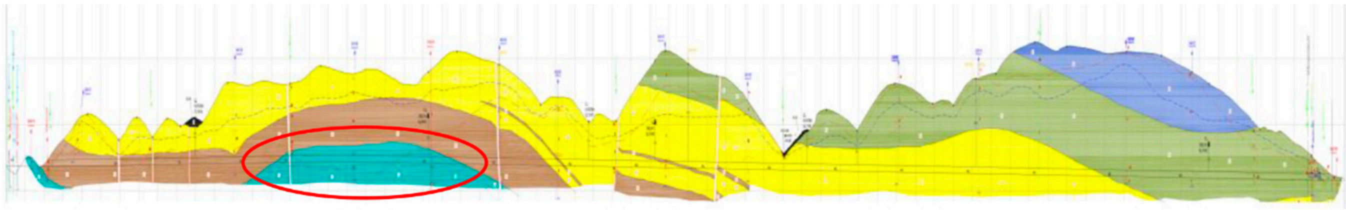

Figure 3. Geological cross-section of the Bolaños tunnel.

DCD Technique

The DCD technique can be used in petroleum and mineral explorations, as well as tunnel projects. One of its typical uses is side-tracking drilling for investigating a certain subsurface region, directing the drill string according to the planned trajectory required in the project. In addition, multiple branches of drill holes can be created, extending out from a single primary hole drilled from one position. The principle of the system has three components: (1) planning the drilling trajectory required with the bending and roll angles required; (2) steerable drilling with a control system to obtain the drilling direction and curvature trajectory; and (3) coring orientation surveying using an electronic multishot system (EMS) to record the inclination and azimuth along the drill hole, verifying the planned trajectory and correcting it if necessary [31,32].

3. Methodology for the Uncertainty Economic Valuation

In this study, uncertainty was defined as the difference between the cost of a part of a tunnel's construction when some variables were unknown and the costs when they were known due to the application of a better technique. Uncertainty was always considered undesirable, and the cost was either higher or lower than initially assessed. If the project cost was higher than the actual final cost, then the developer of the infrastructure—usually the public sector—could waste large amounts of economic resources and the construction company could reach a bankruptcy situation if the initial costs estimated were lower than the actual value. In both cases, society as a whole is negatively affected.

Thus, an approach was proposed for analyzing the costs associated with uncertainty when two drilling techniques—conventional boreholes and directional core drilling—were used during the exploration phase. We determined the costs when using both systems and the lengths of the tunnel recognized with each one. Subsequently, an economic valuation of the uncertainty that existed when using both systems was completed to assess the cost overruns estimated during the exploration phase for both options and the main aspects influenced by a better understanding of the ground conditions. In addition, a comparative analysis was completed to economically assess the uncertainty when using each drilling system. The calculations were based on real average costs from Spain in 2020.

The economic quantification of uncertainty during the exploration and ground characterization phase does not mean that this quantity of money will be saved during the construction phase. In general, the cost during the construction phase will be the same because it is fixed by the ground characteristics. However, it implies that the real cost will be estimated more accurately and known in advance, which will allow for better developing the project, and this will be positive for tunnel construction.

It cannot be considered that all cost overruns and impacts arising from unfavorable site conditions can be prevented if DCD is adopted. The use of DCD can lead to the adoption of mitigation strategies that can reduce both these cost overruns and adverse impacts but it will not entirely eliminate them.

3.1. Borehole Costs

The cost determination of a borehole can be completed using Equation (1), which applies to conventional and DCD techniques, as follows:

$$C_b = C_{b0} + C_b \cdot l_b, \quad (1)$$

where C_b is the total borehole cost (EUR), C_{b0} is the transportation and preparation cost of the drilling equipment (EUR), C_b is the linear drilling cost (EUR/m), and L_b is the borehole length (m).

The costs for transportation and preparation were the same for both drilling alternatives, with an average price of approximately EUR 3000, while the cost per meter drilled was approximately EUR 100 per m for conventional drilling and EUR 200 per m for the DCD technique. This difference per meter drilled was because of the additional equipment required for directional drilling, which had an average rental price of EUR 100,000 per month and a drilling yield of 1000 m per month. In addition, it was considered that each vertical borehole obtained information for a 20 m length of the tunnel (10 m for each side), while the DCD technique obtained information for the whole length of the tunnel's axis.

3.2. Costs Related to Drill and Blast Excavation

Cost overruns are mainly associated with poor rock mass conditions, creating additional costs related to supports, steel, and concrete, as well as working delays.

3.2.1. Support and Lining

A worsening in a rock mass's quality is related to the need for more robust supports, increasing the use of shotcrete, bolts, ribs, or thicker linings. In this regard, Equation (2) considers the additional costs of support materials:

$$C_s = C_{st} \cdot M_{st} + C_c \cdot M_c, \quad (2)$$

where C_s is the total cost (EUR), C_{st} is the price of the steel used for t ribs and rock bolts (EUR/t) (with an average cost of 1750 EUR/t), C_c is the price of concrete (EUR/t) (with an average cost of 85 EUR/t), M_{st} is the mass of the steel (t), and M_c is the mass of the concrete (t).

The typical supports applied in drill and blast excavations are mainly formed by a combination of three elements (bolting, steel sets, and shotcrete), where the quantities and qualities of these elements define their maximum load capacities [44]. Thus, there are many different combinations of these elements, with some well-known and established recommendations depending on rock mass conditions. In this study, we used the approach established by Romana [45], which is based on the approach proposed by Bieniawski [46].

The property definitions of the materials used in the supports were necessary for the analysis, and we used the parameters defined by Cornejo [47] in the Spanish tunnels studied. For instance, one of the more common material combinations was rebar steel bolts with diameters ranging from 25 to 36 mm and maximum tensile strengths ranging from 482 to 844 kN; concrete with compressive strengths ranging from 25 to 45 MPa; and ribs with a TH profile and a yield strength of 240 MPa.

The mass of the steel and concrete used for a tunnel support can be determined following the procedure detailed by Rodríguez and Pérez [44]. Thus, a simplified procedure for tunnel excavation is proposed using Equations (3) and (4), as follows:

$$M_{st} = m_{st} \cdot (L_f - L_0) \quad (3)$$

$$M_c = m_c \cdot (L_f - L_0) \quad (4)$$

where M_{st} is the steel used for the support (t), M_c is the concrete used for the support (t), L_0 is the initial length of the excavated tunnel (m), L_f is the final length of the excavated tunnel (m), m_{st} is the specific steel consumption (t/m), and m_c is the specific concrete consumption (t/m).

Regarding lining usage, the thickness typically applied varies between 35 and 45 cm in most Spanish tunnels, with no variations based on rock mass quality [44]. Therefore, lining was not considered in this analysis.

3.2.2. Performance Decreases and Delays

Quality decreases in a rock mass along a tunnel's layout result in lower excavation advances, increasing the duration of tunnel construction. Equation (5) defines the advancing rate of a tunnel excavated by drill and blast techniques [44], based on the RMR [46]:

$$a_b = \frac{RMR - 20}{10}, \tag{5}$$

where a_b is the advancement per blast (m/blast).

The construction of a tunnel, as with any other economic activity, entails fixed costs, such as salaries, insurance policies, machinery rentals, or fees related to water usage, among many other common factors. Usually, the most important fraction of fixed costs comprises staff salaries, and this cost is considered as the cost of uncertainty associated with duration increases in tunnel construction. Equation (6) defines the number of days required to excavate a tunnel as a function of the number of blasts, and Equation (7) determines its associated fixed costs.

$$T = \frac{L_f - L_0}{n_b \cdot a_b} \tag{6}$$

$$C_f = c_f \cdot T \tag{7}$$

where T is the time required for the tunnel excavation (days), n_b is the number of blasts per day (blasts/day), C_f is the total fixed costs for a given period (EUR), and c_f is the fixed unit cost (EUR/day). A common daily fixed cost is EUR 12,000.

3.2.3. Special Support Treatments

When rock mass conditions have RMR values that range from 10 to 20 points, it is usually necessary to use micropile umbrellas [45], and the same is true when there is an elastic behavior of ICE < 30 [48]. Thus, the number of micropile umbrellas can be calculated by Equation (8) to define the number of micropiles in each umbrella, and the cost using Equations (9) and (10), respectively, can be also be calculated as follows:

$$N_p = \frac{L_f - L_0}{l_m - l_s}, \tag{8}$$

where N_p is the number of micropile umbrellas, l_m represents the lengths of the micropile umbrellas (m), and l_s is the overlap between the micropile umbrellas (m);

$$n_{mp} = n_m \cdot N_p, \tag{9}$$

where n_m is the number of micropiles in each umbrella and n_{mp} is the total number of micropiles; and

$$C_m = c_m \cdot n_{mp}, \tag{10}$$

where c_m is the lineal cost per micropile and C_m is the total cost of the micropile umbrellas.

The typical linear cost of a micropile ranges between 90 EUR/m and 110 EUR/m for drilling diameters of 88.9 mm and 150 mm, respectively.

3.3. Costs Related to the TBM Excavation

The main specific issues in TBM excavations are also caused by unexpected (and not only poorer) rock mass conditions, as in drill and blast, due to much less flexibility in the construction process when using TBMs.

3.3.1. Performance Decreases and Delays

Poor rock mass conditions can lead to increases in excavation times due to poorer excavation performances and squeezing or entrapment, among other issues. Hence, it was necessary to determine the fixed costs using Equation (11). Entrapments can vary considerably in each case, and based on experience from several Spanish tunnels, on average, approximately 30 days is required to restart normal TBM excavations [49].

$$C_{fT} = c_{fT} \cdot (T + T_e) \tag{11}$$

Here, C_{fT} represents the total fixed costs (EUR), c_{fT} represents the daily fixed costs (EUR/day) (considering 30,000 EUR/day as a mean value for the case studies), T is the time required for the excavation (days), and T_e is the time of the entrapment (days).

3.3.2. Support and Lining

The volume of concrete required in a lining segment is defined by Equation (12), and Equation (13) determines the concrete price. On the other hand, the quantity of rebar required and its associated cost can be determined by employing Equations (14) and (15), respectively.

$$V_h = \frac{\pi}{4} \cdot \left(D_e^2 - D_i^2\right) \cdot (L_f - L_o) \tag{12}$$

$$C_h = p_h \cdot V_h \tag{13}$$

Here, V_h is the concrete volume (m^3), D_e is the external diameter (m), D_i is the inner diameter (m), L_f and L_o refer to the stretch of the tunnel analyzed (m), C_h is the total concrete cost (EUR), and p_h is the concrete cost (EUR/m^3). As references, we took HA-70 with a cost of EUR 219.93 per m^3 and HA-45 with a cost of EUR 146.49 per m^3.

$$M_a = m_a \cdot V_h \tag{14}$$

$$C_a = p_a \cdot m_a \tag{15}$$

Here, M_a is the total mass of the steel used in the lining (kg), m_a is the mass of the steel per cubic meter of concrete (kg/m^3), C_a is the cost of the rebar (EUR), and p_a is the unit cost of the rebar (EUR/kg). We considered EUR 0.87 per kg as a reference value.

3.3.3. Cutter Tool Consumption

The number of cutter tools consumed is based on the unit consumption and the volume of rock mass excavated (Equation (16), while its associated cost is included in Equation (17), as follows:

$$N_c = c_u \cdot V_R, \tag{16}$$

where N_c is the number of cutters consumed (pcs.), c_u is the cutter consumption per volume of rock mass excavated (pcs./m^3), and V_R is the rock mass excavated (m^3).

$$C_c = p_c \cdot N_c, \tag{17}$$

where C is the cost of the cutter tools consumed (EUR), p_c is the unit cost (EUR/pcs), and N_c is the number of cutter tools (pcs).

3.4. Costs Related to the Drainage of the Tunnel

The total volume of water extracted from a tunnel is the sum of the different stretches ($V_T = \sum V_i$). Further, additives, such as flocculants or coagulants, are required for its management, as expressed by Equation (18), with an average cost of EUR 0.28 per m^3 for the water treatment.

$$C_T = c_A \cdot V_T \quad (18)$$

Here, C_T is the total cost of the water treatment (EUR), c_A is the cost for each cubic meter of water (EUR/m^3), and V_T is the volume of water extracted (m^3).

The average water flow in a tunnel is defined by Equation (19), and the electric power of the water treatment system is calculated by Equation (20), assuming that the power consumption is directly proportional to the amount of water treated.

$$Q_m = \frac{V_T}{86400 \cdot T_f} \quad (19)$$

$$P_T = c_T \cdot Q_m \quad (20)$$

Here, Q_m is the mean water flow (m^3/s), T_f is the time required to excavate the tunnel (days), c_T is the ratio between the power and the water flow (kW/m^3/s) (with a common value of 1000 kW/m^3/s), and P_T is the total electrical power of the wastewater treatment plant (kW).

In addition, water must be pumped in a tunnel when there is a negative slope in the excavation direction, which requires electrical power that is proportionate to the tunnel length [44]. The mean power required in a stretch from Lo to Lf is defined by Equation (21).

$$P_w = c_L \cdot \frac{L_o + L_f}{2} \quad (21)$$

Here, P_w is the pumping power (kW), and c_L is the proportion factor. In a tunnel with a negative slope of between 1% and 5%, the value of C_L is approximately 0.25 kW/m, and it increases to 0.50 kW/m for negative slopes between 5% and 15%.

Thus, the total energy required for water management is the sum of the water pumping and treatment, assuming that the whole system works 24 h a day (Equation (22)). Equation (23) defines the total energy cost.

$$E = 24 \cdot T_f \cdot (P_T + P_W) \quad (22)$$

$$C_E = c_E \cdot E \quad (23)$$

Here, E is the overall energy consumption (kWh), T_f is the time required to excavate the tunnel (days), and c_E is the energy cost (EUR/kWh), which depends on the type of energy generation. We assumed an energy cost of EUR 0.08 per kWh in this study.

3.5. Costs Related to the Composition of the Material Excavated

The geochemical composition of the material excavated along the tunnel may require different management approaches, such as the construction of landfill sites adequate for the material requirements. Thus, volume must be considered in each scenario, taking into account factors such as over-excavation, bulk factors, and compaction factors. All these elements can increase the cost of tunnel construction (Equation (24)).

$$C_D = c_{d0} + c_d \cdot V_R \quad (24)$$

Here, C_D is the total additional cost for the landfill site, c_{d0} is the preparation cost of the specific landfill site (EUR) (some typical values for these preparation conditions were found to be approximately EUR 100,000), and c_d is the treatment cost of the material disposed of in the landfill site (EUR/m^3), which usually ranges between EUR 1 and 5 per m^3. We considered the worst-case scenario for the analysis in this study. Further, in Equation (24), V_R refers to the volume of the rock or soil excavated (m^3).

3.6. Costs Related to the Geological Gas Emissions

The excavation of a tunnel can produce the emission of gasses initially trapped in the rock mass, such as methane, and this is directly linked to the excavation process [21]. These emissions have an environmental impact that must be quantified in the project stage. In the case of methane, it should be transformed into its carbon dioxide equivalent [21,44] for cost determinations (Equation (25)), as follows:

$$C_{ge} = p_{CO2} \cdot E_g, \quad (25)$$

where C_{ge} is the emissions cost (EUR), p_{CO2} is the price of CO_2 emission rights (EUR/tCO_2) (the CO_2 emission price has varied in recent years from EUR 10 per tCO_2 to the current EUR 50 per tCO_2), and E_g refers to the equivalent carbon dioxide emissions (tCO_2).

3.7. Costs Related to the Use of Special Treatments

In the case of a very weak rock mass, the use of special treatments to consolidate the tunnel face can be necessary to enable the TBM to excavate with an acceptable advancing rate. The total cost of such a treatment can be easily estimated by Equation (26), as follows:

$$C_b = c_b \cdot (L_f - L_o), \quad (26)$$

where C_b is the total cost of the resin (EUR) and c_b is the unit cost of the treatment per meter of the tunnel (EUR/m).

4. Results

The three case studies were analyzed in terms of economic uncertainty quantification considering the usage of conventional boreholes and DCD. The procedure detailed in Section 3 was used to achieve the results from the different case studies analyzed, and we considered the intrinsic characteristics of each tunnel in the analysis. Further details of the calculations are shown in the Supplementary Material.

4.1. Burata Tunnel

The study of the tunnel's rock mass conditions was completed using 29 conventional boreholes (27 that were vertical and 2 that were horizontal). Three DCDs would be sufficient, theoretically, to determine the conditions over the whole tunnel length, with one in each portal and the third above the tunnel layout. Tables 1 and 2 set out the costs of both types of drilling techniques.

Table 1. Analysis of the conventional approach for the Burata tunnel.

Type of Borehole	Number of Boreholes	Total Length (m)	Average Length (m)	Transportation and Preparation (EUR)	Drilling Cost (EUR)	Total Cost (EUR)
Vertical						
$L \leq 50$ m	3	140	46.7	9000	14,000	23,000
50 m < $L \leq 100$ m	4	310	77.5	12,000	31,000	43,000
100 m < $L \leq 150$ m	12	1525	127.1	36,000	152,500	188,500
$L \geq 150$ m	8	1330	166.3	24,000	133,000	157,000
Horizontal	2	250	125	6000	25,000	31,000
Total	29	3555		87,000	355,500	442,500

Considering that each vertical borehole obtains information for a 20 m length of the tunnel and that horizontal boreholes provide information for their equivalent lengths, an investment of EUR 442,500 would determine conditions for 20% of a tunnel's total length (790 of 4000 m). Thus, the investigation unit cost was EUR 560 per meter of tunnel characterized. Further, 20% of the total cost was related to transport and preparation (not drilling). On the other hand, the DCD approach enables the definition of 100% of the tunnel's length with an investment of EUR 882,600 and an investigation unit cost of EUR 220 per m, which focused nearly all of the cost on drilling. The conventional technique unit cost was 2.5 times higher than the DCD unit cost.

Table 2. Analysis of the DCD approach for the Burata tunnel.

Type of Borehole	Number of Boreholes	Total Length (m)	Average Length (m)	Transportation and Preparation (EUR)	Drilling Cost (EUR)	Total Cost (EUR)
From the portal	2	3000	1500	6000	600,000	606,000
Surface above the tunnel	1	1368	1368	3000	273,600	276,600
Total	3	4368		9000	873,600	882,600

The economic analysis of the uncertainty related to the tunnel supports was based on actual data from the project. We used data from Romana [45] to define the type of support required (e.g., bolts, steel sets, and shotcrete) and considered the over-excavation based on Innaurato et al. [50] and Mottahedi et al. [51]. Table 3 summarizes the uncertainty costs related to each element that could be found for the Burata tunnel. Average permeabilities of K = 10 − 6 m/s and K = 10 − 7 m/s were considered for the residual soil and granite, respectively.

Table 3. Uncertainty factors.

Factor	Uncertainty Cost (EUR)
Material related to support	+6,496,040
Fixed costs	+3,600,000
Support treatments	+12,571,200
Water drainage	+1,141,094
Total risk estimated	23,808,334

Regarding the excavation time, an important variation was found when the time increased from an initial 650 days to 950 days. This increase was caused by a lack of knowledge about the whole tunnel layout, which included a longer length of residual soil conditions instead of granite. Thus, the fixed cost rose incrementally by 46%, reaching EUR 3,600,000.

In this case study, the uncertainty created additional costs for all the factors due to the greater length of the residual soil conditions instead of the granite that was expected initially. Altogether, the associated cost due to uncertainty was EUR 23,808,334, which could have been eliminated by using a DCD technique, with an additional initial cost of EUR 442,100. When the DCD cost is compared to the total cost of the tunnel, at 2.2% of the budget, it remained within an adequate range for a project with complex conditions [52]. Every EUR 1 allocated to DCD usage would have reduced the uncertainty by EUR 54, which was in line with the USNCTT [53], involving an uncertainty reduction of EUR 5952 per m of tunnel excavated. This value was quite relevant since the overall construction cost of the tunnel was EUR 10,000 per m.

4.2. Pajares Variant Lot 3 Tunnel

The study of this specific part of the tunnel layout was completed by using only two conventional boreholes, with a total length of 2050 m drilled. The problems found in drilling the boreholes have been described by Del Olmo and Álvarez [54]. On the other hand, one DCD of 1175 m would have been sufficient, theoretically, to determine the characteristics of the rock mass in the tunnel section studied (Figure 4).

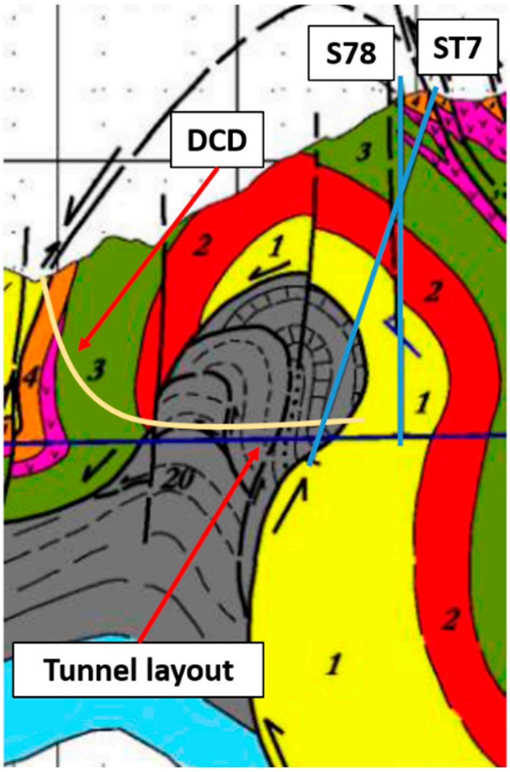

Figure 4. Area of study in the Lot 3 Pajares variant tunnel.

Table 4 shows the costs of the conventional boreholes and the DCD techniques. The critical area, with a length of 850 m, was called the San Emiliano formation, and two boreholes were drilled (one vertical and one inclined) to define the extension and the characteristics of this formation.

Table 4. Conventional and DCD techniques analysis for the Parajes variant tunnel.

	Number of Boreholes	Total Length (m)	Transportation and Preparation (EUR)	Drilling Cost (EUR)	Total Cost (EUR)
Vertical (S-78)	1	950	3000	95,000	98,000
Inclined (ST-7)	1	1100	3000	110,000	113,000
Total conventional	2	2050	6000	205,000	211,000
DCD	1	1175	3000	317,500	320,500

In this case, a large geological structure needed to be defined. Assuming that the conventional drilling provided information about the tunnel between the two boreholes (approximately 250 m of the tunnel's layout), there was an investigation unit cost of EUR 844 per m. On the other hand, a DCD technique, with the layout exposed in Figure 4, is proposed. It would require 1175 m of directional drilling and would have an investigation unit cost of EUR 377 per m in order to determine 100% of the tunnel's layout. Thus, the unit cost of the conventional exploration boreholes is approximately 2.2 times higher than the cost of the DCD technique.

The design and manufacture of the precast lining segments was a very relevant challenge, as has been pointed out by several authors [55–57]. There was a cost increment related to the lining (EUR 1,004,108) due to rock mass conditions that were worse than initially defined by the conventional drilling, and the cost increased from the planned EUR 4,202,085 to a real cost of EUR 5,206,193.

In addition, the advance of the TBM was unexpectedly reduced from 15 m/day to 6 m/day, according to the real advancing rate data [58,59], increasing the duration of the excavation by 54 days due to a poorer performance, which represented a cost increase of EUR 1,620,000 due to unexpected conditions.

The cutter tools consumption was lower in the real conditions due to less abrasive characteristics [60]. There was an expected consumption of 0.7 pcs/m, and in the real conditions, the consumption was 0.04 pcs/m (595 and 232 cutter tools, respectively). Considering the average cost of a cutter at the time of the tunnel's construction (EUR 2500 per piece), EUR 907,500 was saved.

The risks of entrapment and gas emissions were other potential setbacks that did not occur, despite that they were prone to occur in the actual geological conditions found, and therefore, they must be counted in the global assessment of the project [42,43]. The potential entrapment, with an average of 30 days, would have a total fixed cost of EUR 900,000. The geological formation could also contain methane (CH4), with a potential emission of approximately 11 m^3 of methane for every ton of material excavated, based on previous studies [21], with a total of 1,562,000 m^3 of CH4 and, therefore, 25,000 tCO2. Considering the price of each ton of CO2 at the time of the tunnel's excavation (EUR 14 per t), the associated economic risk related to the methane emissions would be approximately EUR 350,000. Table 5 summarizes the uncertainty costs related to each element that could be found in the tunnel.

Table 5. Uncertainty factors.

Factor	Uncertainty Cost (EUR)
Lining segments	+1,004,108
TBM performance	+1,620,000
Entrapment	+900,000
Gas emissions	+350,000
Cutter tools consumption	−907,500
Total risk estimate	4,781,608

Overall, the use of the DCD technique eliminates a risk of EUR 4,781,608, which is EUR 5625 per m of tunnel excavated in the stretch analyzed and equivalent to EUR 14.9 for every EUR 1 invested in DCD. This value was approximately 25% of the total excavation cost per meter, which would assume a very high risk if the stretch was not well-defined.

4.3. Bolaños Tunnel

There was a region in the Bolaños Tunnel with a potential length of nearly 1000 m that required detailed definition of the rock mass characteristics during the excavation stage of the tunnel. In this regard, five vertical boreholes were drilled in the study area. Table 6 sets out the cost assessments of the conventional boreholes and the DCD technique for this particular stretch of the tunnel. Based on the same geological cross-section used to define the conventional vertical boreholes, a single DCD was proposed (Figure 1).

Table 6. Conventional and DCD assessments for the Bolaños tunnel.

	Number of Boreholes	Total Length (m)	Transportation and Preparation (EUR)	Drilling Cost (EUR)	Total Cost (EUR)
100 m < L ≤ 150 m	2	260	6000	26,000	32,000
L ≥ 150 m	3	530	9000	53,000	62,000
Total conventional	5	790	15,000	79,000	94,000
DCD	1	1600	3000	320,000	323,000

The cost distribution for the conventional approach was 16% for transportation and 84% for drilling, resulting in knowledge of only 5% of the tunnel's layout for the area of interest (investigation unit cost of EUR 940 per m). On the other hand, DCD reached 100% definition of the region, and its costs were concentrated on drilling (investigation unit cost of EUR 323 per m), as it can be seen by the red line in Figure 5. In this case, the conventional technique was nearly three times more expensive than the DCD technique.

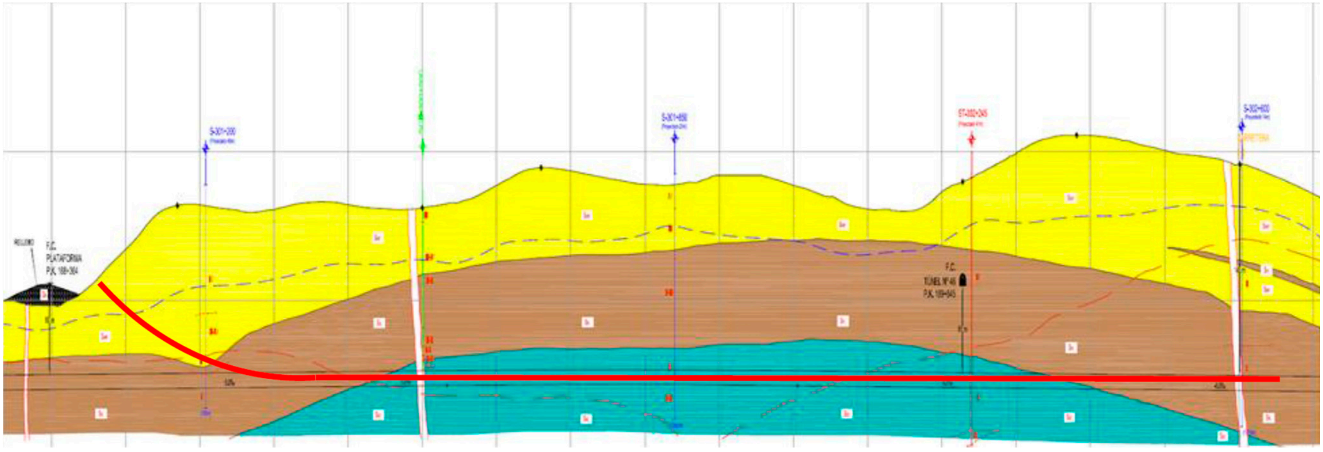

Figure 5. Layout of the DCD technique proposed for the Bolaños tunnel.

Regarding the geochemical composition of the rock mass, the ampelite slates found in the stretch studied could have generated contamination due to the presence of sulphides and heavy metals. Thus, it was considered the worst-case scenario in the analysis, based on the characteristics defined in Section 3, with a total of EUR 600,000 as an additional cost for the management of the rock mass excavated in the affected area. Moreover, the TBM performance was poorer than planned in the project. The expected rate was 25 m/day, whereas the actual excavation rate was 4 m/day, requiring 22 additional days of excavation, which resulted in an additional cost of EUR 660,000. The presence of a rock mass with squeezing characteristics created an additional risk cost of EUR 900,000.

In the case studied, one of the main points of the construction system was the previous treatment of the unstable excavation face using organo-mineral resins. Thus, the resin consumption was higher and, therefore, more expensive. The tunnel in this case study also faced the risk of squeezing due to the presence of ampelite minerals in the slate formation [61]. The unit cost of the treatment could be estimated at EUR 1260 m under normal conditions, and it reached EUR 4620 per m under the squeezing conditions, with 1000 m of poor conditions faced in the analyzed tunnel. Hence, there was a cost overrun of EUR 3,360,000 due to poor knowledge of the rock mass. Table 7 summarizes the overall uncertainty costs of the tunnel.

Table 7. Uncertainty factors found in the Bolaños tunnel.

Factor	Uncertainty Cost (EUR)
Geochemical composition	+600,000
TBM performance	+660,000
Entrapment	+900,000
Organo-mineral resins	+3,360,000
Total risk estimate	+5,520,000

Based on the assessment of the Bolaños tunnel, the DCD technique could have reduced the uncertainty by EUR 5,520,000 in the stretch analyzed (EUR 5520 per m), which represents EUR 6.7 for every EUR 1 invested in DCD.

5. Discussion

The analysis of the three case studies revealed how the use of the DCD technique can help to better characterize rock mass conditions and reduce uncertainty from an economic perspective.

The mean value of the uncertainty in the three tunnels studied was approximately EUR 6000 per m. Thus, an investment of EUR 1 would allow an uncertainty decrease of between EUR 6.7 and EUR 14.9. The unit cost of the conventional borehole technique ranged between two and three times higher than costs related to the DCD option. The total expenditure remained within the recommended cost range defined by Pelizza et al. [62] and several actual projects [63,64], considering the corresponding inflation adjustments.

In contrast to conventional vertical boreholes, the proposed system allows for determining the condition of an entire tunnel layout. The technique could be particularly useful for characterizing shallow tunnels in populated areas, and it could be crucial for defining specific complex areas in deep tunnels. It also allows planners to define the geological domains of a tunnel's layout, identify the groundwater levels, characterize the geomechanical properties and determine the excavated areas requiring degassing in the future. In addition, DCD can be especially relevant when there is a region of the tunnel's layout with potential geochemical risks since conventional drilling only permits the extraction of samples from very local regions.

The approach proposed is especially relevant for TBM tunnels since it is an excavation method with little flexibility compared with the drill and blast method, and requires important knowledge about the rock mass characteristics to avoid unexpected conditions. These situations are noted in the setbacks experienced in the Bolaños and Pajares variant tunnels, where the uncertainties caused deviations in the lining, cutter tools consumption, waste management, and TBM performance. Among the limitations of the study, the TBM entrapment was analyzed considering only the fixed cost, and there could have been additional costs related to repairs or additional equipment required for the procedure.

In addition, the employment of the directional core drilling technique reduces the number of drillings required, and consequently, it also reduces the environmental impact due to a smaller surface being affected. Despite this, such factors have not been quantified, and it is an important component to consider as it could help in the administration of the procedure and with interactions with the inhabitants of such areas. However, health and safety implications for tunnel personnel, such as gas emissions, were kept out of the analysis. Only some uncertainties that were easy to evaluate economically were considered, and the methodology could be extended to other uncertainties with other associated cost overruns.

6. Conclusions

The approach proposed can be used to assess the economic impact of the geological uncertainty inherent in the excavation of a tunnel, considering the main factors in the TBM and drill and blast excavation methods. The system could be especially useful in a future tunnel or area with high probabilities of poor rock mass conditions or other potential anomalies. Three real case studies were analyzed in detail with the method detailed, considering the initial and actual conditions found in the tunnel construction phases.

The use of the directional core drilling technique generally involves higher costs than those related to conventional boreholes, but it has the advantage that information is obtained from the entire length of the investigated tunnel section, and it can be useful from geological, geotechnical, and hydrogeological perspectives. This technique allows planners to define the factors that may create uncertainty in terms of time and cost. In addition, the cost of applying the technique would remain at approximately 2% of a tunnel's execution budget, which is reasonable in geological and geotechnical research campaigns.

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