Jornada sobre tecnologias para presas de hormigon o con plantalla de hormigon

Sliding safety of existing gravity dams

Madrid – April 2008

Regulation

- Regulations for the safety re-assessment of existing dams: not available
- ⇨ …. “Design & Construction”

Regulatory Rules

	Regulatory Rules	Normal practice
Italy	●	
Spain	●	
Portugal	●	
Germany	●	
Norway	●	
Great Britain		●
France		●
Switzerland		●
Sweden		●
Austria		●
China	●	
India	●	
U.S.A.		●
Canada		●

“Sliding Safety” Assessment:

In most Countries:

(Driving Force) vs. (Shear Strength)

- *T/N: only in Norway and Italy*

$$\Rightarrow \quad T \leq \frac{(N\ tg\Phi + C\ A)}{FS} \quad ; \quad \frac{N\ tg\Phi}{FS_1} + \frac{C\ A}{FS_2}$$

- *Or full curve σ-τ (T/N)*

	Strength Reduction Factors (*)					
	Spain	**France**	**Portugal**	**Switz.**	**China**	**India**
Friction tgΦ	**1.5**	**1.5**	**1.5 ÷ 1.2**	**1.5**	**1.3**	**1.5**
Cohesion	**5.**	**3.**	**3 ÷ 5**	**5.**	**3.**	**3.6 ÷ 4.5**

(*) Usual Loads

	Single Global Safety Factor						
	France			Germany	Austria	Switz.	Norway
	(1)	(2)	(3)			(4)	(4)
Usual loads	4.	1.33	1.5	1.2÷1.5	1.5	1.5	1.5
Unusual loads	2.7	1.1	1.2	1.2÷1.3	1.2÷1.35	1.3	1.1
Extr. Loads	-	1.05	1.0	1.2	1.1	1.1	1.1

(1) ; (2) ; (3) : *Barrages en amenagement rural; EDF ; Coyne & Bellier*
(4) : *When cohesion is assumed = 0*

	Single Global Safety Factor			
	Canada-CDSA		Un. Kingdom	USA - BuRec.
	(5)	(6)		
Usual loads	1.5	3.0	3.0	3.0
Unusual loads	1.3	2.0	2.0	2.0
Extreme loads	1.0	1.3	1.0	1.0

(5) *Residual strength*

(6) *Peak strength*

Assessment of existing dams

- If existing dam does not comply with current safety criteria?
- Heavy economical impact
- Credit to a dam for a long service: Yes, but how much?
- Oldest dams often come short of the quality that can presently be reached.
- Existing dam: a peculiar, unique prototype.

⇨ “Standards” may not fit well

SLIDING – Safety Factors

- Different modalities to evaluate shear strength? … Different safety factors!

  (Germany, Canada, Norway)

- Example: CDSA

  without tests → with tests:

3	→	2	Normal Loads
2	→	1.5	Unusual Loads
1.3	→	1.1	Extreme Loads

Safety Assessment
using site specific data

Main information sources:

- Design and construction documentation.
- Periodic inspection and maintenance records.
- Monitoring data.
- In situ and laboratory investigations and tests.

Site specific data
Uplift Pressures

- One of the factors most heavily influencing the sliding safety assessment.

- Actual uplift pressures can vary substantially from standard distributions.

Site specific data
Uplift Pressures

- Evaluation of the uplift pressures by means of numerical analyses: **a difficult task**.

- Numerical modelling of the flow of water through low permeability media with discontinuity surfaces affected by a combination of many factors
  - In addition: strong influence of the foundation treatments (grout curtains, cut-offs, drainage, etc.).

Site specific data
Uplift Pressures

⇨ Monitoring data: very valuable information

- The use of measured uplift pressures distribution must be based on a good knowledge of the geological conditions.

- Reliability and adequacy of measured uplift pressures must be carefully scrutinised

- Terzaghi (1925): "*Minor geological details (features that can be predicted neither from the results of careful investigations of a dam site nor by means of a reasonable amount of test boring) can have a critical impact on uplift pressures ".*

Measured Uplift Pressures

- **Possible non-linear response to headwater variations.**
  - increasing or decreasing gradients depending on how the discontinuities are influenced by the stresses.

- **Rate of uplift response**
  - exceptional loading conditions may be of short duration.
  - unlikely that significant time lag exists in rock foundation

- **Seasonal uplift variations**
  - change of the stress- strain distribution
  - possible influence on the uplift pressures response

Measured Uplift Pressures

- Possible high spatial variability of measured data ⇨ caution in extrapolation or enveloping
- Extrapolation of measured uplift to higher water levels (exceptional floods).

Site specific data
Strength Data

- **Strength parameters:**
  - in the foundation mass (foundation discontinuities)
  - at the concrete-to-rock contact surface
  - in the dam body (lift joints)

- **Basic parameters: Tensile and Shear strength**
  - laboratory tests on samples,
  - in situ strength tests.
  - Geophysical tests (homogeneity of the areas)

Strength Data

The experimental evaluation may be expensive and unavoidably constrained

⇨ **It is important to make full use of literature data, for**:

- preliminary analyses,
- evaluating the benefits of specific investigations,
- Improving confidence in limited site data.

- **Identify the literature data more closely corresponding to the actual situation under examination.**
- **Check the “validity conditions” of the literature data**

Strength Data

- Foundation Joints ⇨ Rock mechanics literature
- Dam-foundation contact surface
- Lift joints

Strength Data
Experimental Experiences

Shear and Tensile Strength, for:

- Dam-foundation contact surface
- Lift joints

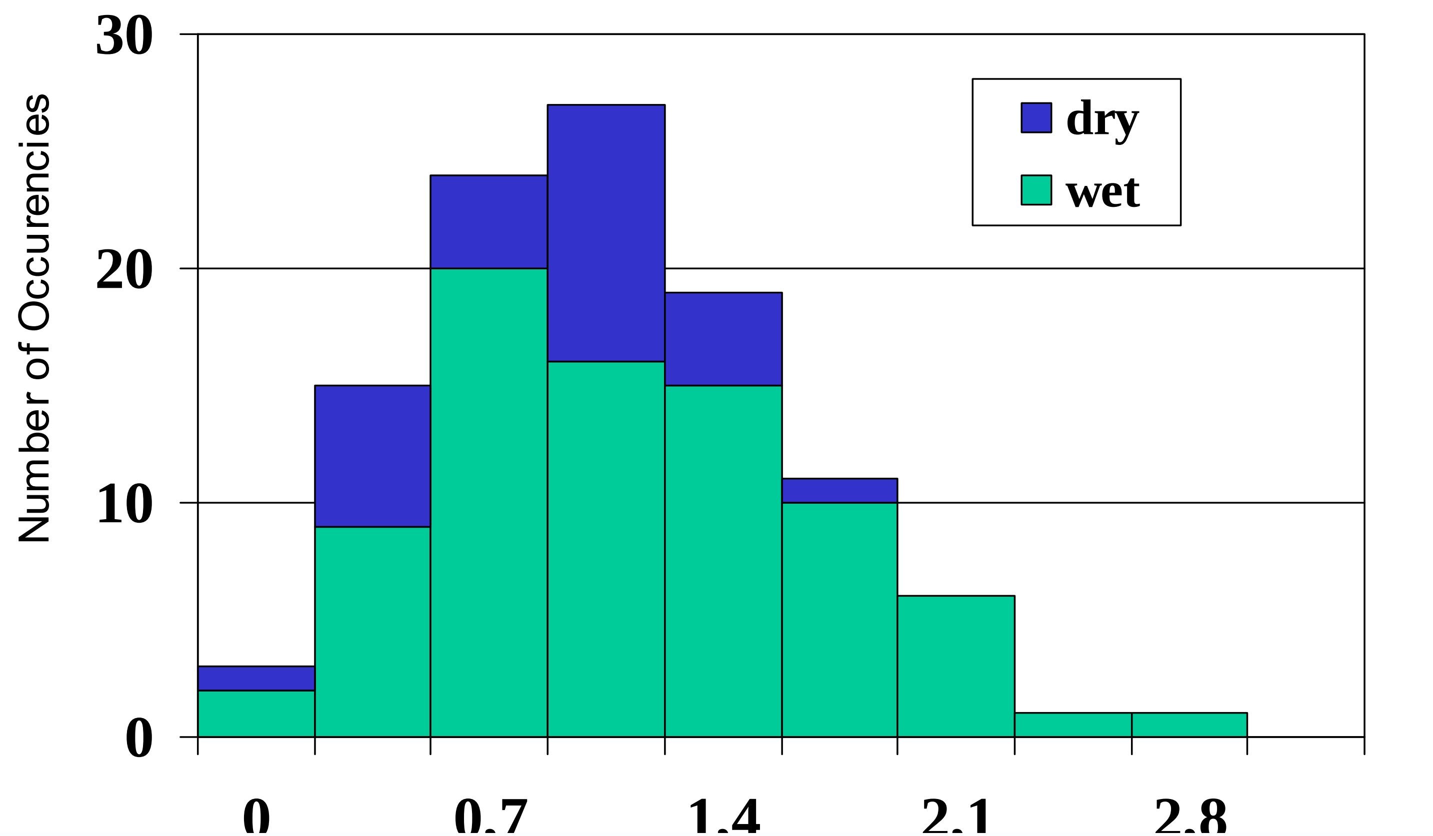
…. a surprisingly large number of important experimental experiences

Study	Publication date	Lift joints		Dam-foundation interface	
		Tensile strength	Shear strength	Tensile strength	Shear strength
Rocha	**1964**				▨
Link	**1969**				▨
McLean et al.	**1988**		▨		
EPRI	**1992**	▨	▨	▨	▨
Pacelli et al.	**1993**	▨	▨		
Lo et al.	**1994**			▨	▨
McColm et al.	**1997**	▨			
Poly. Montreal	**1998**	▨			
ISMES	**1999**				▨
Forrest et al.	**2003**	▨			

Strength Data - Experimental Experiences

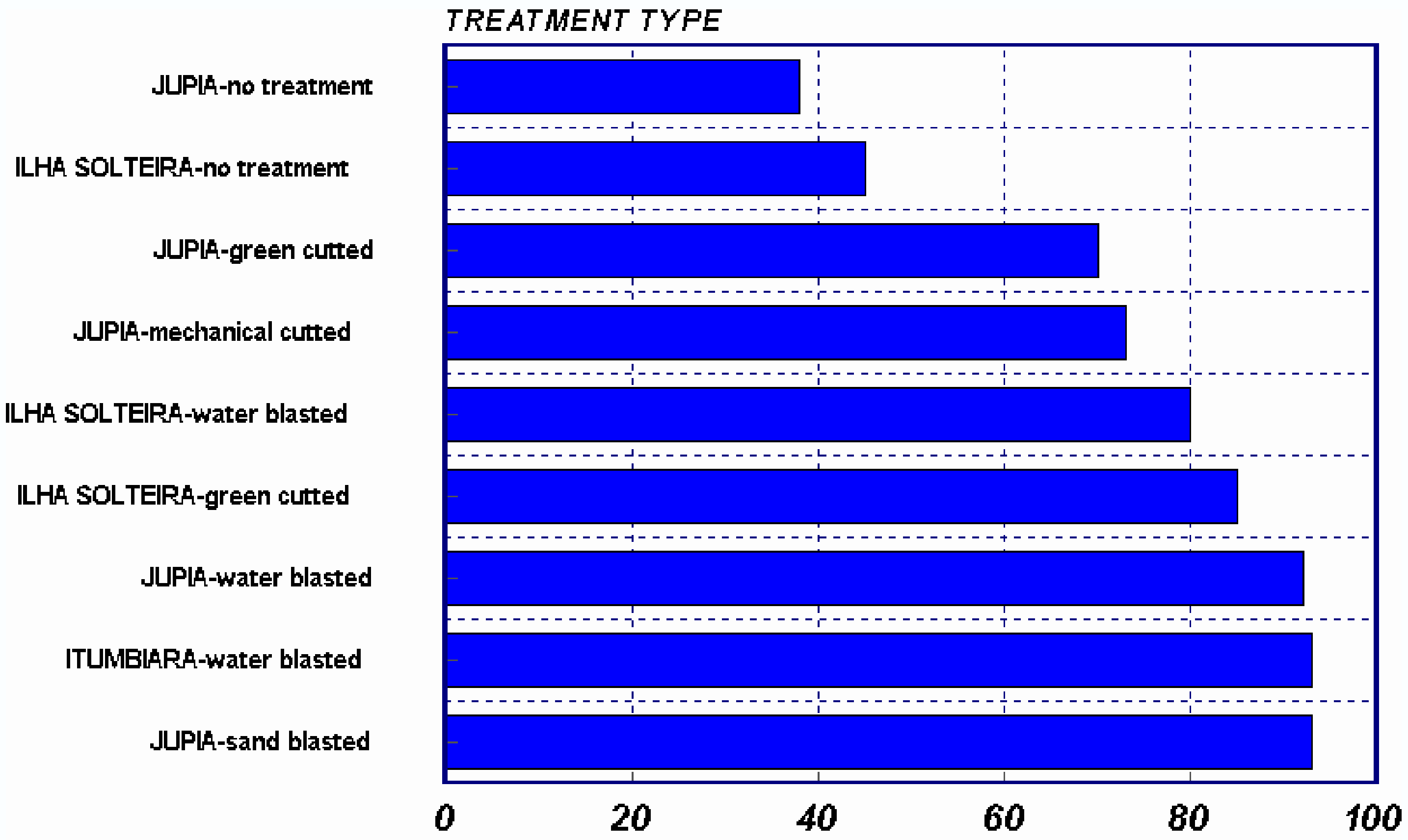
- Some with very wide aims (EPRI).
- Some with very large number of tests (EPRI, Rocha, Link). Some with smaller number of tests and specific aims (Pacelli, ISMES, ...)
- Some mostly based on samples from dams in operation. Some based on samples during dam construction only.
- Some based on in situ tests (Rocha). Some on lab tests only (ISMES).
- Some based on large scale tests (Rocha, ISMES).

Strength Data - Experimental Experiences



Concrete lift joints – Tensile strength (MPa)
(EPRI)

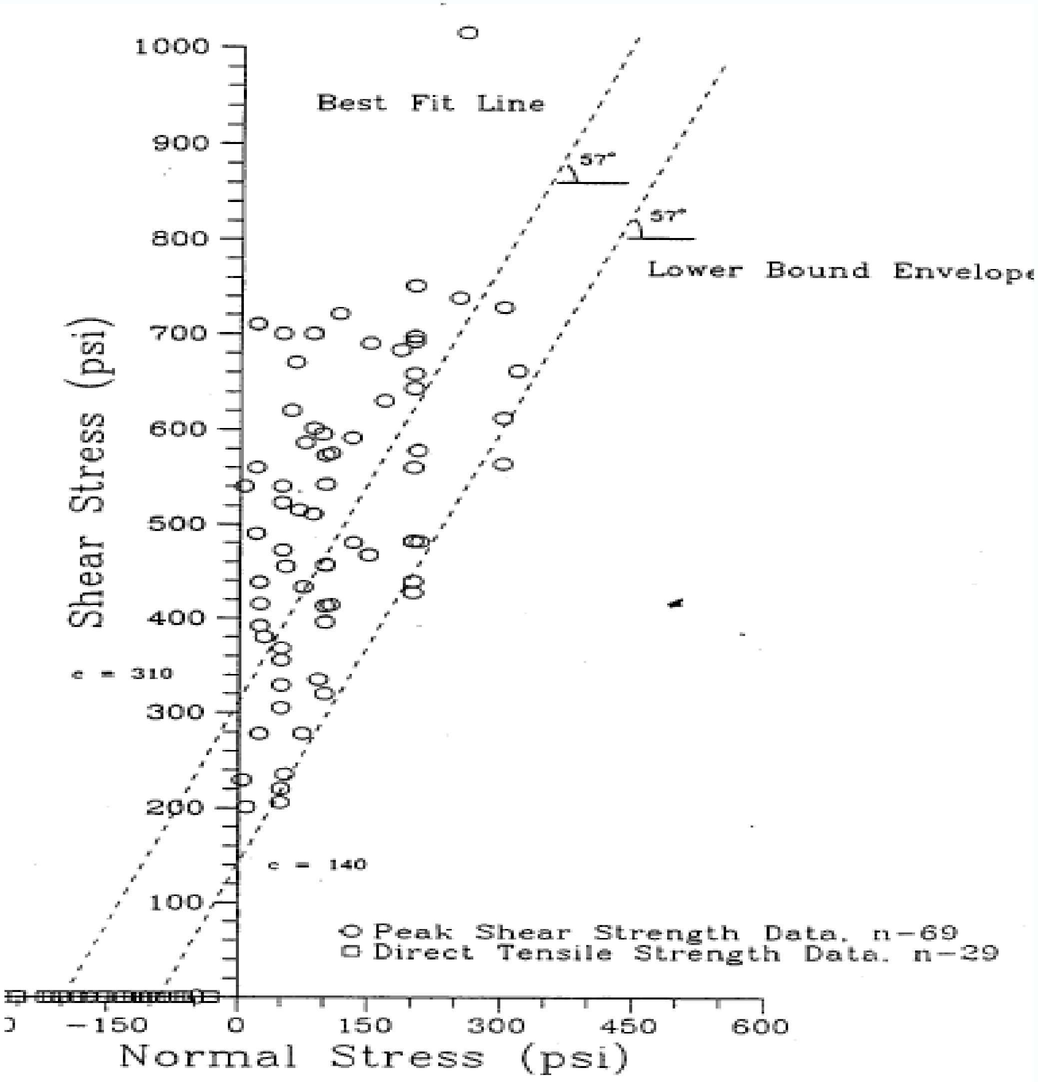
Strength data: Experimental Experiences



Concrete Lift Joints – Tensile Strength

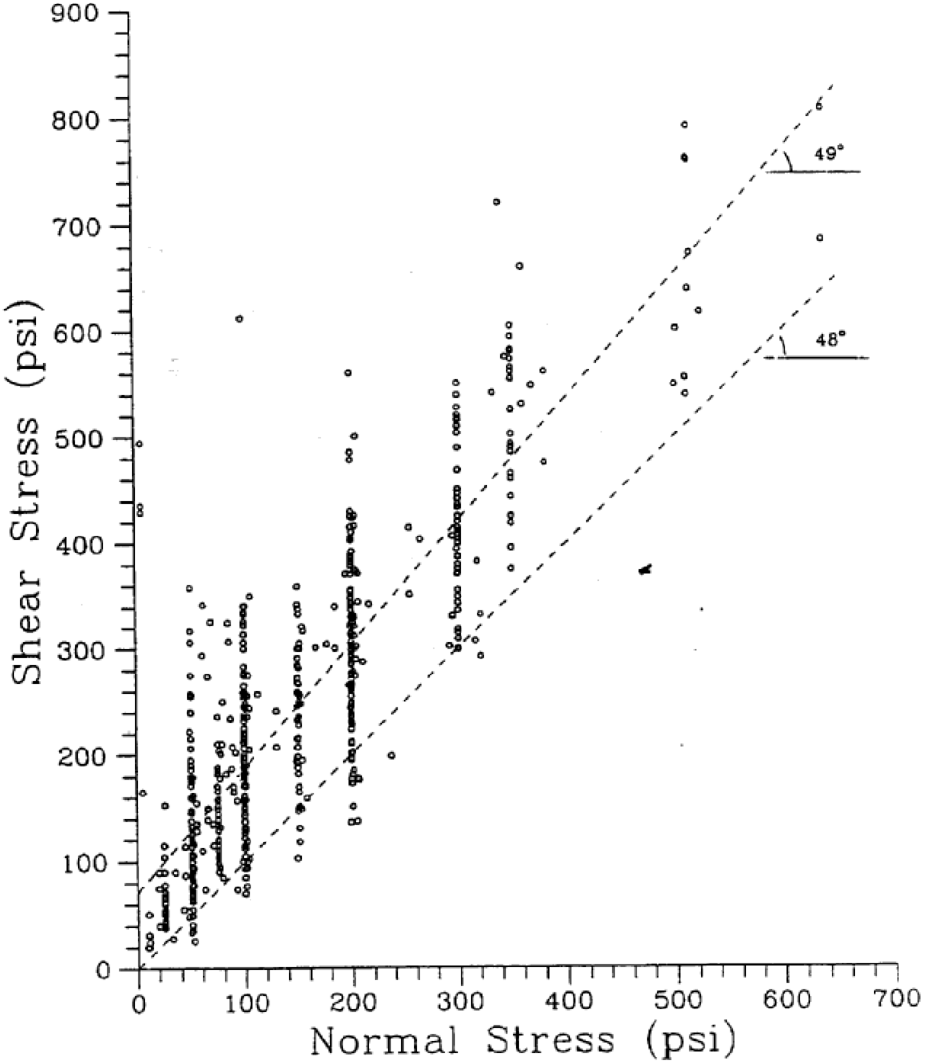
(Pacelli)

Strength data: Experimental Experiences

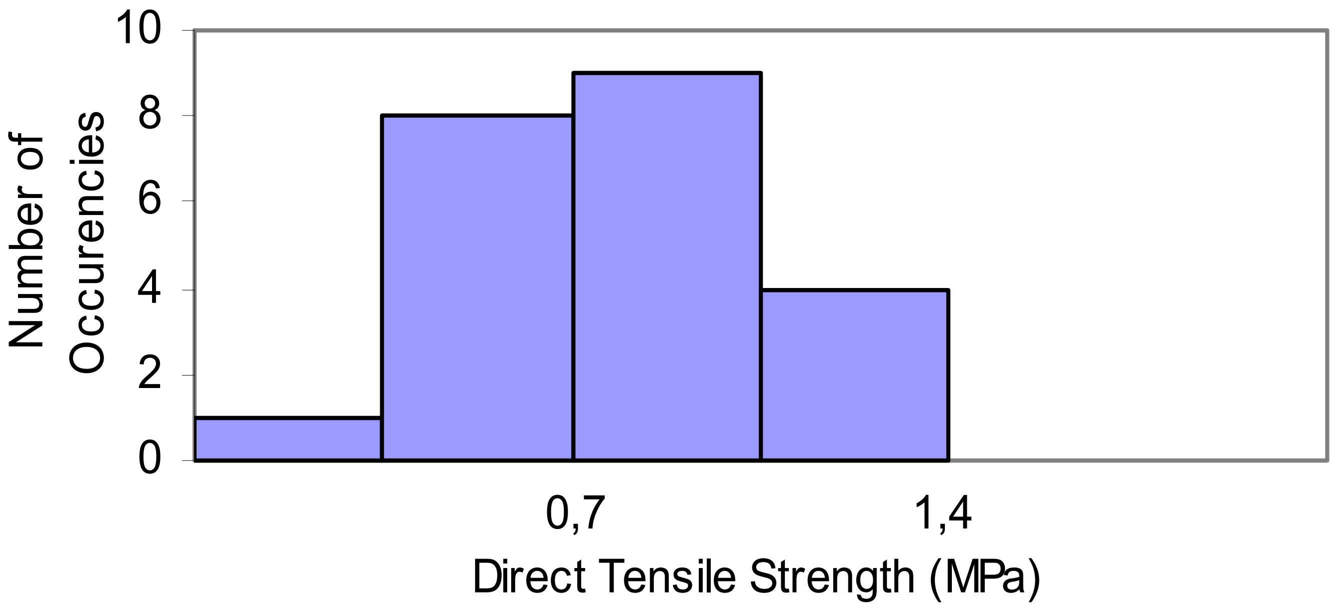


Concrete lift joints. Peak shear strength (EPRI)

Strength data: Experimental Experiences



Concrete lift joints. Residual shear strength (EPRI)



Concrete-to-rock contact - **Tensile strength**

(EPRI)

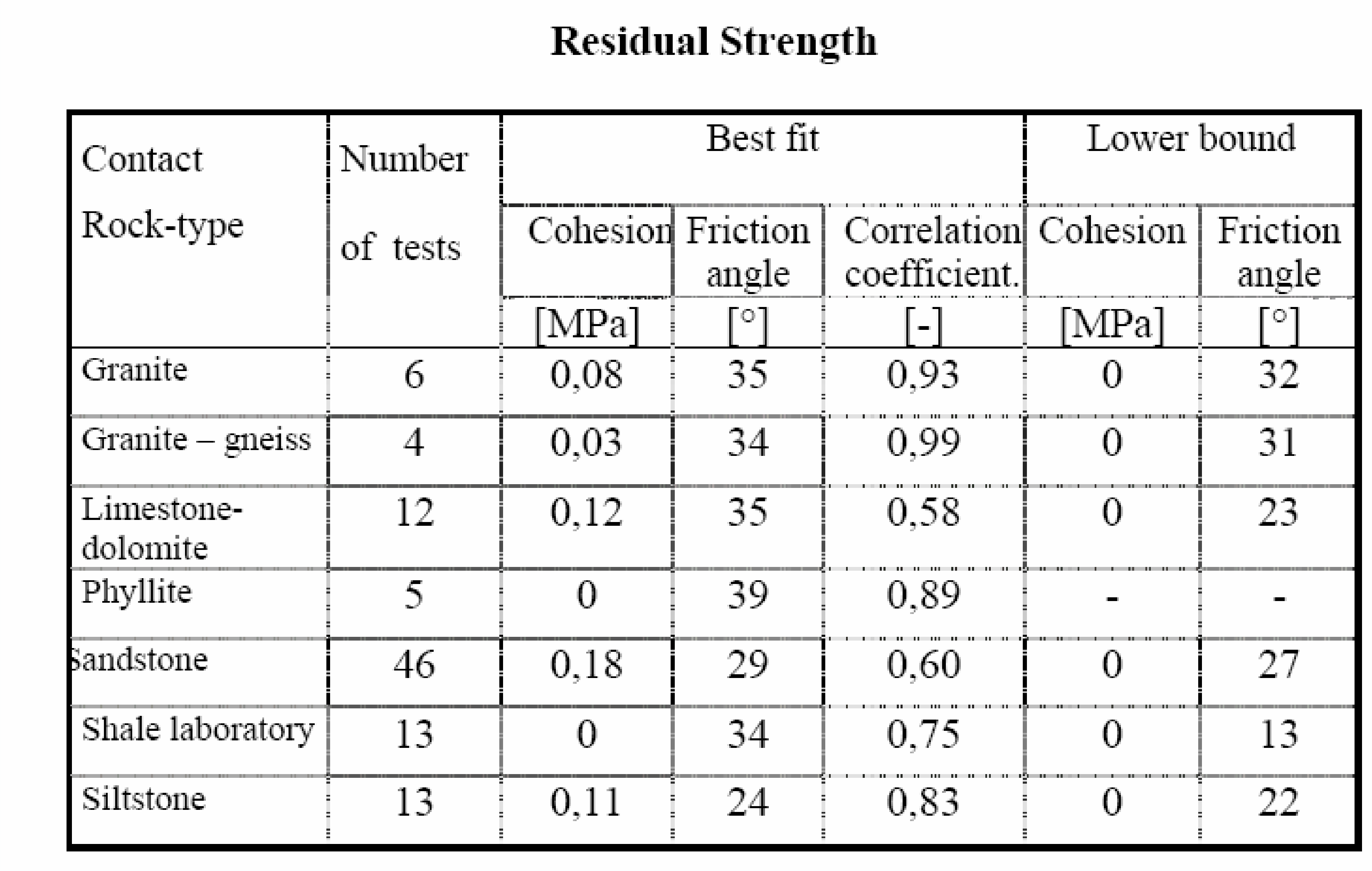
Strength data: Experimental Experiences

Rock-type / *Dam*	N. of tests	**Cohesion [MPa]**	**Friction angle [°]**
•**Altered Granite** / *Alto Rabagao*	8	**0,2**	**56**
Shale / *Bemposta*	8	**0,2**	**60-63**
Shale / *Valdecañas*	3	**0.4**	**62**
Shale / *Miranda*	16	**0,4-0.7**	**60-62**
Shale / *Alcantara*	28	**0,1**	**56**
Sandstone / *Cambambe*	4	**0.2**	**53**

Concrete-to-rock contact - Peak Shear strength

(Rocha)

Strength data: Experimental Experiences



Residual Strength

Contact Rock-type	Number of tests	Best fit			Lower bound	
		Cohesion [MPa]	Friction angle [°]	Correlation coefficient. [-]	Cohesion [MPa]	Friction angle [°]
Granite	6	0,08	35	0,93	0	32
Granite – gneiss	4	0,03	34	0,99	0	31
Limestone-dolomite	12	0,12	35	0,58	0	23
Phyllite	5	0	39	0,89	-	-
Sandstone	46	0,18	29	0,60	0	27
Shale laboratory	13	0	34	0,75	0	13
Siltstone	13	0,11	24	0,83	0	22

Concrete-to-rock contact - Residual Shear strength

(EPRI)

Strength data: Experimental Experiences

LIFT JOINTS

- **Tensile Strength**
  - In general a significant tensile strength.
  - For lift joints with some type of treatment: always in the range of 50-100% of the strength of monolithic concrete, and in most cases not far from it.

- **Shear Strength**
  - Always found to be significant,
  - Cohesion values frequently in the order of 1–2 MPa.

Strength data: Experimental Experiences

DAM-FOUNDATION CONTACT SURFACE

Many of the in situ cored dam-foundation contacts were found intact (bonded)

- **Tensile Strength**
  - Significant strength (08-1.0 MPa), larger than 50% of monolithic concrete.
- **Shear Strength**
  - Significant strength where bonding is effective (failure surface within foundation rock).
  - Significant extra-bonding due to the interposition of cement milk where the cement paste is able to adhere to the underlying rock.

“Techniques for the safety assessment”

- **Traditional well consolidated methods : “limit equilibrium” approach**
  - Mohr-Coulomb “c-φ” , Hoek and Brown, Burton
- **Deformable Body approaches**
  - dam and foundation = deformable bodies
  - taking into account joints/discontinuities
  - linear / non linear
  - coupled /uncoupled
  - …..

Sliding Safety Assessment
Numerical Experiences

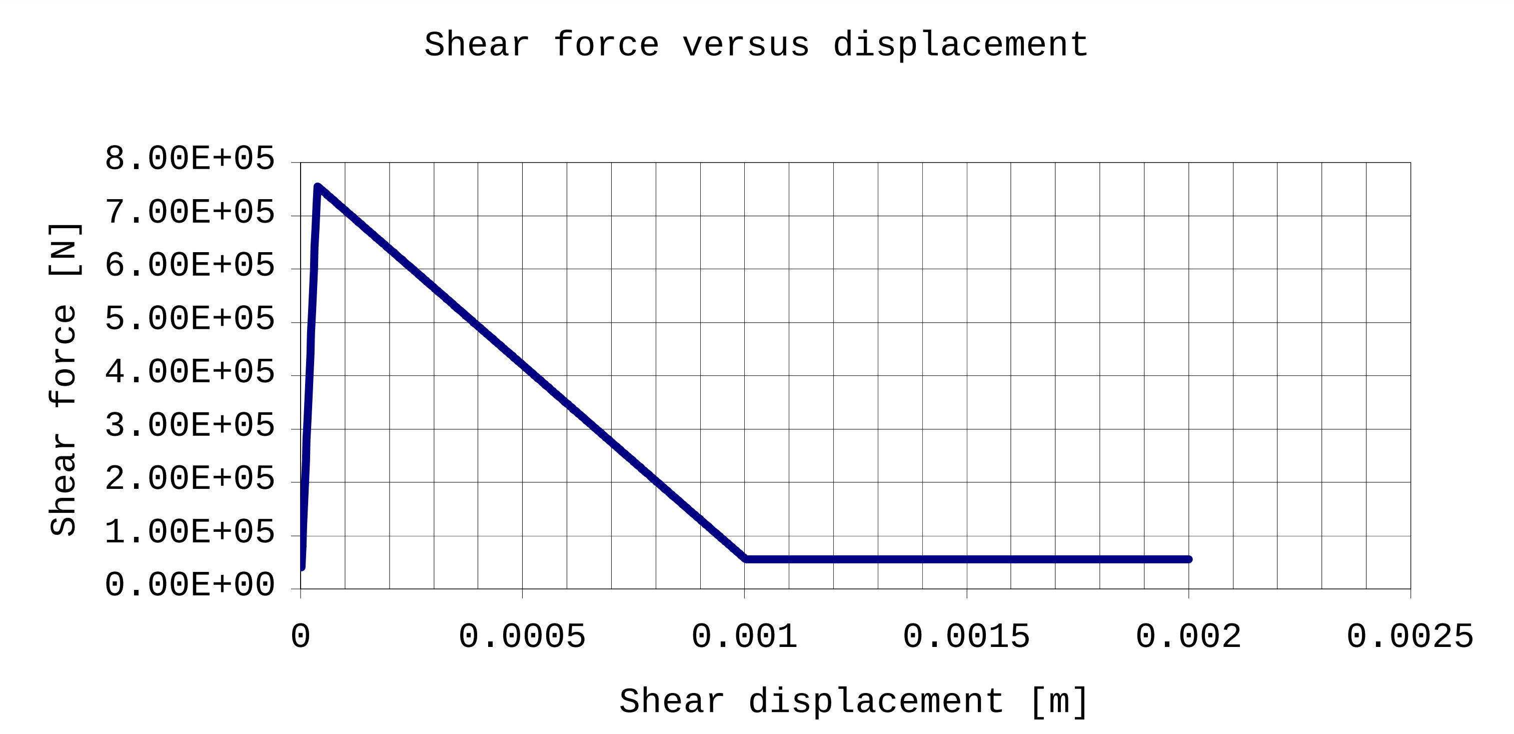
5th International Benchmark Workshop, 1999, by the ICOLD Committee on “Computation”:

- Evaluation of the critical reservoir level associated to the 'imminent failure' of a concrete gravity dam.

- The 'imminent failure' had to be reached by increasing the hydrostatic load.

Numerical Experiences
The 5th International Benchmark Workshop

- Main issue: realistic representation of the sliding conditions of the rock/concrete interface.
- Stress-strain response of the dam-foundation interface:



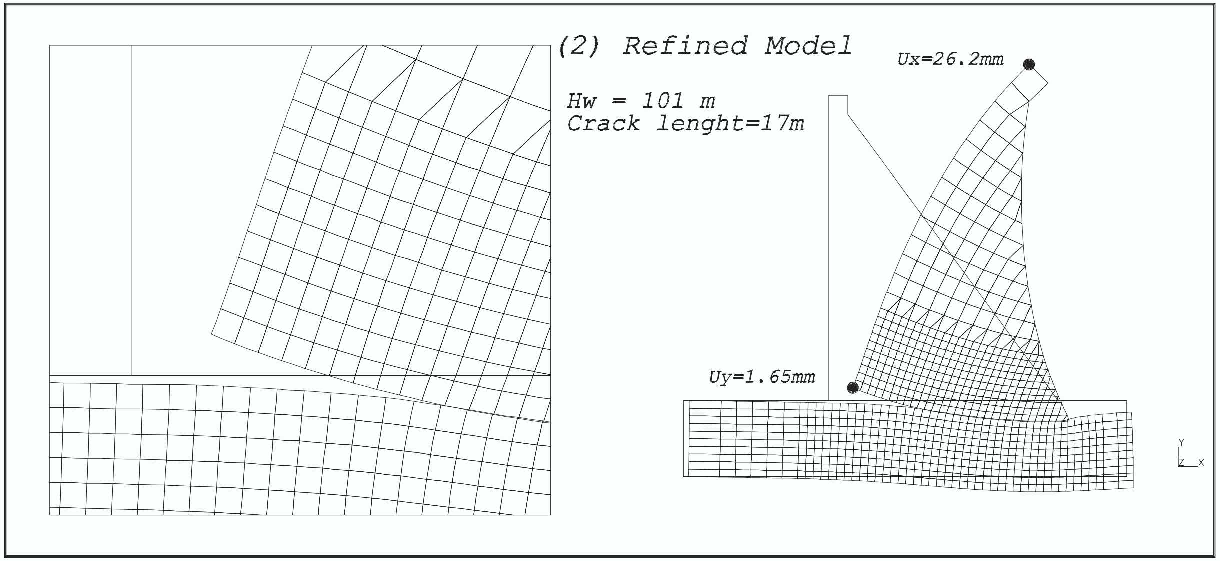
Numerical Experiences
The 5th International Benchmark Workshop

Overall, the following **final remarks** can be made:

- To incrementally arrive at the limit state – full sliding of the dam base - is numerically committing.
- Results significantly depend on meshing strategy and mesh refinement.
- The “water level – crown displacement” curve does not always display the attainment of limit conditions.

Numerical Experiences
The 5th International Benchmark Workshop

- Application of uplift pressures following joint opening: not available in standard F.E. codes ⇨ ad hoc procedures
- Different loading sequences contributed to the scattering of the results.
- ***"The results indicate that several computational and theoretical aspects need to be clarified, to confidently arrive at a robust solution"***



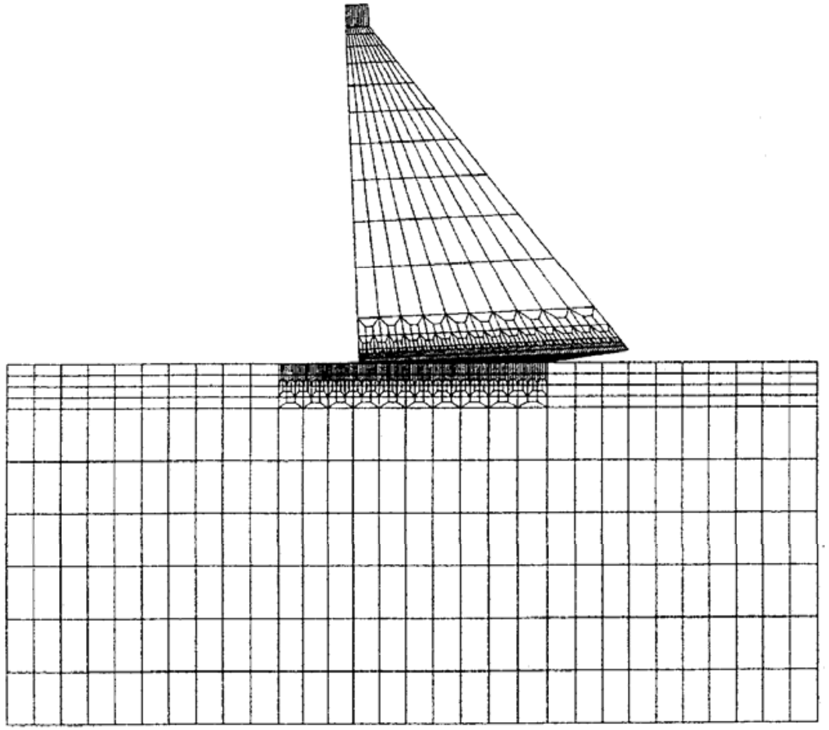
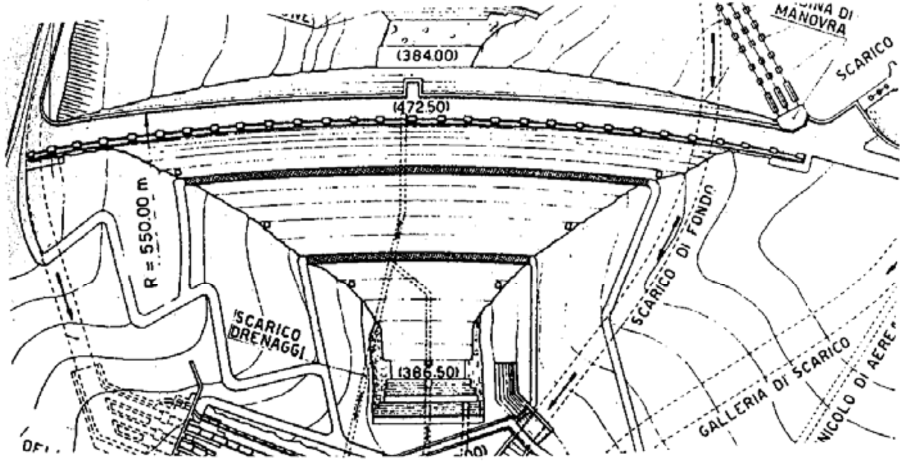


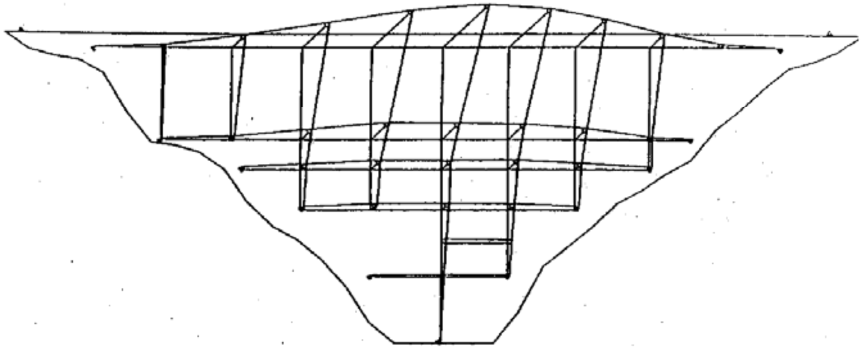
Fig. 5 Deformation of the dam for Case 3 (failure level)

Three dimensional effects

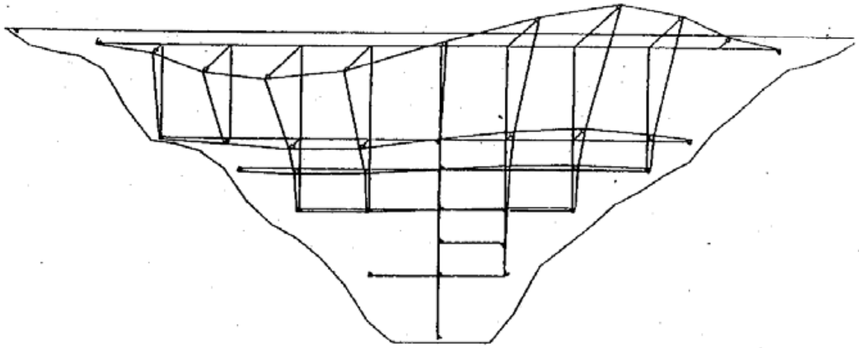
- Significant influence on the ultimate load and failure mechanism
- For gravity dams with arched axis, but also in dams with straight axis.
- Should not be neglected in the safety reassessment of existing dams

- Information about possible 3D effects should be derived from the actual dam behaviour
  - *Monitoring (displacements, joints)*
  - *Investigations*





First mode shape



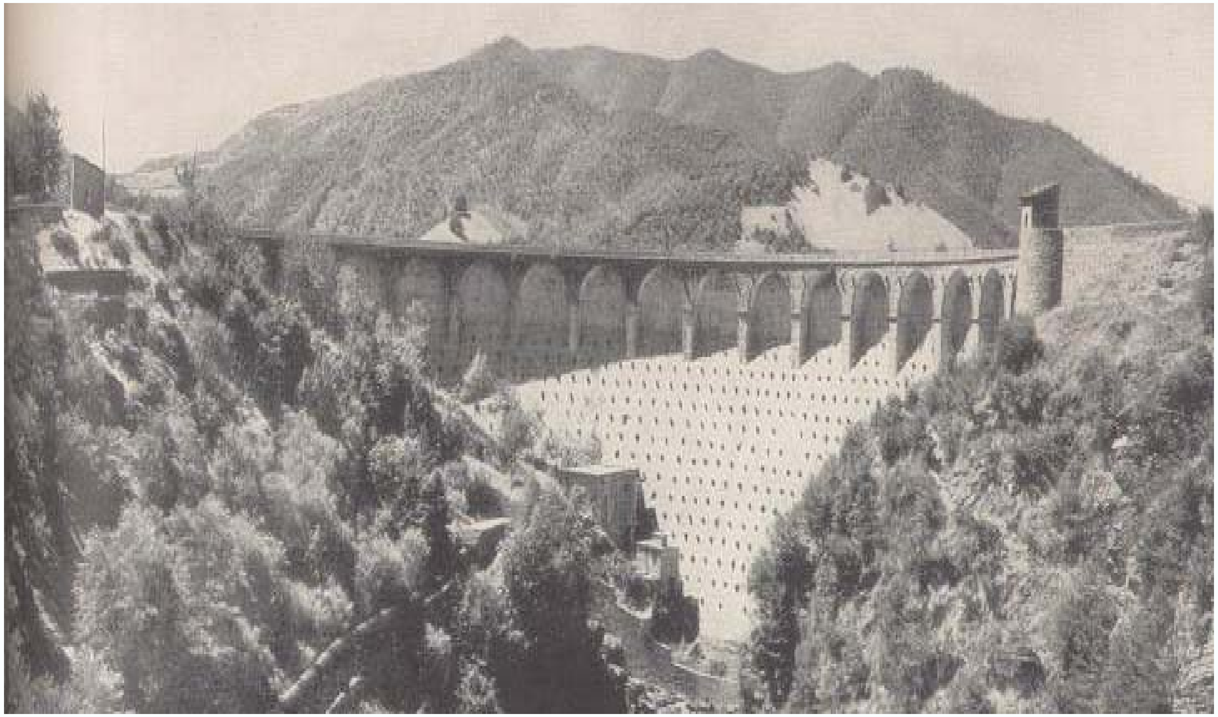
Second mode shape

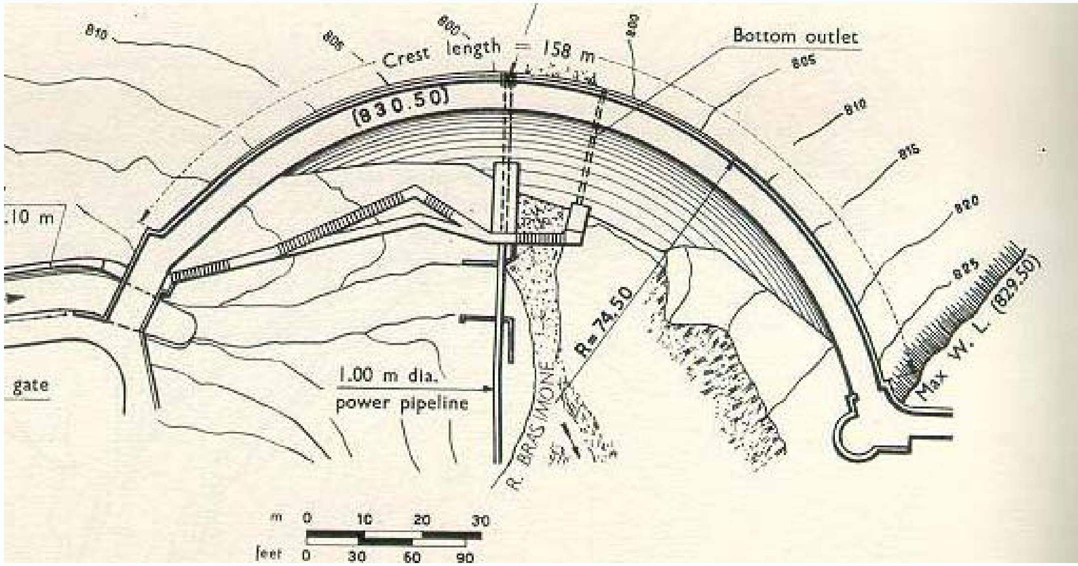
Three dimensional effects

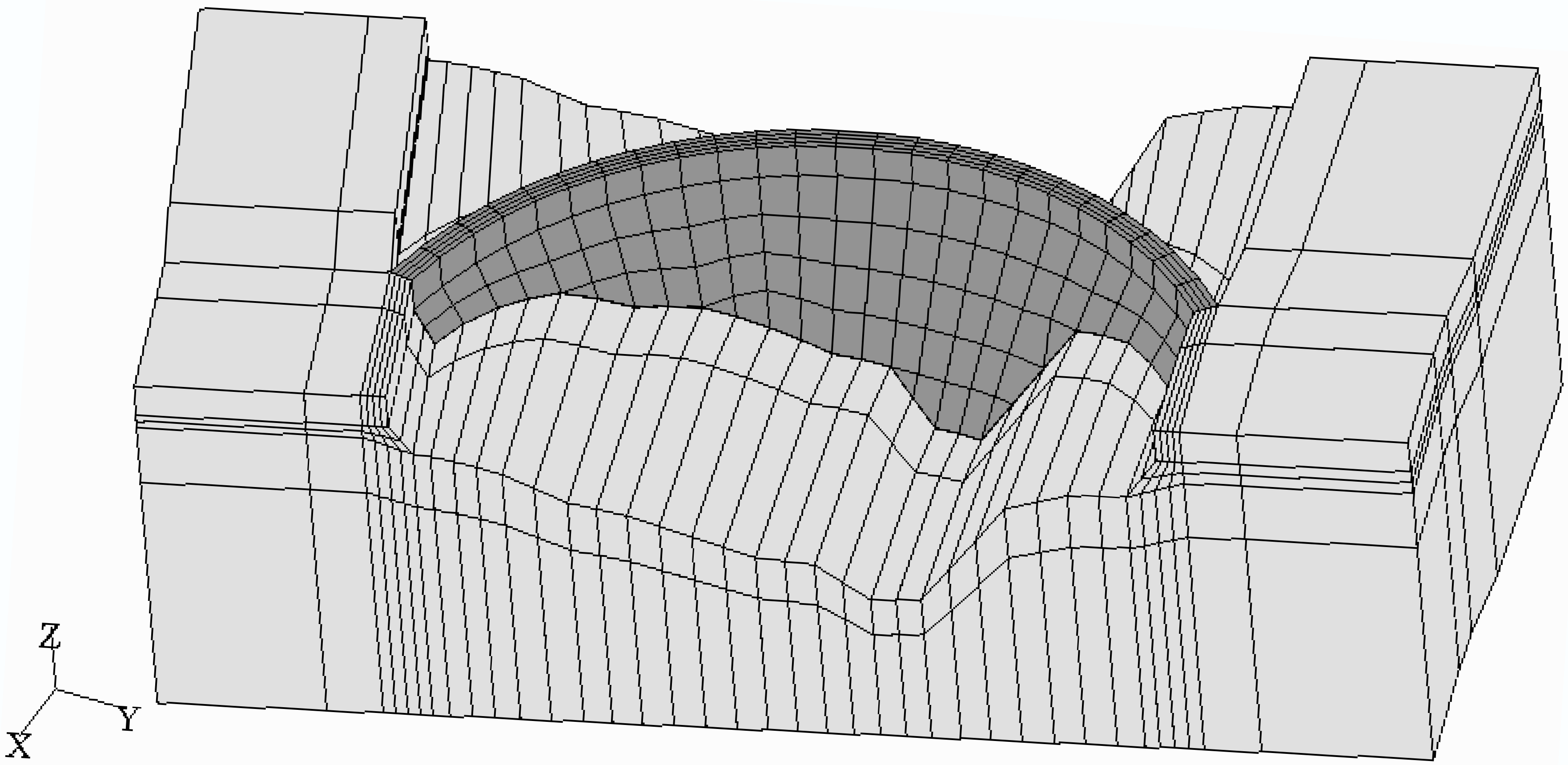
- Techniques for numerical evaluations…..

7th Benchmark Workshop
on Numerical Analysis of Dams
“***Evaluation of Ultimate Strength of Gravity Dams***
With Curved Shape Against Sliding”

September 2003




810
805
800
800
Crest length = 158 m
Bottom outlet
805
810
815
820
825
(830.50)
.10 m
gate
1.00 m dia.
power pipeline
R. BRASIMONE
R=74.50
Max W. L. (829.50)
m 0 10 20 30
feet 0 30 60 90


Z
Y
X

Gravity dams with curved axis

7º ICOLD Benchmark Workshop (2003)

- Different constititutive models, linear and non linear
- “Joints” for the dam-foundation contact surface

Computed values for the “Failure Load”:
in a surprisingly narrow interval:

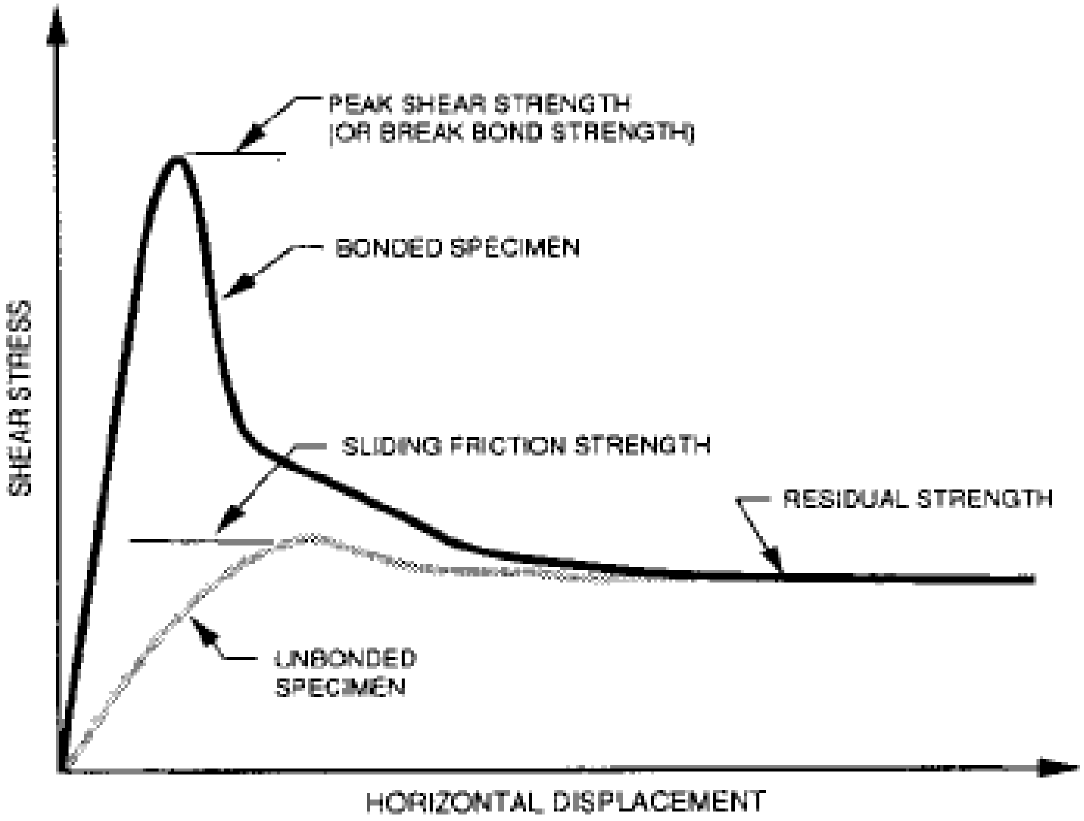
1.18-1.33 (!)

ICOLD – European Club

Web site: *http://cnpgb.inag.pt/icoldClub*

- *“Uplift Pressures Under Concrete Dams – Final Report”,*
- *“Sliding Safety Assessment for Existing Gravity Dams - Final Report”*

Thank you for your attention


PEAK SHEAR STRENGTH
(OR BREAK BOND STRENGTH)
BONDED SPECIMEN
SLIDING FRICTION STRENGTH
RESIDUAL STRENGTH
UNBONDED SPECIMEN
SHEAR STRESS
HORIZONTAL DISPLACEMENT