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Could the New Austrian Tunnelling Method be used safely in cities?

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Budapest, 27 May 2009

Quiz Could the New Austrian Tunnelling Method (NATM) be used safely in cities?

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□ 1.- Yes, of course. No problem at all

□ 2.- Not at all. It is too dangerous

□ 3.- I don't have enough data to make my mind

- If you have answered 1
  you can skip the rest of this presentation
  You cannot lose your time with doubts and reservations.
- If you have answered 2
  you also can skip the rest of this presentation.
  You will need a lot of time to consider, prices, delivery delays, and working problems, of double shield TBMs.
- If you have answered 3
  you can remain here if you wish.
  I will try to give you some information on the question, so you could have more data to make your mind.

Presentation order

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- What is NATM?
- NATM in tunnels now
- The critical convergence
- NATM limitations below cities
- Conclusions

Presentation order

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- What is NATM?
  - Precedents
  - Concepts
  - Technological changes
- NATM in tunnels now
- The critical convergence
- NATM limitations below cities
- Conclusions

There are very different views on NATM

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- For contractors NATM is used in any tunnel supported with shotcrete and bolts, with the lining built as scarce as possible (and allowed by the owner)
- For academicians NATM is a system of equations relating stresses and deformations of terrain and lining, "easy" equations which can be summarized in two simple "characteristic curves"
- For so called "experts" NATM is a method so specific than only can be used successfully by experimented consultants (themselves)
- For people with no engineering knowledge NATM is a effortless system based solely on the use of RMR geomechanics classification
- For many lay people NATM is simply a danger

There is some confusion about names

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- **NATM** (New Austrian Tunnelling Method)
  (L. Von Rabcewicz, Salzburg, 1962)
- **Spritz Betonbauweisse** (Germany, ~1970)
- Méthode **convergence-confinément**
  (Panet, France, 1992)
- **SCL** (Sprayed Concrete Lined Tunnels)
  (ICE, U.K., 1996)
- **NMT** (Norwegian Method of Tunnelling) (Norway)
- Several names in Japan (**CDM, UHVS**)
- **SEM** (Sequential Excavation Method),
  a neutral name more and more frequently used

Too many names for the same dish

A small historic parable

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- Before 1750 there were no economics theories
- Adam Smith (1723-1790), published in 1776 the classic book: "**An inquiry into the nature and causes of the wealth of nations**"
- According Adam Smith, economic equilibrium is naturally achieved when every social agent looks for his own personal profit
- What could have happened if Adam Smith had developed, and patented, a "New Scottish Method of Economics Equilibrium" (NSMEE)?
- It would have been refused by many people:
  - In England for being Scottish
  - In France for being English
  - In Germany for not being German
  - In Spain for not being catholic

Adam Smith

What is NATM?

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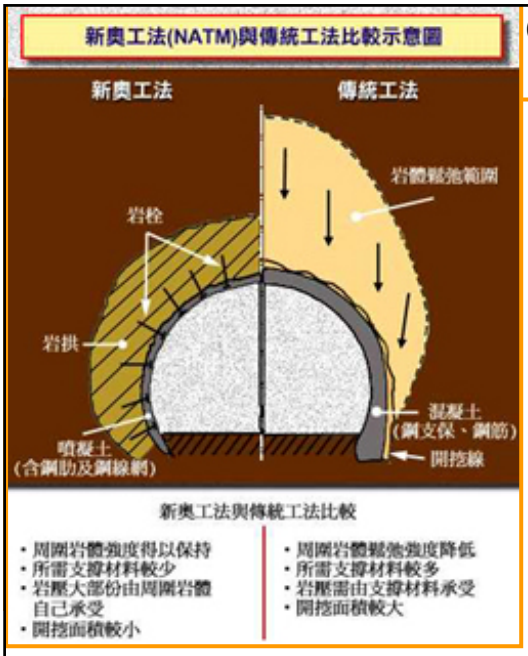
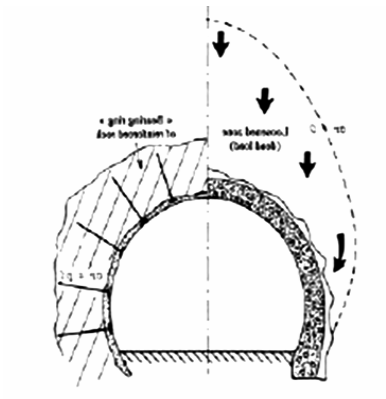
- NATM is really a new paradigm in the tunnel construction
  - Old paradigm: to excavate as you can and to put a rigid primary lining, heavy enough to support the charges due to the broken terrain
  - New paradigm: to excavate with care not to damage the terrain, and to let the terrain to cope with a part of the charge. The flexible primary lining support only the residual charges

Comparisons between NATM and previous concepts





What is NATM?

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- NATM has been possible because of the coincidence of:
  - A century of experience in tunnels crossing below the Alps
  - New concepts in
    - Engineering Geology (Stini)
    - Rock Mechanics (Müller, Rocha)
    - Tunnel design (Rabcewicz, Fenner, Pacher…)
  - A technological revolution
    - Bolts
    - Shotcrete
    - TH steel sets

NATM precedents and polemics

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- Swiss an Austrian authors proposed ideas for/during the excavation of the big European Alpine tunnels (1860-1915). Some of these ideas can be related, as precedents, to NATM: Ritter, 1879; Engesser, 1882; Leon y Wilhem, 1910; Wiesman, 1912 ("Schutzhülle", "Trumpeter's zone"); Maillart, 1923
- Kovari (1993, 1994) has questioned the existence of NATM as a new, and fully scientific, method. For him NATM is only a nickname for the sequel of the above mentioned precedents
- Golser (1996) and others opposed Kovari's views
- Heathrow tunnels collapse (1994) caused a worldwide revision of NATM, due mainly to the English publications about collapses using NATM

Two collapses

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Carmel collapse (Barcelona subway, 2004)

Heathrow collapse (London subway, 1994)

NATM precedents and polemics

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- Heathrow tunnels collapse (1994) caused a worldwide revision of NATM, due mainly to the English publications about collapses using NATM
- It is supposed by many people (and owners) that TBM excavation is the valid alternative against NATM (specially when excavating with closed TBMs, with a maintained earth or bentonite pressure in the front excavation chamber)

Beginnings of NATM

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- First idea by Rabcewicz, after his experience, in world war II, building underground bunkers in the Russian front I
- Rabcewicz (1948, Austrian patent n^{er} 165.573) "Gebirgsdruck und Tunnelbau" (1948)
- Highway tunnels in Caracas (1956-58)
- First? use of shotcrete in a tunnel lining by Brunner (1954)
- Brunner (1958, Austrian patent n^{er} 197.851)
- Rabcewicz's paper in the XIII Geomechanics Colloquium (Salzburg, 1962)
- Rabcewicz's seminal papers ("Water Power" 1964-65)
- Papers by Fenner, Pacher and others
- First urban application in Frankfurt subway by L. Müller (1969) and in other German subways
- NATM is in its fifties: Not so new actually

Technological revolution (1950-60)

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- The first TBM tunnel is bored with a Robbins machine (Hydraulic tunnel at Oahe Dam, USA).
- The first NATM tunnel is excavated with Austrian guidance (Caracas highway to the coast)
- New "soft" excavation techniques appear
- New support techniques are introduced:
  - Bolts in the French iron mines
  - TH forms in the German coal mines
  - Shotcrete with Austrian patent by Brunner
- Rock Mechanics (first mention in the French book by Talobre, 1958; initial development in Salzburg and Lisbon) begins to unveil the rock mass behaviour
- Less manpower is required
- In most occasions NATM is cheaper for not very long tunnels

Some ancient NATM tunnels

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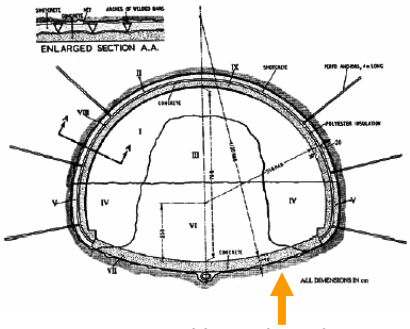

Sequence proposed by Rabcewicz, 1965

Shotcreting in German subways, ~ 1970

NATM concepts as a design philosophy

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OLD (L. Müller,1978)

- *"The New Austrian Tunnelling Method is a concept… where success depends on the application of several principles. The first one is to use the rock mass …..for the support of the terrain charges*
- *To allow deformation is necessary in order to develop the rock mass strength around the tunnel and to minimize the support needs*
- *Deformation must be controlled in order not to weaken the rock mass more than necessary.*
- *Design is done during the excavation"*
- Basic instrumentation control is by convergence measurements

ACTUAL (T. Brown, 1995)

- Terrain strength around the tunnel is mobilized to the maximum possible level
- This is done allowing for a controlled deformation.
- The primary support is installed with strength-deformation characteristics adequate for the terrain and in a compatible time with the terrain deformability
- Instrumentation is used to control the support deformation in order to change (if/when necessary) the initial design and the excavation sequence
- Movements at surface and around the tunnel are controlled in urban environment

NATM as a construction method

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(Romero, 2002)

- Tunnel excavation and support are done in a sequential way.
- The sequence can be changed
- Initial support is by:
  - Shotcrete (often fibercrete)
  - Bolts
  - Steel sets (TH flexible, HEB rigid, reticular)
- Secondary lining is (very often, but not always) concrete put in place with forms.
- When a tunnel is excavated sequentially :
  - NATM is being used as a construction method
  - NATM design philosophy is not necessarily being applied

Differences between NATM in rocks and in soils

- In rocks, deformations are smaller and easier to control
- When a tunnel is excavated sequentially in rocks it is easy to apply NATM
  - As a construction method
  - As a design philosophy
- In soils, deformations are bigger and more difficult to control
- When a tunnel is excavated sequentially in soils it is
  - Easy to apply NATM as a construction method
  - Difficult to apply NATM as a design philosophy

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- NATM limitations below cities
- NATM management needs
- Conclusions

Some modern NATM tunnels

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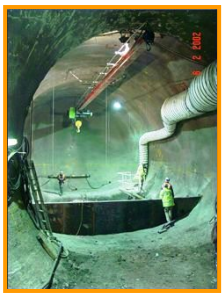

Chunnel crossover cavern

Chunnel rail link

Both U. K.

Mission Valley, California, USA

El Pardo, Madrid, Spain

Technological revolution (1980-95)

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- The NATM method is regularly used in almost every not too long mountain tunnel
- No Austrian guidance is necessary (although Austrian consultants maintain a very high technical level)
- NATM is combined with
  - Very good drill jumbos
  - Mechanical excavation (e. g. roadheaders)
  - New "soft" blasting excavation techniques
- Bolts are normalized and mechanized.
  - There is a type of bolt for every need
- Shotcrete becomes the universal support mean
  - Shotcreting robots achieve outputs of 20 m^3/hour
  - Steel fibers are common as shotcrete reinforcement ("fibercrete")
- Rock Mechanics concepts (e.g. geomechanics classifications and others) are at work in every tunnel
- Computer numerical methods allow for the calculus of any underground excavation
- The necessary manpower is extremely low
- Tunnel construction becomes as safe as any other civil work

Technological revolution (2000-08)

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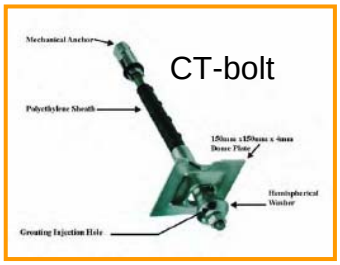
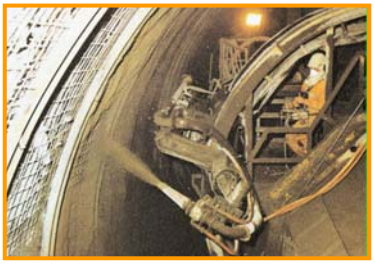
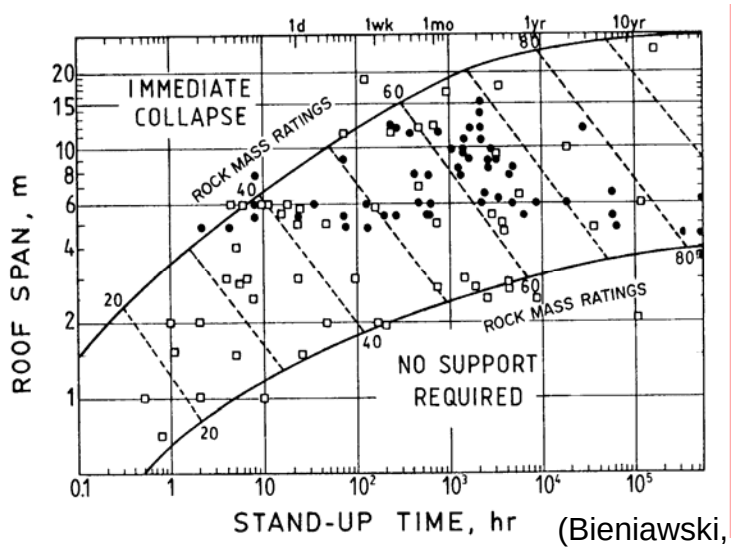




Relationship between NATM and RMR



(Bieniawski, 1989)

Presentation order

- What is NATM?
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Characteristic curves of terrain and lining

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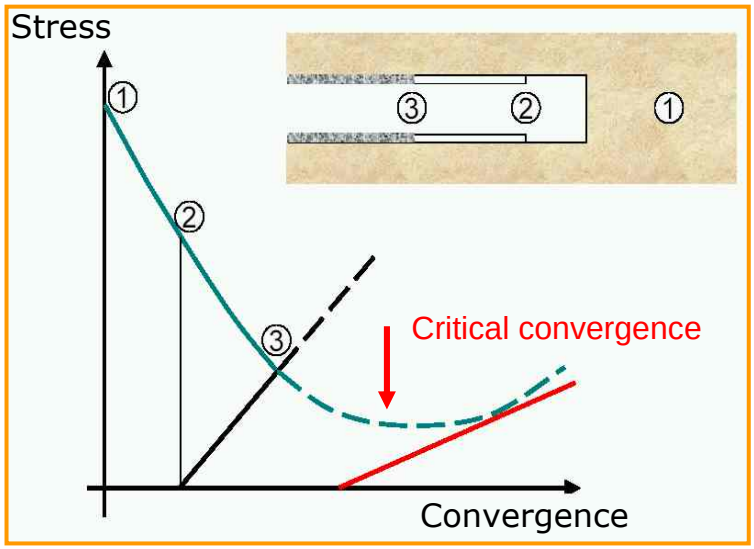

Characteristics curves by Fenner y Pacher (according Rabcewicz, 1965)

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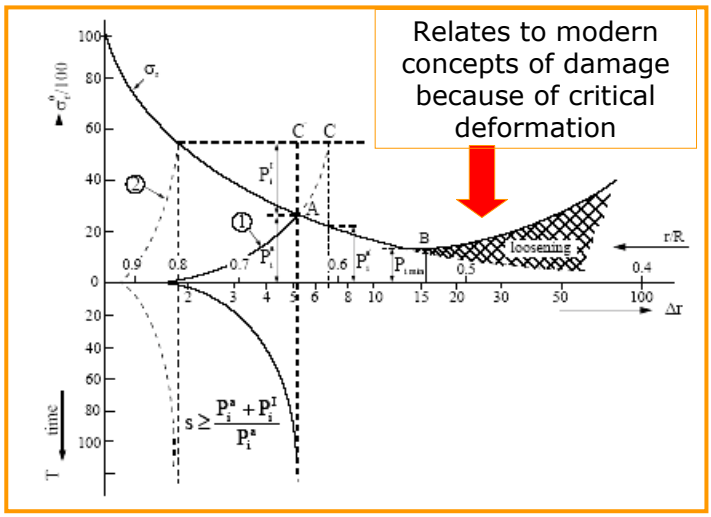

Characteristic curves according to the rock behaviour (Egger, 2000)

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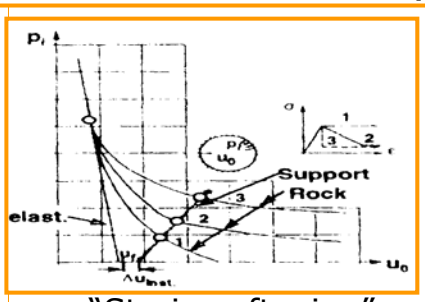
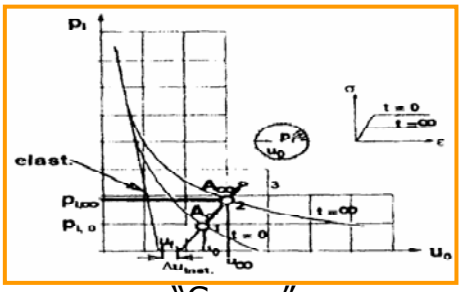
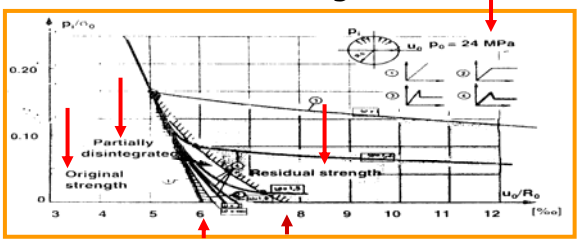


"Strain softening"



"Creep"



(Egger, 2000, for the Lotschberg Base Tunnel)

Japanese data on convergences

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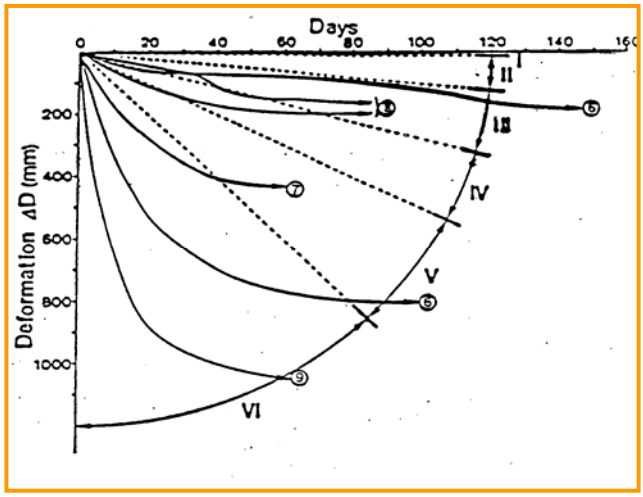
Measured values in Japanese tunnels built in tertiary terrains

(Tanimoto, 1983)



Some data about the critical convergence and applied support pressure

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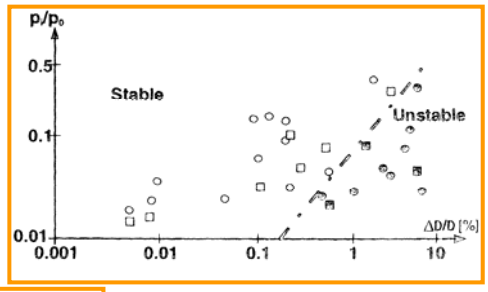
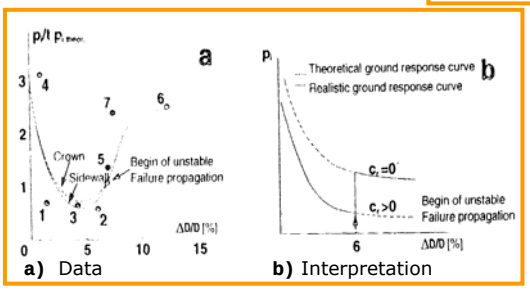
Relationship between critical convergence and applied support pressure
Yamachi et al, 1989





a) Data b) Interpretation

Beginning of instable fracturing.
Indian tunnels
Singh B. et al, 1997

Some critical convergence values

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- As far as I know there is not yet a full study of the values
- Several authors have found different values for the critical convergence
- Tanimoto, 1983 2% (Japan)
- Yamachi el al,1989 2-10% (Japan)
- Singh et al, 1997 4-5% (Himalayan Range)
- Egger, 2000 6-8% (Lotschberg Base Tunnel p_o=24 Mpa; $\varpi = 1{,}6$)
- These values are too high for soils. Collapses have appeared with measured closures as low as 1%

Relationship between closure speeds and depth for the Lotschberg Tunnel

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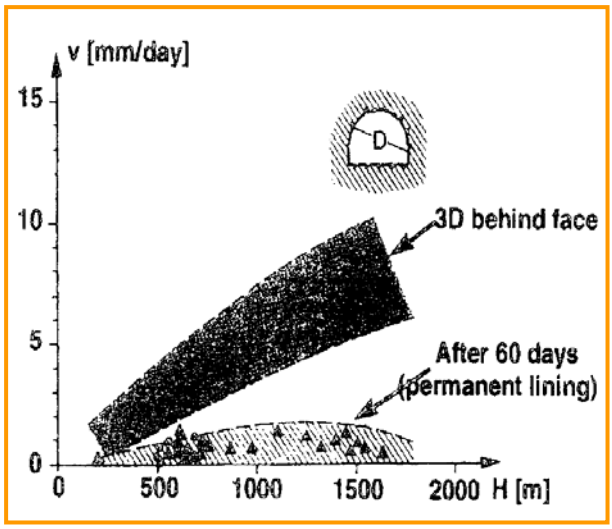

Closure speed is an important control parameter

Egger, 2000

Presentation order

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- What is NATM?
- NATM in tunnels now
- The critical convergence
- NATM limitations below cities (usually in soils)
  - Smaller critical convergences
  - Subsidence damages to buildings
  - NATM management needs, to get good control
- Conclusions

Closures before Heathrow tunnels collapse

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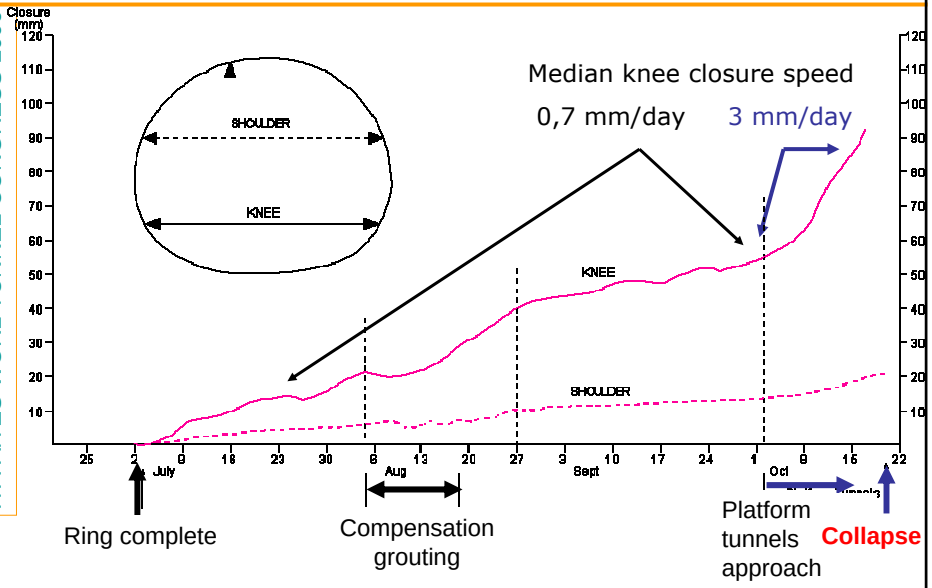

Lessons from the Heathrow tunnels collapse

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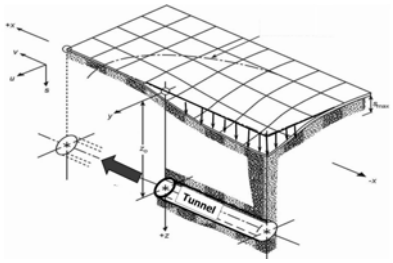
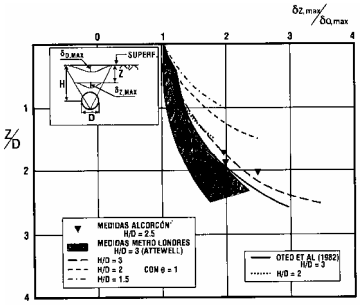
- Good coordination between construction and control people is imperative
- Surface subsidence must be monitorized and controlled
- Structural damage reports (e. g. cracks in shotcrete) must not be ignored
- Compensation grouting pressure must be controlled, and kept below prefixed limits
- Good workmanship is necessary for construction details (e. g. coins, embedments…)
- Repairs require more care than construction itself

- *These conclusions, which are simply pure good sense, were informally transmitted to me by a member of the Inquiry Commission*
- *It can be assumed ("sensu contrario") that some, or all, of these points were ignored and caused the Heathrow collapse*

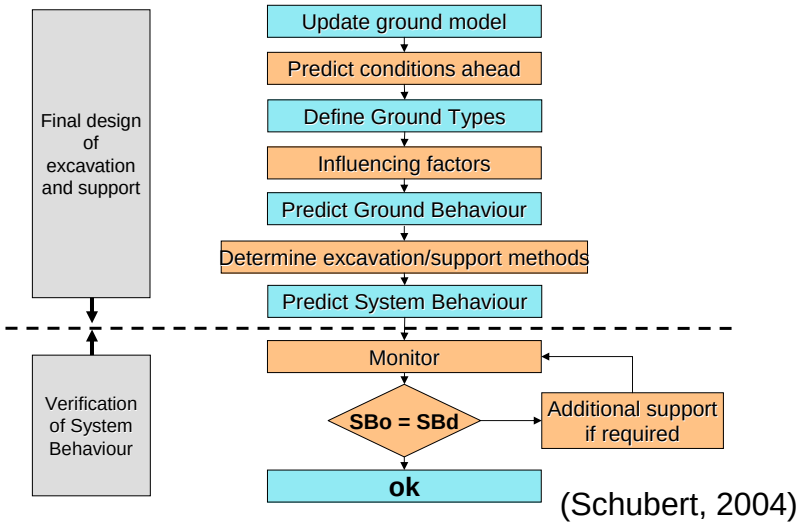
Subsidence damages



Settlement (mm)	Green	<10
	Yellow	10-15
	Red	>15
Angular distortion	Green	<1/1500
	Yellow	1/1500 to 1/750
	Red	<1/750
Horizontal strain (%)	Green	<0,10
	Yellow	0,10 to 0,20
	Red	>0,20



Conceptual model for NATM application



(Schubert, 2004)

NATM organizational requirements to be fulfilled by the owner (Schubert, 2004)

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- Select appropriate team for the investigation and design
  - Early involvement of tunnel designer allows targeted investigation, testing, and ground characterization.
  - Teamwork from the beginning of a project minimizes loss of information
- Make sure that investigation and design are consistent, coherent, and site specific
  - Each tunnel is a prototype.
  - "Copy and paste" designs or "prefabricated" solutions have a high potential to be suboptimal or to not meet site-specific requirements
- Provide a fair and flexible construction contract
  - Contract must allow for adjustment of excavation/support methods
  - Compensation must be fair also in case of deviations
- Assign competent site staff able to:
  - Continuously update ground model
  - Establish an adequate monitoring plan and assess monitoring results
  - React to variability of ground, with real decision- making power

CONCLUSIONS

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- In case the advantages of NATM – flexibility in term of shape, size and support of tunnels, relatively low costs, applicability in nearly all conditions – shall be used, the owner, and the contractor, have to accept their responsibility
- Means and methods to produce safe and economical tunnels with NATM have been tremendously improved over the last decades. It is up to owner and contractor to use them
- In the cities subsidence dangers preclude in many cases the use as NATM method as a full philosophy, looking only for the more economical lining
- NATM construction method, limiting both convergence and convergence speed, can be used safely in the cities
- If NATM is used it is mandatory that sound organization procedures be put in practice by the owner in order to achieve the management level which would assure safety

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That is all. Thank you for your attention

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