TAI

ASSOCIATION INTERNATIONALE DES TUNNELS ET DE L'ESPACE SOUTERRAIN AITES | ITA INTERNATIONAL TUNNELLING AND UNDERGROUND SPACE ASSOCIATION

HEADRACE TUNNEL GEO-HAZARD IDENTIFICATION, BEYOND THE ROCK MASS CLASSIFICATION METHODS

by

A. VANNI, D. VIETTI

LOMBARDI ENGINEERING LIMITED, GIUBIASCO (SWITZERLAND)

alberto.vanni@lombardi.group, davide.vietti@lombardi.group

AGENDA

- Objective
- Specific geo-hazards for hydraulic tunnels
- Limits of rock mass classification methods
- Case-histories

OBJECTIVE

⚠ **DISCLAIMER** ⚠

(…to avoid any technical-diplomatic incident…)

The aim is not to make any judgement of the classification methods themselves (RMR, Q, GSI, etc.).

The aim is to warn the (young) designers about the limits of their applicability, when a proper and complete **hydraulic tunnel** geo-hazard assessment is required.

OBJECTIVE

- To understand that pressure tunnels and infrastructure tunnels are different.
- To understand why the relevant geo-hazard and related risk assessment is different.
- To list the peculiar geo-hazards for pressure tunnels and give indications on their assessment.
- To understand that the risk is high, despite a low probability of occurrence (high impact).
- To understand the limits of applicability of rock mass classification methods for hydro tunnels.

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SPECIFIC GEO-HAZARDS FOR HYDRAULIC TUNNELS – CONCEPTS

The construction of any tunnel induces disturbances in the rock mass.

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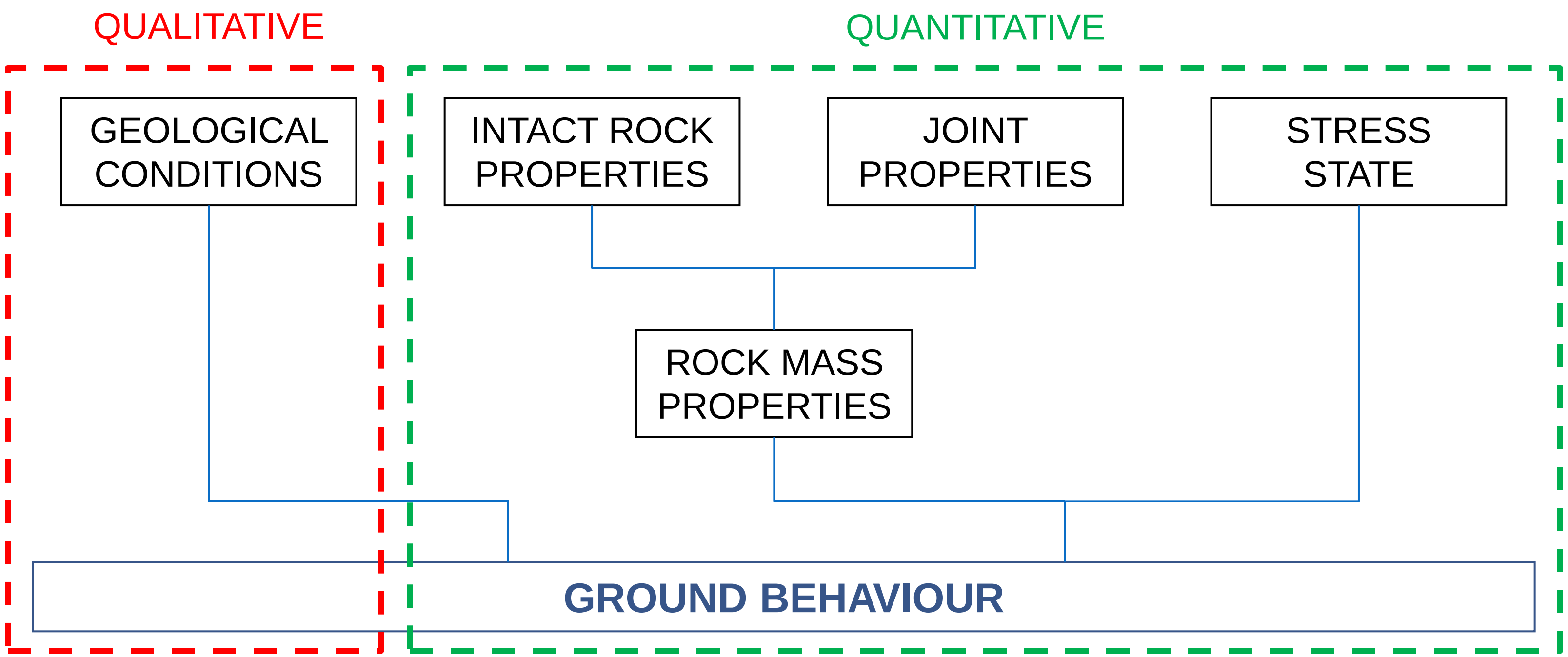
The construction of any tunnel induces disturbances in the rock mass.

For an **infrastructure tunnel**:

- *disturbance* means alteration of the stress state around the excavation (in most cases);
- the worst-case operating condition is not different from the worst-case construction condition;
- supports and final lining are designed basing on geological features, and **geomechanical behavior** (rock wedge instability, ravelling/caving, squeezing, brittle failure, etc.)
- geomechanical behavior is assessed by combining **rock mass quality** (=joint properties: mainly fracturing/alteration) with **relative stress state** (=ratio between rock mass resistance and stress state).

SPECIFIC GEO-HAZARDS FOR HYDRAULIC TUNNELS – CONCEPTS



SPECIFIC GEO-HAZARDS FOR HYDRAULIC TUNNELS – CONCEPTS

The construction of any tunnel induces disturbances in the rock mass.

A **hydraulic tunnel** brings **pressurized water in rock mass** extensive portions:

- the rock mass will find a new equilibrium, in terms of stress state (geomechanical behavior assessment), but also in terms of **physical and chemical equilibrium with water**;
- the new equilibrium will be reached during operation in days, or months, up to years, and often leads to the worst-case operating condition;
- the long-term equilibrium with water does not depend on geomechanical behavior;
- the design solutions can't be based on rock mass classifications only.

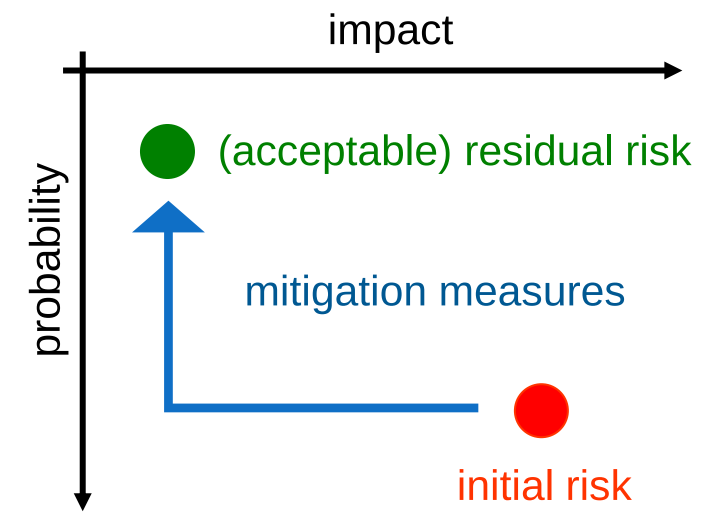
SPECIFIC GEO-HAZARDS FOR HYDRAULIC TUNNELS – CONCEPTS

At **early design stage**, geo-hazard assessment for hydraulic tunnels requires:

- hydraulic characteristics of the waterway (water flux speed, static pressure, transient effects, such as water hammer effect, cavitation risk, pressure pulsations, etc.);
- geological, hydrogeological and geomechanical conditions.

SPECIFIC GEO-HAZARDS FOR HYDRAULIC TUNNELS – CONCEPTS

Although some geo-hazards are associated to a very low probability of occurrence, they must be detected, because their impact could be disastrous, leading to a high risk.



$Risk_{ini} = P \times I$

mitigation measures

$Risk_{res} = P_{red} \times I_{red}$

SPECIFIC GEO-HAZARDS FOR HYDRAULIC TUNNELS – CONCEPTS

The main (disastrous) **impacts** are:

tunnel collapse, which could lead to:

- production loss;
- change in hydraulic section;
- complete obstruction of the water way (plant shutdown due to flow interruption).


Kargi, 2015 (Turkey)

SPECIFIC GEO-HAZARDS FOR HYDRAULIC TUNNELS – CONCEPTS

The main (disastrous) **impacts** are:

uncontrolled leakage, which could lead to:

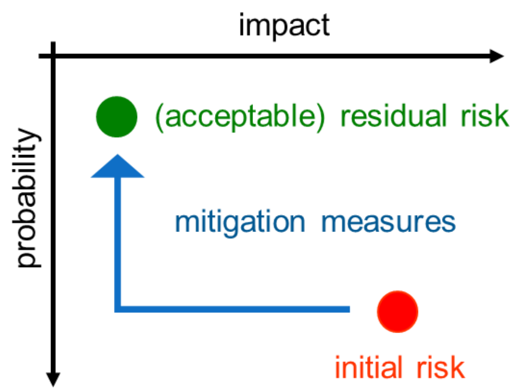
- production loss;
- environmental damages (surface settlements, landslides, inundations, etc.).

Ituango, 2018 (Colombia)

SPECIFIC GEO-HAZARDS FOR HYDRAULIC TUNNELS – CONCEPTS

Early design stage assessment means:

- geo-hazard detection;
- probability of occurrence and impact assessment;
- proper design to mitigate the risk (including alternative alignments!).



…remembering that:

*the Design of the tunnel **cannot be completed** until the end of excavation and a careful evaluation of exposed rock conditions are carried out (Brox, 2011)*

SPECIFIC GEO-HAZARDS FOR HYDRAULIC TUNNELS

The main specific geo-hazards can be grouped into:

- Geological aspects
  - ✓ slaking phenomena
  - ✓ swelling phenomena
  - ✓ karst
- Stress state conditions
  - ✓ hydrojacking/hydrofracturing

SPECIFIC GEO-HAZARDS FOR HYDRAULIC TUNNELS

The main specific geo-hazards can be grouped into:

- Geological aspects
  - ✓ slaking phenomena
  - ✓ swelling phenomena
  - ✓ karst

The concept of rock mass as construction material is here introduced: the rock mass durability must be assessed.

- Stress state conditions
  - ✓ hydrojacking/hydrofracturing

SPECIFIC GEO-HAZARDS FOR HYDRAULIC TUNNELS

The rock slaking effect is a combination of different phenomena, like weathering processes:

- mechanical exfoliation
- wetting and drying
- scour
- hydrolysis

SPECIFIC GEO-HAZARDS FOR HYDRAULIC TUNNELS

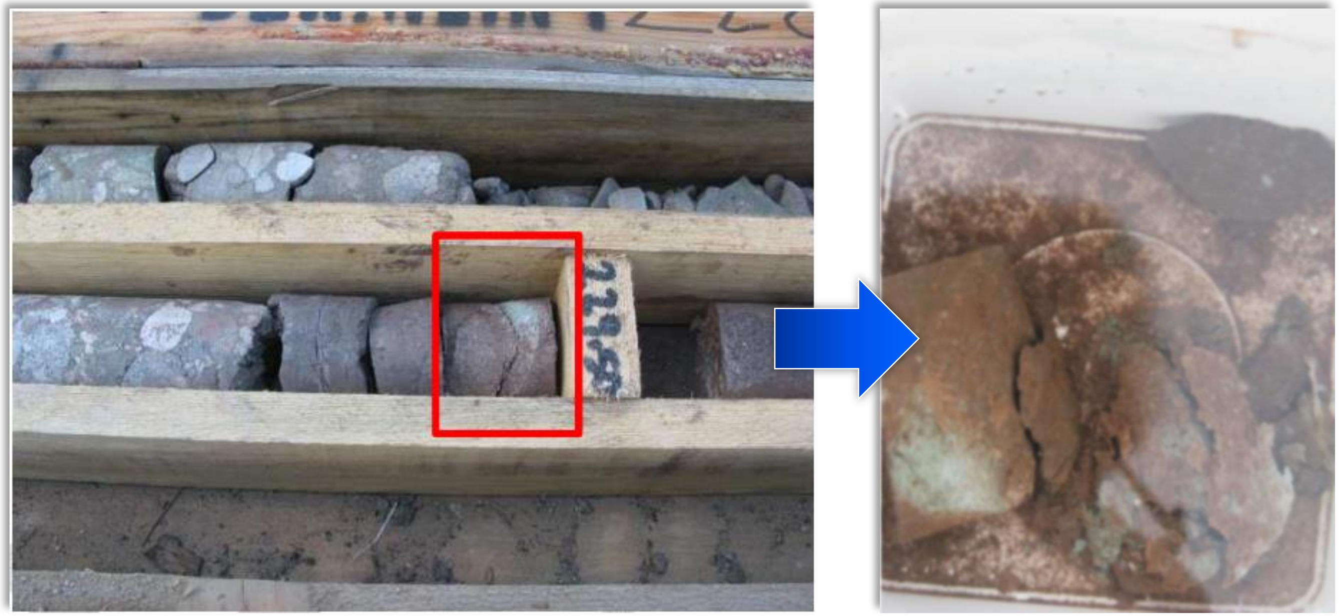
The rock slaking effect is a combination of different phenomena, like weathering processes:

- mechanical exfoliation
- wetting and drying — *The presence of water in the rocks introduces water molecules between mineral grains causing swelling, and shrinkage when drying occurs.*
- scour — *The flow of water over the rock surface, and partially through the rock mass, removes loose particles of weathered rock.*
- hydrolysis — *Reactions between the ions of the minerals in the rocks and the H^+ and OH^- ions of water (flow → removal).*

SPECIFIC GEO-HAZARDS FOR HYDRAULIC TUNNELS

Indications about susceptibility to slaking phenomena are given by:

- immersion of a sample of rock into clean water, according to ISRM (1994);
- immersion of samples in ethylene-glycol solutions to accelerate the process, revealing its potential;
- laboratory tests, according to ISRM (1997) and ASTM (2016).



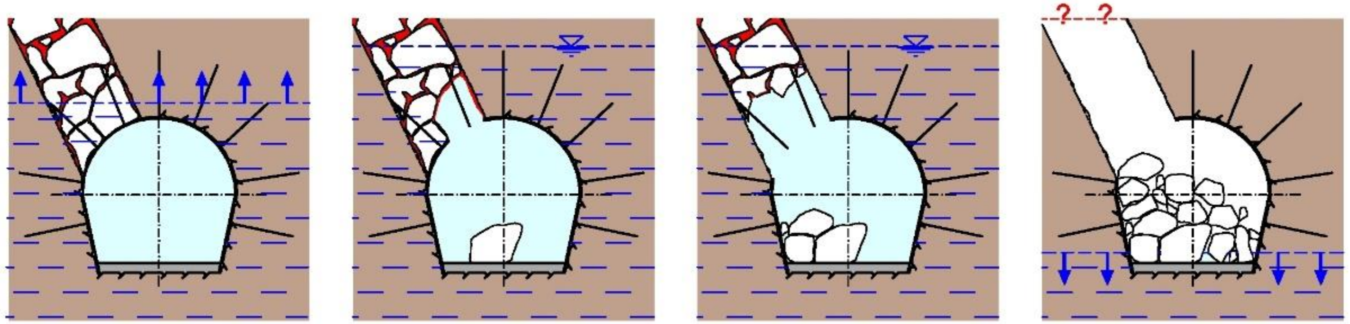
SPECIFIC GEO-HAZARDS FOR HYDRAULIC TUNNELS

Lithologies which are prone to slaking have the following characteristics:

- high content in clay and silt, but only slightly lithified, or of a low grade of metamorphism (tendency of formation of clay minerals, e.g. by weathering or hydrothermal alteration);
- suitable chemical composition (e.g. rocks that formed from aluminosilicate) that could lead to clay mineral formation when fractured and crushed due to tectonic activity (e.g. faults), then subjected to weathering or hydrothermal alteration.

SPECIFIC GEO-HAZARDS FOR HYDRAULIC TUNNELS

Typical collapse sequence in a hydraulic tunnel under operation crossing a weak geological zone:



Commissioning | Beginning of the collapse due to material deterioration and overcoming of support strength | Propagation of collapse | Collapse reaches its final equilibrium

Kargi, 2015 (Turkey)

SPECIFIC GEO-HAZARDS FOR HYDRAULIC TUNNELS

Mineral swelling is the tendency to volumetric expansion of some minerals when they are in contact with water.

During construction is rare to observe the swelling effects, which are more frequently evident at long term (during tunnel operation!).

The most common types of swelling are:

- **clay mineral swelling** (Smectite, Vermiculite, Montmorillonite)
- **sulphate swelling** (2 natures of Calcium sulphate: anhydrite and gypsum)
- **sulphide swelling** (less important in tunneling)

SPECIFIC GEO-HAZARDS FOR HYDRAULIC TUNNELS

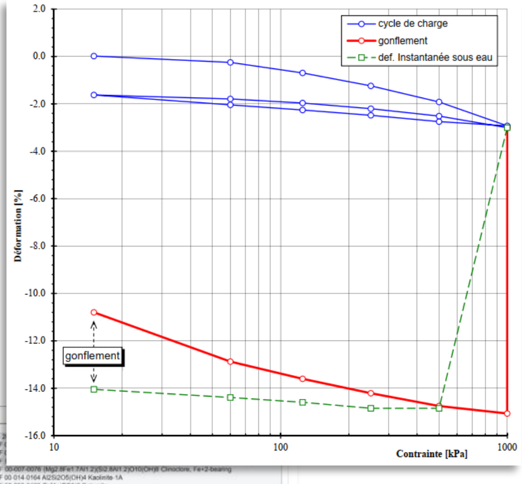
The most relevant contributing factors are:

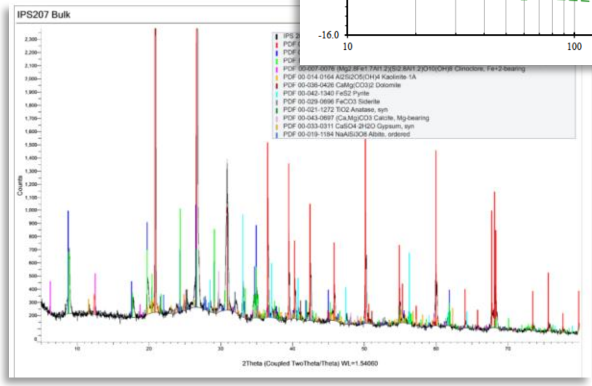
- presence of swell/slake prone lithology (low grade, clay and silt rich rocks, mudstone, or evaporitic rock);
- presence of clay minerals with a certain swelling potential (smectite), or of anhydrite/gypsum;
- clay minerals are often found in gouges and weakness zones, known as swelling clay zones.
- stress relief (e. g. due to excavation process);
- presence of water (also water chemistry has influence);
- hydro-thermal activity around magmatic dikes (magma flows into a crack).

SPECIFIC GEO-HAZARDS FOR HYDRAULIC TUNNELS

Typical laboratory tests to determine the swelling potential:

- SINTEF free swelling test (volume increase of powdered material)
- ASTM D4546-21 (2021) (one-dimensional swelling)
- ISRM free swelling test (1999)
- Huder-Amberg swelling test (oedometer test)
- X-Ray diffractometric tests (clay mineralogical composition).





SPECIFIC GEO-HAZARDS FOR HYDRAULIC TUNNELS

Preliminary indications about the potential volume expansion and the resulting pressure are given, according to Pettersen Skipperwik (2014), Hoek et Al. (2017):

Clay group	Clay minerals	Swelling potential
Kaolinite	-	Not expansive
Chlorite	-	Not expansive
Illite	-	Not expansive
Mixed layer	Illite-Smectite, Corrensite	Moderately expansive
Smectite	Vermiculite	Moderately expansive
	Montmorillonite	Very expansive

SPECIFIC GEO-HAZARDS FOR HYDRAULIC TUNNELS

Preliminary indications about the potential volume expansion and the resulting pressure are given, according to Pettersen Skipperwik (2014), Hoek et Al. (2017):

Degree of swelling	Free swelling [% volume]	Swelling pressure* [MPa]
Inactive	< 100	< 0.15
Slightly active	100-140	> 0.30
Moderately active	140-200	≈ 2.00
Extremely active	> 200	≈ 2.00

(*) Values are indicative.

SPECIFIC GEO-HAZARDS FOR HYDRAULIC TUNNELS

The karst phenomena are based on the progressive mineralogical solution of certain rock types.

The most common soluble rocks are carbonates (principally calcium carbonate, e.g. limestones).

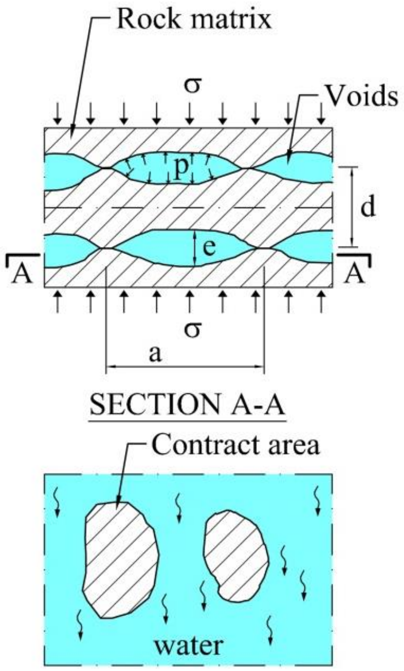
Less common:

- dolomitic rocks (magnesium carbonates);
- gypsum (calcium sulphate).

SPECIFIC GEO-HAZARDS FOR HYDRAULIC TUNNELS

The hydrojacking/hydrofracturing hazard is related to pressure tunnels:

the internal operational pressure
overcomes the natural acting stress state.



Hydrojacking opening of existing cracks

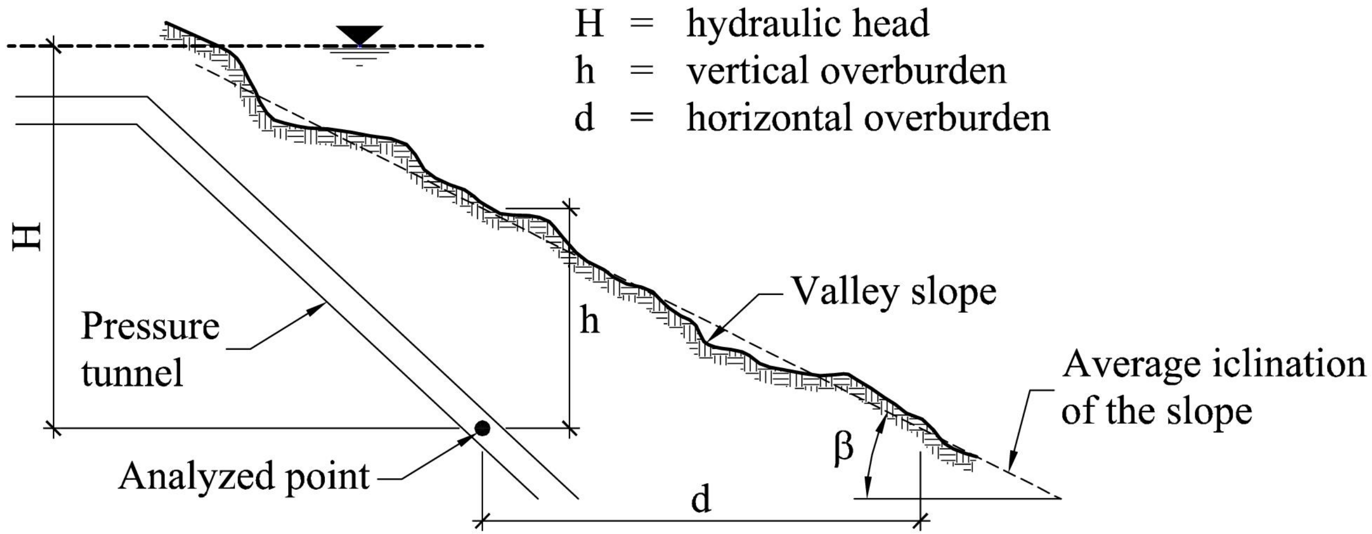
Hydrofracturing development of new cracks within the rock-mass

The main impact is rock mass fracturing and thus uncontrolled leakage.

SPECIFIC GEO-HAZARDS FOR HYDRAULIC TUNNELS

In the common engineering practice, some "*rules of thumb*" exist to assess the hazard:

- the "*Don Deere rule*"
- the "*Norwegian rule*"



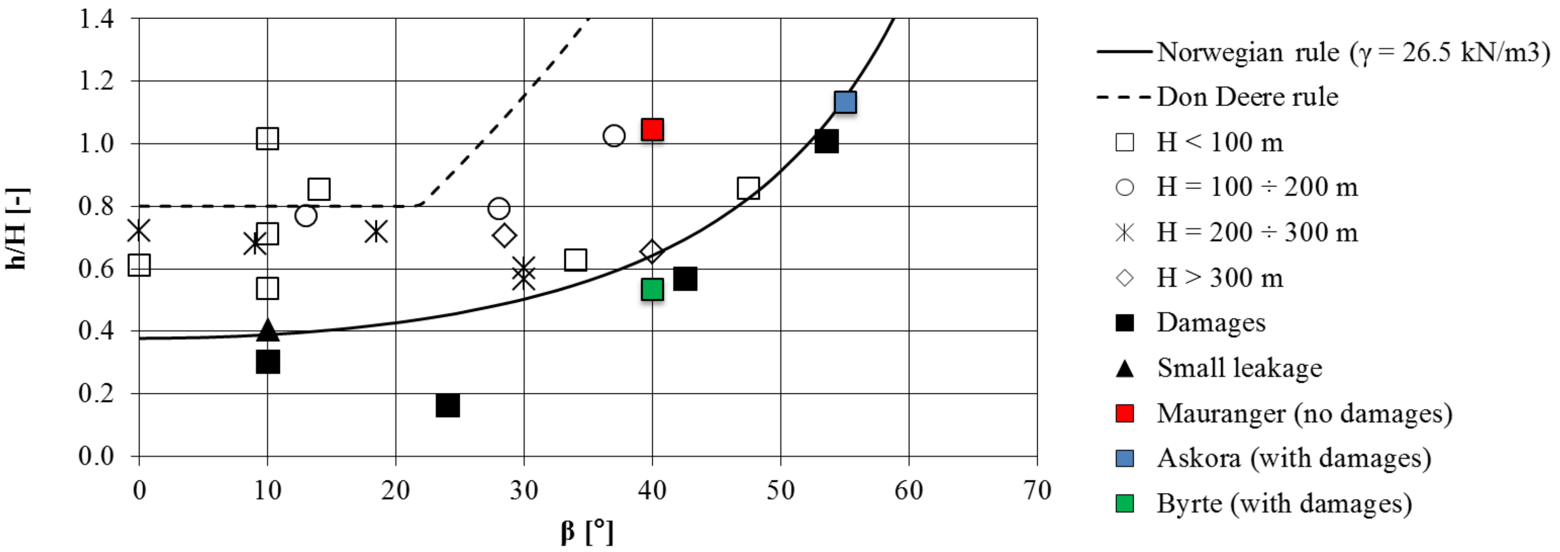
SPECIFIC GEO-HAZARDS FOR HYDRAULIC TUNNELS

In the common engineering practice, some "*rules of thumb*" exist to assess the hazard:

- the "*Norwegian rule*"

$$h > \frac{\gamma_w \cdot H}{\gamma_R \cdot \cos^2 \beta}$$

FS_{min} = 1.10 ASCE/PERI Guides (1989)
FS_{min} = 1.15 Palmstrom, Berdal (1987)
FS_{min} = 1.20 Broch (1982)

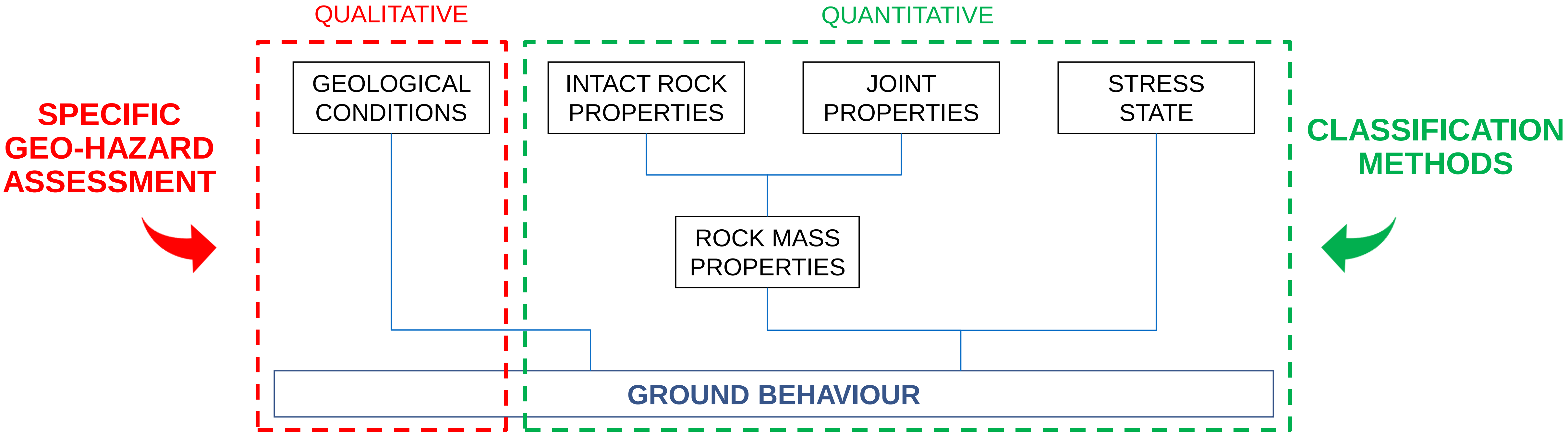


Amberg, Vietti (2015)

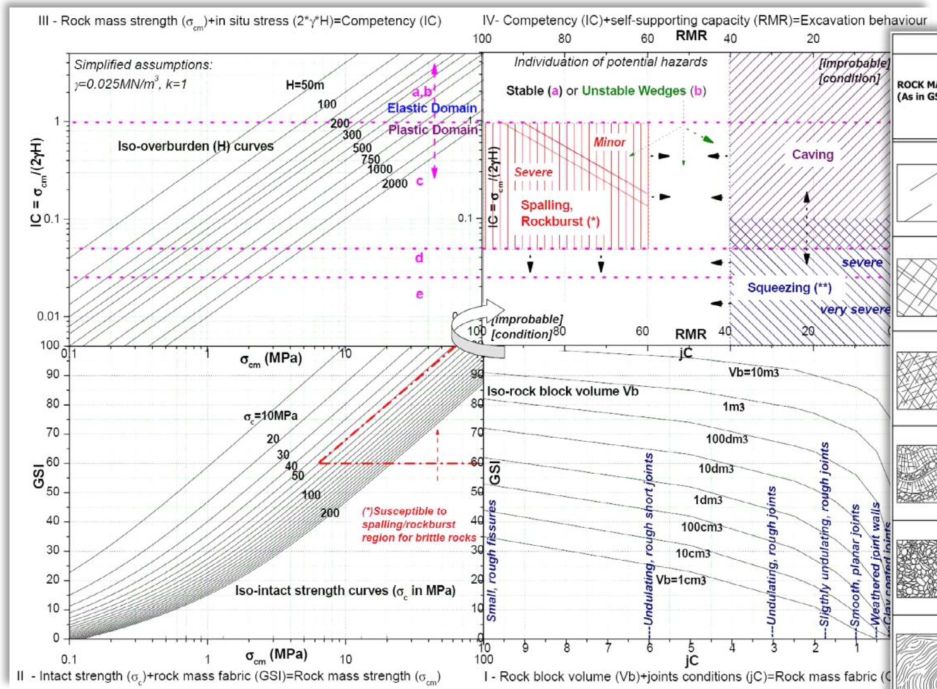
LIMITS OF ROCK MASS CLASSIFICATION METHODS

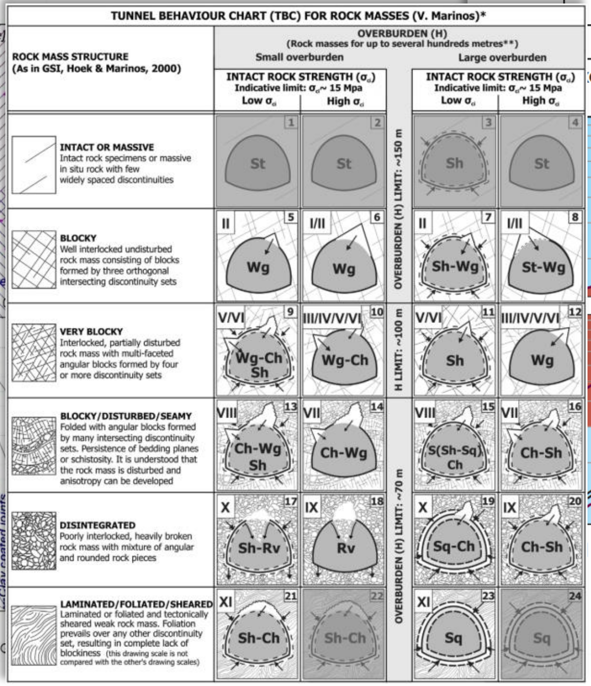
In the common practice, the well-known classification methods mainly refer to the geomechanical behavior during excavation, guiding the designer in the choice of the excavation support.

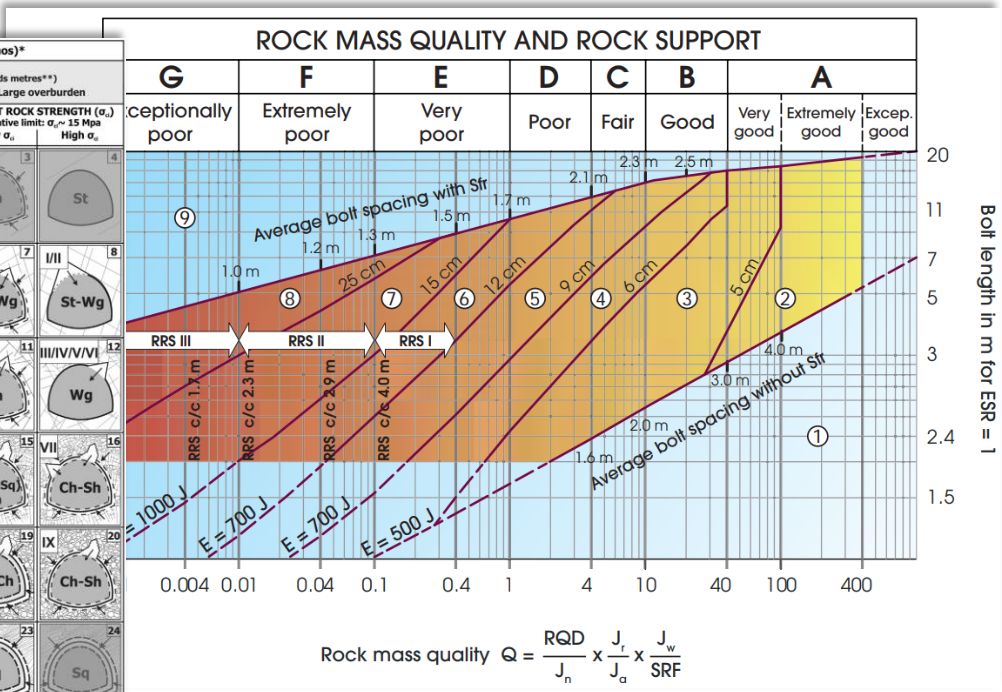
LIMITS OF ROCK MASS CLASSIFICATION METHODS



LIMITS OF ROCK MASS CLASSIFICATION METHODS







LIMITS OF ROCK MASS CLASSIFICATION METHODS

For what reviewed and analyzed, no reference is made to hydraulic tunnel specific geo-hazards. And actually, this is not the goal of the (otherwise reliable) classification methods.

The same Authors mentions (and warns to) some of the relevant predisposing geological factors.

Recommendation to (young) designers:

⚠ Don't rely uncritically on user-friendly charts and graphs, nor on numerical models, to avoid situations like these… ⚠

CASE HISTORIES – KARGI HPP (TURKEY)

- Kargi HPP (102 MW)
- Kizilirmak River, Province of Çorum (Turkey)
- 11.8 km-long and 11-m diameter HRT
- Excavated with both TBM and DBM (2013-2016)

At the end 2016 the tunnel dewatering became necessary, basing on sub-aquatic ROV inspection results, indicating a series of **collapses** had occurred.

The main ones presented similar characteristic:

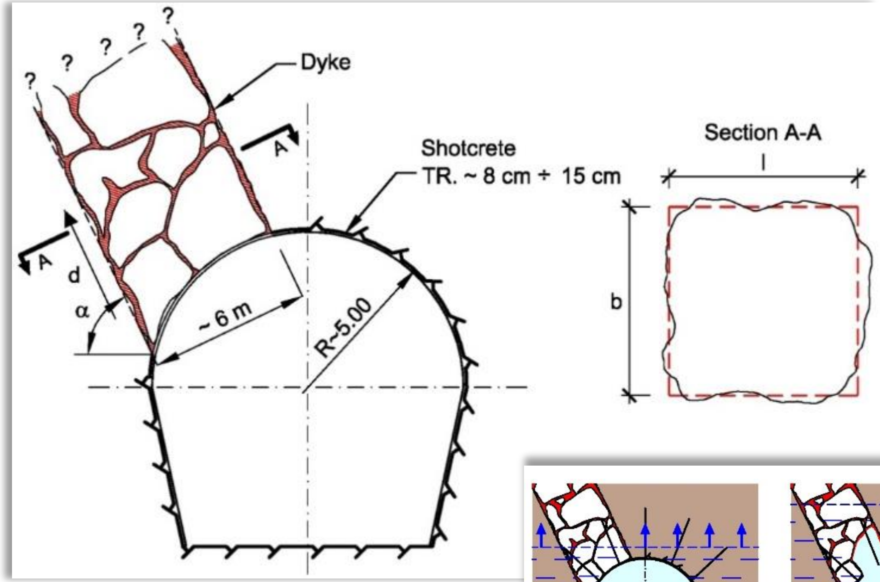
- progressive collapses, up to 40 m high,
- chimney shaped in a **good** surrounding rock-mass context.

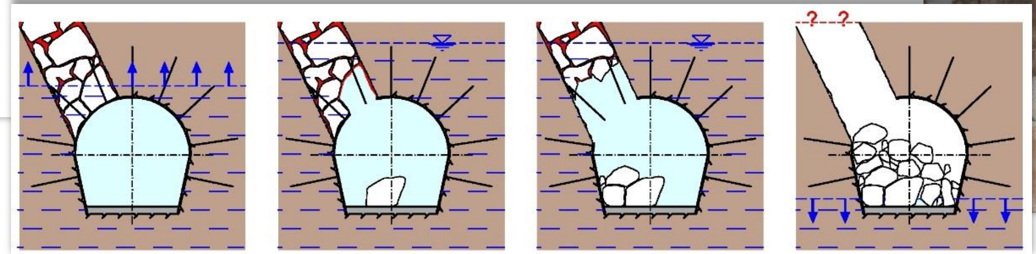
CASE HISTORIES – KARGI HPP (TURKEY)

Weakness zones and intrusive dykes (=fractured rock material contained in a fine-grained gougy matrix, highly sensitive to water).

X-ray diffraction tests confirmed swelling minerals in gauge materials.

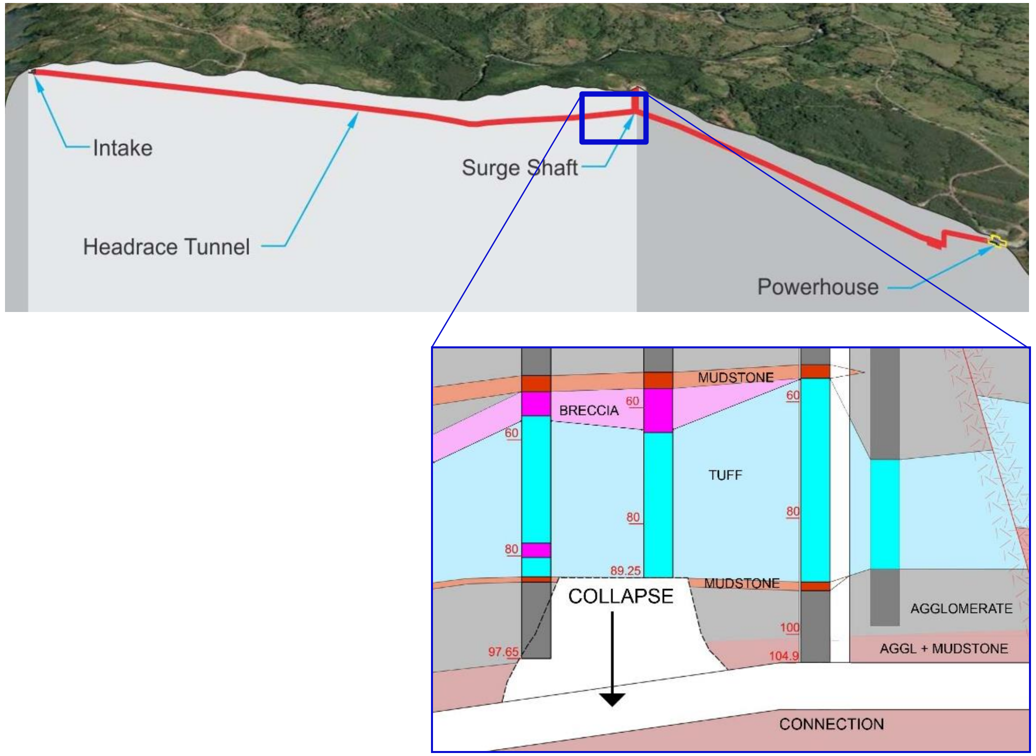
CASE HISTORIES – KARGI HPP (TURKEY)





CASE HISTORIES – ESTI HPP (REP. OF PANAMA)

- Estí HPP (120 MW)
- Chiriquí River, (Rep. of Panama)
- 4.8 km-long and 9-m diameter HRT
- Excavated with DBM (2001-2002).



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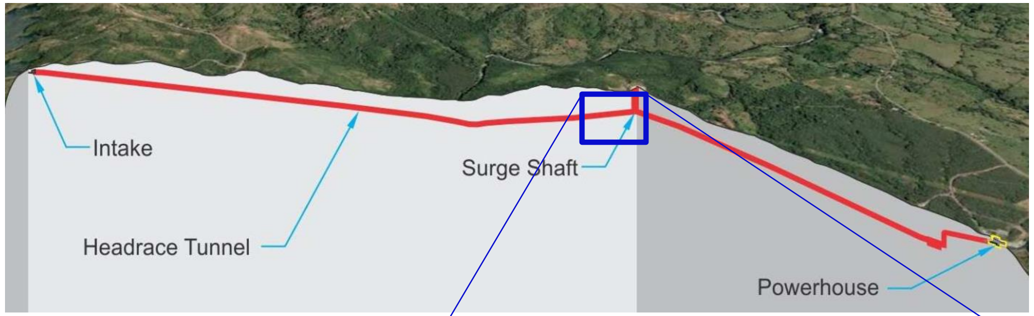
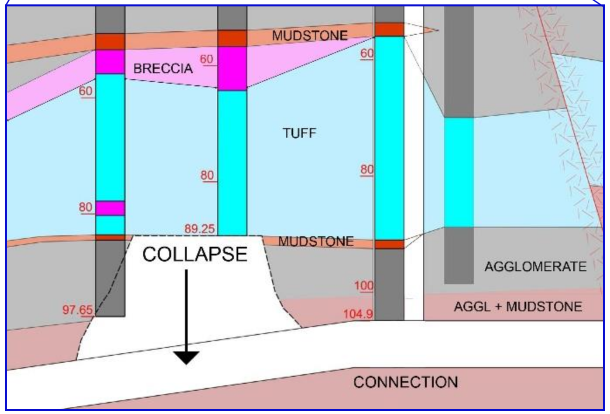


At the end of 2010 a series of **collapses** affected the tunnel.

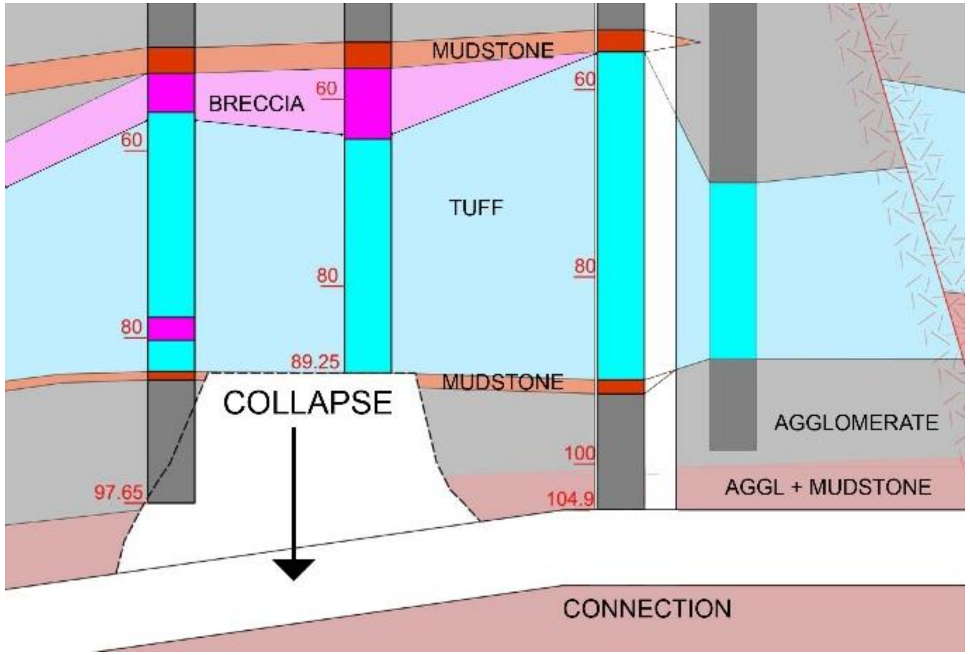
The main collapse was identified near the SS.

The cavity was about 40 m long and about 23 m wide, presenting a sub-horizontal roof set on a stratigraphic contact. The maximum height above the tunnel crown was about 15 m.

The collapse was caused by the progressive failure of rock wedges delimited by stratification of mudstone and breccia layers.



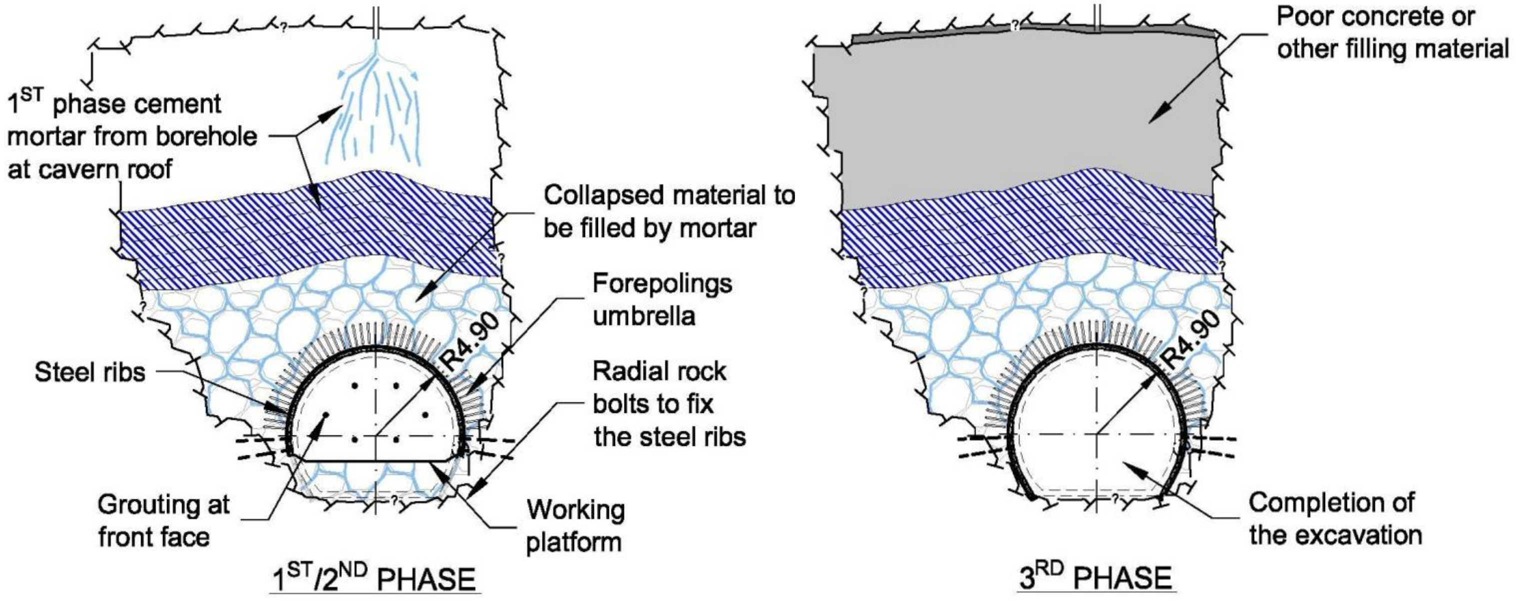
CASE HISTORIES – ESTI HPP (REP. OF PANAMA)



The mudstone from the Estí site did not release any clay particles, nor turned into mud, and did not exhibit significant swelling behavior.

On the contrary, a strong slaking behavior was observed: when subjected to multiple dry/wetting cycles, the original sample turned into chunks.

CASE HISTORIES – ESTI HPP (REP. OF PANAMA)

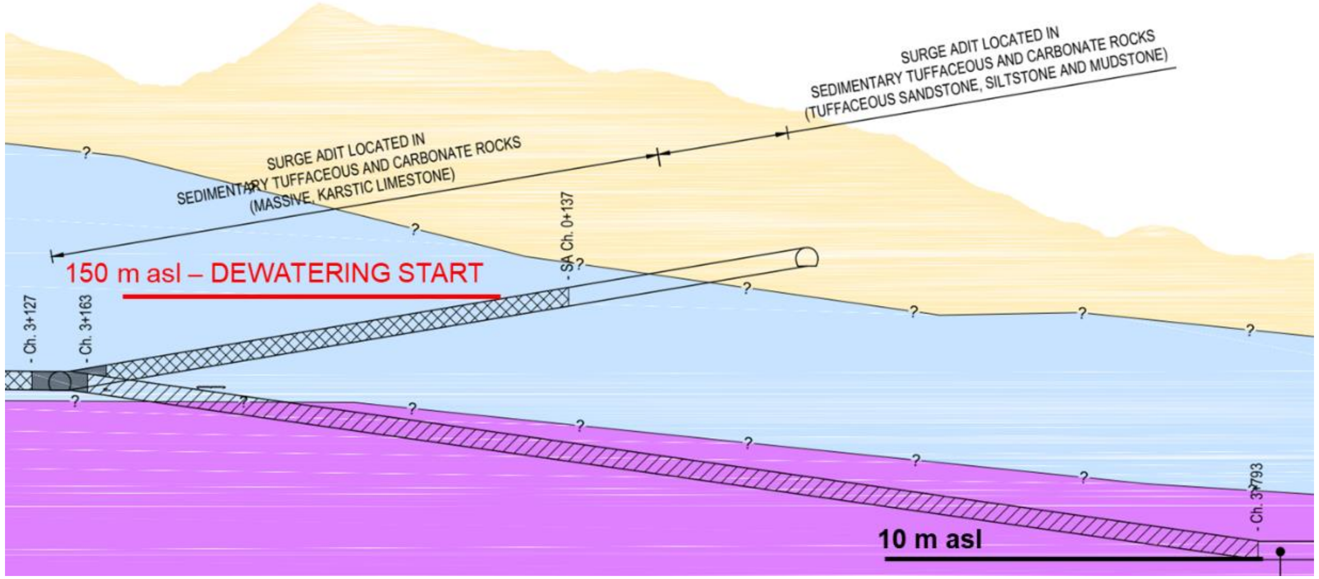


CASE HISTORIES – CHANGUINOLA HPP (REP. OF PANAMA)

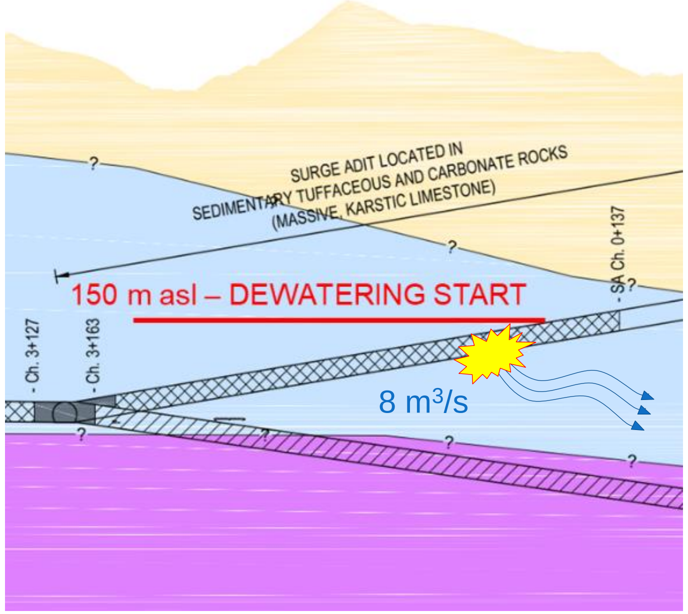
- Changuinola I HPP (213 MW)
- Province of Bocas del Toro (Rep. of Panama)
- 4.1 km-long and 12 m-diameter HRT
- 480 m-long and 12 m-diameter SS
- Excavated with DBM (2008-2010)

The plant operated since 2011, but **leakage** markers were detected in 2015: springs and water outflows were observed at the toe of the slope near the powerhouse.

The amount of leakage had been progressively increasing up to 2017, when dewatering and repairing works became necessary, the assessed water losses being around **10 m³/s**.



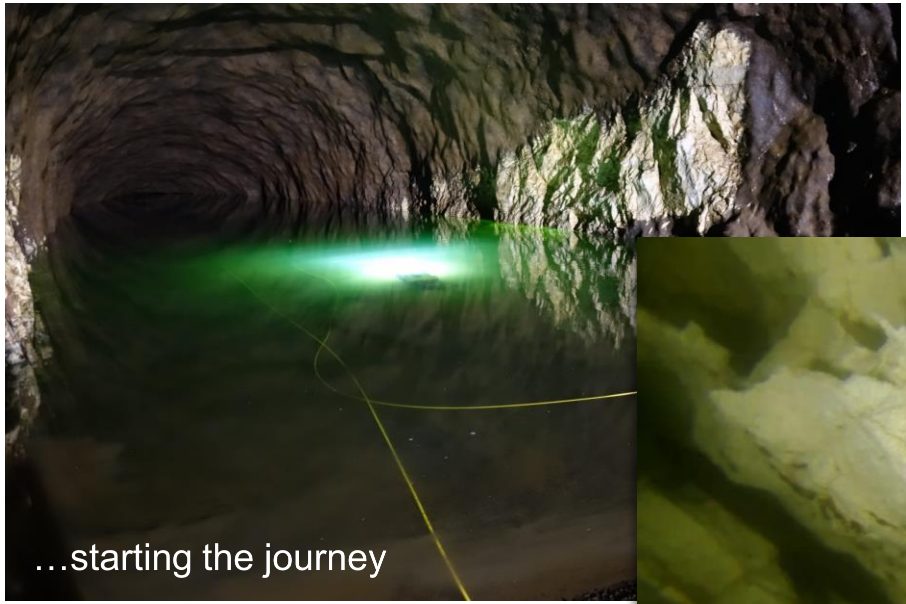
CASE HISTORIES – CHANGUINOLA HPP (REP. OF PANAMA)



Canals at the powerhouse: before dewatering, and after the water level in the Surge Adit had passed the main void during tunnel emptying.

CASE HISTORIES – CHANGUINOLA HPP (REP. OF PANAMA)

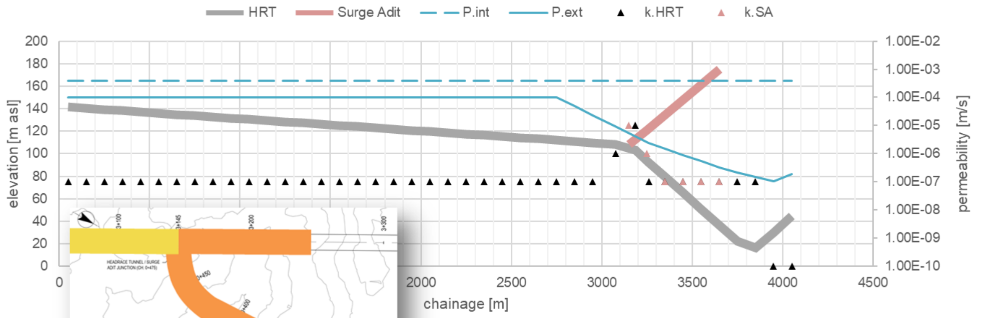
ROV INSPECTION

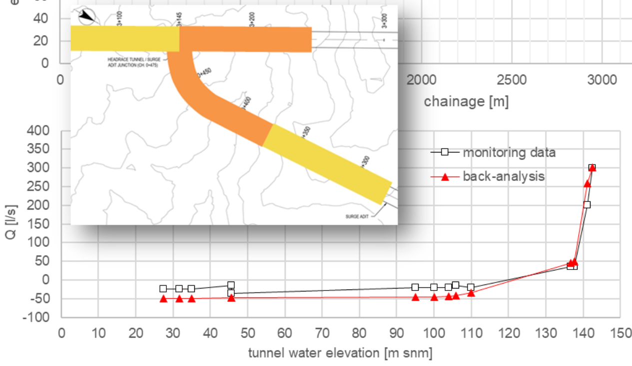

…starting the journey


…sending images

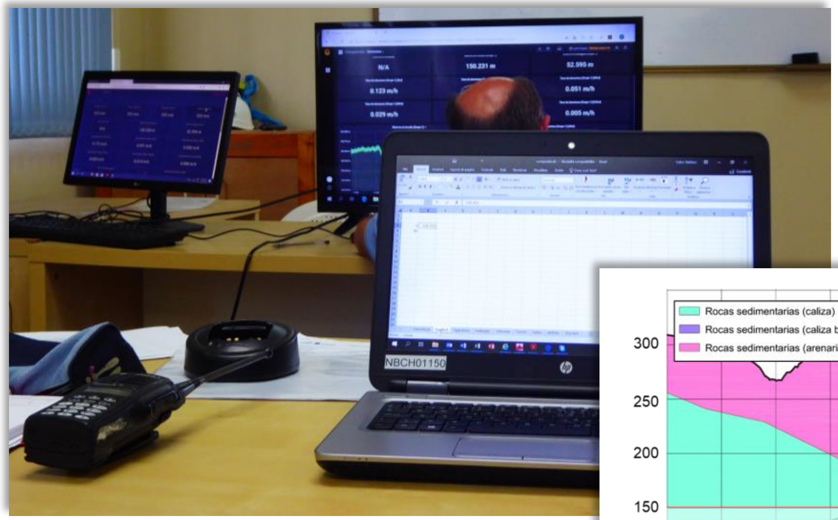

…getting stuck

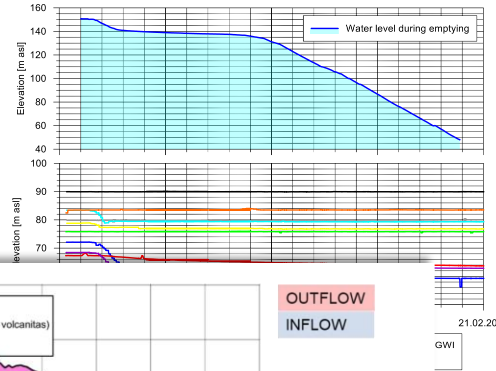
CASE HISTORIES – CHANGUINOLA HPP (REP. OF PANAMA)

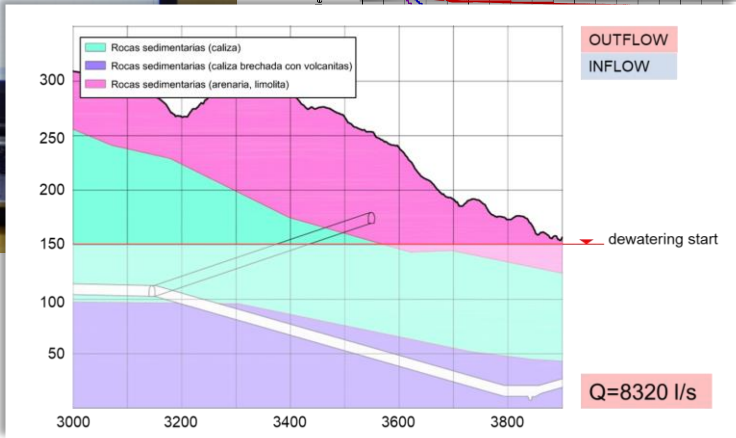




Conductivity range [m/s]	Condition of rock mass discontinuities
< 1E-07	*very tight*
1E-07 - 6E-07	*tight*
6E-07 - 2E-06	*few partly open*
2E-06 - 6E-06	*open*
6E-06 - 1E-05	*many open*
> 1E-05	*open closely spaced, or voids*

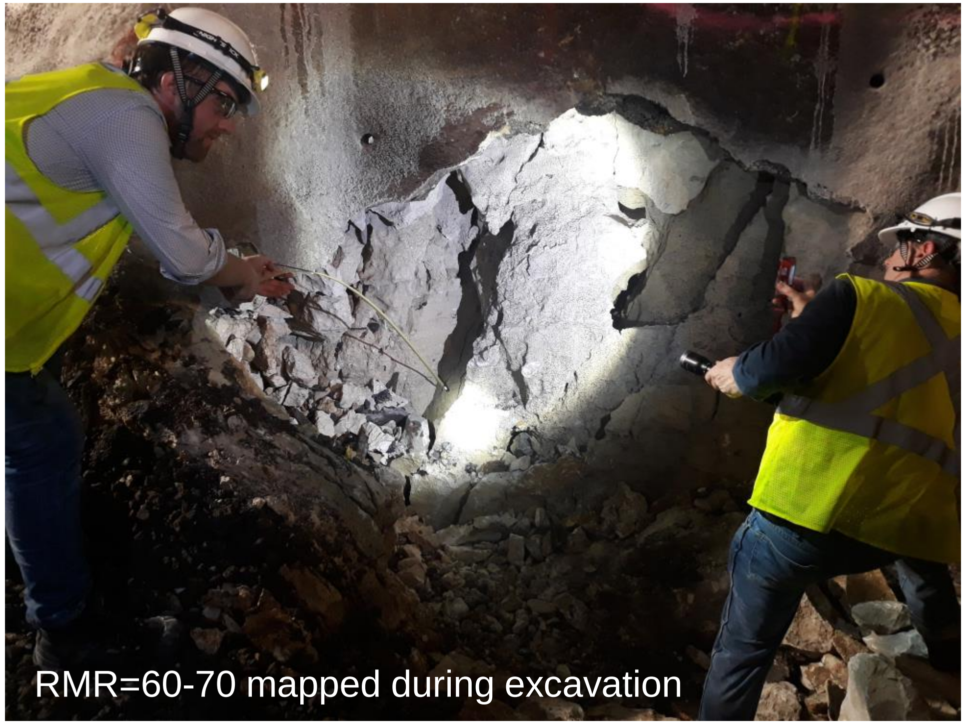




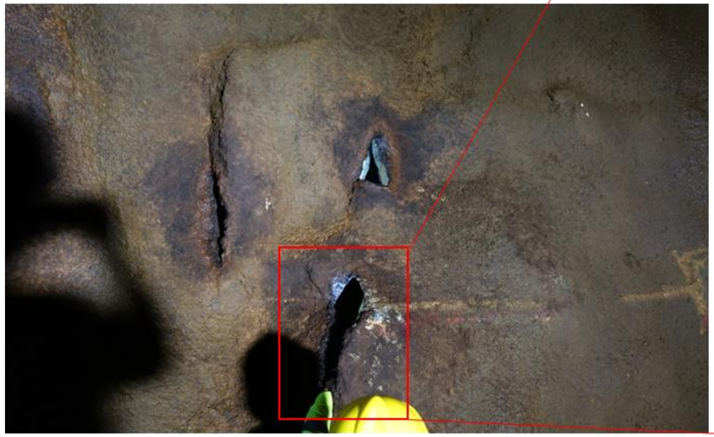


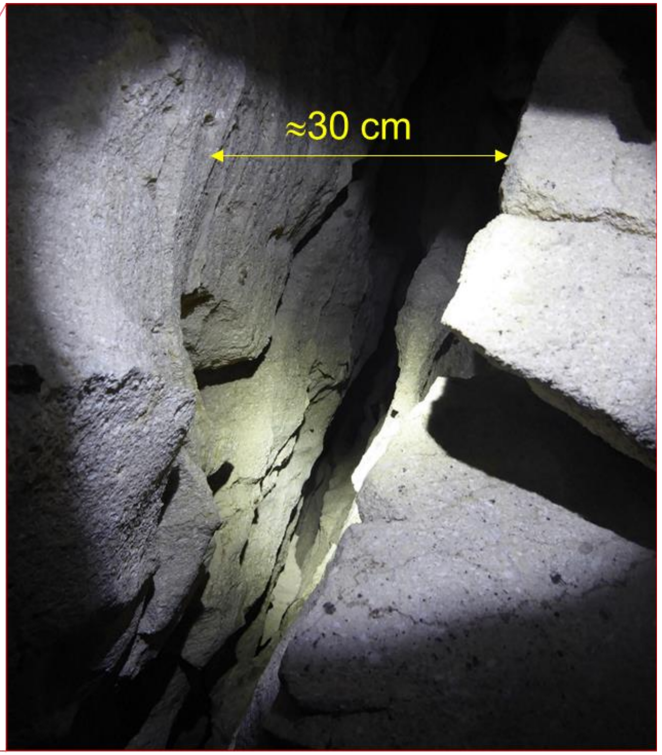
A nonstop monitoring data record and back-analysis during dewatering allowed to anticipate the location of the main leakage source, later confirmed by visual inspection.

CASE HISTORIES – CHANGUINOLA HPP (REP. OF PANAMA)



In few years of operations, the **karst** phenomena developed, generally oriented according to joint sets. The damages were present only in the limestone.



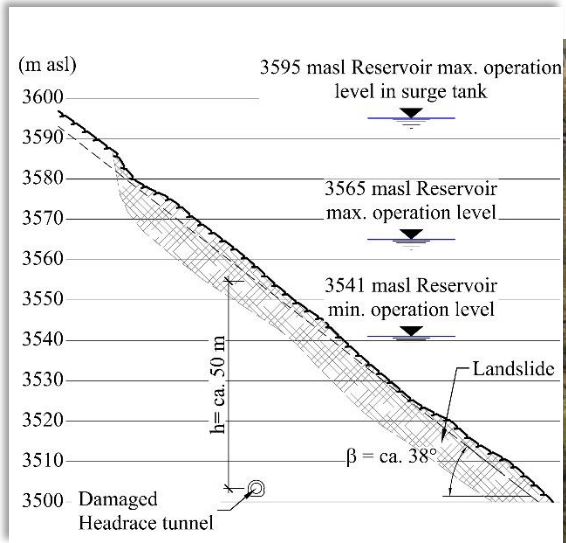


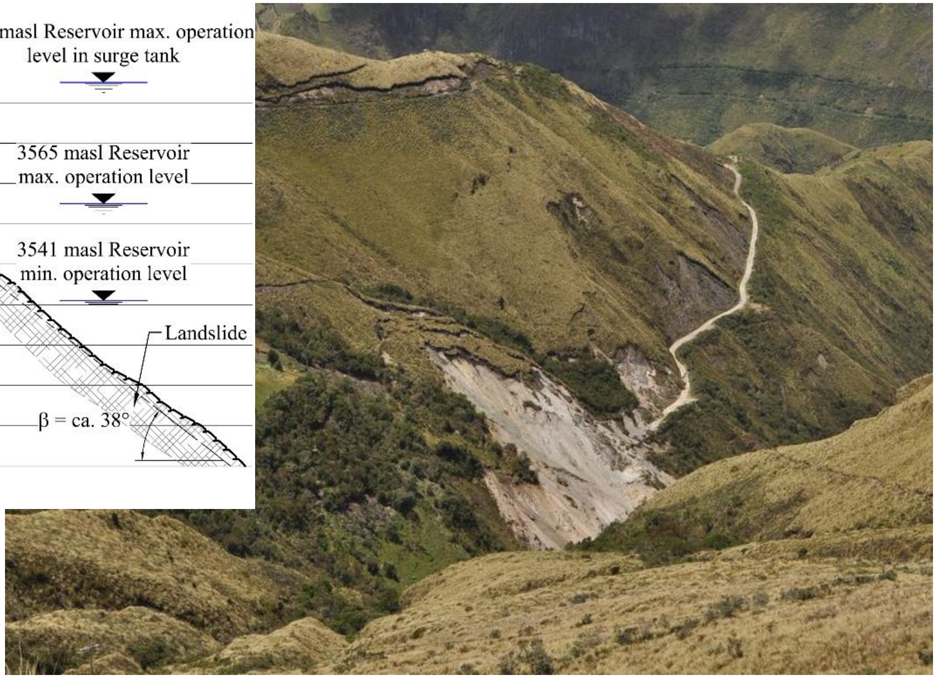
CASE HISTORIES – PISAYAMBO HPP (ECUADOR)

- Pisayambo HPP (73 MW)
- Province of Tungurahua (Ecuador).
- 5'475 m-long and 2.60-m diameter HRT
- Completely concrete lined HRT
- Commissioned by the end of 1977.

After 34 years of normal operation, the plant had to be shut down in 2011: the plant was affected by a landslide of large scale, along about 300 m of the final stretch of the HRT, due to water **leakage**.

The accident occurred in low overburden (≈50 m): the Norwegian Rule application indicates limit conditions. Other factors (tectonic structures, ancient slides) influenced the slope stability.

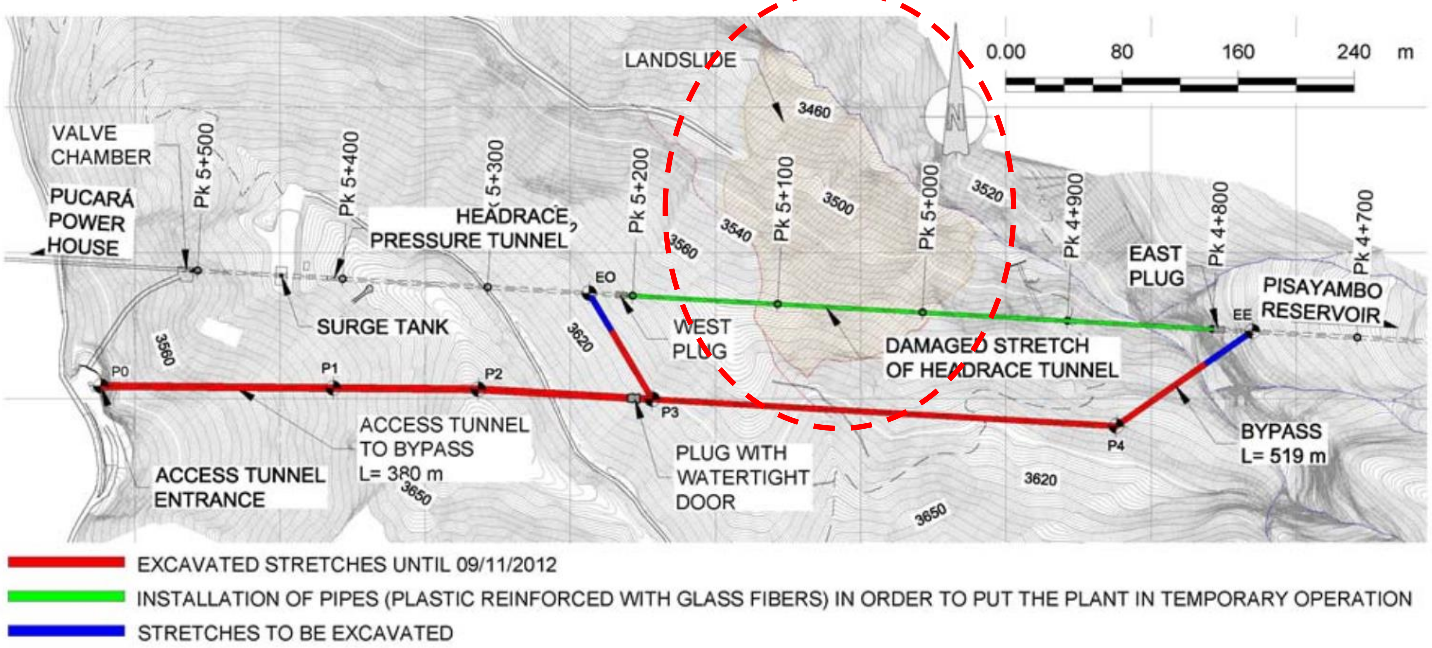


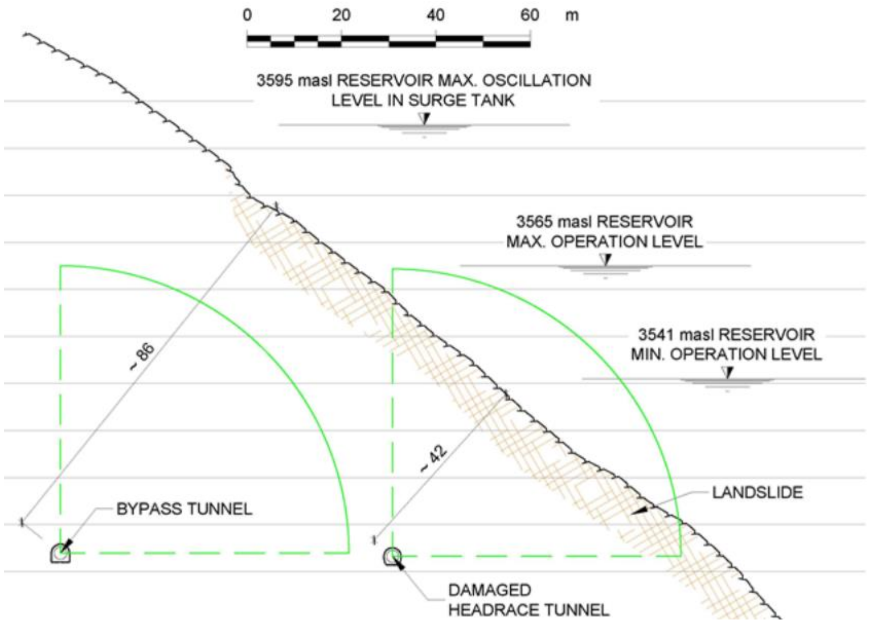


CASE HISTORIES – PISAYAMBO HPP (ECUADOR)

Location and shape of concrete lining cracks along damaged stretches, due to tensile stresses caused by the internal water pressure.

CASE HISTORIES – PISAYAMBO HPP (ECUADOR)





A by-pass of 520 m was excavated, moving the tunnel alignment ≈70 m inside the mountain, to increase the confinement (=overburden).

CONCLUSIONS

- During construction, hydraulic tunnels are equivalent to other underground tunnels, but their operation phase is something peculiar.
- Large quantities of water are brought in the rock mass: if sensitive to water, the rock mass could suffer from degradation. The consequences could be disastrous: collapses, uncontrolled leakages, environmental damages.
- These scenarios must be anticipated, independently from the rock mass classification method assumed to define ground behaviors and support during the excavation.
- A proper assessment is needed since the early design phase, although it is worth remembering that a good pressure tunnel design is completed only at the end of excavation, when actual conditions are defined through tunnel mapping and monitoring data collection.

The judgment of the *"engineer"* in a wide sense
and not only that of the *"specialist in computing"*
should be adequately taken into account.
(G. Lombardi, 2011)

Thanks for your kind attention.