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FÉDÉRALE DE LAUSANNE

UNDERGROUND CONSTRUCTION TECHNOLOGY

Deep Tunnel Project

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1 INTRODUCTION

Within the European interconnection, with the constant growth of transported goods between Italy and Switzerland, a new high-speed railway line has become necessary in order to connect these two countries. Placed between the Mt. Blanc Tunnel and the Simplon Tunnel, this new project will face the problem of overload capacity of the existing lines. This tunnel will link the Italian town of Aosta to the Swiss city of Martigny and it is only a part of the corridor that will connect Italy to the northern part of Europe.

1.1 General Conditions

This report is a preliminary study of this project and it will only analyze the Swiss part of the tunnel that goes from Martigny to the Multifunctional Station, placed near Bourg San Pierre. Adits have also to be provided in order to optimize the excavation process.

The tunnel has to be designed considering the following constraints:

- The minimum radius outside of the tunnel is 500 meters
- The minimum radius inside the tunnel is 4000 meters
- The slope inside the tunnel must be under 1.2 %
- The maximum speed of the train is 250 km/h

Respecting these conditions is fundamental for high-speed tunnels.

For what concerns the slope, it was noticed that the town of Martigny (470 m) is at a lower altitude if compared to the Italian city of Aosta (580 m). Given these altitudes, it is impossible to define the elevation of the entry portal near Aosta without an exhaustive study of the Italian side. It is plausible that the location will be in the upper side of the valley since the city is located at the very bottom, but the exact elevation cannot be determined.

Due to this lack of information, it has been decided to trace our alignment with a constant slope equal to the maximum allowed (1.2%) in order to decrease as much as possible the overburden without reducing the speed of the trains.

1.2 Topography

For what concerns the topographical aspects, it is important to consider the height of the mountains in the area and the elevation of the valley, in order to conceive an itinerary that avoids excessive overburdens and exaggerate rock pressures. On the contrary, overburden smaller than 400m should be avoided wherever possible, otherwise very fractured rock with high hydraulic conductivity might be encountered. These areas are also characterized by very high initial water inflows, with serious drawdown of the water table; late time flows are controlled by surface recharge.

Also, in the sections of the tunnel with small overburden, there is a higher risk of running into loose sedimentary rocks.

In the Grand St. Bernard's area, especially on the left side of the valley, if going southbound, there are mountains such as Grand Combin and Combin de la Tsessette that reach 4000 meters of altitude and an itinerary with such an overburden might encounter squeezing or bursting problems, with non-negligible consequences from an economical point of view and on the choice of the excavation method. Also in the preliminary phase of the project, great overburdens might represent a serious obstacle for the realization of boreholes, and therefore on the profitability of the project itself.

In the area there is a reservoir (Les Toules Dam) that has to be avoided in order to prevent great amounts of water into the tunnel and serious damages to the dam.

The topography is also a clue factor for the positioning of adits and shafts. Accesses to the tunnel have to be provided during the construction phase and the slope of these secondary tunnels doesn't have to exceed 15% in case of adits. For what concerns shafts, the cost is proportional to the depth that has to be excavated. The details for adits and shafts will be analyzed for each alignment in the following chapter.

In order to make reasonable choices during the definition of the tunnel's itineraries, we have used a programmed called "Google Earth", that allowed us to consider all these aspects at once with a reasonable precision and with a great visual interface. This tool also allowed us to have a tri-dimensional view of the area without a visit.

1.3 Geology

Geology is probably the factor that has the most impact on the project and it therefore has to be analyzed with extreme care. Within the geological aspects the kind of rocks, their proprieties and the orientation of discontinuities (geological faults, foliation etc.) have to be considered and analyzed. From a first look at the geological map of the area, it's easy to notice that in the area there is a great diversification of rocks' type and quality. Also, there are different rocks on different sides of the valley: granites dominate the right side, whereas the left side is mostly made of limestone and schist. As will be mentioned later on, from a merely economical point of view, the geology has a great influence on the cost of the project and even if there is no possibility of completely avoiding bad rocks, they can be reduced as much as possible.

As required by the exercise, we have subdivided the whole geology into four different classes:

Au (Limestone, Dolomitic limestone)

CS/SCH (Schist, Calschist)

GP (Micashist and foliated Gneiss)

G-GR (Crystalline Gneiss and Granite)

For each class, an analysis of the RMR for the rock mass quality will be made in chapter 3.4, and also the "Q value" will be taken in account for the rock mass quality. A GSI value will also be found using the table proposed by Hoek-Brown in order to determine where squeezing problems might be encountered.

In the process of defining the sections of the three different alignments, a fundamental hypothesis was made: all the major layers are parallels and have an inclination of 45°.

1.4 Economic Aspects

The optimal itinerary aims at reducing the costs of the project and the duration of the construction site, considering both the topography and the geology of the area.

As mentioned before, the fundamental aspects that have to be considered in order to reduce the costs are: the length of the tunnel, the nature and quantity of the excavated materials and the methods of excavation chosen.

In this phase a first thought has to be given to the planning of the construction phase, to the methods that will be used and to the materials that are going to be excavated.

One thing has to be kept in mind: the shorter itinerary is not always the cheapest one.

The number of intermediate adits and their length also has an influence on the construction cost and on the profitability of the project.

1.5 Social and environmental aspects

Although these aspects are usually neglected, they are probably the most important ones since they link the project directly to the people and to the surrounding environment. In addition to this, in a country like Switzerland, that gives a great value to the protection of the environment, great emphasis has to be given to these aspects and the impacts have to be considered with care.

For what concerns the **Social** aspects, the biggest impact is probably given by the disturbance to the people that live around the constructions site (i.e. portal entry and adits). Of course noises and vibrations during construction have to be reduced the most, but it is also fundamental to choose itineraries that avoid, wherever possible, private homes, existing constructions and villages.

Environmental aspects are, for such a project, unavoidable. In order to reduce them as much as possible, for each itinerary three parameters have to be carefully analyzed: water pollution and circulation, entrance portals and flora & fauna. All these aspects will be considered and deepen in chapter 3 with the multi-criteria analysis.

2 CHOICE OF THE ALIGNMENTS

The aim of this first exercise is to choose three different itineraries to connect the entry portal to the multifunctional station. These three alternatives were chosen according to the five aspects described in Chapter 1. These criteria will be further analyzed and evaluated in Chapter 3, in the context of the multi criteria analysis, in order to find the most suitable option.

2.1 Entry portal

For what concerns the Entry Portal, no major constraints were encountered and many were the conceivable options. The first option wanted to place the entry portal before the city of Martigny (direction Lausanne-Sion) in order to avoid the traffic going through the downtown area and to reduce the impact on the population. This solution, thus theoretically interesting, was soon rejected because the potential link would have had to cross the highway and other main roads. A different solution, easier from a technical point of view, is to place the entrance after the town of Martigny, before the agglomeration of Charrat-les-Chaînes. The detachment will be placed right after the viaduct Av. Des Grandes-Maresches with a curvature radius of 650 meters, a value that is greater than the minimum required (500m). The curvature of the link between the main line and the entrance is constant for the three alignments. A variation has to be done for the second itinerary: the entrance is shifted about 300 meters west of the entrance of itinerary 1 and 3. The purpose of this offset is to allow an angle toward the west side with the same curve radius. The two solutions for the three alignments are represented in Figure 2.1

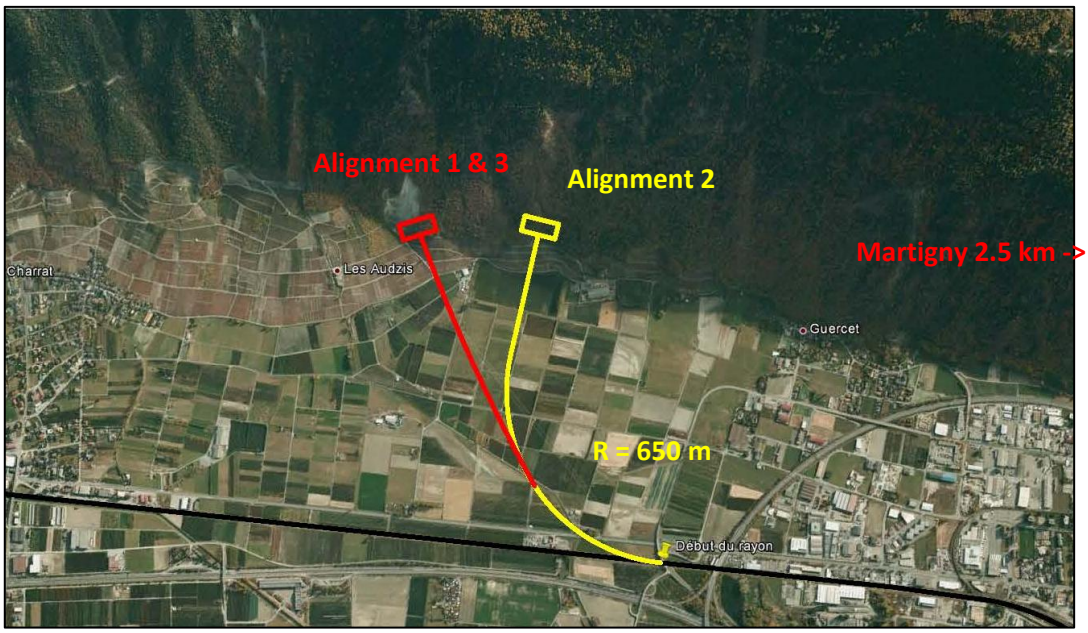


Figure 2.1 - Geographical location of the entry portals

A possible and ideal geometry of the portal is represented in the Figure 2.2

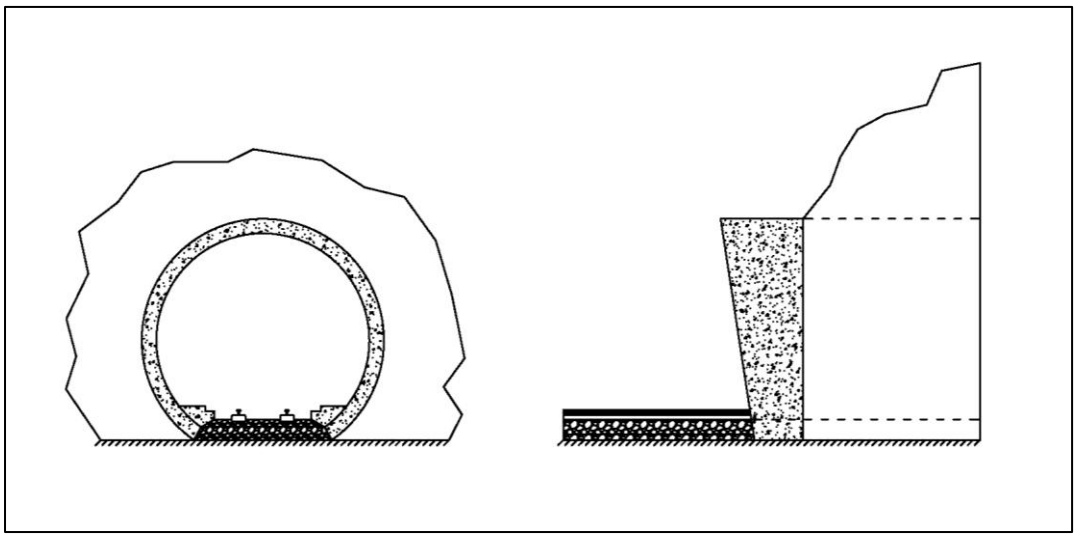


Figure 2.2 – Geometry of the Entry Portal

2.2 Multifunctional station

The multifunctional station has many different roles and these functions may change during the construction and exploiting phase:

CONSTRUCTION PHASE

- It represents and adit/Shaft from where the machines can reach the tunnel. Machines can also start excavating from this point.
- The chamber where an eventual TBM will be assembled could be reused as a main chamber for the multifunctional station.
- It gives a security exit to the workers in case of danger.
- Place where Italians and Swiss will join.

EXPLOITING PHASE

- Security exit for passengers in case of fire or danger.
- Service and Rest are for passengers on the trains.
- Ventilation Systems.

The multifunctional station is placed, according to our project, about one kilometer south of Bourg St Pierre in direction Cordonna, 6 km north of the Italian-Swiss border. This location was chose in order to have a small overburden above the Multifunctional Station and to ease the excavation to reach the site. The location is represented in Figure 2.3.

The place that has been chose is also easy accessible from Bourg St. Pierre.

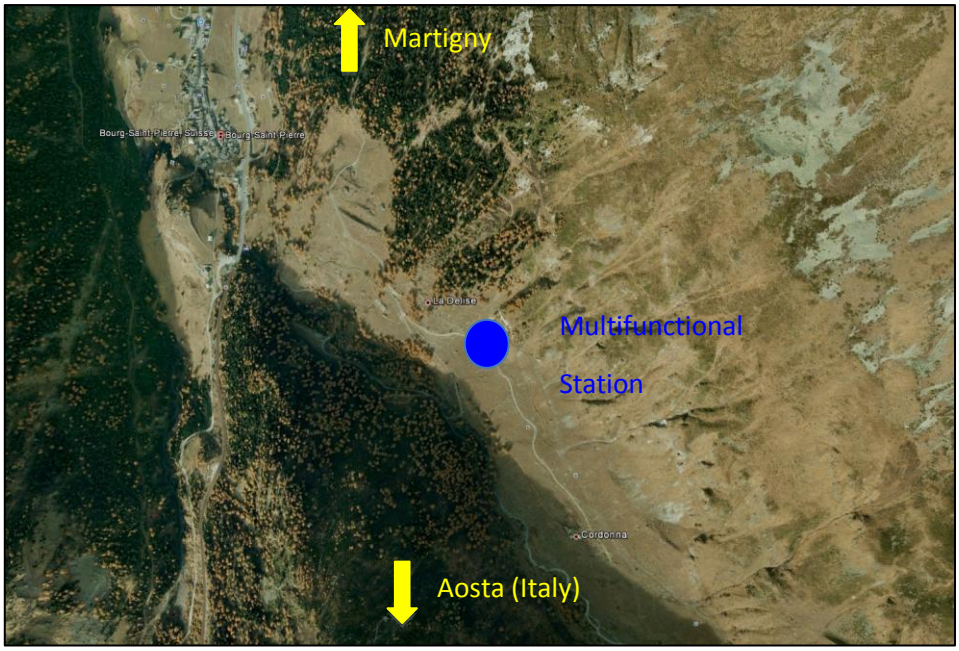


Figure 2.3 – - Geographical location of the Multifunctional Station

2.2.1 Access to the Multifunctional Station

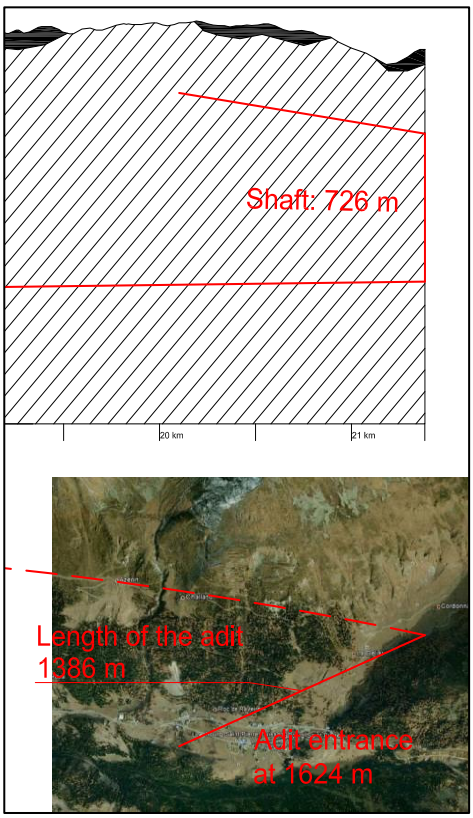


Figure 2.4 – Access to the Multifunctional Station

According to our plan, the Multifunctional Station will be located 932 m below the surface, at an elevation of 698 msl. The access to the multifunctional station in Bourg St. Pierre is granted through the combination of an adit and a shaft.

The first part of the access tunnel will be an adit whose geometry is represented in Figure 2.4 The length will be 1286 m with a dislevel of 200 m; the maximal slope of the tunnel will therefore be 15 %.

In order to link the adit and a shaft, an underground cavern will be necessary.

The shaft will start from the cavern and it will have a depth of 726 m, from an elevation of 1430 m to 698 m. This second part will allow the access directly to the multifunctional station. It is foreseen to construct two parallel shafts: one for the income materials and one for the outcome materials.

The access plan to the multifunctional station is represented in figure 2.4.

2.3 Alignments

As mentioned, the goal of this first exercise is to find three possible alignments for the tunnel from Martigny to Aosta. In order to give an overall view on the chosen itineraries, the three options are presented in Figure 2.5. Details and descriptions of each itinerary can be found in the following paragraphs.

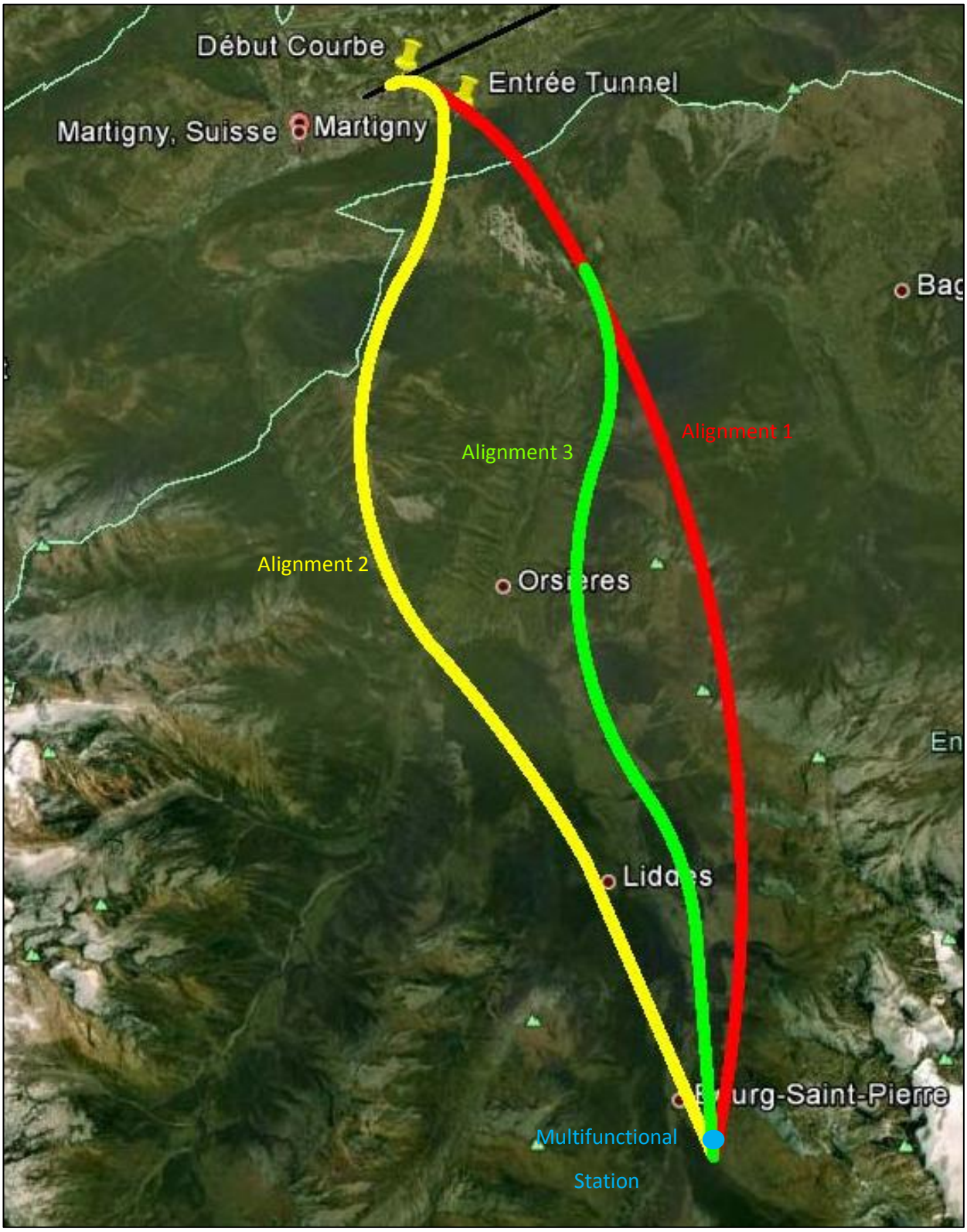


Figure 2.5 – The three chosen alignments

2.3.1 Alignment 1

This alignment is the first one to be chosen and it reaches the multifunctional station in a semi-direct way and with a constant radius of 23 km; the curvature chosen for the itinerary is greater than the minimal value of 4000 m imposed by the exercise. Alignment 1 is represented in Figure 2.5 with a red line.

As will be analyzed in chapter 2.5.1, the second half of this itinerary is all inside the same rock type (Micaschists and Foliated Gneiss, GP) which makes this alignment very flexible: in case of variation of the itinerary during the construction phase, the quality and the type of the rock will remain the same, avoiding problems for the construction technique, especially for TBMs.

This itinerary is located in the middle of the mountain, with great overburdens (that might imply squeezing problems) and with a reduced risk of incoming water.

As mentioned, this was the first itinerary chose and it mostly is a theoretical itinerary: in fact the technical issues have not been considered along the process. The total length of the itinerary is 20,19 km and it is represented in Figure 2.6.

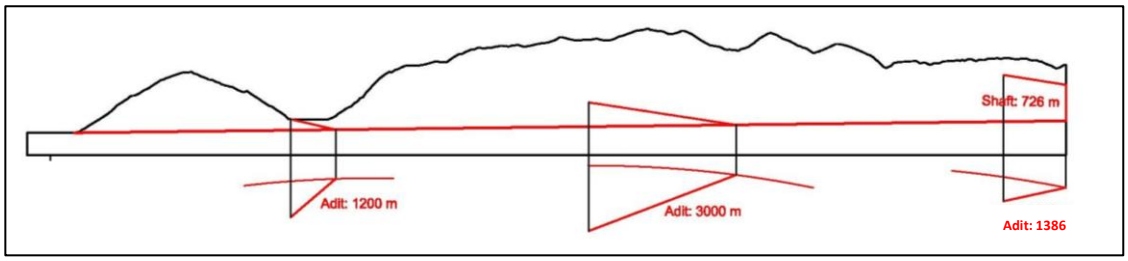


Figure 2.6 – Profile of the First Alignment

The **entrance** is, as explained in chapter 1.2, placed after the city of Martigny and then, with a constant radius of 23015 km, it reaches the multifunctional station placed near Bourg St Pierre.

Adits – For this option two intermediate adits where chosen and they are represented in figures 2.7.

During this preliminary part of the design process, the slope of the adits is fixed at its maximum value of 15%, even if such an elevated value might cause problems in the construction phase. The slope con obviously be reduced, but the consequence would be a longer adit.

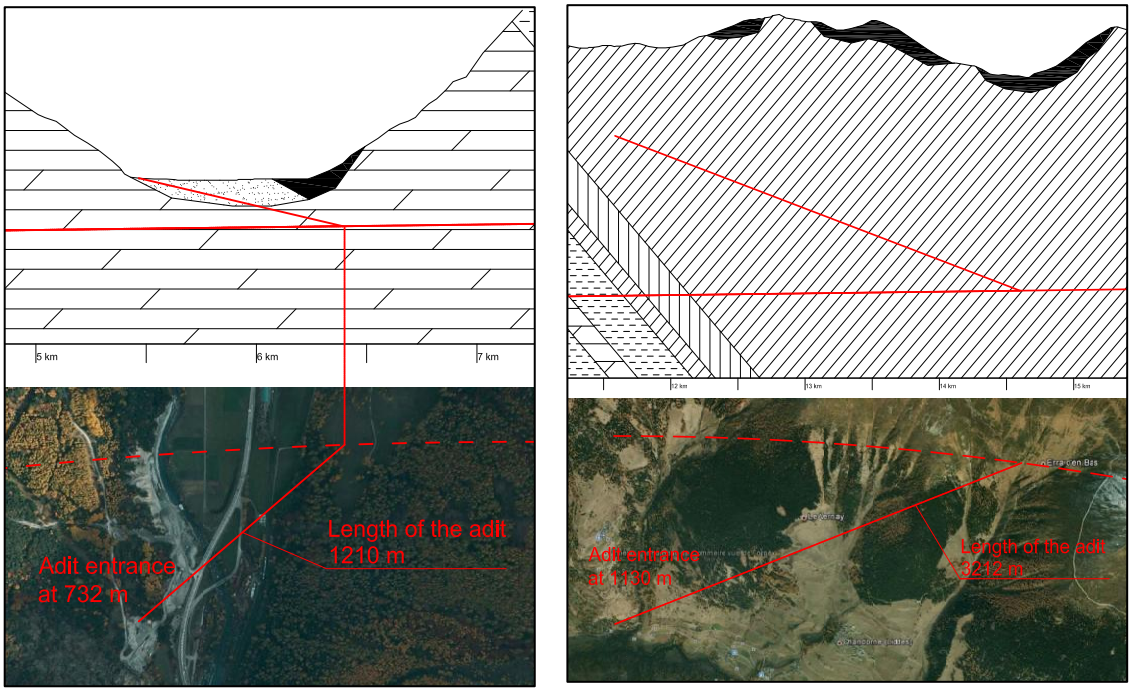


Figure 2.7 – Alignment n° 1, First (left) and second (right) adit

The first adit is placed at PK 5.319 and the total length of this first adits is 1'200 km with a constant slope of 15%. The entrance of the adit is located at a height of 732 msl and the dislevel needed to reach the tunnel is 223 m.

The second adit is placed at PK 13.464 and the total length of the second adits is 3'200 m with a constant slope of 15%. The entrance of the adit is located at a height of 1130 msl and the dislevel needed to reach the tunnel is 1130 m.

ADVANTAGES	DISADVANTAGES
• Constant radius • Semi-direct • Homogeneous Rock in the second part of the tunnel	• Problematic geology • Long intermediate adit • Great overburden • Squeezing problems

Table 2.1 – Advantages and Disadvantages of the alignment n°1

2.3.2 Alignment 2

This alignment is conceived in order to pass in the Mt Blanc area, on the left-hand side of the valley, characterized by really good rock quality. Itinerary n°2 has almost 9'200 m (48% of the total length) inside granite and good gneiss. In the first half of the alignment no squeezing problems will be encountered. The kind of rock that is found along this alignment

is not very variable; inside the same layer, the properties of the rock mass do not change that much.

Possible water income might be found below the first valley, where the depth is only 141 meters and a river passes close to the excavation site. However the rock mass quality is very good and there are few joints sets. This alignment is represented in Figure 2.8.

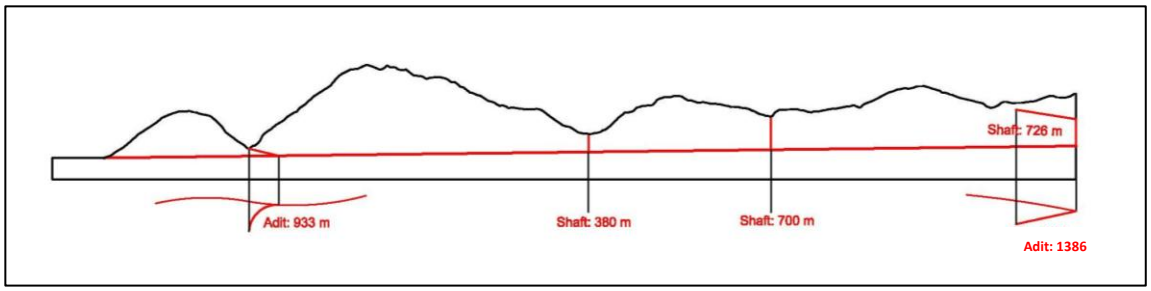


Figure 2.8 – Profile of the Second Alignment

From an economical point of view, this option is more expensive than the others because it foresees two shafts and one adit (without considering the multifunctional station that is common to all alignments)

Adits – For this option three intermediate connections where chosen and they are represented in Figure 2.9.

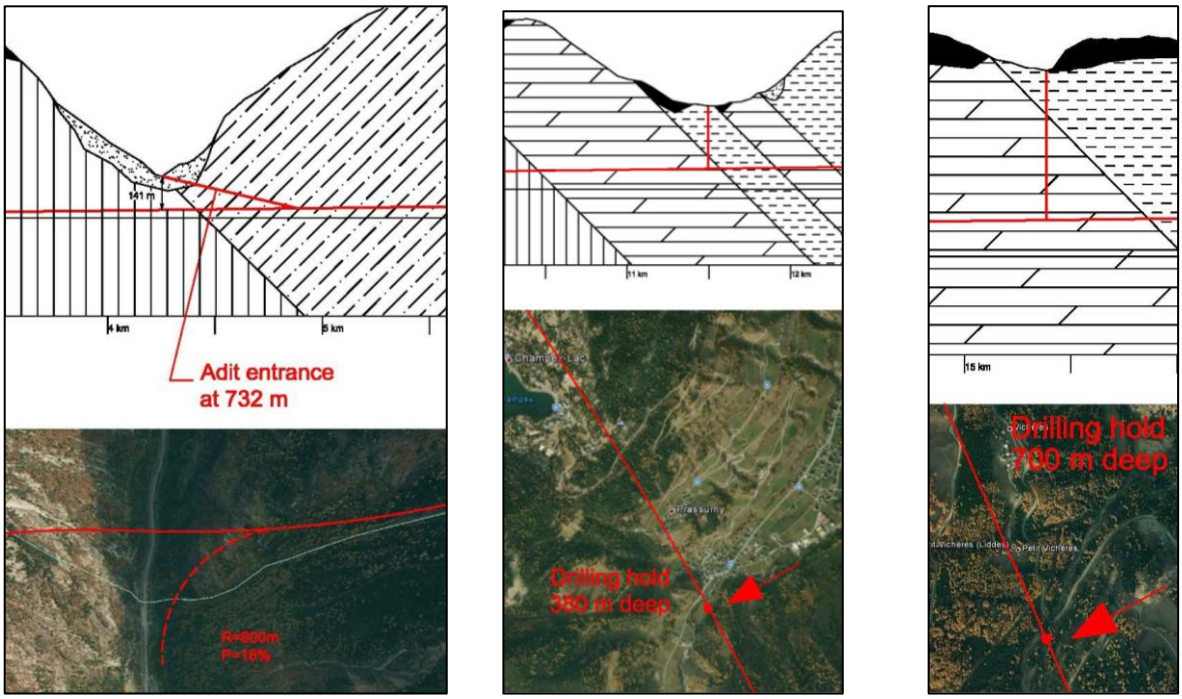


Figure 2.9 - Alignment n° 2, First adit (left), first (center) and second (right) shaft

The entrance of the first adit is placed at PK 3.080 and its total length is 930 m with a slope of 14.5%; the connection of the tunnel is at PK 3.7. The entrance of the adit is located at 600 meter at the left of the alignment in the valley with a dislevel of 654 meter. The external construction site is right next to the river, which may cause problems during the excavation.

The second adit is a shaft placed at PK 10.26 and the total length of the shaft is 380 m. The entrance of the shaft is located in a valley in retreat of the houses at the left of Orsières at an elevation of 967 msl.

The third adit is also a shaft placed at PK 14.12 m and the total length of the shaft is 699 m. The entrance of the shaft is located northwest of the village Liddes a little bit upper in the mountain and is close to the route de Vichères at an elevation of 1329 msl.

ADVANTAGES	DISADVANTAGES
• Good Geology • Little squeezing problems	• Long • Position of the Adits (river) • Water Income problems • Spalling problems

Table 2.2 – Advantages and Disadvantages of the alignment n°2

2.3.3 Alignment 3

This alignment has been chosen in order to avoid great overburdens; the first part is in common with the first itinerary, including the entry portal, then it runs parallel to the valley until it reaches the multifunctional station at Bourg St Pierre. Due to this reason the third alignment is the shortest one and more curvilinear if compared to the others. All the curvatures are above the minimal radius required, which allows the train to travel along the tunnel at the prescribed speed of 250 Km/h.

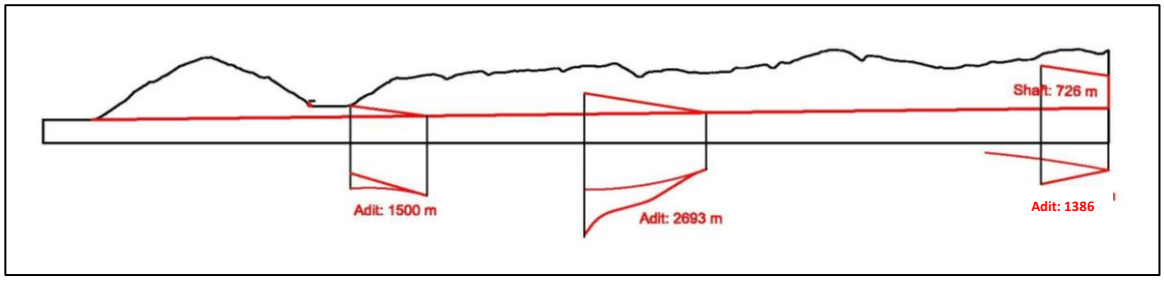


Figure 2.10 – Third alignment

This alignment has a total length of 19’132.5 m. As can be seen from Figure 2.4 the tunnel bends to the right when detaching the main railway line with three consecutives radii whose values are 5’000m, 23’000m and 4’000m. Afterward this itinerary bends to the right, leaving the first alignment and it following the narrowing of the valley for 6400 m with a constant radius of 6600 m. Finally, before reaching the multifunctional station with a straight line of 3900 m, a linking curvature to the right in encountered, whose radius is 5’250 m and whose length is 2880 m.

It should be taken into account that all the connections of straight-curve or curve-curve would be done by clothoids ($R \cdot L = C$). This method will help to change the curvature in a progressive way improving the quality of the train trip in following the railway standards.

Adits – For alignment number 3 two intermediate adits were chosen and they are represented in Figure 2.11:

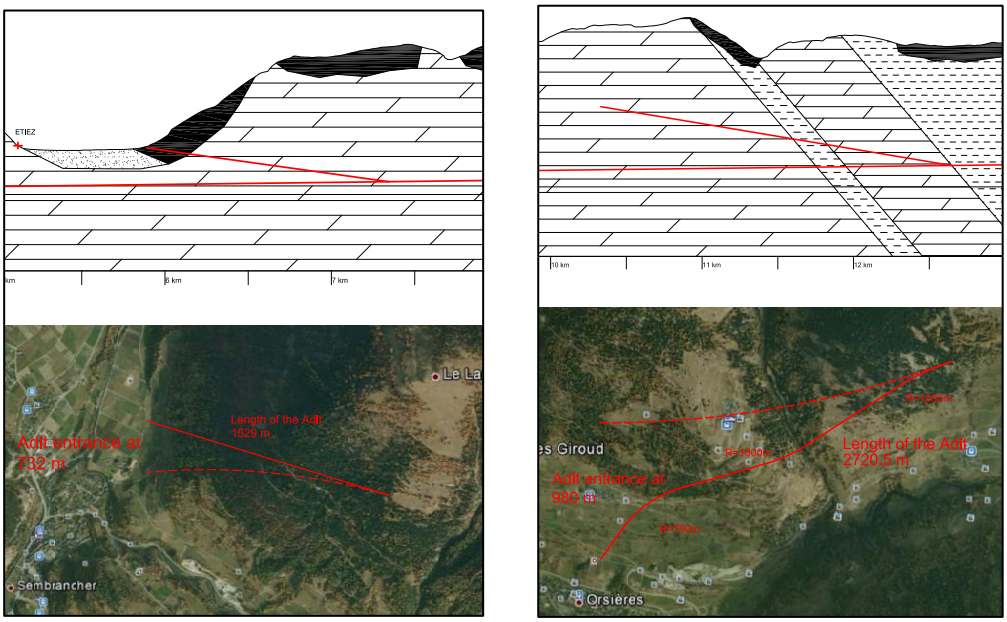


Figure 2.11 - Alignment n° 3, First (left) and second (right) adit

The first adit, placed at PK 6.299, is a straight line that links the main tunnels to the surface with a total length of 1'529 m and a slope of 13%. The entrance is located near villages like Etiez and Sembrancher at an altitude of 732 msl and the adit covers a height difference of 201 m with the main tunnel.

The second adit connects the railway tunnels at PK 11.559, close to Fornex and Chandonne. The entrance is located on the uphill side of Orsières at 980 msl and the dislevel of the adit is around 385m. The length is 2'720.5 m and the profile of the adit is curvilinear with a slope of 14.3%.

Both the adits have a really good road access guaranteed all year long. Also, the location of the entrance is chosen at the bottom of the valley and in front of the mountains, in order to assure a big slope of the profile at the start of the excavation, which allows their entrance directly on the surface, avoiding all starting shafts. However this proximity to the villages could represent a problem for what concerns social disturbances.

ADVANTAGES	DISADVANTAGES
○ Short ○ Small overburden (Max & Av) ○ Adits & Position of sites	○ Some squeezing problems ○ Some areas with bad geology ○ Social Impact

Table 2.3 – Advantages and Disadvantages of the alignment n°3

2.4 Geological Profiles

The coordinates of the three alignments described in sections 2.3.1, 2.3.2 and 2.3.3 were imported into Google Earth and with the elevation tool the heights profiles were obtained. Using the geological maps given in support of this exercise, a geological profile for each section is obtained. The geology was then reduced to the four main classes described in section 1.3 and, according to the instructions, the layers were considered with an inclination of 45°. The profiles obtained are represented in the following paragraphs. The three profiles can be found at the end of section 2.4.3 in Figure 2.12.

2.4.1 Profile n° 1 – Semi Direct

As mentioned in paragraph 2.3.1, this first alignment was chosen without considering any technical of practical issue. Figure 2.12 represents the section found for alignment 1.

In the very first part of the section, **Crystalline Gneiss** (G) is encountered, which is a rock with really good quality. This part is followed by a consistent part of **Limestone** (Au), which is known for having a high hydraulic conductivity that might create problem from a water income point of view. Also the problem of Karst might be encountered in the Limestone section. Great volumes of water inside the tunnel are expected through this section and measures will have to be taken in order to prevent damages and delays. Waterproofing techniques and solutions will be discussed in Chapter 6, in the context of Exercise 5.

The middle part of the itinerary has a great variability and CS/SCh (**Schistes and Calcshist**) are encountered.

The second half of the tunnel is completely excavated into rocks of category GP (**Micashist and foliated Gneiss**) with a poor rock mass quality due to high fracturation.

2.4.2 Profile n° 2 – Quality of the Rock

The Geological profile found for alignment number 2 is represented in Figure 2.11.

According to the Geological Map, in this alignment two very good types of rock can be found: **granite** and **non-foliated gneiss**. This alignment had been chosen in order to follow those two types of rock for 9’200 kilometers and then passing into Limestone, which has fair rock mass quality. The first part in granite is important due to the fact that a valley with a river is encountered; in this section the overburden of the tunnel is relatively small (141 m) and possible water income could represent a problem. For what concerns the position of the

passage below the valley, we have tried to find the biggest overburden possible in the area. Anyway, the rock mass quality of the section is very good and less problems of water income should be encountered.

The overburden of this alignment is between the alignment 1 and 3, because the main parameter in the choice process was rock mass quality rather than maximal overburden. In the first part of the alignment, the tunnel passes under a mountain whose elevation is 2400 m, but no squeezing problem are encountered because the rock mass quality is excellent. However spalling problems might occur.

There is also a part of schist for alignment number 2 that causes squeezing problem, but it is the same for the tree alignments.

2.4.3 Profile n° 3 – Smallest Overburden

As mentioned in paragraph 2.3.1, this third alignment was chosen trying to reduce the maximum and average overburden of the tunnel. Figure 2.12 represents the section found for alignment number 3.

As it has already been explained in the previous sections, this itinerary has the same entrance as the first variant and they share the first part until the village of Etiaz: this explains why the first part of the geology is identical to the first alignment. The profile contains **Crystalline Gneiss** and **Limestone** with the characteristics already explained, but in this case the Au layer is elongated for more than half of the tunnel's length. After this section, a little intrusion of CS/SCh is found before reentering Limestone. **Schistes and Calcshists** reappear in bigger proportion at the end of limestone, creating a few problems for what concerns the quality of the material. At the end of the itinerary, like in the other profiles, the multifunctional station is reached through to a consistent portion of GP (**Micashist and foliated Gneiss**)

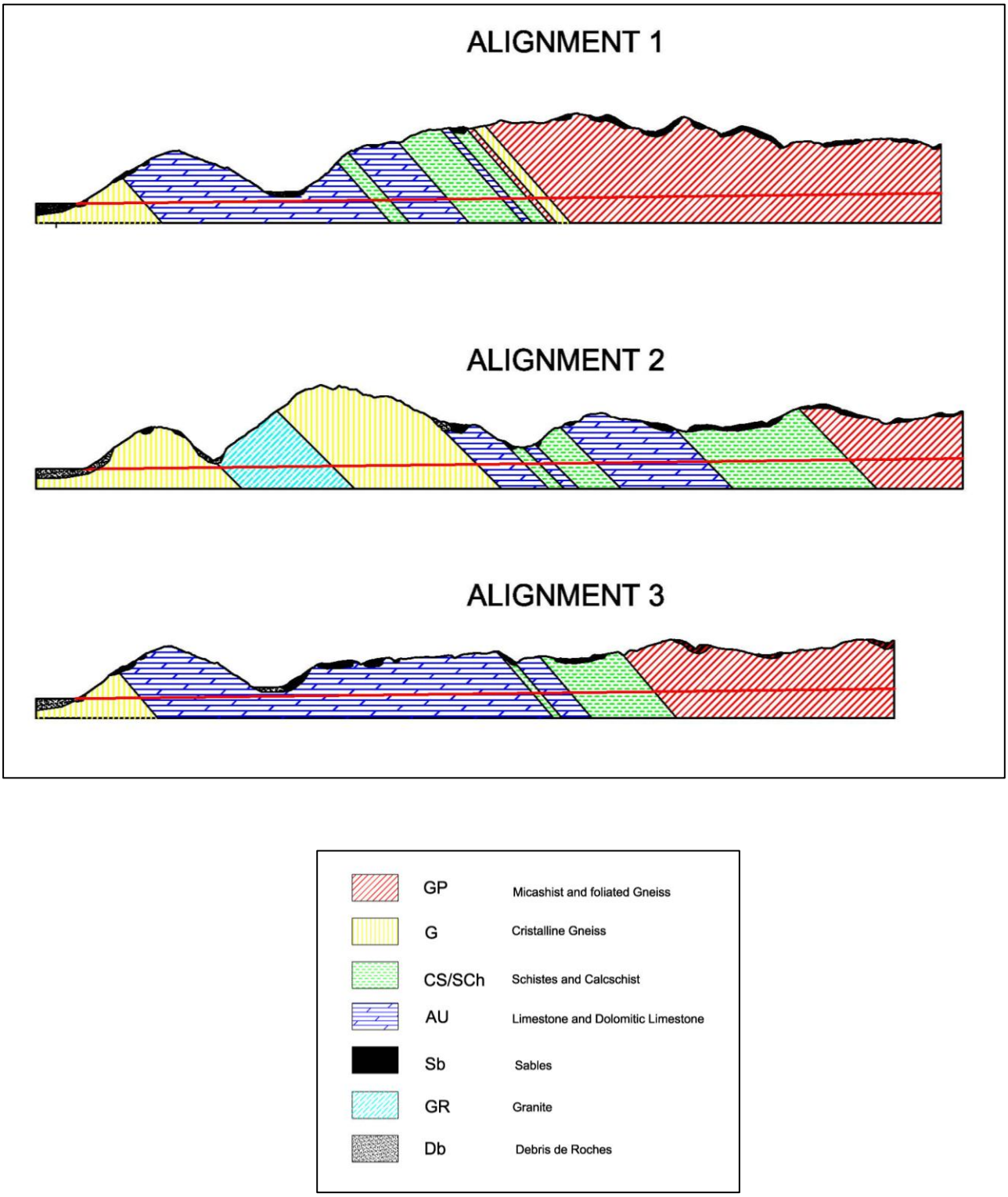


Figure 2.12 – Geological Profiles and Legend

3 COMPARISON AND ANALYSIS OF THE THREE ALIGNMENTS

3.1 Introduction to Multi-criteria Analysis

The multi-criteria analysis is a very powerful tool that allows to select in the most objective way the best solution for the given case. This method takes into account a wide range of parameters, not only certain elements that are particularly related to the construction phase (like geology and topography), which would result into a trivial and granted solution. Parameters have a different weight according to their importance.

For what concerns the tunnel, we have divided all the parameters into five main categories: beside topography and geology, for each itinerary the functionality, the benefits for the population, the economic aspects and the impacts on the environment are also taken into account. All the chosen categories are then subdivided into more specific parameters that allow a deeper analysis, reaching the optimal and final solution.

3.1.1 Weights

The first step is the decision of the importance of each category, which does not correspond to the weight of the single parameters. As mentioned, the total percentage has been subdivided into groups in function of their importance inside our project. This is a more objective way of preceding, otherwise the number of elements in each category and the relative weights might distort the final result.

The percentages that we have applied to the multi-criteria analysis are the following:

- Functionality: 24%
- Geology: 24%
- Economy: 22%
- Topography: 17%
- Social & Environmental impacts: 13%

Weights to the single parameters were assigned according to these percentages.

For what concerns this project **Social & Environmental** impacts are not considered to be as problematic as they are in other works in the Civil Engineering domains (such as dams or highways), due to the fact that the construction site is located deep inside the mountain. The position of the entrance was taken into account during step n°1 in order to reduce the most the number of people affected by the noises and vibrations, therefore the impacts are not a clue factor in the analysis and a value of 13 % was attributed to this category.

The four remaining aspects are considered fundamental for the construction or the viability of the tunnel, but they do not have the same importance.

With the evolution of the technologies, topographical problems have lost importance if compared to the geological ones; topography is generally known, whereas great investments

(investigations through boreholes during pre-study) are needed to reduce the incertitude concerning geology, but it is impossible to completely eliminate it.

Moreover, the importance of each category depends on many factors, such as demand, offer of alternatives, economical level and technological development of the country. In this case, the project is located in Switzerland where the technological development is at high standards and money is not an issue as it is for other countries. In addition there are no reasonable alternatives to this tunnel because nowadays the fastest way of linking Martigny to Torino is through Milano. Within this context, the conclusion is that functionality, intended as efficiency of the line, may be considered as more important than the economic aspect: this explains why a value of 24% was given to functionality and 22% to Economy.

For a correct analysis the relationships between economy, geology and functionality, should be taken into account: in fact they are not completely independents and this correlation could generate repetitions on several elements, which would perturb the final result. As an example, the construction methods involve geology, in particular rock quality and squeezing problems, but they are also a clue factor in the economic aspects affecting the materials, machines and working time.

The results of the analysis correspond to the aspects previously defined and the attribution of the scores is explained below:

Weight	Definition
1	Slightly Important
2	Average Important
3	Important
4	Very Important

Table 3.1 – Weight Scale

Scale	Definition
1	Really Bad
2	Bad
3	Fair
4	Good
5	Excellent

Table 3.2 – Rating Scale

The results of the multi-criteria analysis are listed in the table below:

				1		2		3	
			Weight	Rating	Value	Rating	Value	Rating	Value
Functionality	Construction	Quality of Adits	3	2	6	3	9	4	12
		Flexibility	2	4	8	3	6	2	4
		Position of the sites	3	3	9	1	3	5	15
	Service	Length	2	3	6	3	6	4	8
Topography	Min overburden		2	2	4	1	2	3	6
	Max overburden		3	2	6	2	6	4	12
	Average overburden		3	1	3	3	9	4	12
Geology	Rock mass quality		4	1	4	3	12	2	8
	Variability		2	3	6	4	8	3	6
	Squeezing		2	2	4	4	8	3	6
	Problematic situations		3	2	9	3	9	4	12
Economy	Length		3	3	9	3	9	4	12
	Construction Method		4	2	8	3	12	4	16
	Time/Schedule		3	3	9	4	12	3	9
Social & Environmental	Environmental Impact	Entrances	2	3	6	2	4	3	6
		Water	1	3	3	2	2	3	3
		Flore & Fauna	1	4	4	4	4	4	4
	Social Impact	Noise & Vibration	2	4	8	4	8	2	4
TOTAL					109		129		155

Table 3.3 – Multicriteria Analysis

3.2 Functionality

The functionality factor is divided into two different categories: Construction and Service.

3.2.1 Construction Phase

The construction part contains three subcategories:

- Quality of the adits (Weight: 3) – This part takes into account slope (< 15%), length and efficiency of the connection points along the alignment.
    - **Alignment 1** - Two adits with a constant slope of 15%. The second adit is extremely long (3200m) which has negative consequences on the excavation planning and on the transport of the materials. Rating: 2
    - **Alignment 2** - One adits with a constant slope of 15% and two shafts that will generate problems during the introduction and the extraction of the materials inside and outside of the tunnel; on the contrary three connections well distributed along the tunnel will accelerate the excavation process. Rating: 3
    - **Alignment 3** - Two adits with acceptable lengths and slopes. The distribution of the access tunnels along the alignment is optimal and the position of the adits also takes into account the changes of geological layers. Rating: 4

  The Multifunctional Station is not considered in this analysis since it is common for all the three alignments. For what concerns the entrance, the two options are considered as equals and therefore they are not going to be analyzed.

- Flexibility (Weight: 2) - It evaluates the difficulty of solving a problem during the excavation process; it considers the geological formation around the alignment and how the construction method chosen can adapt to these changes.
    - **Alignment 1** - It crosses the mountains in a deep zone where the material´s quality is quite uniform and there are no important topographical or geological restrictions that could prevent horizontal changes of the alignment. Rating: 4
    - **Alignment 2** - As explained before, this itinerary was designed in order to follow the granites and this represents a restriction since this section is not really wide and the excavation method chosen could not be prepared for a different kind of rock. Rating: 3
    - **Alignment 3** - This layout was designed in order to follow the valley: this represents an important topographical restriction because at certain points the overburdens are not really high and a change of layout can provoke problems of water inflows. Rating: 2

- Construction sites (Weight: 3)- This parameter studies the proximity of an access road to the construction sites in order to facilitate the transportation of the materials; it also considers the elevation and the general conditions of the site, distance to villages and highways. This parameter does not consider the social impact of the construction sites.

- **Alignment 1** - In both cases the entrance is far from the villages and the places are optimal for the placement of a construction site. Rating: 3
- **Alignment 2** - All the potential points of the valley where the construction sites could be located are next to a river; this makes the beginning the excavation more problematic from a practical point of view. Rating: 1
- **Alignment 3** – the adits are close to the villages and located at the bottom of the valley without any requirement of starting shafts and with a big place to settle the construction site. Rating: 5

The adits are considered as a key element and their location during design process of the tunnel should be carefully evaluated. The quality of the adits is something extremely important because the construction planning is defined based on their positions and in case of shafts or really sloped adits, problems in the movement of the materials will occur.

3.2.2 Service

The functionality during the service life is based on the quality of the final tunnel, taking into account the purpose it was built for, which in this case is reducing the travel time from Italy to Switzerland. This factor is usually simplified into two main parameters:

- Length of the tunnel (Weight: 2)
  - **Alignment 1** – 20189 m – Rating: 3
  - **Alignment 2** – 20579 m – Rating: 3
  - **Alignment 3** – 19130 m – Rating: 4

- Speed of the train (Weight: 0)

The second parameter will not be considered because the speed of the train is fixed at 250 Km/h by the minimal radius of the imposed by the project.

3.3 Topography

The topography factor is divided into three elements that evaluate different overburdens. The degree of importance is different according to the problems that will be generated.

- Minimal Overburden (Weight: 2) – Might generate serious water inflows, especially in rocks with high permeability and where the overburden is below 400 m. These flows are characterized by very high initial flows and drawn-dawn of the water table. Late time flows are then controlled by surface recharge. This issue can be accepted if a good waterproof system is provided.
  - **Alignment 1** – 210 m – Rating: 2
  - **Alignment 2** – 141 m – Rating: 1
  - **Alignment 3** – 227 m – Rating: 3

- Maximal Overburden (Weight: 3) – Great overburdens can generate squeezing, spalling and rock burst problems; in certain points these issues can be overpassed

through specific interventions. Great overburdens also create problems in the investigation phase (boreholes)

- **Alignment 1** – 1972.9 m – Rating: 2
- **Alignment 2** – 1892.5 m – Rating: 2
- **Alignment 3** – 1209 m – Rating: 4

- Average Overburden (Weight: 3) – The average overburden define the same problems of the maximal overburden, but in a continuous way. In case of continuous problems, it would be more difficult to solve them because the intervention along the entire tunnel would be too expensive.
  - Alignment 1 – 1242.9 m – Rating: 1
  - Alignment 2 – 978.9 m – Rating: 3
  - Alignment 3 – 834.2 m – Rating: 4

3.4 Geology

This third group comprehends a vast number of elements that have been divided into four sublevels, namely Rock mass quality, Variability, Squeezing and Problematic Situations.

- Rock Mass Quality (Weight: 4) – This section does not only study the quality of the material that will be encountered, but also the properties inside each massif, such as weathering, joints separation etc. For these reasons it is one of the most important criteria of the analysis.
- Variability (Weight: 2) - It considers the problems related to the changes of rock quality inside the same material, unpredictable along the excavation. This parameter has a great influence on the excavation process. We will not take into account the material changes because it's something that is a priori unknown, at least for the given project.
- Squeezing (Weight: 2) – This factor is separated to the others problematic situations due to its importance.
- Problematic Situations (Weight: 3) - It considers rock burst, spalling, wedge failing, raveling, swelling and water income.

3.4.1 Rock Mass Quality

The rock mass quality of each type of rock was found using the RMR method. Initially the rating was given to the following criteria: strength or intact rock material, RQD (%), joints spacing, condition of joints and ground water condition. **Table 3.5** gives an idea of the results for each type of rock. The corrected RMR is also placed in the table for the rock mass quality. As one can notice from the results, the crystalline gneiss and granite (G-GR) have the greatest RMR rating followed by the limestone. Lastly, the foliated gneiss (GP) is placed between limestone and schist (in last position).

Each alignment is analyzed using a rating that is function of the rock mass quality multiplied by the length of the section. The alignment 2 has the longest part of good rock mass quality and has a small part of poor rock quality. The third alignment has a small part of schist (very poor rock quality) but has less good quality rock if compared to the second alignment. The first alignment has a long part of bad rock quality.

The uniaxial compressive strength (UCS) for some rock type is very variable. For example, the UCS of the limestone passes from 100 MPa to 5 MPa. Also the joint set and the joint spacing vary a lot in the same rock type. In addition the water inflow is not constant in a massive of rock. The inhomogeneity of the massif complicates the determination process of the rock mass quality. The big overburden of the tunnel makes also harder to have a precision on the prediction of the rock mass quality. It is usual to accept a level of uncertainty and to be optimal with the survey on the rock mass; for these reasons the worst and the best cases are considered for each type of rock, which means that the lowest values were used to find the worst RMR and the best value for the best RMR. In conclusion an average between the worst and best case was determined.

As mentioned the massif is very variable the quality changes a lot. If we consider AU (Limestone) using the RMR and rock mass quality chart, the worst case classifies the rock mass as very poor whereas for the best case the chart of RMR gives a good rock mass quality.

For the explained reasons, it is difficult to univocally classify each rock without further information.

The RMR value for the Schist and Calcschist is very low and it gives a rock mass quality that varies between poor and very poor. The Schist and Calcshist will have a strong impact on the project because these types of Rock will necessitate expensive stabilization techniques.

The rock mass for GP (Micaschist and foliated Gneiss) is qualified as fair for what concerns the best situation, but in the worst case, the rock mass is very poor. This type of rock would be hard to be excavated with a TBM.

The Crystalline Gneiss and Granite have a very good rock mass quality, even for the worst case.

Table 3.4: Rating for rock mass quality

Description	Rating	RMR
Very poor	1	<20
Poor	2	21-40
Fair	3	41-60
Good	4	61-80
Excellent	5	81-100

Type of Rock		1) Strength or intact rock material UCS (MPa)	2) RQD (%)	3) Joint spacing (m)	4) Condition of joints	5) Ground water	Total RMR	Correction of RMR	Total corrected RMR
AU (Limestone)	**Worst case**	2	3	5	5	0	15	-2	13
	Average	9,5	10	10	10	7,5	47	-2	45
	Best case	17	17	15	15	15	79	-2	77
	Description	5 MPa to 100 MPa (big variability)	0 to 80 % (Big variability)	1 mm to 1 meter (Big variability)	Smooth to rough	Possible water inflows	Big variability	drive with dip at 45°(□)	Fair
CS/SCh (Schist, calcschist)	**Worst case**	2	3	5	0	4	14	-2	12
	Average	2	5,5	5	5	7	24,5	-2	22,5
	Best case	2	8	5	10	10	35	-2	33
	Description	5 MPa to 20 MPa	0 to 25 %	1 mm to 1 cm	Smooth	Low water inflows	Very low rating but constant	drive with dip at 45°(□)	Very poor
GP (Micaschist and foliated Gneiss)	**Worst case**	2	3	8	0	4	17	-12	5
	Average	4,5	8	11,5	5	7	36	-12	24
	Best case	7	13	15	10	10	55	-12	43
	Description	20 MPa to 60 MPa	20 to 60 %	10 cm to 1 meter	Smooth	Low water inflows	low rating and variable	Drive against dip at 45° (□)	Poor
G-GR (Crystalline Gneiss and Granite)	**Worst case**	12	17	20	25	10	84	0	84
	Average	12	18,5	20	25	12,5	88	0	88
	Best case	12	20	20	25	15	92	0	92
	Description	120 MPa to 200 MPa	80 to 100 %	> 2 meter	Rough	Very Low water inflows	Very high rating and constant	drive with dip at 45°(□)	Very good

Table 3.5 - RMR for each type of roc

	Description	length [km]	rating	Total rating	Final score	Changed score
Alignment 1	Crystalline gneiss	1.57	5	7.9	2.4	1
	Limestone	5.29	3	15.9		
	Variation of schist and limestone **	3.83	1.5	5.7		
	Crystalline gneiss	0.33	5	1.7		
	Foliated gneiss	9.17	2	18.3		
	Total length:	20.19	Total rating:	49.5		
Alignment 2	Crystalline gneiss and granite	9.24	5	46.2	3.2	3
	Total of limestone from pk 9.2 to 14.6	4.05	1.5	6.0		
	Total of schist from pk 9.2 to 14.6	1.31	1.5	2.0		
	Schist	3.32	1	3.3		
	Foliated gneiss	2.67	3	8.0		
	Total length:	20.6	Total rating:	65.6		
Alignment 3	Crystalline gneiss	1.52	5	7.6	2.6	2
	First part of limestone	9.16	3	27.5		
	Small part of schist	0.19	1.5	1.1		
	Second part of limestone	0.69	1.5	1.0		
	Long part of schist	1.96	1.5	3.0		
	Crystalline gneiss	5.61	2	11.2		
	Total length:	19.13	Total rating:	50.6		

Table 3.6 - Rating for rock mass quality

Then, when the RMR is found for each type of rock, a rating is associated to the RMR and it is multiplied by the length of each type of rock for the different alignment.

Alignment 1 – This itinerary is the one with the lowest score. Table **3.7** - Rating for variability of the geology

shows that the "changed score" is 1 whereas the final score would be 2.4, this change is made to enlarge the difference between the alignment 1 and 3, otherwise they would have the same score. In the multicriteria analysis the changed score is used. In addition, the first alignment contains the same amount of schist than the alignment 3, but there is more foliated gneiss and less limestone whose RMR rating is lower. This explains why the final score is 1.

Alignment 2 – This is the best itinerary for what concerns rock mass quality because of the first 10 excellent kilometers; the last part involves limestone, schist and foliated gneiss, whose ratings are lower. This explains why the score is not very high, but still higher than the other two options.

Alignment 3: This is an average alignment, which means that the rock mass quality is between the first and the second one. The same amount of schist (bad rock quality) and

crystalline gneiss (good rock quality) is encountered, but there is more limestone and less foliated gneiss.

3.4.2 Variability

The variability is not just related to the alignment passing through different types of rock, but it is also considers the variability of each rock mass inside each section. As an example, the rock mass quality of the limestone is very variable.

Looking at the results on the Table **3.7** - Rating for variability of the geology

one can notice that the first alignment has a medium score because it passes 9.1 kilometers through Limestone, which has a great variability of the rock mass quality. Alignment 3 also has a great part of limestone; therefore the same rating was assigned. The second alignment has the lowest rating because the itinerary passes through a consisted section of crystalline gneiss and granite that are very steady. In addition, this alignment doesn't cross many layers with different rock type.

Concerning the section with a variation of the schist and limestone at pk 6.8 to 10.7 for the alignment 1, the schist has 54 % of this section, the limestone has 41% and the foliated gneiss has 4.3 %. The rating given for this part has 1 because the rock type has big variation.

	Description	Length [km]	Rating	Total rating	Final score
Alignment 1	Crystalline gneiss	1.57	5	7.9	3
	Limestone	5.29	2.5	13.2	
	Variation of schist and limestone **	3.83	1	3.8	
	Crystalline gneiss	0.33	3	1.0	
	Foliated gneiss	9.17	3.5	32.1	
	Total length:	20.19	Total rating:	58.0	
Alignment 2	Crystalline gneiss and granite	9.24	5	46.2	4
	Total of limestone from pk 9.2 to 14.6	4.05	1.5	6.0	
	Total of schist from pk 9.2 to 14.6	1.31	1.5	2.0	
	Schist	3.32	4	13.3	
	Foliated gneiss	2.67	3	8.0	
	Total length:	20.6	Total rating:	75.5	
Alignment 3	Crystalline gneiss	1.52	5	7.6	3
	First part of limestone	9.16	2.5	22.9	
	Small part of schist	0.19	1.5	0.3	
	Second part of limestone	0.69	1.5	1.0	
	Long part of schist	1.96	1.5	3.0	
	Foliated gneiss	5.61	3	16.8	
	Total length:	19.14	Total rating:	51.6	

Table 3.7 - Rating for variability of the geology

3.4.3 Squeezing Problems

The squeezing behavior in a tunnel is a problem that appears under big pressure on a rock mass that has bad properties. This problem is often seen under big depth with bad rock quality mass. The squeezing behavior reduces the cross section of the tunnel creating problems of jamming for Shield TBMs.

For the squeezing behavior, an Excel file was used to see if squeezing problems occurred for each depth and at which level. The first step of the Hoek-Brown method is finding a GSI value for each type of rock, considering the best, average and worst cases.

Table **3.8** shows the different values found for each rock type. The σ_{ci} is given, but the σ_{cm} was found by multiplying σ_{ci} by $\sqrt{S}$ (S is a parameters that changes with rock type and rock mass quality).

An example of the calculations made to obtain the results is reported in section 3.4.3.1.

Type of Rock		Best case	Average	Worst case
AU (Limestone, Dolomitic, Calcaire)	GSI	65	48	30
	D	0	0	0
	σ_{ci} [MPa]	100	52.5	5
	σ_{cm} [MPa]	0.39	7.51	0.02
	S	0.0000	0.0205	0.0000
	Υ[MN/m^3]	0.027	0.027	0.027
CS/SCh (Schist, Calcschist)	GSI	20	13	5
	D	0	0	0
	σ_{ci} [MPa]	20	12.5	5
	σ_{cm} [MPa]	0.23	0.15	0.06
	S	0.0001	0.0001	0.0001
	Υ[MN/m^3]	0.027	0.027	0.027
GP (Micaschist and foliated Gneiss)	GSI	65	43	20
	D	0	0	0
	σ_{ci} [MPa]	60	40	20
	σ_{cm} [MPa]	8.58	5.72	2.86
	S	0.0205	0.0205	0.0205
	Υ[MN/m^3]	0.027	0.027	0.027
G-GR (Crystalline Gneiss and Granite)	GSI	100	90	80
	D	0	0	0
	σ_{ci} [MPa]	200	160	120
	σ_{cm} [MPa]	200.00	160.00	120.00
	S	1.0000	1.0000	1.0000
	Υ[MN/m^3]	0.027	0.027	0.027

Table 3.8 - Rock mass properties

3.4.3.1 Example of calculation for squeezing problems

The first step is to find a GSI (Geological Strength Index for). For the Foliated Gneiss (GP), the GSI is around 43 because the average structure of this rock material is very blocky and the

average surface condition is fair. Also, as a function of the construction method it is possible to find a value of D : Disturbance Factor, which would give a smaller S and increase the strain ε, implying more squeezing problems. For the Foliated Gneiss, the value of D is set equal to 0, assuming that the excavation process will not affect the massif.

$$S = e^{\frac{GSI-100}{9-3D}} = e^{\frac{43-100}{9}} = 0.002$$

The uniaxial compression resistance (σ_{cm}) is calculated with Hoek and Brown Formula, setting $\sigma_3 = 0$. σ_{ci} is the uniaxial compression resistance for intact rock.

$$\sigma_{cm} = \sigma_3 + \sigma_{ci} \cdot \left(\frac{\sigma_3}{\sigma_{ci}} mb + S\right)^{0.5} = \sigma_{ci} \cdot \sqrt{S} = 40 \cdot \sqrt{0.002} = 1.79 \text{ Mpa}$$

The strain "ε" (the tunnel wall displacement $\frac{u_r}{\text{tunnel radius}} \cdot 100$) can be obtained with the equation below. For a depth of 800 meters:

$$\varepsilon = 0.2 \cdot \left(\frac{\sigma_{cm}}{P_0}\right)^{-2} = 0.2 \cdot \left(\frac{1.79}{21.6}\right)^{-2} = 29.12\ \%$$

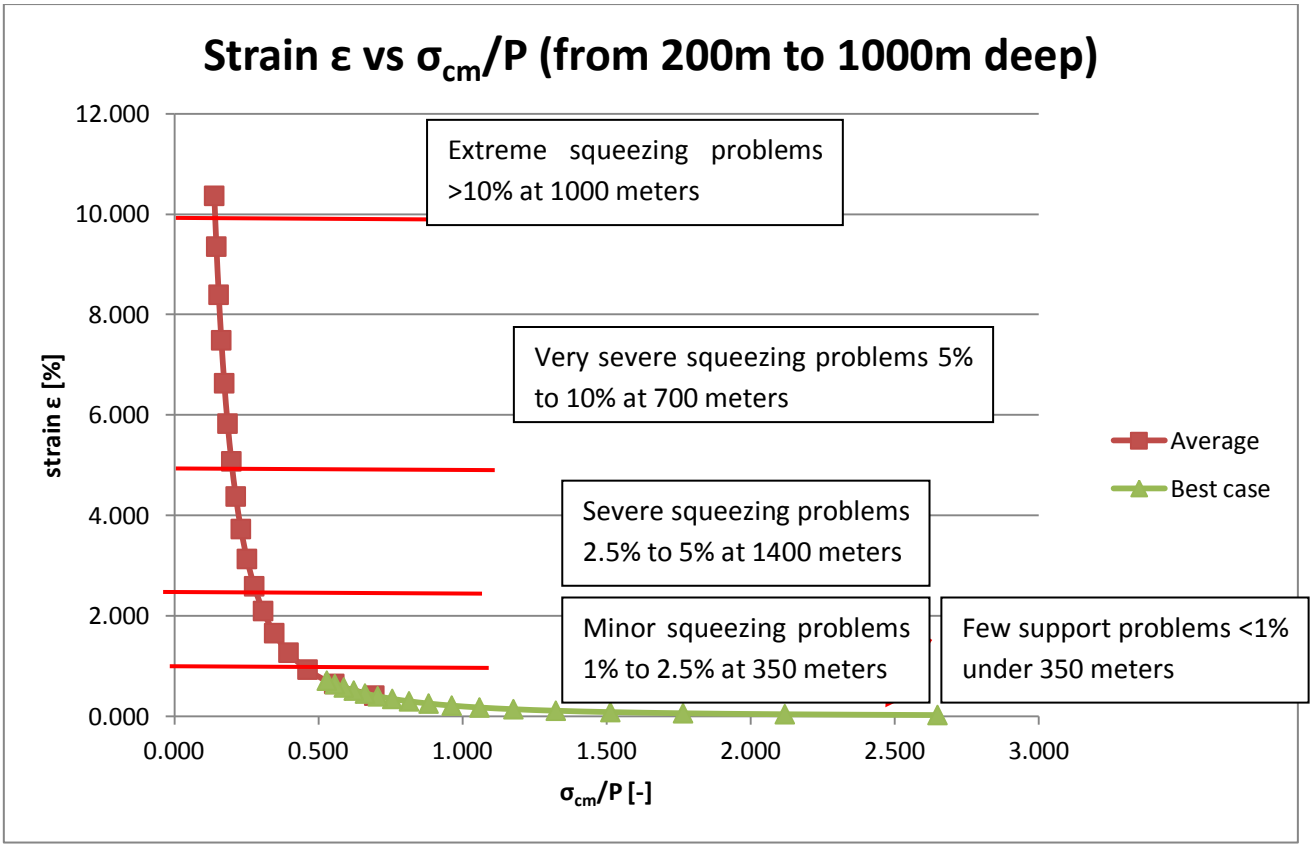
Once the results for each type of rock have been determined, it is possible to build a graph with the strain (ε) as a function of $\frac{\sigma_{cm}}{P}$. Through an Excel file, the P load varies in function of the depth and the strain varies in function of the P load. Here is an example of the calculation.

$$P = \gamma \cdot H = 0.027 \left[\frac{MN}{m^3}\right] \cdot 800\ [m] = 21.6 \text{ Mpa}$$

$$\frac{\sigma_{cm}}{P} = \frac{1.79 \text{ MPa}}{21.6 \text{ MPa}} = 0.08$$

In this case, severe squeezing problems are encountered because ε is higher than 5%. The squeezing problem behavior can be resumed by the following values:

$\varepsilon < 1 = Few\ support\ problems$
$1 < \varepsilon < 2.5 = Minor\ squeezing\ problems$
$2.5 < \varepsilon < 5 = Severe\ squeezing\ problems$
$5 < \varepsilon < 10 = Very\ severe\ squeezing\ problems$
$\varepsilon > 10 = Extreme\ squeezing\ problems$



Graph 3.1 – Squeezing behavior (weak rocks)

3.4.3.2 The rating for squeezing problem for each alignment

After obtaining all the results for the squeezing problem, some considerations have to be made: the first alignment is the worst for what concerns severe squeezing problems that can be encountered along the third (starting at PK 6.86) and the fifth part (starting at PK 11), for a total length of 12.8 kilometers.

The second alignment is the one that was chosen for the good rock and in this section there are 13.3 kilometers with few support problems. In the remaining part of the alignment there are major squeezing problems.

For what concerns the third alignment, it can be placed in between alignment 1 and 2 because there are 10.4 kilometers with few support problems and 5.6 km of severe squeezing problems.

Rating for squeezing problems	
Extreme S. problems	1
Very severe S. problems	2
Severe S. problems	3
Minor S. problems	4
Few support problems	5

	Description	length [km]	rating	Total rating	Final score
Alignment 1	Crystalline gneiss	1.57	5	7.9	2
	Limestone	5.29	4	21.2	
	Variation of schist and limestone **	3.83	1	3.6	
	Crystalline gneiss	0.33	5	2.5	
	Foliated gneiss	9.17	1.25	11.5	
	Total length:	20.19	Total rating:	46.7	
Alignment 2	Crystalline gneiss and granite	9.24	5	46.2	4
	Total of limestone from pk 9.2 to 14.6	4.05	4	14.2	
	Total of schist from pk 9.2 to 14.6	1.31	1	1.3	
	Schist	3.32	1	3.3	
	Foliated gneiss	2.67	3	8.0	
	Total length:	20.6	Total rating:	75.0	
Alignment 3	Crystalline gneiss	1.52	5	6.3	3
	First part of limestone	9.16	4.25	38.9	
	Small part of schist	0.19	1	0.2	
	Second part of limestone	0.69	3	2	
	Long part of schist	1.96	1	1.96	
	Foliated gneiss	5.61	2	11.2	
	Total length:	19.13	Total rating:	60.6	

Table 3.9 - Rating for squeezing problems

3.4.4 Problematic situations

There are six main problematic situations that are considered in this section:

- Water income (3.4.4.1)
- Rock burst
- Spalling (3.4.4.2)
- Wedge failing (3.4.4.3)
- Raveling
- Swelling

Among these main problems, three of them that are not considered in this project: rock burst, raveling and swelling. The **rock burst** is related to the overburden of the tunnel that stresses the rock mass applying a pressure onto a rock section delimited by joint sets that fails because of this pressure; this type of failure is comparable to a column that is too much charged. It often liberates a lot of energy and it can be dangerous for safety. For this tunnel, rock burst is not considered because the joint set is at 45 degree and it is impossible to have

a rock burst failure. Concerning the raveling and the swelling, the types of rocks involved in the three alignments are not subject to these problems.

	Water income		Spalling		Wedge falling		Final score
	Weight	Rating	Weight	Rating	Weight	Rating	
Alignment 1		3		4		2	2
Alignment 2	4	3	3	2	3	3	3
Alignment 3		3		5		2	4

Table 3.10 – Rating for problematic situation

3.4.4.1 Water income

Water income is related to the rock mass jointing, quality of the rock and eventual geological contacts. Each alignment crosses a river: the first alignment at PK 4.3, the second at PK 3.1 and the last one at PK 4.1.

The **second alignment** that has good rock condition below the river with granite and gneiss, but there are possible fractures between the crystalline gneiss and the granite close to the river; the river is at 141 meter above the tunnel. For the same alignment, it is also possible to encounter water problems at PK 8.8 due to the Champex lac that is located about 900 meters above the tunnel and it is near a possible joint between two rock types: the crystalline gneiss and the limestone. Taking into account all these considerations for alignment 2, the rating is 3 because there is possible water inflow at some point, but at the worst part (pk 3.1) the rock mass quality is very good.

For the **first alignment**, the rating 3 is also given because there are no fracture problems between two different rock types (like in the second alignment), but the rock mass quality is not very good and very permeable below the river (limestone). The problem with limestone is that the rock mass has many joint families and water can easily pass into the rock mass and at PK 4.3 the ground cover between the river and the tunnel is only 210 meters.

The **third alignment** has also limestone below the first river and the depth of the tunnel is at 210 meters. The rating that is given to this alignment is also 3, for the reasons explained above.

3.4.4.2 Rock spalling

The rock spalling was calculated with an Excel table considering the best case, the average and the worst case for the σ_{ci}. When $\frac{z}{\sigma_{ci}}$ gives a value higher than seven, spalling may take place. As a general rule, Spalling only occurs in good rocks, with σ_{ci} > 100 MPa due to their brittle behavior (failure in elastic domain). In this case, the table below represents the spalling values in function of the depth for the limestone.

σ_{ci}=		100
depth [m]	**z/σ_{ci}**	**Spalling may take place**
100	1.0	No
200	2.0	No
300	3.0	No
400	4.0	No
500	5.0	No
600	6.0	No
700	7.0	No
800	8.0	Yes
900	9.0	Yes
1000	10.0	Yes

Table 3.11 – Spalling problems

Table 3.12 shows how the spalling ratings were assigned for each section:

	Spalling Problems for:	length [km]	rating
Alignment 1	Crystalline gneiss	0.3	4
Alignment 2	Crystalline gneiss and granite	3.5	2
Alignment 3	-	0	5

Table 3.12 – Rating for spalling problems

The **first alignment** has a good rating because spalling problems are only encountered in a minimal section of the tunnel (300 m)

The worse score concerning the spalling problem is given to the **second alignment** because of the brittle behavior of the rocks that are found in the first part of the tunnel (3.5 km). In the second part of the tunnel an inelastic behavior is found and Spalling problems don't occur.

Finally, **the third alignment** has the best rating (5) because no Spalling problems are encountered.

3.4.4.3 Wedge Failing

The wedge failing depends on the rock mass, on the presence of many family joint and on the direction of the excavation. The joint sets are all at 45 degree perpendicular to the tunnel, which means that if the excavation goes with the dip, it is favorable to very favorable, but if the excavation is against the dip, it is unfavorable to very unfavorable. For each alignment, the direction of excavation is not taken in account for the multicriteria analysis, but it will be considered for the chosen alignment (Chapter 4).

Alignment 1 and 3: The rating 2 is given because both the first and the third alignment have a consistent part of limestone, schist and foliated gneiss, which could be blocky to very fractured.

Alignment 2: For what concerns the second alignment, the part of the tunnel that is inside granite and crystalline gneiss has no problems of wedge failing, but after PK 9.24, wedge failing problems can be found. That explains why the wedge failing rating (3) is bigger than the two other alignments.

3.5 Economy

- Construction Method (Weight: 4) – This is considered the main element in the economic aspect. The choice of the excavation method depends on many factors and it considerably affects a big part of the construction costs. For this reason it is fundamental to make an economic analysis of the different solutions, analyzing both with benefits and risks, before the final decision.
    - **Alignment 1** - The long part inside the foliated Gneiss with high overburden (and therefore squeezing problems) forces to work with conventional methods, which is not optimal for such a long section. Rating: 2
    - **Alignment 2** - The geology allows to choose good and efficient solutions, also in economic terms, but the complex system of entrances to the tunnel with two shafts and one adit will increase the costs. Rating: 3
    - **Alignment 3** - The disposition, length and type of the adits allow an easier solution for what concerns the construction methods. Inside the final section, through the schistes, this alignment has the same problems explained for the other cases. Rating: 4

- Length (Weight: 3) – The direct relationship between length and cost seems evident, which makes it a very important parameter. The weight that is given is smaller than expected because this parameter has already been considered in section 3.2 (Functionality).
    - **Alignment 1** – 20189 m – Rating: 3
    - **Alignment 2** – 20579 m – Rating: 3
    - **Alignment 3** – 19130 m – Rating: 4

- Time and Schedule (Weight: 3) – A delay in the construction phase results into more expenses for the constructor (salaries, taxes and machines' rental) and a reliable planning is therefore fundamental. The ideal solution would be to have short adits that generate a minimal time loss and a good geographical distribution.
    - **Alignment 1** – The design foresees two adits; the part of Foliated Gneiss is the biggest one and a long second adit will increase the excavation timing. Rating: 3
    - **Alignment 2** – Three intermediate accesses, more specifically two shafts that require a long excavation process. The rock is good and the benefits of having

three intermediate entrances will not save as much time as in worse geological situations. Rating: 3

- **Alignment 3** – It has a good balance of adit and tunnel excavation due to the adits' number, lengths and geographical distribution. Rating: 4

3.6 Social and Environmental Impacts

An importance of 13% was given to this point and it was divided into two main categories:

3.6.1 Environment

- Entry Portal & Adits (Weight: 2) – The entry portal and the different adits definitely have an important impact on the environment. The parameters that are considered in this analysis are the number of adits and the lengths of each access tunnel. The first and the third alignment have two intermediate adits, whereas the second has been conceived with one adit and two shafts. Itinerary 1 & 3 have tow entries, and the entries are placed in fairly good location from an environmental point of view, therefore a score of 3 is given. To second itinerary a value of 2 is attributed due to three intermediate adits, among which one of them will require deforestation.

- Groundwater and Runoff water (Weight: 1) – Since a hydrological analysis on the area has not yet been done, the data in our possession is not sufficient to evaluate the risk for each itinerary. We have therefore decided to attribute a score of 3 (Fair) for the first and the third alignment. The entrance of first adit in itinerary n° 2 is located right next to a river and a greater impact on the water flow can be foreseen, due to construction site and the activity of the machines. A value of 2 (bad) is therefore given.

- Flore & Fauna (Weight: 1) – For what concerns the plants and the animals, the impact of a tunnel is a priori not invasive and a common value of 4 (good) was given to all alignments.

3.6.2 Society

- Noise & Vibrations (Weight: 2) – This point is probably critical for what concerns the public opinion and acceptance of the project. If neglected, this point can lead to discussions, disagreements and delays. We imagine that all precautions will be taken in order to reduce at maximum the noises and the vibrations produced in the construction site, therefore the score is given according to the distance of the houses to the entrances. Adits for itineraries 1 & 2 are far away from the villages; therefore a score of 4 (good) is given. For what concerns the third itinerary, the intermediate entrance is located 250 m from Orsière and a lower value is attributed.

3.7 Discussion of the Results

The values, ratings and scores assigned to each parameter are summarized in Table 3.3 – **Multicriteria Analysis**, along with the final results. As expected, the third itinerary largely obtained the highest value (155) and it is therefore chosen for the next four exercises of the projects. The difference with the other two alignments is considerable: 26 points with the second itinerary and 46 with the first one. The other two alignments will not be discussed any further.

One remark that has to be made: the chosen itinerary resulted to be the best one out of the three chosen during the first exercise, which doesn't correspond to the best alignment in an absolute and objective way. In practice more than three alignment are considered (for the Lötschberg Tunnel, this procedure was called Spaghetti Solution), which allows a broader and deeper evaluation of the situation.

4 CONSTRUCTION METHODS & EXCAVATION PLANNING

Once the final alignment has been determined, along with the location of adits, shafts and construction sites, the next step is the selection of the construction methods and the creation of the excavation planning. The two processes are extremely linked between them because of the different advancement rates of the many working methodologies. **This section of the project is critical for ensuring good results in terms of time, quality and economy.** An error in the selection of the machines or in the prevision of the advancing speed can generate serious delays, increments in construction costs and, in the worst case, an in-situ project modification.

4.1 Construction methods

This tunnel construction is divided into three segments:

- Entrance (PK 0 to 0.2)
- Section 1 (PK 0.2 to PK 11.56)
- Section 2 (PK 11.56 to PK 19.13)

For each section different construction methods have been selected and they will be analyzed in the following paragraphs.

4.1.1 Entrance

This initial part of the tunnel is really short (around 200m) but it must be separated to the others due to a sandy part perforated with conventional method.

The conventional method used in this section is the Italian Method: full face with non-continuous excavation. It consists of making a grouting of the front part before each excavation step in order to improve the geological properties of the massive and to avoid face stability problems. It's a cyclical process, which mainly involves excavation, mucking and grouting in addition to shotcreting.

A forepoling is also applied along the first few meters of the tunnel, where the thin soil layer above the tunnel can produce important stability problems. This technique is applied until an overburden equal to diameter is reached, i.e. where the collapse probability is reduced to acceptable values.

4.1.2 Section 1

The location is ideal for a TBM excavation: in fact the assemblage can be done on surface, close to the city of Martigny where the materials can easily arrive in a non-expensive way.

The geology is mainly made of gneiss and limestone with a great variability of its properties; probably an ideal geology for a double-shield TBM, but the water inflows under the valley (where the overburden is low) could provoke problems on the telescopic joint of the shields. Ina addition the price of a Double Shield TBM is higher than a Double Gripper TBM.

Finally, all this drawbacks led to the conclusion that the use a double gripper TBM with a tractor could represent a better option. If compared to the single gripper TBM, this machine uses a double gripper support, which represents an advantage with rocks whose resistant conditions are worse. The explanation is that a bigger surface of contact applies a lower pressure on the adjacent rock. In addition the tractor is an element placed ahead of the cutterhead with the objective of making an axial pilot tunnel before the arrival of the machine to control the quality of the rock along the excavation. In case bad rock is encountered (unrealistic because the average quality of the rock is good) injections, radial bolts and steel ribs can be used to improve the stability of the ground. It is an automatic process where all dispositions for the reinforcing elements are coupled to the machine. The solutions adopted to solve the water income problems will be explained in Chapter 6.

The last kilometer before reaching the intermediate cavern involves an intrusion of schists (200 m), quite problematic for the grippers because of the quality of the rock that is not good enough to create a sufficient support. The solution is the excavation of the intrusion starting from the intermediate cavern with NATM; when the TBM reaches this point from the other side, excavation will stop and the machine will be transported by rails to the cavern for disassembly.

4.1.3 Section 2

It is formed by two different geological zones. In the first part there are Schisst and Calcschists with very severe or extreme squeezing problems that depend of the overburden and on the rock quality, which is really bad. In the second part there are Micaschist and foliated Gneiss with few situations of very severe squeezing problems and the quality of the rock is also not good.

The attacks are done by the second adit and by the multifunctional station; both of them with Conventional Methods. The reason why such a method has been chosen for the first case is clear: in fact the geology and the squeezing problems don't allow any other technique: in fact a Gripper TBM cannot be used because of the quality of the rock; the use of a Shield TBM would be too difficult due to the squeezing problems along the itinerary (the result might be a TBM stuck in the tunnel due to the elevated friction between the rock and the shield). For the second layer the decision of using Drill & Blast was related to the risk/benefits analysis. The risk of using a TMB on such a massif is not compensated by the time benefits that would result (Section 4.3): in fact the critical path is the section of the tunnel arriving from the second intermediate adit. The difference in excavation time between a TBM and a drill & blast is 100 days that compared to the total excavation time negligible.

The conventional method chosen is NATM (New Austrian Tunneling method), one of the fastest conventional methods. It is a partly face method that works perfectly for rock tunnels where the length of the tunnel is not sufficient to use a TBM or in case other geotechnical factors don't allow it. The main difference with the other conventional methods (Belgian method, German method, etc.) is the requirement of high cohesion and friction angles to assure the front stability: in fact the opening is done in two steps (Figure 4.1) and there is a bigger zone without subjection before the application of the temporary support. These two

different parts are named *top heading* and *benching;* their depth in tunnel axis direction will be bigger in case of a better rock, improving the speed and the efficiency of the excavation.

Figure 4.1 – NATM and temporary support

4.2 Technical Details of the Excavation Process

- **Railway tunnels** – Two parallel tunnels have to be designed. The axes distance is between the two tunnels is 30 m. Each tunnel has a diameter of 8.8 m to ensure space for the final lining, drainage and ventilation system. Obviously the internal diameter must allow the circulation of the trains at 250Km/h.

- **Section** – An example of the section of the tunnel is given in Figure 4.2

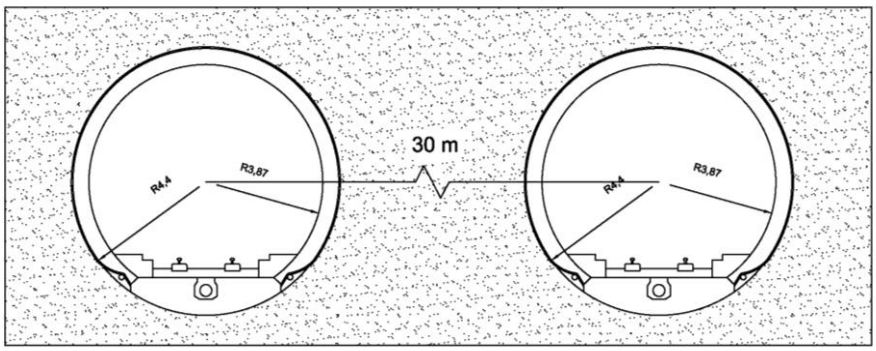


Figure 4.2 – Cross section of the tunnels

- **First Adit** – It is used as maneuvering tunnel during the construction phase. This adit will serve different purposes:
    - Exit for dug materials that can be placed close to the exit point without needing any treatment.
    - Entrance for materials coming from the road network, which avoids longer and more expensive transports that might create congestions in the area.
    - During the exploitation phase, this adit will be used as emergency exit.

The diameter of the adit is 5m, sufficient to move the materials with trucks. The excavation will be done through NATM.

- **Adit 2** – Critical point in the definition of the final planning. This adit will be connected to the main tunnel by a cavern and it will be used not only as an exit for the pieces of the disassembled TBM but also as entrance and exit of machines and materials during the construction of the cavern. Two attack fronts start from this adit. The diameter of the adit is 5m, sufficient to move the materials with trucks. The excavation will be done through NATM.
- **Shaft** – It will have a circular shape with a bigger diameter than the adits because of the complexity of the vertical movement on these kinds of entrances. It's therefore necessary to carefully choose a diameter which allows the entry of trucks and machinery; one thing that has to be taken into account is that trucks are longer than higher. The diameter chosen for each shaft is 8m. The excavation is done in soft rock (Micaschist and foliated Gneiss) with conventional methods and a piles wall will be placed on the top to ensure the stability of the excavation.
- **Connection tunnels –** They are done every 500m. The diameter of these tunnels is 6m. They allow air movement from one side to the other one. This is relatively important because the speed of the trains inside a completely closed tunnel could produce aero-dynamical problems. These constructions will also be useful for an evacuation in case of fire and for maintenance. The construction of these tunnels will not interfere with the excavation of the main lines, since they will be completed in parallel with the principal excavation.
- **Multifunctional station –** Because of its dimensions, at least 6 months are required for the excavation. The working procedure is similar to the conventional methods used for tunnels: at first dig galleries are constructed with a temporally support and enlarged only when the final dimension is reached.
- **Caverns** – The excavation procedure is quite similar to the previous one, but the time requirement is less due to its dimensions. The estimated time for the construction of a cavern is 30 days.
- **TBM Cutterhead** – The design contains 60 cutters, a common value for this cutterhead dimension and rock characteristics. Each cutter applies a force lower than 250 KN; a bigger force could produce damages on these cutters before the expected time. This condition leads to work with a maximal admissible force of 18000 KN, the product of the number of cutters and their admissible force.

4.3 Excavation planning

The excavation planning is a fundamental tool in a tunnel project that allows to control the timing of the different excavations.

The average advancement rate depends on the rock quality and on the excavation method; for what concerns this project, the methods used are Gripper TBM and Conventional.

	Average Advancement rate (m/day)		
Excavation method	Bad cond.	Av. cond.	Good cond.
Drill and blast	2	6	12
Gripper TBM	1.5	13	30

Audit no.	Description of the audit	Length or depth [m]	Rock type	Rock condition	Time [days] with drill and blast	Total for each part [days]
Adit 1a	Straight tunnel with 13% slope	257	Sand		129	
Adit 1b	Straight tunnel with 13% slope	1200	Limestone	fair	200	329
Adit 2a	Three curve with 14.3% slope	2479	Limestone	fair	413	
Adit 2b	Small part of schist before	242	Schist	poor	121	
Adit 2c	Cavern	75	Limestone	fair	25	559
Shaft part a	Tunnel with 15% slope	1286	gneiss foliated	fair	214	
Shaft part b	Cavern	75	gneiss foliated	fair	25	
Shaft part c	Vertical shaft 1	726	gneiss foliated	fair	363	602
Shaft 2	Vertical shaft 2	726	gneiss foliated	fair	183	
Multi. Station	Multifunctional station	-	gneiss foliated	fair	183	

Table 4.1 – Time schedule for the adit

Table 4.1 was made to determine the excavation time for the adits, the cavern, the shaft and the multifunctional station. The adit has the same excavation time as the tunnel and the drill and blast method is required. For the other kinds of infrastructures (shaft, cavern and multifunctional station), a longer excavation period is required if compared to a normal tunnel excavation. For example, the advancing rate for the shaft is 2 meter/day and 3 meter/day for the cavern. The multifunctional station is longer to be excavated due to its complexity and the time of construction will be approximately 6 months. The last column in the Table 4.1 represents the total time in term of days to complete the adit. This column is important in order to obtain the table 4.2 because it will be added to the total excavation time for the tunnel and it will give the critical time schedule for the whole tunnel. For example, the green part in table 4.1 represents the access to the multifunctional station; the green part of the table 4.2 represents the excavation of the tunnel that must be done after the excavation of the shaft. Those two parts must be added together to have the whole excavation time of the shaft and the tunnel. A 6 months difference is foreseen for the second tunnel.

Table 4.2: Time of excavation with different methods

Section	Description of the section	Length [m]	Rock type	Rock condition	Time with different excavating method [days]					Total for each part [days]
					Drill and blast	Readheader	Gripper TBM	Shield TBM	Double Shield TBM	
Part 1a	first part in moraine	202	moraine	-	101					
Part 1b	Assemble the TBM 1 (and the TBM 2 six months later)	-	-	-	182.5					
Part 1c		1316	Granite	good	110	132	44	44	33	
Part 1d		9159	Limestone	fair	1527	1832	705	611	458	
Part 1e	disassemble the TBM 1	-	-	-				183		
Part 1f	disassemble the TBM 2	-	-	-				183		1202
Part 3a	Longest part of schist	1963	Schist	poor	982	1963	1309	196	196	1723
Part 3b	From pk 11.5 to 10.7 the limestone	682	Limestone	fair	114	136	52	45	34	
Part 3c	From pk 10.9 to 10.5 the schist	193	Schist	poor	97	193	129	19	19	769
Part 4		5510	Gneiss foliated	fair	918	1102	424	367	276	1703

The table 4.2 represents the calculations that have been done for the time schedule with different methods. The darker cells represent the chosen method, for example, in the section “Part 1” in pink, the chosen method is the TBM shield. The time of each different method is calculated by dividing the length of the section to excavate with the advancement rate in meter per day of the method. The quality of the rock mass can also influence the advancing rate (m/day) of the method.

The total number of days (1202 days) for the first part (in pink) is calculated by adding the time of excavation of each type of rock with the TBM, with the assembling of the first TBM and the disassembling of both TBM. For this section, the assembling of the second TBM is not taken in account because it is done while the tunnel is excavated with the first TBM.

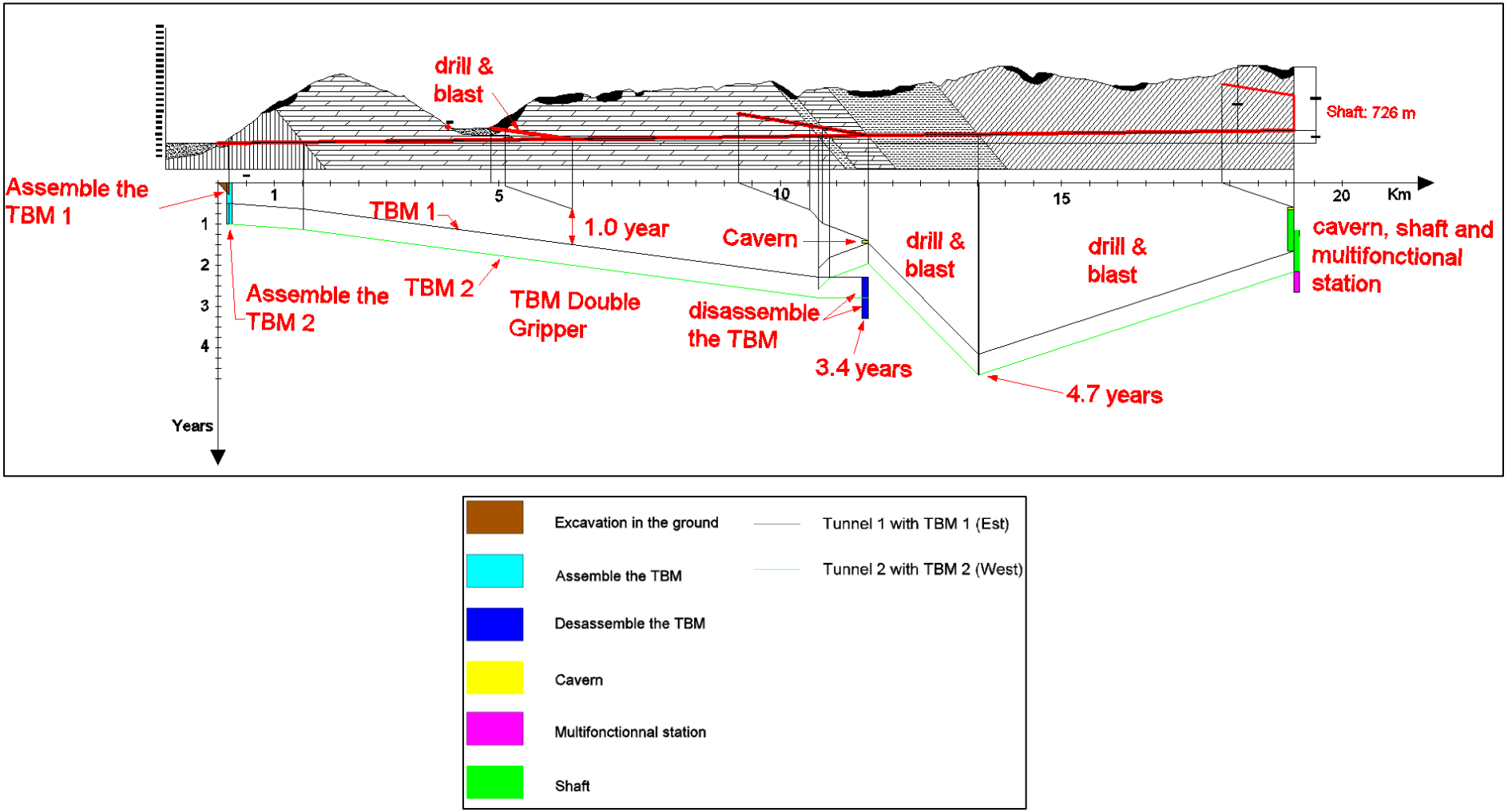


Figure 4.3 - Graph of time schedule

This planning shows that there is more than one critical path. If the path that starts in the Adit 2 and finish in the section 2 or the path that stars in the access tunnel for the shaft have a delay it will lead to a general delay of the excavation completion, which is **4.7 years**.

On the other side, there are some elements with a gap. In the section 1 the gap is 1.3 year and in the first adit there is one more year in relation with this digging section. This is explained by the fact that the adit should be finish before the arrival at the connection point of the excavation of section 1. The planning also shows the earliest moment when an excavation can start, but normally the works start later in order to reduce the costs, taking into account that a new critical path should not be created.

Two tunnels in parallel are excavated, one for each direction, therefore two TBMs will be used. The equipment for the conventional excavation (electrohydraulic jumbo, retro excavators, etc.) is also doubled. Only in the cavern the equipment will be unique because the excavation on the north side is really short and the parallel sections will be dug one after the other one.

Respecting the adits, two shafts and the corresponding access tunnels will be done to work as emergency exits and during the construction they will improve the performance of the process. One will work as entrance for the machines and materials, and the other for the exit of the rock. The longitudinal adits are less stiff in the movements than the shafts and that explains why two parallel adits are not constructed.

As mentioned before, the parallel tunnels and shafts are delayed 6 months in order to avoid constructive problems. The advanced tunnel allows to obtain geotechnical information that will be useful to increase the speed and reduce the costs of the second tunnel.

5 GROUND TREATMENT AND TEMPORARY SUPPORT

5.1 Ground Treatment

During the excavation of the tunnel, a few major problems could be encountered and therefore prevented using techniques to reinforce the massif; most of the issues were already explain in chapter 3, and they involve water income, squeezing problem, spalling rock and wedge failing. Grouting before the excavation is a technique that strengthens and seals the rock mass. If the rock mass has a lot of joint set and is very fractured, the grouting treatment techniques is a good choice because the concrete will penetrate into the cracks of the rock mass improving its stiffness. In the 3rd alignment there is a long section of limestone a material that, in general, does not produce serious squeezing problems; this section of the tunnel will pretreated using grouting methods more for waterproofing reasons rather than for structural ones. In addition, rock has smaller pore volume and since the rock is not homogeneous, it is possible to have large joints. Thicker grouts must be used to avoid material loss in the joints.

Since there are two different techniques to excavate the tunnel (TBM and drill and blast), the grouting techniques are also different.

- Grouting with a TBM machine – For the first 12 km, the tunnel will be excavated with a TBM and a special method of pre-grouting the face of the tunnel will be used. The TBM absolutely needs to be equipped with a drill machine in the front face and the drill hold must have a minimum length of 25 meters in front of the face, like shown in Figure 5.1.

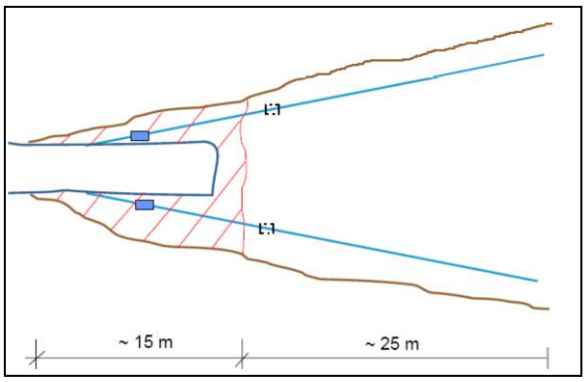


Figure 5.1 – TBM grouting

- Grouting for the conventional method: Starting at PK 12 until the multifunctional station located at PK 19, typical injections with a length of 21 meters will be done. For this method, an angle of 7 degrees and a distance of 1.2 meters between the holds for the injection will be needed. The machine for the drill and blast technique will also perforate the holes for the injection.

The parts of the alignment that are shown in red in Figure 5.2 represent the extreme squeezing problems that require a grouting treatment before the excavation. Three are the sections that have to be analysed.

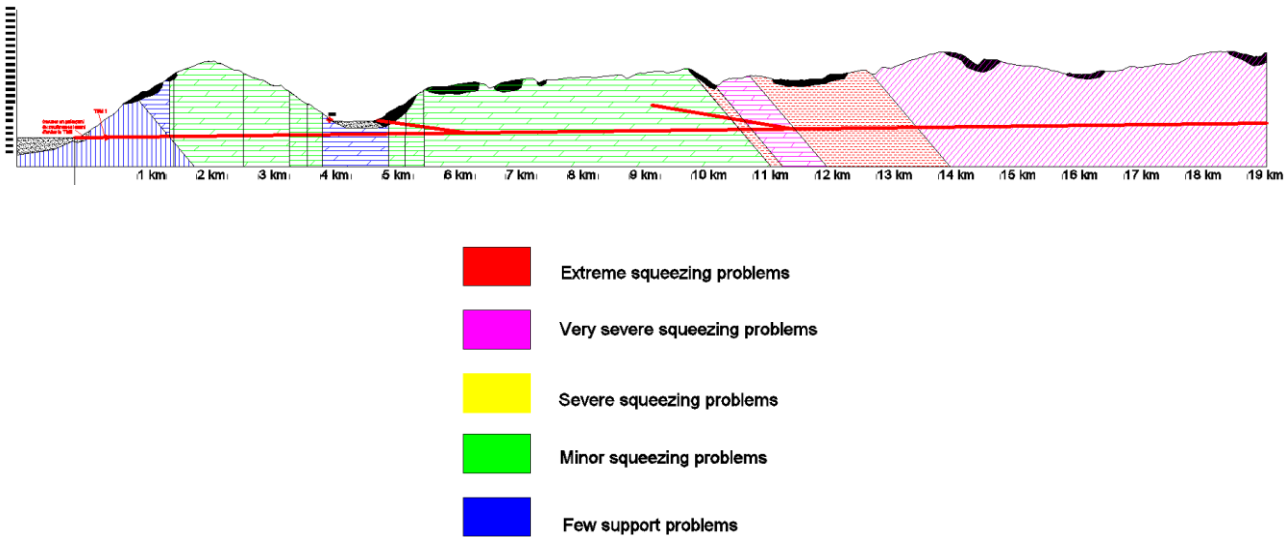


Figure 5.2 - Schema of squeezing problems

For the **first part** (from PK 1.7 to 2.8), the grouting is required for waterproofing reasons even if this section has few deformation problems: in fact limestone is not likely to squeeze. Grouting will improve the strength of the rock mass and, together with the watertight membrane, it will create a waterproof shield.

The **second part**, which goes from PK 12 to 14, is made of schists and it is highly fractured with extreme squeezing problems. The grouting in this section will also improve the strength of the rock mass and it will reduce the deformations. There is also a little part of schists at PK 11.2, whose length is 300 meters, that will be treated exactly like that the other sections with extreme squeezing problems.

The **third part** that needs to be grouted is the second blue part (from PK 4 to PK 5) because it has a water income problem and to avoid problem with the TBM it is important to grout this part from the face of the excavation.

5.2 Excavation scheme for conventional methods

The excavation scheme was chosen according to the corrected RMR value. The ratios that correct the RMR are a function of the orientation of the joint set and depend on the direction of the excavation. All the lithological contacts have an orientation of 45° perpendicular to the face of the tunnel. The direction of the excavation has an impact on the correction of RMR depending if the excavation goes with the dip or against the dip. Figure

5.3 shows that an excavation with a direction from Aosta to Martigny is unfavorable because the bloc has no support and it can easily fall in the excavation face.

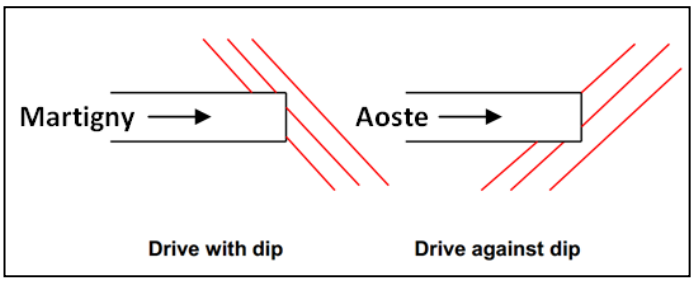


Figure 5.3 - The dip versus of the tunnel

The parts of the tunnel that will be excavated with the conventional method are the two adits, the schist section from PK 12 to 14 and the foliated gneiss. Also the last part of limestone, with the schistes intrusion will be excavated with the same method.

The first adit will be excavated in a limestone rock mass and is going with the dip at 45 degree. The rock mass RMRs were corrected with the value "-2", which gives a fair rock mass quality with a final RMR of 45.

The advancement of the top heading will be two meters at the time and the temporary support will be placed from 1 to 0.5 m after the excavation. The remaining part will be benched down around 20 meters behind the excavation phase in order to grant some space for maneuvering.

The second adit will be excavated with the same technique used for the previous adit. For what concerns the temporary support, changes have to be made in the schists part: in fact the support needs to be installed immediately after the excavation. The remaining part will be supported with the same technique explained for the first adit.

The section of the tunnel after the second adit will be excavated in a schist part from pk 12 to 14. This part is made of highly fractured rock mass and the excavation is going with the dip at 45 degree; the RMR corrected for this section is 22. Because of the RMR between a poor rock and a very poor rock, the excavation scheme will be done with a method used for a very poor rock mass. The excavation will be done with multiple drifts, one meter advance in top heading. The support will be installed concurrently with excavation and the shotcrete will be placed immediately after blasting.

Type of Rock	Total Rating	Correction of RMR	Total corrected rating	Rock mass class	Excavation
AU (Limestone)	15	-2	13	III - Fair rock RMR: 41-60	Top heading and bench 1.5-3 m advance in top heading. Commence support after each blast. Complete support 10 m from face
	47	-2	45		
	79	-2	77		
	Big variability	drive with dip at 45°(⍰)	Fair		
CS/SCh (Schist, calcschist)	14	-2	12	IV - Poor rock RMR: 21-40	Top heading and bench 1.0-1.5 m advance in top heading. Install support concurrently with excavation, 10 m from face.
	24	-2	22		
	35	-2	33		
	Very low rating but constant	drive with dip at 45°(⍰)	Very poor		
GP (Micaschist and foliated Gneiss)	17	-12	5	IV - Poor rock RMR: 21-41	Top heading and bench 1.0-1.5 m advance in top heading. Install support concurrently with excavation, 10 m from face.
	36	-12	24		
	55	-12	43		
	low rating and variable	Drive against dip at 45° (⍰)	Poor		
G-GR (Crystalline Gneiss and Granite)	84	0	84	I - Very good rock RMR: 81-100	Full face 3 m advance.
	88	0	88		
	92	0	92		
	Very hight rating and constant	drive with dip at 45°(⍰)	Very good		

Table 5.1 – Corrected RMR and excavation methods

5.3 Temporary support

The Barton method (Q-system) was used to design the reinforcement for each part of the tunnel. This method consists to find a value Q with the rock mass property. There are many parameters that affect the value of Q. The joint set number (J_n) decreases the value of Q when the number of joints is higher; also the joint roughness number (J_r) increases Q when the joints are rougher. In case of more alteration, weathering and filling of the rock mass joint, Q decreases. The calculations also take into account the water reduction factor (J_w): if there is more water in the joints, the rock mass is weaker because the joint results more slippery. Finally the stress reduction factor (SRF) reduces Q with greater depth because it increases the stress in the rock mass making it weaker. The formula to calculate Q is shown below:

$$Q = \left(\frac{RQD}{J_n}\right) \cdot \left(\frac{J_r}{J_a}\right) \cdot \left(\frac{J_w}{SRF}\right)$$

The value of Q was computed for each rock type and for different depths. Also, when there is a higher possibility of water income, the Q value is calculated with a lower joint water

reduction factor (J_w): for example at the PK 4.3 the overburden of the limestone section is only 210 meters and water income is expected. The ESR parameter (excavation support ratio) is 1.0 because the category of the tunnel is D (major road and railway tunnels).

Table at the bottom of the page shows the different parameters used for the section at PK 4.3.

Parameters	value	Description
γ=	27	[kN/m3]
σ_C moy=	52,5	MPa
RQD=	40	(%)
J_n=	12	This is an average, of joint spacing 1mm - 1 meter
J_r=	2	smooth - rough
J_a=	2	no cla fraction, ϕ_r=10-35 degree
J_w=	0,33	Considering the worst case for the water income section.
ESR=	1	major railway tunnel
D=	4,4	[m] the diameter of the tunnel

Table 5.2 – Parameters for the calculation of "Q"

From those parameters, it is possible to calculate Q in function of the stress σ_1 found with the depth. The "Q" number is 1.57 at a depth of 200 meters in the water income section for the limestone; the calculation is reported in Table 5.3

Profondeur H en (m)	σ_1 [Mpa]	σ_c/σ_1	SRF [Mpa]	Q
200	5,4	9,7	0,7	1,57

Table 5.3 – Calulation of Q at PK 4.3

The last step is to calculate D_0 with the diameter of the tunnel divided by the ESR number:

$$D_0 = \frac{(height\ in\ meter)}{ESR}$$

Knowing the final value of Q and the ratio (D_0), it is possible to use the Figure 5.4 to design the temporary support. The temporary support includes the bolt spacing in concreted area, the bolt length in meter and the thickness of the shocrete.

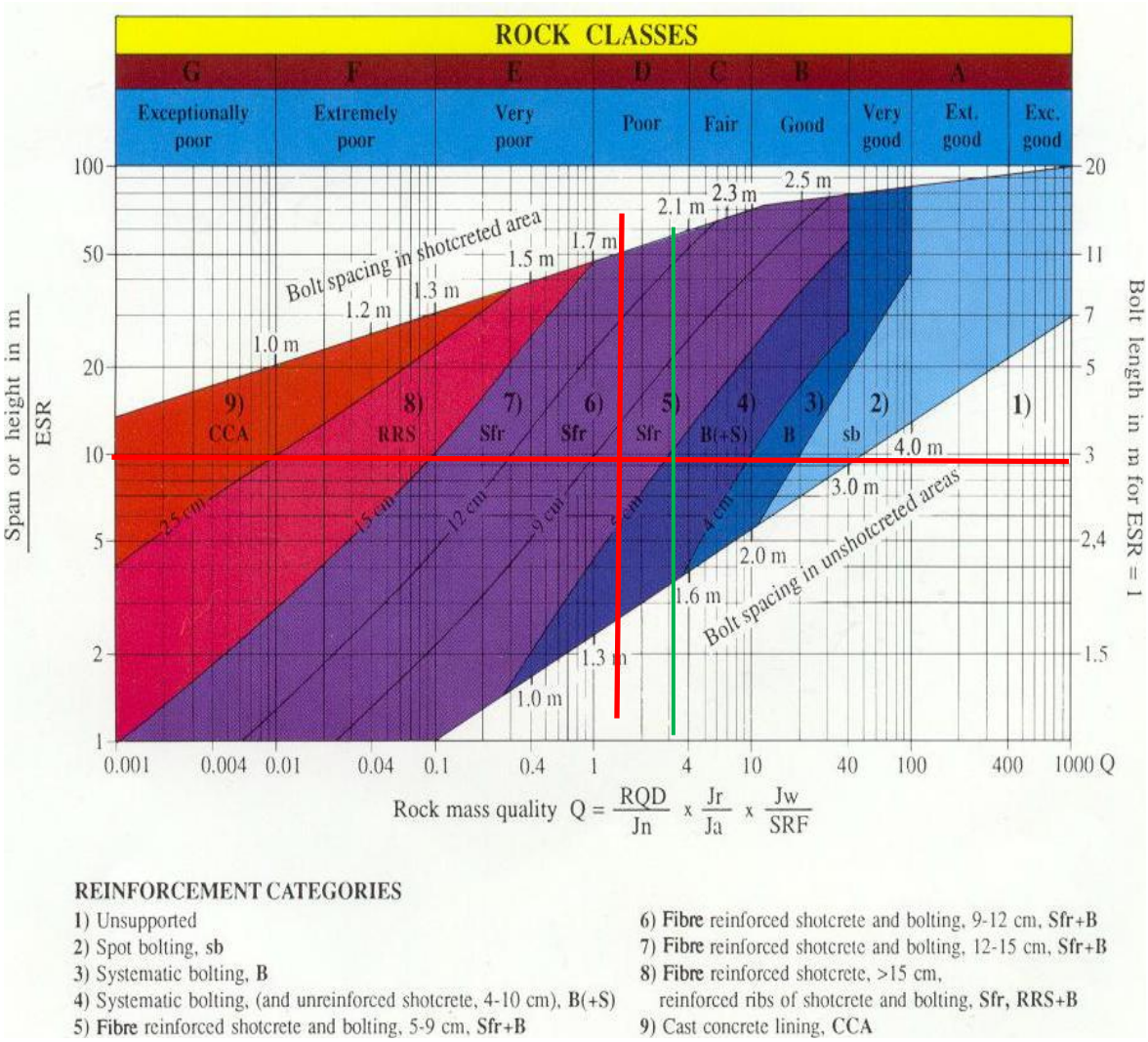


Figure 5.4 – Graphic of the temporary support design (ex. For Limestone)

For the first part of the tunnel (crystalline gneiss in pale blue) for a length of 1.25 kilometers, since the rock mass quality is very good, shotcrete doesn't have to be added, but only spot bolting need to be used. The support for this section is just for safety purposes in case of wedge failing.

The yellow part is made of limestone with severe to extreme squeezing problems and the temporary support will be determined using the same value of Q. The Q in case of severe squeezing problems is 0.02 and 0.01 for extreme squeezing problems; the difference between these two values is extremely small that it doesn't affect the design of the temporary support. The thickness of the shotcrete will be 20 cm and 1 meter spacing will be respected between the bolt and the length will be 2.2 meters.

The blue part (limestone with water income) has a value of Q = 1.57. This part was analyzed separately from the limestone rock mass because the water income has an impact on the value of Q. However the Q value obtained has a higher value due to the smaller depth. The temporary support for this part consists of 5 cm of shotcrete with 1.8 meters of bolt spacing and a length of 2.2 meters.

The red part (schist rock mass) has a “Q” of 0.0011 because it is a very weak rock mass. The calculation of Q is given below:

$$Q = \left(\frac{RQD}{Jn}\right) * \left(\frac{Jr}{Ja}\right) * \left(\frac{Jw}{SRF}\right) = \left(\frac{20}{15}\right) * \left(\frac{1}{6}\right) * \left(\frac{1}{200}\right) = 0.0011$$

Parameters	number	Description
γ=	27	[kN/m3]
σc_moy=	12.5	Mpa
RQD=	20	(%)
J_n=	15	This is an average, of joint spacing 1mm - 1 cm
J_r=	1	smooth
J_a=	6	Filling with clay with ϕr=10-20 degree
J_w=	1	Dry
SRF=	200	
ESR=	1	major railway tunnel
D=	9	[m] the diameter of the tunnel

Table 5.4 - Parameters for calculation of Q (Schist)

Because of the small value of “Q” (0.0011), it is possible to read on the graph that the bolt spacing is under a meter in the shotcreted area. The chosen spacing will be 0.75 meters because it is easier to work with an approximate spacing. Also, it is possible to read on the graph that the tunnel requires a shotcrete thickness of 30 cm. The bolt length will be 2.9 meters.

The final part made of Foliated Gneiss (pink) has a Q of 0.007. The temporary support for this part is found with the graphic method that gives a thickness of 20 cm, a bolts spacing of 0.9 meters and a bolt length of 2.9 meters.

Figure 5.6 represents graphically the temporary support that will be used during the construction phase.

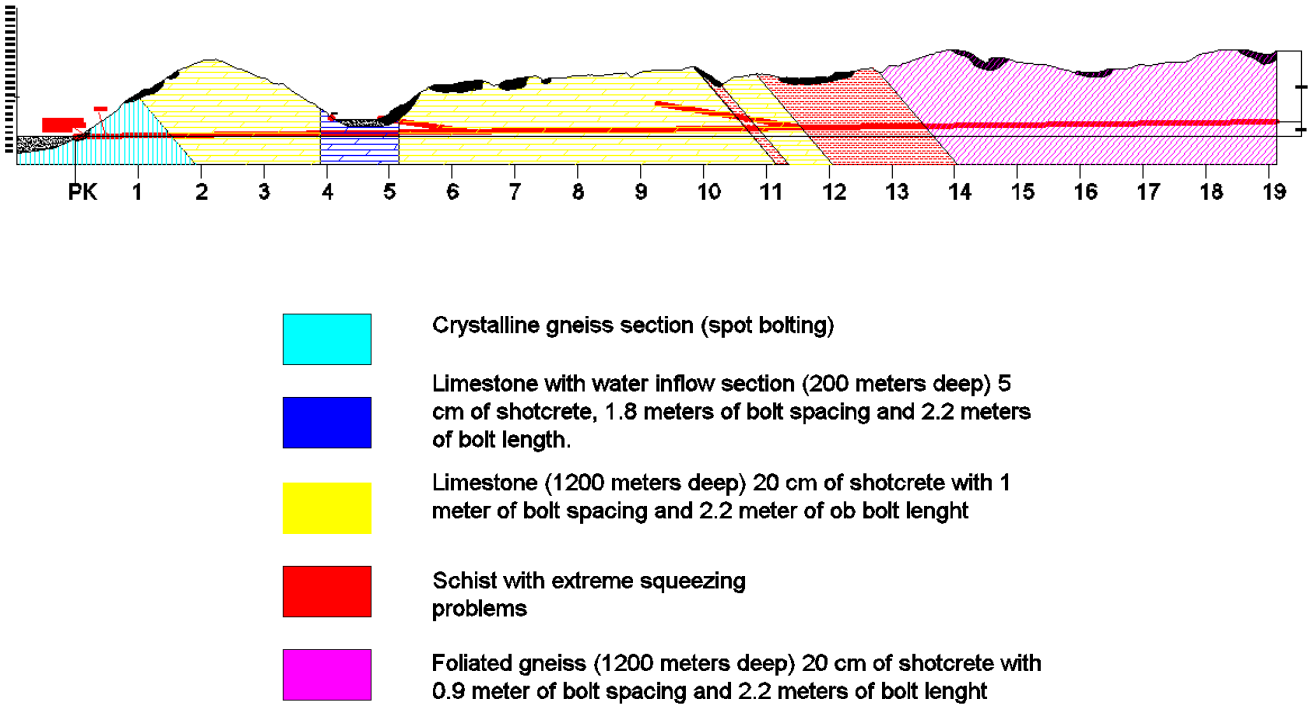


Figure 5.5 – Schema of the temporary support

6 WATER PROOFING AND DRAINAGE

Water income during the construction of a tunnel can create serious problems and delays. The flows entering the excavation site and the already constructed part of the tunnel have to be avoided or limited.

Heading inflows occur when a water-bearing zone is penetrated during tunneling and the major consequences of such an event are immediate flooding and ground collapse. Water income can also represent a danger for the workers in the construction site.

The quantity of water inflows depend on mainly two parameters:

1. **Fracturation Degree** - the more a rock is fractured, the higher its permeability.
2. **Overburden** – The smaller the overburden, the higher the possibility that the surface aquifer reverses inside the tunnel. As a general rule, hydraulic properties of the rocks increase with depth and great overburdens should prevent the income of great quantities of water.

Measures have to be taken in order to avoid risks and waterproofing techniques are extremely important especially in shafts, adits and wherever the excavation is performed downhill. In the main tunnels the uphill or downhill sections are defined based on the excavation plan defined in section 4.

Controlling water income is also important during the service life of the tunnel, in order to reduce long terms damages and increase the durability of the construction.

Not all the rocks have the same permeability and the water coming from certain massifs, such as Limestone, can dissolve minerals of the rock itself. Limestone can also create problem due to the Karsts phenomenon. According to the hydrogeological properties of each kind of rock that is encountered along the excavation of the itinerary, different techniques will be used for the different layers.

Before getting into the details of our project, an overview of the main techniques that are used in the domain of tunnel to prevent water income is presented in the following paragraphs.

6.1 Umbrella Solution

The umbrella solution is a partial waterproofing technique. The section of an umbrella solution is made of an upper part, generally called "*Crown*" and two waterproof sides. This system must be combined to a drainage system that collects the water at both sides of the tunnel and evacuates them. One should keep in mind that drainage might affect the distribution of hydraulic head by attracting groundwater and great variation of the water table can be produced. As mentioned, this solution might have serious environmental

impacts and specific studies should be done in order to prevent damages to existing structures, depletion of natural spring and destruction of ecosystems.

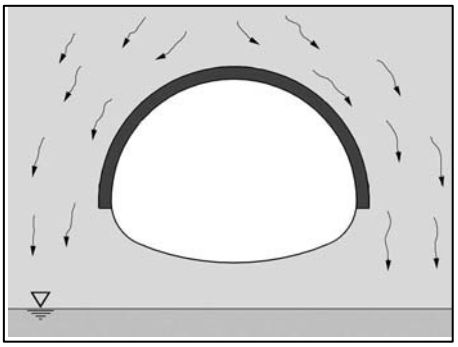


Figure 6.1 – Umbrella Solution (Kolymbas, 2006)

This technique is mainly used when the level of water table of the aquifer is located below the tunnel excavation level, which is therefore not exposed to hydrostatic pressure. In this case water can only come from the upper part of the massif and the Umbrella solution represents a reasonable option. If compared to the other techniques, the umbrella solution is less expensive and reasonably efficient.

6.2 Submarine Solution

This second technique is mainly used when the tunnel excavation level is located below the groundwater table. In this situation the tunnel is under pressure and a complete and all-embracing waterproofing system must be applied. With this technique, the tunnel is therefore isolated from the rest of the massif and the impact on the environment is largely reduced if compared to the Umbrella solution. Figure 6.2 represents a cross section of the tunnel with the application of a submarine solution:

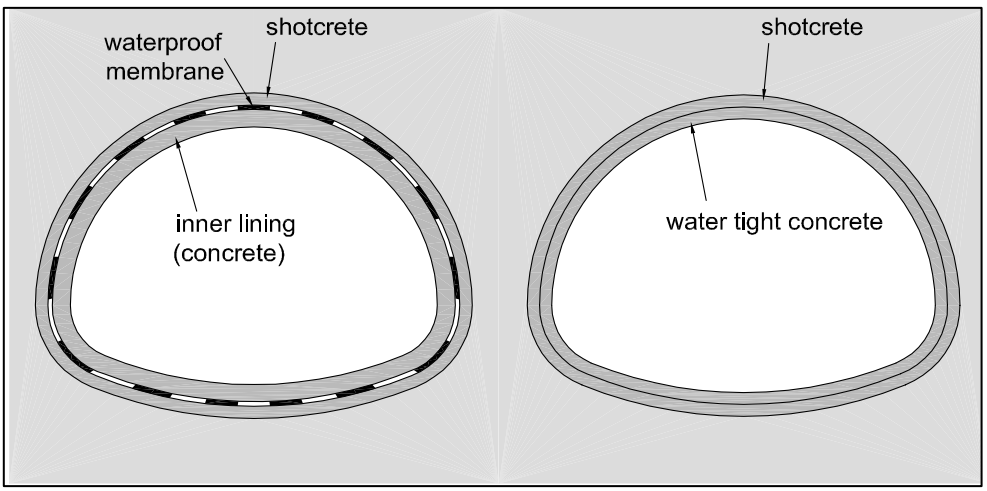


Figure 6.2 – Submarine Solution (Kolymbas, 2006)

The kind of material used for the waterproof layer depends on the value of water pressure in the rock. In general:

$P_{water} < 3$ bar	watertight concrete
$3 \text{ bar} < P_{water} < 15$ bar	watertight membranes
$P_{water} > 15$ bar	watertight membranes & grouting

Each material will be described and analyzed in the following paragraphs.

6.2.1 Watertight Concrete

A concrete in order to be considered as waterproof, has to fulfill some special criteria. The water income takes place through fissures that should therefore be prevented. The iron bars that are placed inside the concrete can reduce the creation of fissures, but they don't avoid percolation of water from the outside to the inside. A technique that is commonly used to reduce the income water is the placement of a foil between the external shotcrete and the concrete.

Another preferential way for water to enter the tunnel is through joints whose number has to be reduced and whose layout has to be carefully designed.

A great advantage of the waterproof concrete is that eventual leakages can be easily localized inside the tunnel and measures can be taken before substantial damages take place.

6.2.2 Watertight Membranes

The most common materials that are used are Geosyntetics membranes. They are applied directly on the rough concrete with an intermediate layer of geotextile in order to avoid tearing and damages of the membrane.

For what concern the choice of the membranes, two materials should not be used in tunneling:

1. **Polyester** since hydrolysis can destroy it
2. **PVC** due to its toxicity during combustion

6.2.3 Grouting

This technique is used to create a shield around the tunnel in case of great water pressures. This technique is very efficient, but it has to be realized in advance, before the excavation line reaches the problematic section. As explained in Chapter 5, this technique is usually used for both water control and temporary support.

6.3 Drainage system

The drainage system is not a waterproofing solution and through its installation, water income is not avoided, but it is constrained along certain paths in order to prevent damages to the structure. It's therefore a way of controlling the direction of water and its importance is fundamental during the service life of the tunnel.

According to the USCE the drainage system should always be operational and the conception has to be done in order to guarantee access for inspections and maintenance

The type of drainage system required in a tunnel depends on the tunnel itself, on its depth and on groundwater conditions (USCE 5.9.d.1). Some tunnels may not require special drainage and others may require drainage to limit the pressure behind the lining or to remove water due to condensation and leakage through the tunnel joints.

The main components of a typical drainage system are:

3. Water captures – The water that enters the tunnel is constrained to follow certain paths. Usually drains are inserted inside the walls in order to avoid overpressures and fissures.
4. Water transfer – After being collected, inflow discharges are transferred to a main pipe in order to be evacuated. This pipe can either be located in the middle of the cross section (Figure 6.5), of on the side (Figure 6.4). Slope has to be designed accordingly.
5. Purification – Water has to be treated before returning it to the environment.
6. Restitution

A big problem that concerns drainage systems is the sediment transportation. Particular attention has to be made to the Limestone are: in fact this rock can create the clogging of the drainage system.

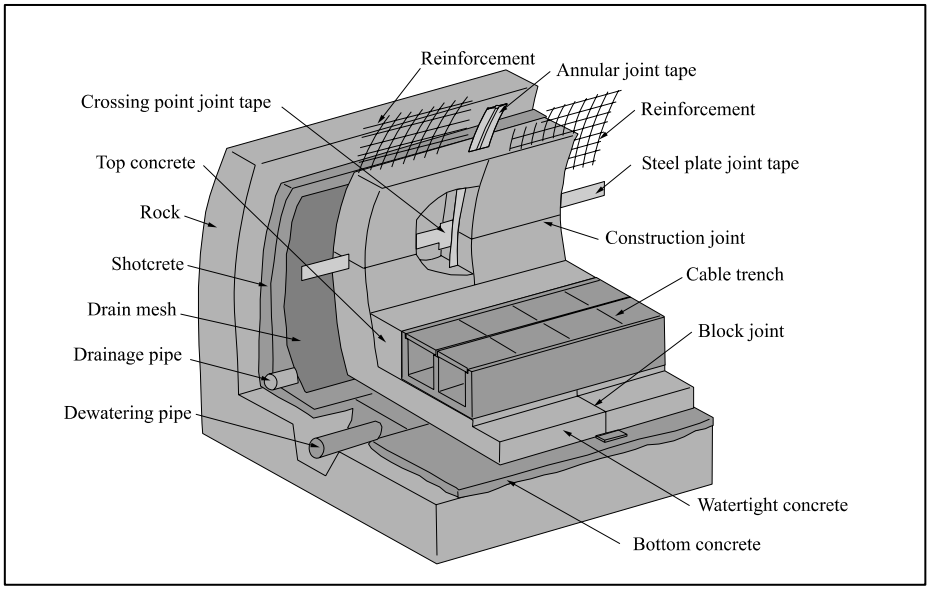


Figure 6.3 – Drainage system of a railway tunnel

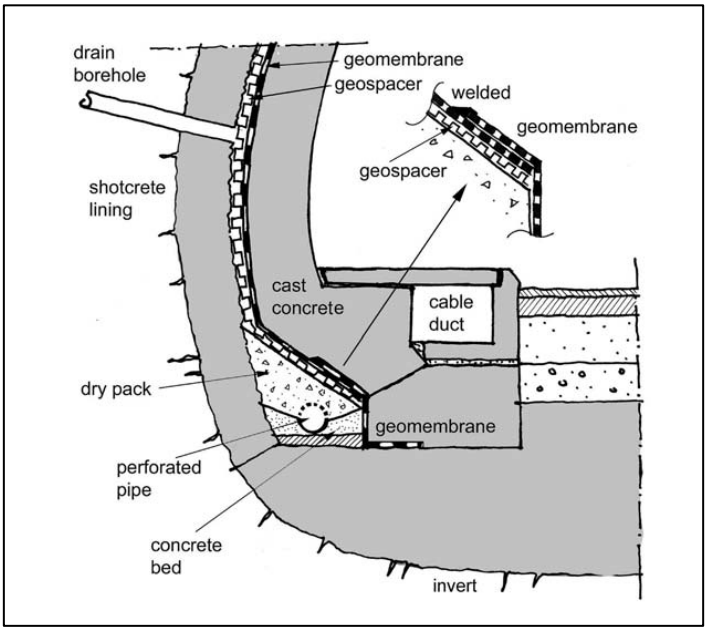


Figure 6.4 – Elements of a drainage system with lateral collector

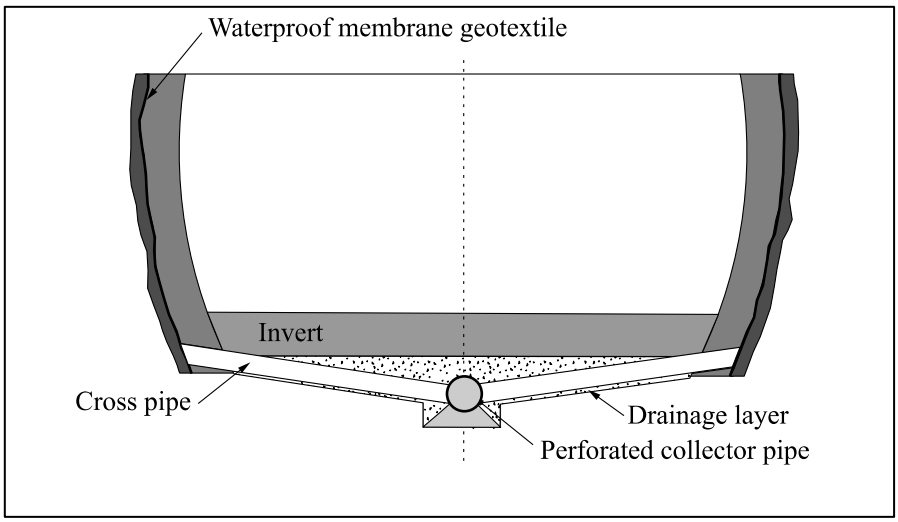


Figure 6.5 – Drainage System with central collector pipe

6.4 Chosen Solution

For what concerns our alignment, the following solutions have been chosen:

7. PK 0 to 0.2 – Rock Debris (Db) - **Umbrella Solution**

   A low cover characterizes this section and great water inflows could take place. Since eventual incoming water could easily be evacuated, an Umbrella Solution is

recommended for this first section. A Submarine seems exaggerated for such a short section.

8. PK 0.2 to 1.5 – Crystalline Gneiss (G) - **Umbrella Solution**

This section has a good rock quality and a relatively elevated average overburden. The part that could represent problems from a hydraulic point of view, is the initial one (km 0.2 to km 0.35, where the thickness of the covering layer is below 400 m, but great water volumes are not expected and considering the small length of the part, they could easily be evacuated through the drainage system. In the remaining part of the section, water income should not represent, a priori, a significant issue. For the explained reasons an Umbrella Solution is proposed.

9. PK 1.5 to 10.7 – Limestone (Au) - **Submarine Solution**

This section of the tunnel is definitely the longest and most problematic one. It is entirely made of Limestone, which has a great hydraulic conductivity and great volumes of water might enter the tunnel. As mentioned in the introduction, Limestone (Au) is a rock that can dissolve minerals (calcium carbonate) and the Karsts phenomenon can be encountered during the excavation.

For this reasons a Submarine solution is highly recommended for this section.

In addition, at PK 4.12 a low valley is encountered with a minimum overburden of 200 m. At this point, great volumes of water could enter the tunnel. At the bottom of the valley there is a river (water table known), which implies that the pressure around the tunnel will be 20 bars. For the reasons explained in section 6.2, a grouting solution in addition to the watertight membrane seems appropriate.

10. PK 10.7 to 10.9 – Schistes and Calschists (CS/SCh) - **Submarine Solution**

For this section a Submarine Solution is chosen, independently from the mass properties of the rock encountered: the length of this layer is less that 200 m and from an economical, technical and practical point of view it is better to continue with the same technique.

11. PK 10.9 to 11.6 – Limestone (Au) - Submarine Solution

For the reasons explained before, a Submarine Solution is recommended.

12. PK 11.6 to 13.5 – Schistes and Calschists (CS/SCh) - **Umbrella Solution**

As mentioned before, the hydraulic qualities of the rock should increase with depth. Considered the considerable overburden, great volumes of water are not expected and an Umbrella solution is therefore chosen.

13. PK 13.5 to 19.1 – Micashists and Foliated Gneiss (GP) - **Umbrella Solution**

The choice of one solution over the other depends mainly on the fracturation degree of the massif. These parameters are uncertain and unknown for the given project. For the same reasons explained for section 6, an Umbrella Solution is foreseen, but the optimal solution might change if the properties are found to be worse than expected.

Figure 6.6 schematically represents the techniques that have been chosen in order to guarantee the impermeability of the tunnel.

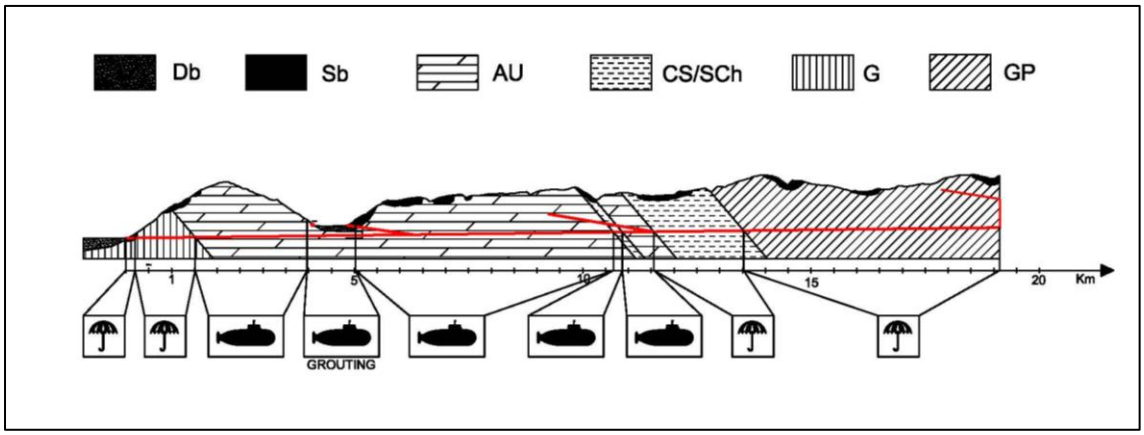


Figure 6.6 – Waterproofing techniques

6.5 General Considerations

The above-discussed solution is completely based on theoretical concepts since real and reliable data on hydraulic performance of the rock was not accessible for the exercise.

The permeability of the different rocks has to be known in order to choose the optimum solution. Investigations such as the Lungeon tests or the pumping tests should be done in order to determine these parameters.

Another phenomenon that could be encountered is the Karst. For what concerns our project it is impossible to know a priori if this problem will occur, but Geophysics tests are recommended in order to evaluate this risk. Injections might be used to fill the empty spaces in case this problem occurred.

For what concerns the submarine solution in the Limestone section, it is hard to say a priori which one will be the material used: measurements of water pressure and permeability have to be known for such a choice to be reasonable.

7 PERMANENT SUPPORT AND TUNNEL CONSERVATION

7.1 Permanent Support

The permanent support has different functions. Principally, as the names recalls, it works as a support for the excavated section but, like it was explained in chapter 6, the structural function is associated to a waterproofing shield.

This tunnel is excavated using three different methods, two conventionals and a Gripper TBM, but all of them use same methodology to settle the permanent support: the formwork.

The framework (Figure 7.1) is a machine that covers more or less 3/4 of the cylinder but a preparation of the bottom is necessary. After settling the waterproofing membrane (if necessary) and the drainage system, concrete is jetted until the final height is reached. This layer will absorb the charges that the train will apply to the ground without generating settlements problems.

In order to improve the security on the bottom of the tunnel, where stresses could be bigger and problematic, two sidewalks are settled, one on each side; they will help avoiding problems of tunnel closing. The sidewalks also have other functions such as providing a walking area in the tunnel in case of fire.

The final lining disposition consists in an elevation of the formwork, composed of three semi-circles; the arms are opened until they are tight to the sidewalks and fixed to the tunnel. With the aid of a pump, the concrete is projected symmetrically on both and then vibrated. After 8-10 hours it is retired and the machine advances. The machines used measure around 15-18m and it's possible to make two concreting cycles in one normal working day. If the construction is 24h/day the process could reach 3 cycles/day.

The choice of the characteristics of the concrete is based on the depth of the tunnel and the fissuration problems. For the given case K_0 can be considered close to 1 at this depth and it explains why a solution with non-reinforced concrete has been chosen. As well known, concrete does not work under traction and in this situation it will only need to work under compression because pressure all along the contour of the tunnel is the same. The concrete resistance is estimated to be 25 MPa, because higher values might produce elevated temperatures, increasing the probability of creating fissures that could develop problems in the waterproof system. The typical thickness used on simple concretes linings is 25 cm.

This process will not produce substantial delays because the lining of the tunnel is settled behind the excavation and in general works with a speed around **30**m/day, faster than the excavation in average ground conditions.

Figure 7.1 – Permanent Support

Figure 7.2 represents the final lining chosen for the tunnel:

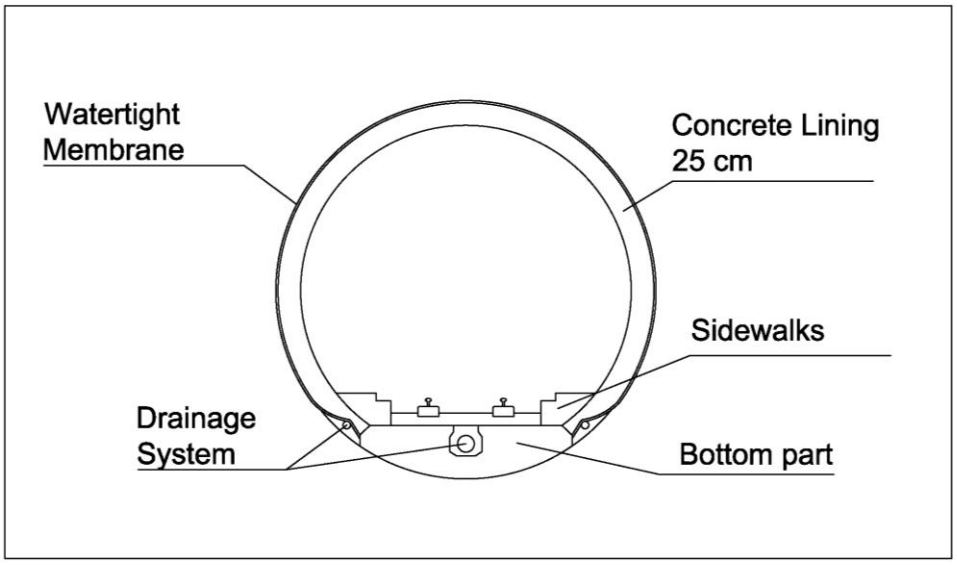


Figure 7.2 – Final lining

7.2 Tunnel Conservation

Exactly like the others constructions in the domain of Civil Engineering, tunnels are subjected to degradation and the conditions evolve with time. The functionality of a tunnel derives from a complex interaction of systems; the failure of one of them might compromise the whole structure, reducing both exploitation and safety standards.

The quality of the tunnel and the safety level have the tendency to reduce overt time (Figure 7.3); when these values reach the threshold defined by the law, interventions become necessary in order to reestablish the initial level.

During the service life of a tunnel, there exist two main types of interventions:

- **Routine maintenance** – Continuous reparations and activities in order to maintain the safety level at its highest, avoiding severe damages with extreme reparation costs. Despite these reparations, long-term degradation processed cannot be avoided and more important interventions will be needed over time. The routine maintenance can be divided into two main procedures:

    - Routine – Actions that have to be repeated on a regular basis and the time interval has to be respected in order to avoid a failure of the system. These actions have to be foreseen in the maintenance plan.
    - Preventive – Actions that have to be foreseen in the maintenance plan, but only applied when certain specific, but predictable conditions appear. Examples of these interventions are tunnel washing and ice/snow removal.

- **Rehabilitation repair** – When the safety/quality level reaches unacceptable values, interventions are necessary. These actions usually follow a detailed Verification.

A combination of these two interventions is therefore necessary in order to maintain a certain safety level required by the law. The behavior of the Quality/Safety level over time is represented in Figure 7.3.

Indicators are therefore fundamental in order to evaluate the quality/safety level of the tunnel.

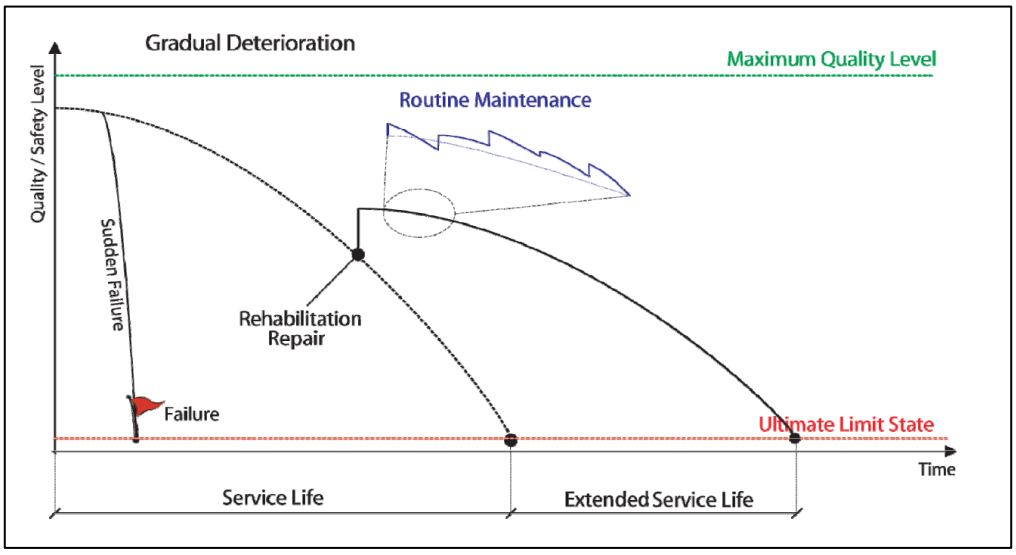


Figure 7.3 – Evolution of the safety level over time

These interventions have a considerable cost that has to be taken into account. **The maintenance plan of a tunnel is therefore as crucial as its economic impact.**

7.2.1 Damages inside Tunnels

The damages can concern the rock mass or the final lining. A non-exhaustive list of the most common damages that can be found inside a tunnel is presented in Table 7.1 :

RISK	EFFECTS, DAMAGES	SOLUTION, INTERVENTION
Water Income	Ice formation Interruption of operation Corrosion of concrete elements	Waterproofing Sealing joins Drainage Substitution of damaged elements
Joint damage	Loss of strength Bond weakening Water inflow	Joints renewal Lining replacement
Cracks	Water inflow Local failure	Grouting, Injections reinforcement
Chipping (scaling)	Loss of strength Local failure	Lining renewal reinforcement
Deformation	Cracking Profile reduction Local or Global Collapse	Lining replacement reinforcement

Table 7.1 – Common damages inside tunnels

7.2.2 Inspections

Inspections are necessary in order to evaluate the conditions of the tunnels and auscultation is extremely important in order to plan the schedule and the level of the intervention.
Three types of inspection have to be planned in order to detect eventual damages in the structure and to identify the causes:

- **Principal Inspections** – Held every 6 years and they consist of a complete visual control and of a comprehensive analysis of the tunnel conditions (general inspections). During these inspections, all aspects are evaluated and recorded. Typical activities during a Principal Inspections (PI) are:
    - Visual Inspection
    - Rebound Hammer
    - Profile Measurements
    - Deformations
    - Track Axis and track Geometry
    - Scanner measurements

- **Intermediate Inspections** – Held with a minor frequency than the principal inspections and they generally evaluate the level of a particular aspect (local inspections). For the given project, intermediate inspections are foreseen every year, according to necessities.

- **Special Inspections** – Held in specials occasions, after exceptional events or sudden problems. During these inspections, the following activities are conducted.

    - Detailed Investigations of damaged zones
    - Non-destructive testing methods
    - Core drilling and Laboratory test

7.2.3 Maintenance Plan

The opening of the Tunnel is foreseen in 2025. According to the law, the tunnel must have a service life of 100 years.
The maintenance plan designed for the tunnel is presented in Figure 7.2:

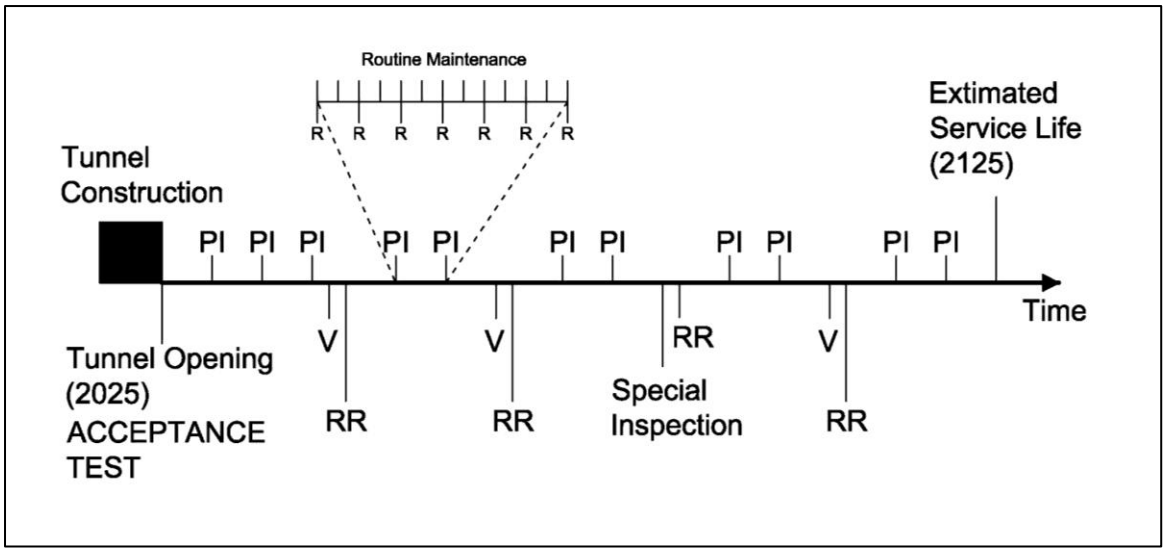


Figure 7.4 – Maintenance plan

- **PI – Principal Inspection**: Held every 6 years. The main activities that are performed during the inspections are presented in Chapter 7.2.2. In case of combination of PI with Verifications, then the Principal Inspections are postponed to 6 years after the detailed Verification.

- **V – Verification**: Specific and detailed inspections that for the given project were decided to be held every 20 years from the Acceptance Test. The main activities that are performed during a Verification are:
    - Drill bores for lining / geological investigations
    - Material testing
    - Endoscopy
    - Water analysis
    - Geological Investigations
    - Non-destructive tests (Georadar and Infrared Thermography)

- **Special Inspection**: A Special Inspection has to be performed after an exceptional event (fire, shock, earthquake). It is impossible to foresee when these events will take place; as an example a Special Inspection is indicated in the maintenance plan, followed by a Repair Rehabilitation
.

- **RR – Repair Rehabilitation**: Verification and Special Inspection are followed by a Repair Rehabilitation during which the level of security quality is brought back to acceptable values. It is hard to foresee the extent of the reparations that will have to take place and their importance depends on the results of the inspections.

- **R - Routine Inspections**: All along the service life of the tunnel, its behavior has to be analyses and monitored. These inspections are fundamental to decide if further investigations are requires. The Intermediate inspections consist of an overall analysis of the tunnel and its major components.

- **Routing Maintenance**: As explained in the introduction, some actions have to be completed on regular bases. Examples of these interventions are:
    - Cleaning of water drainage to avoid clogs of the systems
    - Repair joins
    - Clean internal walls, ruined by pollution inside the tunnel
    - Test of monitoring devices.

The tunnel might be operational after 100 years, if the conditions allow it, but interventions and a new maintenance plan will have to be provided.