DAM ENGINEERING – NEW CHALLENGES

PEDRO S. SÊCO E PINTO
NATIONAL LABORATORY OF CIVIL ENGINEERING (LNEC)
UNIVERSITY NEW OF LISBON
UNIVERSITY OF COIMBRA
PORTUGAL

TOPICS

- DAM DESIGN CRITERIA
- LESSONS FROM DAM BEHAVIOR DURING EARTHQUAKES
- ANALYSIS OF DAM STABILITY DURING EARTHQUAKES
- RESERVOIR TRIGGERED SEISMICITY
- PROTOTYPE DYNAMIC TESTS
- AGEING EFFECTS
- REHABILITATION OF DAMS
- BENEFIT AND CONCERNS OF DAMS
- RISK ANALYSIS
- FINAL REMARKS AND TOPICS FOR DISCUSSION

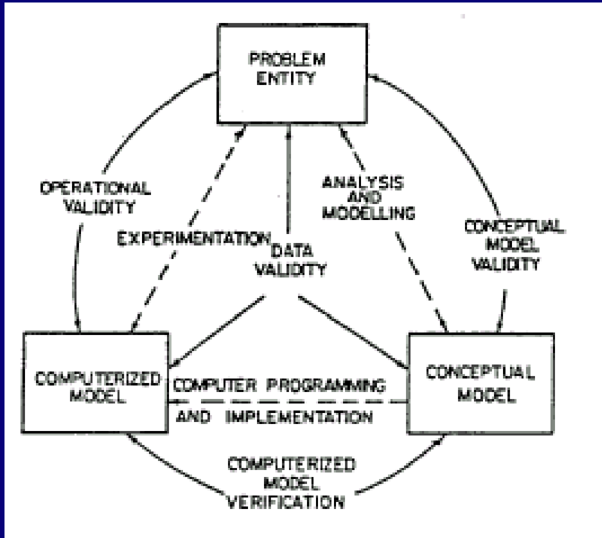
LOVE, SHAKESPEARE, HAMLET

WHERE LOVE IS GREAT, THE LITTLEST DOUBTS ARE FEAR ;

WHERE LITTLE FEARS GROW GREAT, GREAT LOVE GROWS THERE

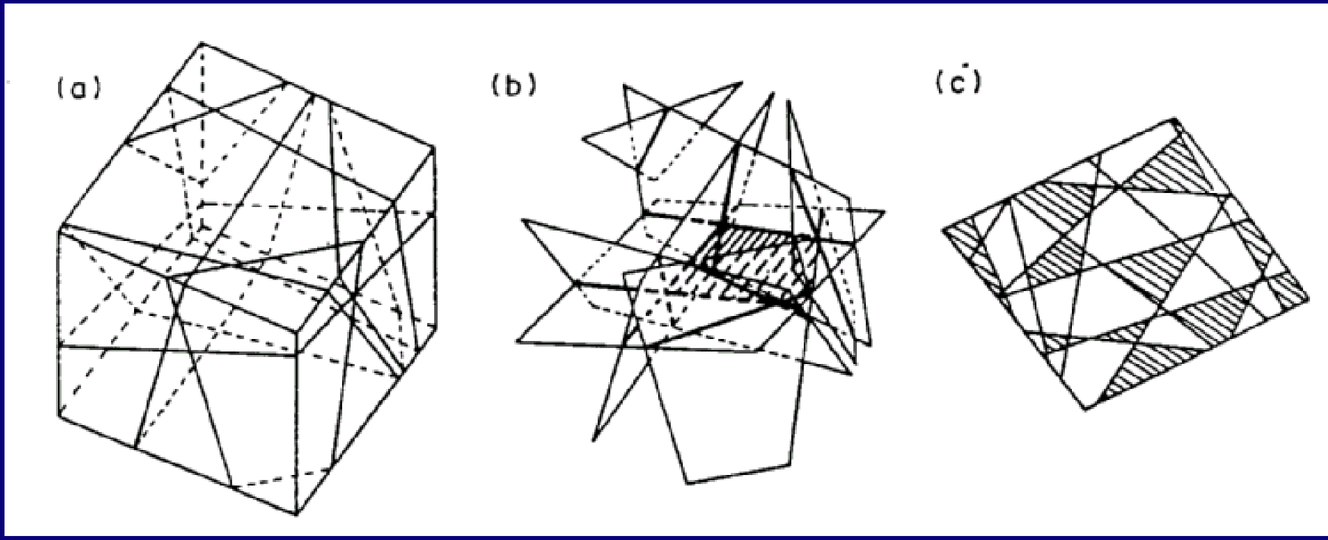
VERIFICATION AND VALIDATION OF MODELS

- RELATIONS BETWEEN THE PHYSICAL PROBLEM, THE CONCEPTUAL MODEL AND THE COMPUTER MODEL
- ICOLD CONSIDERS THAT THE FOLLOWING ASPECTS SHOULD BE CHECKED:
  - JUSTIFICATION OF THE WHOLE MODELING METHOD
  - VALIDATION OF THE COMPUTER CODE
  - QUALITY ASSURANCE OF THE COMPUTATION PROCESS



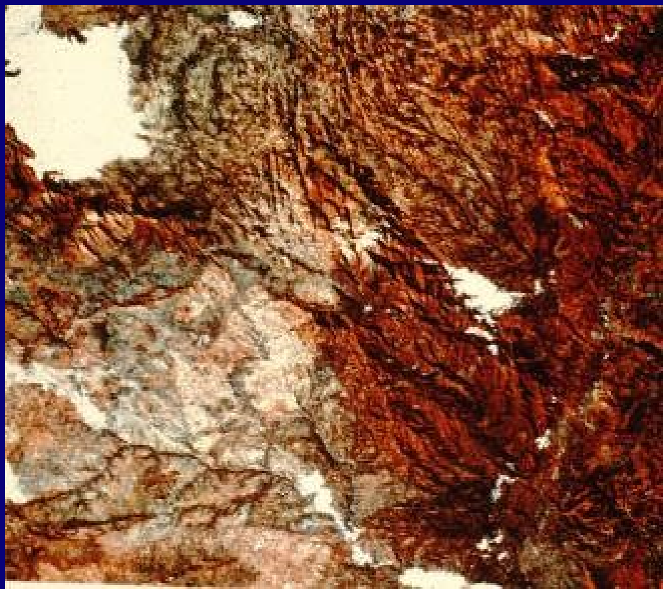
FOUNDATION STUDIES

- DISCRETE ELEMENT MODELS ARE USED FOR JOINT ROCK MEDIUM
- VENEZIANO POLYGONAL MODEL
- DERSHOWITZ POLYGONAL MODEL



FOUNDATION STUDIES

- SOIL MATERIALS ARE ESTIMATED BY GEOPHYSICAL TESTS, SPT TESTS, CPT TESTS, SEISMIC CONE AND PRESSUROMETER TESTS
- THE NONLINEAR DYNAMIC SOIL-STRUCTURE INTERACTION OF EARTH DAM SUBJECTED TO SV WAVES WAS INVESTIGATED BY A COUPLE FINITE ELEMENT BOUNDARY ELEMENT FORMULATION



ALVITO DAM CASE STUDY

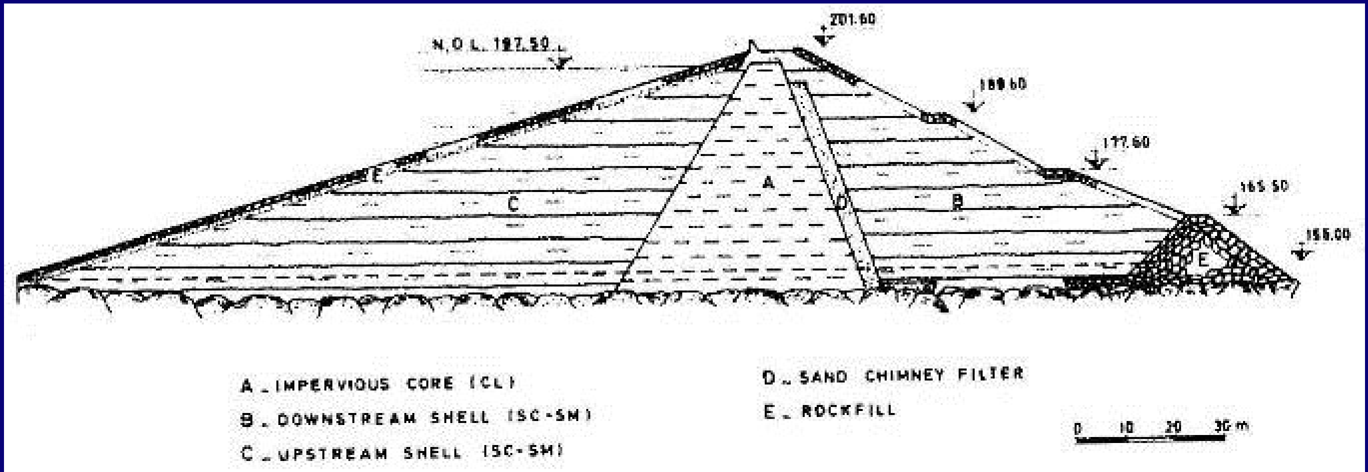


Fig. 4 – Alvito cross-section

A two dimensional plane strain analysis in total stresses of Alvito dam was done using hyperbolic stress - strain law. The construction stage was simulated in ten layers and the analysis of reservoir filling in three steps

Also an incremental stress-strain relationship (modified cam-clay model that takes into account the consolidation of partly saturated clay soils with varying permeability and compressibility of the pore fluid was developed

ALVITO DAM CASE STUDY

Alvito dam

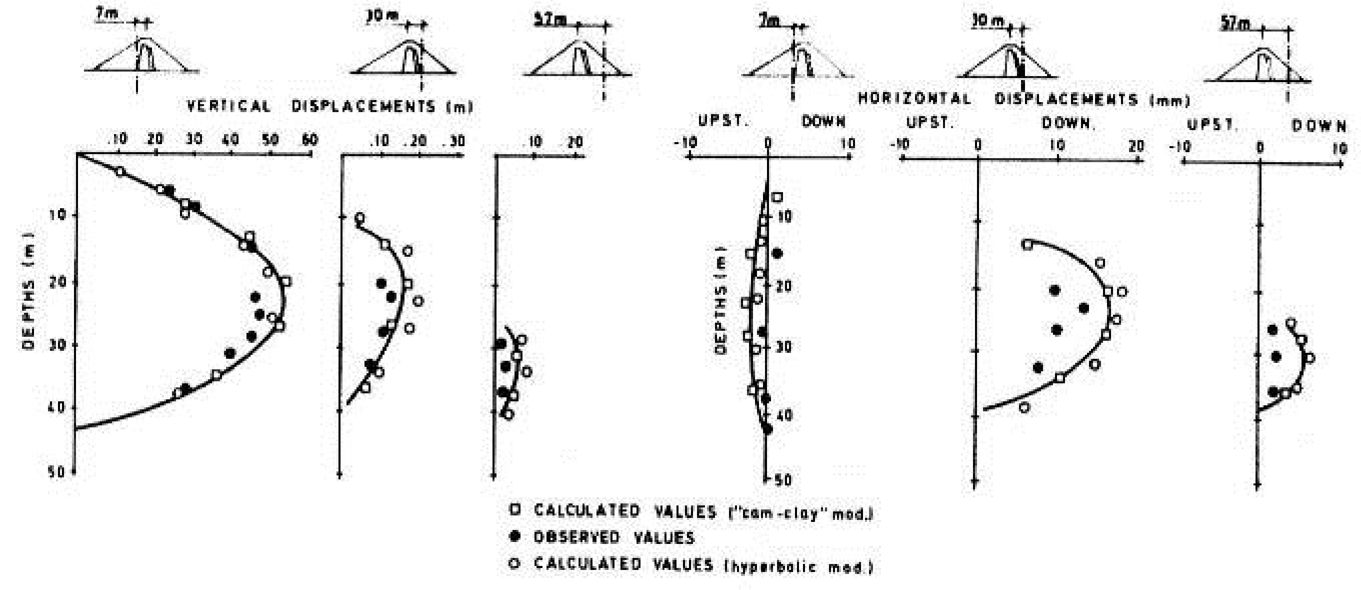


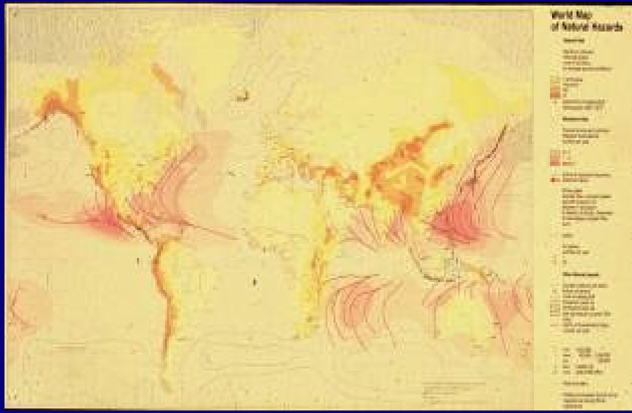
Fig. 5 - Values predicted by the two rheological models

HISTORICAL BACKGROUND EARTHQUAKES

- According to Aristotle (384-322 B.C.) in his book Meteorologica earthquakes were produced by the dried exhalations (spirits or winds) in caves inside the earth which trying to escape make the earth shake
- Martin Lister in England and Nicolas Lemery in France in 17^{th} century were the first to propose that earthquakes were produced by large explosions of inflammable material formed by a combination of sulfur, coal, niter and other products accumulated in the interior of earth. The explosive theory was also proposed by Newton`s Optics (1718).
- In France the world was considered a good place in which everything that happened was viewed to be "for the best" and earthquake was considered with optimism. Voltaire in his novel Candide presented a hard attack to this optimistic view point. Also Kant and Rosseau defended the optimist position

LESSONS FROM DAM BEHAVIOR DURING EARTHQUAKES

- SLIDING OR SHEAR DISTORTION OF EMBANKMENT OR FOUNDATION
- TRANSVERSE CRACKS
- LONGITUDINAL CRACKS
- LOSS OF FREEBOARD DUE
  TO COMPACTION OF
  EMBANKMENT OR FOUNDATION
- RUPTURE OF UNDERGROUND CONDUITS
- OVERTOPPING DUE TO SEICHES IN RESERVOIR



LESSONS FROM DAM BEHAVIOR DURING EARTHQUAKES

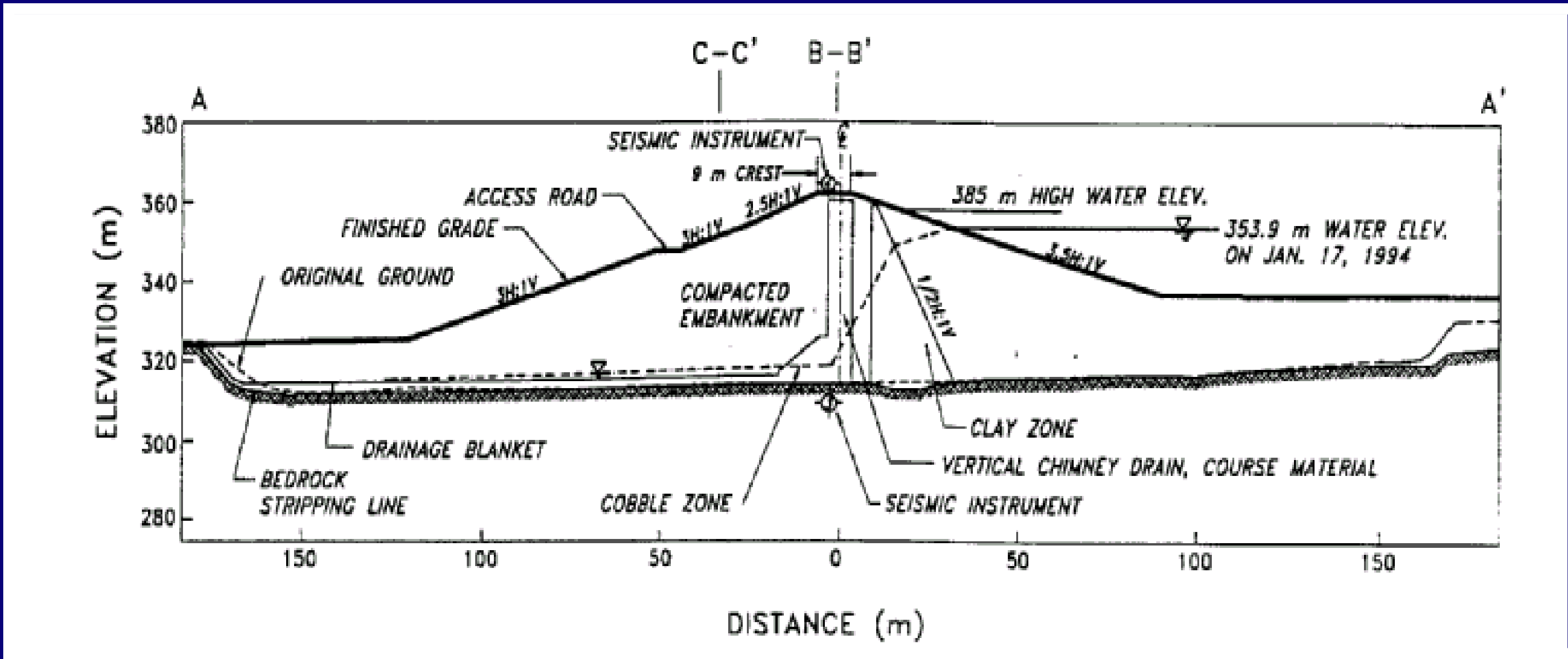
- OVERTOPPING DUE TO SLIDES OR ROCKFALLS INTO RESERVOIR
- DISRUPTION OF DAM BY MAJOR FAULT MOVEMENT IN FOUNDATION
- DIFFERENTIAL TECTONIC GROUND MOVEMENTS
- FAILURE OF SPILLWAY OR OUTLET WORKS
- PIPING FAILURE THROUGH CRACKS INDUCED BY GROUND MOTIONS
- LIQUEFACTION OF EMBANKMENT OR FOUNDATION

SAN FERNANDO EARTHQUAKE, FEBRUARY 9, 1971

NORTHRIDGE EARTHQUAKE

- 12 EARTH DAMS EXHIBITED MINOR CRACKING
- LOS ANGELES DAM EXPERIENCED PEAK
- ACCELERATIONS 0.42g AT THE ABUTMENT TO 0.56g AT THE CREST
- MAXIMUM CREST SETTLEMENT OF 90mm
- HORIZONTAL MOVEMENTS OF 55mm

Cross-section of Los Angeles dam (after David and Bardet, 1996)



KOBE EARTHQUAKE

- DAMS NEAR THE EPICENTER WERE SHAKEN STRONGLY
- SAFETY INSPECTIONS OF DAMS SHOWED NO DAMAGE TO DAMS WHICH AFFECTED THEIR SAFETY AND NO IMMEDIATE PROTECTIVE COUNTERMEASURES WERE REQUIRED

Upstream slide Kitayama dam

KOCAELI EARTHQUAKE

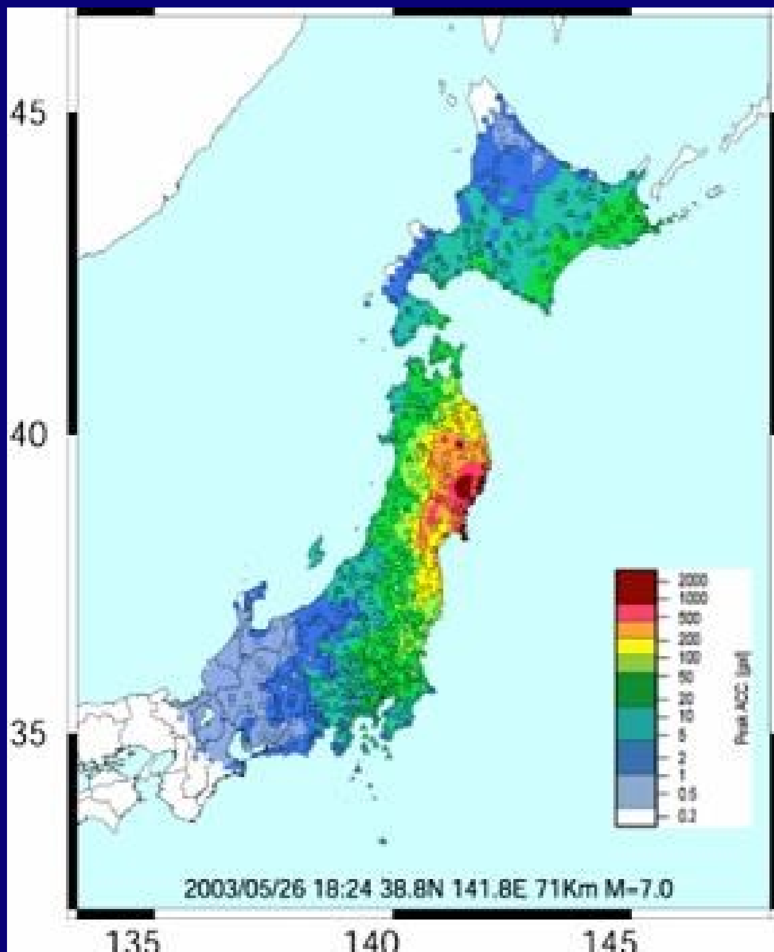
- **GOKÇE DAM, 50m HIGH NO DAMAGE DURING EARTHQUAKE**
- **YUVAÇIK DAM, 108 M HIGH VERY LITTLE DAMAGE WITH SETTLEMENT OF 100 mm**

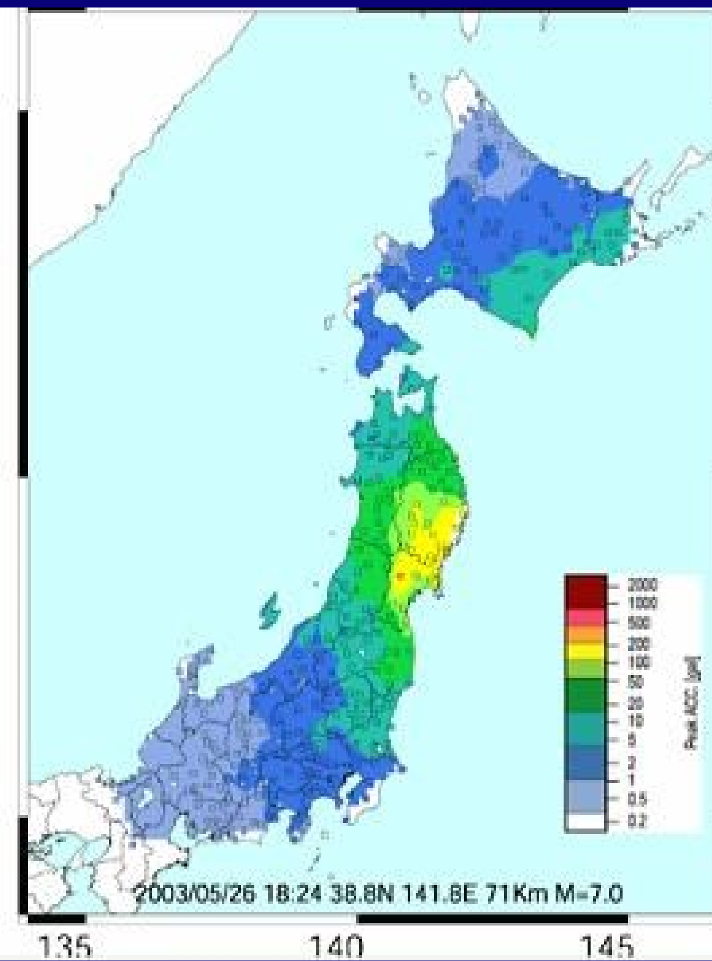
CHI-CHI EARTHQUAKE

- SHUI-SHI AND TOULIH DAMS SETTLED ABOUT 0.3m
- SHUI-SHI DAM HAD LONGITUDINAL CRACKS
- TOULIH DAM PERFORMED WELL

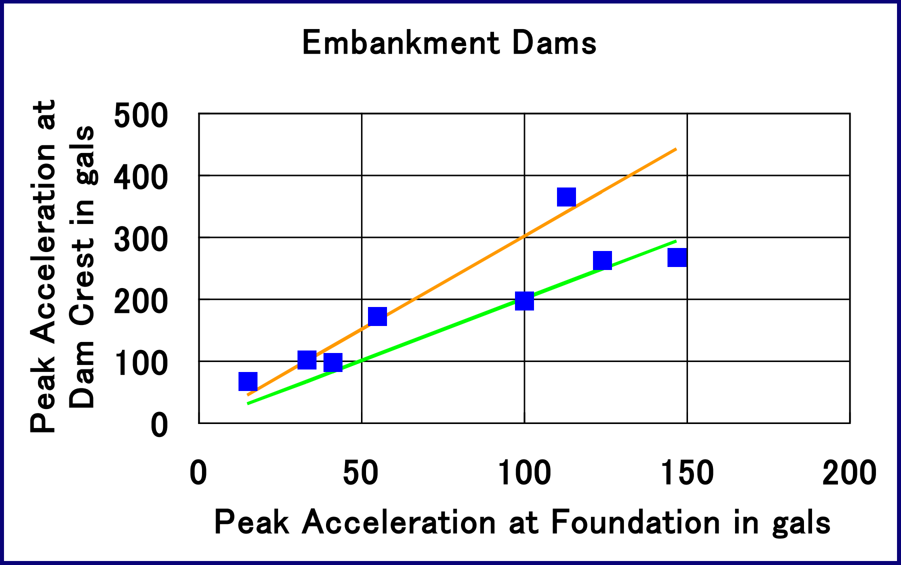
Shih-kang weir

26 May 2003 EARTHQUAKE IN JAPAN

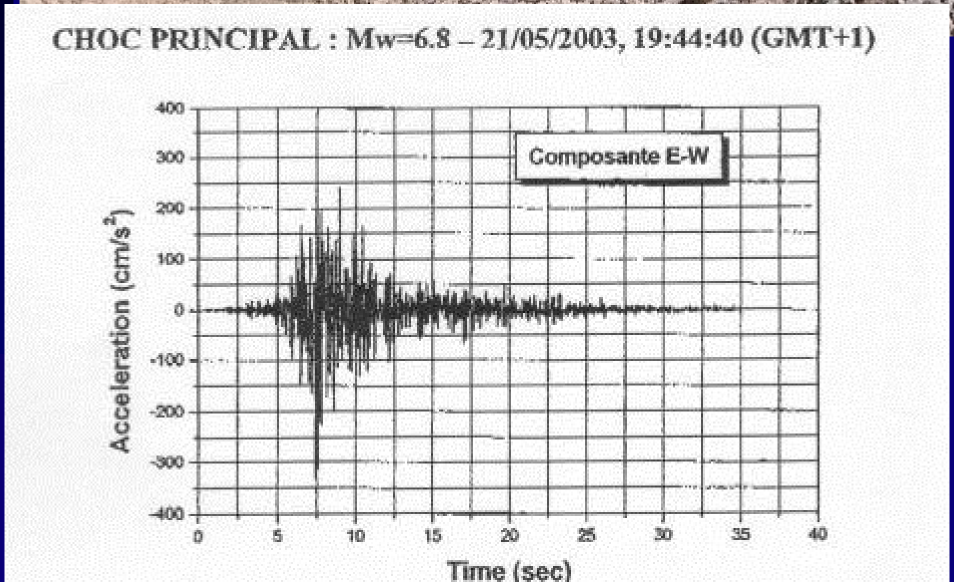




26 May 2003 EARTHQUAKE IN JAPAN



EARTHQUAKE 21 MAY 2003-ALGERIE



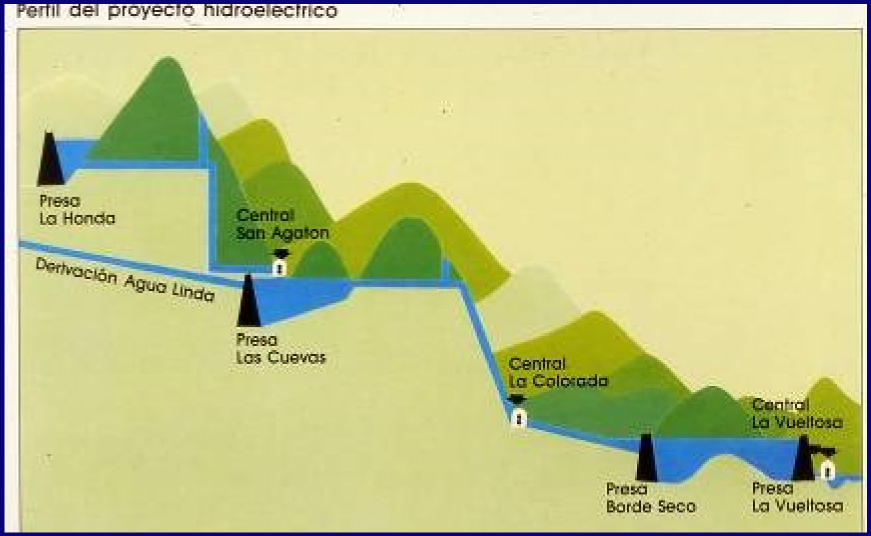
ANALYSIS OF DAMS STABILITY DURING EARTHQUAKES

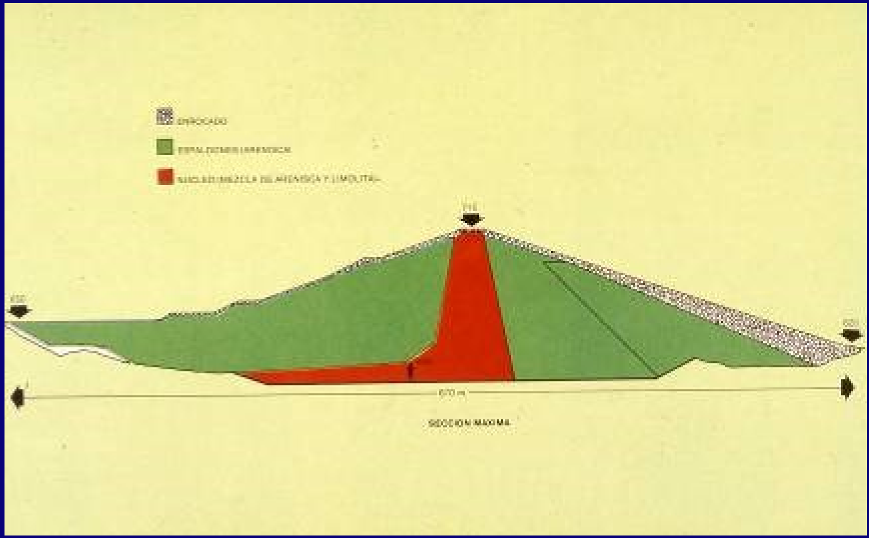
- EXPERIMENTAL MODELS
  - SHAKING TABLE
  - CENTRIFUGE TESTS
- MATHEMATICAL MODELS
  - PSEUDO –STATIC ANALYSES
  - SIMPLIFIED PROCEDURES TO ASSESS DEFORMATIONS
  - DYNAMIC ANALYSIS

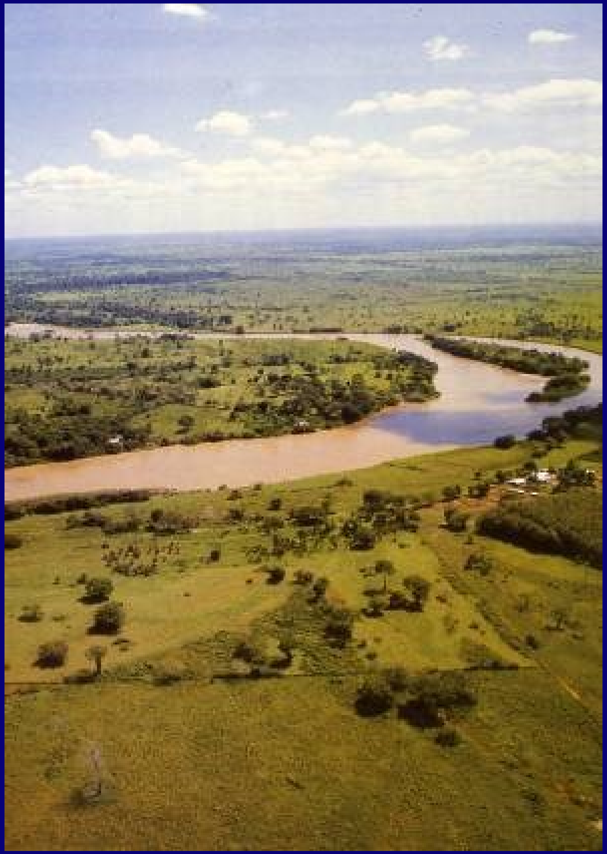
SELECTION OF DESIGN EARTHQUAKES

- REGIONAL GEOLOGIC STUDY MINIMUM A 100 KM RADIUS AROUND THE SITE BUT SHOULD BE EXTENDED TO 300KM
- FOR THE OBE A PROBABILISTIC APPROACH IS USED
- FOR THE MDE BOTH DETERMINISTIC AND PROBABILISTIC APPROACHES ARE USED

LAS CUEVAS DAM – CASE STUDY







LAS CUEVAS DAM – CASE STUDY

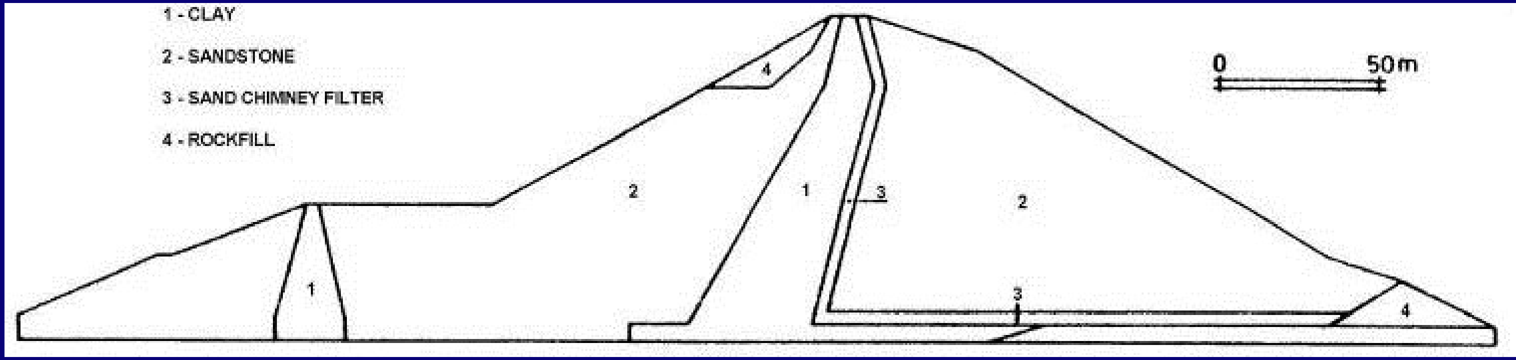


Fig.8 – Las Cuevas dam cross-section

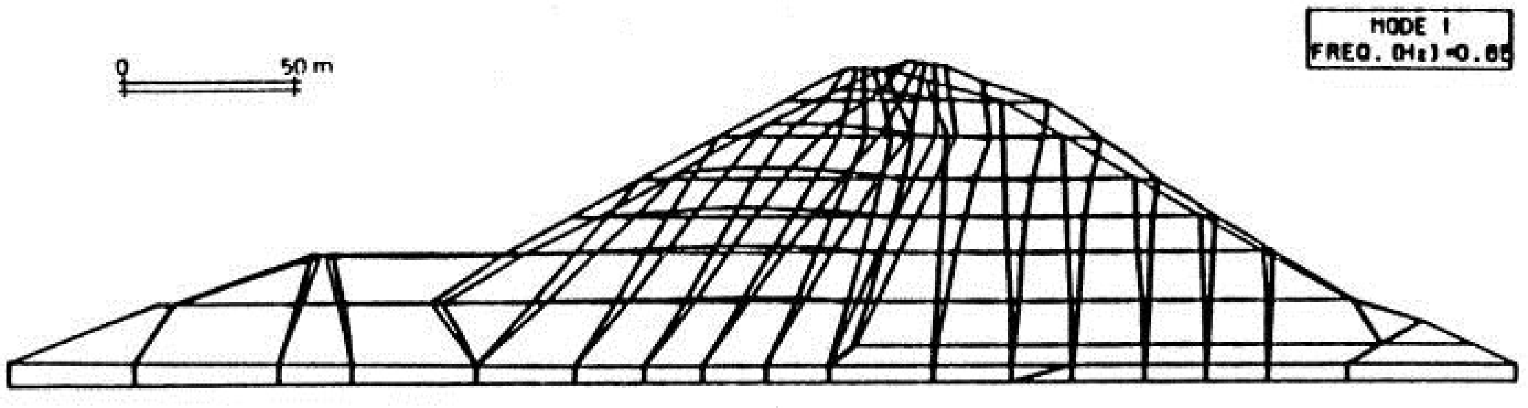


Fig. 9 – 2D first vibration mode

LAS CUEVAS DAM – CASE STUDY

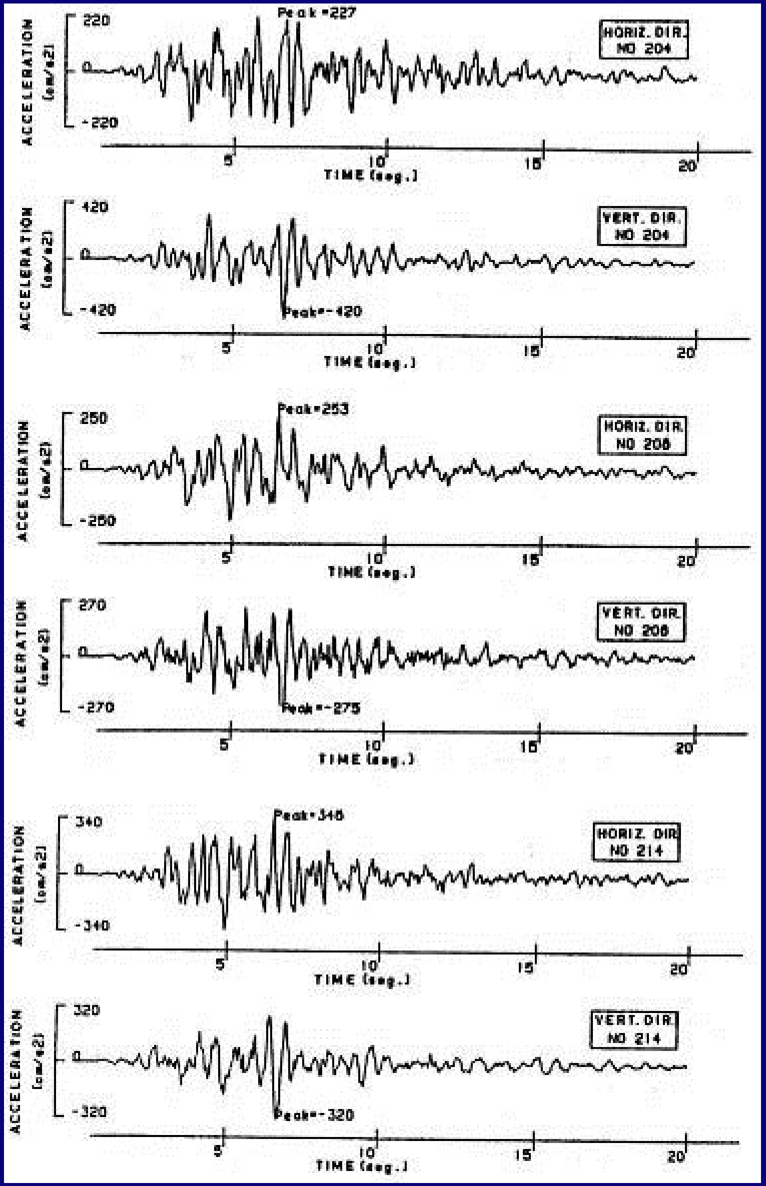


Fig. 10 - Maximum accelerations responses

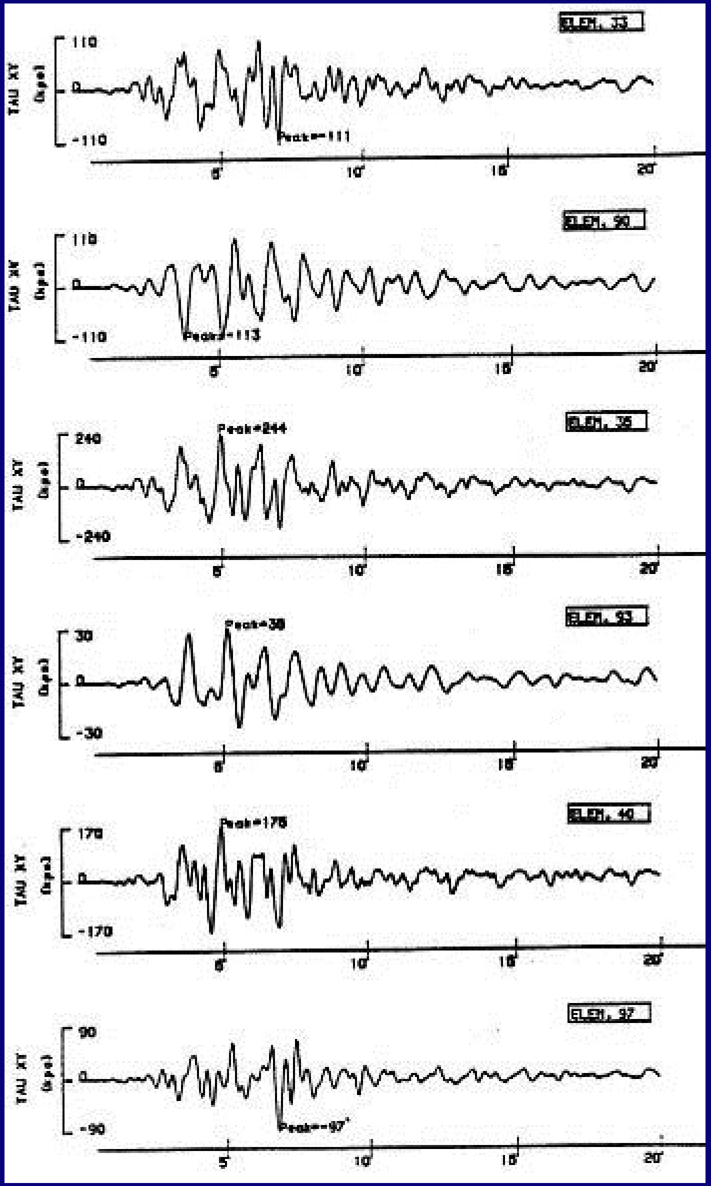


Fig. 11 – Shear stress time histories

LAS CUEVAS DAM – CASE STUDY

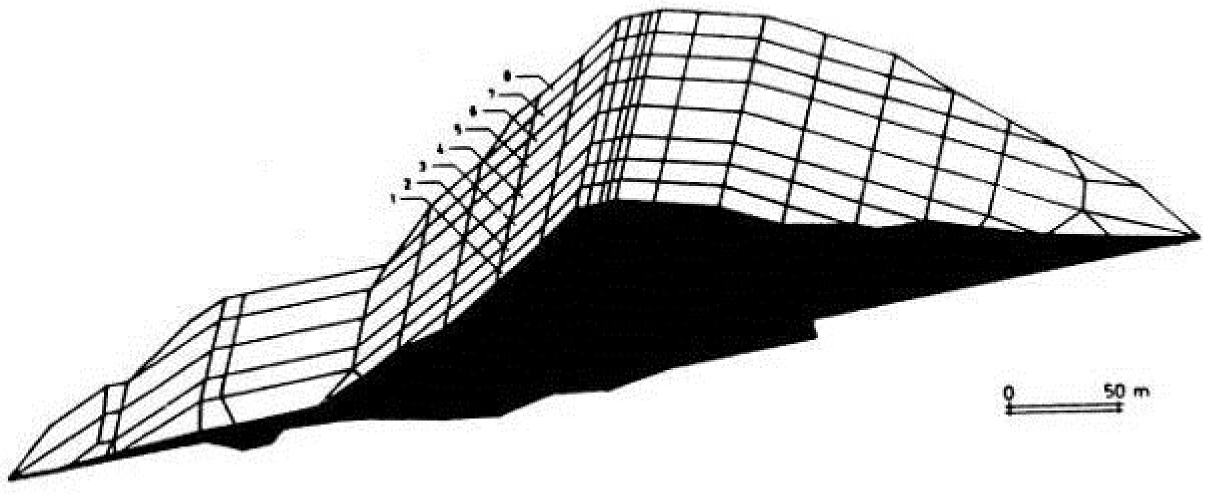


Fig. 13 – 3D finite element mesh

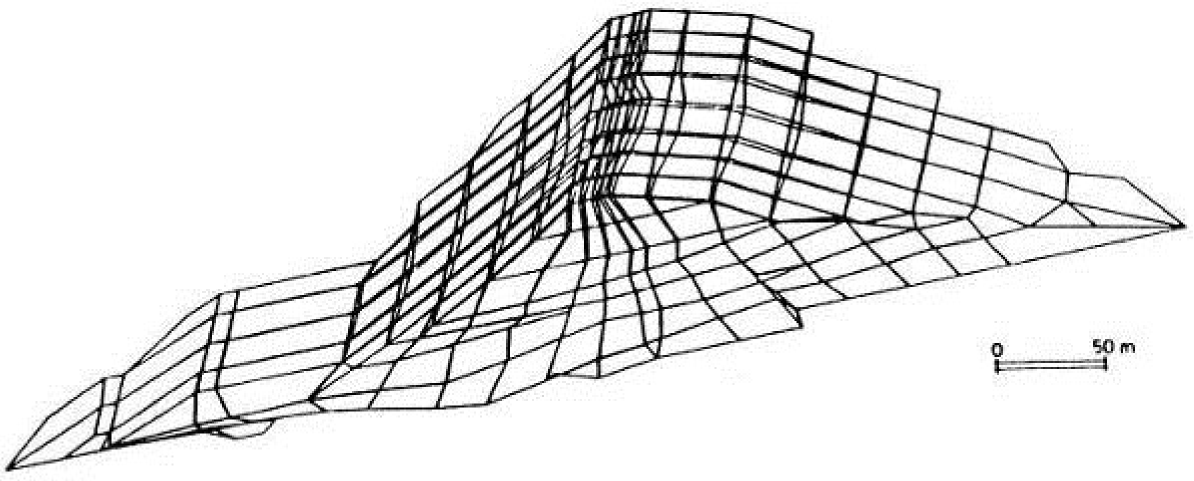


Fig. 14 – 3D first vibration mode

HYDRODYNAMIC EFFECTS OF RESERVOIR

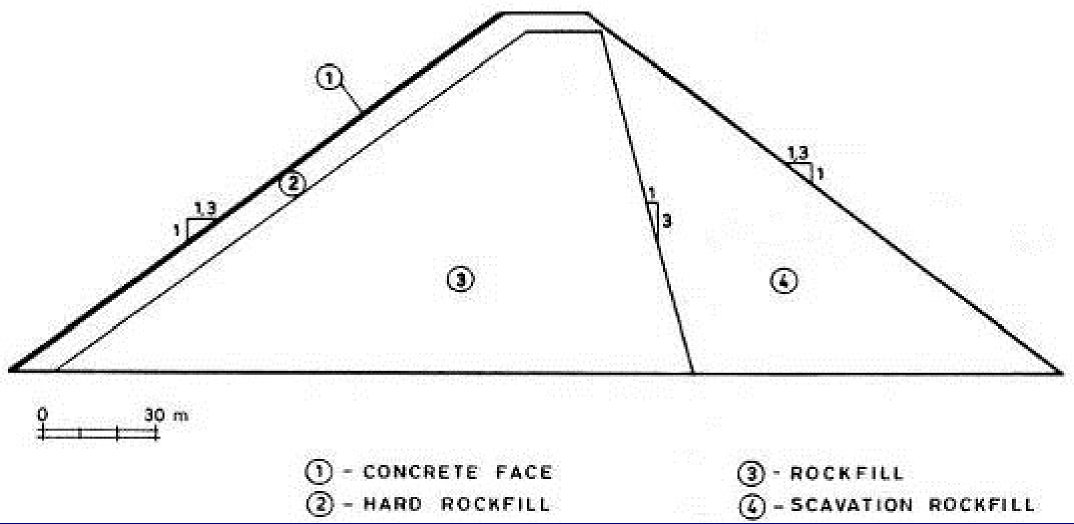


Fig. 15 – Concrete face rockfill dam section

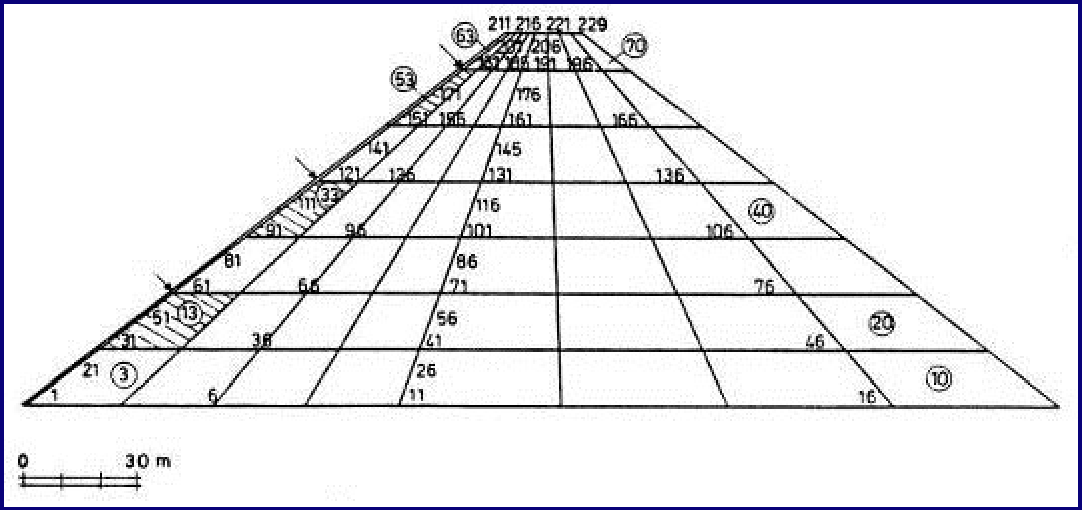


Fig. 16- Finite element mesh

HYDRODYNAMIC EFFECTS OF RESERVOIR

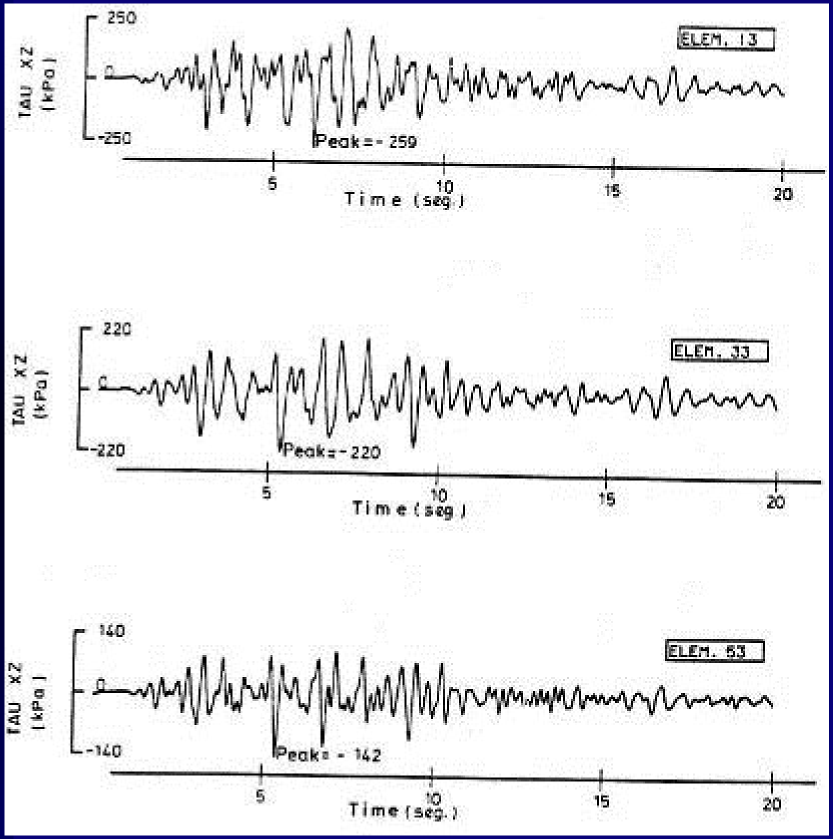


Fig. 17 – Shear stress – time story for finite elements nº 13, 33 and 53

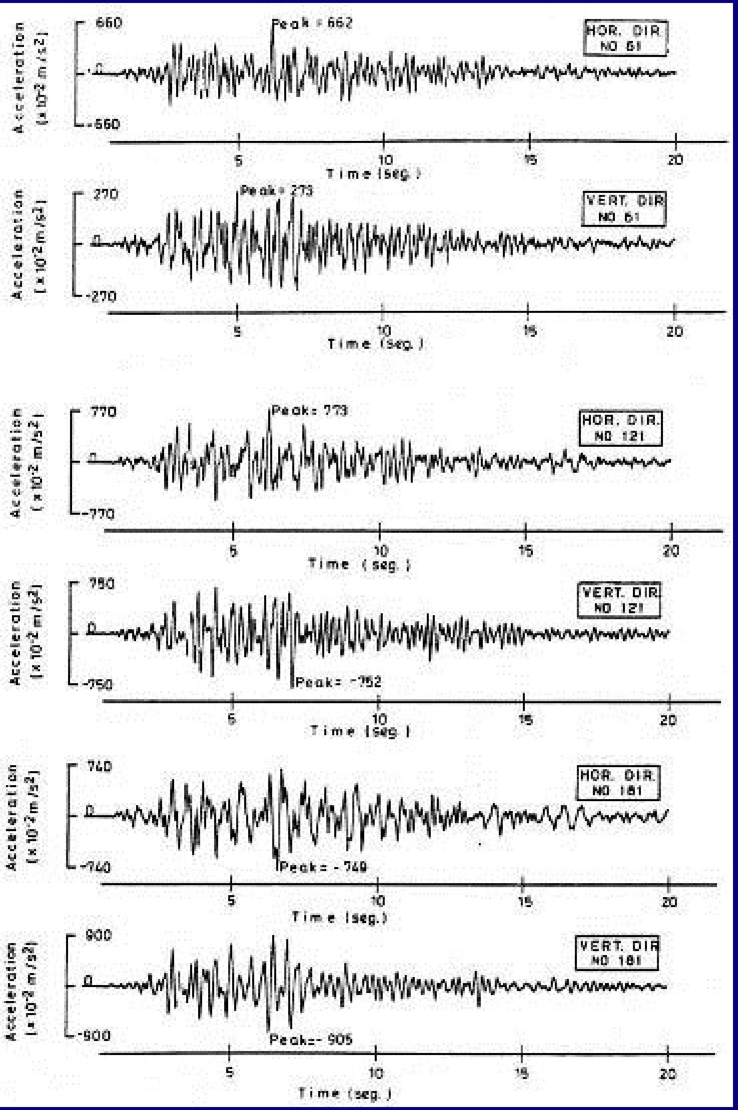


Fig. 18 – Horizontal and vertical accelerations for nodal Nº 61, 121 and 181

RESERVOIR INDUCED SEISMICITY

- **DAMS HIGHER 100 m**
- **LARGE RESERVOIRS GREATER THAN 500x 10^6 m^3**
- **HISTORICAL SEISMICITY AND SURVEYS OF GEOLOGICAL STRUCTURES**
- **INSTALATION OF A PERMANENT NETWORK**

Table 5 Examples of dams with induced seismicity

DAM	Country	Type	Height (m)	Reservoir volume (x 10^6 m^3)	Year of impounding	Induced seismicity		Prior seismicity
						M	year	
Marathon	Greece	gravity	63	41	1930	5	1938	moderate
Hoover	U.S.A.	arch-gravity	221	36703	1936	5	1939	---
Kariba	Zimbabwe/ Zambia	arch	128	160368	1959	5,8	1963	low
Haifengkiang	China	buttress	105	10500	1959	6,1	1962	aseismic
Koyna	Índia	gravity	103	2708	1964	6,5	1967	low
Kremasta	Greece	embankment	165	4750	1965	6,3	1966	moderate
Roi Constantine	Greece	embankment	96	1000	1969	6,3		moderate
Oroville	U.S.A.	embankment	236	4298	1967	5,7	1975	moderate
Nurek	Tajikistan	embankment	330	11000	1972	5	1977	moderate
Tarbella	Pakistan	embankment	143	14300	1974	5,8	1996	low
Aswan	Egypt	embankment	111	163000	1974	5.3	1981	aseismic

PROTOTYPE DYNAMIC TESTS

- STRESS LEVEL IS ALWAYS VERY LOW
- FOR CONCRETE DAMS FORCED VIBRATION ARE IMPORTANT TO VALIDATE THE ANALYTICAL MODEL
- THE DAM RESPONSE TO VIBRATIONS IS RECORDED BY SEISMOMETERS

Table 6 - List of dams subjected to dynamic excitation

Nº	Name	Type	Country	Height (m)	Type of Recorded Vibrations
1	Santa Felicia	ED	U.S.A.	83	Seismic, ambient, forced, hydrodynamic
2	Brea	ED	U.S.A.	27	Seismic
3	Carbon Canyon	ED	U.S.A.	33	Seismic
4	Bouquet	ED	Yugoslavia	60	Forced
5	Mavroro	ED	Japan	56	Forced
6	Kisenyama	RD	Japan	95	Seismic, ambient, forced
7	Shimokotori	RD	Japan	119	Seismic, ambient, forced
8	Nikappu	RD	Japan	103	Seismic, ambient, forced
9	Talaragi	RD	Japan	65	Seismic, ambient, forced
10	Sannokai	ED	Japan	37	Seismic
11	Ainono	ED	Japan	41	Seismic
12	Ushino	RD	Japan	21	Seismic
13	Kamishiba	AD	Japan	110	Forced
14	Mainadisauro	AD	Italy	136	Forced
15	Pacoima	AD	USA	128	Forced
16	Cabril	AD	Portugal	136	Forced
17	Aguieira	MAD	Portugal	89	Forced

AGEING EFFECTS

- AGEING IS A CLASS OF DETERIORATION ASSOCIATED WITH TIME
- THE METHODS USED ARE INSPECTION, TESTING AND MONITORING
- THE PROGRESS IN SAFETY OF DAMS IS DUE THE IMPROVEMENTS OF DESIGN AND CONSTRUCTION

REHABILITATION OF DAMS

- **DAM DETERIORATION RELATED WITH SETTLEMENT OF FILL OR FOUNDATION , POOR CONCRETE AND SHRINKAGE CRACKS**
- **DANGERS TO GEOMEMBRANES ARE DUE FALLING ROCK, BLOWS FROM HEAVY FLOATING OBJECTS, ULTRAVIOLET RADIATIONS**
AND WILLFUL DAMAGE

BENEFITS AND CONCERNS OF DAMS

- BENEFITS OF DAMS WITH THE MULTIPURPOSE USES
- PREDOMINANT CONCERN ABOUT RESERVOIRS IS RESETTLEMENT
- SOCIAL, POLITICAL AND ENVIRONMENTAL CONSEQUENCES ARE IMPORTANT

RISK ANALYSES

- TO IDENTIFY REAL RISKS ASSOCIATED WITH TYPE AND HEIGHT OF DAM
- THREE QUESTIONS: WHAT CAN GO WRONG? HOW LIKELY IS IT? WHAT DAMAGE WILL IT DO?
- RISK ANALYSIS TO GUIDE FUTURE INVESTIGATIONS TO MAKE DECISIONS ON DAM SAFETY
- DISCUSSIONS RELATED FAILURE MODES AND EFFECTS ANALYSIS(FMEA) , FAILURE MODE, EFFECTS AND CRITICALLY ANALYSIS (FMECA), EVENT TRESS ANALYSIS (ETA), FAULT TREE ANALYSIS (FTA)

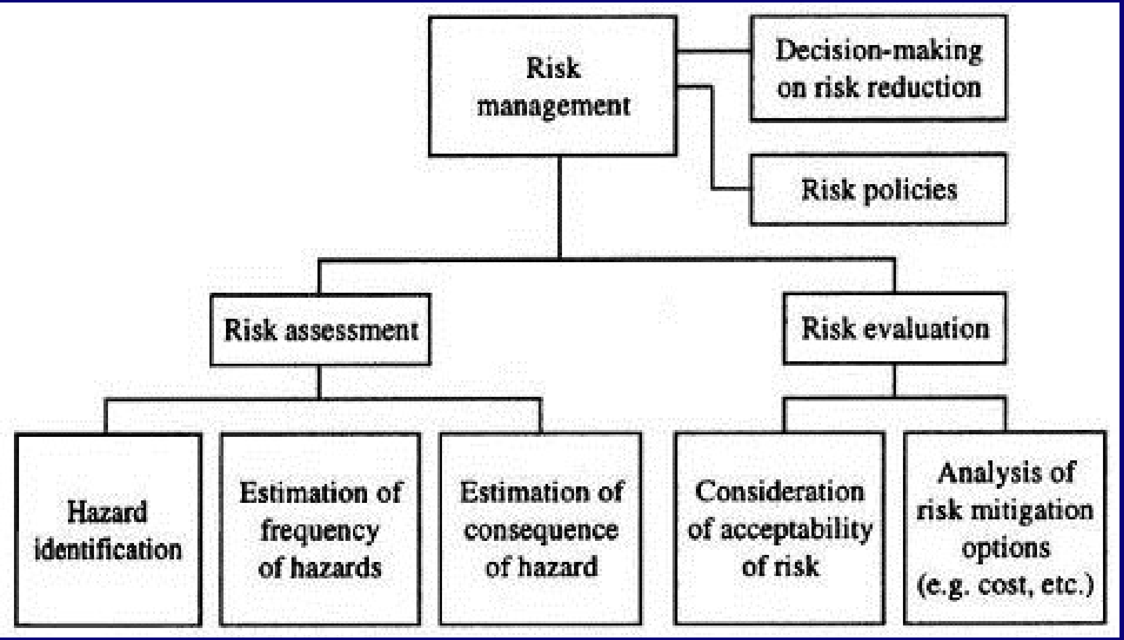
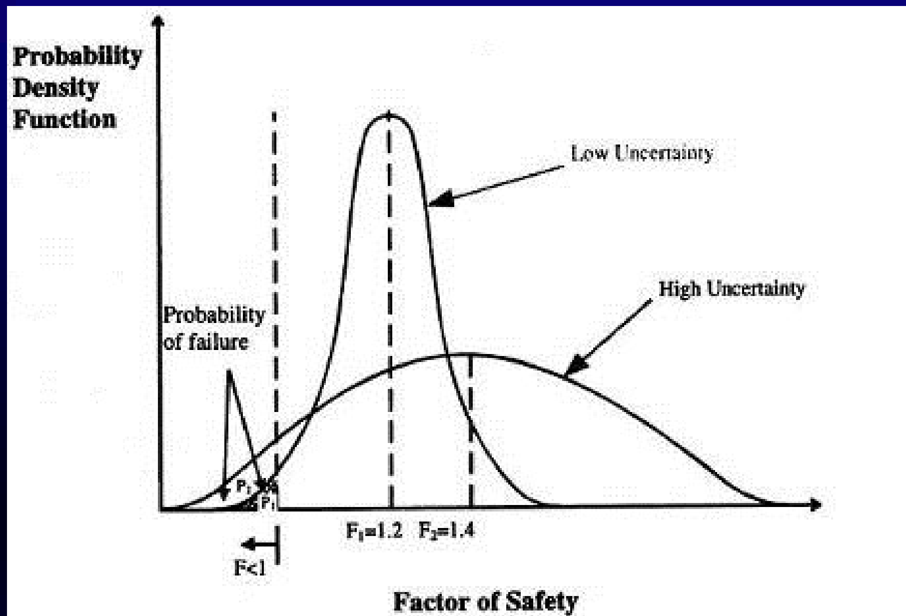


Fig. 20 – Framework for risk management (after Ho et al, 2000)

RISK ANALYSES



Note : $P_2 > P_1$ although $F_2 > F_1$, i.e. a higher factor of safety does not necessarily correspond to a lower probability of failure, depending on the degree of uncertainty involved.

Fig. 21 -Relation between factor of safety and probability of failure (after Lacasse & Nadim, 1998)

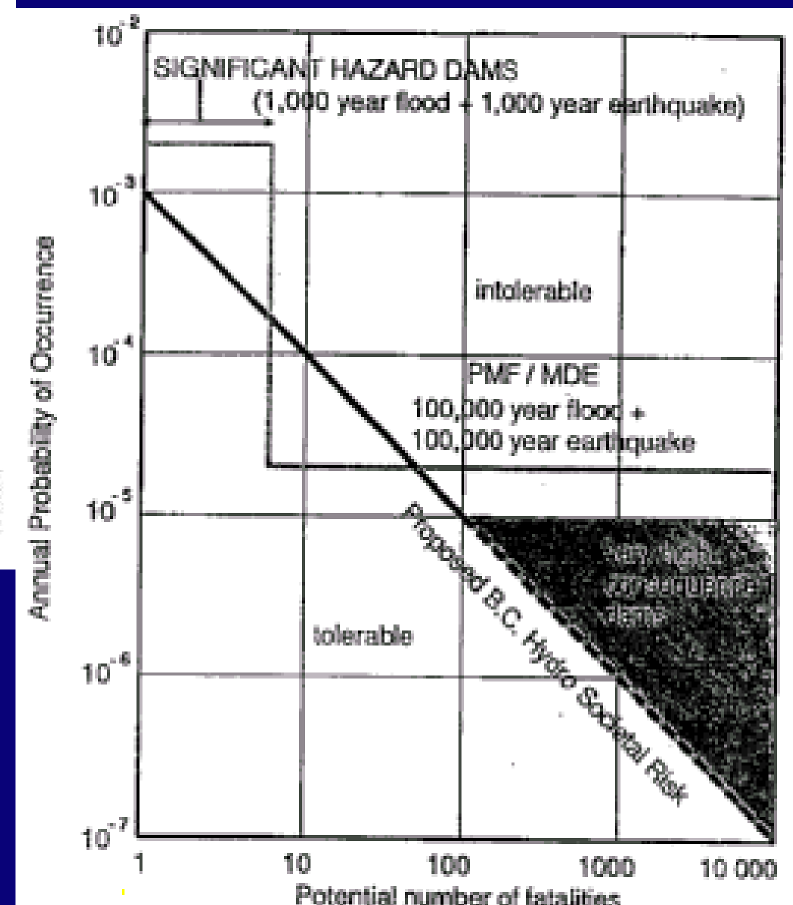


Fig. 22-Incremental hazard criteria (after Salmon and Hartford, 1995b)

FINAL REMARKS AND TOPICS FOR DISCUSSION

- BEST APPROACH FOR VALIDATION OF COMPUTER CODES
- DISCRETE ELEMENT MODELS TO REPRODUCE OPENINGS OF JOINT ROCK MEDIUM
- CRITERIA TO SELECT RECURRENCE PERIOD FOR MCE AND OBE
- EFFICIENCY OF NEW METHODS TO INVESTIGATE TRENCHES

FINAL REMARKS AND TOPICS FOR DISCUSSION

- ADVANTAGES AND DIFFICULTIES OF RISK ANALYSES FOR SAFETY DECISIONS
- SCIENTISTS MUST RECOGNIZE THAT LPEEs ARE A SPECIAL CHALLENGE BECAUSE IT BECOMES EXCEEDINGLY DIFFICULT TO ESTIMATE THEIR RECCURRENCE TIME FROM STATISTICAL ANALYSES
- CONTINUOS EDUCATION IS HIGHLY RECOMMENDED TO FOLLOW THE VERY FAST DEVELOPMENTS OF EARTHQUAKE GEOTECHNICAL ENGINEERING AND PARTICULARLY OF DAM ENGINEERING
- EARTHQUAKES REMIND OUR SOCIETY FOR THE RESPONSABILITY OF MANAGEMENT OF DISASTERS INFLICTED BY NATURAL CATASTROPHES WITH AVALABLE MODERN TOOLS

HIPPOCRATES

"The art is long
and life is short
experience is fallacious
and decision is difficult"