EOSC433/536:

Geological Engineering
Practice I – Rock Engineering

# Lecture 3:
# Phenomenology & Observational Approach to Design

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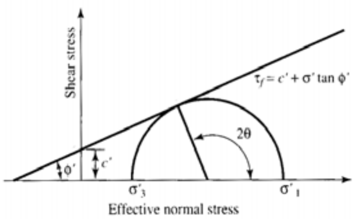
## Phenomenology – "That Which Appears"

**Phenomenology**: *the investigation and description of phenomena, as experienced or observed, as a means to grasp the logical cause behind a phenomena. Implicit is a trust that analyzing behavior can provide one with a greater understanding of nature.*

For example, one observes a phenomenon and asks how/why that specific phenomenon occurs (i.e. inductive reasoning).

*Samples removed from a triaxial cell have inclined failure planes, therefore failure must have occurred through shear and the development of shear fractures.*



# Phenomenological -vs- Mechanistic

Such approaches are 'holistic' and generally disregard details of the underlying mechanisms while concentrating on the overall performance of the system.

Mechanistic approaches on the other hand, try to break the problem/system down into its constituent parts to understand the cause and effect relationships (and their evolution), which govern the behaviour of the system.

*Close examination of rock samples during triaxial testing shows that failure involves the localization of a failure surface through the initiation, propagation and coalescence of micro-cracks, and that the failure mode is only in shear for cases involving high confinement (vs. extensile under low confinement).*

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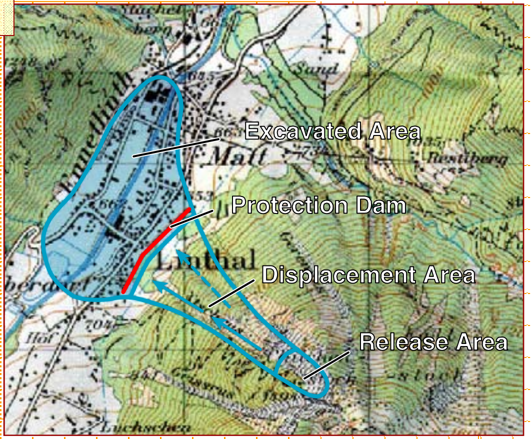
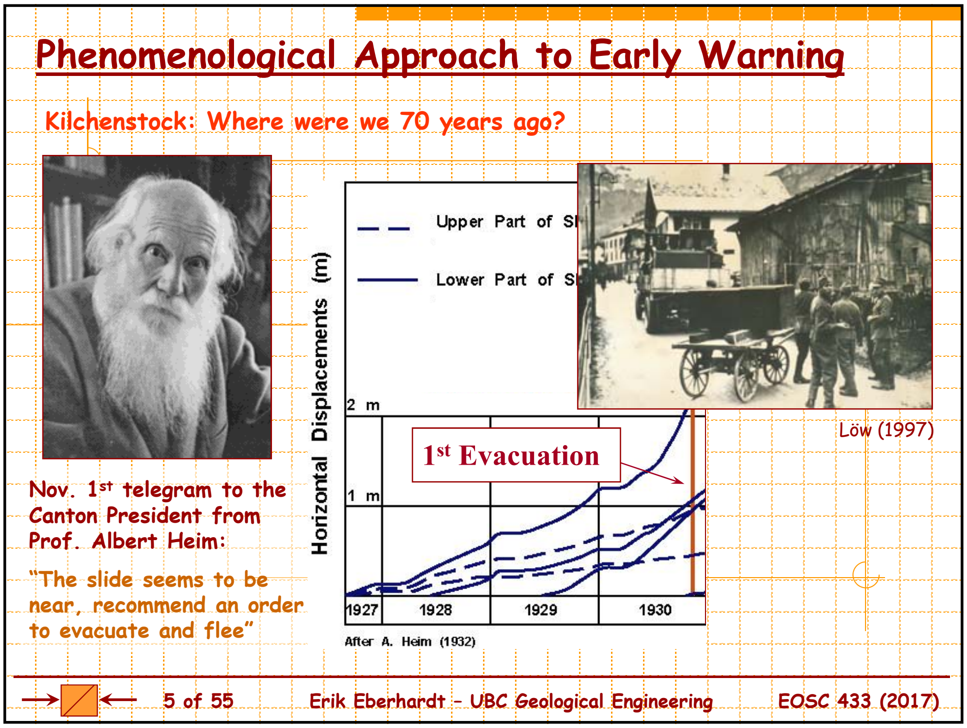
# Phenomenological Approach to Early Warning

**Kilchenstock, Switzerland (1930)**



Löw (1997)



# Phenomenological Approach to Early Warning

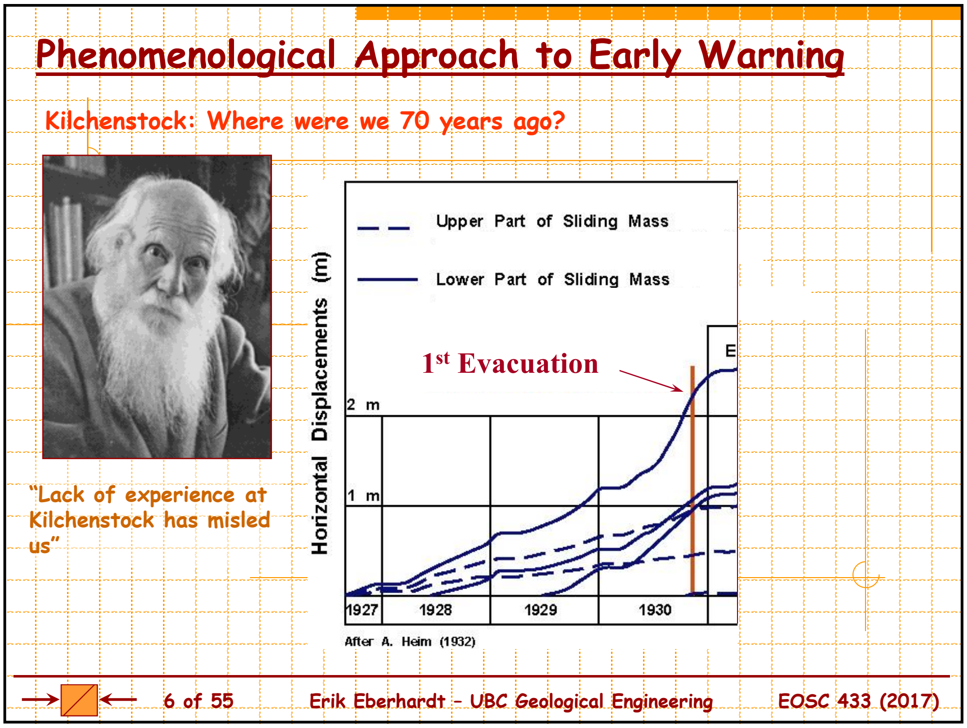
Kilchenstock: Where were we 70 years ago?

Nov. 1st telegram to the Canton President from Prof. Albert Heim:

"The slide seems to be near, recommend an order to evacuate and flee"

After A. Heim (1932)

Löw (1997)

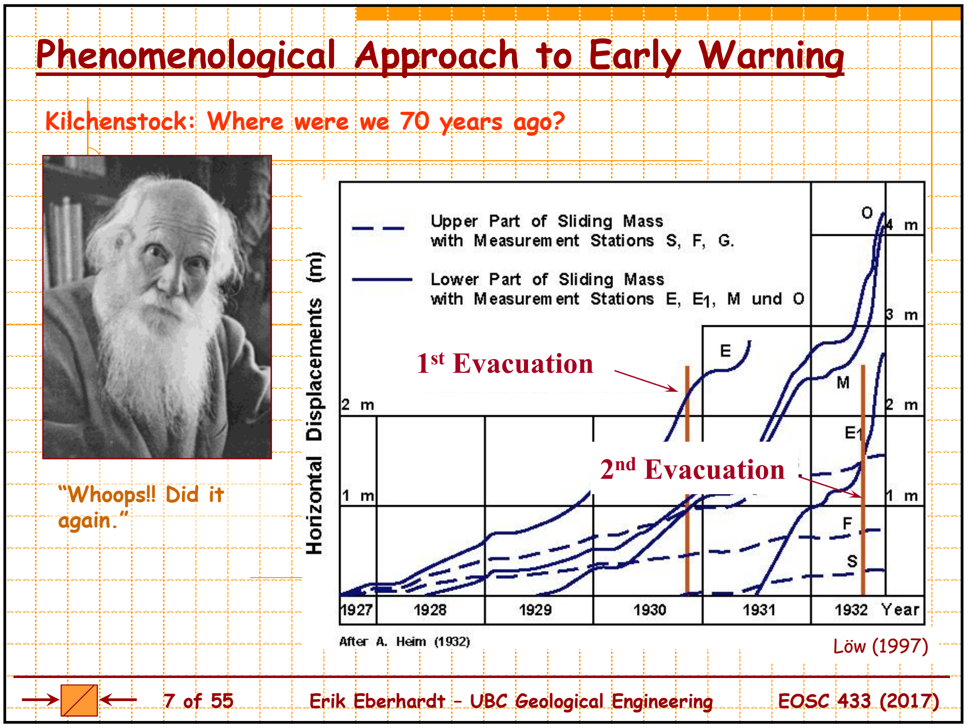


# Phenomenological Approach to Early Warning

Kilchenstock: Where were we 70 years ago?

"Lack of experience at Kilchenstock has misled us"

After A. Heim (1932)



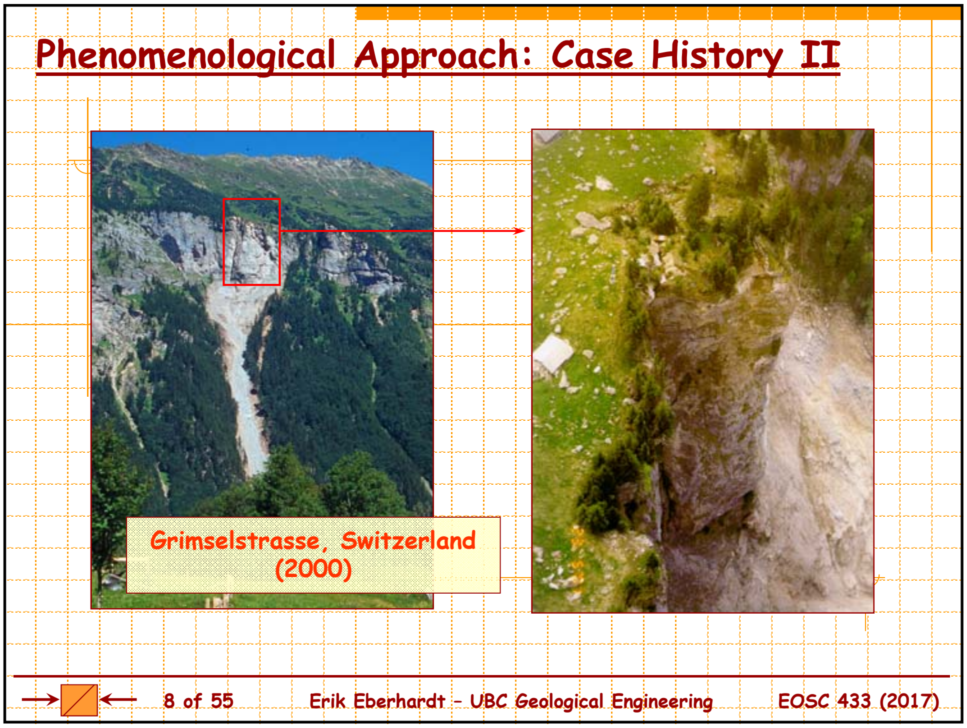
# Phenomenological Approach to Early Warning

Kilchenstock: Where were we 70 years ago?

"Whoops!! Did it again."

After A. Heim (1932)

Löw (1997)

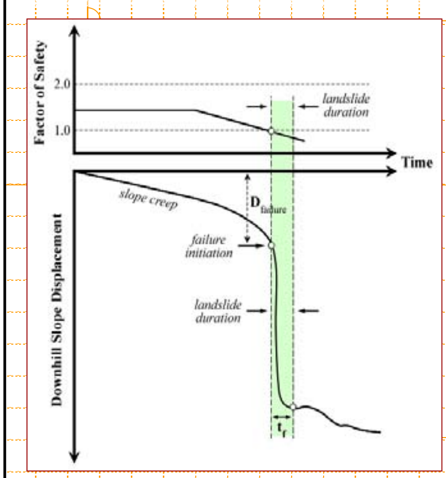


# Phenomenological Approach: Case History II

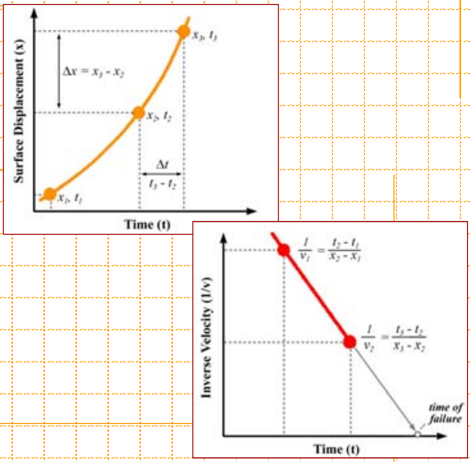
Grimselstrasse, Switzerland (2000)

# Rock Slope Monitoring & Early Warning

## Temporal Prediction of Failure:



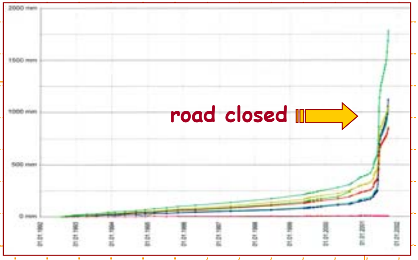
Terzaghi (1950)



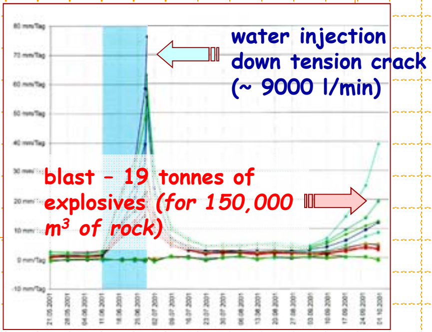
Fukuzono (1990)

# Phenomenological Approach: Case History II

## Temporal Prediction of Failure:



road closed



**water injection down tension crack (~ 9000 l/min)**

**blast – 19 tonnes of explosives (*for 150,000 m$^3$ of rock*)**

## Phenomenological Approach: Case History II

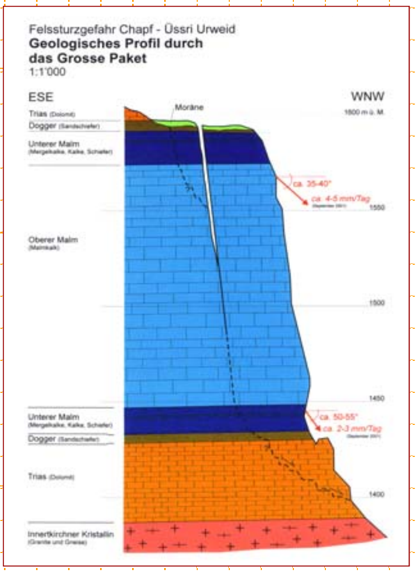
## Phenomenological Approach: Case History II

The following summer…

Gruner (2003)

Despite the monitoring data indicating that failure was imminent, and having redirected 9000 l/min from a surface stream down the rear tension crack, it still took two large blasts (> 19 tonne) to bring the “unstable” material down.

# Phenomenological Approach: Limitations



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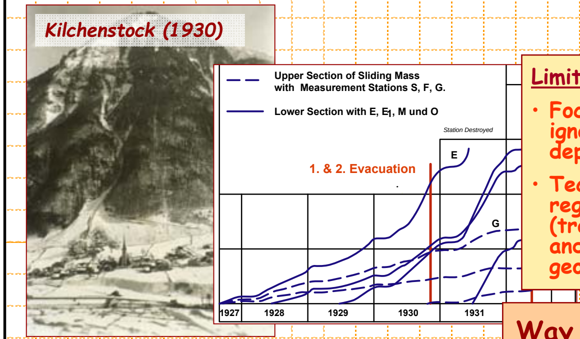
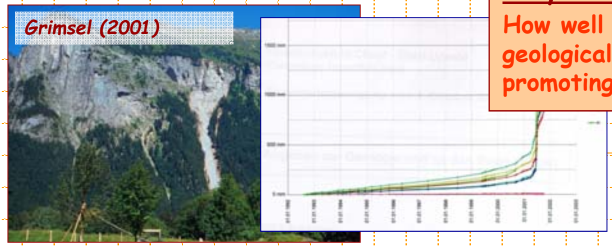
# Phenomenological Approach: Limitations



**Limiting Factors:**

- Focuses on surface measurements, ignoring changes in behaviour with depth.
- Technique applied in the same way regardless of failure mode (translational slide, topple, etc.) and/or data source (crack meter, geodetic monuments, etc.).



**Way forward?:**

How well do we understand the geological factors and mechanisms promoting instability?

Eberhardt (2008)

# Role of Investigative & Performance Monitoring

**Investigation**:
- To provide an understanding of the ground conditions, for prefeasibility and design purposes.
- To provide input values for design calculations.
- To check for changing ground conditions as the project develops, or advance/progress to greater depths.

**Monitoring**:
- To assess and verify the performance of the design.
- To calibrate models and constrain design calculations.
- To provide a warning of a change in ground behaviour, thus enabling intervention to improve safety or to limit damage through a design change or remediation measure.

# Investigative Monitoring: Case History III

Campo Vallemaggia, Switzerland

# Case History - Campo Vallemaggia

**Geology** - *gneisses & schists*
**Mechanism** – *translational slide*
**Surface Area** ~ 6 km$^2$
**Total Volume** ~ 800,000,000 m$^3$
**Average Velocity** ~ 5 cm/year
**Maximum Depth** ~ 300 m

**Background**:

For more than 200 years, the villages of Campo Vallemaggia and Cimalmotto have been slowly moving atop a deep-seated rockslide in the southern Swiss Alps. Over this time, numerous mitigation measures have been carried out to stabilize the rockslide but with limited to no success. These works largely focussed on minimising erosion at the toe of the landslide. More recently, the need to stabilize the slope was becoming critical as with each passing year the two villages were being pushed closer to the edge of a 100-m high erosion front at the foot of the rockslide.

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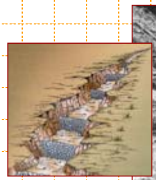
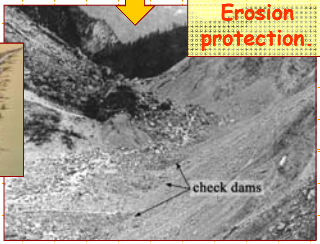
# Case History - Campo Vallemaggia

Uncertainty in stabilizing the rockslide came about from two competing arguments as to the cause of the slope movements.

**Opinion #1**: Massive erosion at the toe of the slide acts to reduce passive resistance.

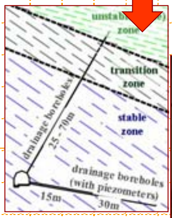
**Solution**: Erosion protection.



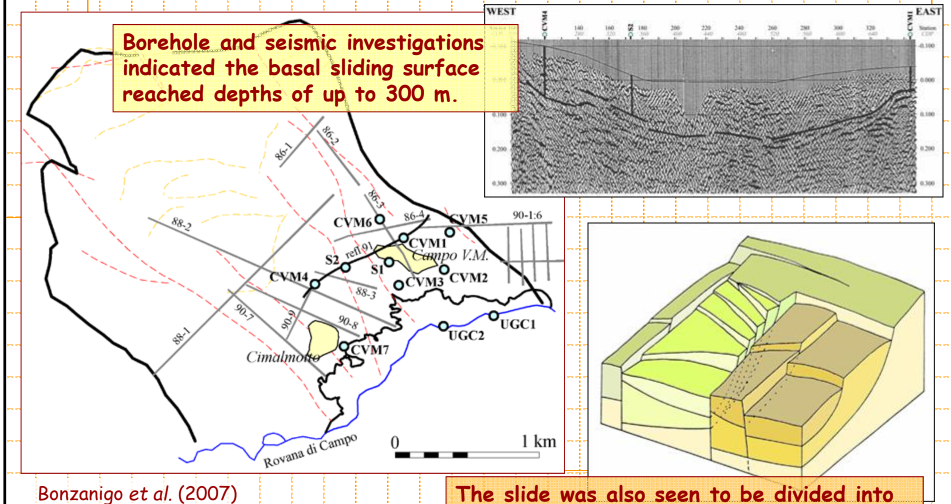


**Opinion #2**: Deep artesian water pressures act to reduce the effective strength along the slide surface.

**Solution**: Deep drainage.



# Campo Vallemaggia – Field Investigations

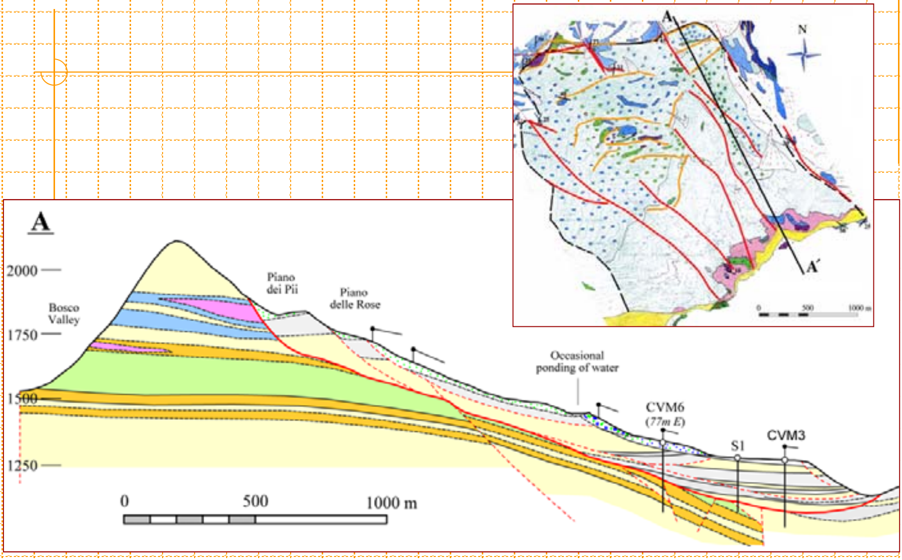


Borehole and seismic investigations indicated the basal sliding surface reached depths of up to 300 m.

The slide was also seen to be divided into two main bodies, separated by a large fault running the length of the rockslide.

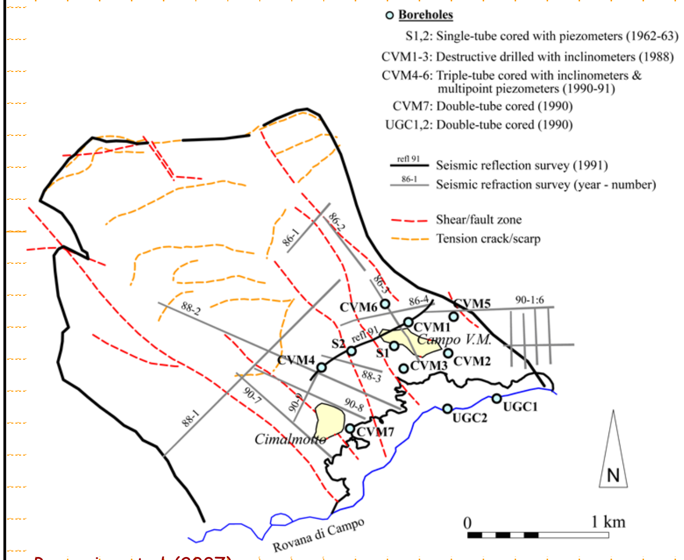
Bonzanigo *et al.* (2007)

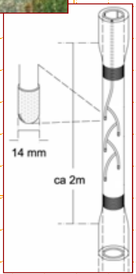
# Campo Vallemaggia – Geology



Bonzanigo *et al.* (2007)

# Campo Vallemaggia – Subsurface Monitoring





Bonzanigo *et al.* (2007)

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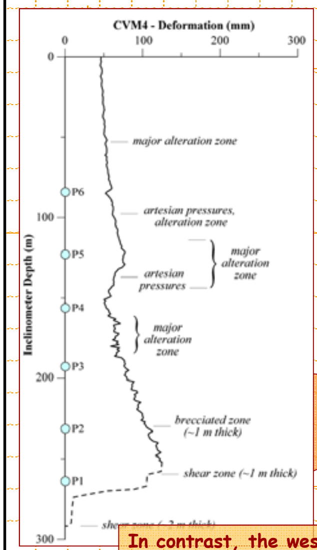
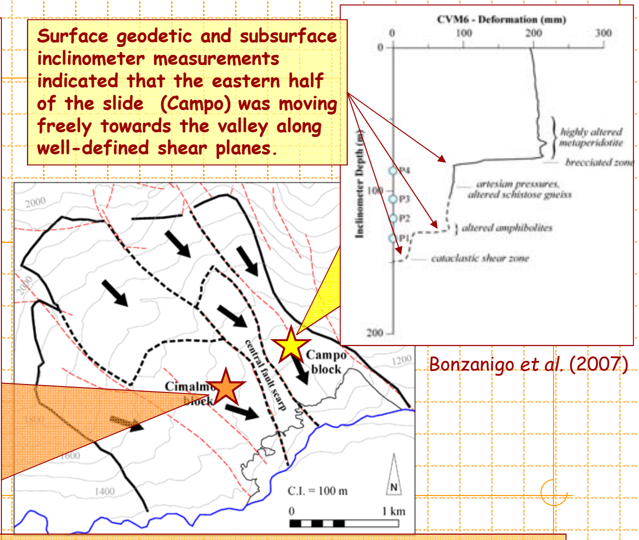
# Campo Vallemaggia – Displacement Monitoring



Surface geodetic and subsurface inclinometer measurements indicated that the eastern half of the slide (Campo) was moving freely towards the valley along well-defined shear planes.

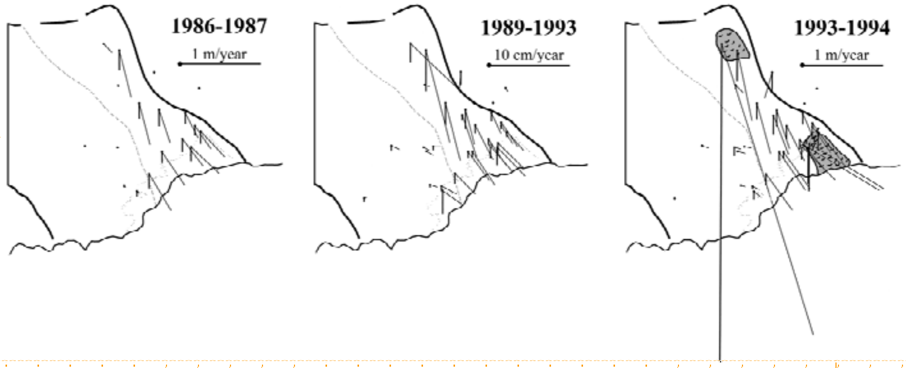


Bonzanigo *et al.* (2007)

In contrast, the western half (Cimalmotto) was inhibited in its movement by the neighbouring Campo block resulting in a more diffused behaviour with depth.

# Campo Vallemaggia – Displacement Monitoring

Historical geodetic measurements – Total Station



Bonzanigo *et al.* (2007)

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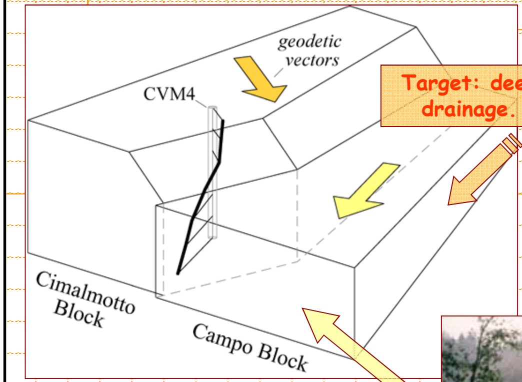
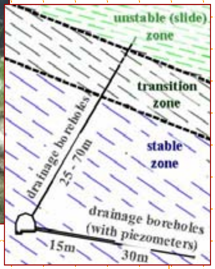
# Campo Vallemaggia – Slide Kinematics

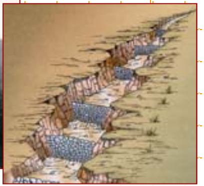


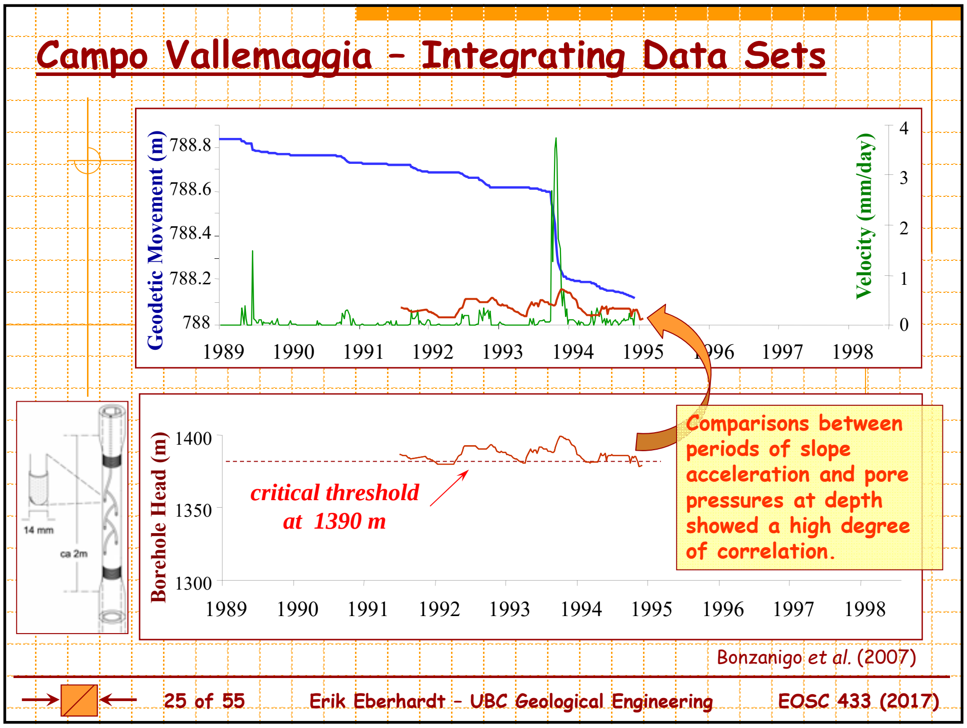
Bonzanigo *et al.* (2007)

Target: deep drainage.



Target: erosion protection.



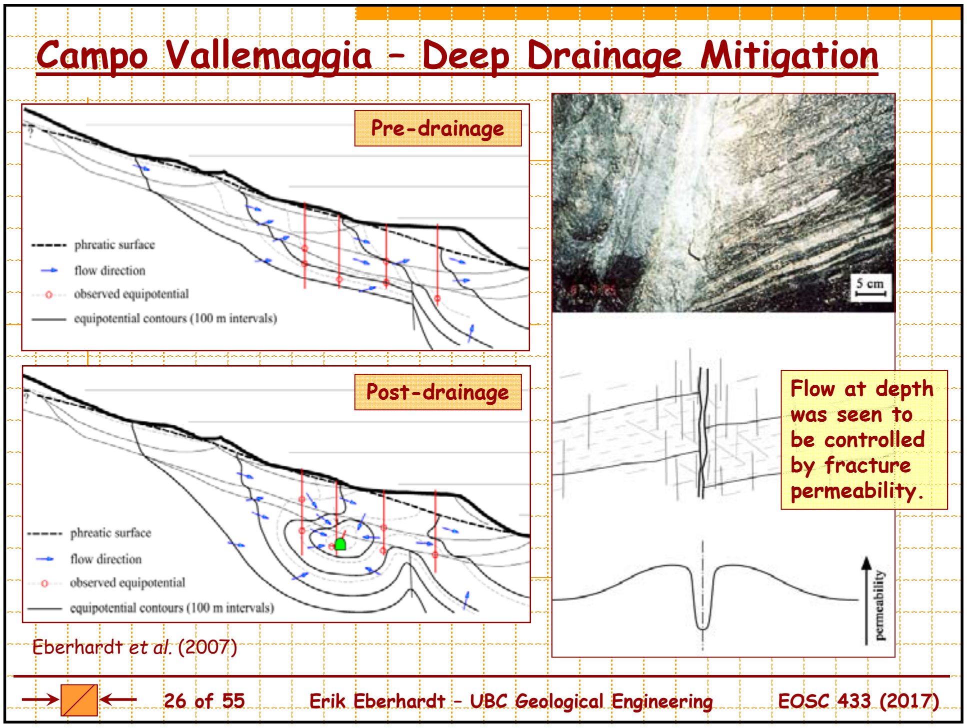


## Campo Vallemaggia – Integrating Data Sets

*critical threshold at 1390 m*

Comparisons between periods of slope acceleration and pore pressures at depth showed a high degree of correlation.

Bonzanigo *et al.* (2007)



## Campo Vallemaggia – Deep Drainage Mitigation

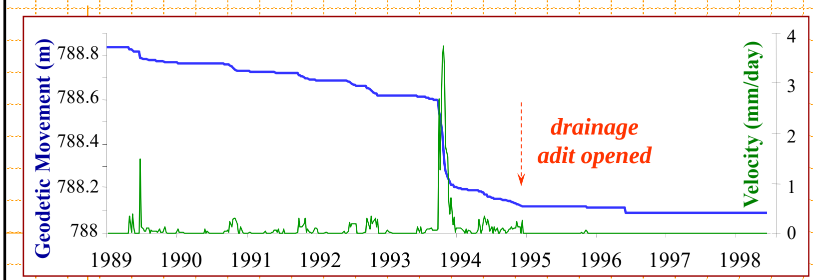
**Pre-drainage**

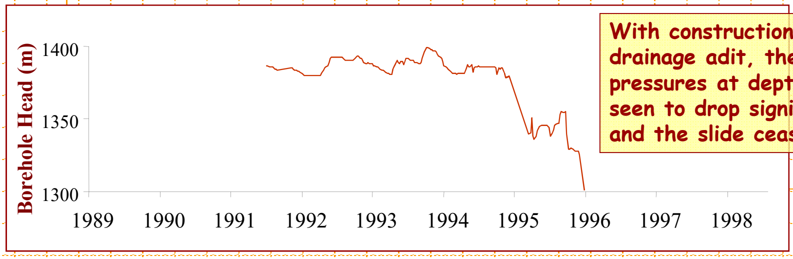
**Post-drainage**

Flow at depth was seen to be controlled by fracture permeability.

Eberhardt *et al.* (2007)

# Campo Vallemaggia – Deep Drainage Mitigation



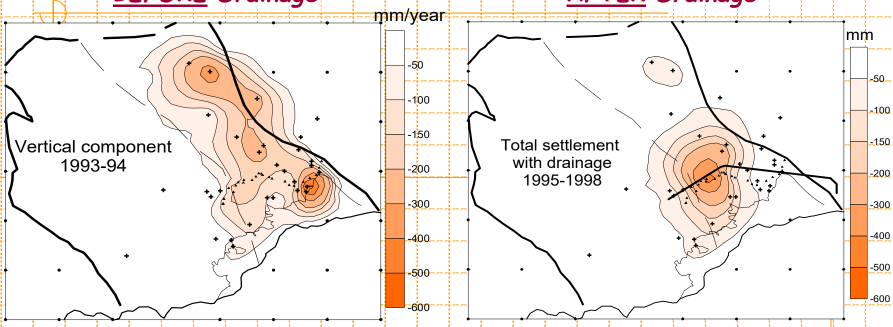


With construction of the drainage adit, the pore pressures at depth were seen to drop significantly and the slide ceased moving.

Eberhardt *et al.* (2007)

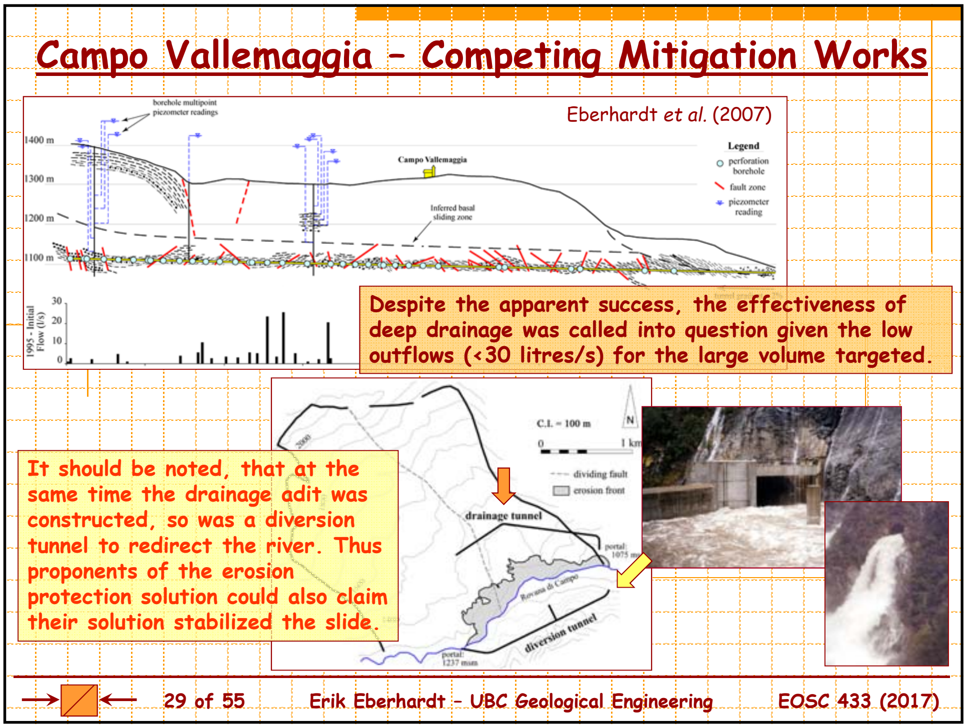
# Campo Vallemaggia – Deep Drainage Mitigation

*BEFORE Drainage* *AFTER Drainage*



Eberhardt *et al.* (2007)

*… geodetically measured surface displacements showing down-slope displacements before deep drainage, and the development of a settlement trough (i.e. consolidation) after deep drainage.*

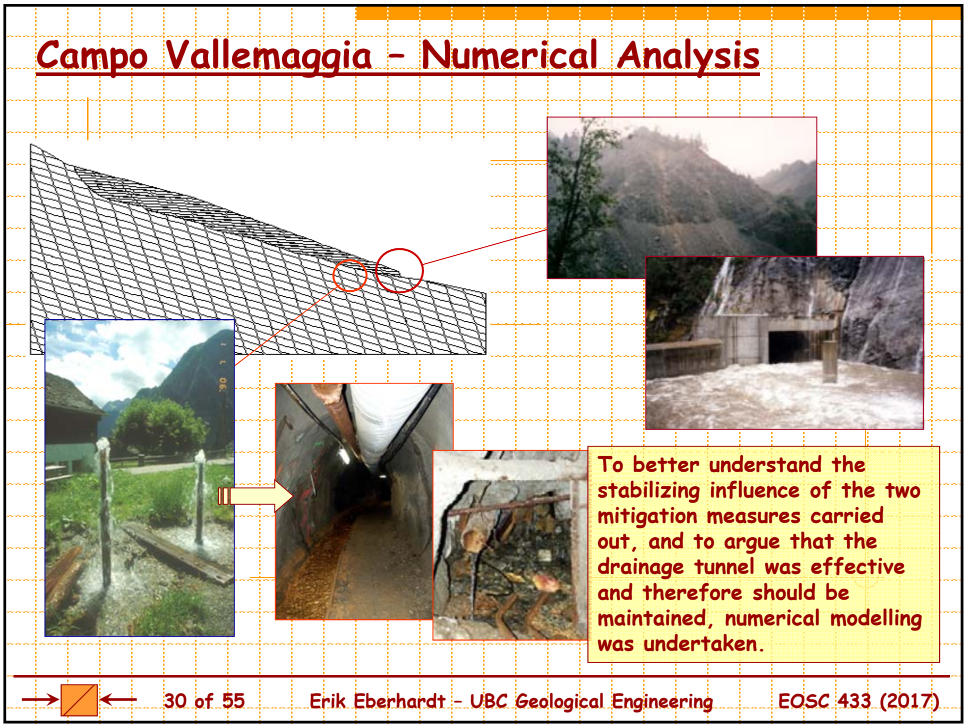


## Campo Vallemaggia – Competing Mitigation Works

Eberhardt *et al.* (2007)

Despite the apparent success, the effectiveness of deep drainage was called into question given the low outflows (<30 litres/s) for the large volume targeted.

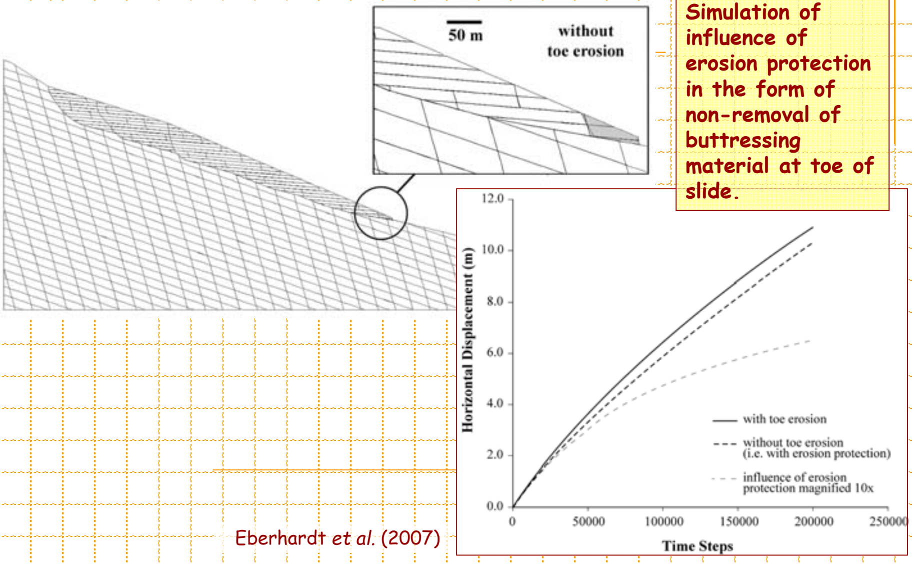
It should be noted, that at the same time the drainage adit was constructed, so was a diversion tunnel to redirect the river. Thus proponents of the erosion protection solution could also claim their solution stabilized the slide.



## Campo Vallemaggia – Numerical Analysis

To better understand the stabilizing influence of the two mitigation measures carried out, and to argue that the drainage tunnel was effective and therefore should be maintained, numerical modelling was undertaken.

# Campo Vallemaggia – Numerical Analysis



Simulation of influence of erosion protection in the form of non-removal of buttressing material at toe of slide.

Eberhardt *et al.* (2007)

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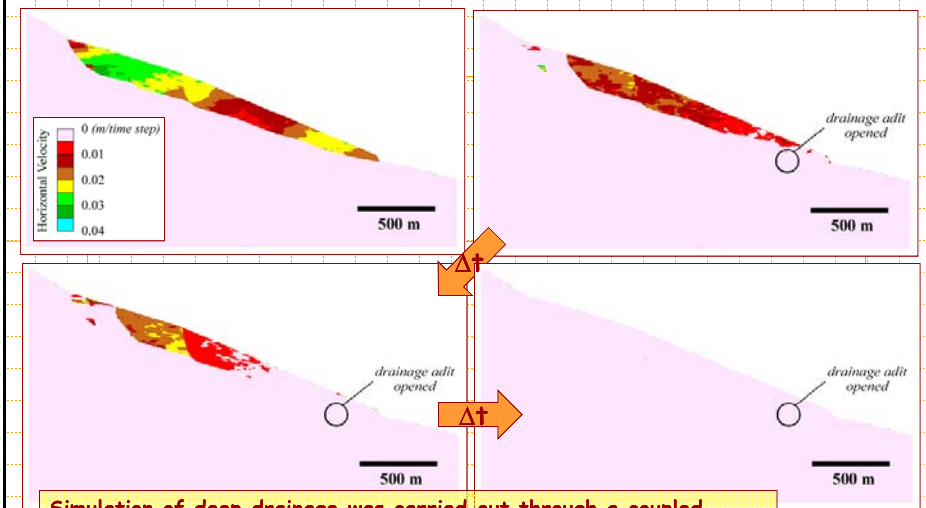
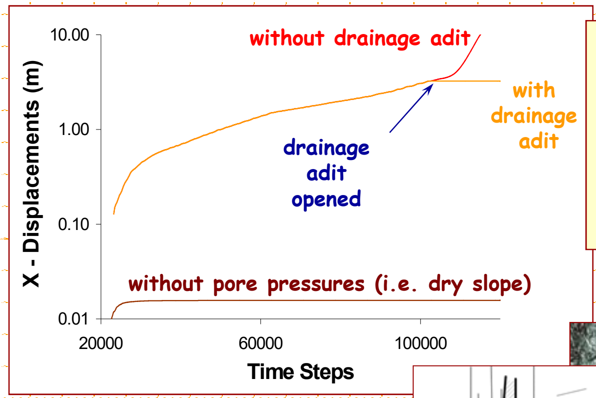
# Campo Vallemaggia – Numerical Analysis



Eberhardt *et al.* (2007)

Simulation of deep drainage was carried out through a coupled hydromechanical distinct-element analysis, using measured borehole pore pressures to constrain the model.

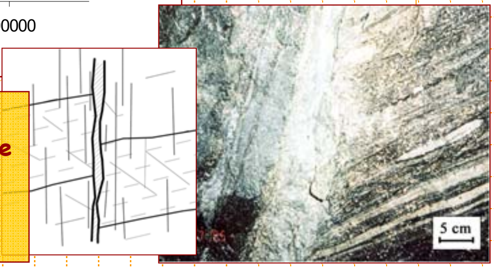
# Campo Vallemaggia – Conclusions



Eberhardt *et al.* (2007)

Distinct-element models verified that very little drainage is required (approximately 10 l/s) to significantly reduce pore pressures and to stabilize the slope.

Fracture permeability corresponds to low storativities, therefore large water outflows through drainage are not necessary to achieve significant reductions in head.



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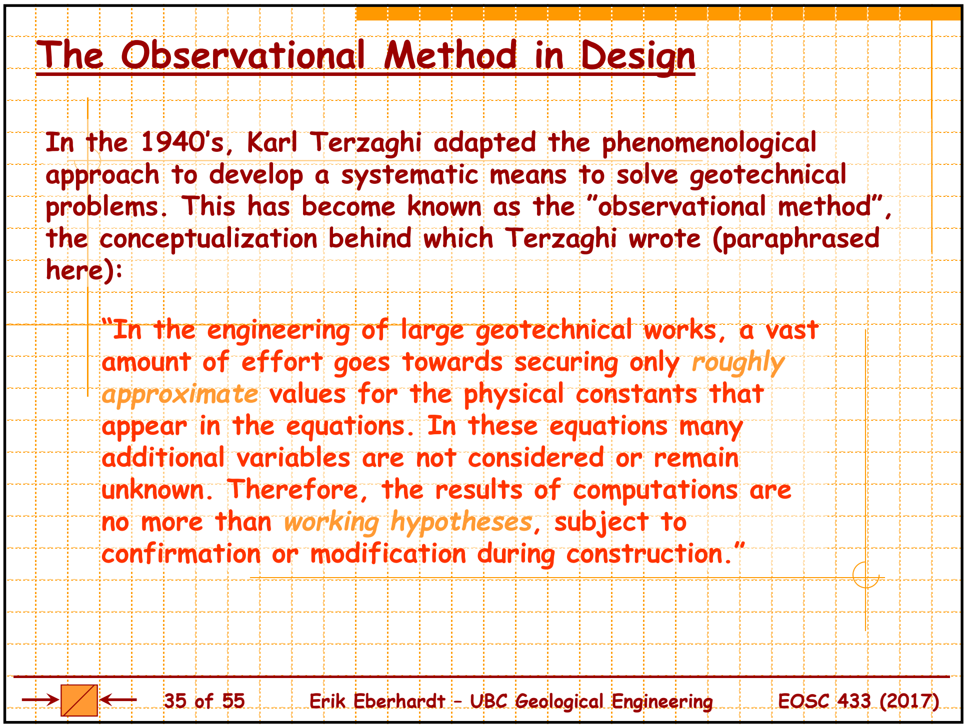
# Aiding the Judgment Process

- ✓ The more complex the model, the more input parameters it requires and the harder it becomes to determine these parameters without extensive, high quality (and of course, expensive) field investigations and laboratory testing;
- ✓ As such, we should always begin by using the simplest model that can represent the key behaviour of the problem, <u>and</u> increase the complexity as required.

> *"Everything should be made as simple as possible… <u>but not simpler</u>".*
>
> *- Albert Einstein*

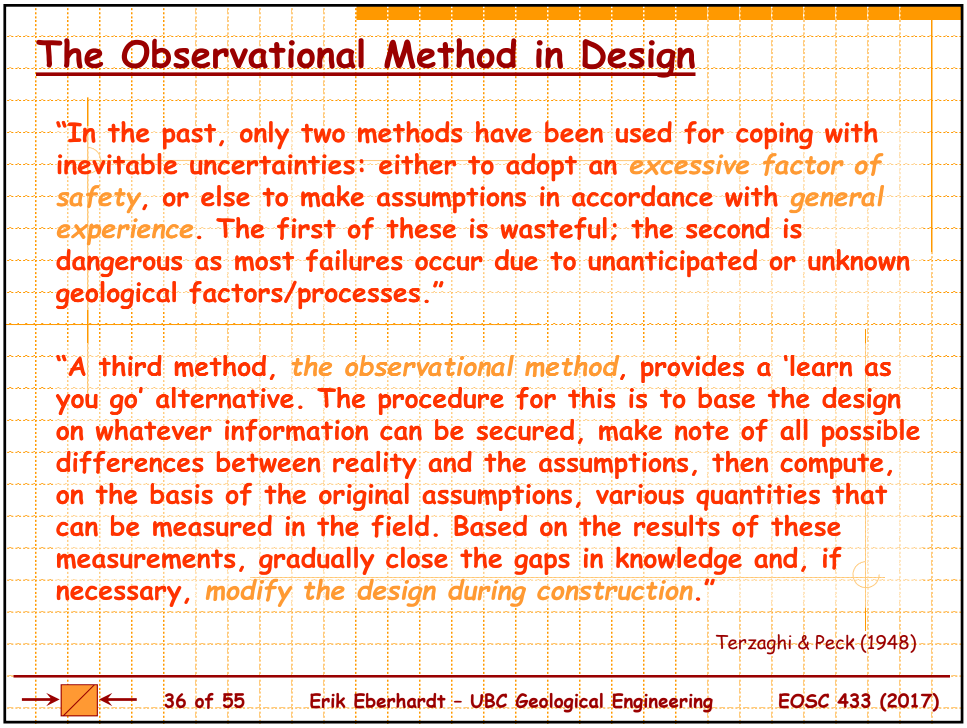
> "Numerical modelling should not be used as a substitute for thinking, but as an aid to thought and engineering judgment"



## The Observational Method in Design

In the 1940's, Karl Terzaghi adapted the phenomenological approach to develop a systematic means to solve geotechnical problems. This has become known as the "observational method", the conceptualization behind which Terzaghi wrote (paraphrased here):

> "In the engineering of large geotechnical works, a vast amount of effort goes towards securing only *roughly approximate* values for the physical constants that appear in the equations. In these equations many additional variables are not considered or remain unknown. Therefore, the results of computations are no more than *working hypotheses*, subject to confirmation or modification during construction."



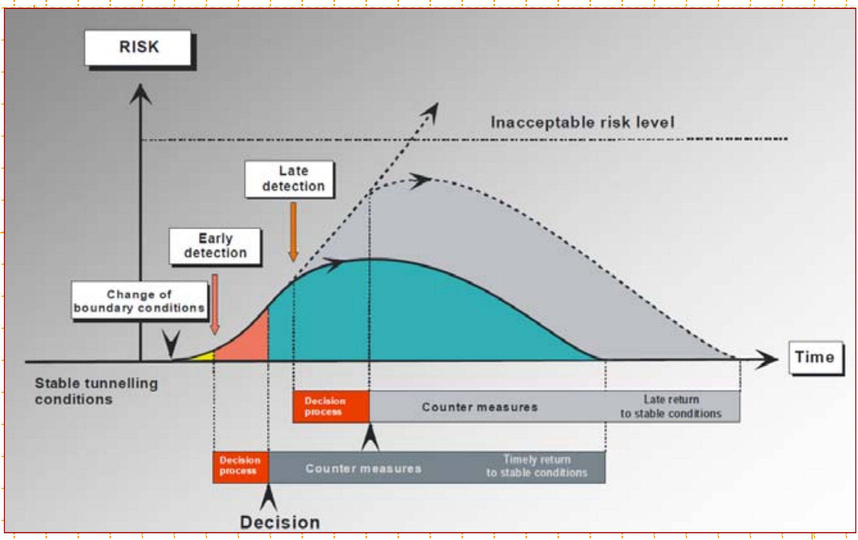
## The Observational Method in Design

"In the past, only two methods have been used for coping with inevitable uncertainties: either to adopt an *excessive factor of safety*, or else to make assumptions in accordance with *general experience*. The first of these is wasteful; the second is dangerous as most failures occur due to unanticipated or unknown geological factors/processes."

"A third method, *the observational method*, provides a 'learn as you go' alternative. The procedure for this is to base the design on whatever information can be secured, make note of all possible differences between reality and the assumptions, then compute, on the basis of the original assumptions, various quantities that can be measured in the field. Based on the results of these measurements, gradually close the gaps in knowledge and, if necessary, *modify the design during construction*."

Terzaghi & Peck (1948)

## Geo-Risk Management



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## The Observational Method in Design

In brief, the complete application of the method embodies the following components:

a) Sufficient exploration to establish the general nature, pattern and properties of the soil deposits or rock mass;

b) Assessment of the most probable conditions and the most unfavourable conceivable deviations from these conditions;

c) Establishment of the design based on a working hypothesis of behaviour anticipated under the most probable conditions;

d) Selection of quantities to be observed as construction proceeds and calculation of their anticipated values on the basis of the working hypothesis;

# The Observational Method in Design

In brief, the complete application of the method embodies the following components (continued):

e) Calculation of values of the same quantities under the most unfavourable conditions compatible with the available data concerning the subsurface conditions;

f) Selection in advance of a course of action or modification of design for every foreseeable significant deviation of the observational findings from those predicted on the basis of the working hypothesis;

g) Measurement of quantities to be observed and evaluation of actual conditions;

h) Modification of design to suit actual conditions.

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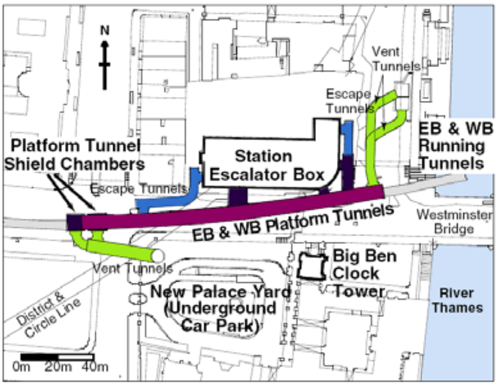
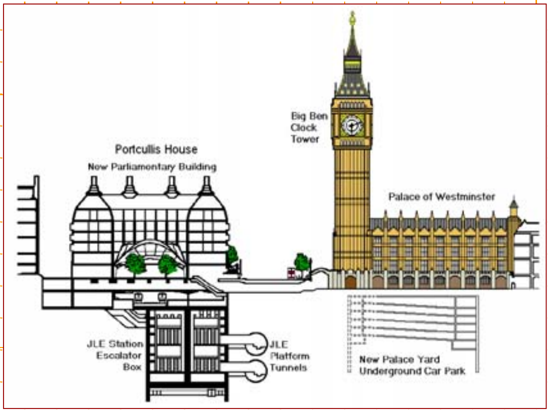
# Observation Method Example – Jubilee Extension

The Jubilee Line Extension to the London Underground, started in 1994 and called for twin tunnels 11 km long, crossing the river in four places, with eleven new stations to be built, eight of which were to be underground. One of the more problematic of these was a station placed right opposite Big Ben.



# Observation Method Example – Jubilee Extension

The technical implications were immense. Built in 1858, Big Ben is known to be on a shallow foundation. It started to lean towards the North shortly after completion. Any ground movement in the vicinity would exaggerate this lean, and threaten the stability of the structure.



Burland *et al.* (2001)

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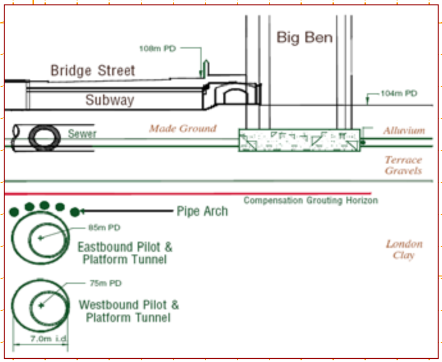
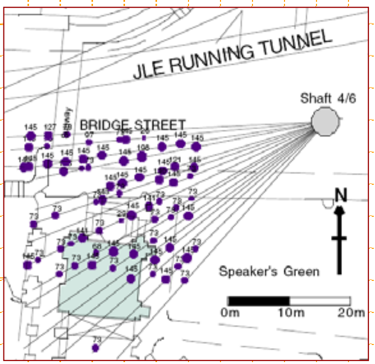
# Observation Method Example – Jubilee Extension

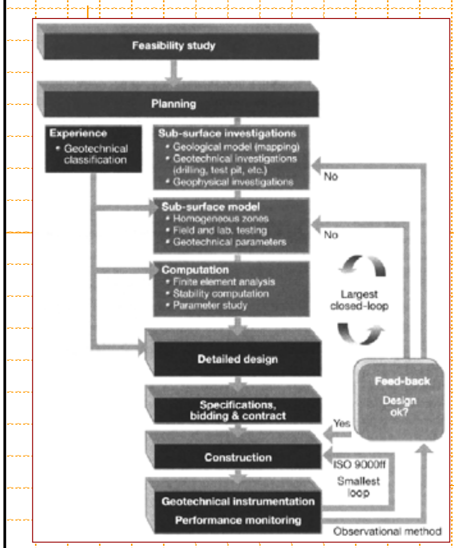
To deal with excavation-induced settlements that may irreversibly damage historic buildings in the area, the design called for the use of compensation grouting during tunnelling. In this process, a network of horizontal tubes between the tunnels and the ground surface is introduced, from which a series of grout holes are drilled. From these, liquid cement can be injected into the ground from multiple points to control/prevent movement during excavation of the main tunnels.





Burland *et al.* (2001)

# Observation Method Example – Jubilee Extension



*The observational method:*

- 'learn as you go'
- base the design on information that can be secured, making note of all possible differences between reality and the assumptions
- compute, based on original assumptions, various quantities that can be measured in the field
- based on the results of these measurements, gradually close the gaps in knowledge and, if necessary, *modify during construction*.

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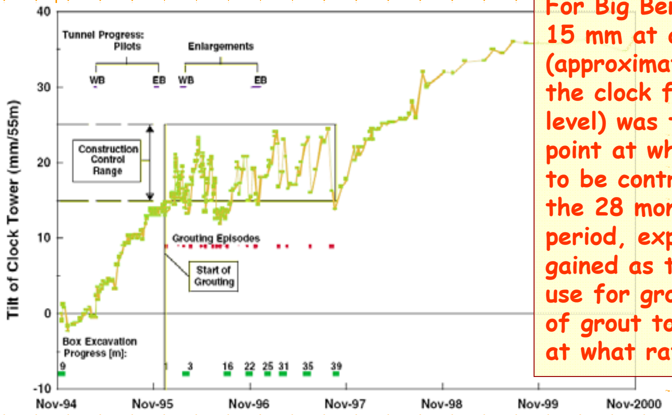
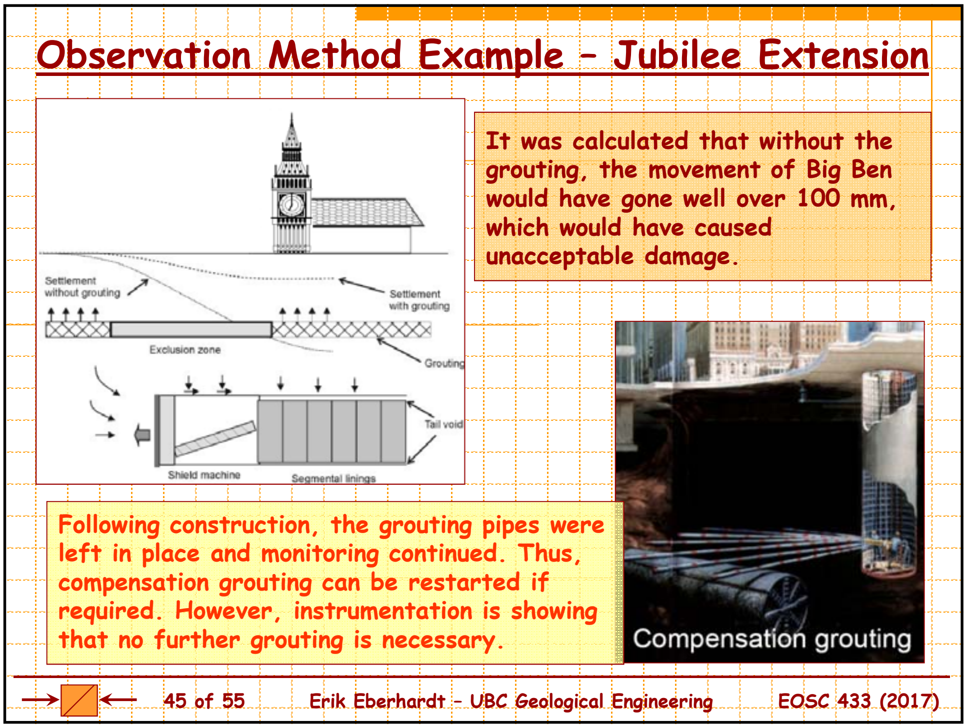
# Observation Method Example – Jubilee Extension

Instrumentation was attached to Big Ben and to the buildings in the vicinity to measure movement (with some 7000 monitoring points), and computers were used to analyze the data to calculate where and when the grout has to be injected.



For Big Ben, a movement of 15 mm at a height of 55m (approximately the height of the clock face above ground level) was taken to be the point at which movement had to be controlled. Throughout the 28 month construction period, experience had to be gained as to which tube to use for grouting, the volume of grout to be injected and at what rate.

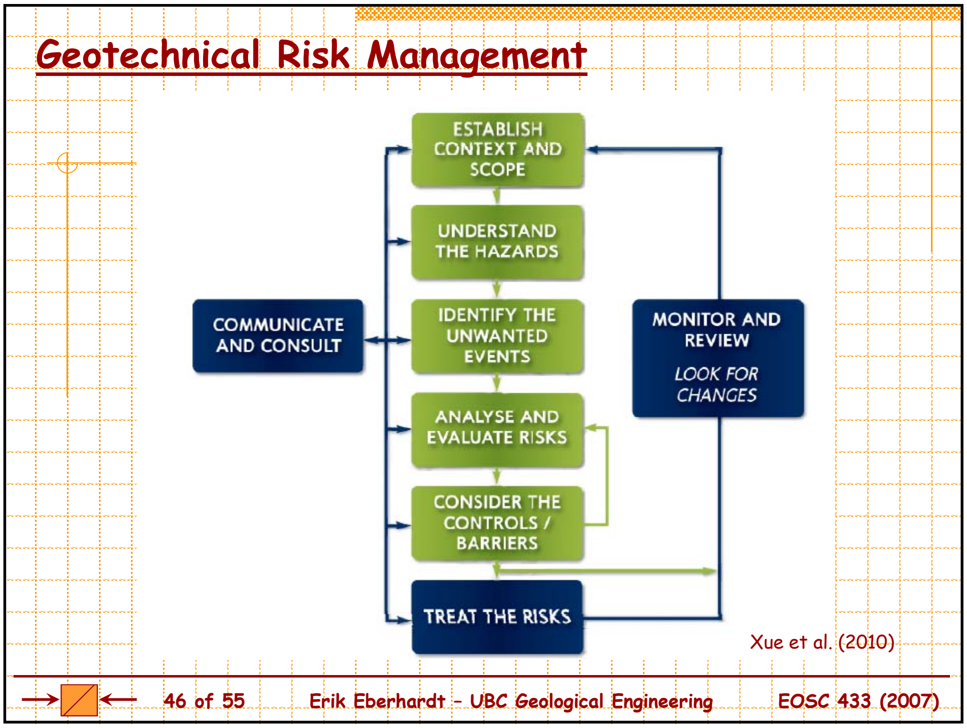
Burland *et al.* (2001)



# Observation Method Example – Jubilee Extension

It was calculated that without the grouting, the movement of Big Ben would have gone well over 100 mm, which would have caused unacceptable damage.

Following construction, the grouting pipes were left in place and monitoring continued. Thus, compensation grouting can be restarted if required. However, instrumentation is showing that no further grouting is necessary.



# Geotechnical Risk Management

ESTABLISH CONTEXT AND SCOPE

UNDERSTAND THE HAZARDS

IDENTIFY THE UNWANTED EVENTS

ANALYSE AND EVALUATE RISKS

CONSIDER THE CONTROLS / BARRIERS

TREAT THE RISKS

COMMUNICATE AND CONSULT

MONITOR AND REVIEW

*LOOK FOR CHANGES*

Xue et al. (2010)

# Trigger Action Response Plan (TARP)

Hawley et al. (2009)

**Trigger Action Response Plans (TARPs) define the minimum set of actions required by site personnel in response to the deviation in mine conditions from normality. They are usually implemented in parallel with early warning monitoring. A typical system of trigger points might be as follows:**

→ The initial trigger point for concern should be if the movement rate is double the survey accuracy from the last reading. In this case the reading should be repeated as soon as possible, and if correct, additional readings should be taken at an increased frequency.

→ The 2nd trigger point would be if movement rates double over two consecutive readings. In this case, the area of movement should be inspected. If the cause of movement can't be determined, mining in the area should be reduced or suspended and the reading frequency increased.

→ If an increase in movement greater than four times the survey error is recorded for *any* reading when there has been no previous activity, operations should be notified immediately and the area cleared until the point has been resurveyed. If the reading is confirmed, the area should remain cleared until the situation has been investigated.

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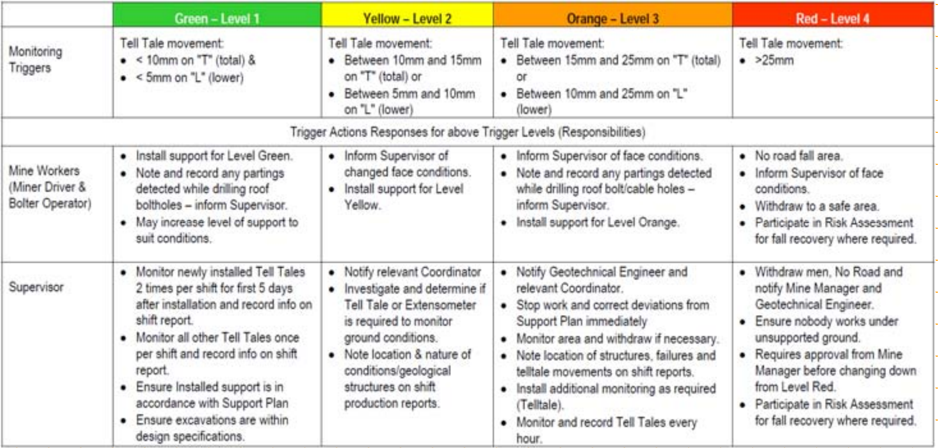
# Trigger Action Response Plan (TARP)

Xue et al. (2010)



| | Green – Level 1 | Yellow – Level 2 | Orange – Level 3 | Red – Level 4 |
|---|---|---|---|---|
| Monitoring Triggers | Tell Tale movement:<br>• < 10mm on "T" (total) &<br>• < 5mm on "L" (lower) | Tell Tale movement:<br>• Between 10mm and 15mm on "T" (total) or<br>• Between 5mm and 10mm on "L" (lower) | Tell Tale movement:<br>• Between 15mm and 25mm on "T" (total) or<br>• Between 10mm and 25mm on "L" (lower) | Tell Tale movement:<br>• >25mm |
| Trigger Actions Responses for above Trigger Levels (Responsibilities) | | | | |
| Mine Workers (Miner Driver & Bolter Operator) | • Install support for Level Green.<br>• Note and record any partings detected while drilling roof boltholes – inform Supervisor.<br>• May increase level of support to suit conditions. | • Inform Supervisor of changed face conditions.<br>• Install support for Level Yellow. | • Inform Supervisor of face conditions.<br>• Note and record any partings detected while drilling roof bolt/cable holes – inform Supervisor.<br>• Install support for Level Orange. | • No road fall area.<br>• Inform Supervisor of face conditions.<br>• Withdraw to a safe area.<br>• Participate in Risk Assessment for fall recovery where required. |
| Supervisor | • Monitor newly installed Tell Tales 2 times per shift for first 5 days after installation and record info on shift report.<br>• Monitor all other Tell Tales once per shift and record info on shift report.<br>• Ensure Installed support is in accordance with Support Plan<br>• Ensure excavations are within design specifications. | • Notify relevant Coordinator<br>• Investigate and determine if Tell Tale or Extensometer is required to monitor ground conditions.<br>• Note location & nature of conditions/geological structures on shift production reports. | • Notify Geotechnical Engineer and relevant Coordinator.<br>• Stop work and correct deviations from Support Plan immediately<br>• Monitor area and withdraw if necessary.<br>• Note location of structures, failures and telltale movements on shift reports.<br>• Install additional monitoring as required (Telltale).<br>• Monitor and record Tell Tales every hour. | • Withdraw men, No Road and notify Mine Manager and Geotechnical Engineer.<br>• Ensure nobody works under unsupported ground.<br>• Requires approval from Mine Manager before changing down from Level Red.<br>• Participate in Risk Assessment for fall recovery where required. |

## Trigger Action Response Plan (TARP)

| | Green – Level 1 | Yellow – Level 2 | Orange – Level 3 | Red – Level 4 |
|---|---|---|---|---|
| Site Geotechnical Engineer | • Check shift reports for changed conditions.<br>• Routine monitoring and mapping.<br>• Have all Support Plans prepared and signed off.<br>• Provide plots of instrument results.<br>• Ensure all support consumables are available on site.<br>• Conduct duties as defined in PHMP Responsibilities. | • Consult with relevant Supervisor and Coordinator<br>• Check shift reports for changed conditions.<br>• Inspect, and map within 48 hrs of report.<br>• Determine whether remedial action is required.<br>• Determine level of monitoring required.<br>• Review TARP levels & triggers if necessary.<br>• Review instrument monitoring intervals. | • Consult with relevant Supervisor and Coordinator<br>• Inspect and map area as soon as practicable within 12 hours of report.<br>• Determine whether additional support is required and other corrective actions.<br>• Determine level of monitoring required.<br>• Participate in Strata Control PHMP meetings.<br>• Review TARP conditions & triggers if necessary. | • Consult with Mine Manager, relevant Supervisor and Coordinator<br>• Inspect area as soon as practicable and within 4 hours of report.<br>• Assist with the development of a recovery plan.<br>• Provide recommendations regarding reducing level of support.<br>• Participate in Risk Assessment for fall recovery where required. |
| Underground Mine Manager | Monitor shift reports. | • Monitor shift reports.<br>• Note changed conditions.<br>• Review and approve any proposed change to TARP. | • Consult with Geotechnical Engineer, relevant Supervisor and Coordinator<br>• Authorise Recovery Plan<br>• Partake in Strata Control PHMP meetings and advise SSE on recommended response.<br>• Review and approve any proposed change to TARP. | • Advise SSE on recovery plan.<br>• Authorise reduction of level of support.<br>• Notify Site/Industry Safety & Health Representatives and Inspectorate as required. |

Xue et al. (2010)

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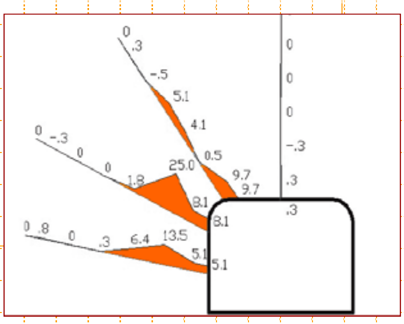
## Monitoring & Optimization: Smart Cables

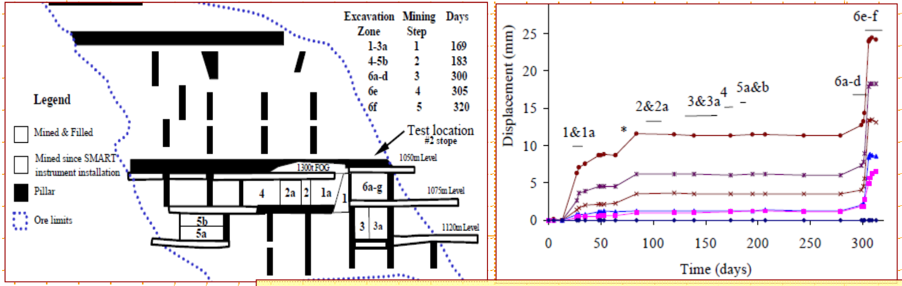
The SMART (Stretch Measurement to Assess Reinforcement Tension) Cable combines the support capabilities of a 7-strand cable bolt with the sensory capabilities of a multipoint borehole extensometer without changing the load-bearing properties of the cable. This allows a standard cable in the support pattern to be directly replaced with an instrumented cable capable of carrying out the support requirements of the one it replaces, as well as providing a clear indication of the cable loading at six points along its length.



# Monitoring & Optimization: Smart Cables

Load determination is based on the stretch of the cable bolt. The results may be used to assess the factor of safety of the support, thereby optimising support design and minimising risk. The SMART Cable can be supplied as a plain seven-wire strand cable bolt, garford bulb or bulge cable layout with variable bulb spacings and debonded sections.

The instrumentation does not affect the bond strength properties of the cable, and can be installed by a cable bolt crew as a routine installation.

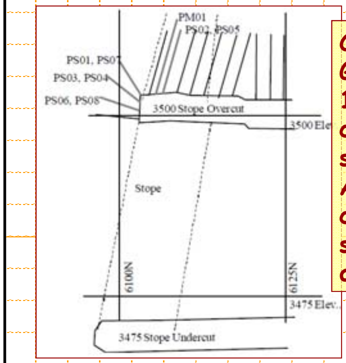


| Excavation Zone | Mining Step | Days |
|---|---|---|
| 1-3a | 1 | 169 |
| 4-5b | 2 | 183 |
| 6a-d | 3 | 300 |
| 6e | 4 | 305 |
| 6f | 5 | 320 |

SMART Cable response in relation to blast sequencing.

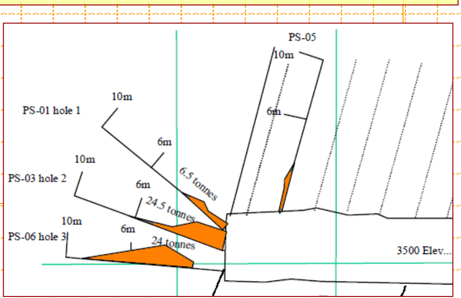
Bawden & Lausch (2000)

# Case History - Smart Cables



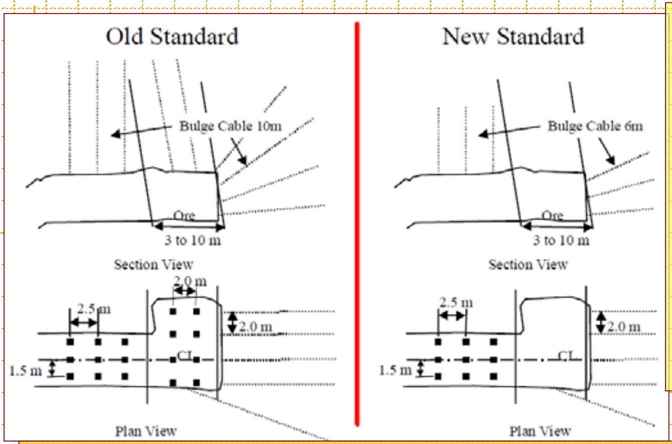
Cable bolt optimization study at the Barrick Gold Bousquet mine, conducted for a stope at 1370 m depth. The original support design called for installation of 530 meters of single strand Garford bulge cable per stope overcut. At an average cost of $35/m this resulted in a cost of $18,550 per stope, and the mine was spending a total of $1.52 million/year to install a total of 43,500 meters of cable bolts.

The SMART cables in the lower two hangingwall holes all loaded to near rupture, whereas the back SMART cables recorded little movement, and hence minimal load development, with no movement deeper than 2.5 m into the back.



Bawden & Lausch (2000)

# Case History – Smart Cables



Bawden & Lausch (2000)

Based on these results, the cable support was redesigned. Hangingwall cable bolting requirements were reduced by 63% for the primary stopes and 46% for the secondary stopes.

This support optimization study resulted in an annual reduction of 9,300 meters of cabling for an annual cost saving of $325,000 [projected cost savings for the remaining five years of reserves of $1.5 million]. The total instrumentation cost for the study was <$20,000.

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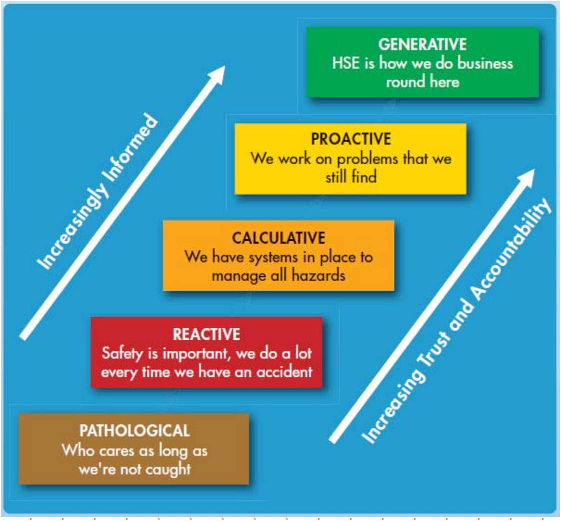
# Risk Management Approaches



**GENERATIVE**
HSE is how we do business round here

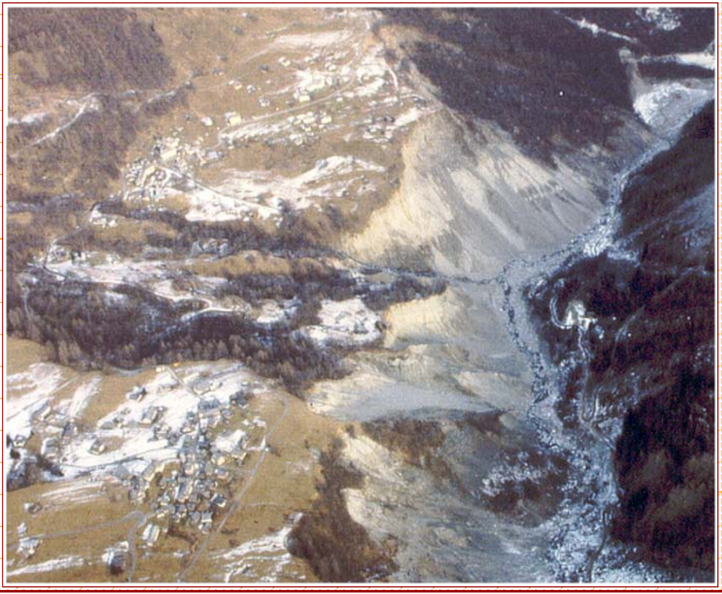
**PROACTIVE**
We work on problems that we still find

**CALCULATIVE**
We have systems in place to manage all hazards

**REACTIVE**
Safety is important, we do a lot every time we have an accident

**PATHOLOGICAL**
Who cares as long as we're not caught

## Case History - Campo Vallemaggia



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## Case History - Campo Vallemaggia

**Geology** - *gneisses & schists*
**Mechanism** – *translational slide*
**Surface Area** ~ 6 km$^2$
**Total Volume** ~ 800,000,000 m$^3$
**Average Velocity** ~ 5 cm/year
**Maximum Depth** ~ 300 m

**Background**:

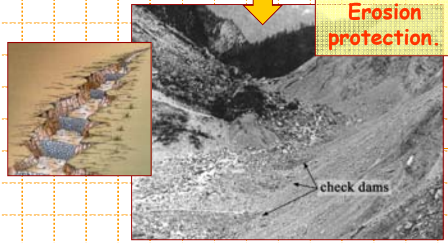
For more than 200 years, the villages of Campo Vallemaggia and Cimalmotto have been slowly moving atop a deep-seated rockslide in the southern Swiss Alps. Over this time, numerous mitigation measures have been carried out to stabilize the rockslide but with limited to no success. These works largely focussed on minimising erosion at the toe of the landslide. More recently, the need to stabilize the slope was becoming critical as with each passing year the two villages were being pushed closer to the edge of a 100-m high erosion front at the foot of the rockslide.

# Case History - Campo Vallemaggia

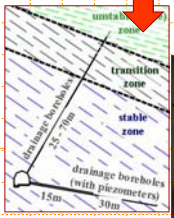
Uncertainty in stabilizing the rockslide came about from two competing arguments as to the cause of the slope movements.

**Opinion #1**: Massive erosion at the toe of the slide acts to reduce passive resistance.

**Opinion #2**: Deep artesian water pressures act to reduce the effective strength along the slide surface.



**Solution**: Erosion protection.



**Solution**: Deep drainage.

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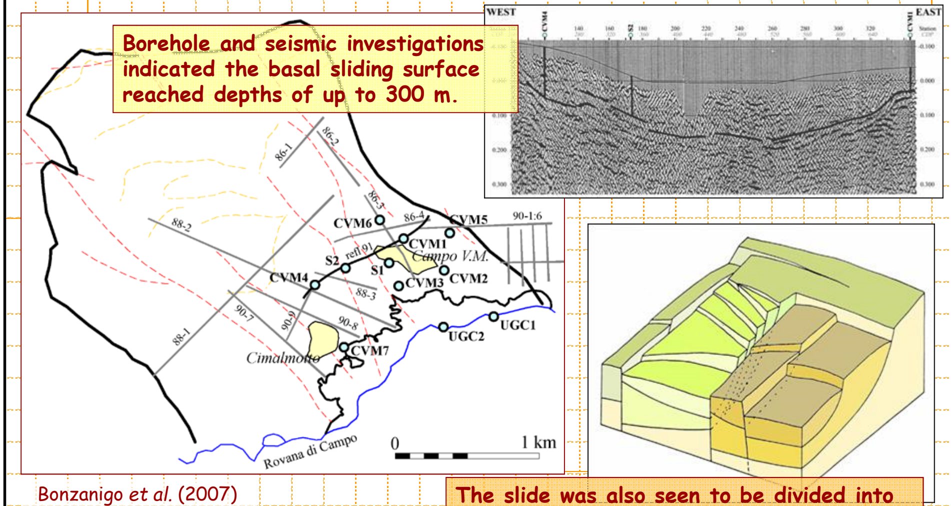
# Campo Vallemaggia – Field Investigations

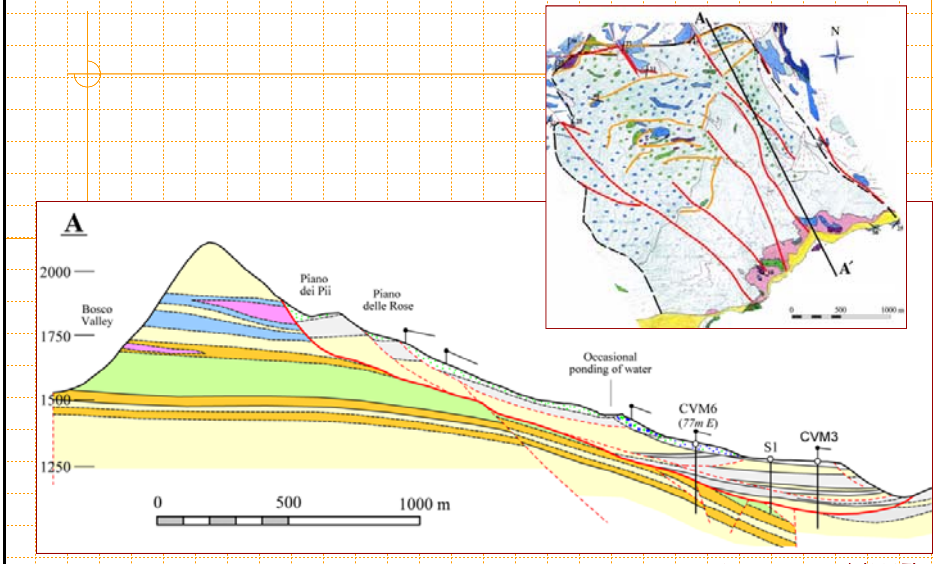


Borehole and seismic investigations indicated the basal sliding surface reached depths of up to 300 m.

Bonzanigo *et al.* (2007)

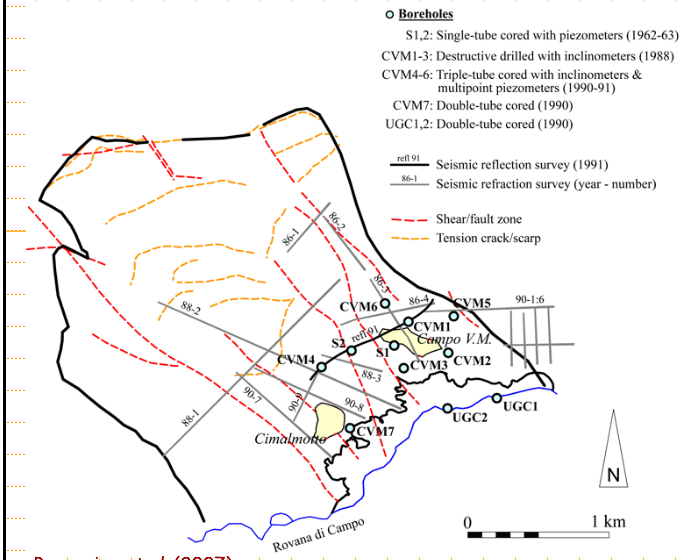
The slide was also seen to be divided into two main bodies, separated by a large fault running the length of the rockslide.

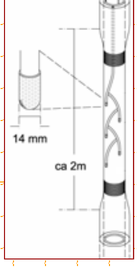
# Campo Vallemaggia – Geology



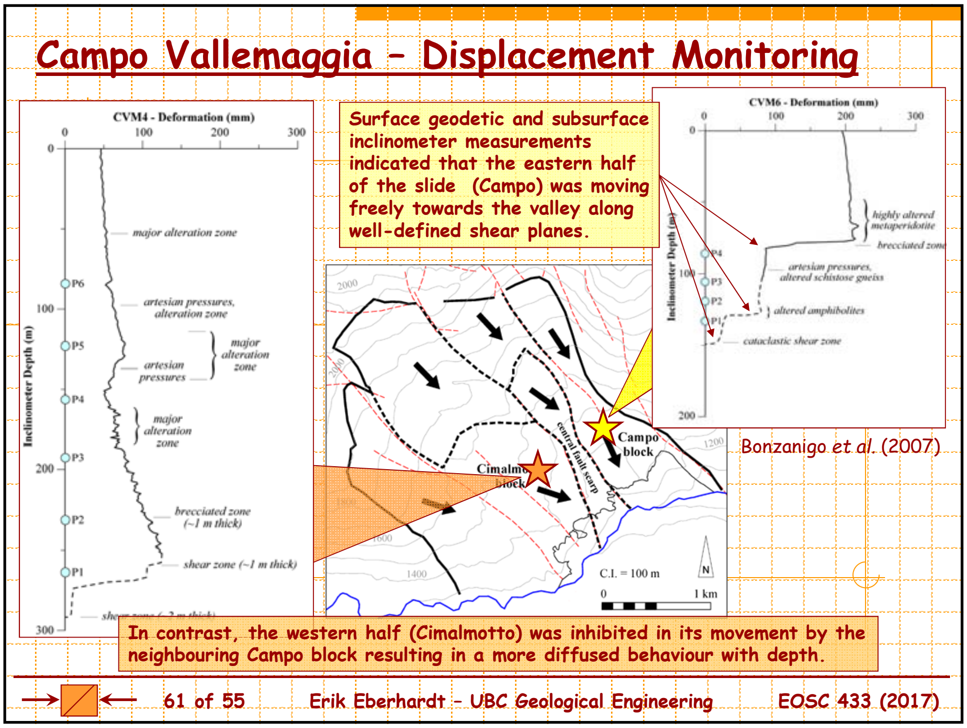
Bonzanigo *et al.* (2007)

# Campo Vallemaggia – Subsurface Monitoring





Bonzanigo *et al.* (2007)

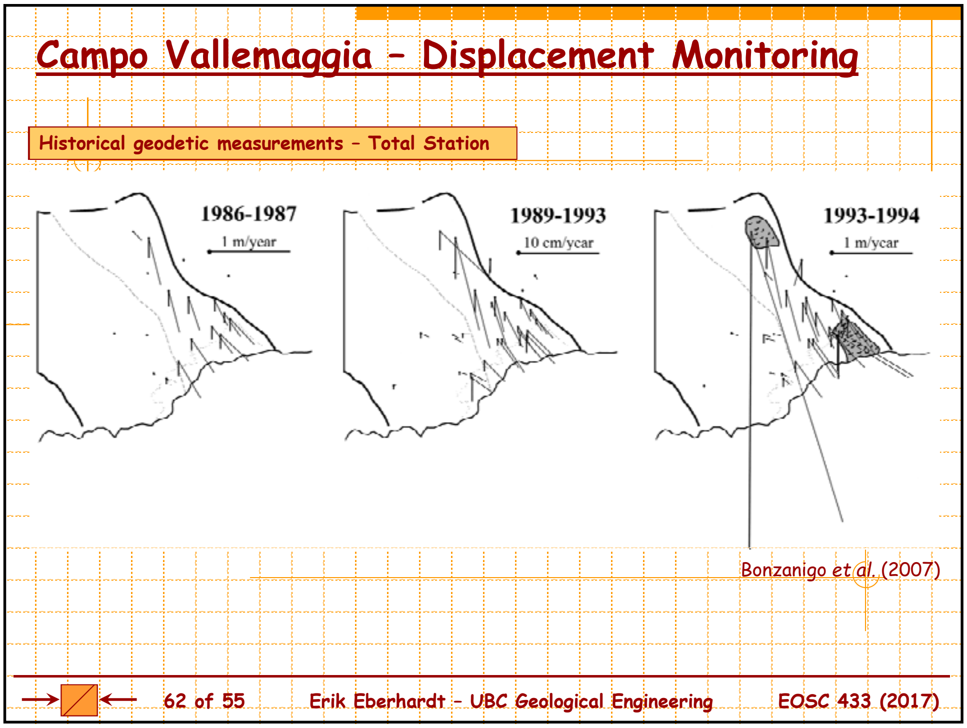


# Campo Vallemaggia – Displacement Monitoring

Surface geodetic and subsurface inclinometer measurements indicated that the eastern half of the slide (Campo) was moving freely towards the valley along well-defined shear planes.

Bonzanigo *et al.* (2007)

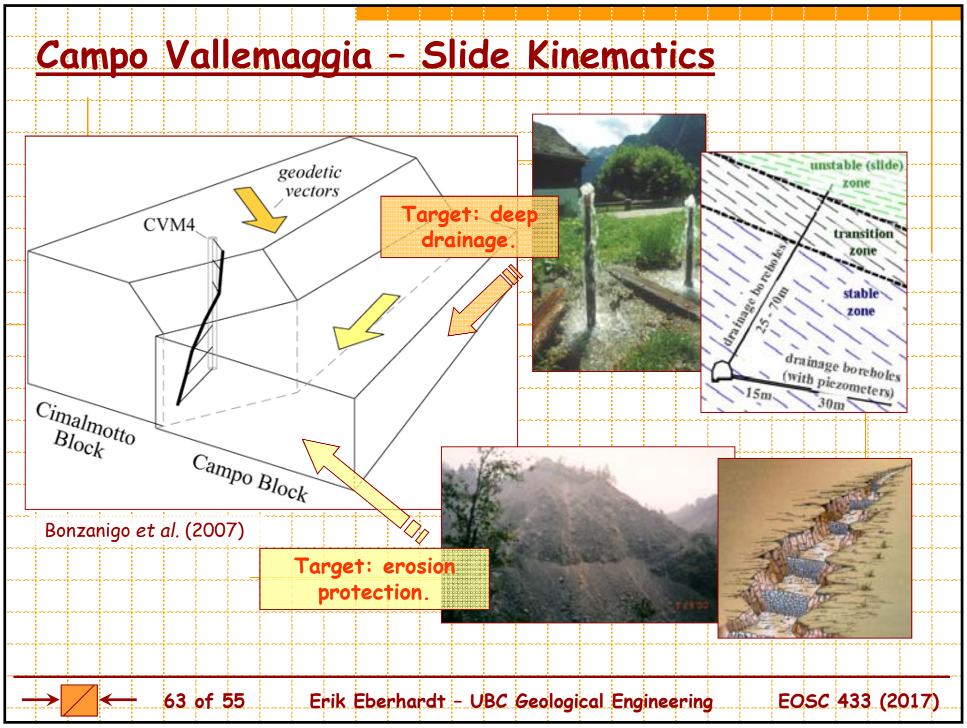
In contrast, the western half (Cimalmotto) was inhibited in its movement by the neighbouring Campo block resulting in a more diffused behaviour with depth.



# Campo Vallemaggia – Displacement Monitoring

Historical geodetic measurements – Total Station

Bonzanigo et al. (2007)

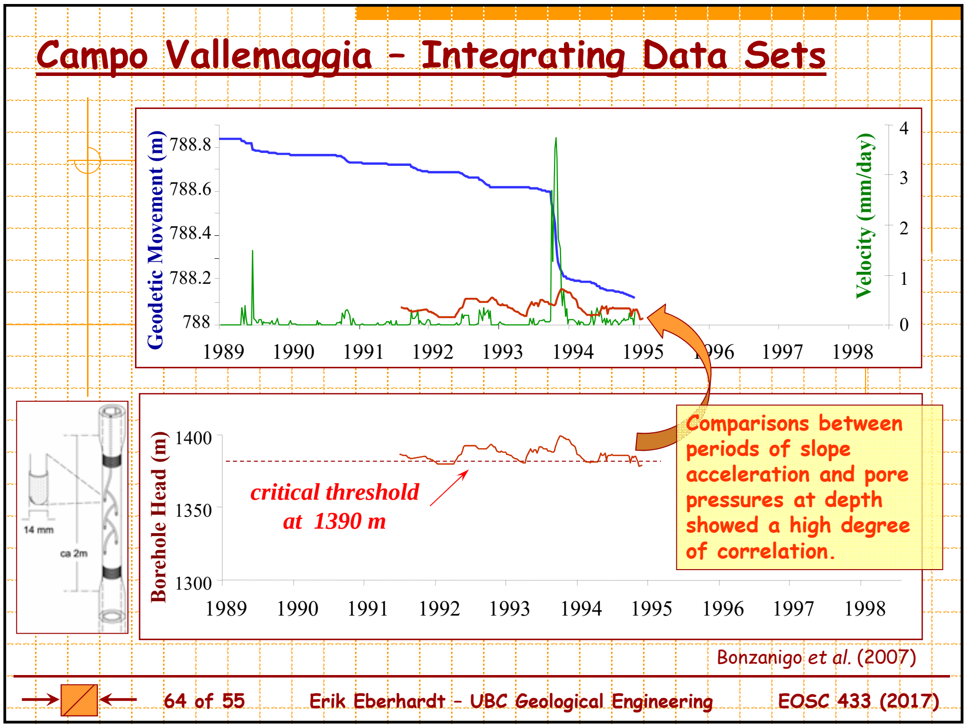


# Campo Vallemaggia – Slide Kinematics

Target: deep drainage.

Target: erosion protection.

Bonzanigo *et al.* (2007)

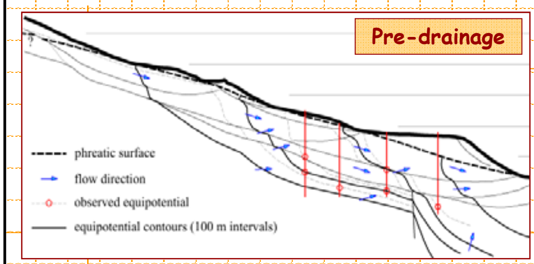


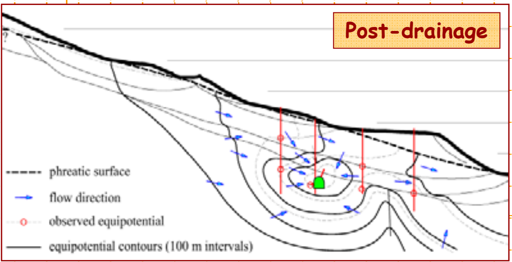
# Campo Vallemaggia – Integrating Data Sets

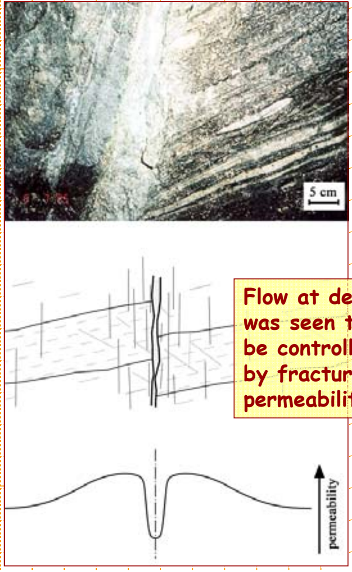
Comparisons between periods of slope acceleration and pore pressures at depth showed a high degree of correlation.

Bonzanigo *et al.* (2007)

# Campo Vallemaggia – Deep Drainage Mitigation







Flow at depth was seen to be controlled by fracture permeability.

Eberhardt *et al.* (2007)

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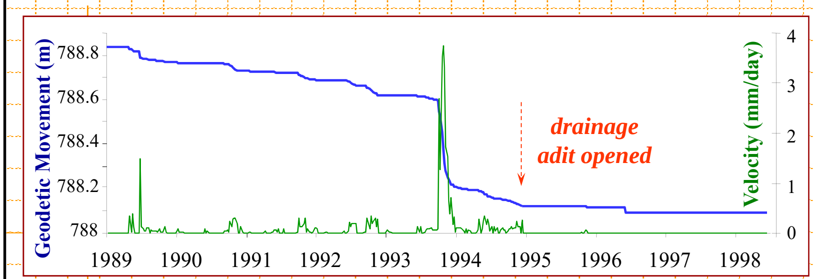
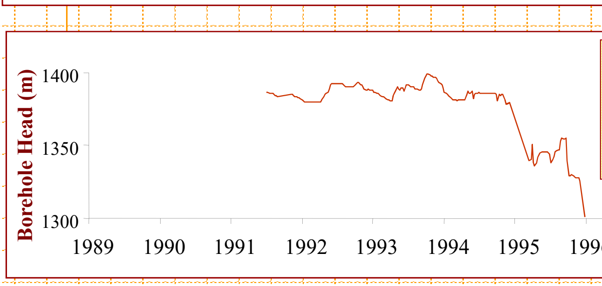
# Campo Vallemaggia – Deep Drainage Mitigation

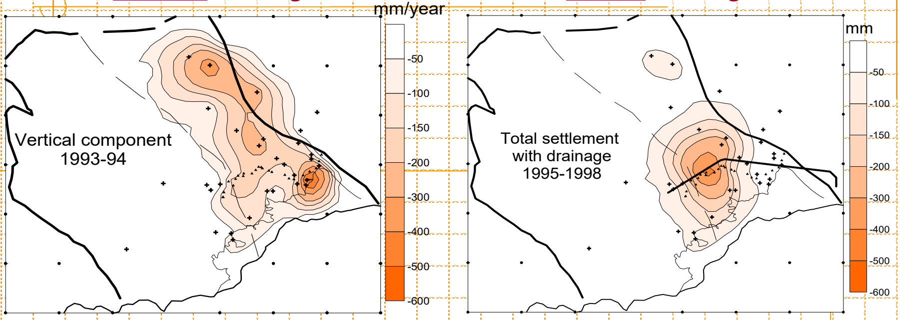




With construction of the drainage adit, the pore pressures at depth were seen to drop significantly and the slide ceased moving.

Eberhardt *et al.* (2007)

# Campo Vallemaggia – Deep Drainage Mitigation



*BEFORE* Drainage

*AFTER* Drainage

Eberhardt *et al.* (2007)

*… geodetically measured surface displacements showing down-slope displacements before deep drainage, and the development of a settlement trough (i.e. consolidation) after deep drainage.*

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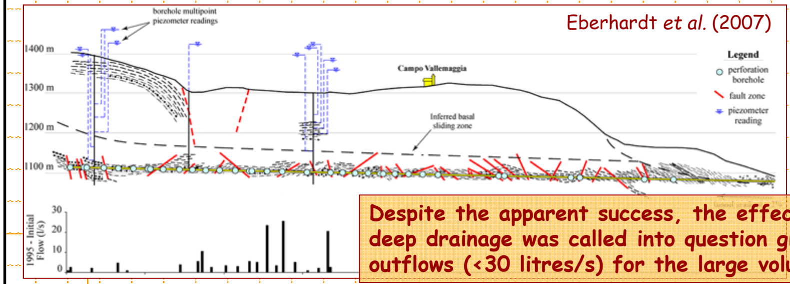
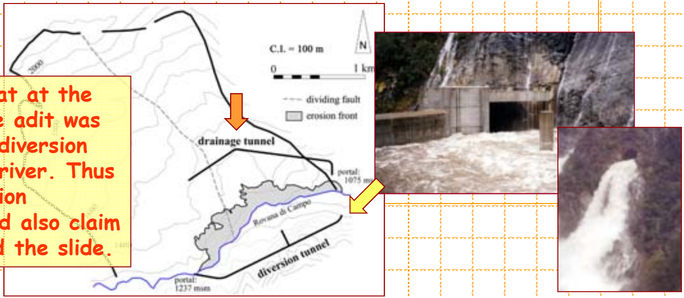
# Campo Vallemaggia – Competing Mitigation Works



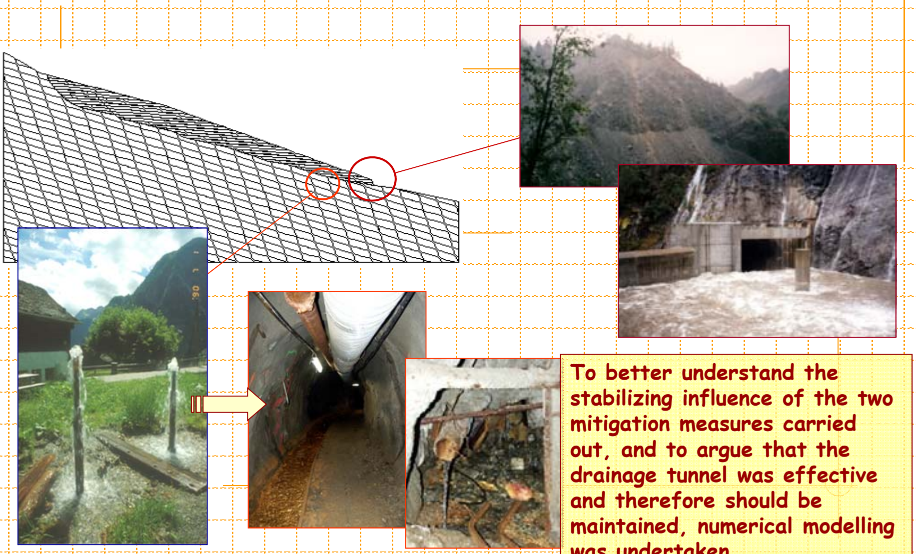
Eberhardt *et al.* (2007)

Despite the apparent success, the effectiveness of deep drainage was called into question given the low outflows (<30 litres/s) for the large volume targeted.



It should be noted, that at the same time the drainage adit was constructed, so was a diversion tunnel to redirect the river. Thus proponents of the erosion protection solution could also claim their solution stabilized the slide.

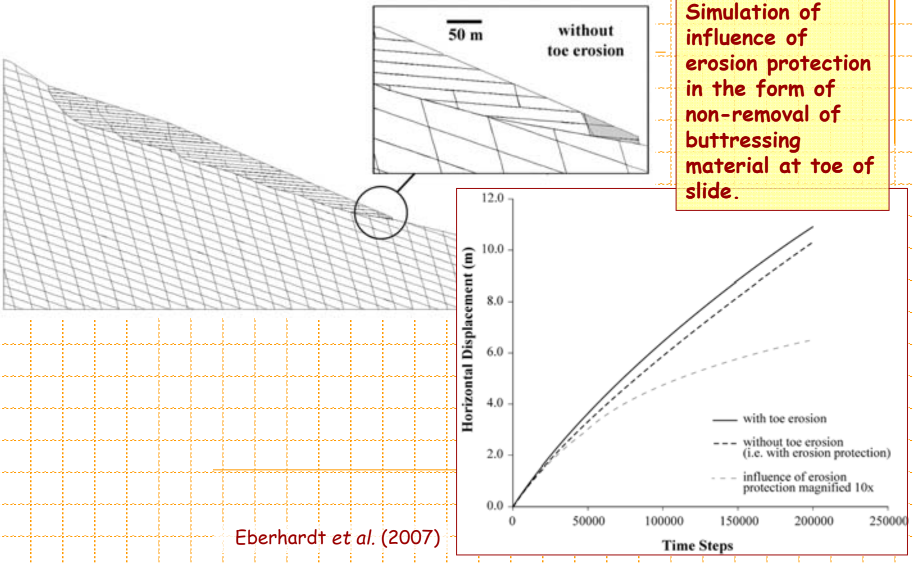
# Campo Vallemaggia – Numerical Analysis



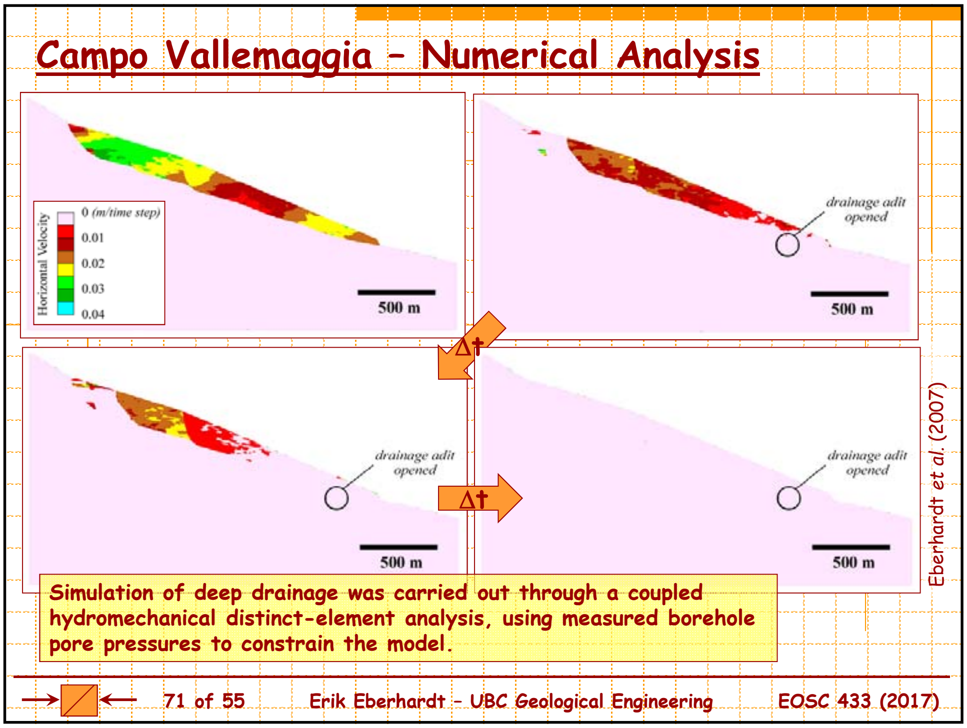
To better understand the stabilizing influence of the two mitigation measures carried out, and to argue that the drainage tunnel was effective and therefore should be maintained, numerical modelling was undertaken.

# Campo Vallemaggia – Numerical Analysis

Simulation of influence of erosion protection in the form of non-removal of buttressing material at toe of slide.



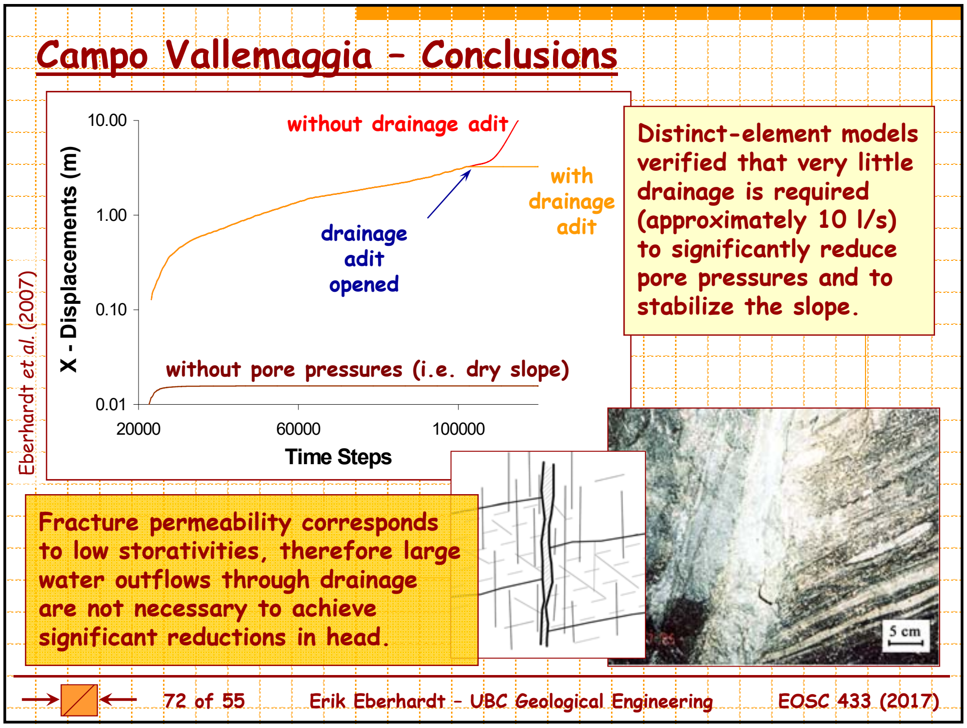
Eberhardt *et al.* (2007)



## Campo Vallemaggia – Numerical Analysis

Eberhardt *et al.* (2007)

Simulation of deep drainage was carried out through a coupled hydromechanical distinct-element analysis, using measured borehole pore pressures to constrain the model.

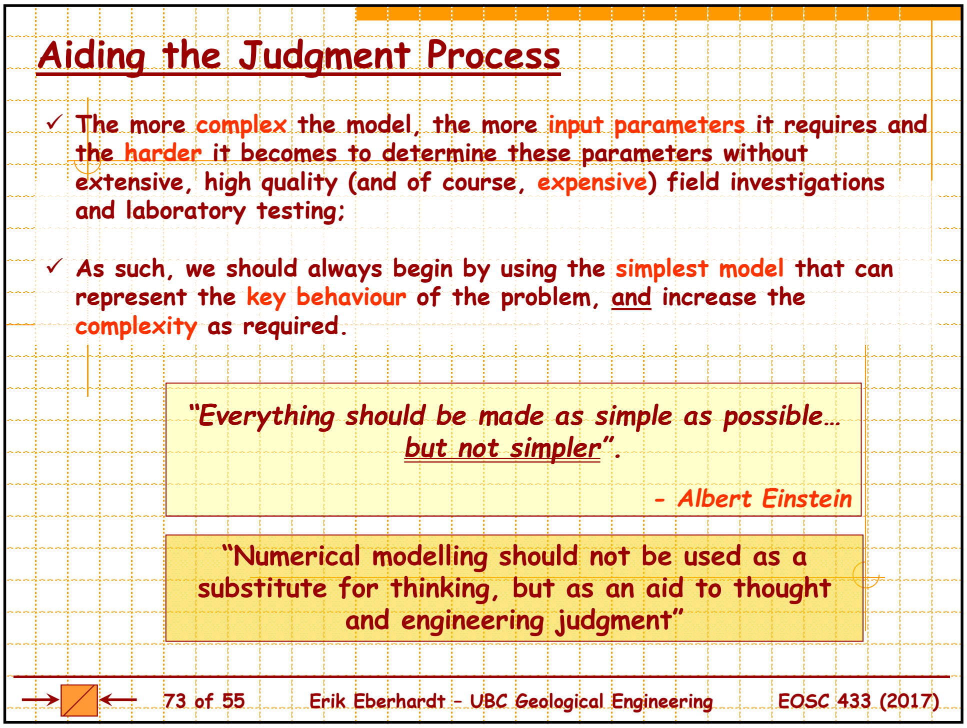


## Campo Vallemaggia – Conclusions

Eberhardt *et al.* (2007)

Distinct-element models verified that very little drainage is required (approximately 10 l/s) to significantly reduce pore pressures and to stabilize the slope.

Fracture permeability corresponds to low storativities, therefore large water outflows through drainage are not necessary to achieve significant reductions in head.

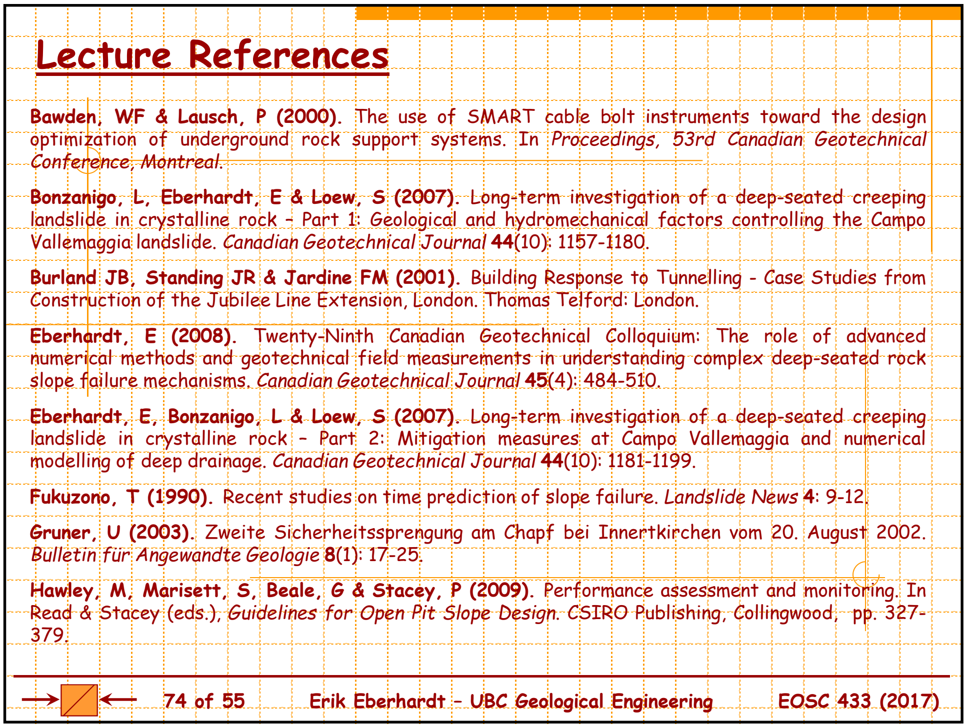


# Aiding the Judgment Process

- ✓ The more complex the model, the more input parameters it requires and the harder it becomes to determine these parameters without extensive, high quality (and of course, expensive) field investigations and laboratory testing;
- ✓ As such, we should always begin by using the simplest model that can represent the key behaviour of the problem, and increase the complexity as required.

> *"Everything should be made as simple as possible… but not simpler".*
>
> *- Albert Einstein*

> "Numerical modelling should not be used as a substitute for thinking, but as an aid to thought and engineering judgment"



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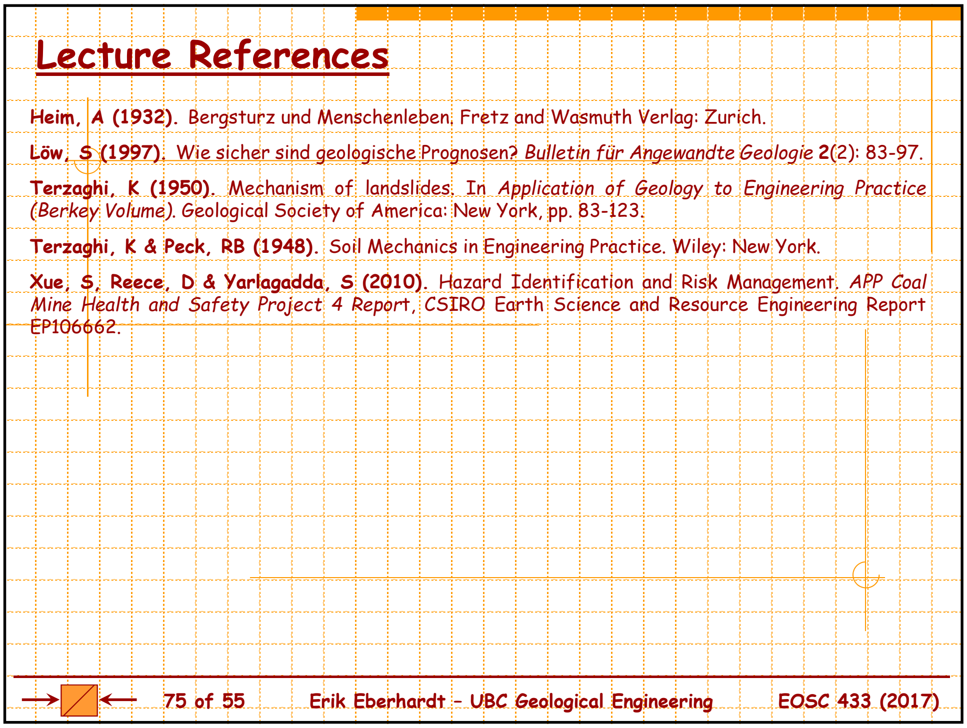

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