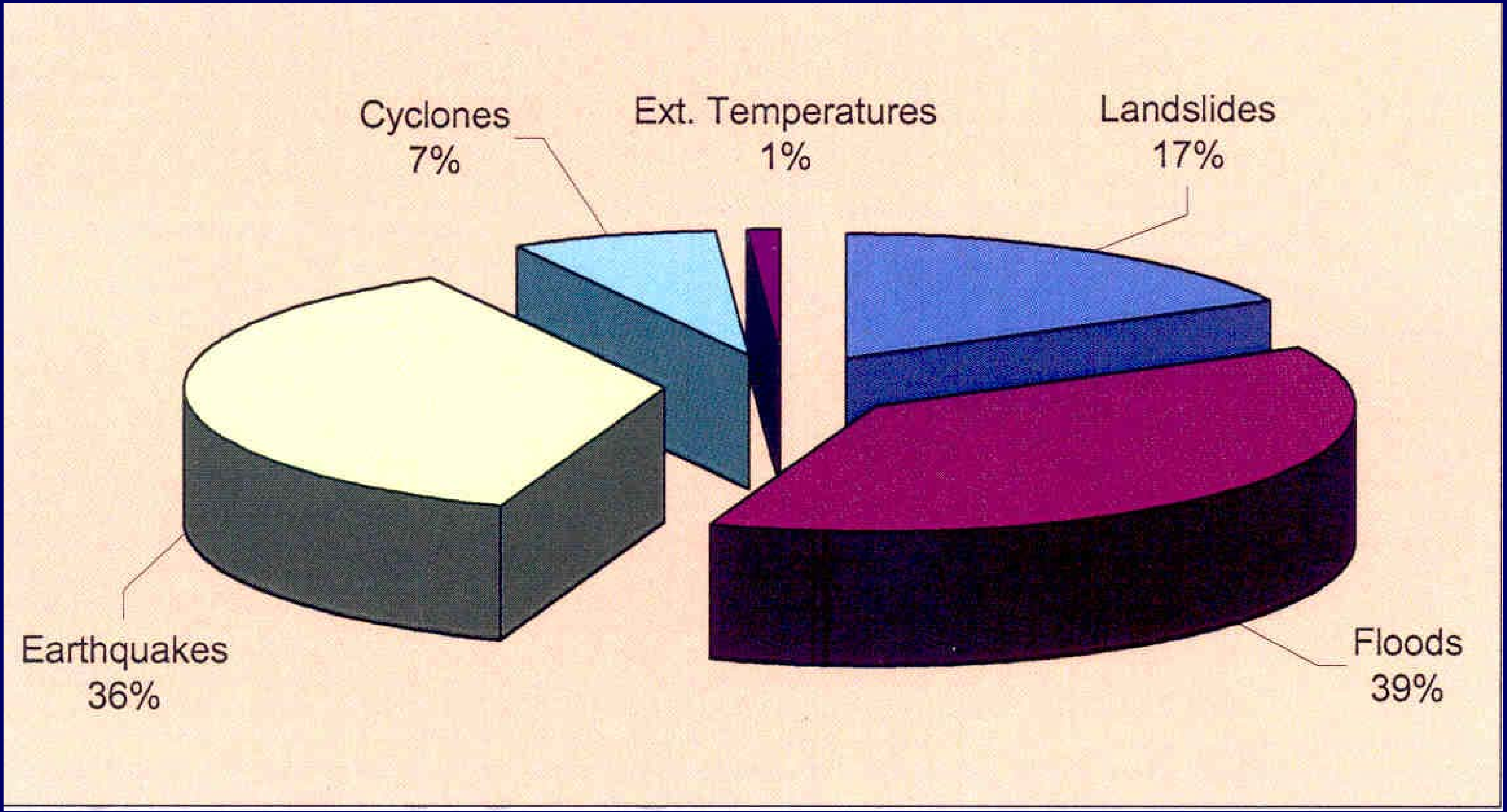
LANSLIDES ANALYSIS UNDER STATIC AND SEISMIC CONDITIONS

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

TOPICS

- INTRODUCTION TO HAZARDS
- TRIGGERED MECHANISMS OF LANDSLIDES
- GEOTECHNICAL CHARACTERIZATION METHODS
- ANALYSIS OF LANDSLIDES STABILITY UNDER STATIC AND SEISMIC CONDITIONS
- MONITORING AND SAFETY EVALUATION
- PREVENTION, MITIGATION AND REHABILITATION METHODS
- RISK ANALYSIS
- CASE STUDY 1: CASTRO DAIRE LANDSLIDE
- CASE STUDY 2: JOSEFINA LANDSLIDE
- FUTURE DEVELOPMENTS
- FINAL COMMENTS

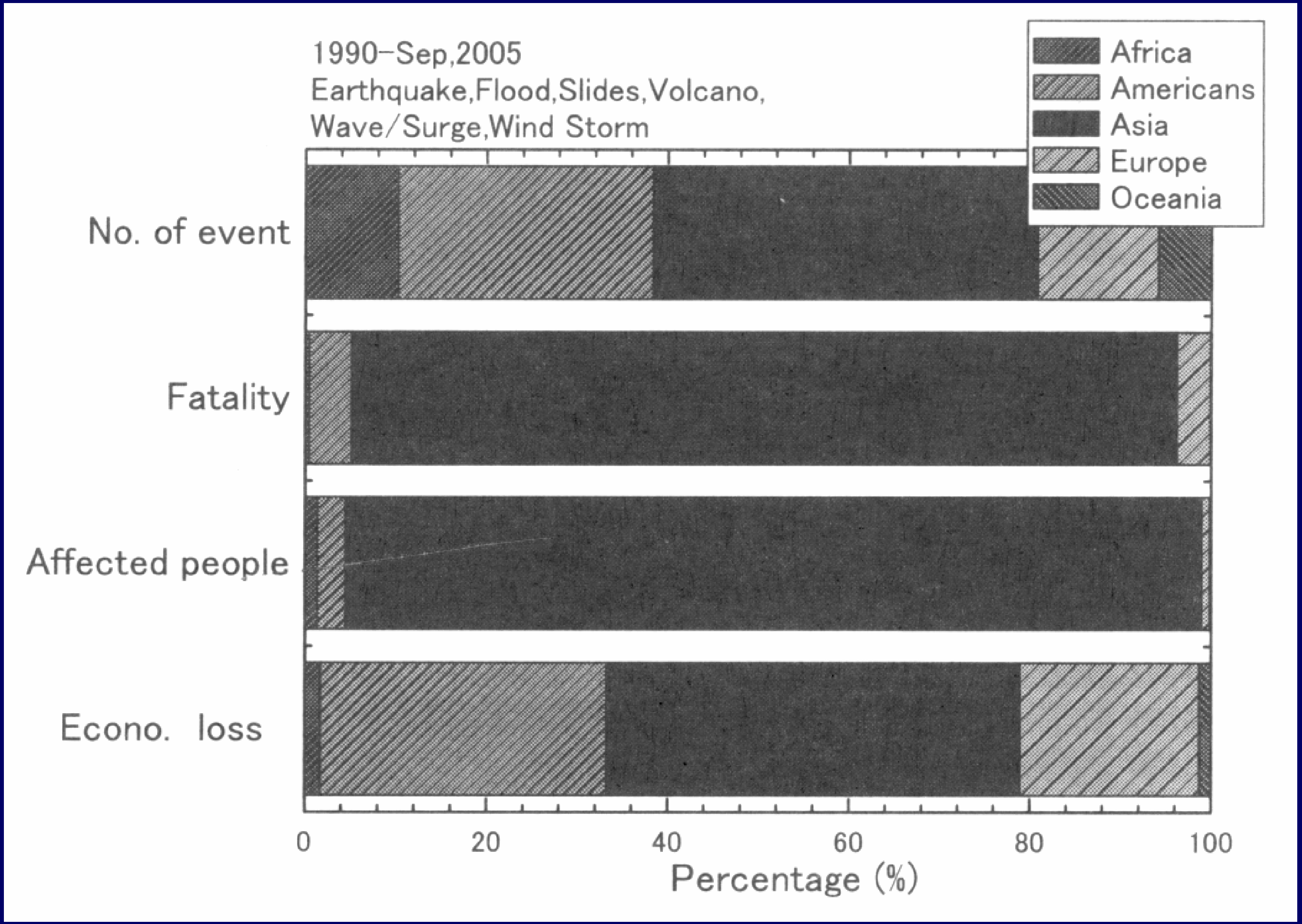
CASUALTIES FOR DIFFERENT NATURAL (source CRED)



CLASSIFICATION OF NATURAL DISASTERS (source CRED)

- Drought
- Earthquake
- Epidemic
- Famine
- Extreme Temperature
- Flood
- Insect infestation
- Slide
- Volcano
- Wave/Surge
- Wild fires
- Wind storm

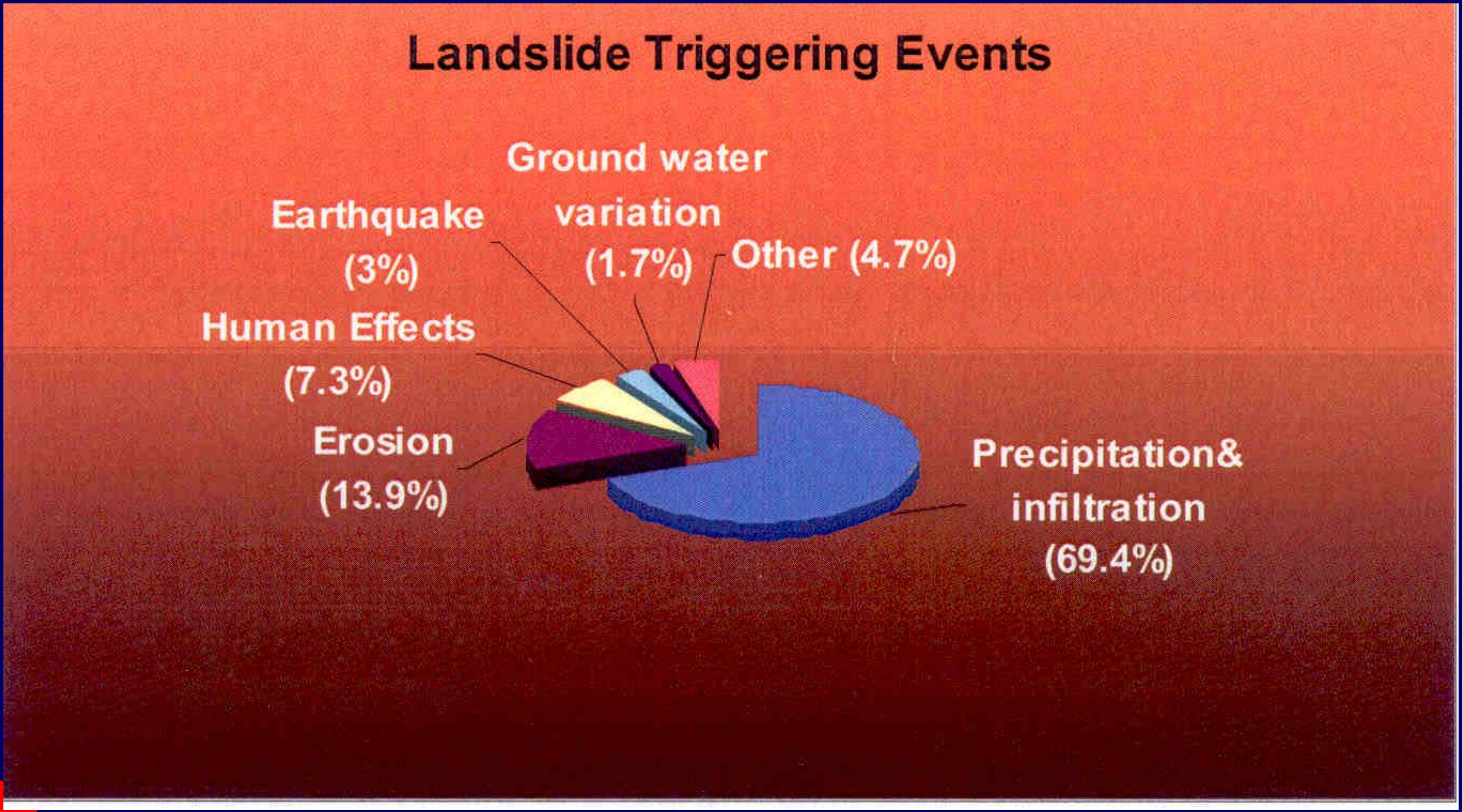
REGIONAL PERCENTAGE OF GEODISASTERS IN RECENT
PERCENTAGE OF GEODISASTERS IN RECENT 15 YEARS (source CRED)



EXTREME EVENTS

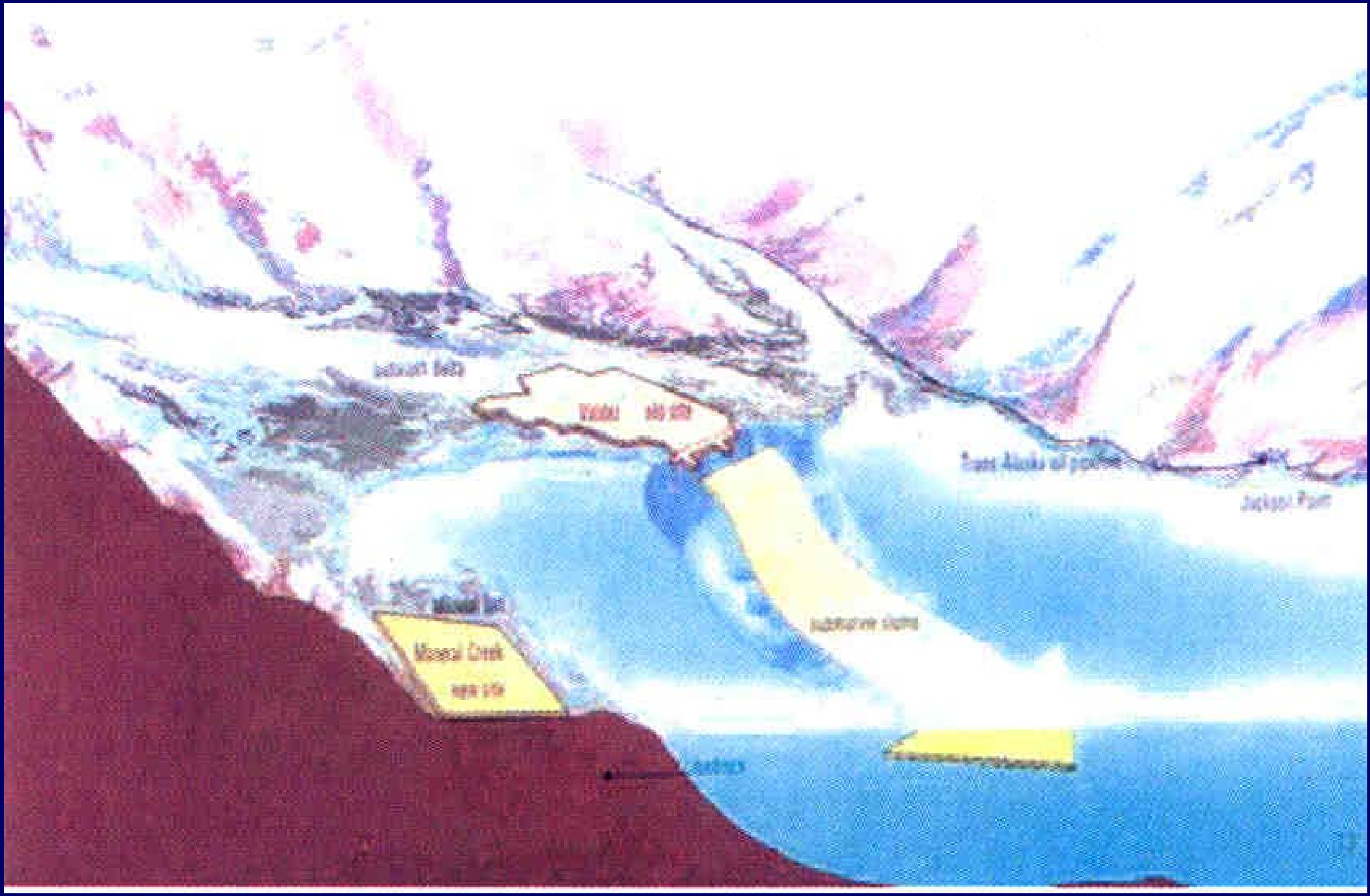
- The 2004 Indian Ocean Tsunami with more than 240 thousands lives
- _Bhola cyclone in November 1970 with winds of 190 km/h in Bay of Bengal with a death toll of 500 000 and 100 000 people missing
- __The volcano of Tambora (Indonesia) with a violent eruption killed 92 000 people
- _Due 1923 Great Kanto earthquake more than 140 000 people were killed in and around Tokyo
- _The 1976 Tangshan earthquake (M7.8) in China claimed 242 000 lives and is a typical extreme event
- _The most recent Pakistan earthquake (M7.6) on October 8, 2005 killed more than 75000 people

LANSLIDE TRIGGER MECHANISMS (reference AVI Database)



EL SALVADOR SLOPE AFTER EARTHQUAKE
13 January 2001

ALASKA EARTHQUAKE, 1964



Chi-Chi EARTHQUAKE, 1999-Shallow Disaggregated Slides (courtesy Nicholas Sittar)

Chi-Chi EARTHQUAKE, 1999-Shallow Disaggregated Slides (courtesy Nicholas Sittar)

Chi-Chi EARTHQUAKE, 1999-Rock Falls (courtesy Nicholas Sittar)

ROCK FALL, KOBE EARTHQUAKE, 1995
(courtesy Nicholas Sittar)

FLOW SLIDES AND DEBRIS
DENALI EARTHQUAKE, 2002

Bedding Parallel to Slope Niigata Perfecture (courtesy R.Keyen, USGS)

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Italy-Val Pola 1987 landslide (after GEOTECHNET, 2005)

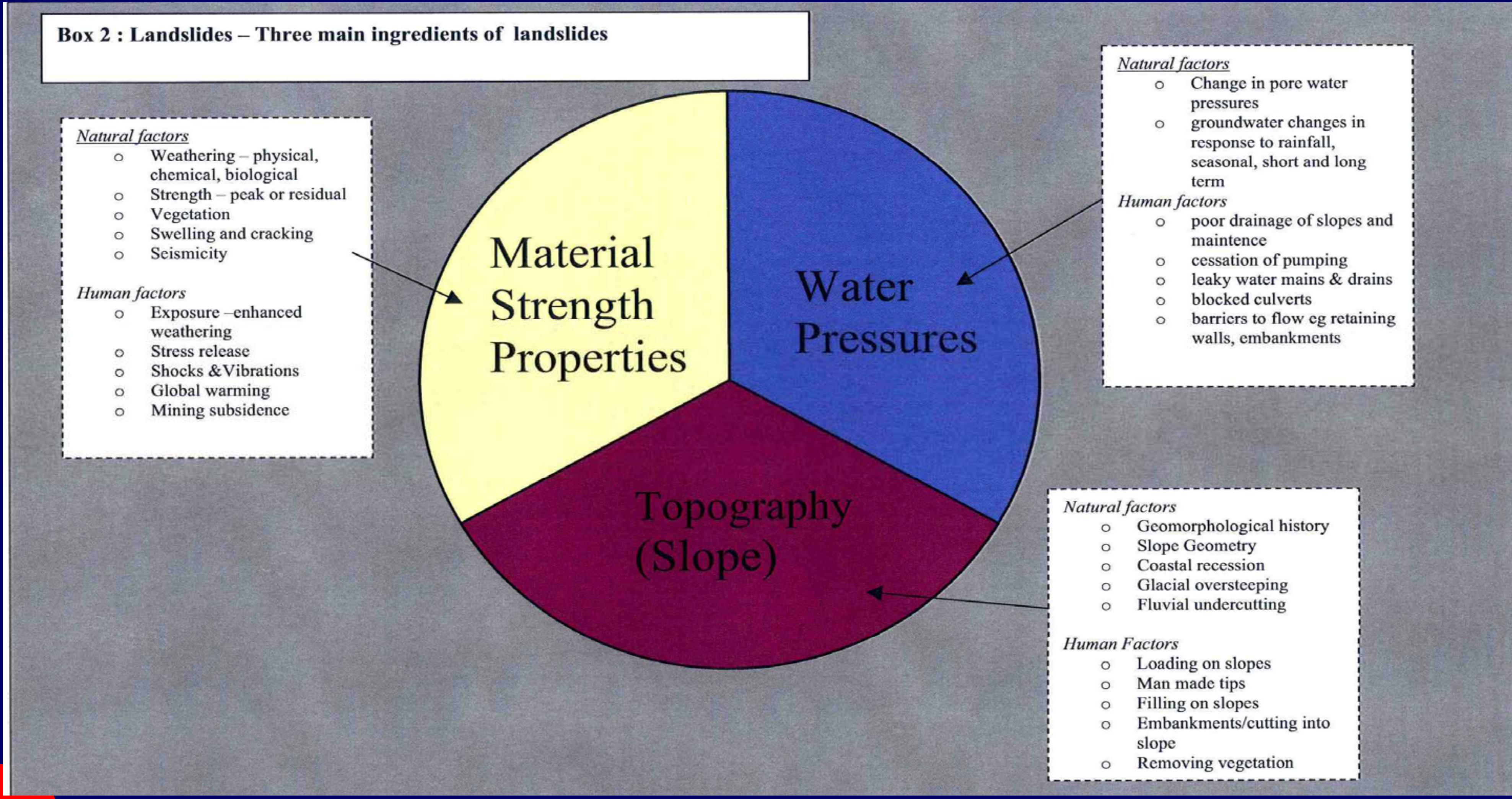
Switzerland houses and road swept away (after GEOTECHNET, 2005)

Shum Wan road landslip –August 1995–Hong Kong

Landslide in Rissa, Norway (1978)

Landslide in Varna (Romania)

LANSLIDES –THREE MAIN INGREDIENTS (after GEOTECHNET)



LOSS OF LIFE FROM LANDSLIDES

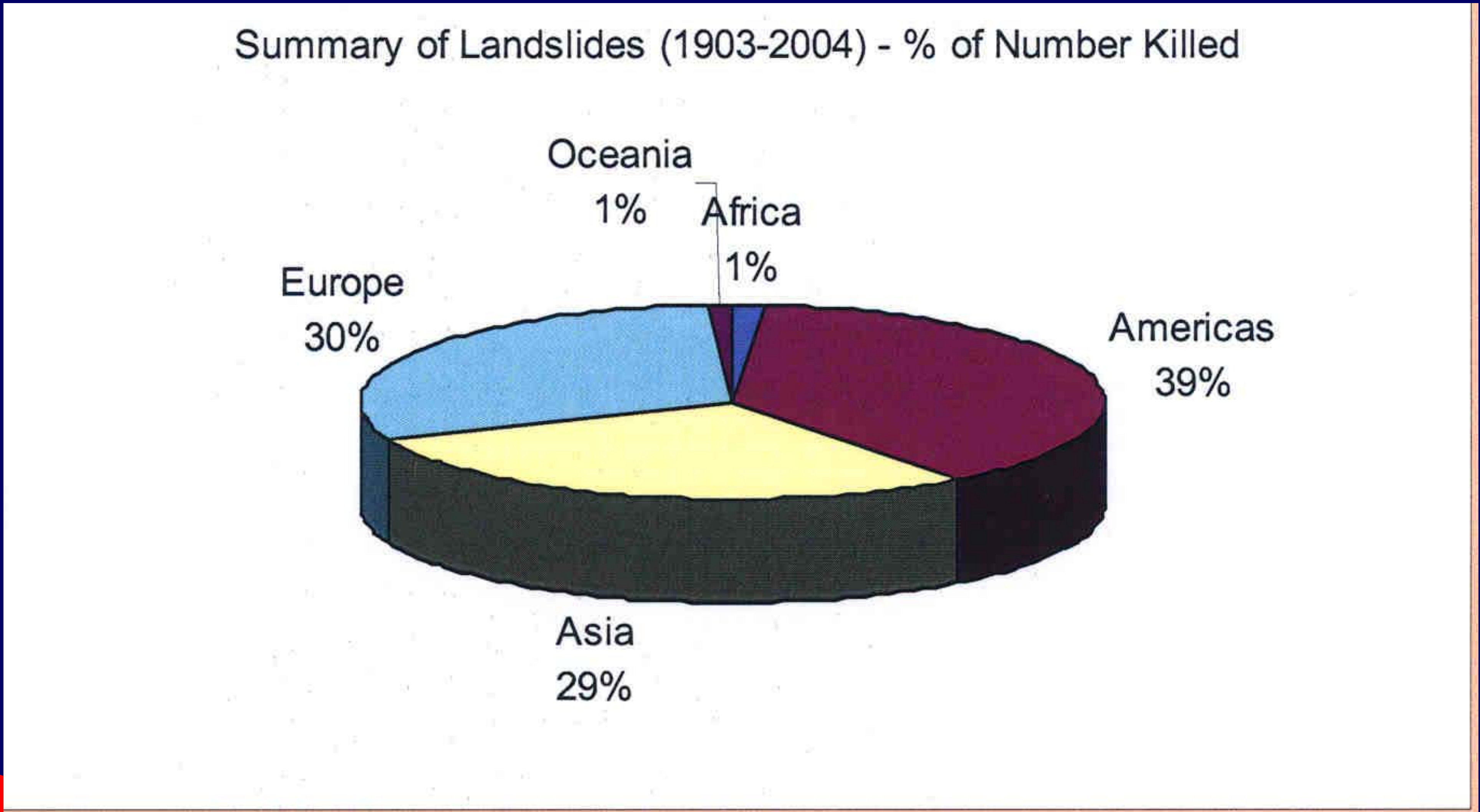


Table 2 - Field tests

Test	Parameters for stress state					Strength Parameters			Parameters for deformation		
	γ	I_d	K_o	OCR	S	S_u	c	ϕ	E	G_{max}	M
CPTU	x	x	x	x	x	x	x	x	x		x
SPT		x			x	x	x	x	x		x
Vane shear			x	x	x	x	x		x		
Pressiometer			x			x	x	x	x		
Penetrometer						x	x	x	x		
Dilatometer	x	x		x		x		x	x	x	x

Table 3 - Laboratory tests

Test	Strength Parameters			Deformation Parameters		
	S_u	c	ϕ	E	G_{max}	M
Direct shear		x	x			
Uniaxial compaction				x		
Triaxial	x	x	x	x		
Odometer						x

Table 4 - Field tests

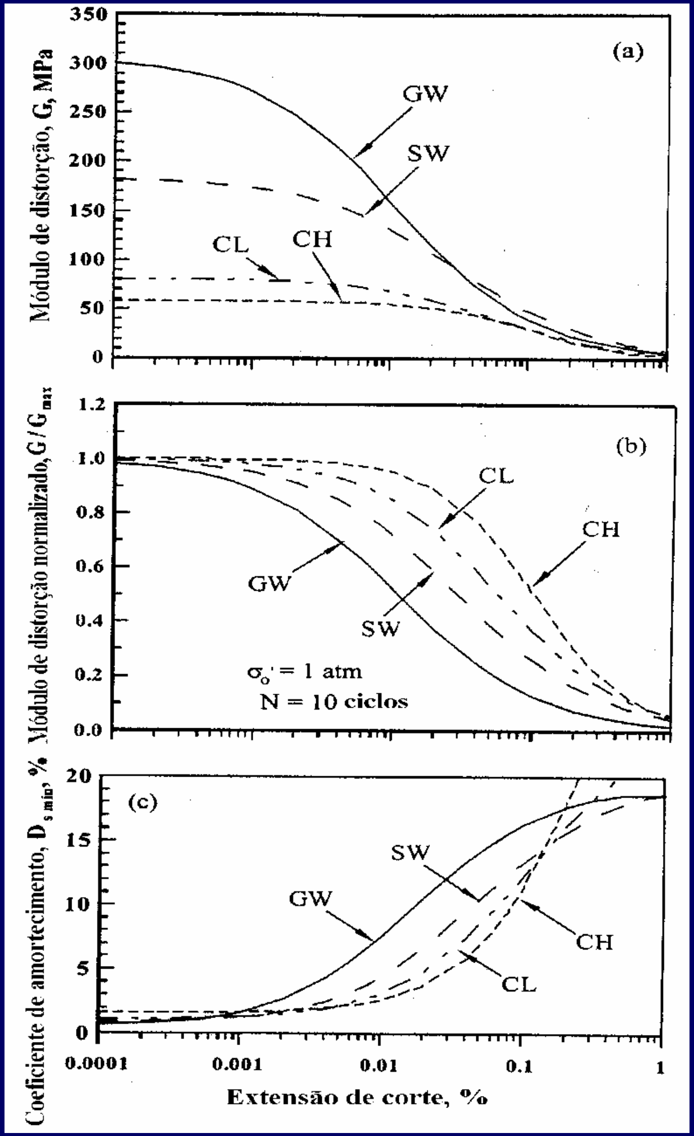
Tests	Parameters		
	V_p	V_s	G_{max}
Refraction	x	x	x
Uphole	x	x	x
Downhole	x	x	x
Crosshole	x	x	x

Table 5 – Laboratory tests

Tests	Parameters			
	G	E		G_{max}
Resonant Column	x	x	x	x
Cyclic Triaxial	x	x	x	
Cyclic simple shear	x	x	x	
Cyclic torsional shear	x	x	x	

Laboratory Devices

Variation of shear modulus and damping ration with shear strain



SLOPE STABILITY

Pseudo-Static Method

Rigid Block Models

Dynamic Analysis

FH = 0,5 αgrγf SW/g for the horizontal direction

FV = ± 0,5 FH in the vertical direction when Spectrum Type 1 is applicable

FV = ± 0,33 FH in the vertical direction when Spectrum Type 2 is applicable

SLOPE STABILITY

Simplified methods shall not be used for soils capable of developing high pore water pressures or significant degradation of stiffness

Topics that deserve more consideration

- Residual strenght of soil
- Rock slope stability
- Mitigation methods

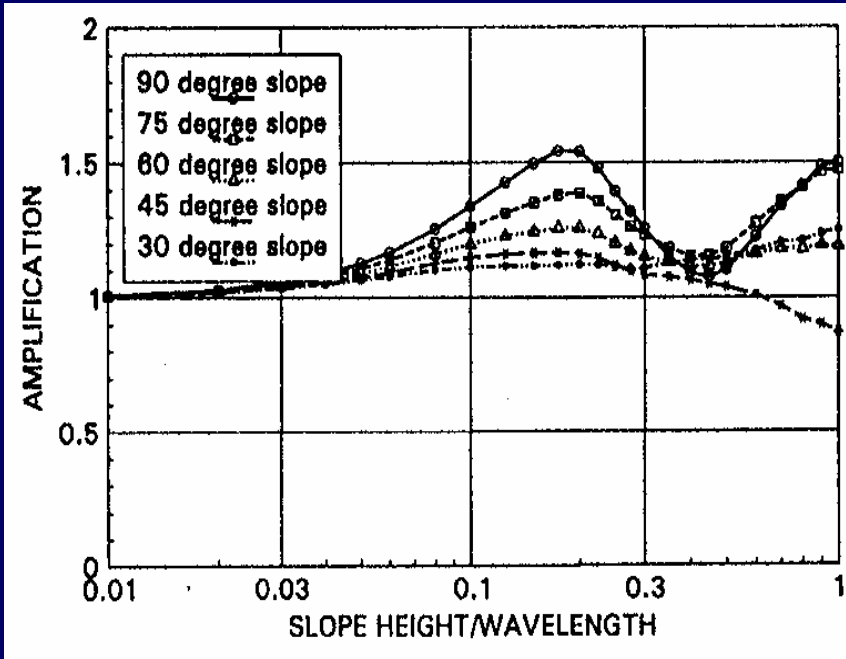
TOPOGRAPHIC AMPLIFICATION

For slopes with height greater than 30 m.
The following recommendations are given:
(i) for slopes angles less than 15° the topography effects can be neglected
(ii) for isolated cliffs and slopes a value of $S \geq [1,2]$ should be used
(iii) for slopes angles > 30° a value of $S \geq [1,4]$ should be used and $S \geq 1,2$ for smaller slope angles
(iv) in the presence of a looser surface layer more than [5] m thick, the smallest value given in (ii) and (iii) shall be used increased by at least [20%]

TOPOGRAPHIC AMPLIFICATION

- Studies conducted by Idriss (1968) on 27 and 45 degrees clay slopes by f.e.m. have shown that the magnitude of peak surface acceleration was greater at the crest surface of the slope than at points lower on the slope, but comparing the peak ground acceleration at the crest to that at some distance behind the crest in some cases the acceleration at the crest was much greater, in other case cases there was little difference. The natural period of the soil column was responsible for much more amplification of the input motion than the slope geometry.

Paolucci and Rimaldi (2002) have pointed that amplification factors for 2D analyses are of the same range of EC8, but for 3D analyses the values are 25% higher.



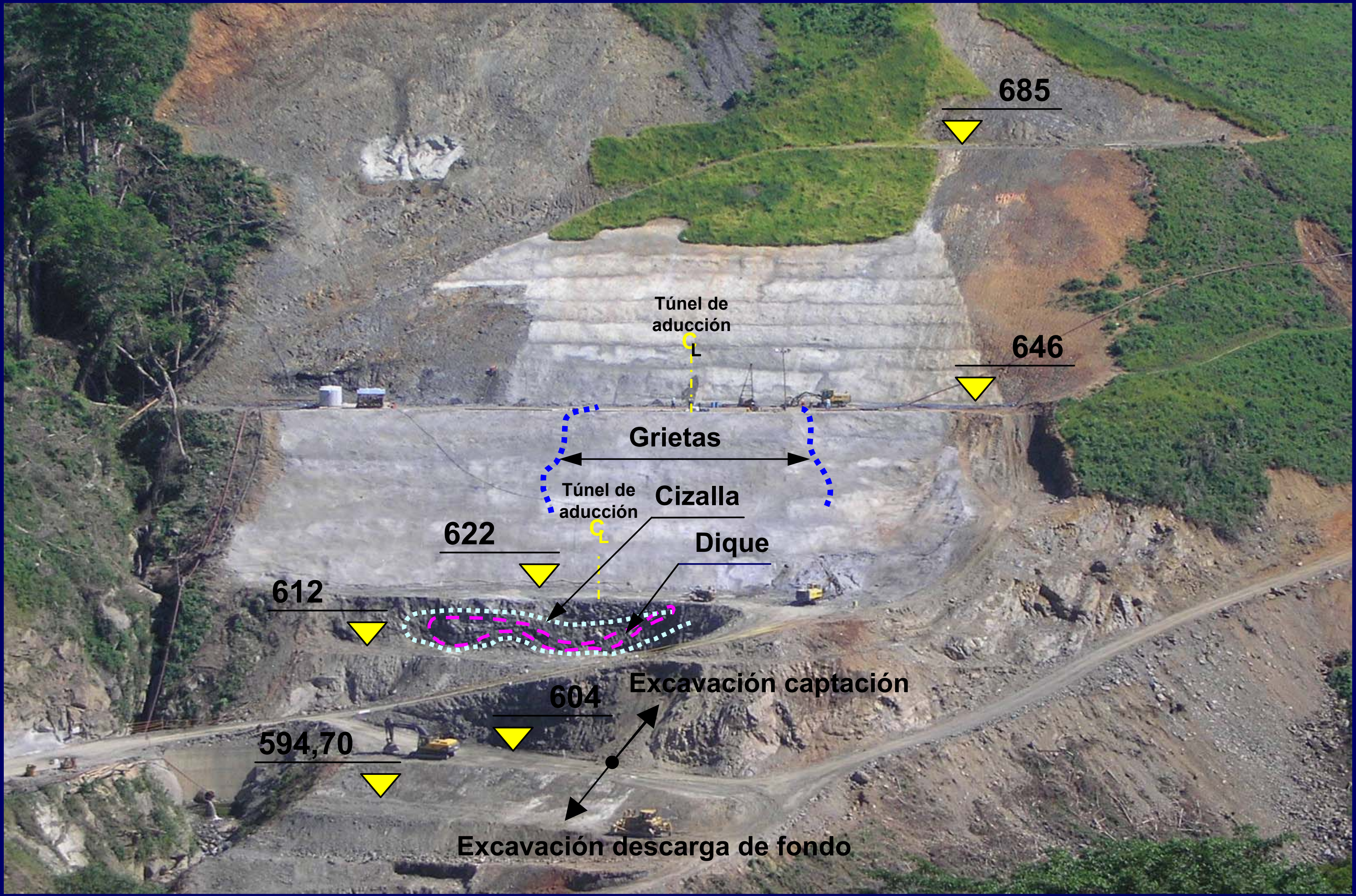
- Ashford et al (1997) concluded that topographic effects can be normalized as a function of the ratio of the slope height and wave length of the motion

ANALYSIS OF SLOPES STABILITY DURING EARTHQUAKES

EXPERIMENTAL MODELS
- SHAKING TABLE
- CENTRIFUGE TESTS

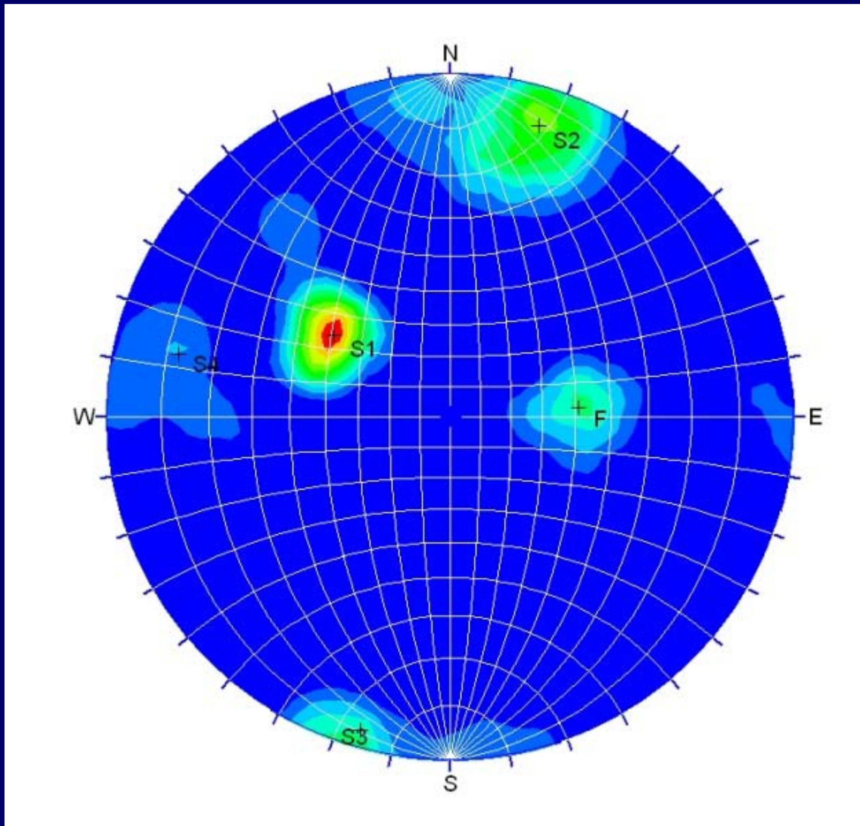
MATHEMATICAL MODELS
- PSEUDO –STATIC ANALYSES
- SIMPLIFIED PROCEDURES TO ASSESS DEFORMATIONS
- DYNAMIC ANALYSIS

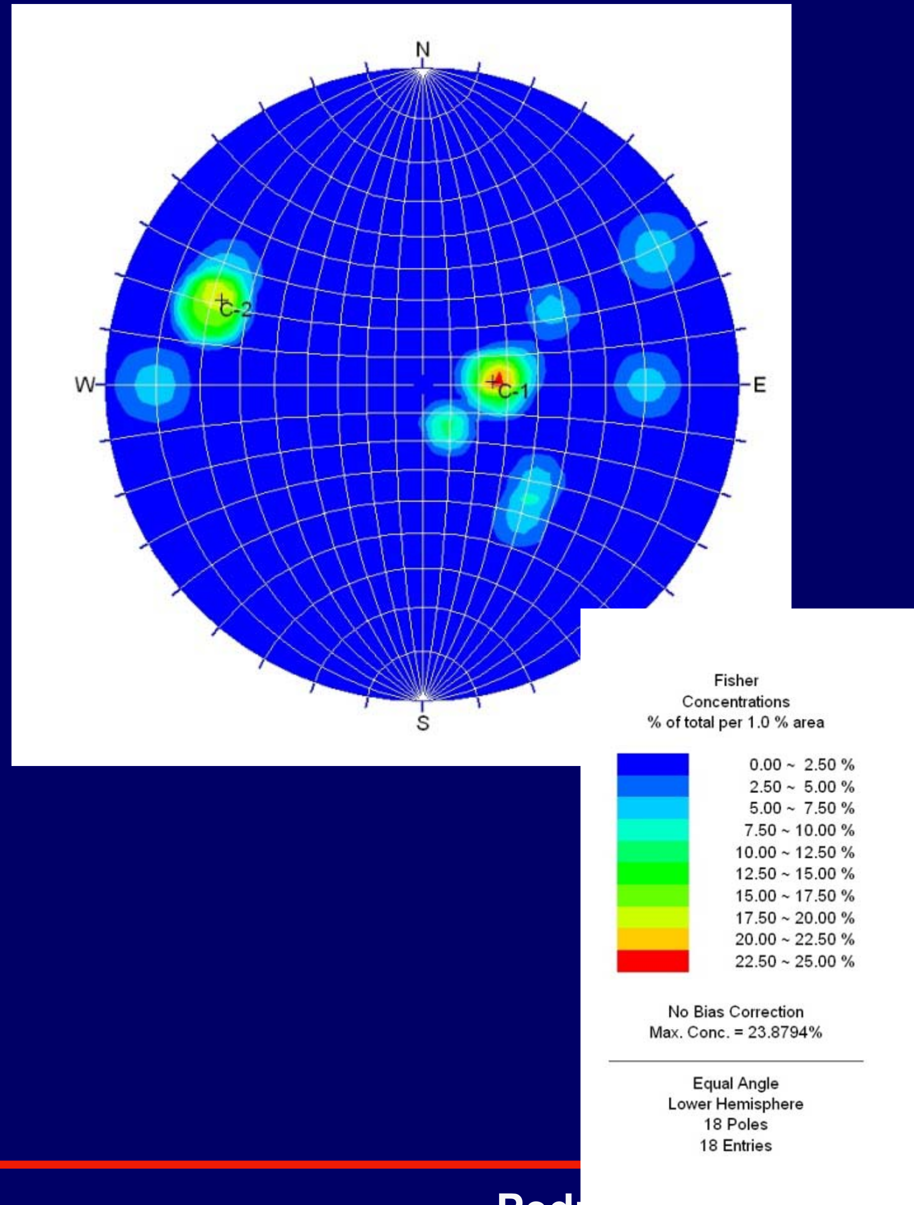
SLOPE VUE



685
Túnel de aducción
CL
646
Grietas
Túnel de aducción
CL
Cizalla
622
Dique
612
Excavación captación
604
594,70
Excavación descarga de fondo

FOLIATION AND JOINT PLOT





Foliación: N04W/41SW

Sistema S1: N35E/45SE

Sistema S2: N73W/83SW

Sistema S3: N74W/87NE

Sistema S4: N13E/78SE

ROCK BOLTS

GENERAL VUE

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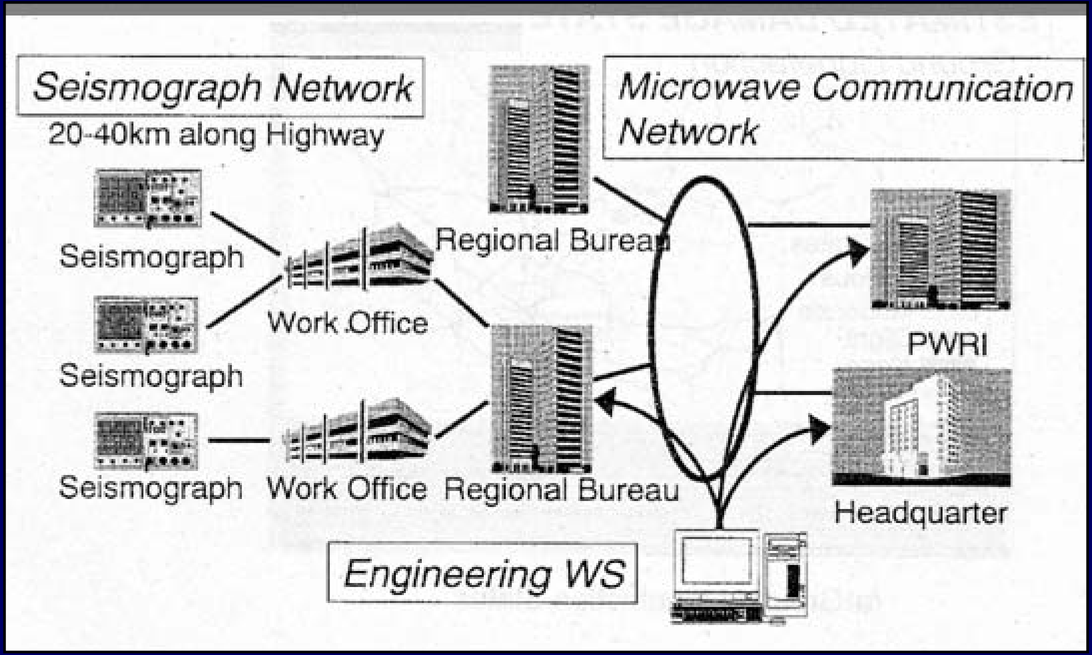
OBSERVATION PLANS

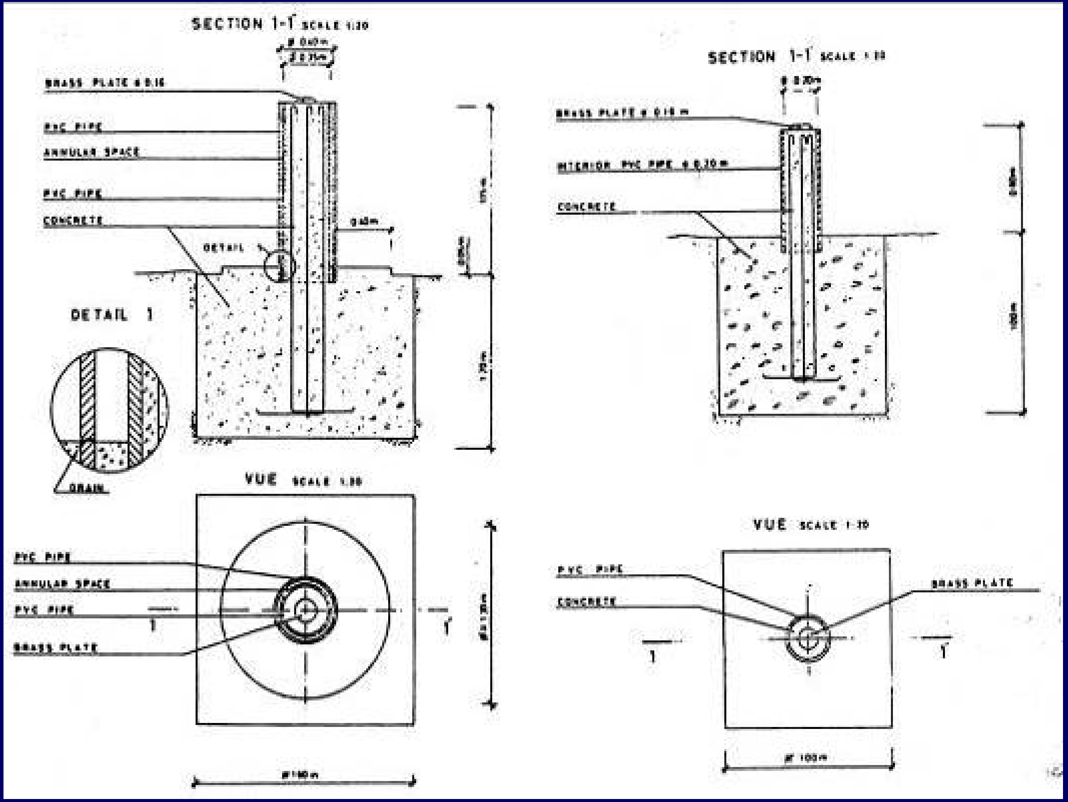
RISK FACTORS ARE RELATED WITH ENVIRONMENTAL, RELIABILITY AND HUMAN AND ECONOMIC HAZARD

NETWORK OF SEISMIC RECORDING STATIONS SHALL BE INSTALLED PRIOR TO RESERVOIR FILLING



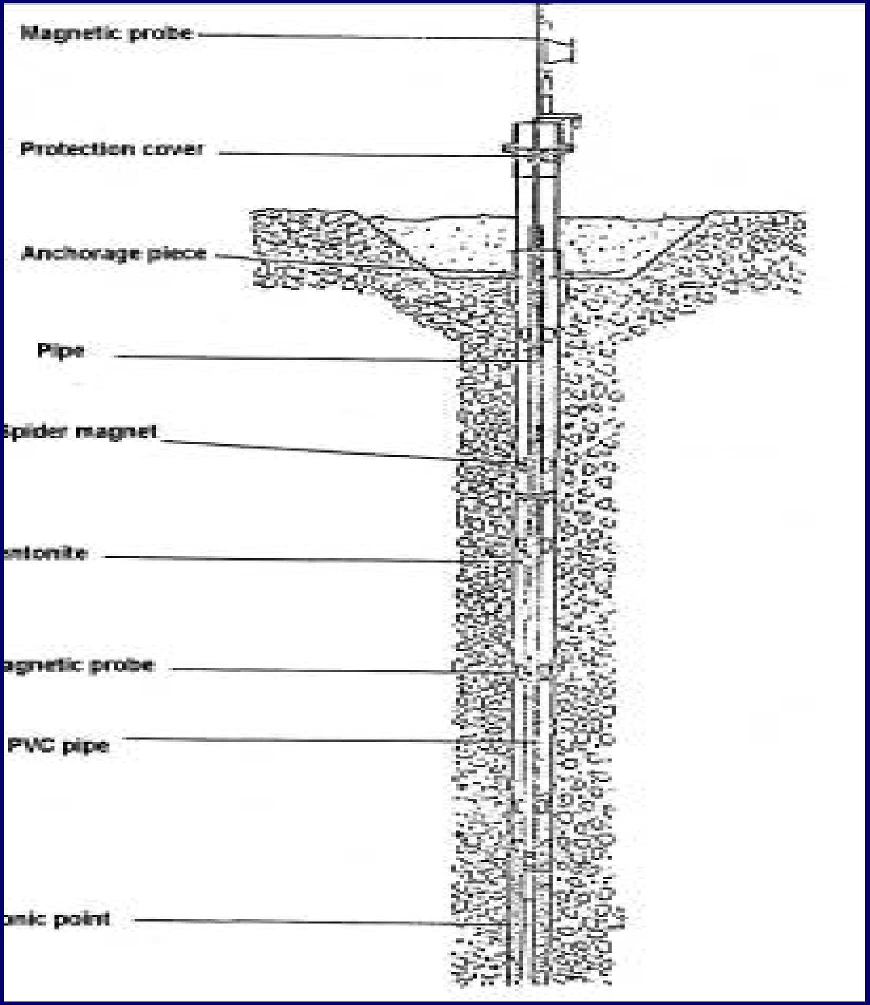
SURFACE MOVEMENT MEASURING DEVICES

Application of techniques of trilateration measurement technology has achieved the degree of precision required to assure, with confidence, the safety and integrity of the dams



VERTICAL INTERNAL MEASURING DEVICES

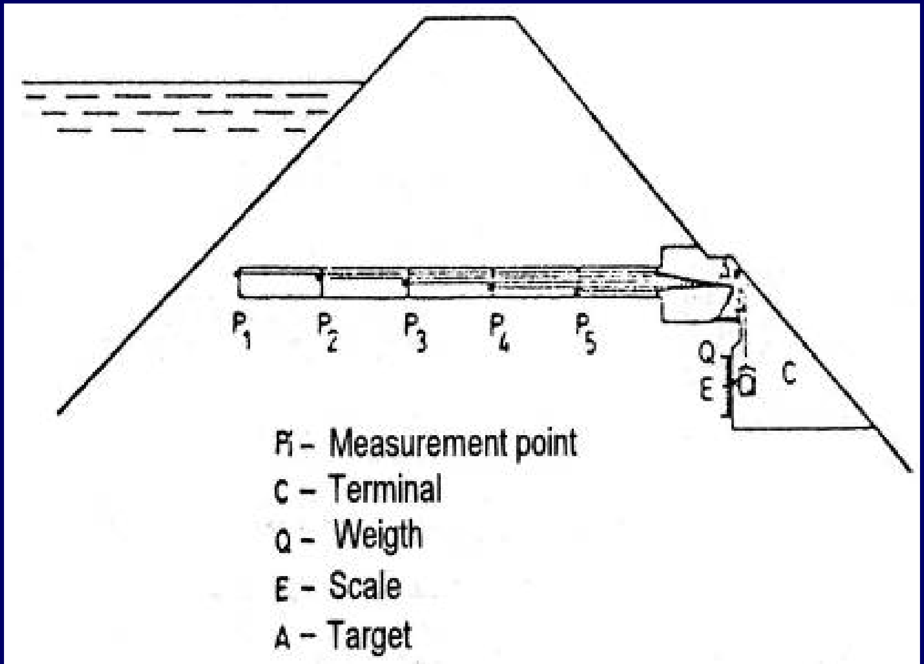
Magnetic probe
Pneumatic settlement sensor



HORIZONTAL INTERNAL MEASURING DEVICES

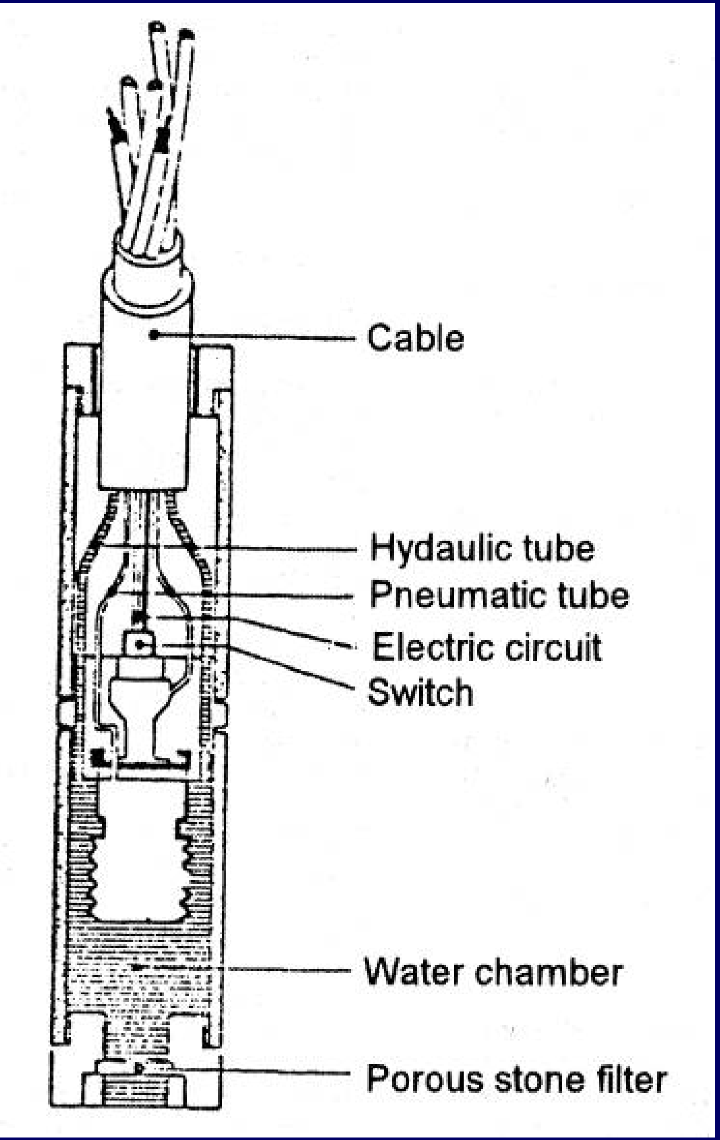
Inclinometers

Extensometers



PORE PRESSURE MEASURING DEVICES

Vibrating - wire piezometer
Hydraulic twin-tube piezometers
Hydraulic Piezometers
Pneumatic piezometers



SEISMIC INSTRUMENTATION

SEISMIC INSTRUMENTATION TO ASSESS SEISMICITY AROUND THE RESERVOIR AND THE RESPONSE OF THE DAM

STRONG –MOTION ACCELEROGRAPHS, PEAK RECORDING ACCELEROGRAPHS AND SEISMOSCOPES

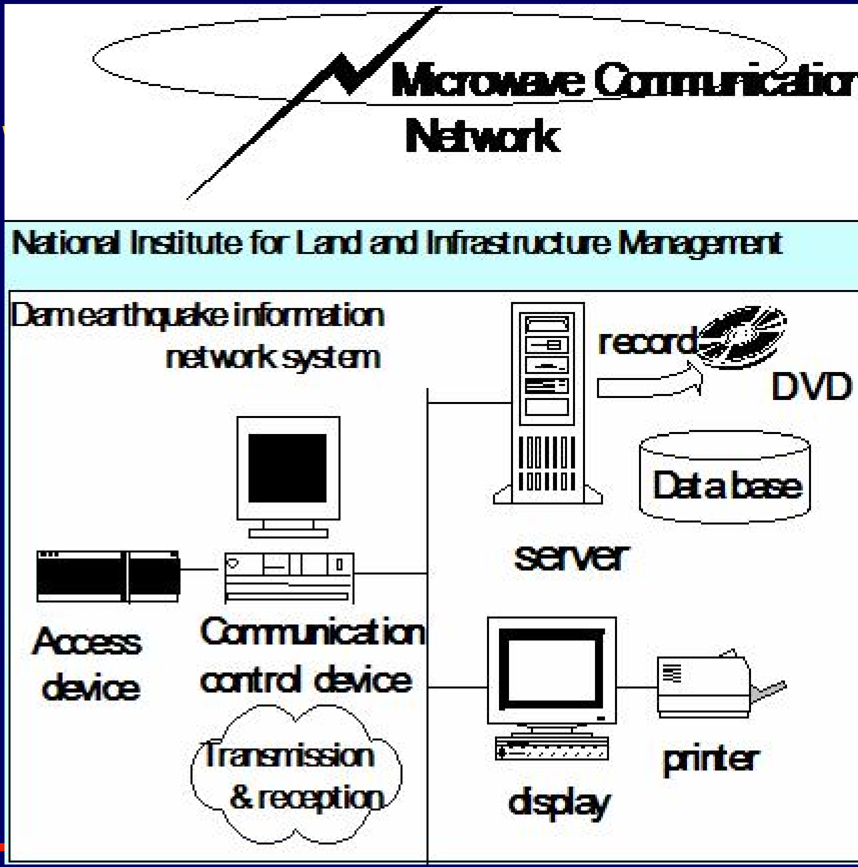
DATA ACQUISITION

AUTOMATIC SYSTEM ALLOWS A RAPID DATA PROCESSING AND REDUCTION OF PERSONAL

AUTOMATIC SYSTEM IMPLIES AN INCREASE OF COMPLEXITY AND CAN BE DESTROYED BY AN EARTHQUAKE

DATA MANAGEMENT

COLECTION OF DATA FOR SOME INTERVALS
CHECK OF DATA TO ASSESS THE RELIABILITY
DATA STORAGE
MANAGEMENT OF ANOMALIES
POSSIBILITY OF COMMUNICATION REMOTE UNITS



DATA VALIDATION

COMPARISON OF THE READINGS WITH ESTABLISHED LIMITS

USE OF STATISTICAL, DETERMINISTIC OR HYBRID MODELS

USE OF BACK ANALYSIS METHODS FOR THE INTERPRETATION OF THE BEHAVIOR OF SLOPES

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SAFETY CONTROL

REGULAR MEASUREMENTS
USING INSTRUMENTATION
DATA VALIDATION
DATA STORAGE
SAFETY EVALUATION
CORRECTIVE ACTIONS

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VISUAL INSPECTIONS

INSPECTIONS BEFORE THE FIRST FILLING

INSPECTIONS AFTER THE FIRST FILLING

INSPECTIONS AFTER EXCEPTIONAL OCCURRENCES

DURING INSPECTIONS THE FOLLOWING ASPECTS DESERVE ATTENTION: DAM BODY, SPILLWAY, OUTLET WORKS, RESERVOIR AND ACCESS ROAD

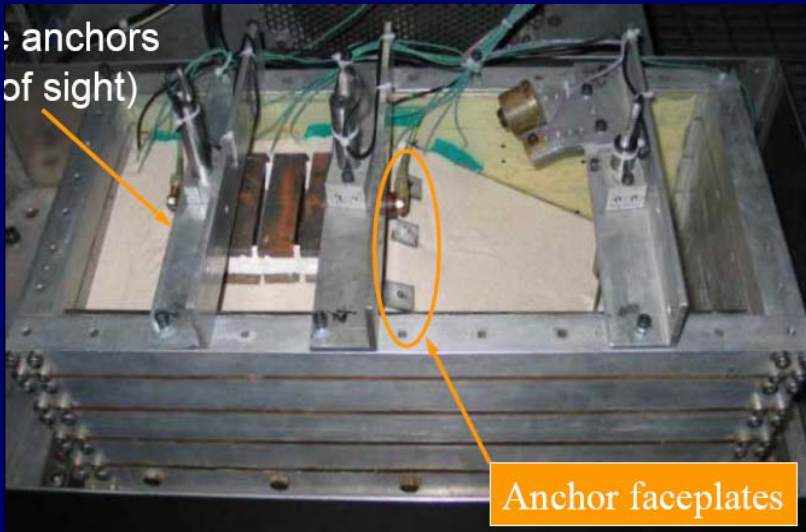
MITIGATION METHODS

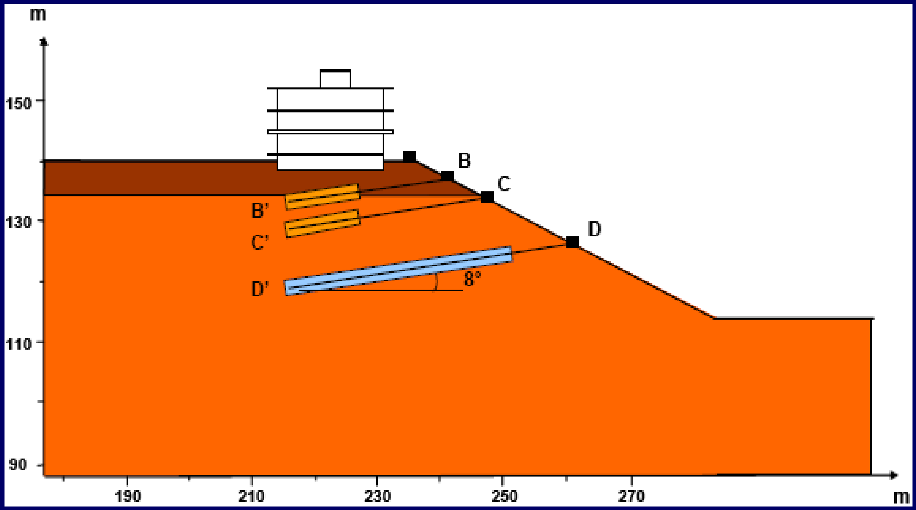
Two mitigation methods namely anchors and soft layers were applied to study the case of Aegion slope. The following conclusions were obtained (Stamatopoulos, 2005):

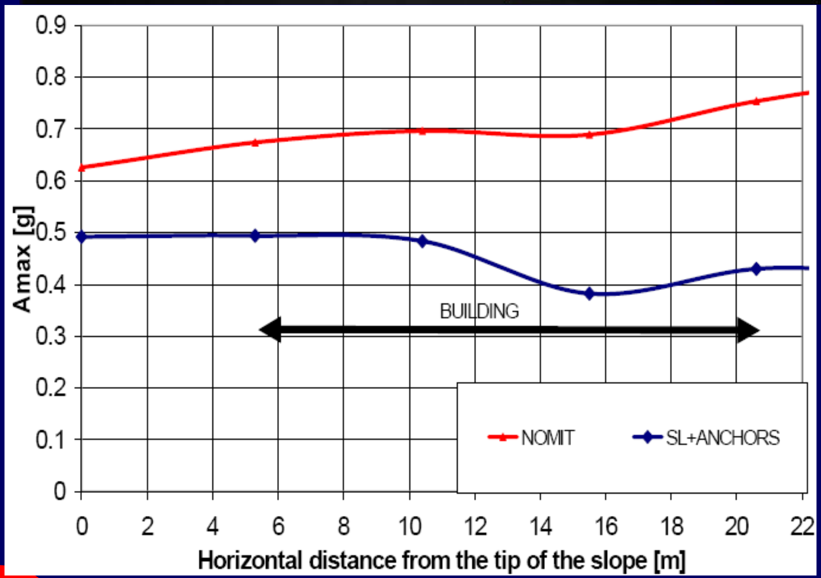
(i) With the use of anchors the whole body connected with anchors will move with less total and differential acceleration. There is a need to optimise the anchors inclination and length.

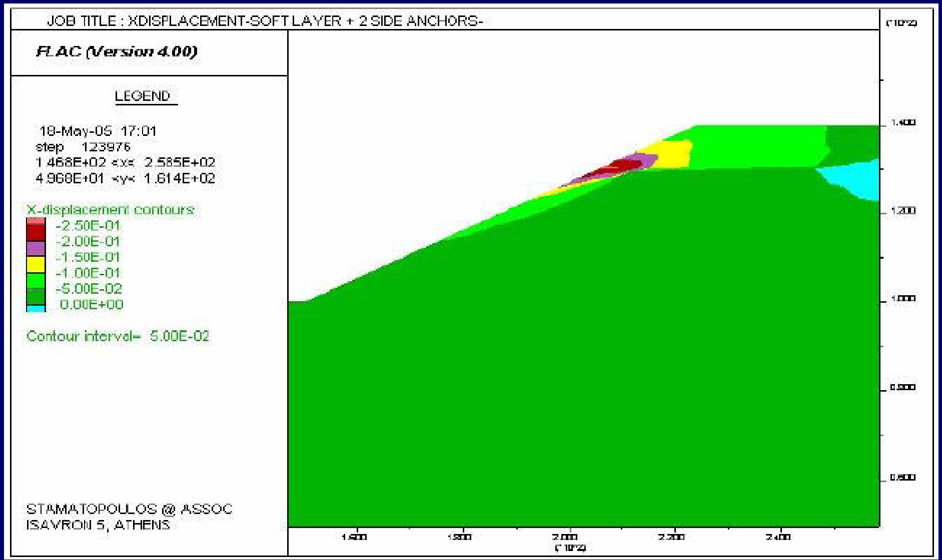
(ii) The use of soft barrier will allow a decrease of acceleration and consequently a reduction of displacement.

MITIGATION METHODS



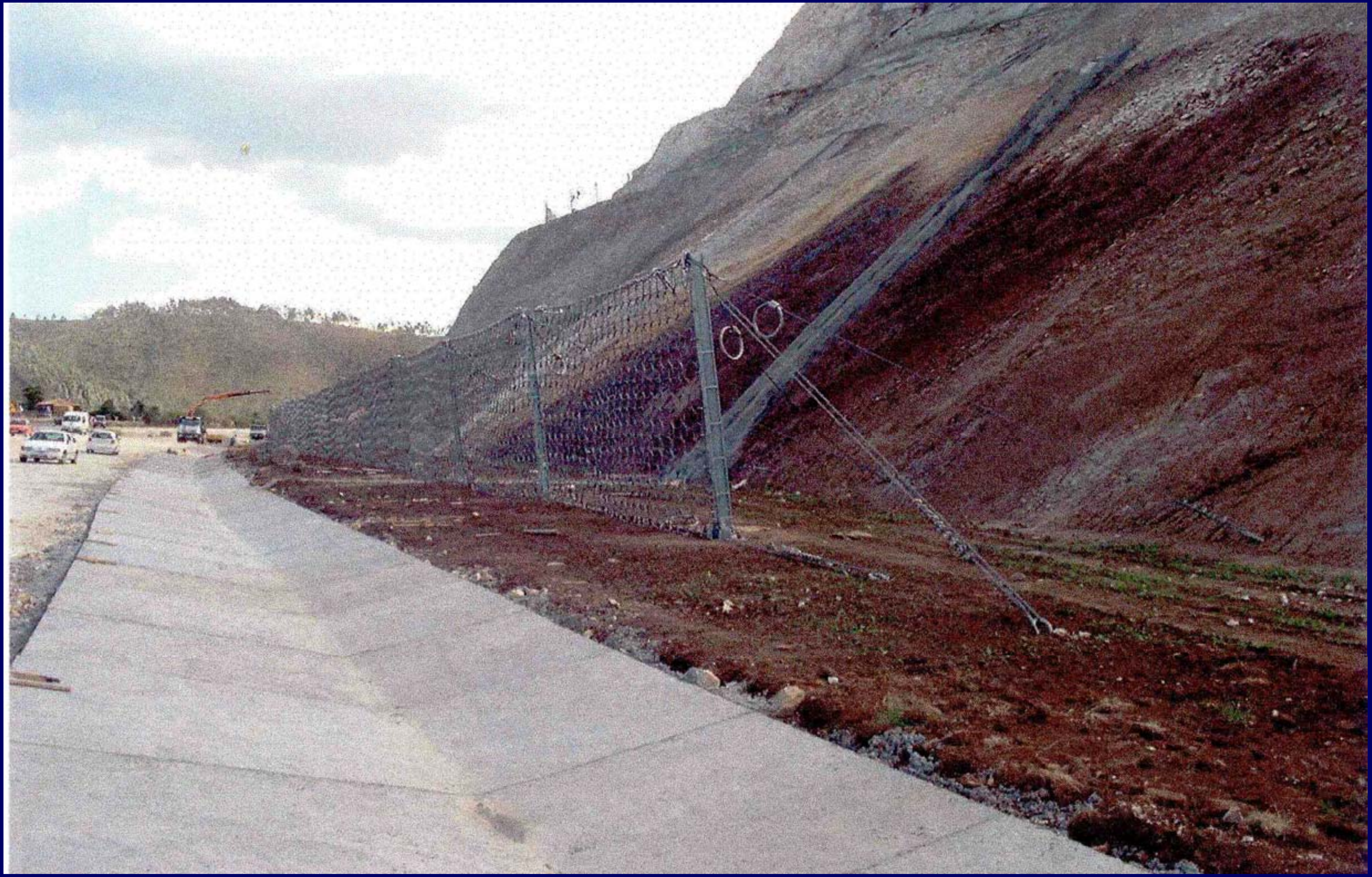




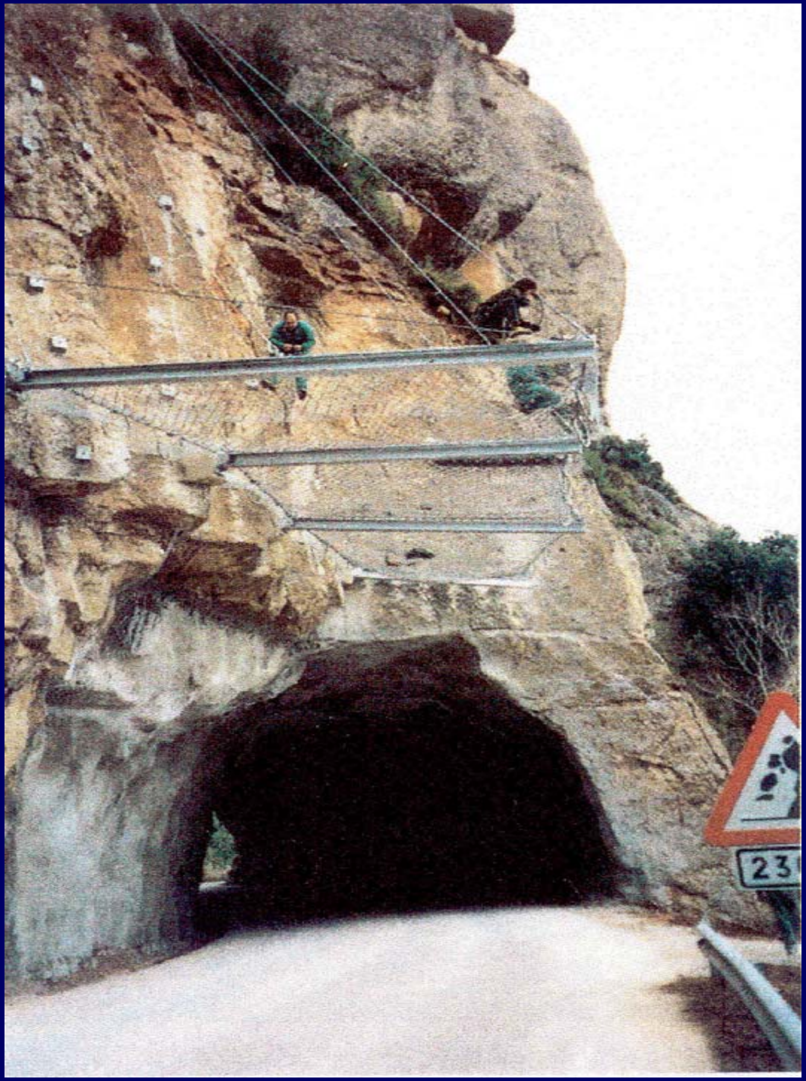


MITIGATION METHODS
Rock Barriers

MITIGATION METHODS
Barriers



BARRIERS



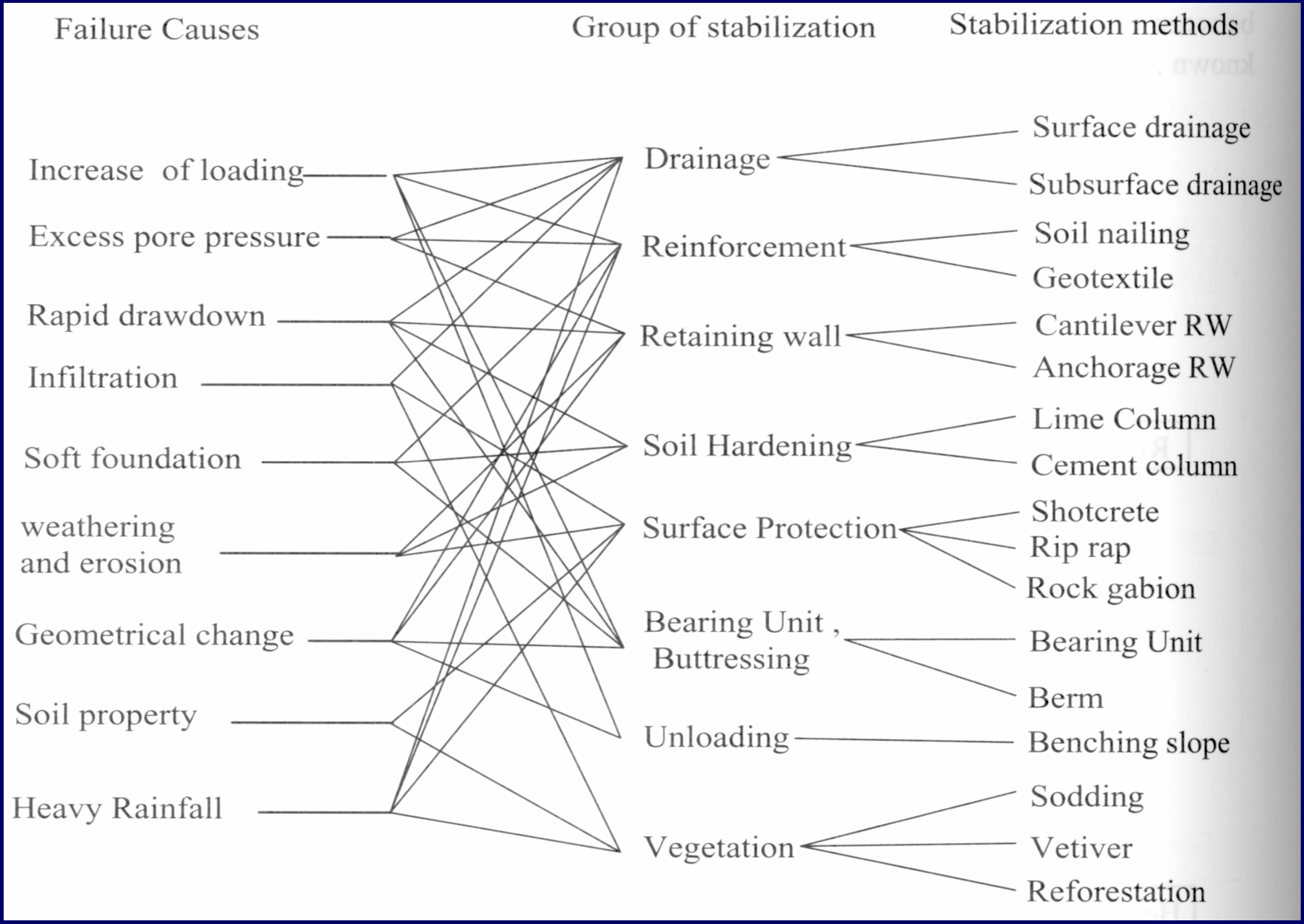
BLOCK FALL

LANDSCAPE TREATMENT
Planting

LANDSCAPE TREATMENT

CONSTRUCTION TO LIMIT DEBRIS FLOW

SCHEMATIC DIAGRAM FOR ANALYSED THE SUITABLE RULES

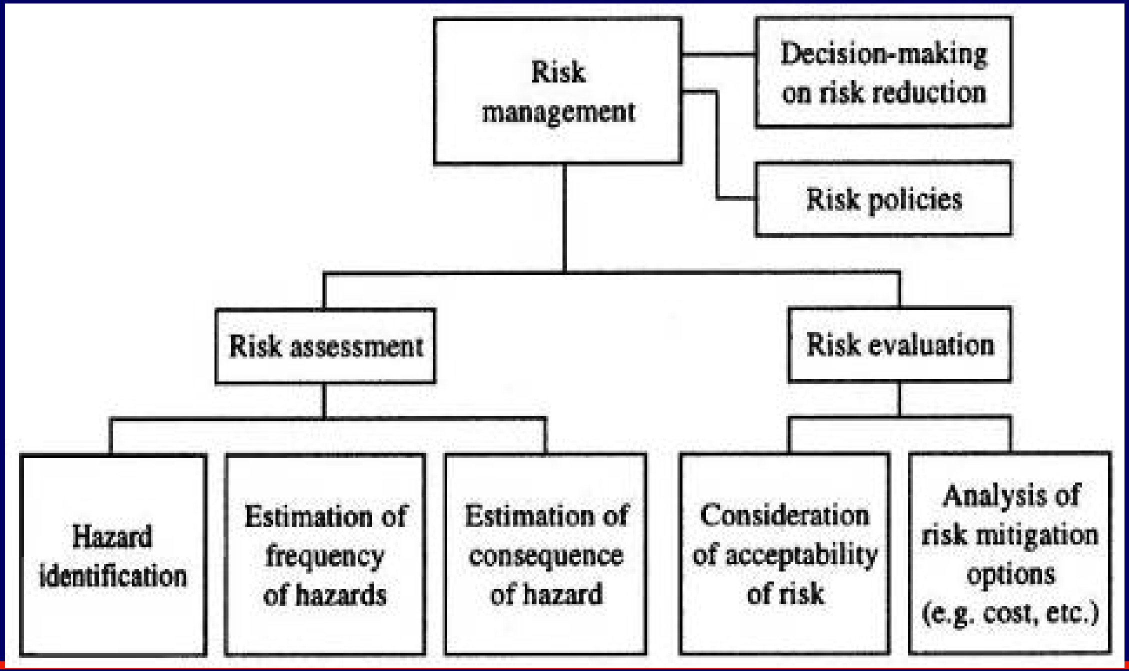


APPROACHES FOR MITIGATION SLOPE MOVEMENTS AND THEIR CONSEQUENCES

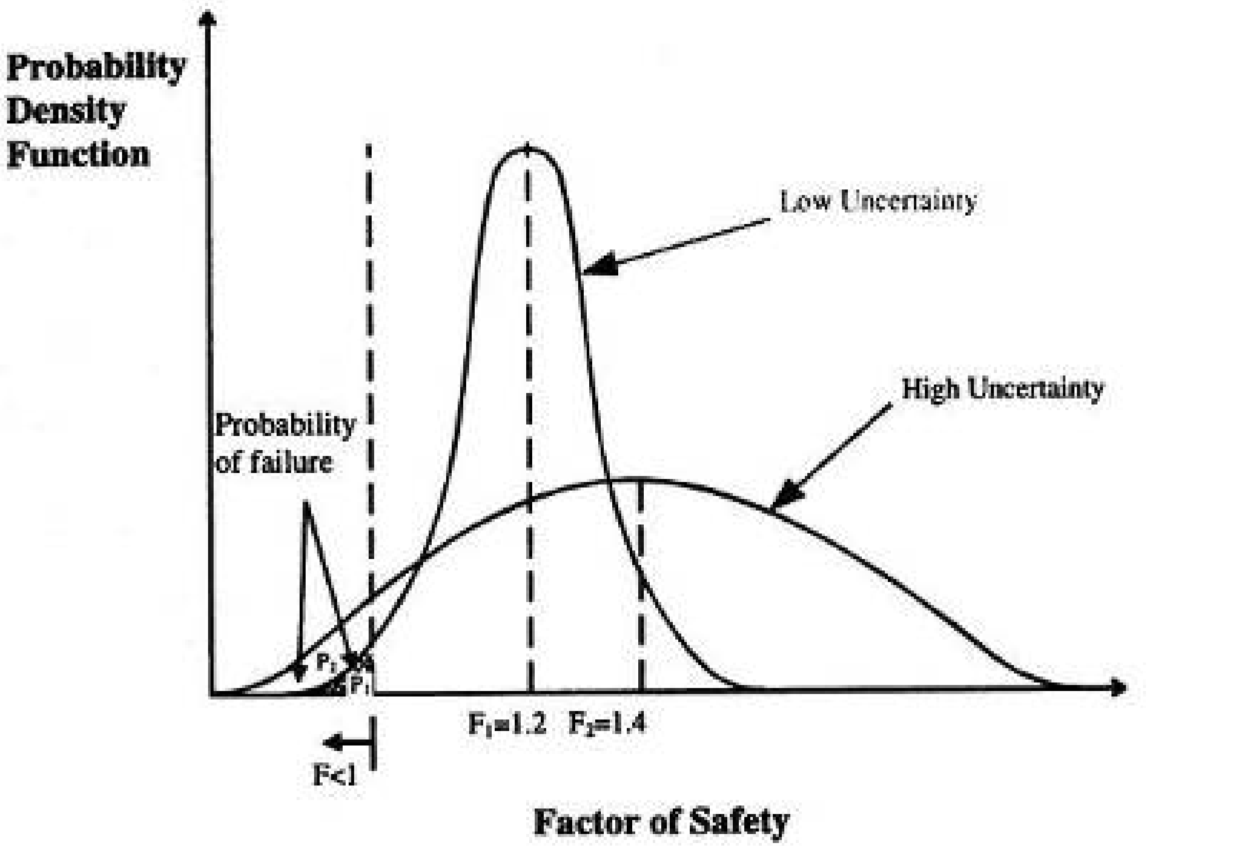
	Eliminates the problem or reduces the consequences	Decreases driving forces	Increases resisting forces
Intervention on:			
• **Material, controlling laws and parameters**			
• Removal of unstable material	●		
• Total or partial substitution of the sliding mass with material with better mechanical and drainage characteristics			●
• Electro-osmosis			●
• Soil treatment with lime, cement or other additives			●
• Thermal treatment			●
• Etc.			
• **Predisposition factors**			
• Nailing, piling, anchoring, bolting			●
• Earthworks for decreasing driving forces		●	
• Buttress or counterweight fills		●	
• Etc.			
• **Trigerring or aggraving factors**			
• Surface drainage			●
• Subsurface drainage (trenches, subhorizontal drains, drainage wells, etc.)			●
• Protection against erosion		●	
• Etc.			
• **Movement consequences**			
• Protection against falling or sliding materials (catch nets and walls, sheds, tunnels, etc.)	●		
• Dykes for containing mudflows, debris flows, etc.	●		
• Etc.			

RISK ANALYSES

TO IDENTIFY REAL RISKS ASSOCIATED WITH TYPE AND HEIGHT OF SLOPE
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

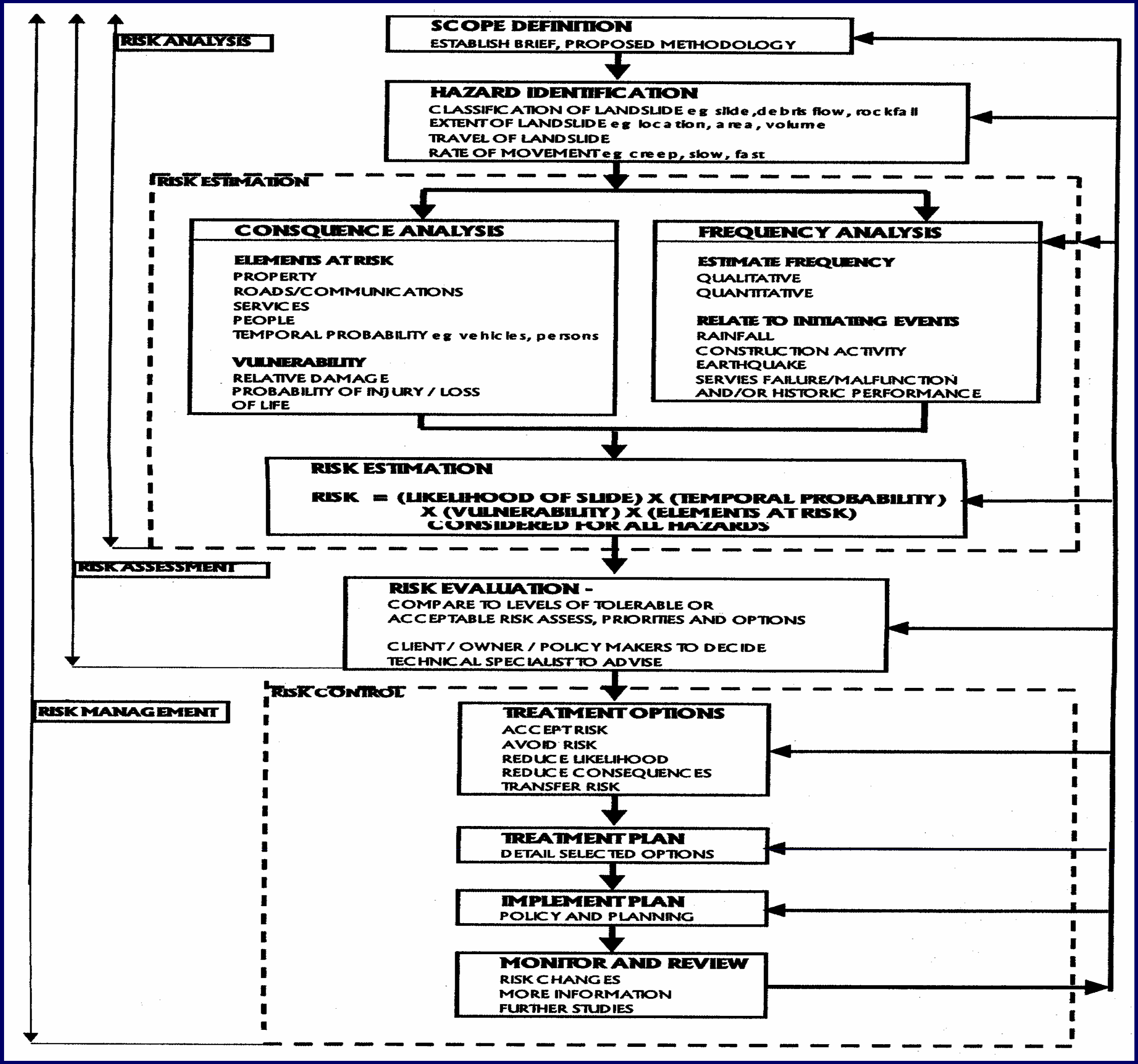


RISK ANALYSES
(after Lacasse and Nadim)

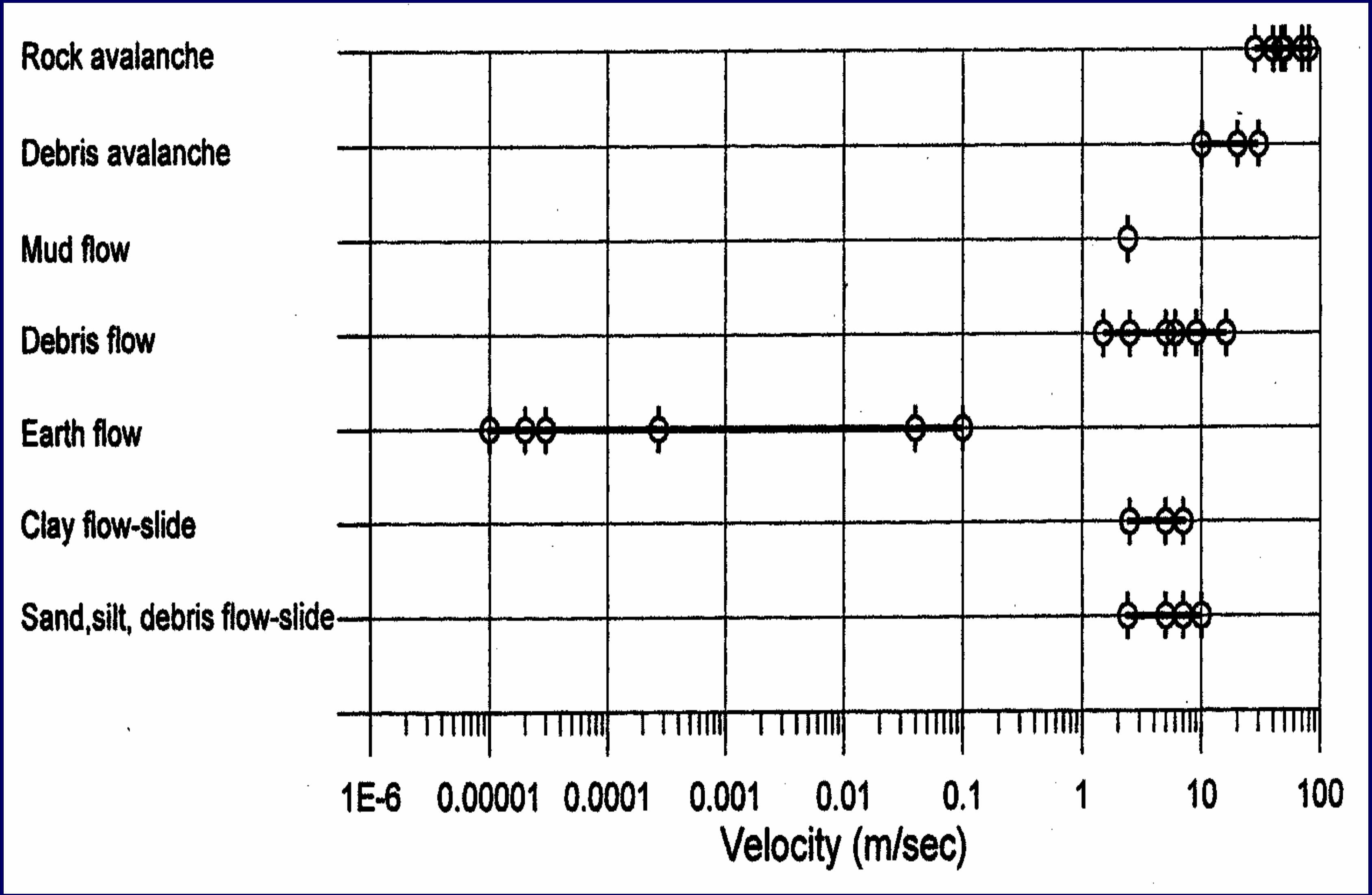


Note : $P_2 > P_1$ although $F_2 > F_1$, i.e. a higher factor of safety does not necessarily correspond to a lower probability of failure, depending on the degree of uncertainty involved.

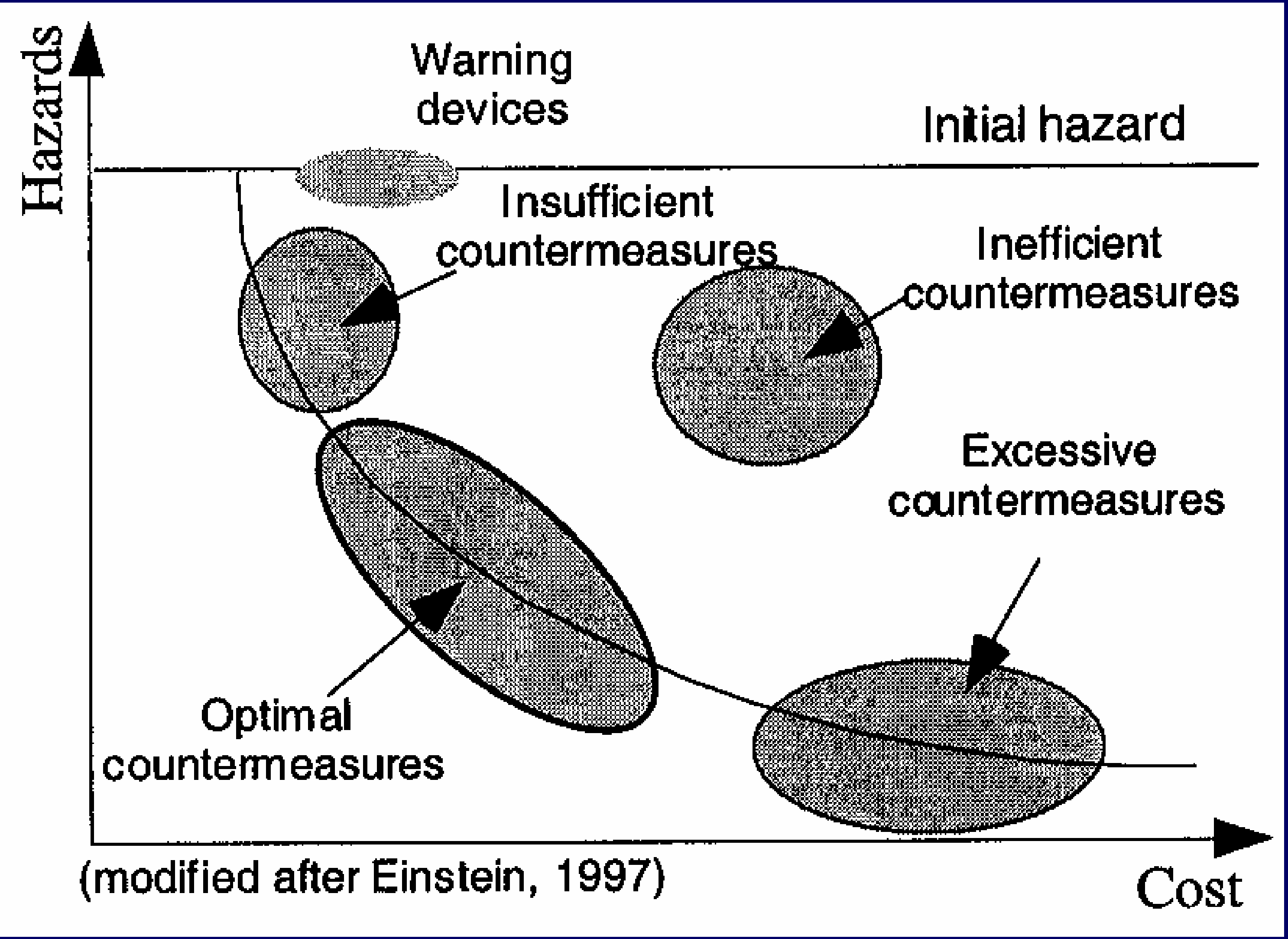
RISK MANEGEMENT FRAMEWORK(AGS, 2000)



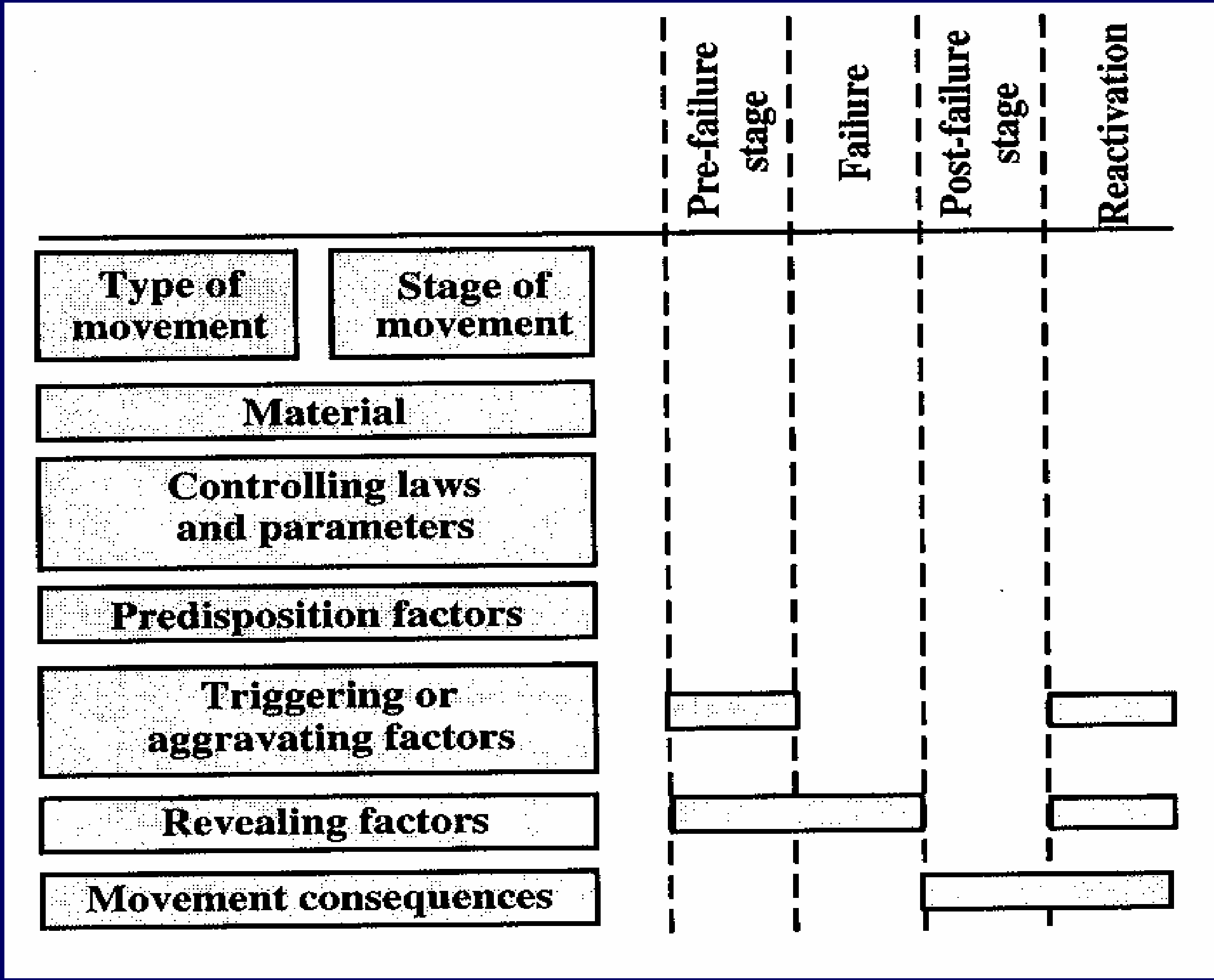
HAZARD REDUCTION – COST OF INTERVENTION ANALYSIS



HAZARD REDUCTION – COST OF INTERVENTION ANALYSIS



POSSIBLE AVENUES FOR WARNING SYSTEMS



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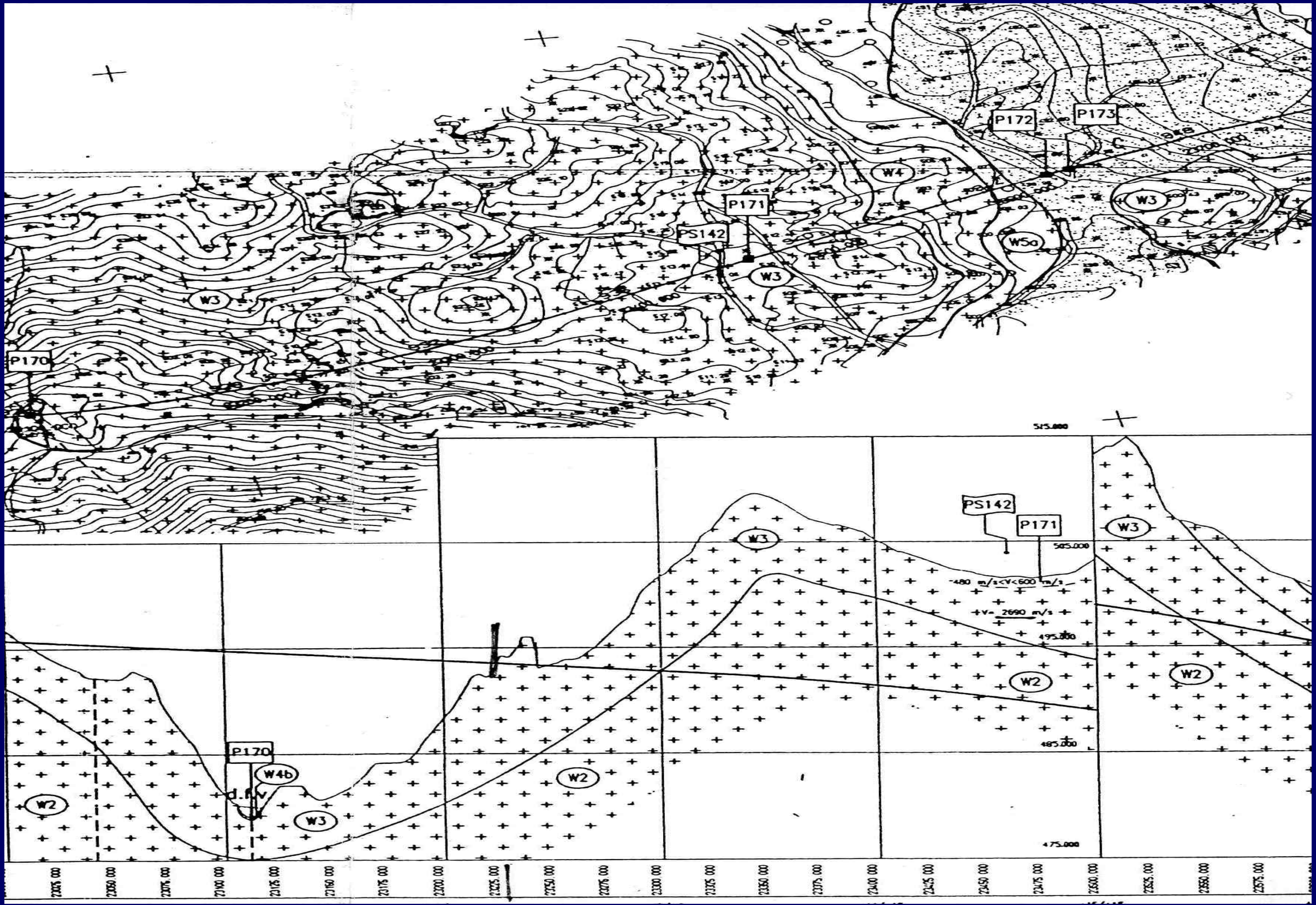
CASTRO DAIRE LANDSLIDE

PLAN AND GEOTECHNICAL PROFILE



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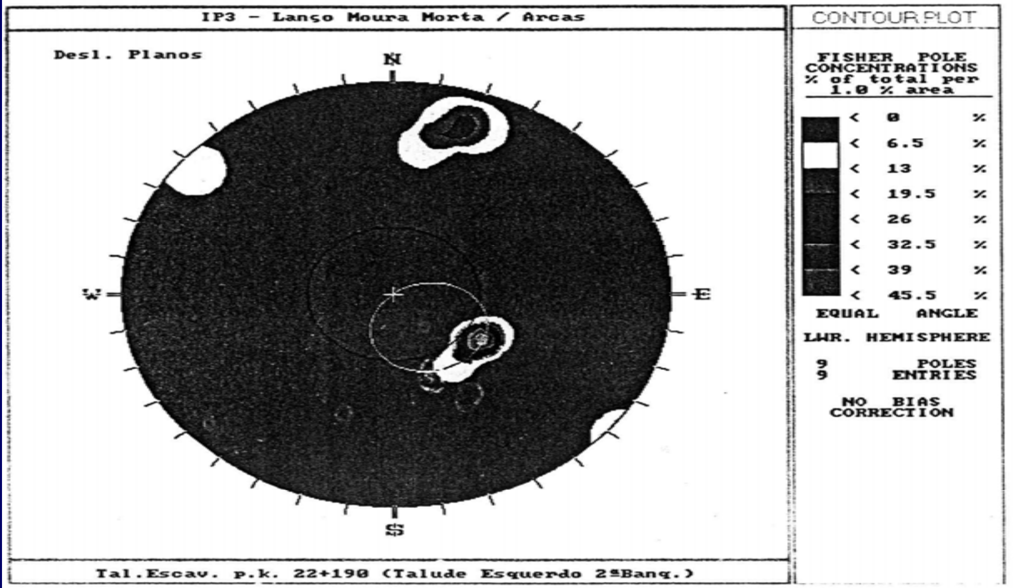
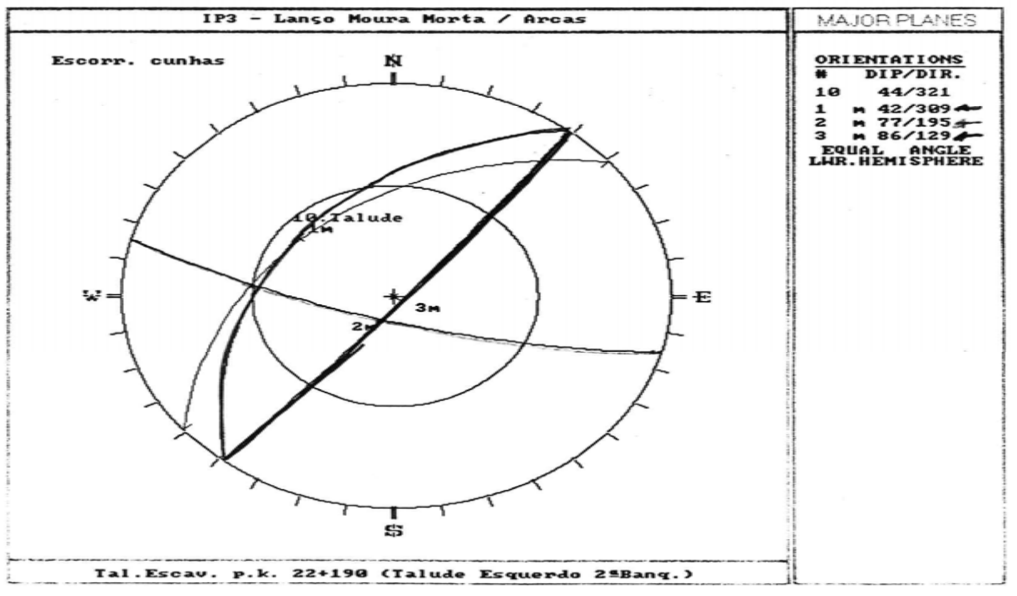
REPRESENTATION OF DISCONTINUITIES





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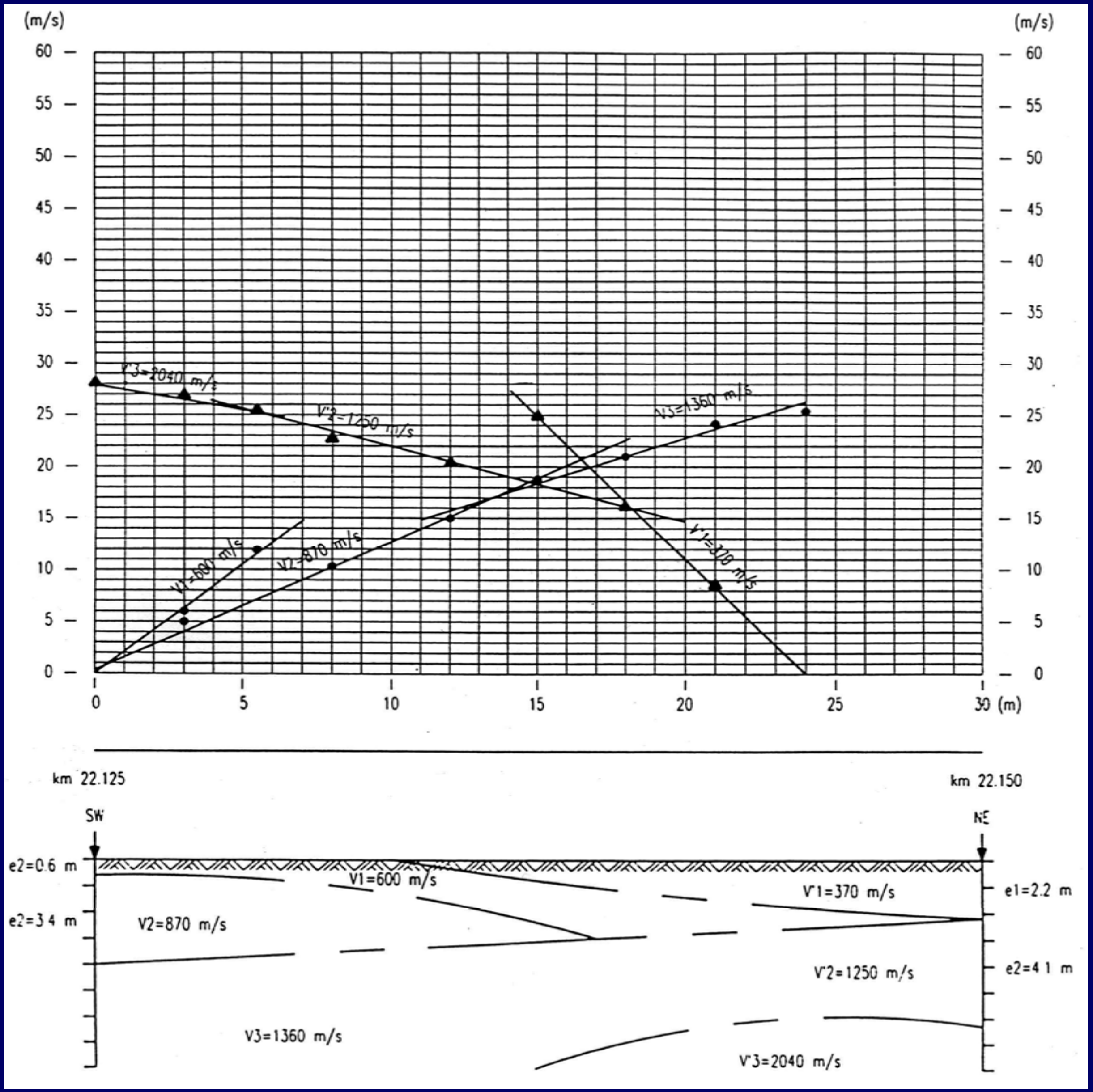
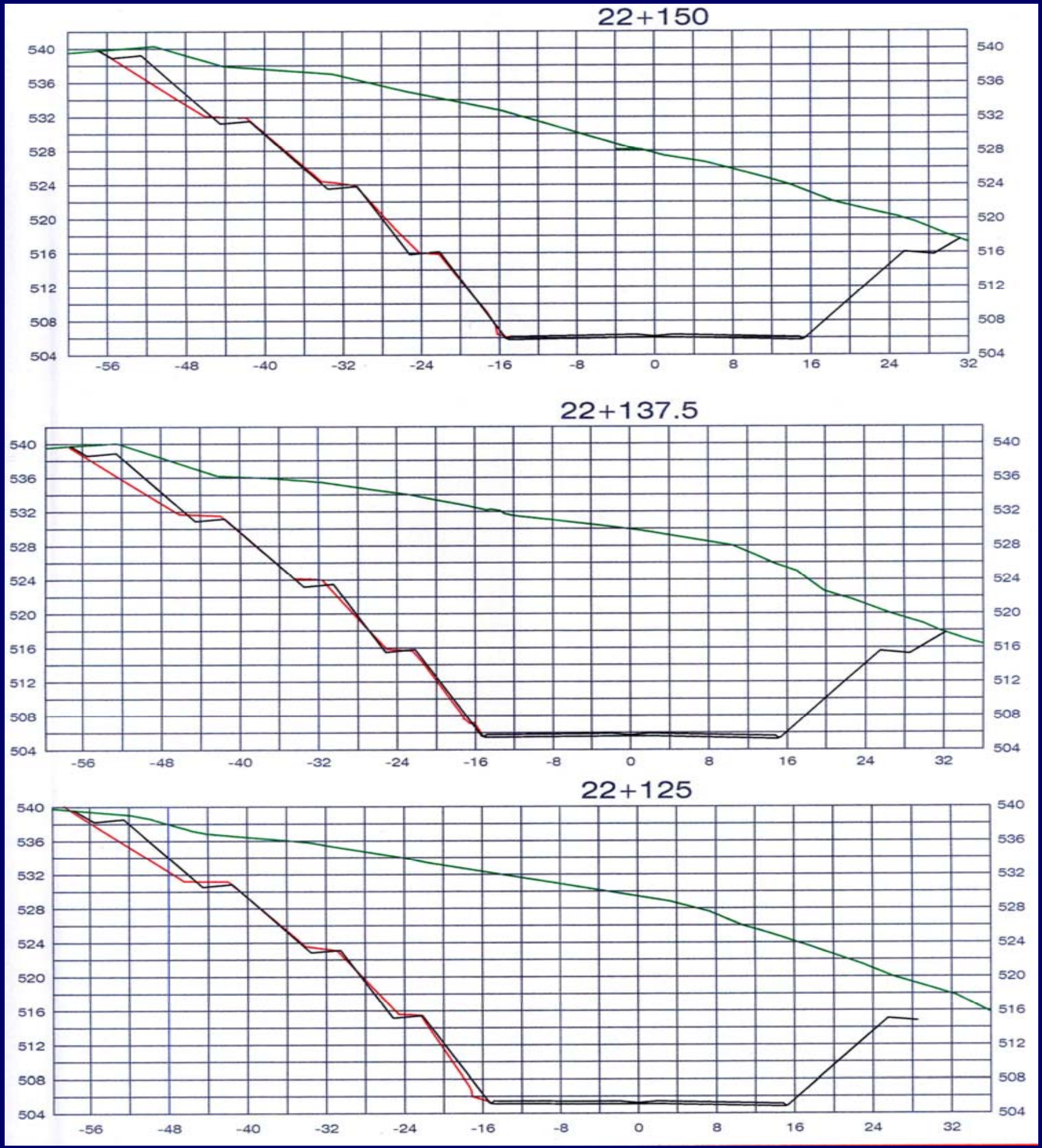
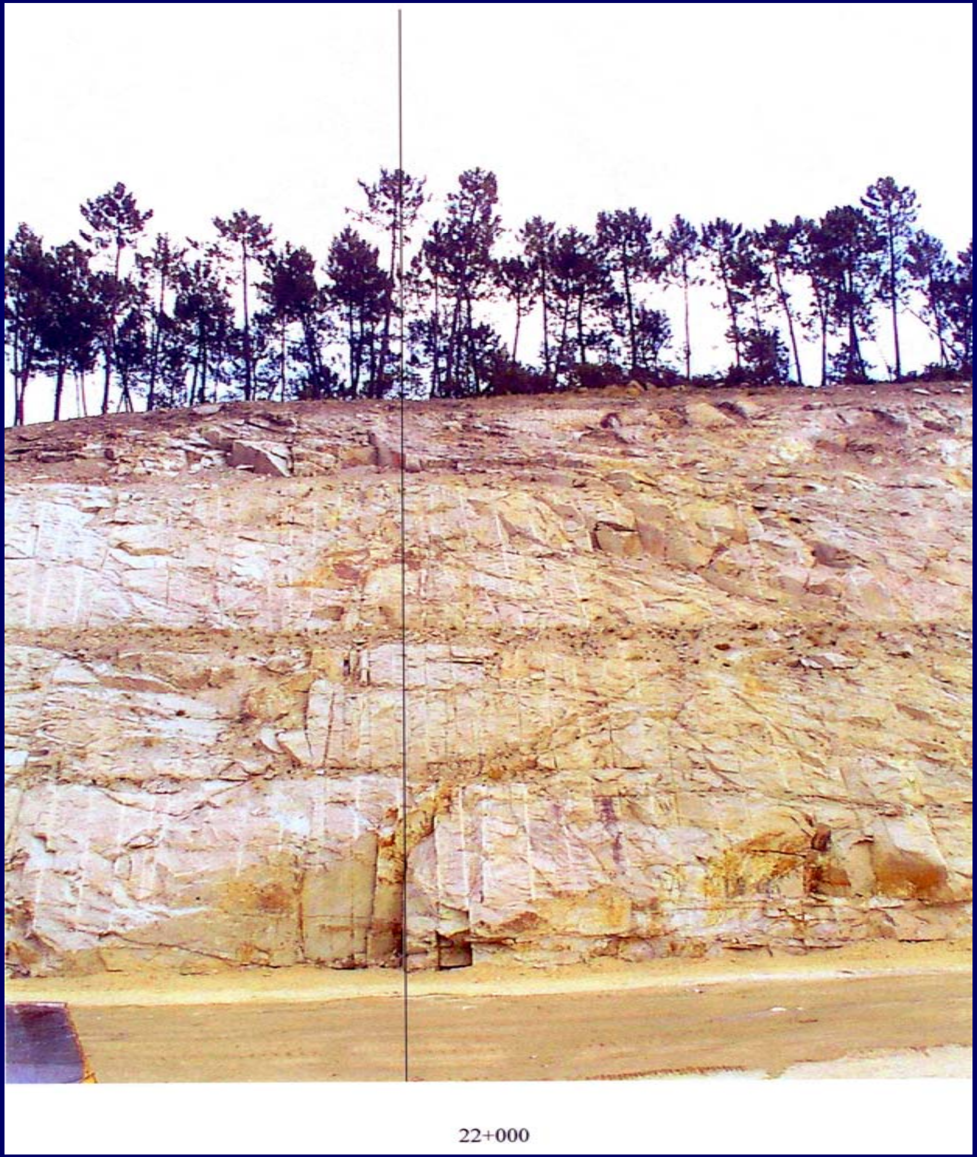
SEISMIC PROFILE



SLOPE EXCAVATION



SLOPE VUE



SLOPE VUE BEFORE DRAINAGE

22+025 (antes de executar dreno e colector)

SLOPE FAILURE

2ª queda ao km 22+175 – 22/10/2001

2ª queda ao km 22+175 – 22/10/2001

BIENIAWSKY RATINGS FOR RMR (1979)

PARAMETER	RANGES						
UCS	> 250 MPa	100-250 MPa	50-100 MPa	25-50 MPa	5-25 MPa	1-5 MPa	< 1 Mpa
rating	15	12	7	4	2	1	0
RQD	90-100%	75-90%	50-75%	25-50%		< 25%	
rating	20	17	13	8		3	
spacing of discontinuities	> 2 m	0.6-2 m	0.2-0.6 m	0.06-0.2 m		< 0.06 m	
rating	20	15	10	8		5	
Condition of discontinuities	very rough not continuous no separation unweadered	slightly rough separation < 1mm slightly weadered	slightly rough separation < 1mm highly weathered	Slikensided or gouge < 5mm or separation 1-5mm continuous		soft gouge > 5mm or separation > 5mm continuous	
rating	30	25	20	10		0	
Groundwater in joints	Dry	Damp	Wet	Dripping		Flowing	
rating	15	10	7	4		0	

ADJUSTMENT RATING FOR JOINTS

CASE	ANGLE	Very favourable	Favourable	Fair	Unfavourable	Very unfavourable
P	αj - αs	> 30º	30º - 20º	20º - 10º	10º - 5º	< 5º
T	αj - αs - 180º					
P/T	F1	0.15	0.40	0.70	0.85	1.00
P	βj	< 20º	20º - 30º	30º - 35º	35º - 45º	> 45º
P	F2	0.15	0.40	0.70	0.85	1.00
T	F2	1	1	1	1	1
P	βj - βs	> 10º	10 - 0º	0º	0º- (-10º)	< -10º
T	βj + βs	< 110º	110º - 120º	> 120º	--	--
P/T	F3	0	- 6	- 25	- 50	- 60

P Plane failure

T Toppling failure

ADJUSTEMENT RATING FOR METHODS OF EXCAVATION OF SLOPES

METHOD	Natural slope	Prespliting	Smooth blasting	Blasting or mechnical	Defficient blasting
F4	+15	+ 10	+ 8	0	- 8

TENTATIVE DESCRIPTION OF SMR CLASSES

CLASS	V	IV	III	II	I
SMR	0 - 20	21 - 40	41 - 60	61 - 80	81 - 100
Description	Very bad	Bad	Normal	Good	Very good
Stability	Completly unstable	Unstable	Partially stable	Stable	Completly stable
Failures	Big planar or soil-like	Planar or big wedges	Some joints or many wedges	Some blocks	None
Support	Reexcavation	Important/ corrective	Sistematic	Occasionnal	None

SMR CLASSIFICATION

$$SMR = RMR - (F1 \times F2 \times F3) + F4$$

SMR CLASSIFICATION		
RMR PARAMETER	***RMR RATING***	***DESCRIPTION***
Strength of intact material	2	POOR
Rock quality designation	3	POOR
Spacing of discontinuities	8	POOR
Condition of discontinuities	0	FAIR
Groundwater conditions	7	FAIR
BASIC RMR RATING	**20**	**POOR ROCK**
SMR PARAMETER	***SMR RATING***	***DESCRIPTION***
F1	0.15	FAVOURABLE
F2	0.85	UNFAVOURABLE
F3	-50	UNFAVOURABLE
F4	+9	PRESPLITING + SMOOTH BLASTING
SMR 32.3 - Bad slope, unstable, planar or big wedges failures, important corrections		

RELATIVE RELIEF VALUES AND THEIR CLASSES

Relative relief	Susceptibility	Parameter S_r
0 - 75 m/Km^2	very low	0
76 - 175	low	1
176 - 300	moderate	2
301 - 500	medium	3
501 - 800	high	4
> 800	very high	5

CLASSIFICATION OF LITHOLOGIC INFLUENCE

Lithology	Susceptibility	Value S_l
Permeable limestone, slightly fissured intrusions, basalts, etc., low degree of weathering, low water table, clean rough fractures, high shear strength rocks.	low	1
High degree of weathering of above mentioned lithologies and hard massive clastic sedimentary rocks; low shear strength sherable fractures.	moderate	2
Considerably weathered sedimentary intrusive metamorphic volcanic rocks, compacted regolithic soils, etc.	medium	3
Considerably weathered hydrotermaly altered rocks of any kind, strongly fractured and fissured clay filled poorly compacted pyroclastic and fluvio-lacustrine soils, shallow water tables.	high	4
Extremely altered rocks, low shear resistance alluvial colluvila and residual soils, shallow water tables -	very high	5

CLASSES OF AVERAGE MONTHLY PRECIPITATION

Average monthly precipitation (mm/month)	Assigned value
< 125	0
125 - 250	1
> 250	2

WEIGHTING FOR ANNUAL PRECIPITATION

Summation of Precipitation averages	Susceptibility	Value S_h
0 - 4	very low	1
5 - 9	low	2
10 - 14	medium	3
15 - 19	high	4
20 - 24	very high	5

INFLUENCE OF SEISMIC INTENSITY

Intensities (MM) Ts = 100 years	Susceptibility	Value T_s
III	Slight	1
IV	Very low	2
V	Low	3
VI	Moderate	4
VII	Medium	5
VIII	Considerable	6
IX	Important	7
X	Strong	8
XI	Very strong	9
XII	Extremely strong	10

INFLUENCE OF RAINFALL PRECIPITATION

Maximum rainfall	Rainfall	Susceptibility	Value T_p
n>10 years; Tp=100 years	n<10 years; average		
< 100mm	< 50mm	Very low	1
101 - 200	51 - 90	Low	2
201 - 300	91 - 130	Medium	3
301- 400	131 - 175	High	4
> 400	> 175	Very high	5

CLASSES OF POTENCIAL LANDSLIDE HAZARDS

Value from equation (2)	Class	Susceptibility of hazard
0 - 6	I	Negligible
7 - 32	II	Low
33 - 162	III	Moderate
163 - 512	IV	Medium
513 -1250	V	High
> 1250	VI	Very high

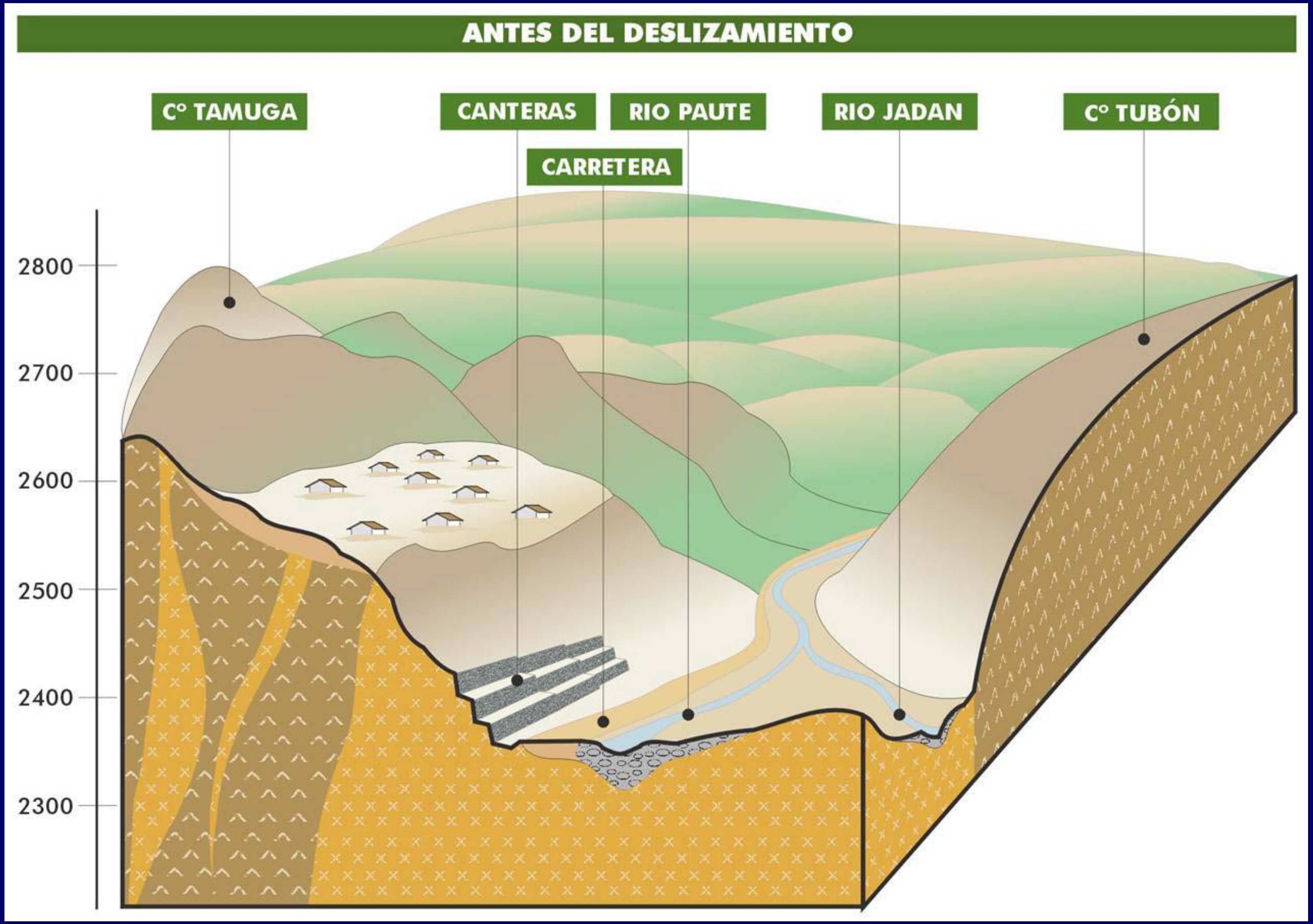
Proposed maximum LHEF rating for different contributory for LHZ mapping

Contributory Factor	Maximum LHEF Rating
Lithology	2
Relationship of structural discontinuities with slopes	2
Slope morphometry	2
Relative relief	1
Landuse and Landcover	2
Groundwater condition	1
Total	10

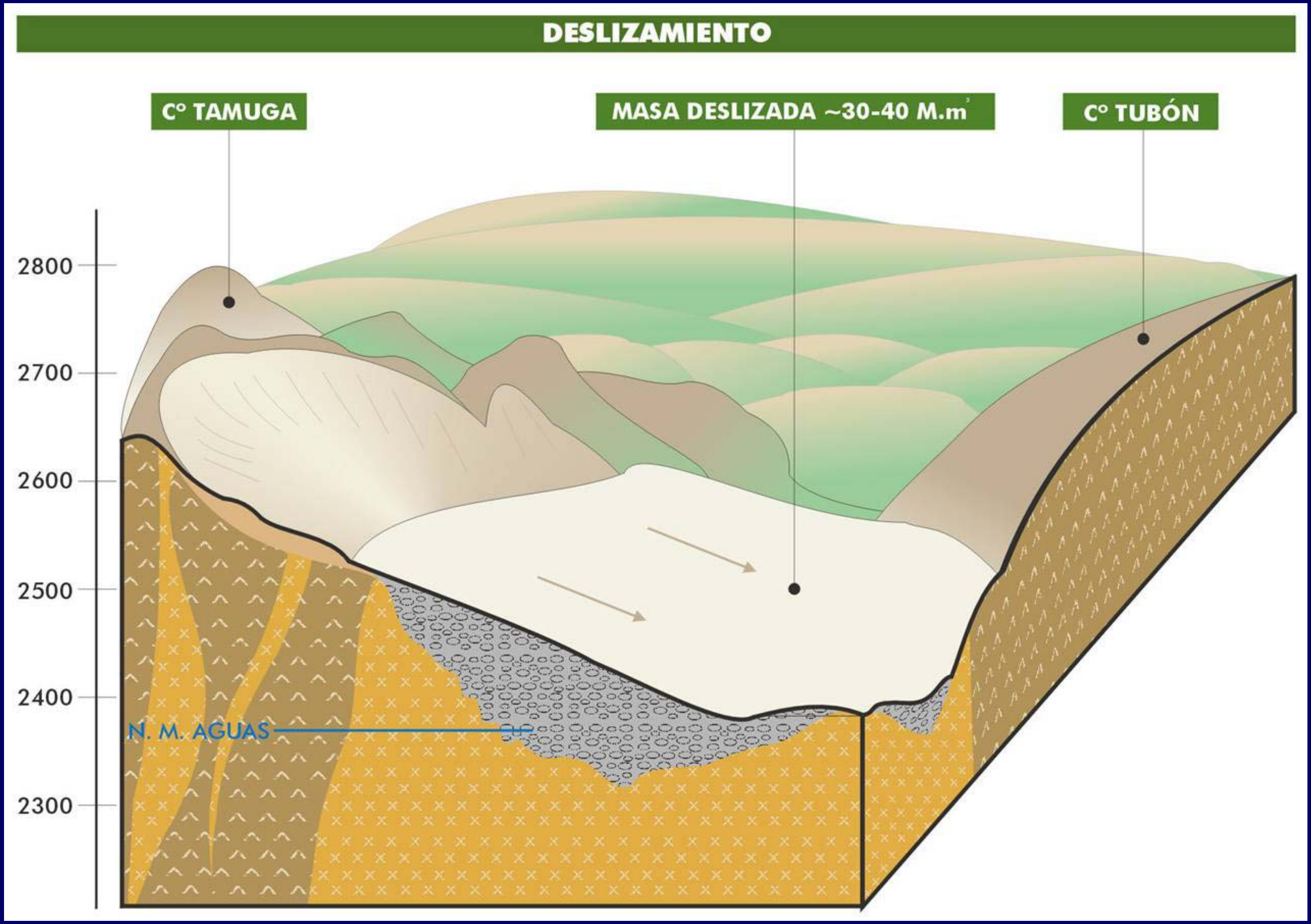
Proposed maximum LHEF rating

Zone	TEHD Value	Description of Zones
I	< 3.5	Very low hazard (VLH) Zone
II	3.5 – 5.0	Low hazard (LH) Zone
III	5.1 – 6.0	Moderate hazard (MH) Zone
IV	6.1 – 7.5	High hazard (HH) Zone
V	> 7.5	Very High hazard (VHH) Zone

Josefina Landslide - Ecuador



Josefina Landslide - Ecuador



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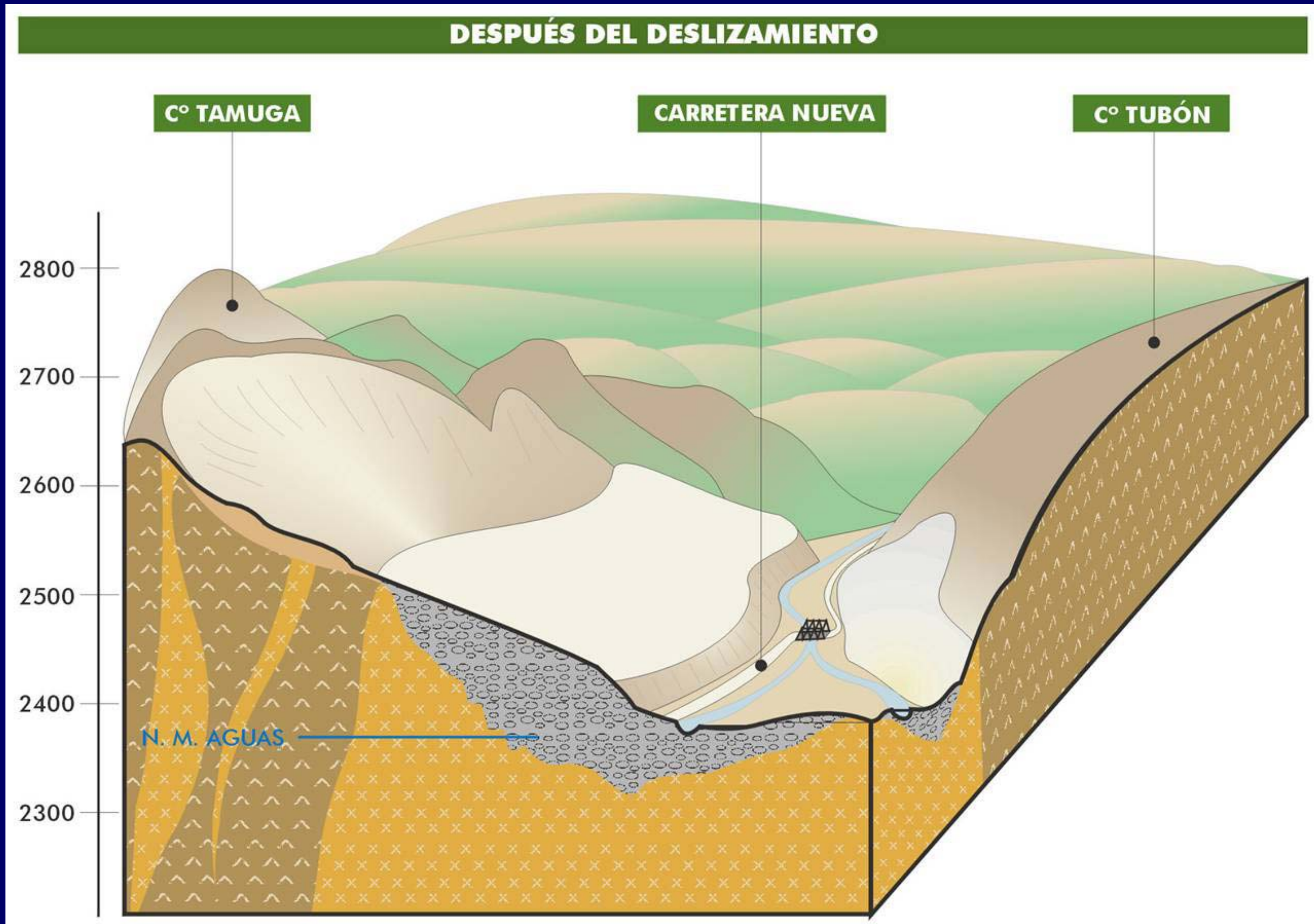

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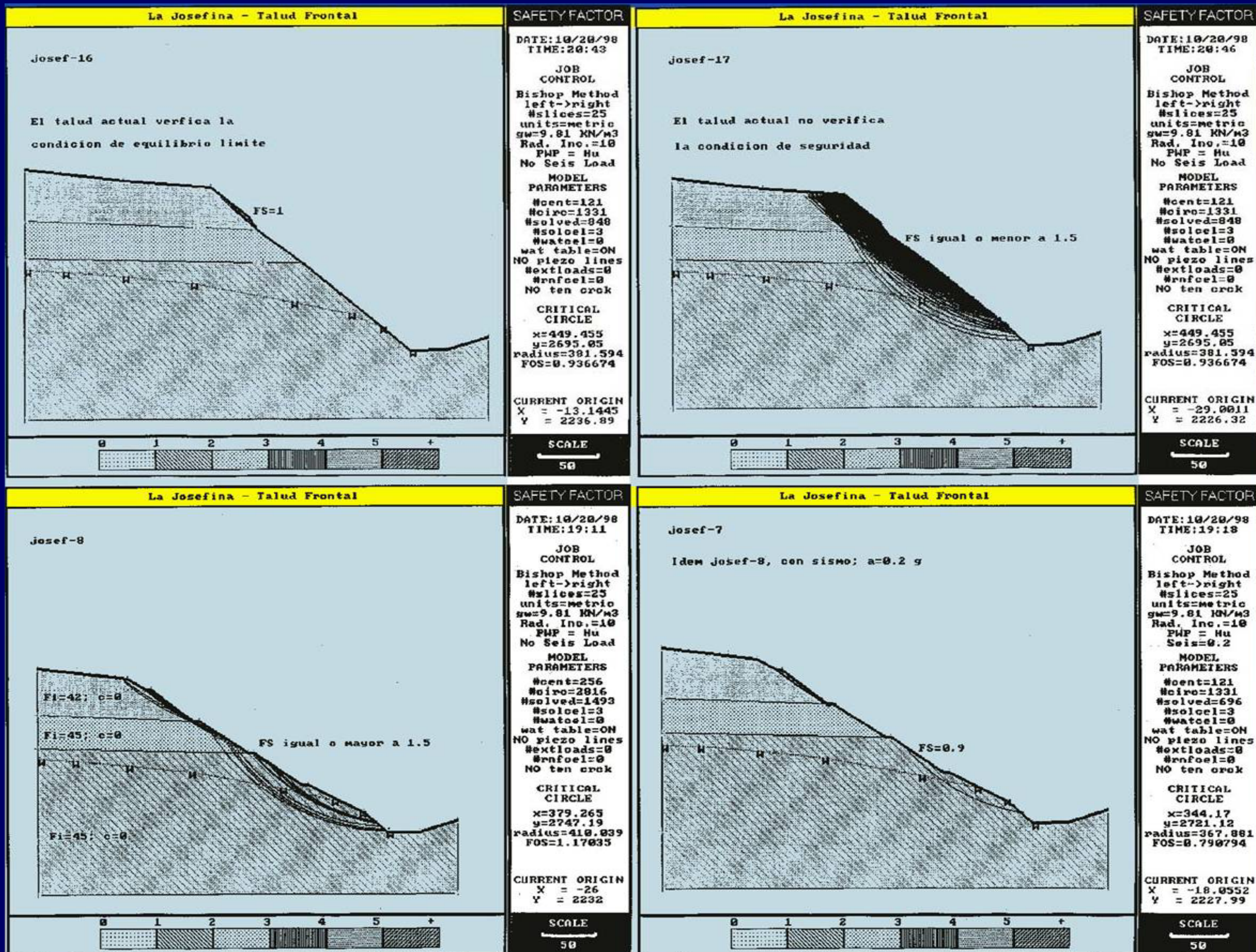

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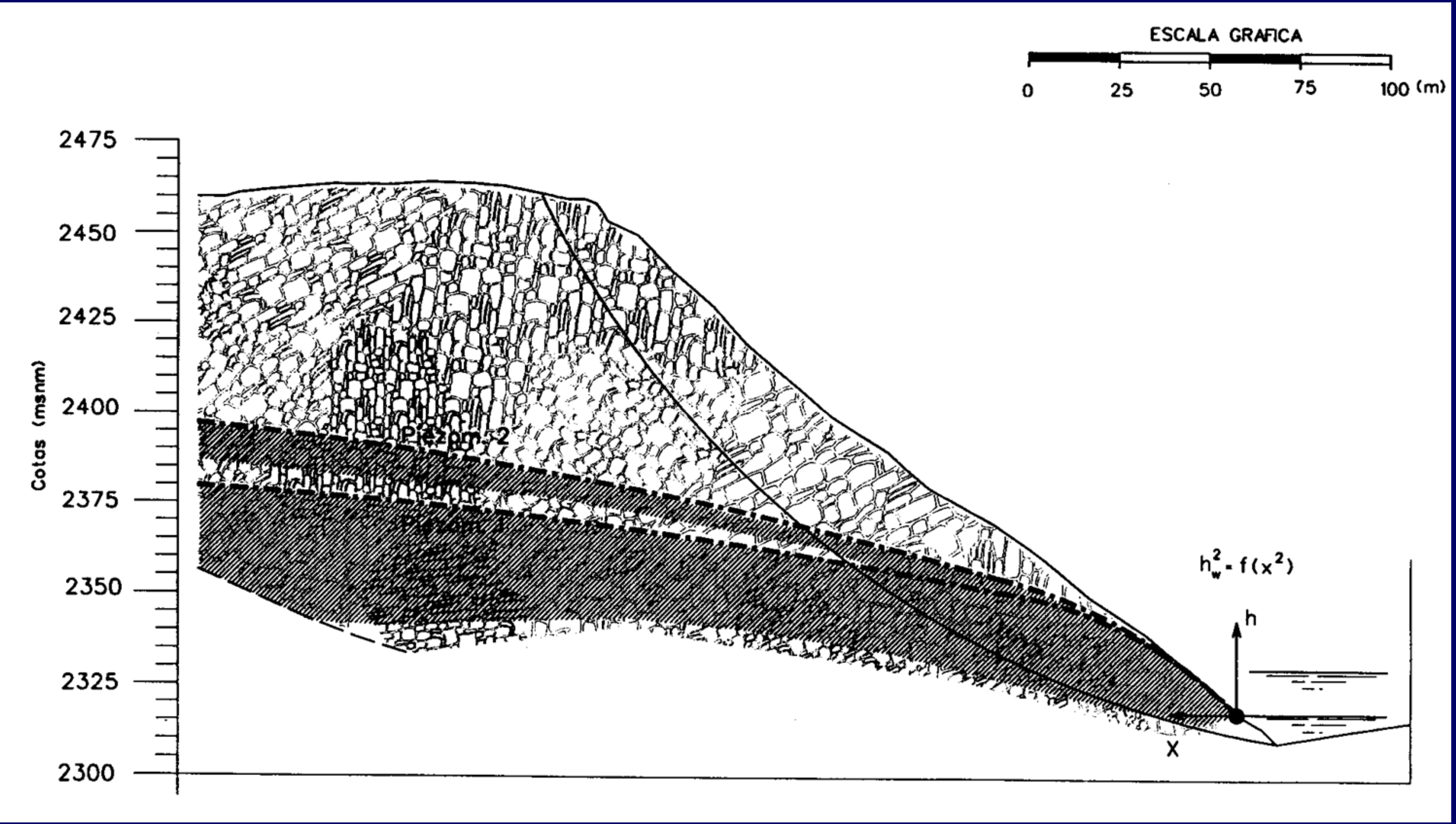

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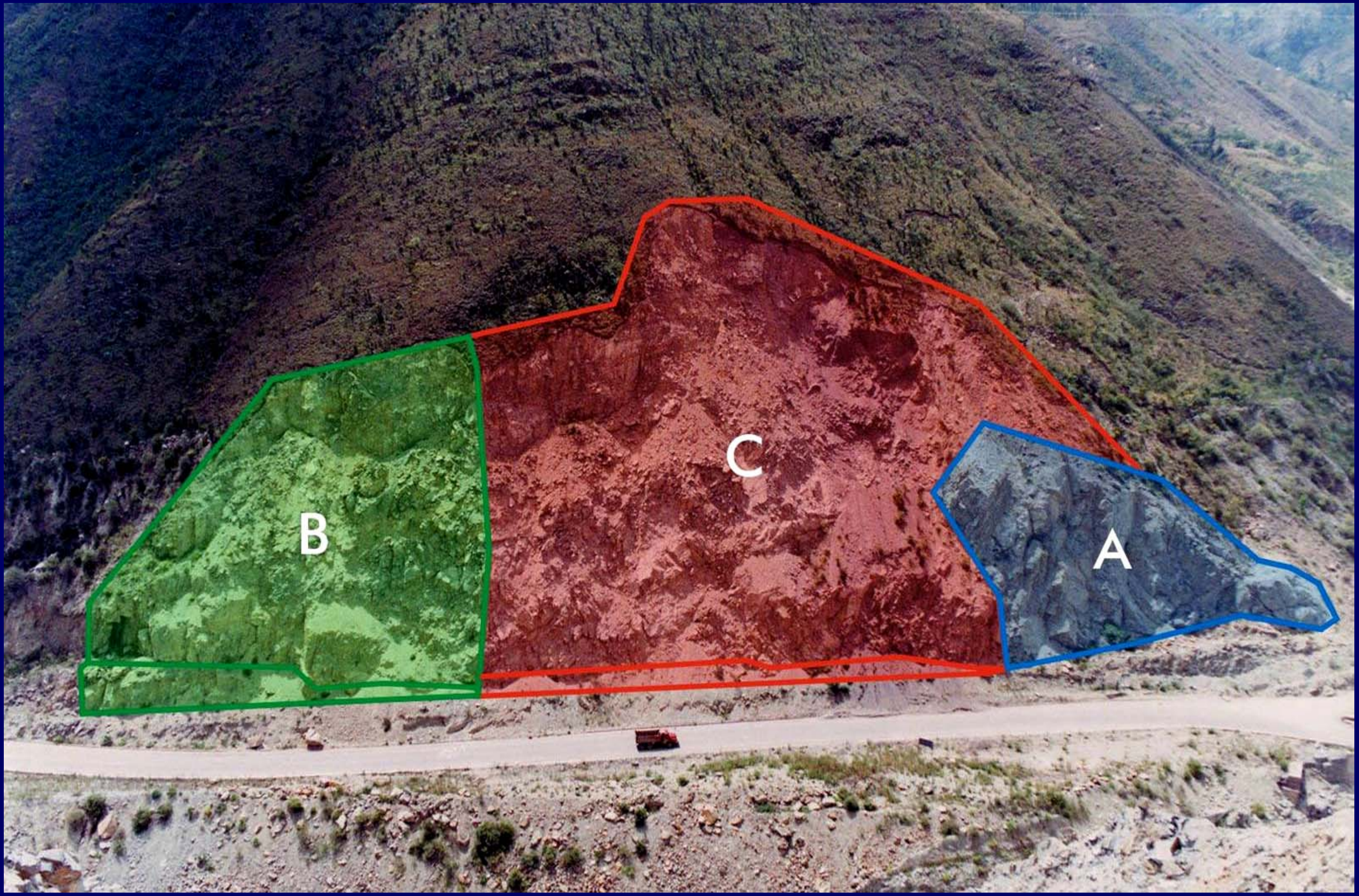

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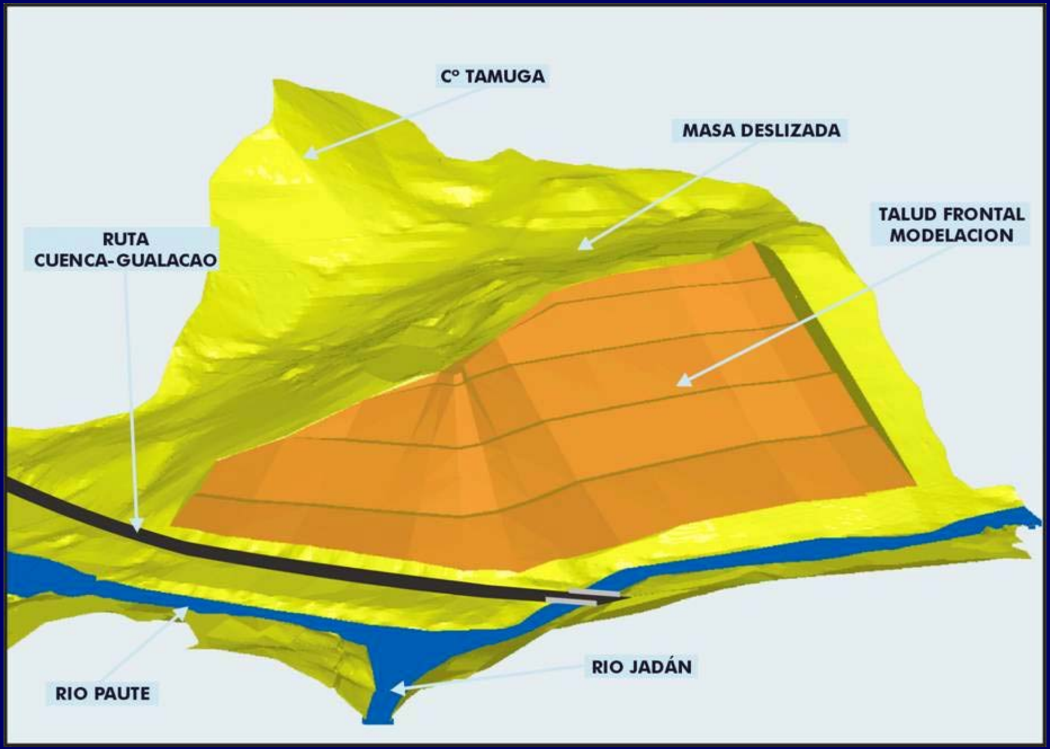

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