On the concept of “Risk Analysis-driven Design”

G. Russo, P. Grasso and L. P. Verzani
Geodata Engineering (GDE), Torino, Italy.
A. Cabañas
Codelco, Santiago, Chile.

ABSTRACT: In the current tunneling practice, the Risk Analysis and the structural Design are frequently considered two separate and independent items. On the contrary, according to the Geodata Engineering (GDE) approach they are integrated in one unique rational process, completely developed by probabilistic method, structuring the so-called “Risk Analysis-driven Design (RAdD)”. The key points of this innovative approach are presented, with general reference to one of the most recent application, in particular related to the construction of the tunnels to the new productive level of the El Teniente mine (Chile). El Teniente Mine, with more than 2400 kilometers of tunnels excavated is the largest underground copper mine in the world. The tunnel works for the new mine level, located at 1000 m depth, are actually under construction, permitting to complete the design process and check the foreseen geological-geomechanical scenarios.

1 Introduction

In the current tunneling practice, the Risk Analysis and the structural Design are frequently considered two separate and independent items. On the contrary, according to the Geodata Engineering (GDE) approach they are integrated in one unique rational process, structuring the so-called “Risk Analysis-driven Design (RAdD)”. In the Figure 1, the basic flowchart is remarked, showing as well as it is combined with the Italian Guidelines for Design (SIG, 1997) to guarantee a complete treatment of all the fundamental items.

Recently, some key concepts of RAdD have been also shared in the AFTES Recommendations (2012).

In the present paper, a short insight in the RAdD approach is presented, with particular reference to some more recent practical applications, developed by the collaboration with Ingeroc (Santiago), mainly involving the access tunnels to the new production level of the El Teniente mine.

2 El Teniente mine

El Teniente Mine, located in the Libertador General Bernardo O’Higgins Region 80 km southeast of Chile’s capital Santiago, is the largest underground copper mine in the world, with more than 2400 kilometers of mine drifts and tunnels producing more than 400000 tons per year of fine copper recovered from the ore, either as refined ingots or as copper cathodes.

As a result of ore processing, nearly 5000 tons of molybdenum are recovered as a by-product.

The owner of the mine, Codelco (Corporación Nacional del Cobre de Chile, División El Teniente), is currently developing the New Mine Level Project to ensure the continuity of the exploitation and the increase of ore production.

The New Mine Level (NML) project, located at 1000m depth, is being planned to extend the life of the mine by 60 years, entering production phase in 2017. New reserves of 2020 million tons at present with 0.86% average copper grade and 220 ppm of molybdenum, will maintain the mine’s production at its 137000 tons/day.
A significant component of the NML project is the construction of 24 km of access tunnels, which began in March 2012, consisting of two adits ($L_{tot}=6$ km), proposed by the Contractor (CTM – Constructora de Túneles Mineros, joint venture between Vinci and Soletanche Bachy), and two main tunnels ($L_{tot}=9+9$ km): a tunnel for vehicular access of personnel and a twin conveyor tunnel for the transport of the ore. All the underground advancements are in conventional drill and blast method (D&B). The construction in process of these tunnels have been described by Decman et al. (2013) and Kontrec et al. (2013).

### 3 Key elements of RAAdD

The design and construction of long tunnels particularly those at great depth, is generally associated with a high level of risks due to a whole series of uncertainties involved. The risk should not be ignored, but managed through the implementation of a specific Risk Management Plan (RMP, Grasso et al. 2002; 2006), fully integrated in each part of the design study, in accordance to a real development of a "Risk Analysis-driven Design" (RAAdD).

While it is recommended the specific reference to the cited papers for a detailed insight in the RMP methodology, including the basic definitions and classifications for the Risk Analysis (see also ITA, 2004), in the following focus is centered to the sequential steps for the RAAdD development.

In particular, with reference to the flow chart in the Figure 1, some relevant features of the design process are remarked. As it will be evident, the systematic implementation of the probabilistic approach is a key element in each step of the study.
3.1 Reference geological scenarios

As above commented, the tunnels design and construction involve a high level of risk mainly due to geological-geomechanical uncertainties. Uncertainty mainly concerns the inherent variability of the input geo-parameters and the real state of each parameter along the tunnel, conditioning the excavation behaviour.

![Figure 5](image1.png)  Different type of uncertainties (Hoffman and al., 1994).

The two types of uncertainties described can be reasonably related to the Type A and B reported in the Figure 5 (Hoffman et al., 1994, Russo et al. 1999).

To manage the different types of uncertainties basically the following procedure are applied:

- Type A: on the basis of the statistical best-fitting of the available data, adequate probabilistic distributions are associated to each geomechanical parameters (Figure 6);
- Type B: three geological-geomechanical scenarios are considered to simulate the reference context: 1) Favorable, 2) Most likely and 3) Unfavorable scenario. Evidently, this approach permits to consider different faults extensions, contacts positions, parameter values, classification assessments, etc. In some case, as for the example reported in the present paper, the Most likely scenario is considered coincident with the Basic Design developed by the Owner (here called “H_lik”) and the effective position with respect the other scenarios is consequently checked.

![Figure 6](image2.png)  Managing parameter variability by best-fitting of the statistical data (above) and probabilistic calculations (below; example of quantitative GSI assessment).

In Figure 7, the reference “H-Lik” scenario for the examined example is reported, remarking the presence of n.11 Rock Mass Unit (RMU), as well various faults and tectonic/volcanic contacts between the igneous rock masses.

![Figure 7](image3.png)  The reference “H-lík” scenario for the Access tunnels to the new productive level of El Teniente mine.
In Figure 8, a simple example of the expected distributions of the GSI index for the three scenarios is reported, as resulting by the performed additional study.

<table>
<thead>
<tr>
<th>GSI</th>
<th>Probability (%)</th>
<th>GD_unf</th>
<th>H lk</th>
<th>GD_fav</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>14</td>
<td>20</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>47</td>
<td>5</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>38</td>
<td>75</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>36</td>
<td></td>
</tr>
</tbody>
</table>

Figure 8: Example for one RMU of the expected GSI distribution for the three scenarios (note: class 5=GSI<21;…class 1=GSI>80).

3.2 Hazard identification and quantification

Defined the geological setting, the reference context for the Designer is completed by the consequent identification of the main hazard for tunneling and their evaluation in terms of probability of occurrence and the specific intensity.

Two main categories of hazard events are identified in connection to geological and geomechanical issues (Figure 9), namely:

- Hazard phenomena associated with unfavorable geological conditions.
- Geomechanical hazard related to rock mass behaviour upon excavation.

Figure 9: Identification of the main hazards for tunnel excavation and support.

Geomechanical hazards are mainly related to ground behaviour upon excavation, thus taking into account the intrinsic properties of rock masses and the associated stress conditions. The forecast analysis for evaluating the response upon excavation and then the most probable hazard is performed for each RMU by necessarily taking into account both stress and geostatic analyses, as shown in the flow chart of Figure 10.

Figure 10: Simplified scheme for identifying the excavation behaviour by Stress and Geo-structural analyses (Russo and Grasso, 2007).

The reference classification of the excavation behaviour is consequently based on both stress and geo-structural type analysis (11).

![Figure 11: GDE classification of the excavation behaviour (same reference than Figure 10).](image)

The matrix that results from such a double classification approach allows an optimal focalization of the specific design problem.

Furthermore, a rational choice of the type of stabilization measures may be derived as a function of the most probable potential deformation phenomenon that is associated to the different stress and geostatic combination.

For the quantification of the probability of occurrence of the hazards, the probabilistic analytical method is applied, by implementing the Convergence-Confinement (C.Carranza T. solution, 2004) for each RMU and geo-scenario. Some examples of the results are presented in Figure 12.

Consequently, the probability of occurrence of the different hazards are derived for the different scenarios (Figure 13)

Figure 12: Example of the probabilistic results of the analyses of excavation behavior, with specific reference to the GDE classification in Figure 11.

Figure 13: Resulting probability of occurrence of the different geomechanical hazards. As already remarked, note that the H_lik scenario has been derived by interpreting the Basic Design of reference.

3.3 Evaluation of the Initial risk

The calculation of the probability of occurrence of the hazards and the estimate of the potential impact on tunnelling (D&B and TBM) allow for the initial Risk Register compilation (Figure 14).

Figure 14: Example of the initial risk estimation as resulting from the probabilistic calculations and the potential impact on tunneling. For the classification, basic reference is done to ITA (2004, see also Figure 15), according to which: R=P*I, where R=Risk; P=Probability of occurrence; I=Impact. Risk may result: Unacceptable (Red), Unwanted (Yellow) and Negligible/Acceptable (Green). The analysis is performed for either D&B and TBM excavation.

A longitudinal profile with representation of the initial risk along the tunnel is consequently realized, so providing the fundamental basic starting point for the Design actions (Figure 15).
3.4 Mitigation measures and Residual risk

On the basis of the Hazard and Risk Register, the appropriate mitigation measures (i.e. design solutions) are selected, both for D&B and Double Shielded TBM excavation. An indicative example of typical mitigation measures for traditional D&B excavation related to each type of hazards is reported in Figure 16. Consequently, according to the rational illustrated in Figure 17, the mitigation measures are assembled to compose the Section Type of support (Figure 18). According to the hazard specificity, adequate calculation methods are consequently adopted for the structural design.
As remarked in the flowchart of Figure 1, an iterative process is implemented to dimensioning the support section type and estimating the residual risk. The latter estimation is based on the evaluated potential damages (Figure 19) and allows for updating the Risk Register (Figure 14), up to mitigate any Unacceptable risk. Moreover, for the residual Unwanted risk, an adequate counter-measures are consequently predefined.

3.5 Structural verification and design

Empirical, analytical and numerical methods are usually implemented by the probabilistic approach to verify the primary support and the final lining.

In particular, according GDE standard:

- Empirical methods are generally limited to the case of response to excavation in elastic-domain or very limited extension of plastic/damaged zone, where rock block falling is the typical instability. In Figure 20, an example of application of the RMi system is reported.
Analytical methods, such as the “Convergence-Confinement” method, are applied to model support system that can be reasonably referred to a circular section subjected to isotropic stress conditions. In particular, the Capacity-Demand calculation is implemented to estimate the structural safety margin (Figure 21) of the Section Types.

Numerical methods are used to verify the final lining, as well as all the cases in which anisotropy does not allow for the described simplification intrinsic to the analytical method. In the case, the Point Estimated Method (PEM, Rosenblueth, 1975) is used for probabilistic analysis.
4 Probabilistic time & cost estimation

On the basis of the expected distribution of Section Types along the tunnels, the probabilistic estimation of the construction time and cost is finally developed, incorporating also the estimated probability and impact of the residual risk.

In particular, the calculation involves the probabilistic assessment of

• the unitary cost of the Section Types;
• the relative advance rate;
• the time & cost estimation of the residual risk (“accidents” in Figure 23)

Figure 23. Example of time & cost probabilistic estimation normalized with respect the resulting mean value of the H-lik scenario. Note that the upper shaded clouds incorporate a 5% for year increasing of costs for inflation, etc.

As it can be observed, mainly on the basis of the geomechanical classification assessments, either the Favorable and Unfavorable scenarios result in the case some better than the basic reference scenario. In particular, by referring to the obtained Expected Values (EV), it is obtained:

• EV_{FAV} \approx 0.85 \text{ EV}_{H\text{LIK}}
• EV_{UNFAV} \approx 0.95 \text{ EV}_{H\text{LIK}}

In other words, the reference scenario results about correspondent with the simulated unfavorable scenario and therefore it appears reasonable to expect some more favorable conditions.

5 Construction phase

As observed in the Section 2, the construction of the tunnels and realtive adits is actually in progress and GDE provides with a specific team on site collaboration and technical support to Codelco. This is evidently fundamental to control and manage all the construction aspects and check the effective advantages of the proposed approach.

In this challenging phase, the same basic concepts described in the previous sections are implemented.

For example, the main hazards for the excavation are systematically checked during the advancements of the tunnels, by very detailed face mapping and the concurrent application of the “GDE Multiple graph” (Russo, 2008, 2013).

The GDE multiple graph is composed by 4 sectors (Figure 24), each of them finalized to a user-friendly quantification of the following engineering equations (proceeding clockwise from the bottom-right quadrant to the top-right):

1. Rock block volume (V_b) + Joint Conditions (jC) = Rock mass fabric (GSI);
2. Rock mass fabric (GSI) + Strength of intact rock (\sigma_c) = Rock mass strength (\sigma_{cm})
3. Rock mass strength (\sigma_{cm}) + In situ stress = Competency (IC)
4. Competency (IC) + Self-supporting capacity (RMR) = Excavation behaviour (\rightarrow\text{Potential hazards})

Figure 24. Application of the GDE Multiple graph for one of the main access tunnels (TAP) in the RMU-V1.
“wedge instability-rockfall” are in the case the main type of hazards.

6 Conclusion

The main features of the Risk Analysis-driven Design (RAvD) developed by Geodata Engineering have been described.

The key concept of RAdD is that the Design and the Risk Analysis are not two separate item, but a unique and fully probabilistic integrated process.

In each phase of the study, uncertainty and variability are adequately taken into account and reliability analysis are consequently performed to check the support system and lining.

A practical application has been presented, with specific reference to the design and construction of the tunnels to the new productive level of the El Teniente mine (Chile).

REFERENCES

AFTES 2012: Recommandation sur la caractérisation des incertitudes et des risques géologiques, hydrogéologiques et géotechniques. Tunnels et Espace Souterrain - n°232.


Kontrc P., Constandinidis V. 2013. Engineering geological characterization of the rock mass in the Adit P4600, Project El Teniente, Chile, ITA symposium Croatia, 7-8 May.


