Rock mass characterization for engineering design

Compilation of case studies of applied geophysics for tunnels

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How rock mass characterisation and geophysical investigation can help a geotechnical engineer?

Serre de la voûte (Italie)

Characterisation and analysis of an existing tunnel for developing an enlargement project ensuring stability of the crown.

Rock physics methods

Surface geophysics

10-100 m scale

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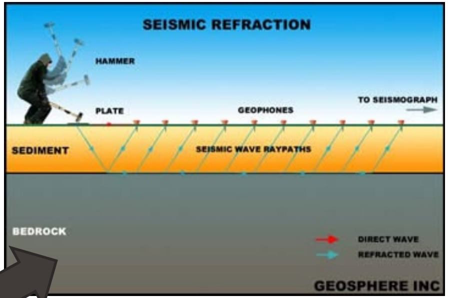
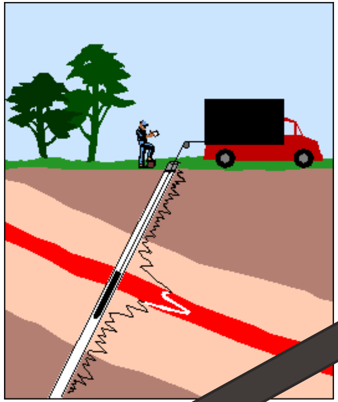


Borehole geophysics

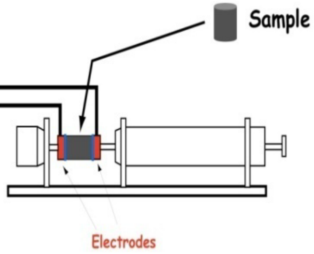
m scale



Petro-physics

cm scale

Elec impedanc e, Vp, Vs

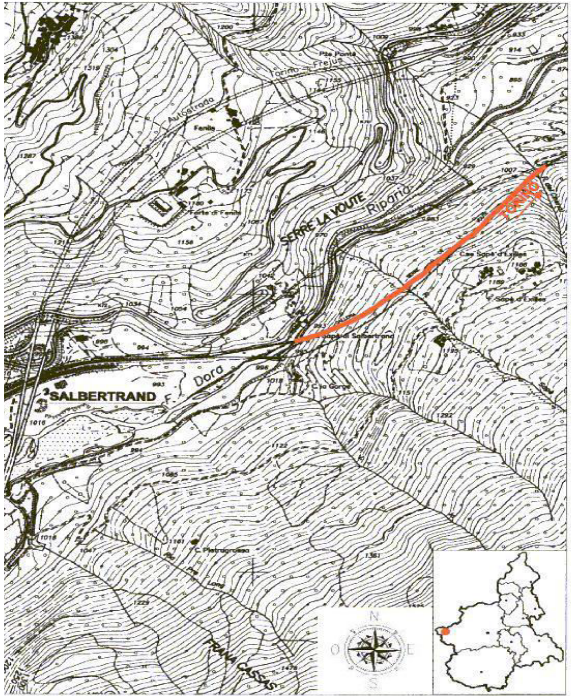


Structures / Tunnels

After Violay & Sandrone - Géotechnique Suisse Kolloquium 24. September 2018

Case study: Serre de la Voûte tunnel

- Constructed on the second half of the 19th century
- Length: ~1100 m
- Maximum depth: 1135 m
- Geological formation: Calcschist



Deep sliding movement

- Evaluate the influence of this phenomenon on the behaviour of the tunnel
- Analysis of the deformations along the tunnel

Tunnel refurbishment design

Adapt the refurbishment design as well as possible to the existing structure

Need for:

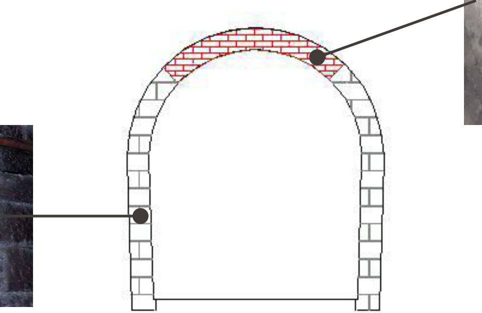
- Detailed characterisation of the tunnel (construction and operation data are necessary)
- Improving the available information by means of further investigation and analysis (characterisation and modelling)
- Designing an appropriate refurbishment, trying to solve two or more problems within the same refurbishment project, e.g. renewal of a damaged lining and the enlargement of a tunnel profile

Visual inspection

Horseshoe shaped tunnel

Crown: small cement bricks

Side walls: rock blocs masonry

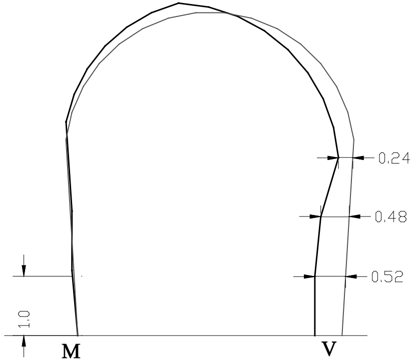


Local hammering for checking the deterioration degree of the rock blocs:

Sclerometer results	Zone (cm from the surface) ↓ +	Material
No response	0.5 -1.0	Dust, result of several years of operation
9-13	2	Highly weathered material
26-39	2.5 - 3	Sound material

Visual inspection

- The majority of the masonry joints is highly weathered
- Dripping points, mainly located on the tunnel crown
- Local deformation of the side wall on a 30 m long zone close to the North portal
- Convergences monitoring during 7 years → no remarkable changes → local event



Tunnel enlargement by lowering the invert may affect the equilibrium conditions!

Geophysical investigation

The deformed zone in the side wall has been tested with Ground Probing Radar (G.P.R.) and Miniature Seismic Reflection (M.S.R.)

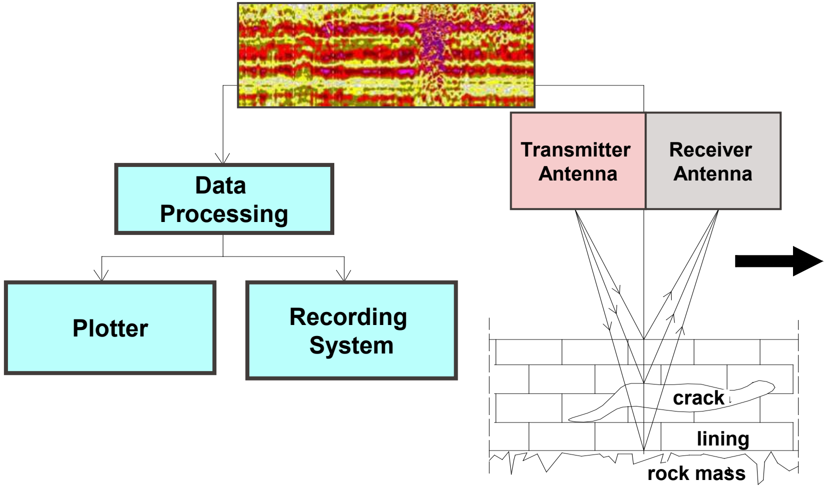
G.P.R.

- 3 horizontal profiles (about 30 m long and with a distance of about 0.5 m one from another)
- 6 vertical profiles (about 2 m long with a distance of about 2 m one from another)
- 2 antennas 900 and 500 Hz (different depth and detail scale)

M.S.R.

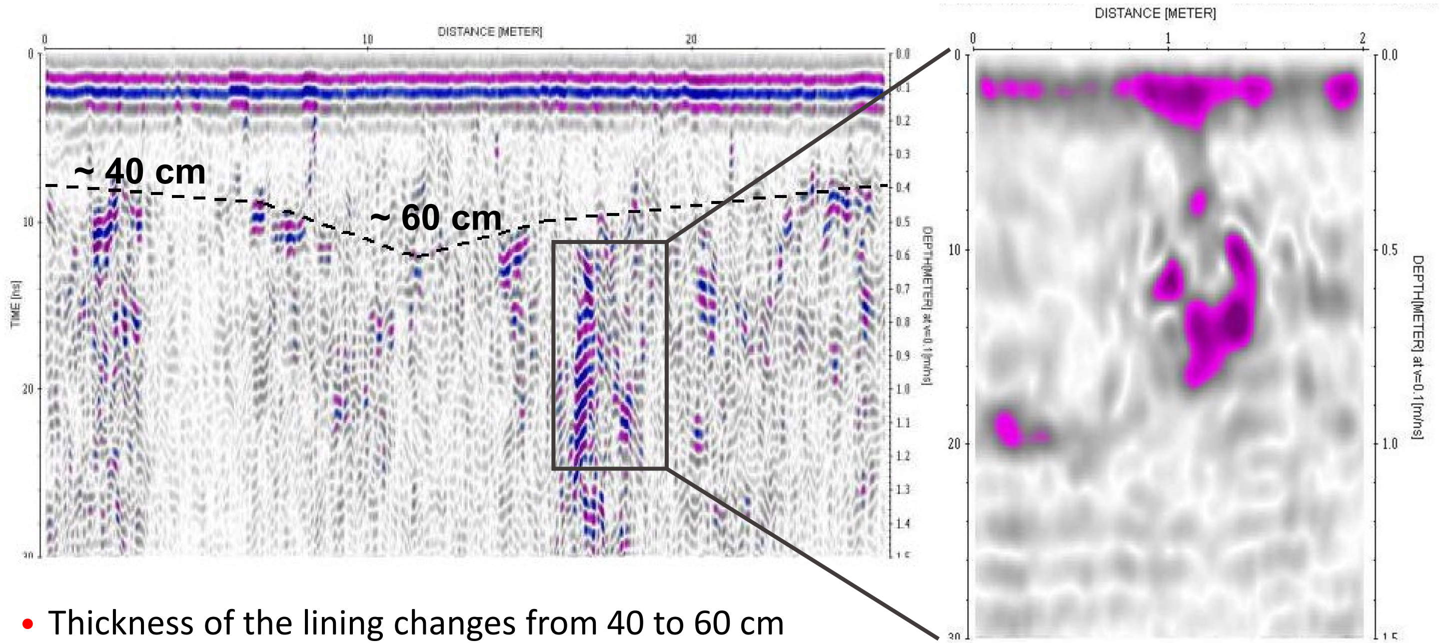
- 2 horizontal profiles (about 30 m long, respectively at 1 and 2 m from the side wall foot)

GPR Method



- GPR system detects reflections of electromagnetic radiation emitted by a portable radar transmitter (antenna)
- The antenna is moved across the surface and a transit time curve is generated and plotted thereby locating defects or irregularities
- The reflection comes from objects, defects and layers which alter the speed of transmission of the radar signal

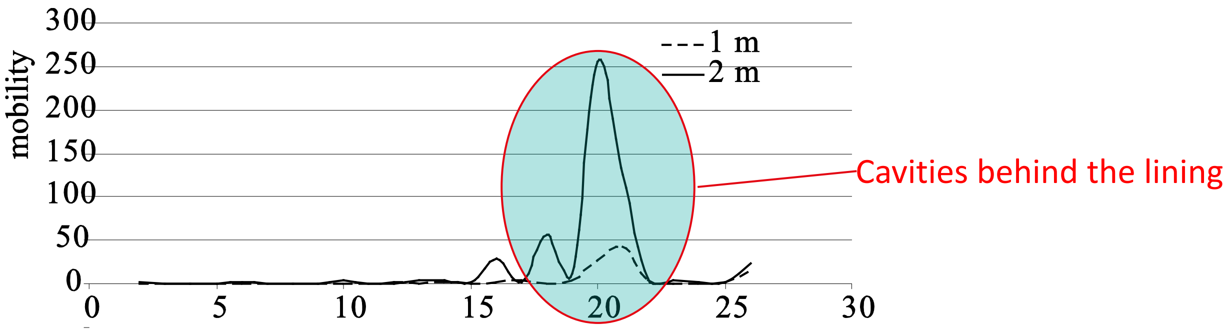
GPR Results



- Thickness of the lining changes from 40 to 60 cm
- Masonry blocks characterised by a quite homogeneous rock and the ground mass behind which, on the opposite, results very heterogeneous
- Cavities or backfilling material with bad quality behind the lining in the deformed zone

MSR Results

- The propagation of the elastic waves in a medium depends on the physical properties of the material
- The *Mobility coefficient* is strictly connected with the stiffness of the material:



➔ Side wall deformation was probably due to water infiltration that also contributed to washing out the backfilling material

Lab Tests

- Boreholes are necessary for validating the non destructive investigation results
- Test on cores allows the characterisation of materials for numerical modelling

2 boreholes in the deformed side wall and 1 in the other one:

Masonry ~ 40-60 cm

Backfilling ~ 20 cm

Rock → lower quality than masonry blocs

Brazilian tests → σ_t = 3-5 MPa

UCS tests → σ_c = 31-49 MPa (! schistosity)

UCS with axial and circumferential strains

→ E = 28.5 GPa; ν = 0.2

Lab Tests Results

- Several discontinuities behind the lining
- Compared to the expected quality of the rock mass the deformed zone is characterised by a poorer quality of the materials
- Though the tunnel convergences seem to be stabilised, the connection between the lining and the rock mass is not ensured and lowering the invert may cause side wall collapse

Local reinforcement of the lining, improving the interface between excavated rock mass and lining and lowering the side wall foundations

Numerical Modelling

Main objectives:

- Identification of the most critical working steps during tunnel enlargement
- Verification of the chosen solutions for tunnel reinforcement and support

Modelling:

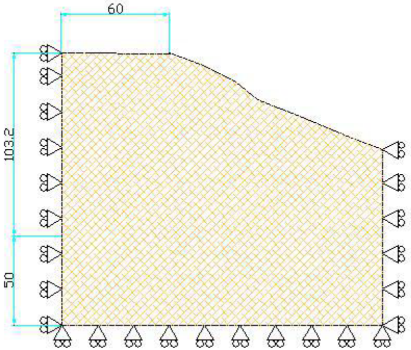
- FLAC 2D (Itasca Consulting Group)
- Mechanical parameters for rock mass and lining determined by in situ and laboratory investigations

Main results:

- Yielded zones, mainly concentrated on the lower part of the side walls as well at the interface between the masonry blocks and the crown
- Identification of the zones where it was necessary to improve the lining stability by reinforcing of the existing structure before lowering the invert with a road header

Numerical Modelling

Both the rock mass and the lining behave as elasto-plastic media according to the Mohr-Coulomb criterion.



Initial - Good rock

E = 8,5·106 kPa
ν = 0,30
φ = 30°
c = 250 kPa
γ = 2,6 t/m3

Tunnel excavation - Bad rock

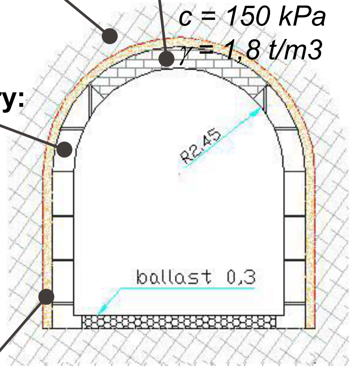
E = 3,5·106 kPa
ν = 0,28
φ = 28°
c = 200 kPa
γ = 2,6 t/m3

Tunnel lining – Brick:

E = 1,2·106 kPa
ν = 0,14
φ = 29°
c = 150 kPa
γ = 1,8 t/m3

Tunnel lining – Masonry:

E = 1,05·107 kPa
ν = 0,28
φ = 37°
c = 280 kPa
γ = 2,6 t/m3

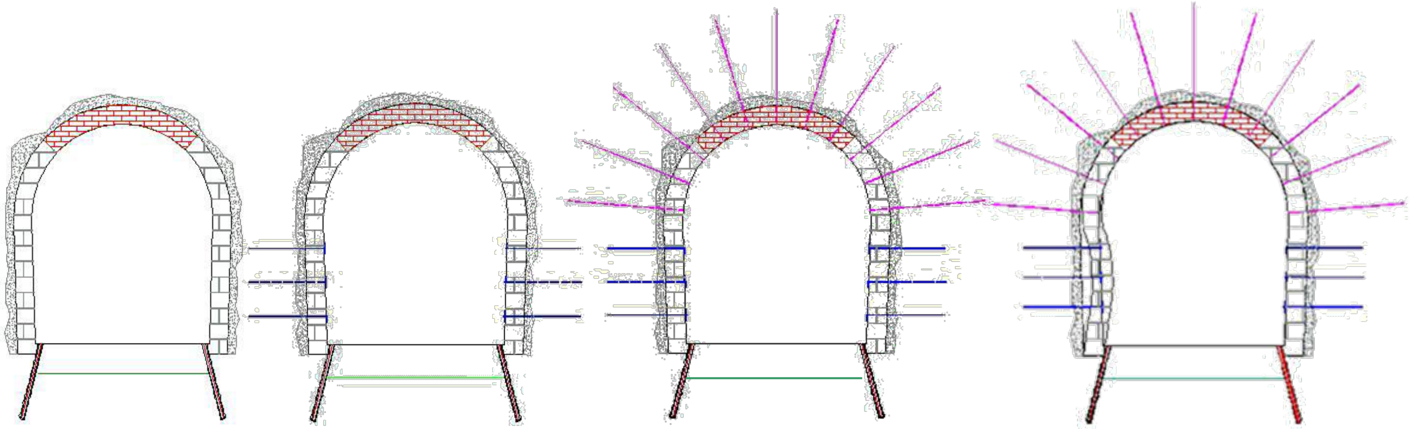


Interface rock – lining:

E = 1,0·106 kPa
ν = 0,12
φ = 24°
c = 50 kPa
γ = 2,0 t/m3

The lining was represented by cohesion and friction angle of an equivalent material which combined together blocs and mortar joints characteristics.

Support solutions



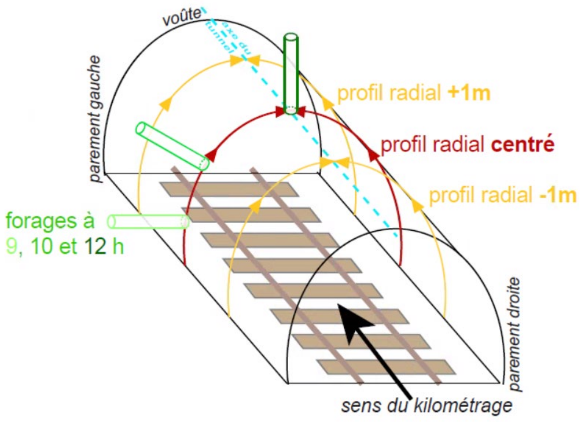
- Improve the wall lining foundation: injected micro-piles
- Improve the coupling between rock mass and lining: local injections of the cavities behind the lining
- Improve the stability of the lining: systematic bolting of the crown and the side walls / local repair (rebuild) in the deformed zone
- Verify the effectiveness of reinforcements: monitoring evolution of cracks, fissures and convergences

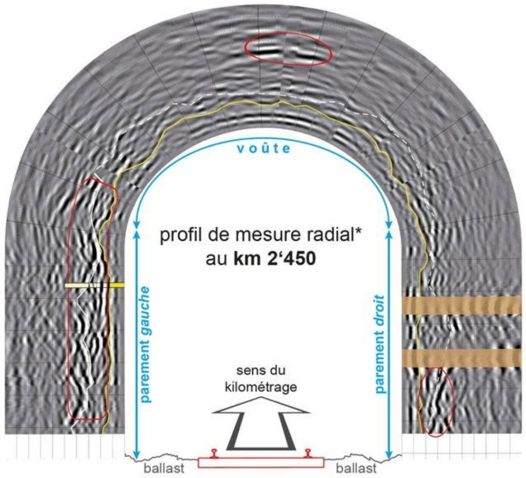
Conclusion

- A specific procedure has been adopted before proceeding with the tunnel refurbishment:
  - *Tunnel general conditions evaluation* → Visual inspection and geophysical methods
  - *Verification and mechanical characterisation of the tunnel* → Convergence analysis, Geophysical investigation and Laboratory tests
  - *Analysis and design* → Numerical simulation of the enlargement intervention
- **In situ geophysical and laboratory investigations together with numerical simulation results allowed choosing appropriate reinforcement and refurbishment methods before lowering tunnel invert**
- Refurbishment works were carried out with good results in term of performances and without major problems

Use of Georadar in tunnel

Case study: Ligne CFF NE-CF



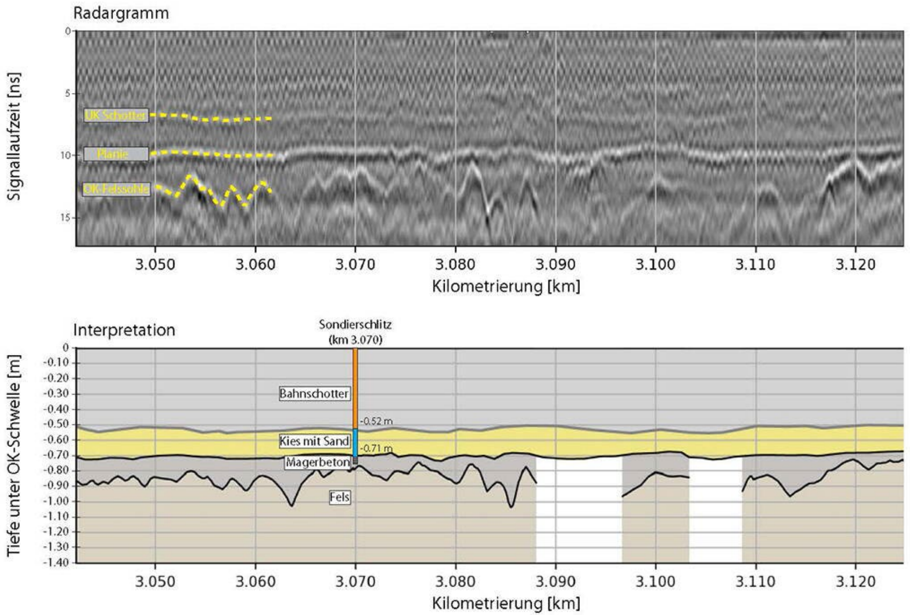


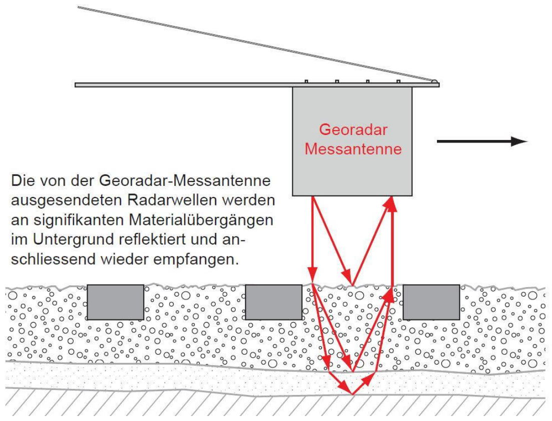
Upgrading and maintenance of railway tracks and structures, in particular historic tunnels of varying lengths, all over 160 years old.

Georadar investigation of natural stone masonry linings was done in order to have a general view on the geometry of the lining and the quality of the lining / rock mass interface

Geophysical measurements were coupled with local investigation / core drilling and lab tests.

Case study: Wipkingertunnel





- Double-track tunnel, 1.3 km long
- Night closure of about four hours
- Locate the presence of a concrete invert under the track ballast
- Calibration by sampling drill holes

Case study: Simplontunnel

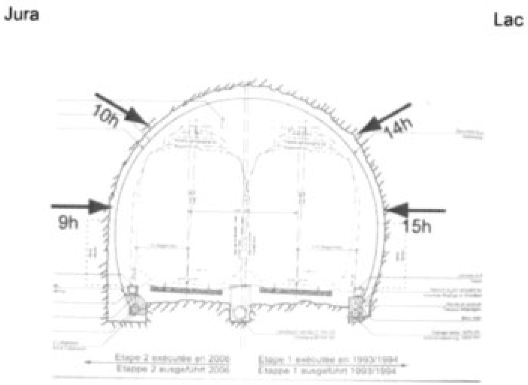
Results:

Based on the analysis, various locations with the same problem were identified

- Single-track tunnel, 20 km long
- Short closures
- Locate the presence of holes / cavities under the track without ballast removal
- Calibration by sampling drill holes

Case study: Vingelztunnel

- Caracterisation of defects in definitive lining (insufficient thickness of the concrete and cavities behind the lining)



Quelle: Bericht GEOTEST *Auscultation du tunnel de Vigneules, 2011*

Results: Based on the analysis, various locations with insufficient concrete thickness or cavities at the rear of the cladding were identified

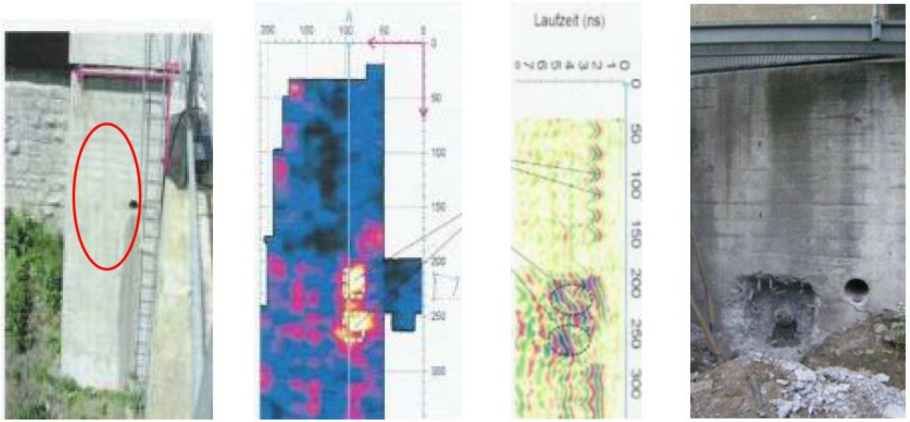
Logistics: ~2 km of measurements (incl. local drilling) during one night (< 3 hours per track)

Other applications: Detection of existing anchors

- Identifying existing anchors behind concrete wall.
- Avoiding dismantling of the entire structure

Verankerte Bauwerke
Überwachung, Lokalisierung

Rohrbachbrücke Wassen



vermutete ein-betonierte Anker | Georadar-aufnahme | Georadar-auswertung | frei gespitzter Ankerkopf

Quelle: *EBT-Grundmodul IB, Stutzbauwerke* - Stand Herbst 2018

Tunnel du Col des Roches

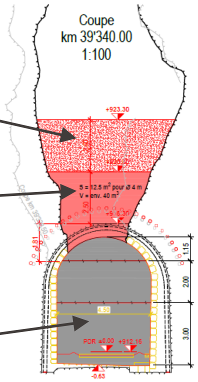
Case Study: Karst instability

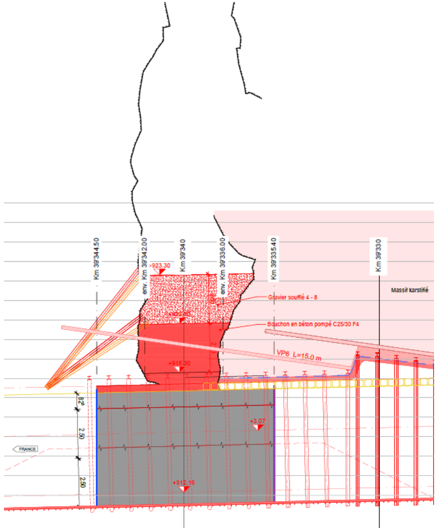
- During refurbishment works a karst was encountered, according to the old tunnels profiles this should have been on the opposite side of the tunnel!!

Gravel filling permanent

Concrete filling permanent

Concrete filling temporary





Ligerztunnel

Use of several geophisical method to better assess the geological / hydrogeological risks for a new tunnel

Projet STEP 11: doublement des capacités Ligerz-Twann (tunnel de Ligerz)

Risques hydrogéologiques: investigations géophysiques

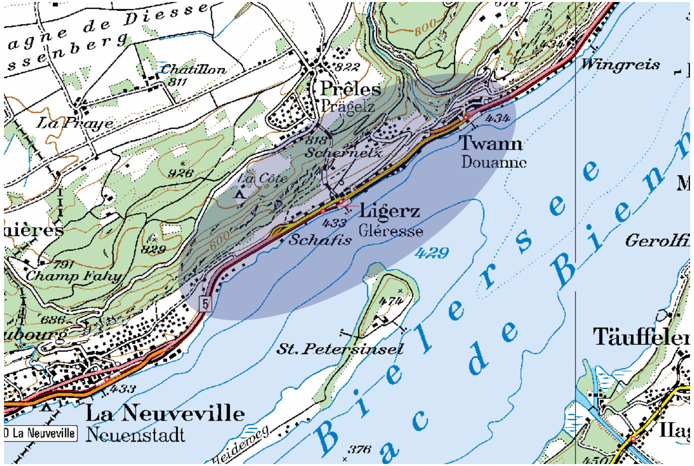
CFF, I-PJ-RWT-PJM-PBA, Olivier Saugy, Berne, 11.09.2014

1.1 Etude préliminaire

Ligne DfA 210: La Neuveville – Twann (env. km 91.7 à km 96.8)

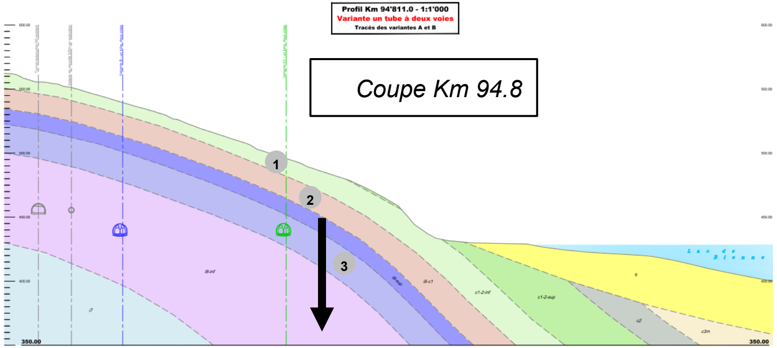
Tronçon: *Unique tronçon à simple voie de la ligne du pied du Jura (en raison de l'abandon du projet Rail 2000 en 1992)*

Objectif: doubler les capacités (=2ème voie)



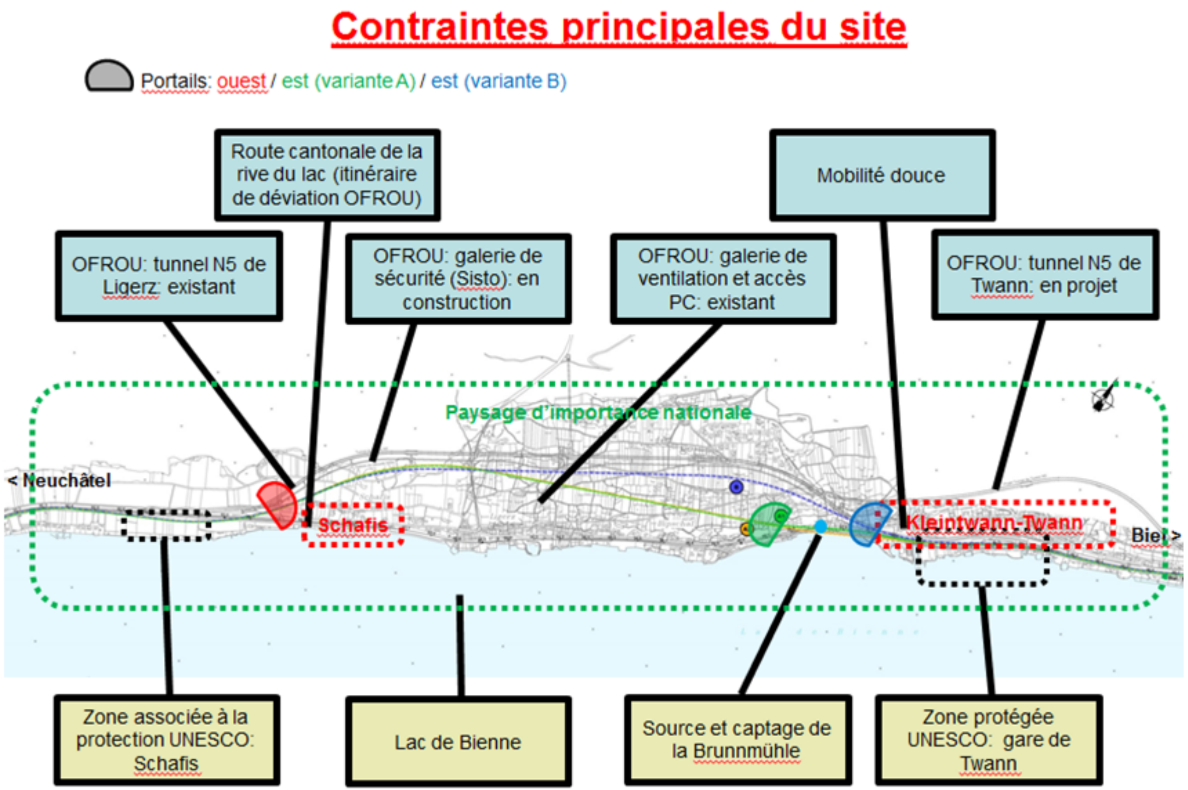
1.2 Variantes étudiées

- → 2 tracés (A: +/-idem projet 1992; B: récupération du portail N5)
- → A1: sortie sur la rive; A2 sortie sur le lac (remblayage du lac)



1. *Calcaires (pas très durs); nappes fissurales localisées*
2. *Marno-calcaire (Golberg +/- étanche)*
3. *Calcaires assez durs; karsts et nappe plus importante*

2. Conditions cadre
2.1 Rappel des contraintes



2.2 Brunnmühle: caractéristiques

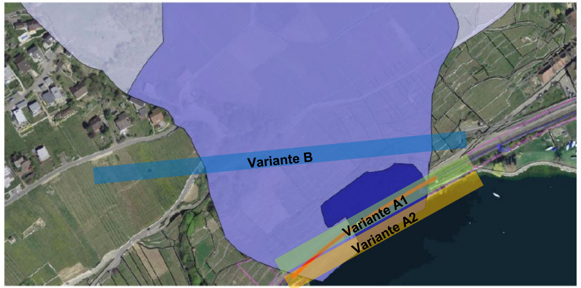
- → Source d'importance régionale exploitée par l'association TLN (3 communes) pour la distribution d'eau potable
- → Débit minimal de 0.1 m3/s, débit moyen approche 0.5 m3/s et débit max. jusqu'à >1 m3/s
- → Bassin versant: env. 60 km2 (depuis le Chasseral)
- → Captage actuel: sous le RC ! (voie CFF actuelle et RC en S1 !)
- → Captage futur: 2 puits inclinés de captage -> projet de construction d'une nouvelle station de pompage et traitement de l'eau

3. Enjeux et risques relatifs aux souterraines

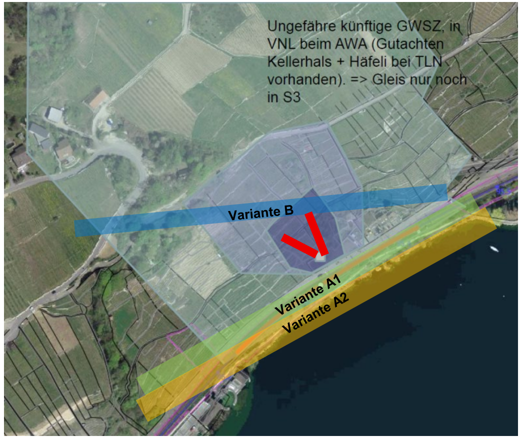
1. **Construction en zone S** (S3, S2 et S1); **choix de la variante de tracé**
2. **Faisabilité technique de certains ouvrages**
3. **Risques relatifs aux eaux souterraines**
   - Risque d'accident de chantier (venue d'eau, effondrement, blocage du tunnelier)
   - Risque de drainage du massif et de diminution du débit de la source
   - Risque de pollution des eaux souterraines

3.2 Zones de protection (Construction en zones S)

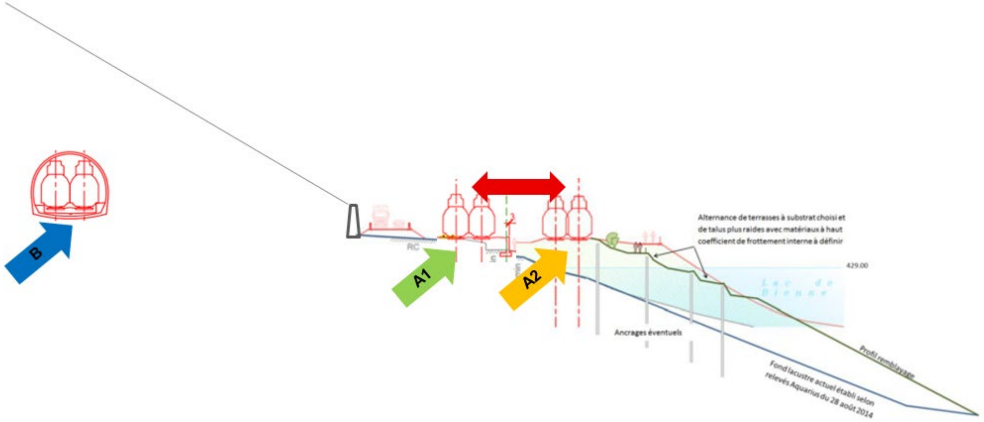
Heutige GWSZ



Zones actuelles



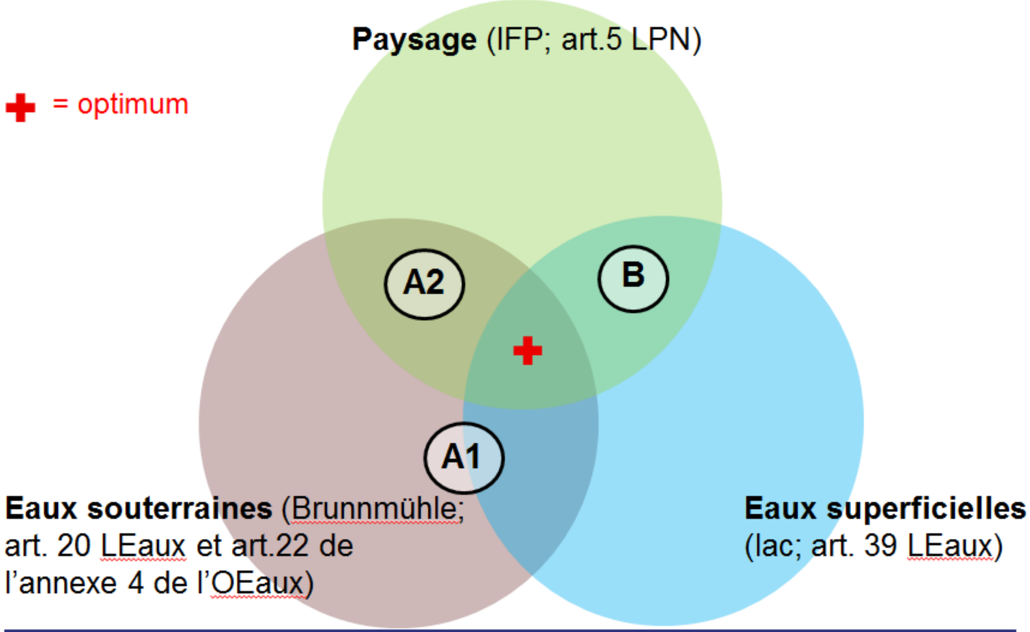
Zones selon projet «nouveau captage»



3.3 Choix de la variante de tracé

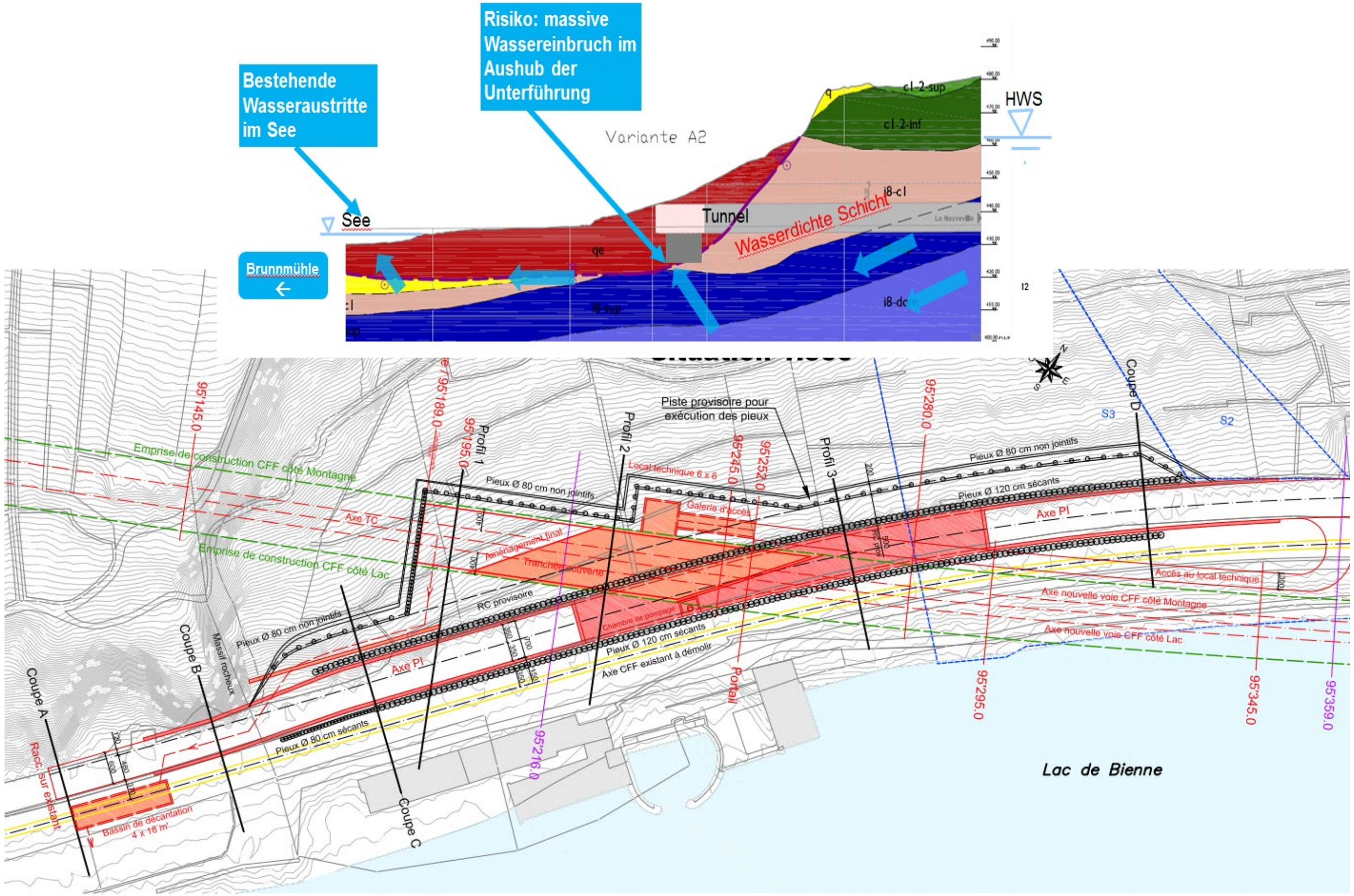
Aspects légaux et réglementaires:

Loi fédérale sur la protection de la nature et du paysage (LPN)



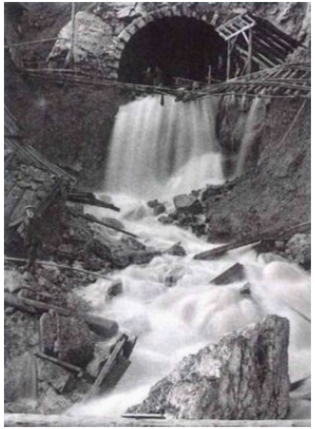
Loi fédérale sur la protection des eaux (LEaux)

3.4 Faisabilité du PI routier du portail est (variante A)

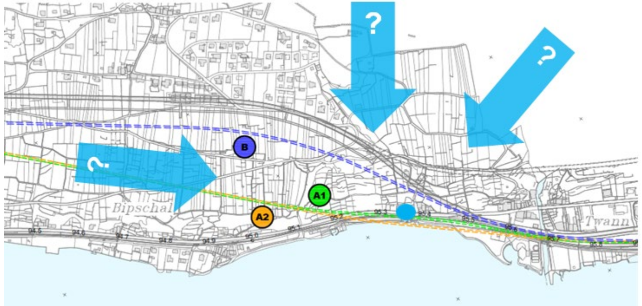


3.5 Risques relatifs aux eaux souterraines

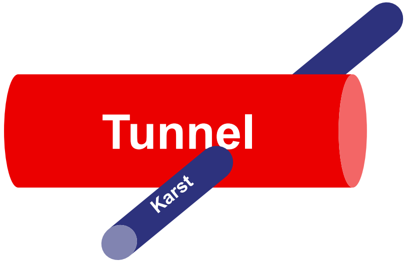
Risques	Chantier	Exploitation
Accident de chantier: - Grosse venue d'eau (exemple du tunnel du Mont d'Or) - Effondrement de radier (Tunnel Vue des Alpes) - Blocage d'un tunnelier	X	
Pollution des eaux souterraines: - turbidité, hydrocarbures, autres polluants	X	X
Drainage du massif et assèchement de source: - Une galerie de sondage située à l'est de la Brunnmühle a déjà eu un impact significatif sur certaines sources	X	X



Il y a un grand potentiel pour la formation de Karsts; mais comment l'eau arrive-t-elle à la source ?



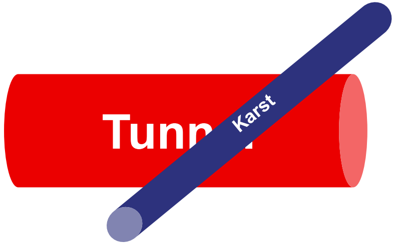
3.6 Situations possibles: karst de petite section



Gestion venue d'eau

Débit issu d'un conduit recoupé par la galerie de sécurité (recoupement admis à 440 m)								
	Diamètre conduit (L=100 m)							
Charge	0.2 m	0.4 m	0.6 m	0.8 m	1 m	1.5 m	2 m	Q amont
498.35	64.9	406	1166	2407	4134	10146	10760	11030
490.95	60.6	380	1095	2273	3941	8655	8852	8970
479.94	53.7	338	983	2081	3515	4355	4287	4425
478.7	52.9	333	928	2024	3136	3482	3503	3648
477	51.5	317	894	1438	1572	1630	1628	1770
470.14	45.8	265	463	537	545	544	538	685
460.14	35.5	152	226	235	235	231	225	360
450	24	95	112	112	111	104	98	242
441.7	6.9	5	2	0	0	0	0	124
	+ 10 L/s si 435m	+ 55 L/s si 435m	+ 60 L/s si 435m	+ 65 L/s si 435m	+ 70 L/s si 435m	+ 70 L/s si 435m	+ 60 L/s si 435m	

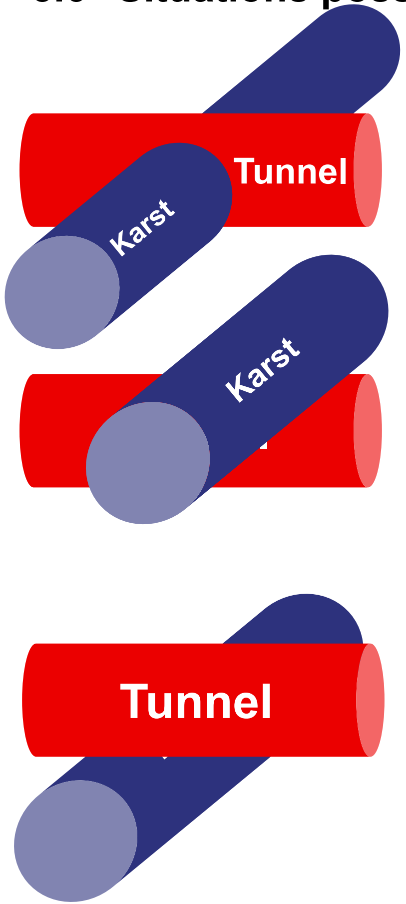
Tableau 3. Débit probable en cas de recoupement d'un conduit karstique en fonction du diamètre du conduit et de la charge hydraulique du système au moment du recoupement.



Avec de la chance, rien ne se passe !

Risque de pollution du tunnel → karst

3.6 Situations possibles: karst de grande section



Accident majeur.
Blocage du tunnelier possible (fluage de matériaux argileux de remplissage)

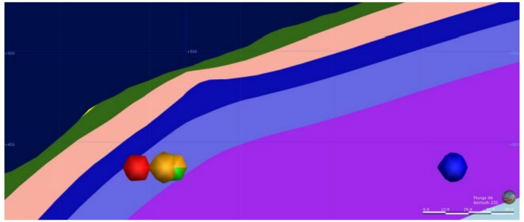
Probablement de grosses venues d'eau vont apparaître lors de la décompression du massif (et lors du percement des clous)

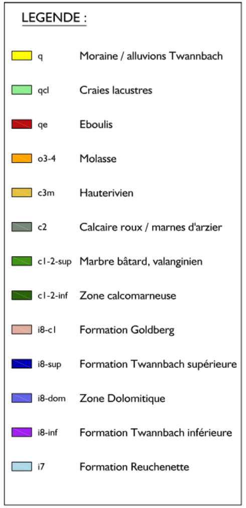
Risque d'effondrement du radier du tunnel

4. Modélisation 3D

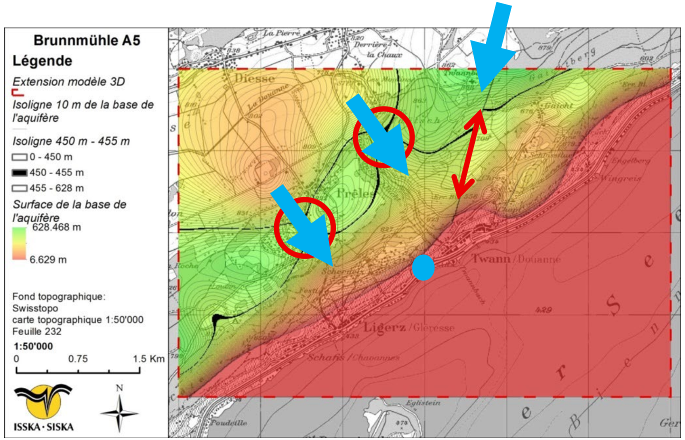
Beaucoup de données sont disponibles (sondages, levés géologiques du tunnel routier):

1. Modélisation «locale» (zone des tracés du tunnel), avec informations détaillées sur les différentes couches géologiques:
   - ➢ *Pronostic géologique pour le tunnel*





2. Modélisation «régionale» (>bassin versant de la Brunnmühle), avec principales unités géologiques
   - ➢ *Détermination de la base étanche (couche d'Effingen) des horizons aquifères → 2 seuils mis en évidence + une grosse fracture à l'est*



5. Relevés de terrains et des venues d’eau, sondages

1. **Levés géologiques de surface** :

- *Zones de fractures observables en surface (reporté sur carte): 2 familles de fractures*

2. **Campagne de relevé des zones de venues d’eau** dans les chambres des drains latéraux du tunnel routier (NB: pression d’eau dans le massif parfois >30m):

- Zones avec venues d’eau dans le tunnel routier (reporté sur carte)

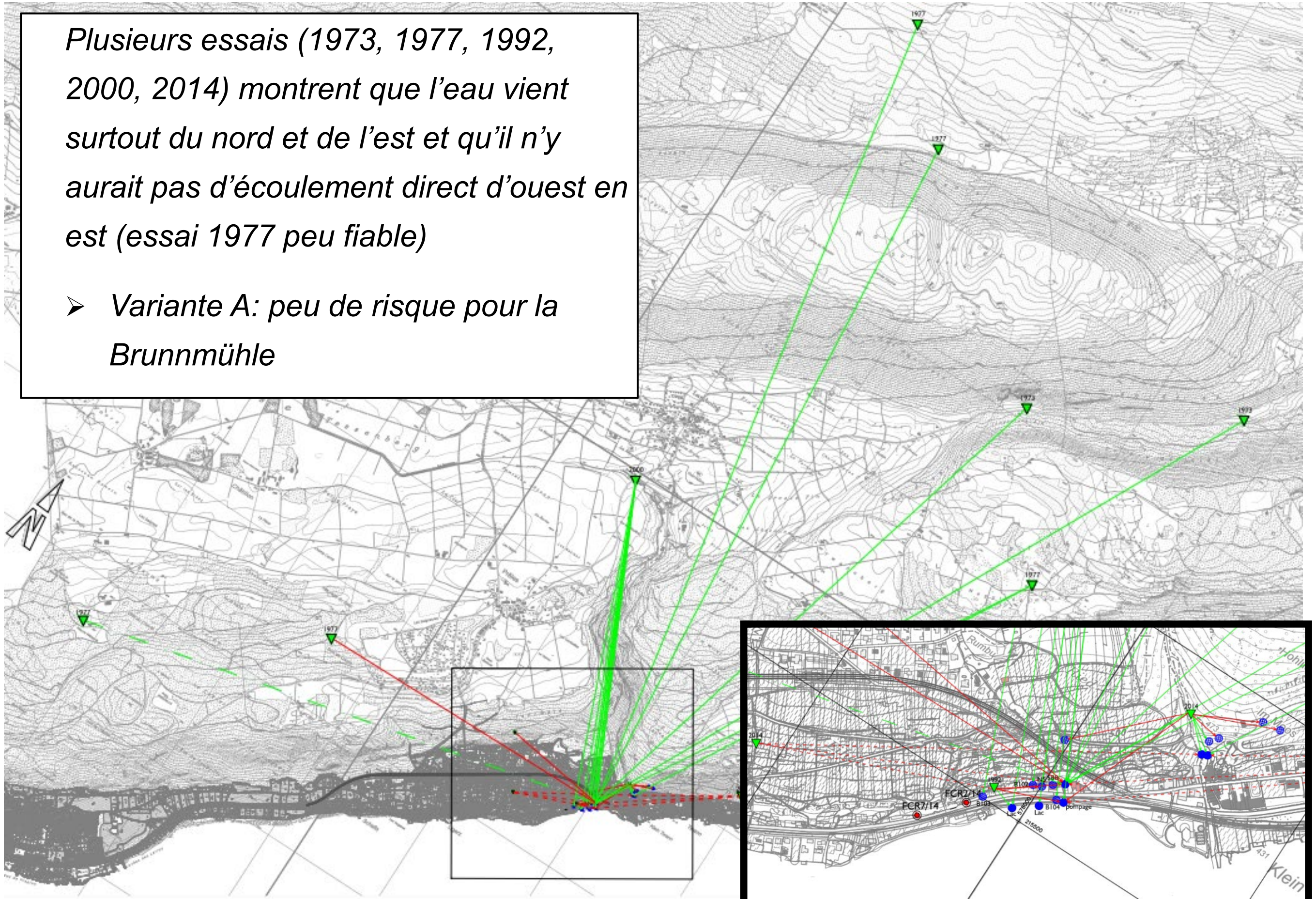
3. **Sondages carottés** (2) dans la zone du portail est de la variante A

- *Extension du Goldberg (couche étanche nécessaire pour construire le PI de la variante A)*
- *Estimation du débit attendu dans la fouille du PI (essai de pompage)*
- *Evaluation de la possibilité de capter les eaux ailleurs qu’à la Brunnmühle (nécessaire pour la variante B)*

6. Essais de traçage

Plusieurs essais (1973, 1977, 1992, 2000, 2014) montrent que l'eau vient surtout du nord et de l'est et qu'il n'y aurait pas d'écoulement direct d'ouest en est (essai 1977 peu fiable)

- *Variante A: peu de risque pour la Brunnmühle*

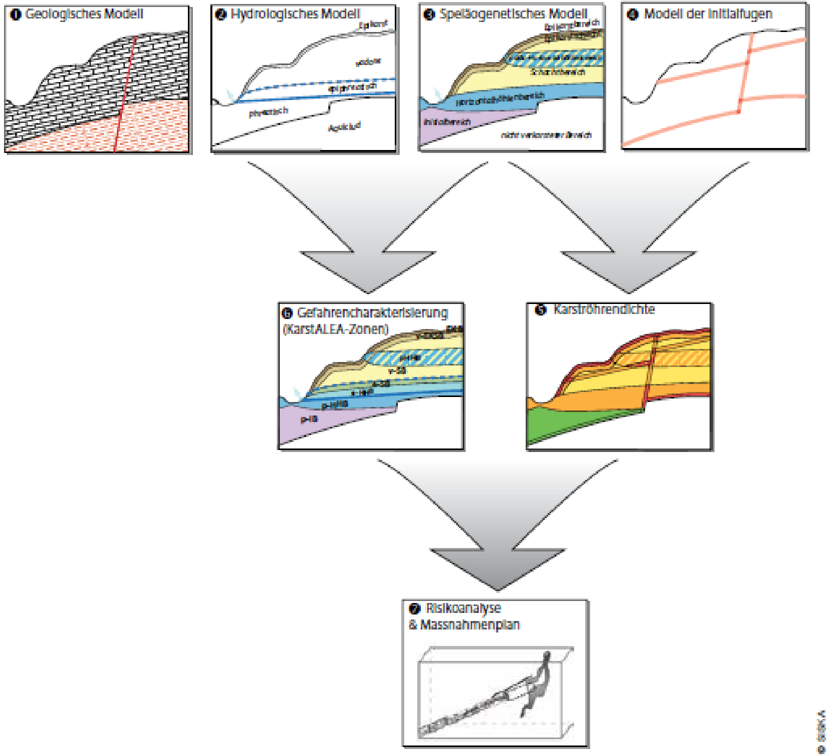


7.1 Approche KarstALEA

Méthode probabiliste *d'estimation du risque* *de trouver des karsts; développée par l'ISSKA (Institut Suisse de Spéléologie et de Karstologie, La Chaux-de-Fonds).*

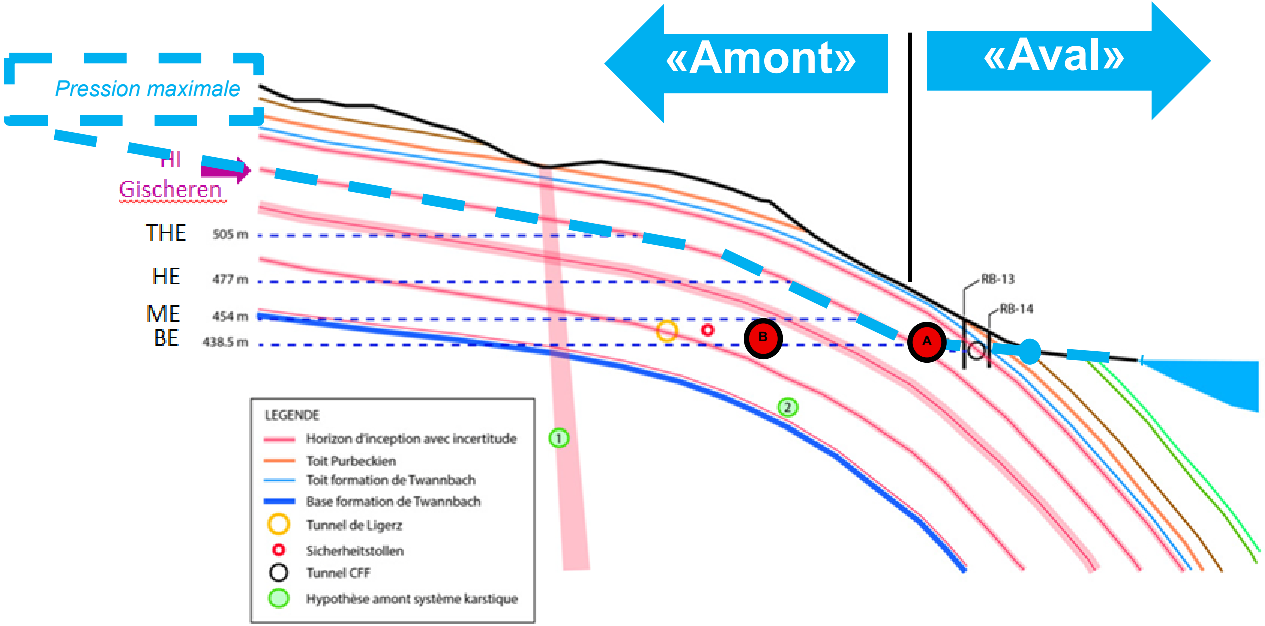
Etude de 4 modèles:

1. *Géologie (données de forages, relevés,…)*
2. *Hydraulique (recherche d'un réseau hydraulique équivalent; essais de traçage, débits, pressions,…)*
3. *Spéléogénèse: grottes existantes, niveaux de battement de la nappe,…*
4. *Horizons d'inception: horizons/fractures préférentiels de formation des karsts*



7.2 Horizons d'inception

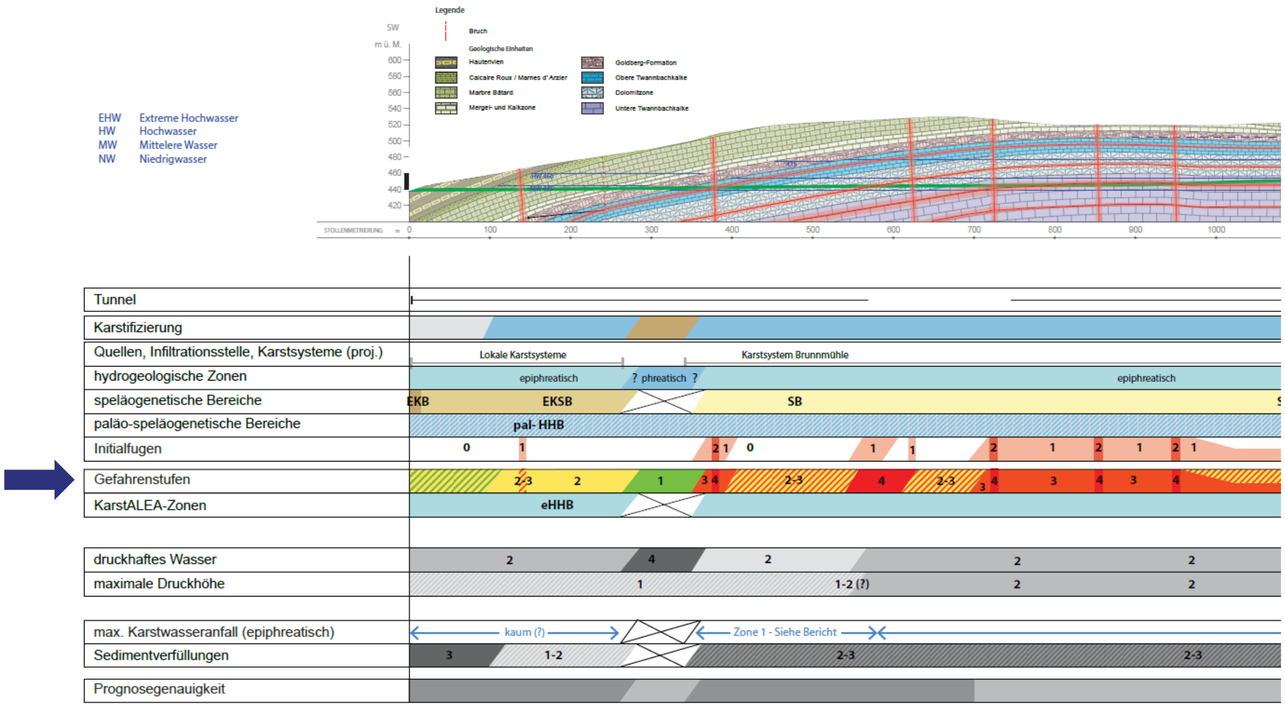
Bonne corrélation entre la position de l'HI Gischeren et la rupture des pressions dans le massif rocheux → 2 zones de régimes hydrauliques différents



- Rupture hydraulique dans l'aquifère du Malm (admis sur HI de Gischeren)
- Mise en charge possible > 70m

7.3 Profil de risque

Pour un tracé donné (ici la Sisto de l’OFROU), classification du risque (note 1 à 4) par filtrage/superposition des différents modèles.



8.1 Micro-gravimétrie: méthode

Mesure très fine des micro-variations de la densité du sous-sol; réalisé de nuit dans le tunnel routier. Mise en évidence des anomalies correspondant soit à des zones de fracturation, soit à des grottes.

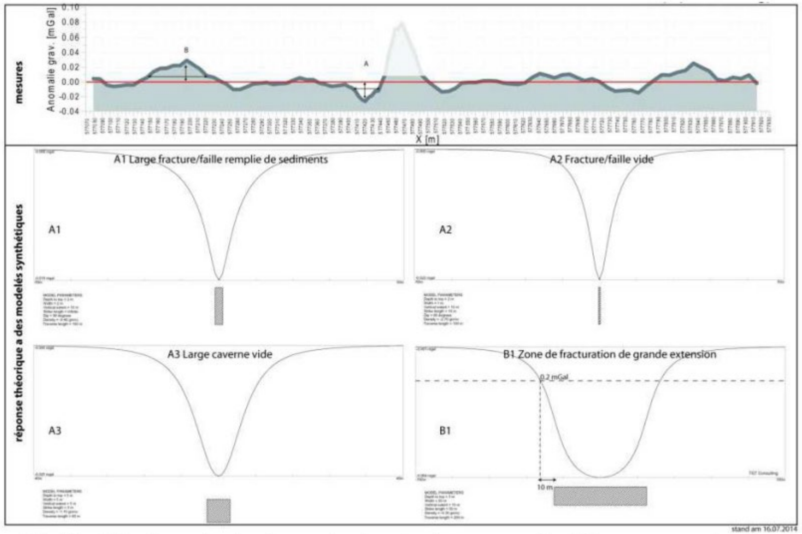


Figure 25 : Modélisations de structures simples de réponse gravimétrique comparable à celles mesurées

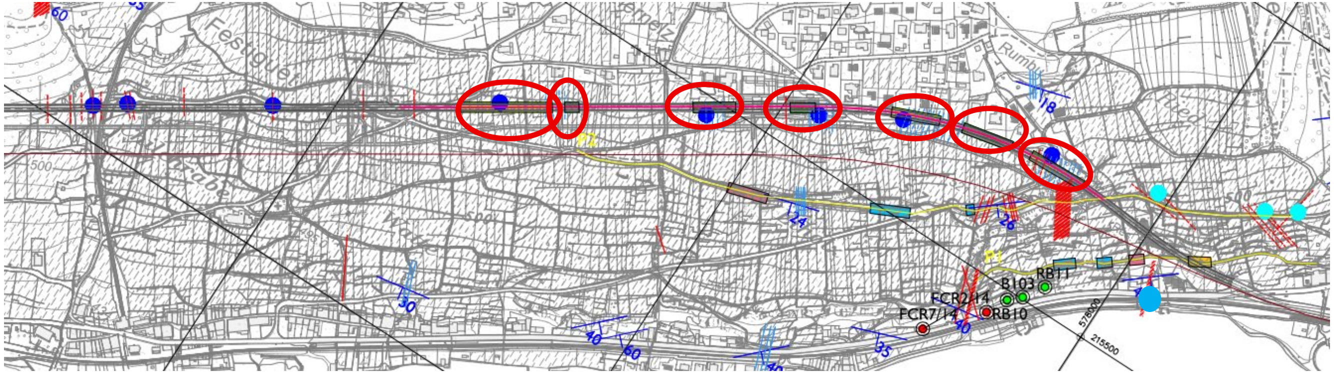
Relevé géométrique des points mesurés

Analyse par filtrage des anomalies régionales

Recherche des anomalies résiduelles

8.2 Micro-gravimétrie: résultats

- *7 zones d'anomalies mises en évidence*
- *Bonne concordance avec les zones où des zones fracturées ont été observées lors du percement du tunnel routier*
- *Bonne concordance avec les venues d'eau dans le drainage du tunnel routier (toutes sont mises en évidence par les mesures de micro-gravimétrie !)*

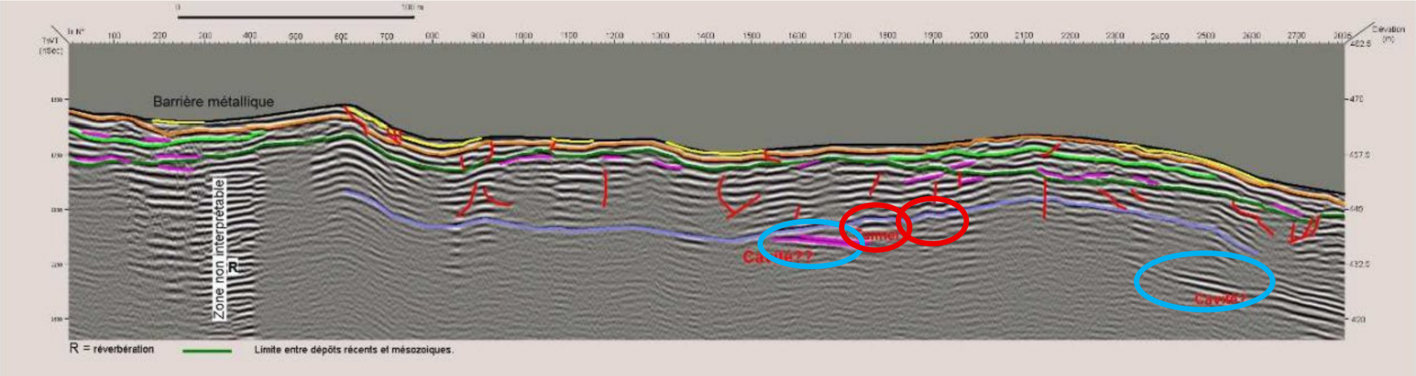


- ✓ *Nécessité d'avoir une topographie «simple»*
- ✓ *Met en évidence les accidents géologiques de grande ampleur (pas les structures très fines situées juste sous la surface)*

9. Georadar

Emission-réception d'une onde électromagnétique (25MHz); le choix de la fréquence détermine la profondeur d'investigation → 20-30m s'il n'y a pas de terrain meuble

- *Trace de cavité à l'altitude 430-438m vers la Brunnmühle; autre cavité possible à l'est de la Br.*
- *Image des tunnels souterrains (N5 et Sondierstollen)…<u>mais il fallait connaître leur existence pour le percevoir !</u>*
- *Nombreuses fractures*



10.1 Tomographie électrique: méthode

Mesure de la résistivité des sols/roches entre électrodes disposées le long d'un profil (dans notre cas les chemins communaux); «trainé électrique» avec de multiples points de mesure, permettant une évaluation de la résistivité en profondeur

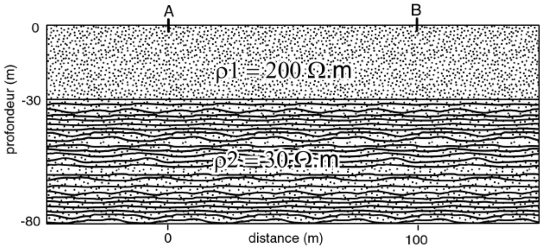


Figure A: modèle

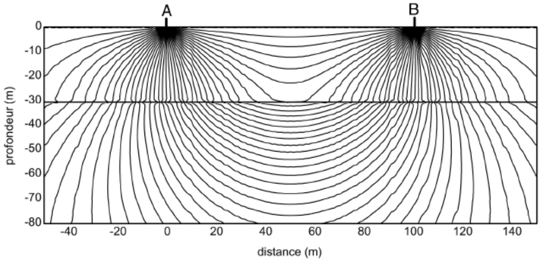


Figure B: champ électrique

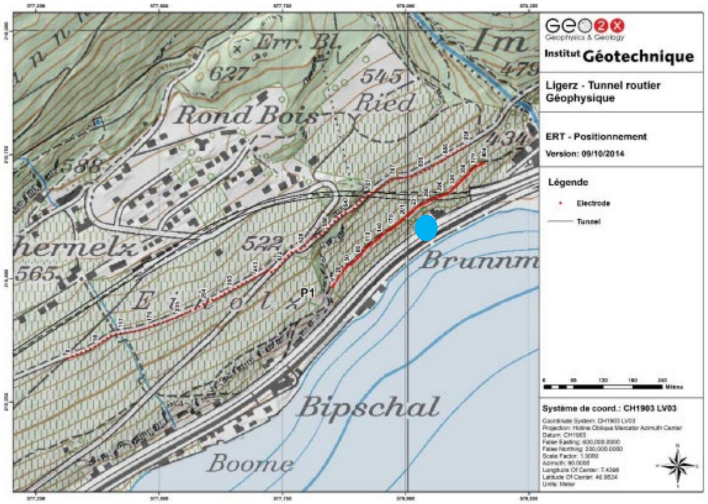
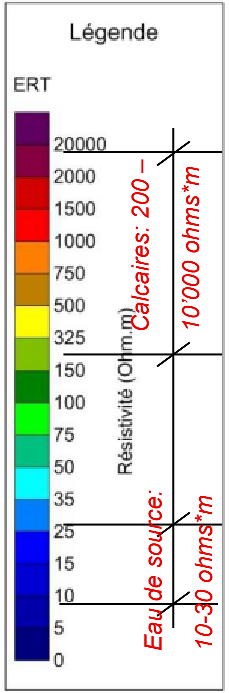
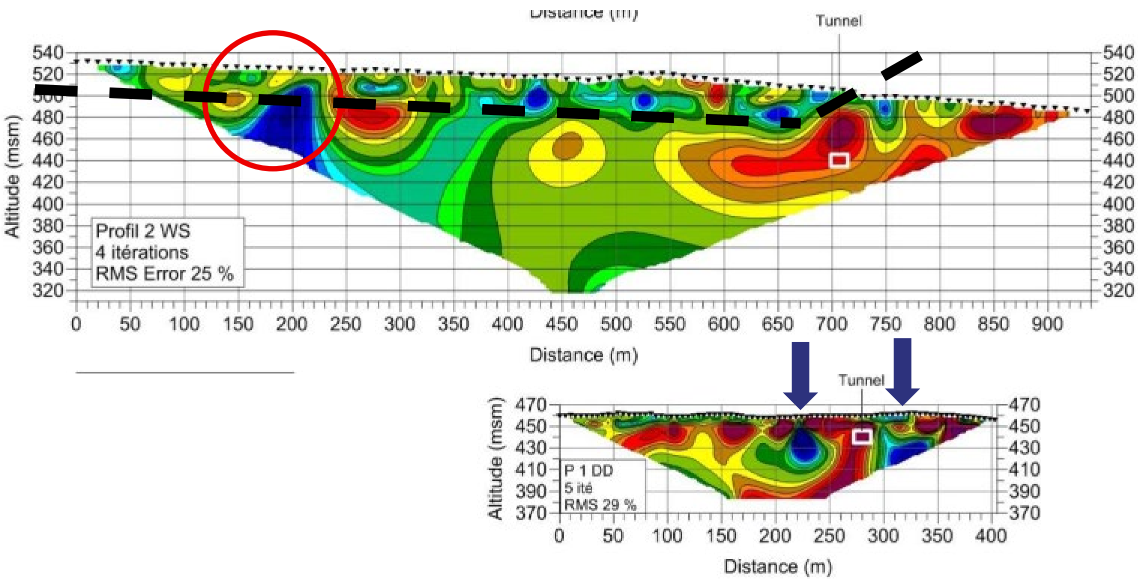


Figure 12: Acquisition ERT - Positionnement des profils et distances le long des profils

10.2 Tomographie électrique: résultats

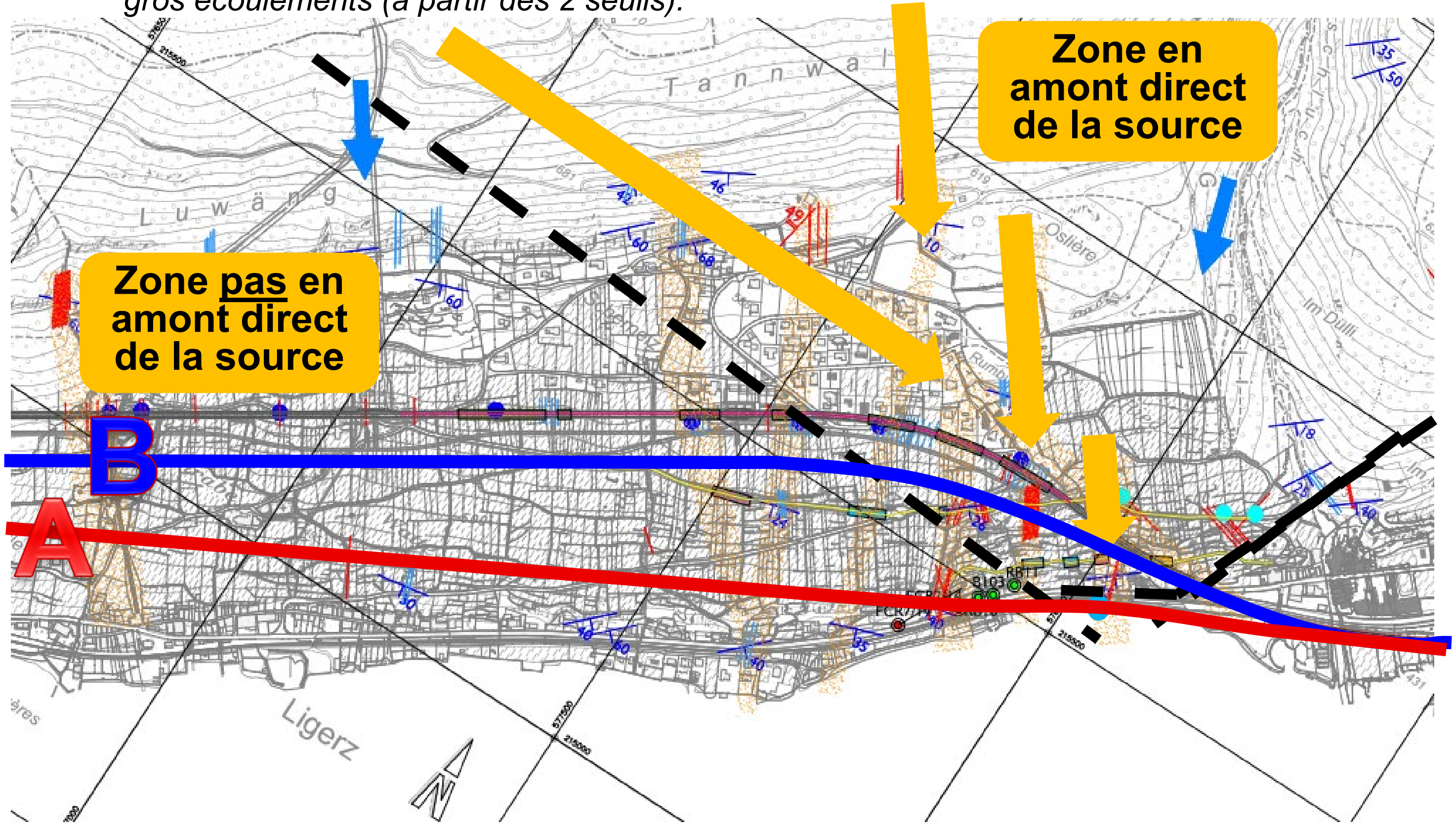




- *1 grosse anomalie sur le grand profil (correspond à une zone de risque 4 d'après KarstALEA et à une anomalie gravimétrique)*
- *Brunnmühle et karst possible à l'est du tunnel sur le petit profil*
- *Interface entre Golberg (marneux = conducteur) et calcaire du Twannbach*

11.1 Principaux résultats

Superposition des informations → fractures et couloirs de déformation où sont logés les gros écoulements (à partir des 2 seuils).



12. Considérations pratiques

- ✓ **Méthodes de géophysique (= information spatiale diffuse) très utiles en complément de sondages carottés (= information ponctuelle précise)**
- ✓ Coût de la géophisique pour cette étude: env. 40’000.- (comparaison: 2 sondages env. 90’000.-)
- ✓ Rapide (env. 8 jours) , non destructif, peu de difficultés d’accès

«WARNING»:

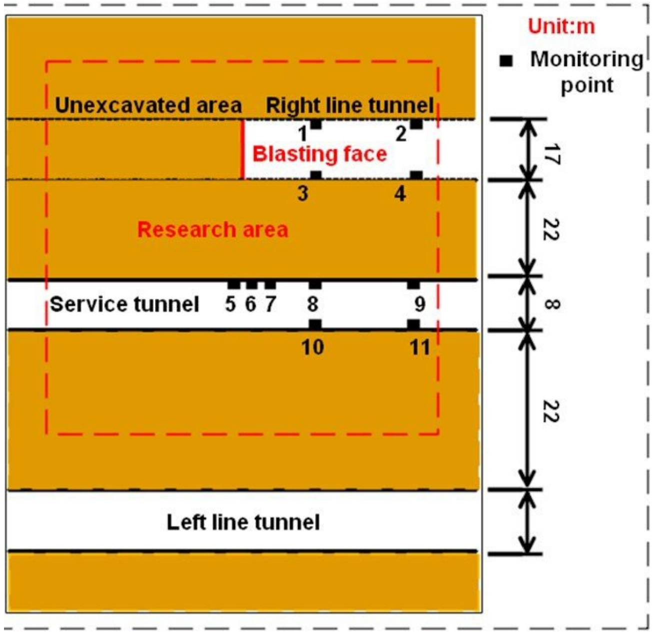
- Topographie: difficile à interpréter si topographie accidentée
- Obstacles: tunnels, éléments métalliques,…
- LC: interférence possible pour certaines méthodes
- Ne pas extrapoler en-dehors des limites de validité des résultats
- Ne peut être utile que si mis en œuvre et interprété par des spécialistes

Vibrations monitoring in Tunnels

Monitoring of vibrations that result from human activities such as construction activities, and nearby vehicular or machinery operations.

Monitoring the impact of construction activities on existing tunnel structures

- Ensure stability, integrity of the existing tunnel during nearby construction activities
- Avoid tunnel closures during construction activities in the surrounding
- Assess potential risks and define a monitoring concept (accelerometers, geophones, and seismometers)
- Define key parameters and zones to be monitored as well as appropriate instrumentation and thresholds (e.g. Frequency thresholds considering the source, i.e. type of machinery / activity. High-frequency vibrations, often caused by machinery, generally have less impact on deep rock layers. Prolonged vibrations potentially causing cumulative damage. Higher amplitudes carry greater risk of structural damages..)
- Calibrate the measurements



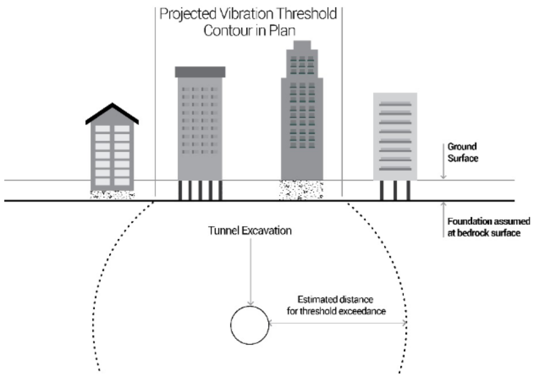
Vibration monitoring during tunnel excavation

Survey of the impact of tunnel excavation on nearby constructions

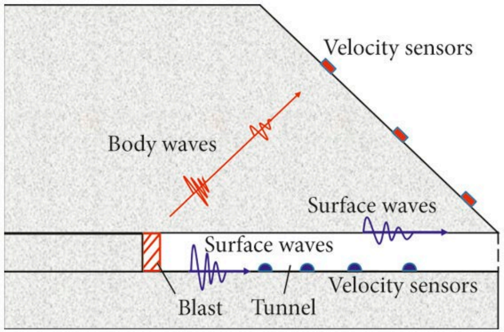
EPFL

Monitoring the impact of tunnel excavation on surrounding structures

- Tunnel projects near **sensitive structures** (e.g. historic buildings)
- Geophones may be used to measure the **vibrations induced by tunnel excavation with drill & blast or TBM** on neighbourhood structures/infrastructures
- Compiling a **monitoring concept**
  - Identify sensitive surrounding structures
  - **Defining vibration thresholds** considering excavation method / rock mass quality / structure conditions and type
- Better **risk management**

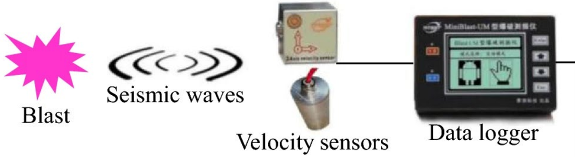


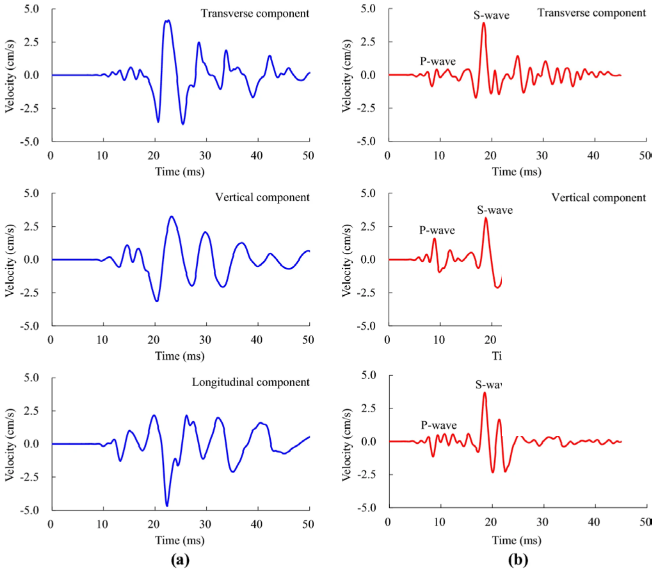
(Stantec Consulting Ltd, 2019)



Monitoring the impact of tunnel excavation on surrounding structures

- **Geophones** are placed on the surface/on the structure so that they could **detect the velocity of the waves induced by the tunnel excavation.**





Modified after Yang & al. 2019