# A FRAMEWORK FOR THE RISK ANALYSIS OF THE GIBRALTAR STRAIT RAILWAY-LINK TUNNEL

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SYNOPSIS: The Gibraltar strait railway-link tunnel to connect Spain and Morocco is one of the most challenging engineering undertakings in modern tunneling. In fact, the realization of about 42 km of tunnel under the sea, crossing complex clayey formations in the presence of water pressures, up to 50 bars, is surely beyond the limits for the current tunneling technologies. The recent discovery of two deep, paleo-channels, some kilometers wide, filled with deposits of clayey breccias, as revealed by the off-shore investigations, has shown a further worsened picture of the already unfavorable geotechnical context. A selected group of international geo-engineering companies and experts, under the general coordination and management of the two leading companies, SECEG and SNED, appointed by the Governments of Spain and Morocco, respectively, are actually carrying out an update of the conceptual design aimed both to confirm the feasibility of the tunnel and identify the optimal design solution. Intuitively, such an optimal technical solution can only be selected on the basis of an adequate risk analysis, which is the guideline for the whole design process. The framework of such an analysis is described in detail in the paper and the preliminary results explained.

## 1 – INTRODUCTION

The Gibraltar strait railway-link tunnel to connect Spain and Morocco is one of the most challenging engineering undertakings in modern tunneling. In fact, the realization of about 42 km of tunnel under the sea, crossing complex clayey formations in the presence of water pressures, up to 50 bars, is surely beyond the limits for the current tunneling technologies. The recent discovery of two deep, paleo-channels, some kilometers wide, filled with deposits of clayey breccias, as revealed by the off-shore investigations performed at the end of the nineties, has shown a further worsened picture of the already unfavorable geotechnical context. In fact, the breccias appears to be originated from a series of relatively-recent, gravitational collapses of the flyschiod borders of the submarine erosion valleys; and currently, even the hypothesis of “under-consolidation” of the breccias in the paleo-channels cannot be rejected with confidence.

A selected group of international geo-engineering companies and experts, under the general coordination and management of the two leading companies, SECEG and SNED, appointed by the Governments of Spain and Morocco, respectively, are actually carrying out an update of the conceptual design aimed both to confirm the feasibility of the tunnel and at the same time to identify the optimal design solution for the project from the different points of view (construction, safety, maintenance, time & costs, etc.). Intuitively, such an optimal technical solution can only be selected based on an adequate risk analysis, which is also the basic input to and guideline for the whole design process, from the actual preliminary phases to the construction details.

The framework of such a risk analysis, with special emphasis to the construction issues, is described in detail in the following and the preliminary results explained.

## 2 – GEOLOGICAL SETTING

The actual orientation of the ongoing study indicates that the deepest point of the tunnel alignment should be reasonably positioned about 475m below the sea level, i.e. with a ground overburden of about 175m and therefore subjected to a water pressure of almost 50bar. According to this hypothesis, the tunnel should basically across two distinct geological environments (see also Fig.6):

- flyschiod formations (Cretaceous to Lower Miocene), with different lithological composition and degree of tectonization (Figg.1 & 2);
- in correspondence of two central paleo-channels (1-2km width), clayey breccias (Quaternary) of gravitational origin from the collapse of the flyschioid borders (Fig.3).

In addition, although not found at tunnel level but some tens of meters above, the presence of lenses of variously cemented, bioclastic sands and gravels, have been detected in one of the two channels, both at the top covered by a coralline crust.

*Fig.1: Sub-vertical arenaceous flysch on the Spanish border of the Gibraltar strait*

From a geomechanical point of view, n.7 principal groups have been consequently distinguished, in agreement with the expert opinion of prof. P. Marinos, as schematically reported in Tab. 1.

| Ground type | Description | GSI (typical values) |
|---|---|---|
| I | Flysch with prevalent thick layers of sandstones and/or limestone | 45-55 |
| II | Flysch with sandstone and siltstone/clayey shale in similar amounts | 35-45 |
| III | Flysch with predominant clayey shale over sandstone | 30-35 |
| IV | Flysch with predominant clay shale and/or siltstone | 25-30 |
| V | Tectonized clayey flysch | 15-25 |
| VI | Clayey breccias with lithoid fragment of flysch | n.a. |
| VII | Variously cemented sands with gravels (→calcarenite) * | n.a. |

*Tab. 1: Main geomechanical groups ("ground types")*
*Notes: *not found at tunnel level; GSI=Geological Strength Index [6],[9]; n.a.=not applicable*

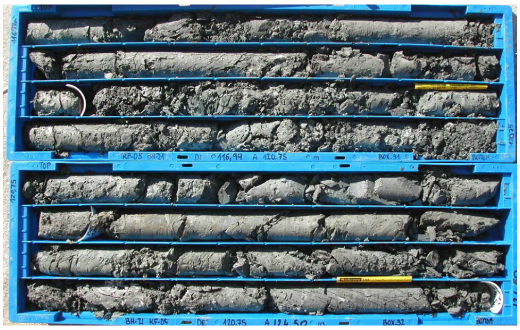


*Fig.2: Example of tectonized clayey flysch (type V) from off-shore borehole*

*Fig. 3: Sample of the clayey breccias (typeVI)*

Given the very poor geotechnical properties, the very high pore pressure and very low permeability, the Clayey Breccias (Type VI) appear to be probably the most problematic context for the construction of the tunnel. The complex off-shore condition has not permitted the recover of fully undisturbed samples for laboratory tests and additional investigations are actually in process to check the reliability of the results.

Among others, it is important to observe that very low values of the undrained cohesion with respect the corresponding effective stress have been derived from some tests: such a result, coupled with the ones of some edometric tests, may also enforce the hypothesis of a state of under-consolidation of the breccias, i.e., in other words, of the presence of an excess of pore pressure.

## 3 – RISK ANALYSIS

### 3.1 – Generalities

The scope of a risk analysis is mostly the identification and quantitative prediction of negative effects brought about by the occurrence of hazardous events, as well as of the mitigation measures to reduce the risk to an acceptable level [4]. The main definitions of the terms used are reported in Tab. 2.

| Term | Definition |
|---|---|
| Hazard (H) | Potential source of harm |
| Harm (→Impact I) | Physical injury or damage to the health of people, property, environment |
| Probability (P) | Extent to which an event (→harm) is likely to occur |
| Risk (R=PI) | Combination of the probability of occurrence of harm and the severity of that harm |
| Mitigation measure | Means used to reduce risk |
| Residual risk | Risk remaining after preventive measures have been taken |

*Tab.2: Basic terms and definitions for Risk Analysis [7]*

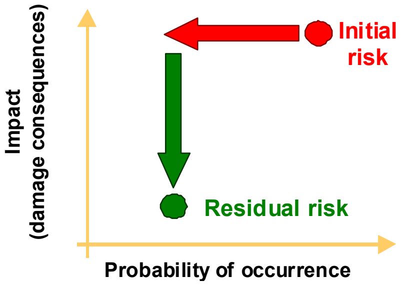


*Fig.4: Strategies for reducing the risk [4]*

A logical and sequential framework has been established for the risk analysis and subsequent design development of the tunnel, which comprise such basic steps:

a) identification of the principal hazards for tunneling and quantification of their relative probability of occurrence, intensity and potential relevance (→Hazard's register);
b) identification of the potential impacts/damages that can be caused by the identified hazards;
c) quantification of the construction risks, as the product between the probability of occurrence of the hazards and their potential impacts (→Risk register);
d) definition of the mitigation measures and estimation of the residual risk.

A synthesis of the process is presented in the following sections.

### 3.2 – Hazards identification and register

*Fig.5: Failure of the invert for swelling behaviour of clayey flysch in the experimental Malabata well on Moroccan coast of the Gibraltar strait*

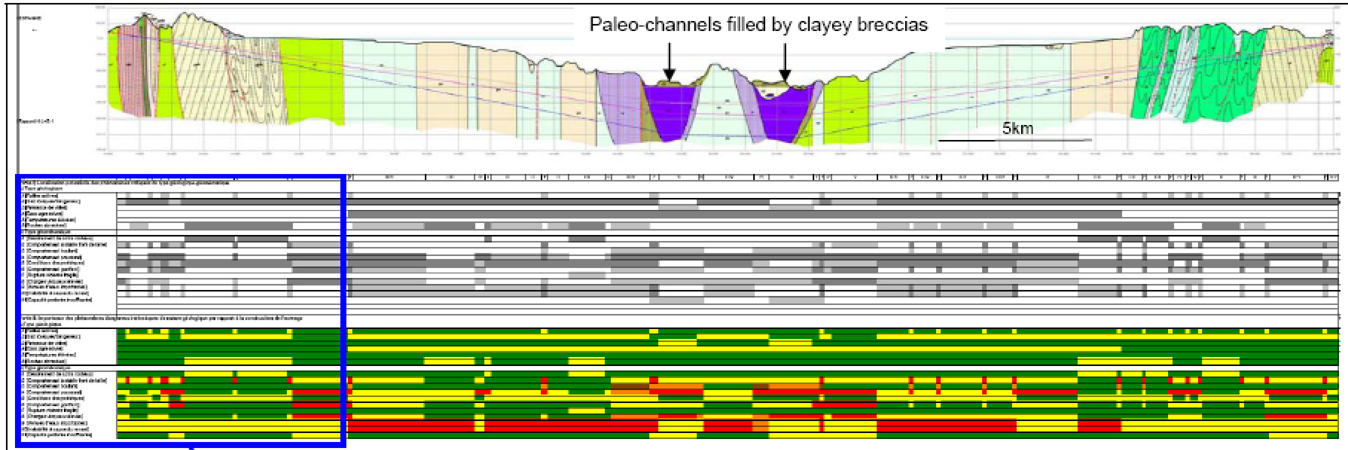
The first step of the risk analysis is the identification of the potential hazards for the tunnel construction. Moreover, an evaluation of both their probability of occurrence and potential importance for tunneling (combination of probability and impact of the hazard) is here considered useful for a general setting of the expected criticalities. For such a purpose, the distinction between geological and geomechanical hazards has been also considered.
As synthesis of the analysis, the resulting "Hazards register" is presented in Tab. 3, while in Fig.6 a preliminary attempt of location of each hazard along the tunnel axis is schematically reported.

| **Hazard phenomena** | **Reference** | **P** | **I** | **Importance** |
|---|---|---|---|---|
| A1. Active faults | Faults/tectonic contacts | 2 | 2 | M |
| A2. Noxious/dangerous gases | Ground types I-II-III-IV | 3 | 1 | M |
| | Others | 1 | 1 | L |
| A3. Presence of voids/cavities | Ground type VI | 2 | 2 | M |
| A4. Aggressive waters | On land section | 1 | 1 | L |
| | Off shore section | 3 | 1 | M |
| A5. High temperatures | | 1 | 1 | L |
| A6. Abrasive rocks | Ground types I-II | 3 | 1 | M |
| | Ground type III | 2 | 1 | L |
| | Others | 1 | 1 | L |
| B1. Rock wedge fall | Ground types I-II | 3 | 1 | M |
| | Others | 1 | 1 | L |
| B2. Unstable behaviour of tunnel face/contour of excavation | Ground types V-VI | 2 | 2 | M |
| | Faults and tectonic contacts | 3 | 2 | H |
| B3. Flowing behaviour | Ground type V (faults, etc.) | 1 | 3 | H |
| | Possible finding of type VII | 1 | 3 | H |
| B4. Squeezing behaviour (1) | Ground types I-II | 1 | 1 | L |
| | Ground type III | 2 | 2 | M |
| | Ground type IV | 3 | 2 | H |

| **Hazard phenomena** | **Reference** | **P** | **I** | **Importance** |
|---|---|---|---|---|
| | Ground type V | 3 | 3 | H |
| | Ground type VI | 3 | 3 | H |
| B5. Asymmetric deformation and loading conditions | Ground types I-II | 3 | 1 | M |
| | Ground type III | 3 | 1 | M |
| | Ground type IV | 2 | 1 | L |
| | Ground type V | 1 | 1 | L |
| | Ground type VI | 1 | 1 | L |
| | Faults/tectonic contacts | 3 | 1 | M |
| B6. Swelling behaviour (see Fig. 3.2.2) | Ground type V | 3 | 2 | H |
| | Ground types IV-VI | 2 | 2 | M |
| | Others | 1 | 1 | L |
| B7. Instability caused by sudden fragile rupture phenomena (rockburst) (2) | Ground types I-II ($\sigma_V$>~7MPa) | 2 | 2 | M |
| | Others | 1 | 1 | L |
| B8. Mobilization of viscous type high loads (in the long term) | Ground types I-II | 1 | 1 | L |
| | Ground types III-IV | 2 | 2 | M |
| | Ground type V | 3 | 2 | H |
| | Ground type VI | 3 | 2 | H |
| B9. Huge water inflows possibly pressurized | Off-shore section: | | | |
| | Ground types I-II-III | 2 | 3 | H |
| | Ground types IV-V-VI | 1 | 3 | H |
| | Faults/tectonic contacts | 2 | 3 | H |
| | On land section: | | | |
| | Faults/ tectonic contacts | 2 | 3 | H |
| | Others | 1 | 2 | M |
| B10. Face and/or tunnel walls collapse due to piping type rupture | Off-shore section: | | | |
| | Ground types I-II-III | 2 | 3 | H |
| | Ground types IV-V-VI | 1 | 3 | H |
| | Faults/tectonic contacts | 2 | 3 | H |
| | On land section: | | | |
| | Faults/tectonic contacts | 2 | 3 | H |
| | Others | 1 | 2 | M |
| B11. Bearing capacity problems | Ground types V-VI | 2 | 2 | M |

*Table 3: Hazard register for geological (A) and geomechanical (B) phenomena*

*Notes:(1)The Marinos and Hoek method [9] has been adopted for the classification of squeezing; (2)the approaches proposed by Diederichs [1] and Hoek and Brown [5] have been implemented to quantify the probability and intensity of brittle type rock failure.*



| Occurrence for length of the tunnel | Probability class | Description |
|---|---|---|
| <1 over 10.000m | 1 | Unlikely |
| 1 for 1.000÷10.000m | 2 | Occasional |
| 1 for 100÷1.000m | | |
| 1 for 10÷100m | 3 | Likely |
| 1 for <10m | | |

Classification of the probability of occurrence (ITA,2004, simplified)

| Hazard's importance | | Impact (I) | | |
|---|---|---|---|---|
| | | 1 | 2 | 3 |
| Probability (P) | 3 | M | H | H |
| | 2 | L | M | H |
| | 1 | L | M | H |

Fig.3.2.1: Longitudinal profile of the tunnel with indication of the main geological and geomechanical hazards for tunnelling (H=high, M=medium, L=low importance).

Note: in the upper part (gray scale) the probability of occurrence of the hazards is represented, while in the lower part (coloured) the classification of the importance of the hazard is displayed.

At the moment, the real extension of the two paleo-channels is "under-discussion": the violet shadows indicate the relative max extension according to the most unfavourable scenario.

### 3.3 – Risk identification and register

Further to the identification and estimation of the hazard phenomena, the related potential harms (or damages) have been identified and consequently the qualitative assessment of the risks for the tunnel construction is derived, as reported in the Tab.7.
In the same table a column is introduced where possible risk reduction measures to be adopted in the design phase are pointed out, with reference to the detailed list of Tab.8. Similarly to the described procedure for the estimation of the hazard's importance, the classification schemes reported in Tab. 4, 5 and 6 have been adopted.

| Occurrence for length of the tunnel | Probability class | Description |
|---|---|---|
| <1 over 10.000m | 1 | Unlikely |
| 1 for 1.000÷10.000m | 2 | Occasional |
| 1 for 100÷1.000m | | |
| 1 for 10÷100m | 3 | Likely |
| 1 for <10m | | |

*Tab.4: Classification of the probability of occurrence [8, simplified]*

| Potential consequences | | | |
|---|---|---|---|
| | Delay (months) | Simplified classification | |
| Disastrous | >24 | Critical | 3 |
| Severe | 6-24 | | |
| Serious | 2-6 | Medium | 2 |
| Considerable | 0.5-2 | | |
| Insignificant | <0.5 | Negligible | 1 |

*Table 5 : Classification of potential consequences in terms of delayed construction period [8, simplified]*

| | | Potential consequences | | |
|---|---|---|---|---|
| | | Low | Medium | High |
| Frequency | | 1 | 2 | 3 |
| Likely | 3 | **M** | **H** | **H** |
| Occasional | 2 | **L** | **M** | **H** |
| Unlikely | 1 | **L** | **M** | ▨ **H** |

| Risk | | Risk acceptance criteria |
|---|---|---|
| H | High | Unacceptable |
| M | Medium | Acceptable after implementation of adequate counter-measures |
| L | Low | Acceptable |

A distinct mark is associated to the special case of low probability and high impact.

*Tab.6: Construction risk classification (above) and associated acceptance criteria (below).*

**A) Excavation progress and interaction with surrounding ground**

| N. | Potential damage | Hazard phenomenon originating the damage | Qualitative analysis of the Primary Risk | | | Mitigation measures (ref.Tab. 8) | Qualitative analysis of the Residual Risk | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | P | I | Risk | | P | I | Risk |
| R1 | Blocking of TBM shield | B1,B2,B7 | 2 | 2 | **M** | A,B,C,E,(F) I,L | 1 | 2 | **M** |
| R2 | Tunnel walls instability (→lining failure) | A1,B1,B4, B5B6,B7, B8 | 3 | 3 | **H** | A,B,C,E,(F) I,L | 1 | 2 | **M** |
| R3 | Overbreak | B1,B2,B3 | 2 | 2 | **M** | A,B,C,E,(F) J,KI,L | 1 | 2 | **M** |
| R4 | TBM blocking due to face instability (chimney collapse) | B2,(B4) | 2 | 2 | **M** | A,B,C,(D),EG,H I,L | 1 | 2 | **M** |
| R5 | TBM trapping | B4,B5,B6, B10 | 3 | 3 | **H** | A,B,C,(D), (E),GH,I,L | 2 | 3 | **H** |
| R6 | High water inflows on the TBM | B3,B9,B10 | 3 | 3 | **H** | A,B,C,(E), J,K,IL | 1 | 3 | **H** |
| R7 | TBM mechanical failures | B3,B5,B9, B10 | 3 | 2 | **H** | A,B,C,(E), G,H,JK,I,L | 1 | 3 | **H** |
| R8 | TBM “sinking” | A3,B11 | 2 | 3 | **H** | A,(B),C,D, (E),I | 2 | 3 | **H** |
| R9 | Anomalously high temperatures | A5 | 1 | 1 | **L** | A,(Q) | 1 | 1 | **L** |
| R10 | Noxious or dangerous gases | A2 | 3 | 2 | **H** | A,O,N | 1 | 2 | **M** |
| R11 | Excessive excavation tools wear | A6 | 2 | 1 | **L** | | 2 | 1 | **L** |
| R12 | Lining chemical attack | A4 | 3 | 1 | **M** | P | 1 | 1 | **L** |
| .... | .... | | | | | | | | |

**B) Other construction risks (preliminary indication)**

| | |
|---|---|
| R13 | Obstruction or ineffectiveness of the preventive drainage system |
| R14 | Ineffectiveness of preventive consolidation treatments |

| | |
|---|---|
| R15 | Conditioning problems inside the excavation chamber |
| R16 | Obstruction/rupture of the mucking system |
| R17 | Power supply failure/interruption |
| R18 | Water treatment system failure |
| R19 | TBM driving difficulties |
| R20 | Ring segments structural failure (for defective construction) |
| R21 | Washing away of injected mortar behind the rings |
| .... | .... |

*Tab.7: Risks Register (note: other specific construction risks must be analyzed in the next design phases)*

| Code | Risk mitigation measures description |
|---|---|
| A | Investigations ahead the tunnel face |
| B | Controlled drainage ahead the tunnel face (active drainage where necessary) |
| C | Ground pre-consolidation by grouting (eventually reinforced) |
| D | Controlled ground injection (for accelerating drainage and consolidation [3]) |
| E | Ground pre-support by means of forepoling with steel elements |
| F | Radial bolting during the advance |
| G | Shield conicity (or equivalent measures) |
| H | Over-excavation |
| I | Face stabilization with earth counter-pressure |
| J | Regulation of water inflows by means of apertures along the shield |
| K | Catching and treatment of water inflows |
| L | Tunnel walls deformation stabilization by means of reinforced precast rings |
| M | Injections behind the rings |
| N | Non-deflagrating equipments |
| O | Forced ventilation |
| P | Use of special cements in presence of aggressive waters |
| Q | Cooling system |
| R | ... |

*Tab. 8: Interventions and mitigation measures (with reference to the adoption of an earth-pressure balance TBM (EPBS))*

The role played by the mitigation measures on the construction initial Risks, in terms of reduction of the probability of occurrence and/or of reduction of the impact is summarized in Table 9.

| Qualitative analysis of construction risks | | | | → | Qualitative analysis of Residual Risks | | | |
|---|---|---|---|---|---|---|---|---|
| | Impact | | | | | Impact | | |
| Freq. | 1 | 2 | 3 | → | Freq. | 1 | 2 | 3 |
| 3 | R12 | R7,R10 | R2,R5,R6 | Risk mitigation measures | 3 | 🟩 | 🟪 | 🟪 |
| 2 | 🟦 | R1,R3,R4 | R8 | | 2 | 🟦 | 🟩 | R5,R8 |
| 1 | R9 | R11 | ▨ | → | 1 | R9,R12 | R1,R2,R3,<br>R4,R9,R10,R11 | R6,R7 |

*Table 9: Synthesis of the mitigation of risk by the application of the described design measures: the change of relative position of each risk from the left to the right matrix shows the main action of the mitigation measure considered.*

On the basis of the performed analysis, two main risks for tunnel construction appear clearly dominant as primary consequence of the geomechanical and hydrogeological setting:

- The risk associated to large water inflow/ water pressure in correspondence of fractured (permeable) rock masses, or unforeseen lenses of sands and gravels (type VII);
- the risk of trapping of the TBM for very high squeezing behaviour in coincidence with poorest flyschiod rock masses (mainly type V) and, overall, of the clayey breccias in the two paleo-valley. As above reported, especially in the latter context the risk of “sinking” of TBM appears also relevant in the current preliminary design phase.

As previously described, despite that some possible mitigation measures have been typologically individuated, the resulting residual risk has been considered still as “high”, considering the special technologies and very innovative technical solutions necessarily involved. Consequently, the update of the advanced conceptual design is actually focused on the above described criticalities and special issues, while waiting for the results of the new geotechnical investigations in process. Detailed numerical modeling of forced consolidation process for the clayey breccias by drainages and/or innovative controlled ground injections are for example reported in [2] and [3].

## 4 – CONCLUSIONS

A framework of the risk analysis developed for the on-going update of the advanced conceptual design of the Gibraltar strait tunnel has been presented. The main hazards and risks for tunneling have been listed and quantified, as well as the correspondent mitigation measures and the residual risk. On the basis of such an analysis, the update of the advanced conceptual design is today rationally concentrated on the residual criticalities and all the studies in process are effectively and efficiently proceeding towards the optimal mitigation of the residual risks related to the feasibility of this challenging work.

### 3.3 – Acknowledgements

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