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CONTRIBUIÇÃO DA INSTRUMENTAÇÃO NO AMBITO DO PRINCIPIO DA TENSÃO EFETIVA.

GESTÃO DE RISCO E SEGURANÇA DE BARRAGENS.

Pedricto Rocha Filho – Consultor.

BRASILIA, 28/NOVEMBRO/2019.

ESTRUTURA DA APRESENTAÇÃO

1- Principio da Tensão efetiva
1.1 Formulação Geral
1.2 Formulação Aproximada
1.3 Representação Gráfica: Mohr Coulomb/Tresca.
1.4 Trajetória de Tensões.

2- Deslocamentos.

3- Exemplos.
3.1 Tensões Totais.
3.2 Poro Pressão: induzida e percolação.

4- Projeto P&D Light-Moiras.

5- Considerações Finais.

- The Effective Stress Principle J. ALCOVERRO.
- Mathematical and Computer Modeling 37 (2003) 457-467. Elsevier.

ABSTRACT-THE BEHAVIOUR OF SOIL AT THE MACROSCOPIC SCALE DEPENDS ON THE BEHAVIOUR OF ITS COMPONENTS AND ON THE INTERACTIONS BETWEEN THEM AT THE MICROSCOPIC SCALE. HERE, ASSUMPTIONS ARE MADE ONLY AT THE MICROSCOPIC SCALE AND, BY USE OF A SUITABLE AVERAGING PROCEDURE; CONSEQUENCES AT THE MACROSCOPIC SCALE ARE DERIVED. AT THE MICROSCOPIC SCALE, THE SOIL IS ASSUMED TO BE MADE OF BULK PHASES AND INTERFACES, BOTH HAVING VERY GENERAL CONSTITUTIVE RELATIONS. AT THE MICROSCOPIC SCALE, THE INCOMPRESSIBILITY OF ALL BULK PHASES, INCORPORATED BY USE OF A THERMODYNAMIC THEORY OF CONSTRAINED MATERIALS, IMPLIES THAT A GIVEN THERMOKINETIC PROCESS EXPERIENCED BY THE SOIL DOES NOT DEPEND ON AN ARBITRARY AND UNIFORM VARIATION OF THE SPHERICAL PART OF THE STRESS TENSOR FIELD AT ALL POINTS OF THE SOIL. AT THE MACROSCOPIC SCALE, THAT THERMOKINETIC PROCESS APPEARS NOT TO BE INFLUENCED BY CERTAIN VARIATIONS OF THE MACROSCOPIC STRESSES AND EXCHANGES OF MOMENTUM OF THE BULK PHASES. AN EXTENSION TO THE CASE THAT ONE BULK PHASE IS COMPRESSIBLE IS ALSO PRESENTED. FINALLY, VERSIONS OF THE EFFECTIVE STRESS PRINCIPLE COMMONLY USED IN SOIL MECHANICS FOR SATURATED AND UNSATURATED SOILS ARE DERIVED AS PARTICULAR CASES.

THE EFFECTIVE STRESS PRINCIPLE
The **Microscopic** Scale

$$\frac{\partial}{\partial t}(\rho\psi) + \nabla \cdot (\rho\psi\mathbf{v}) + \nabla \cdot \mathbf{i} - \rho f = \rho G,$$

$$\frac{\partial^s}{\partial t}(\rho^s\psi^s) + \nabla^s \cdot (\rho^s\psi^s\mathbf{v}^s) - 2\rho^s\mathbf{w} \cdot \mathbf{n}K_M\psi^s + \nabla^s \cdot \mathbf{i}^s - \rho^s f^s = \rho^s G^s + \sum_{\alpha}(\mathbf{i} + \rho\psi(\mathbf{v} - \mathbf{w}))|_{\alpha} \cdot \mathbf{n}^{\alpha}, \qquad (1)$$

$$\sum_{\alpha\beta}(\mathbf{i}^s + \rho^s\psi^s(\mathbf{w} - \mathbf{u}))|_{\alpha\beta} \cdot \mathbf{n}^{\alpha\beta} = 0.$$

$\frac{\partial}{\partial t}$ = *time derivate holding the space position constant*

∇ = *is the spacial gradient operator*

ρ = *is the mass density (per unit volume)*

Ψ = *microscopic termodynamic property*

ψ = *is the specific (per unit mass of bulk phase) value of* Ψ

v = *is the velocity of the particles*

i = *is the nonconvective flux of* Ψ

f = *is the specific supply of* Ψ

G = *is the specific production of* Ψ

n = *is a unit normal to the interface*

K_M = *is the corresponding mean curvatrue of the interface*

$\frac{\delta^s}{\partial t}$ = *time derivate holding the intrinsic position on the interface constant*

$\nabla^s = (1 - n \otimes n) \cdot \nabla$ *is the surface gradient operator*

w = *is the velocity of the interface in the space*

ρ^s = *is the surface mass density (per unit area)*

ψ^s = *is the specific value of* Ψ

i^s = *nonconvective flux of* Ψ

f^s = *is the specific supply of* Ψ

G^s = *is the specific production of* Ψ

n^α = *is the unit normal to the interface pointing away* α

K_M = *is the corresponding mean curvatrue of the interface*

THE EFFECTIVE STRESS PRINCIPLE
The Macro**scopic** Scale

$$\frac{\partial}{\partial t}(\rho^{\alpha}\psi^{\alpha}) + \nabla\cdot(\rho^{\alpha}\psi^{\alpha}\mathbf{v}^{\alpha}) + \nabla\cdot\mathbf{i}^{\alpha} - \rho^{\alpha}f^{\alpha} = \rho^{\alpha}G^{\alpha} + \hat{\psi}^{\alpha},$$

$$\frac{\partial}{\partial t}\left(\rho^{\alpha\beta}\psi^{\alpha\beta}\right) + \nabla\cdot\left(\rho^{\alpha\beta}\psi^{\alpha\beta}\mathbf{v}^{\alpha\beta}\right) + \nabla\cdot\mathbf{i}^{\alpha\beta} - \rho^{\alpha\beta}f^{\alpha\beta} = \rho^{\alpha\beta}G^{\alpha\beta} + \hat{\psi}^{\alpha\beta},$$

$$\hat{\psi}^{\alpha\beta\gamma} = 0,$$

$\frac{\partial}{\partial t}$ = *time derivate holding the space position constant*

∇ = *is the spacial gradient operator*

ρ = *is the mass density (per unit volume)*

Ψ = *microscopic termodynamic property*

ψ = *is the specific (per unit mass of bulk phase) value of* Ψ

v = *is the velocity of the particles*

i = *is the nonconvective flux of* Ψ

f = *is the specific supply of* Ψ

G = *is the specific production of* Ψ

THE EFFECTIVE STRESS PRINCIPLE

In Soil Mechanics

$${}^{\mathrm{SM}}\mathbf{T}^{\alpha} \equiv (\varepsilon^{\alpha})^{-1}(\mathbf{T}^{\alpha} - \varphi^{\alpha}\mathbf{1}).$$

T = is the Cauchy stress tensor

α = is the bulk phase

ε^{α} = is the volume fraction of bulk phase α

φ = potential field

- Engenharia:.. dominada e regida pelo conceito da aproximação. ARTE DA APROXIMAÇÃO… distinto de SIMPLIFICAÇÃO
- APROXIMAÇÃO: Determinação de um valor que, sem ser o exato, não é muito diferente deste.
- Esta aproximação foi estabelecida por Terzaghi originando a GEOTECNIA...
- Geotecnia: É a ciência aplicada PARA O ESTUDO DO COMPORTAMENTO TENSAO X DEFORMAÇÃO X TEMPO de solos e rochas em seu estado natural e construído.

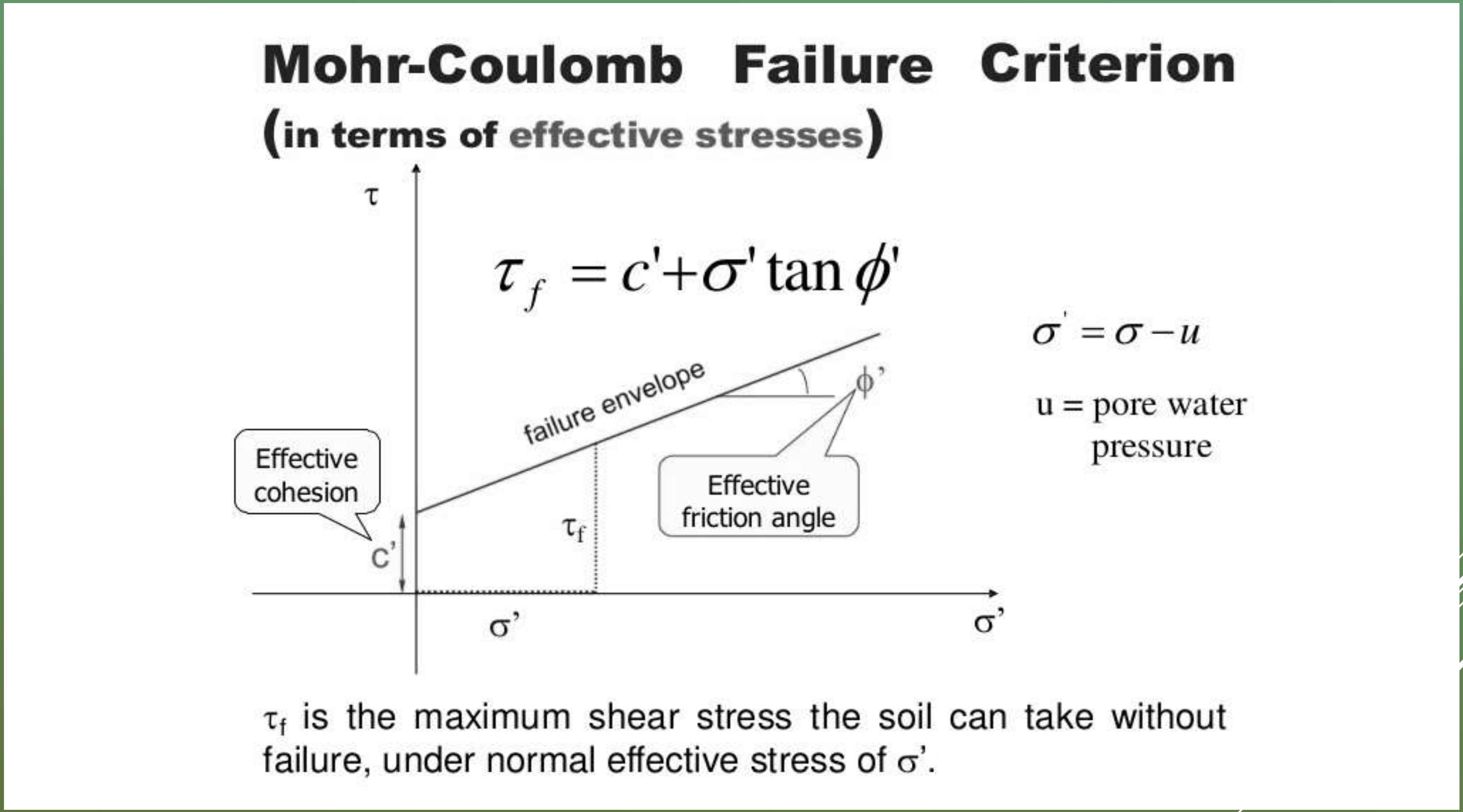
Resistência ao Cisalhamento

$$\tau = c' + \ \sigma'_n \ x \ tan\emptyset'$$

PRINCIPIO DA TENSÃO EFETIVA

TERZAGHI 1925- Erdbaumechanik auf Bodenphysikalischer Grundlage, Liepzig- Vienna.

$$\sigma'_n = [\,\sigma_n - U]$$



Mohr-Coulomb Failure Criterion

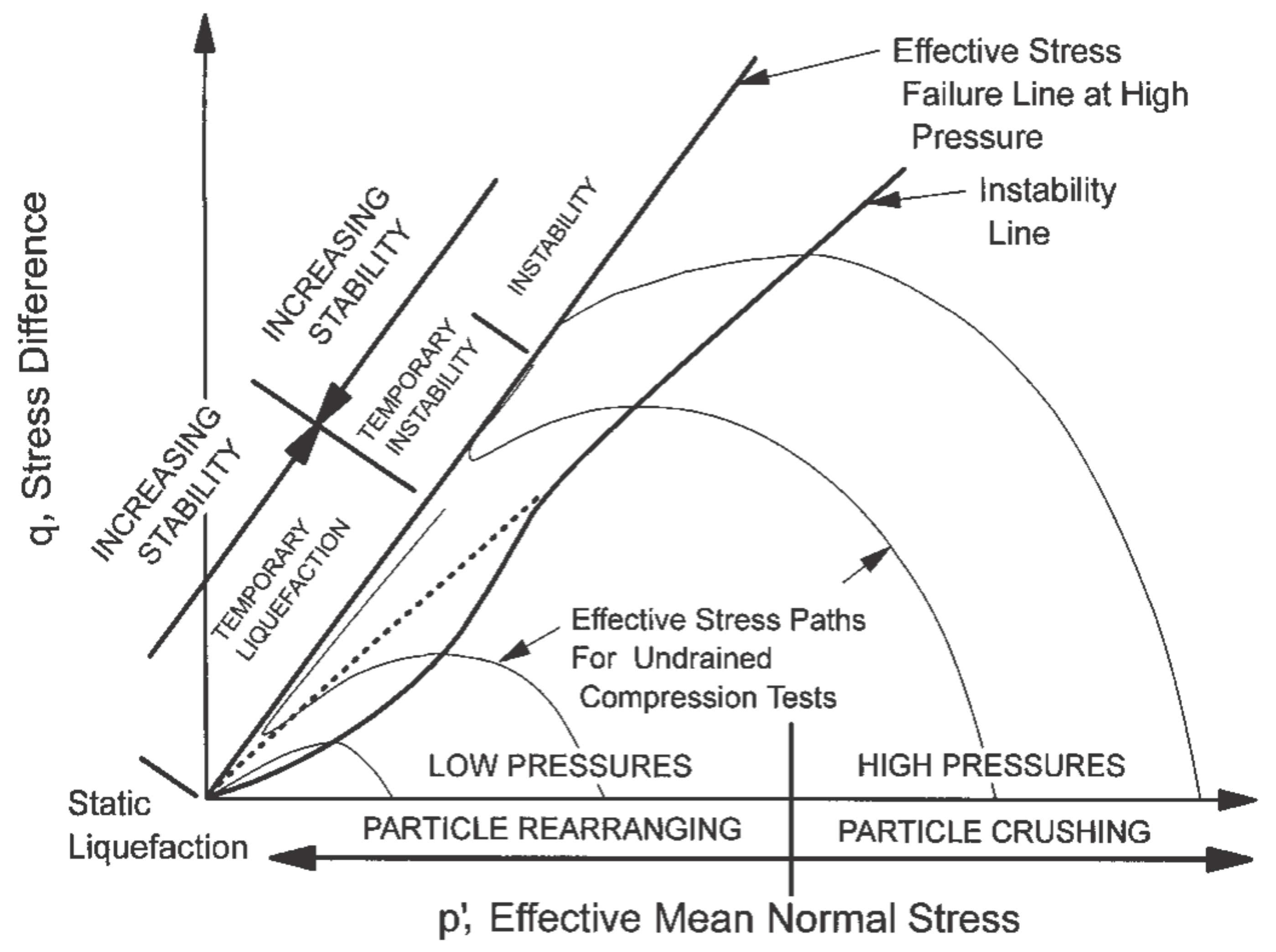
(in terms of **effective stresses**)

$$\tau_f = c' + \sigma' \tan \phi'$$

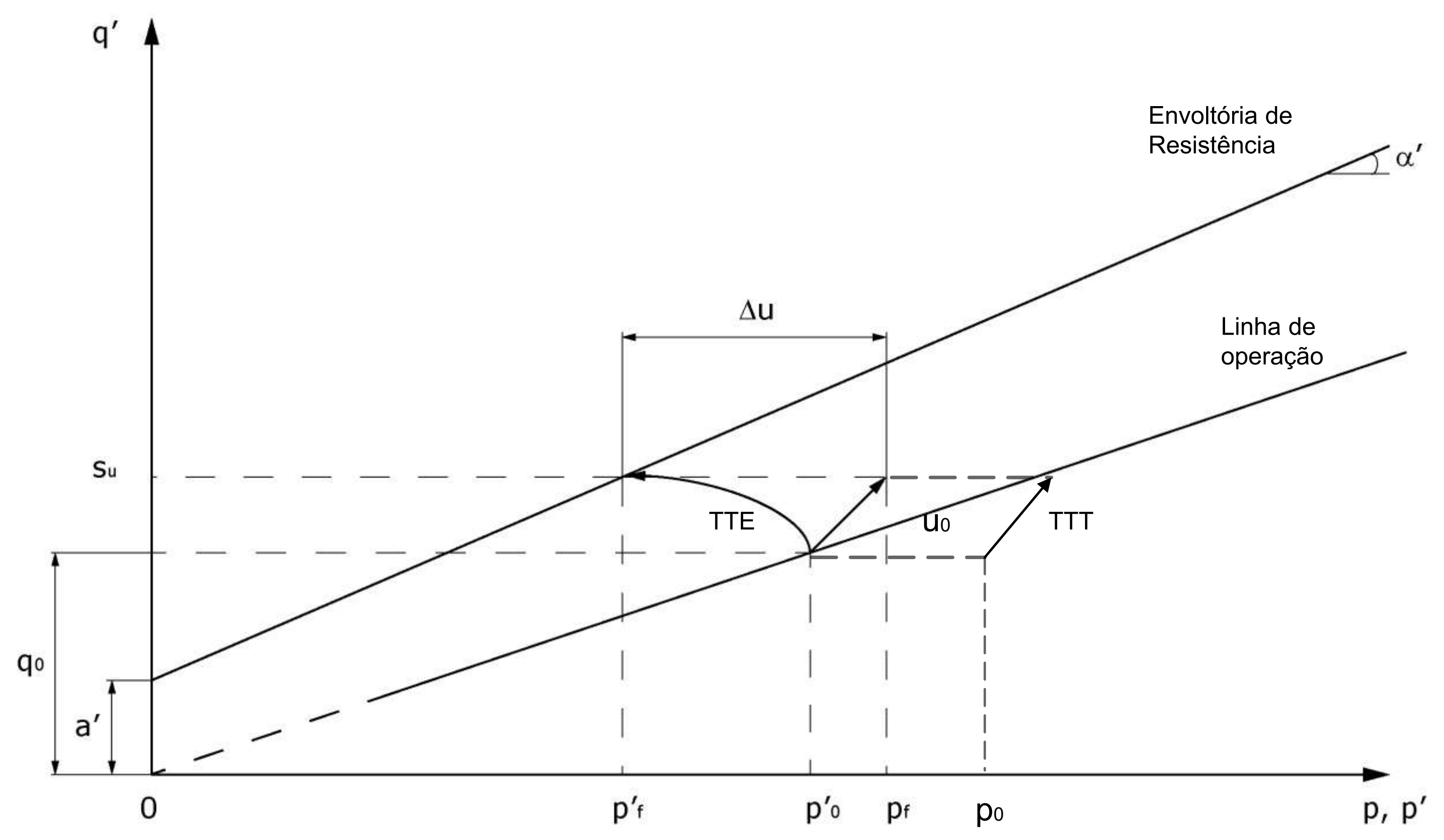
$$\sigma' = \sigma - u$$

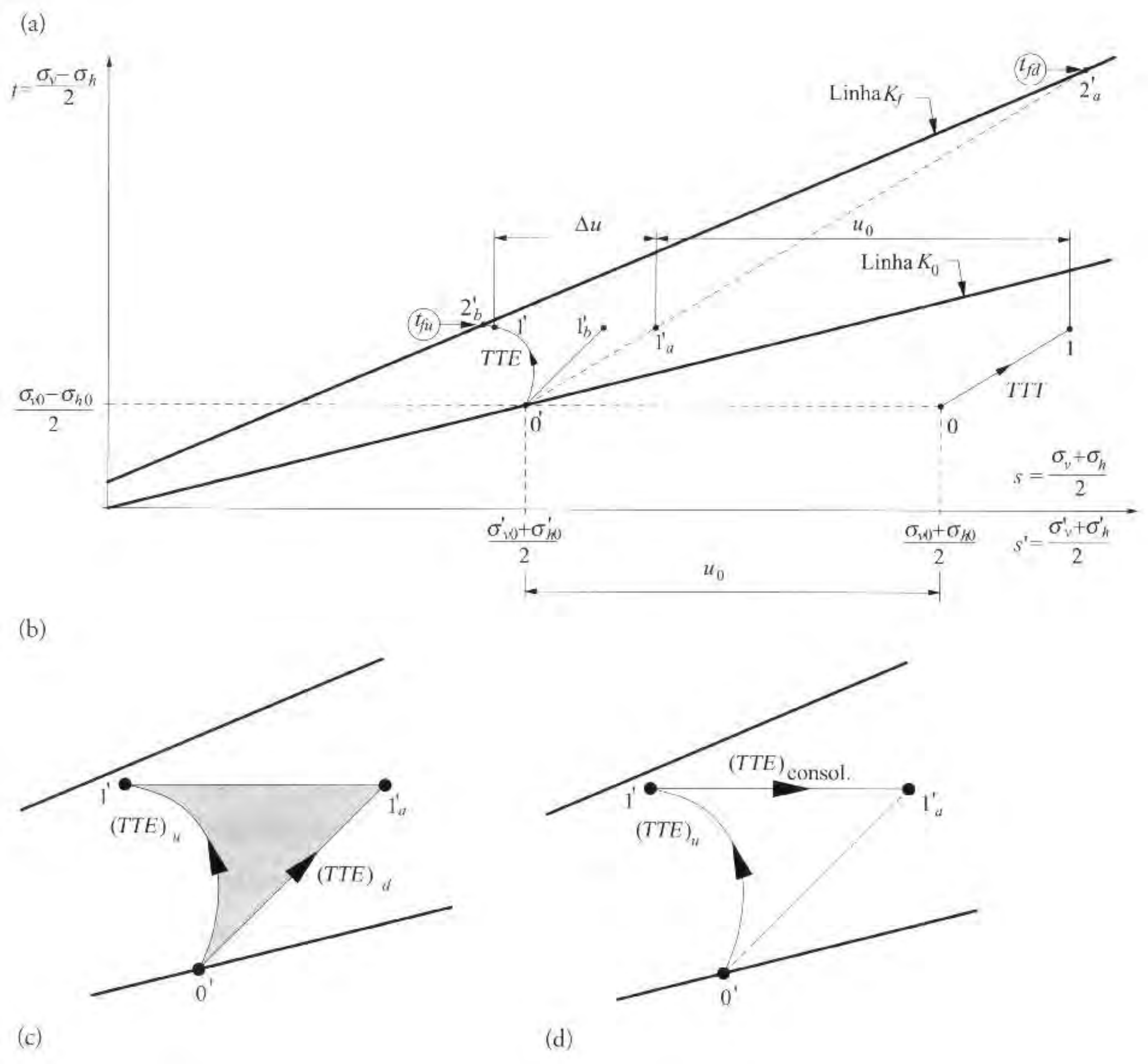
u = pore water pressure

τ_f is the maximum shear stress the soil can take without failure, under normal effective stress of σ'.



(Yamamuro & Lade, 1996)


q′
Envoltória de Resistência
α′
Δu
Linha de operação
su
TTE
u0
TTT
q0
a′
0
p′f
p′0
pf
p0
p, p′


(a)
$t = \frac{\sigma_v - \sigma_h}{2}$
Linha K_f
t_{fd}
$2'_a$
Δu
u_0
Linha K_0
t_{fu}
$2'_b$
1'
$1'_b$
$1'_a$
TTE
1
TTT
$\frac{\sigma_{v0} - \sigma_{h0}}{2}$
0'
0
$s = \frac{\sigma_v + \sigma_h}{2}$
$\frac{\sigma'_{v0} + \sigma'_{h0}}{2}$
$\frac{\sigma_{v0} + \sigma_{h0}}{2}$
$s' = \frac{\sigma'_v + \sigma'_h}{2}$
u_0
(b)
1'
$1'_a$
$(TTE)_u$
$(TTE)_d$
0'
(c)
$(TTE)_{consol.}$
1'
$1'_a$
$(TTE)_u$
0'
(d)

Estado de Tensões Totais:

- σ_X
- σ_Z
- σ_Y

$$\begin{cases} \sigma_Z = \gamma \text{ x } Z \\ \sigma_X = \sigma_Y = [K] \text{x } \sigma_Z \end{cases}$$

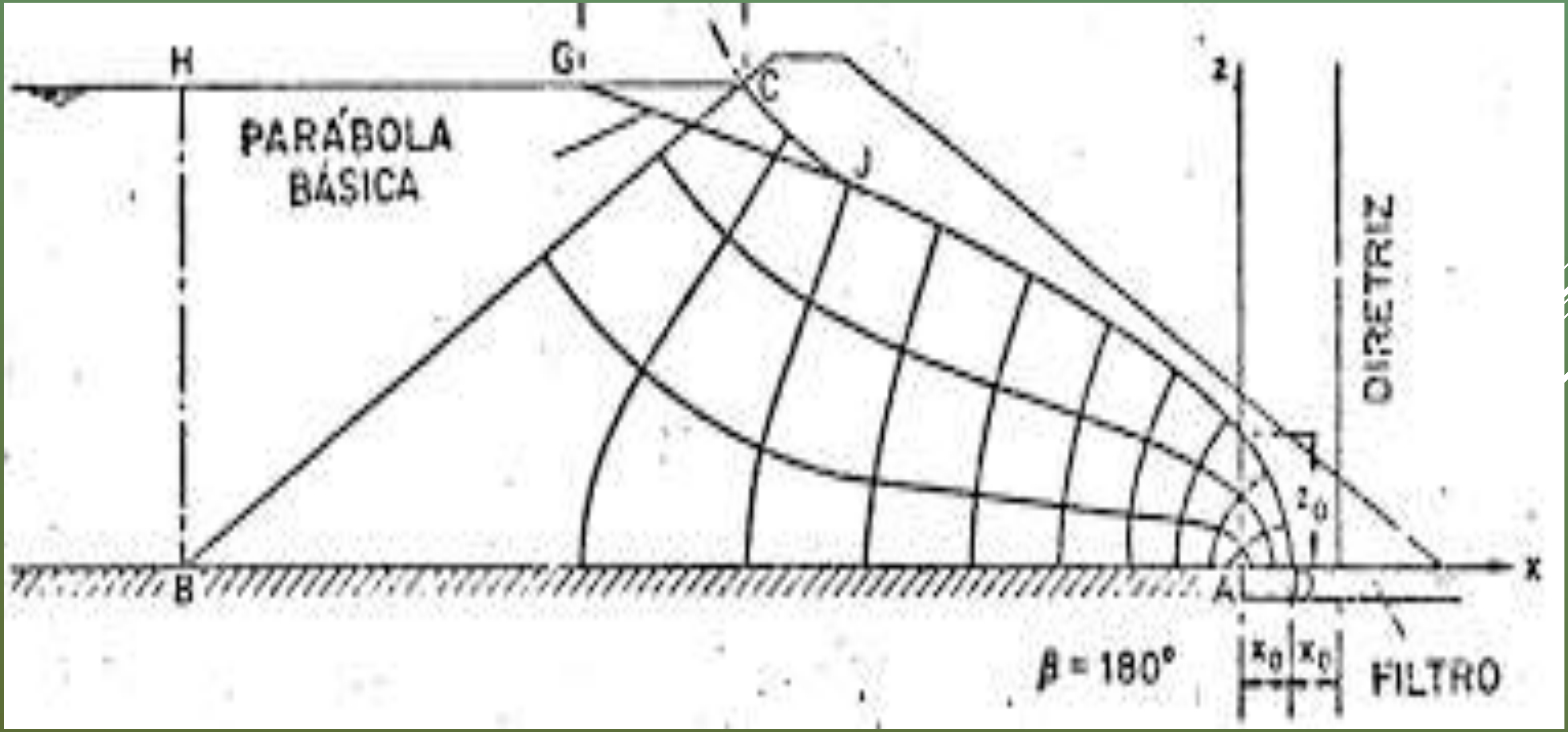
σ_Z *>TENSÕES GEOSTÁTICAS x ARQUEAMENTO*

PORO PRESSÃO INDUZIDA

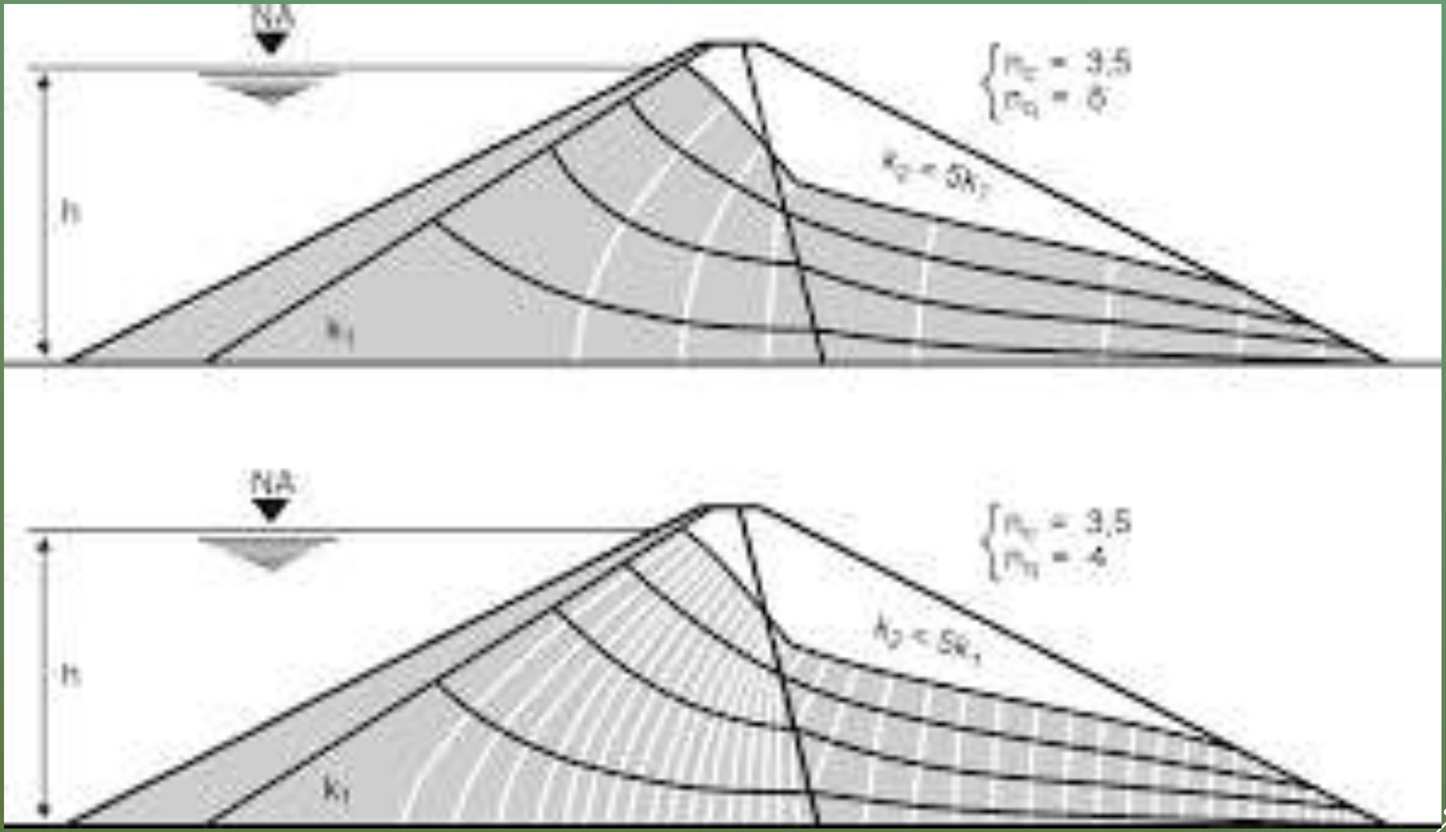
- $\Delta U = \beta\left(\frac{\Delta\sigma_1 + \Delta\sigma_2 + \Delta\sigma_3}{3}\right) + \alpha\left[\sqrt{(\Delta\sigma_1 - \Delta\sigma_2)^2 + (\Delta\sigma_1 - \Delta\sigma_3)^2 + (\Delta\sigma_2 - \Delta\sigma_3)^2}\right]$

- $\Delta U = \Delta\sigma_3 + \mathrm{A}\,(\Delta\sigma_1 - \Delta\sigma_3)$.

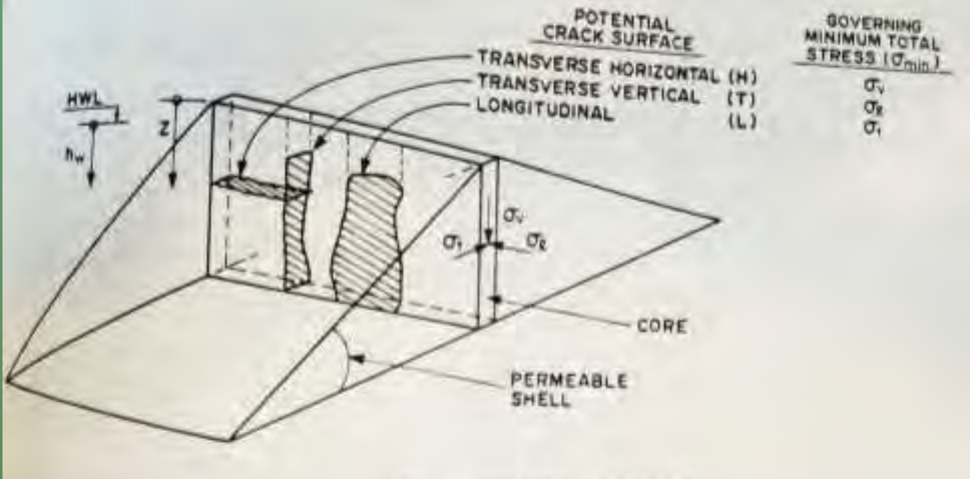
PORO PRESSÃO- PERCOLAÇÃO/REDE DE FLUXO
EQUAÇÕES DE LAPLACE/ LEI DE DARCY



PORO PRESSÃO- PERCOLAÇÃO/REDE DE FLUXO.
EQUAÇÕES DE LAPLACE/LEI DE DARCY.



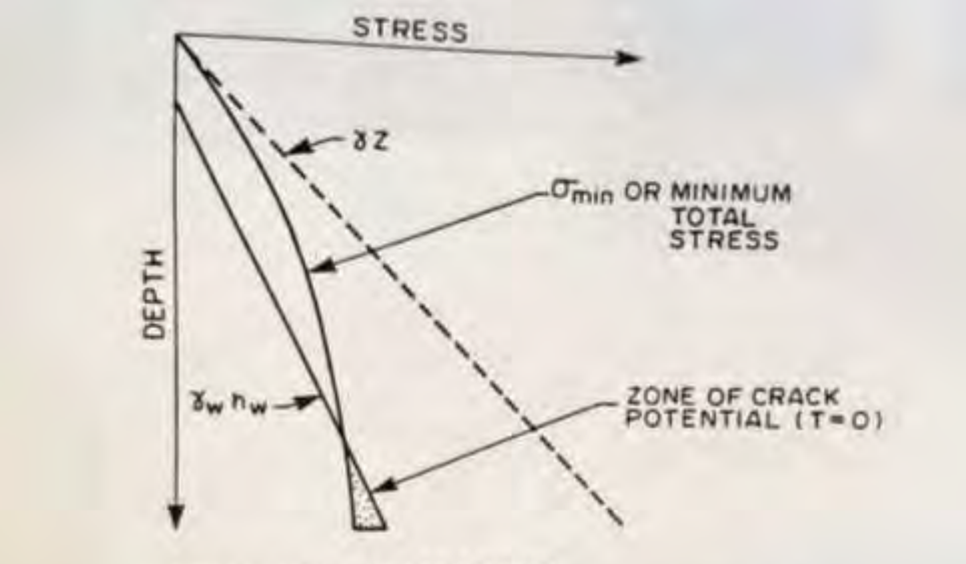
Hydraulic Fracturing Mechanism in Plane Strain



σ_v = VERTICAL STRESS

σ_ℓ = LONGITUDINAL STRESS

σ_t = TRANSVERSE STRESS

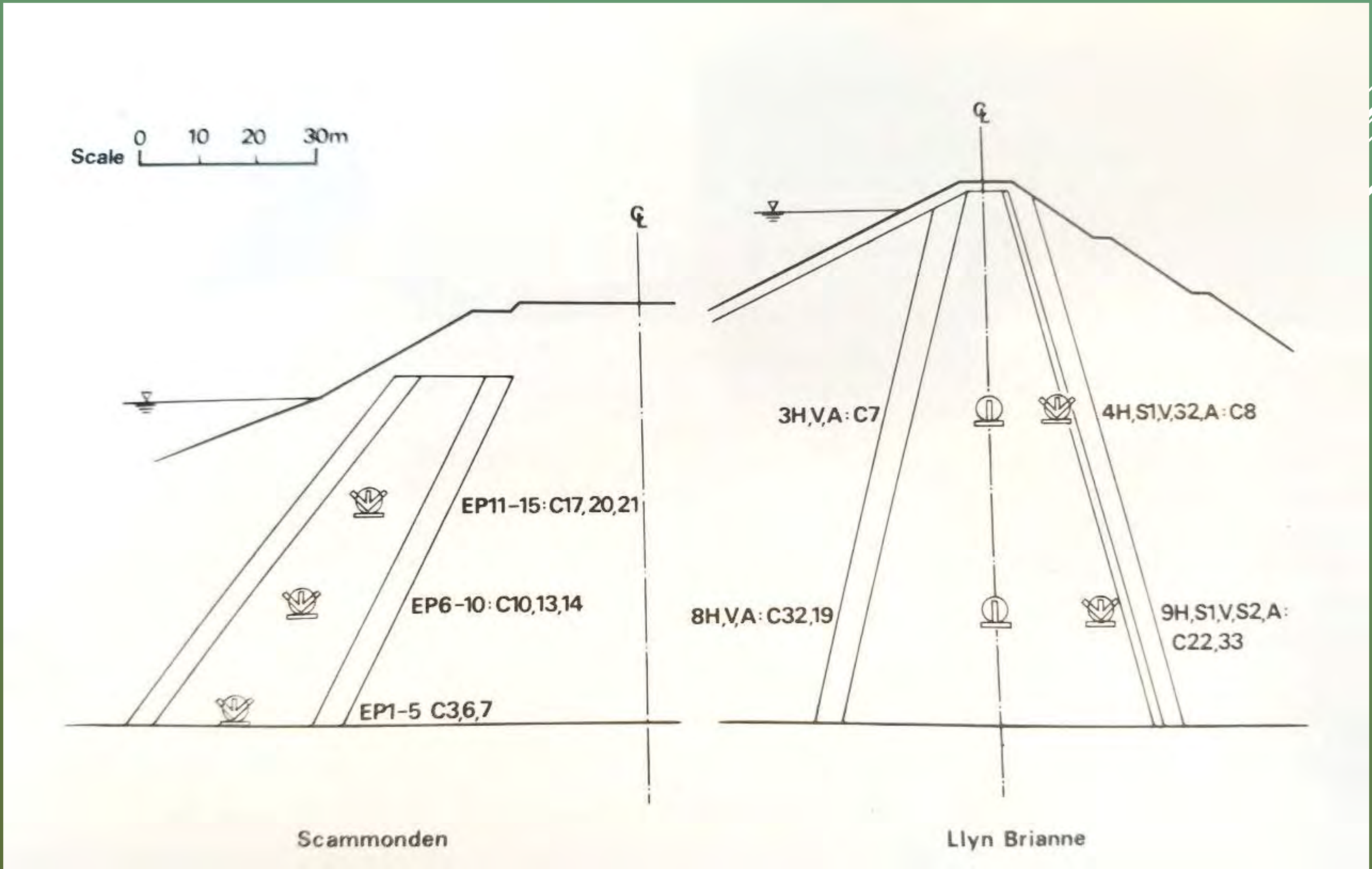


CRITERION FOR CRACKING

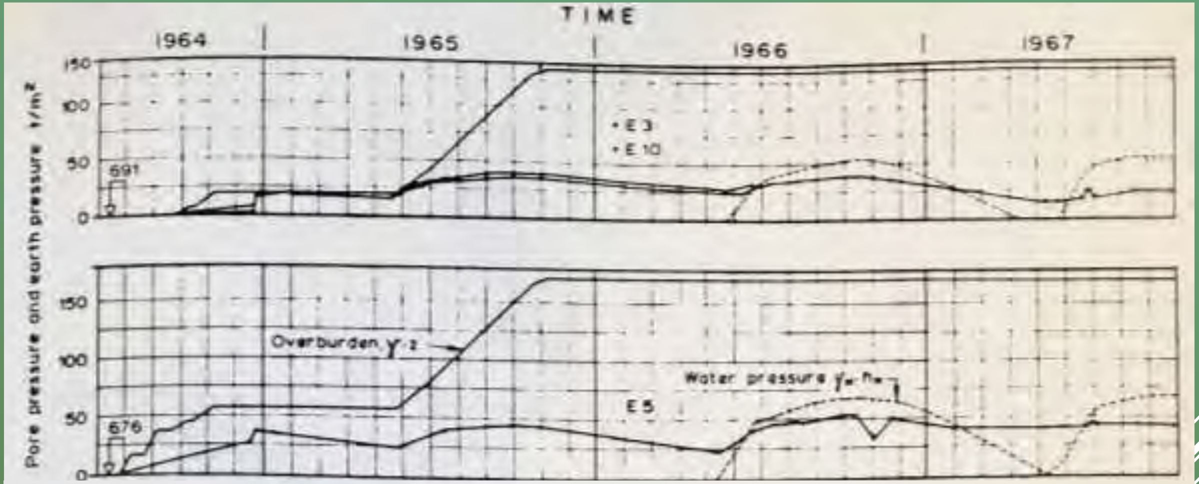
EFFECTIVE STRESSES $\gamma_w h_w \geq T + \sigma'_{min} + P_o$

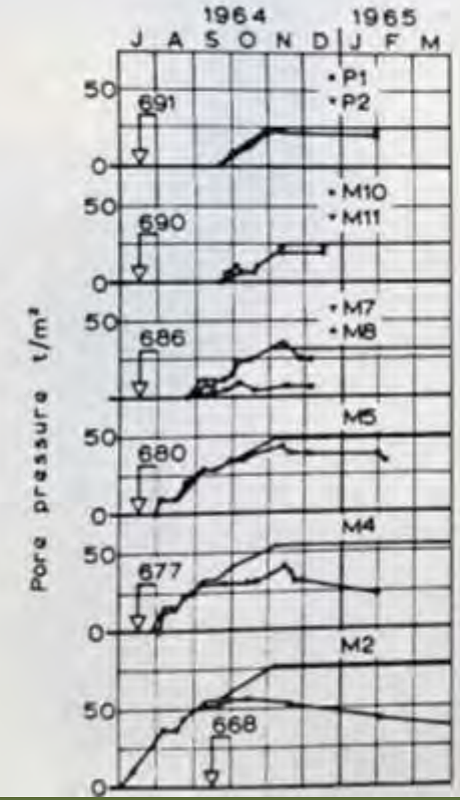
TOTAL STRESSES $\gamma_w h_w \geq T + \sigma_{min}$

Cross-sections of both dams showing positions of earth pressure (EP) cells



Hyytejuvet Dam; After Kjaernsli and Torblaa (1968)





HYTTEJUVET DAM

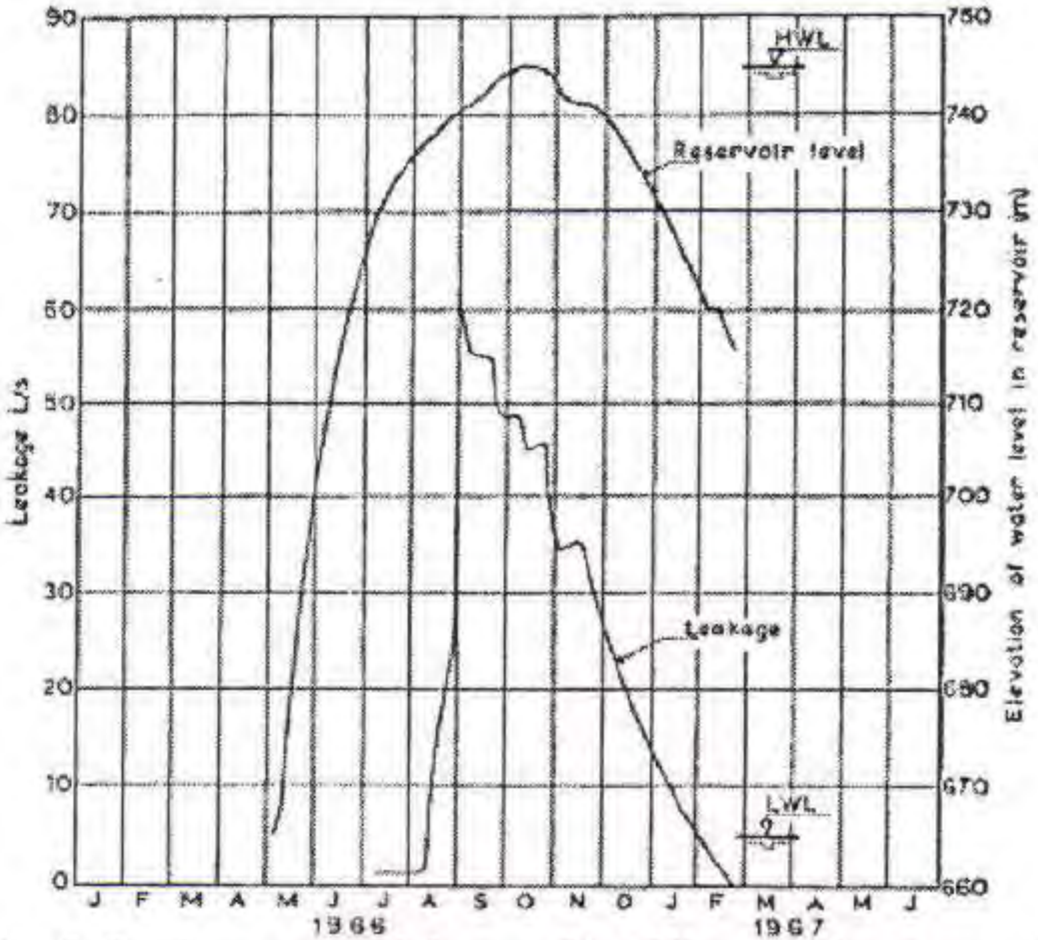


Fig. 5. Leakage record during first filling of the reservoir (reproduced from Kjærnsli and Torblaa 1968).

HYTTEJUVET DAM

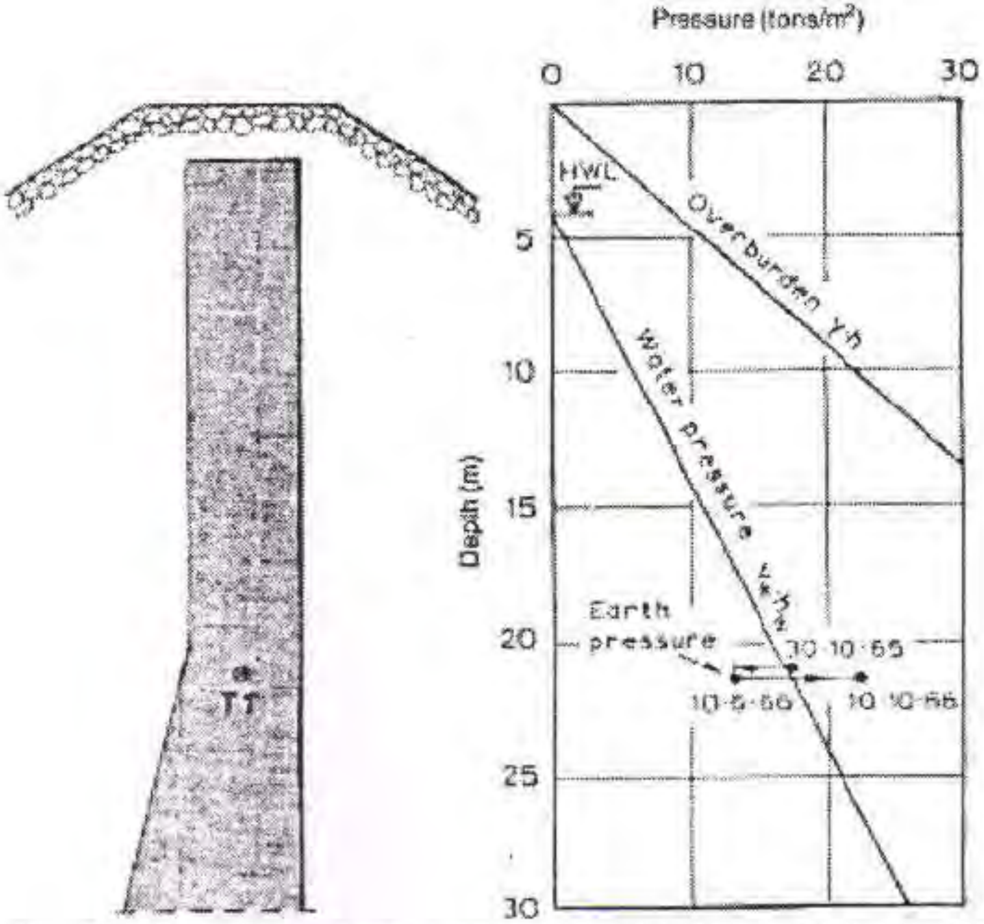
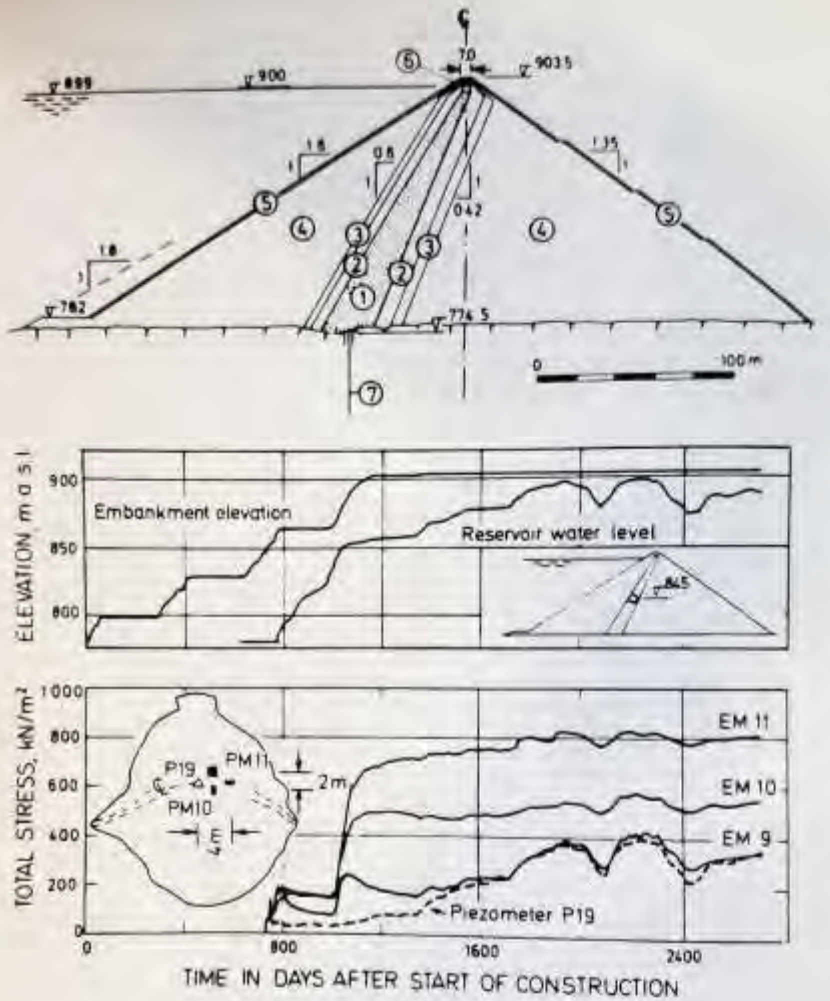


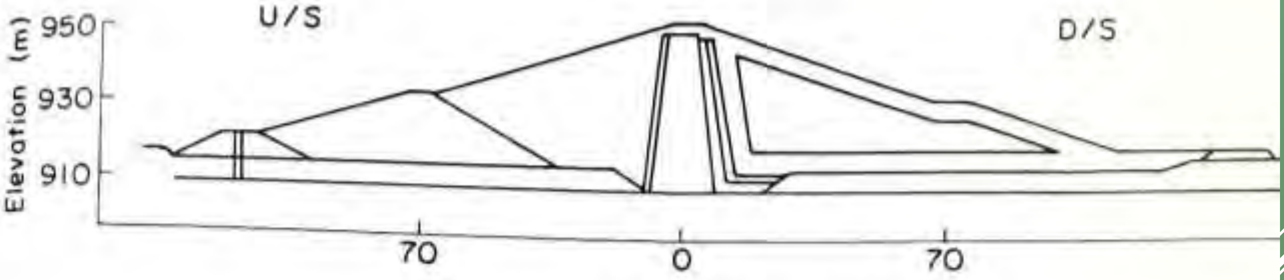
Fig. 6. Measured earth pressures (1 ton/m2) in relation to water pressure and weight of fill (reproduced from Kjærnsli and Torblaa 1968). γ unit weight of soil; h depth; γ_w unit weight of water; h_w water depth.

Svartevann Dam; After Dibiagio et al (1982)

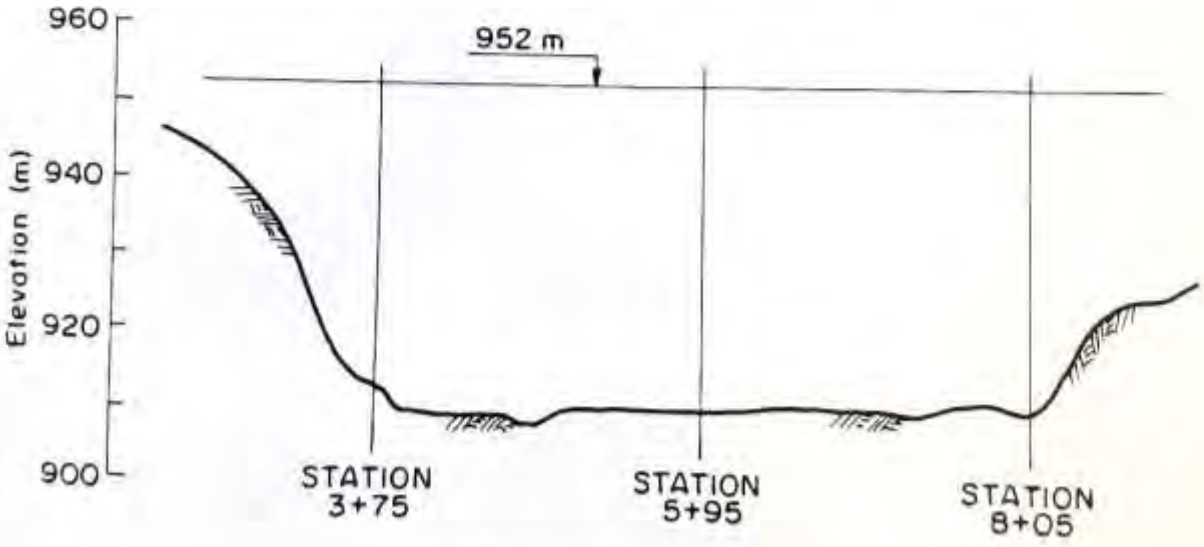


TOTAL STRESS CELL	POTENTIAL CRACK SURFACE	σ (kPa)	$\gamma_w h_w$ (kPa)	P_a kPa
EM9	H	>600 (EST.)	530	400
EM10	T	580	530	400
EM11	L	820	530	400

Dickson Dam Cross-Sections, after Alberta Environment (1986)

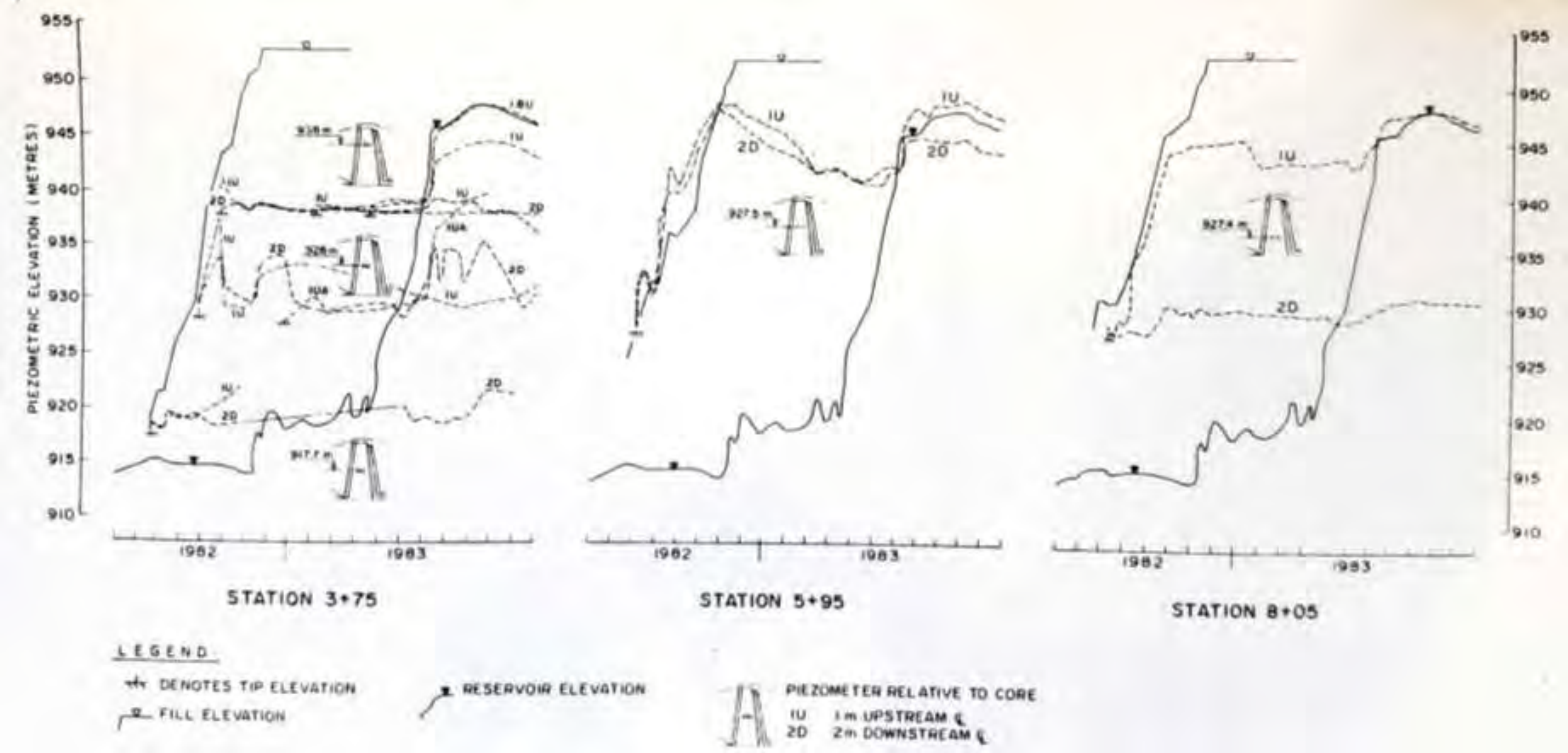


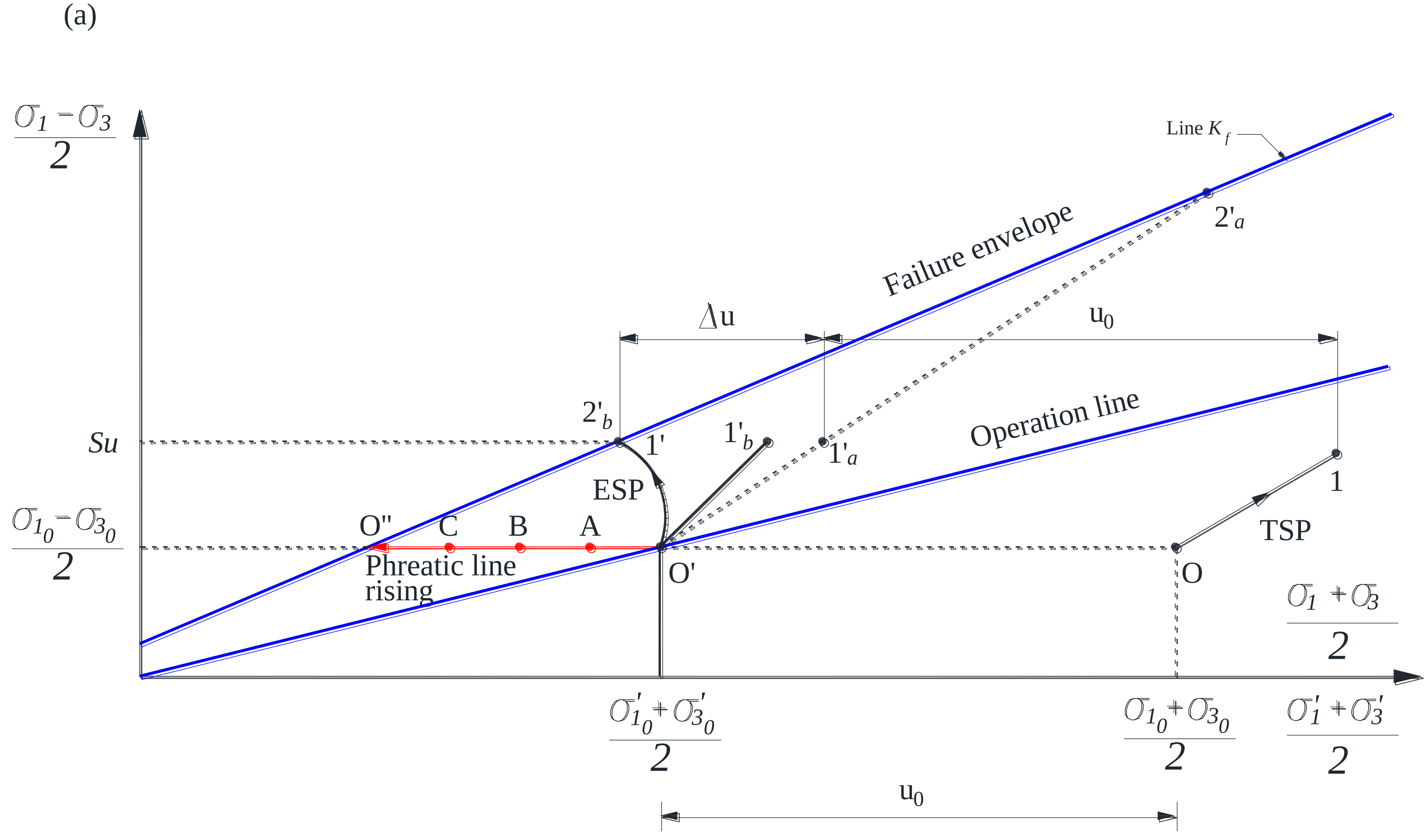
TRANSVERSE CROSS-SECTION



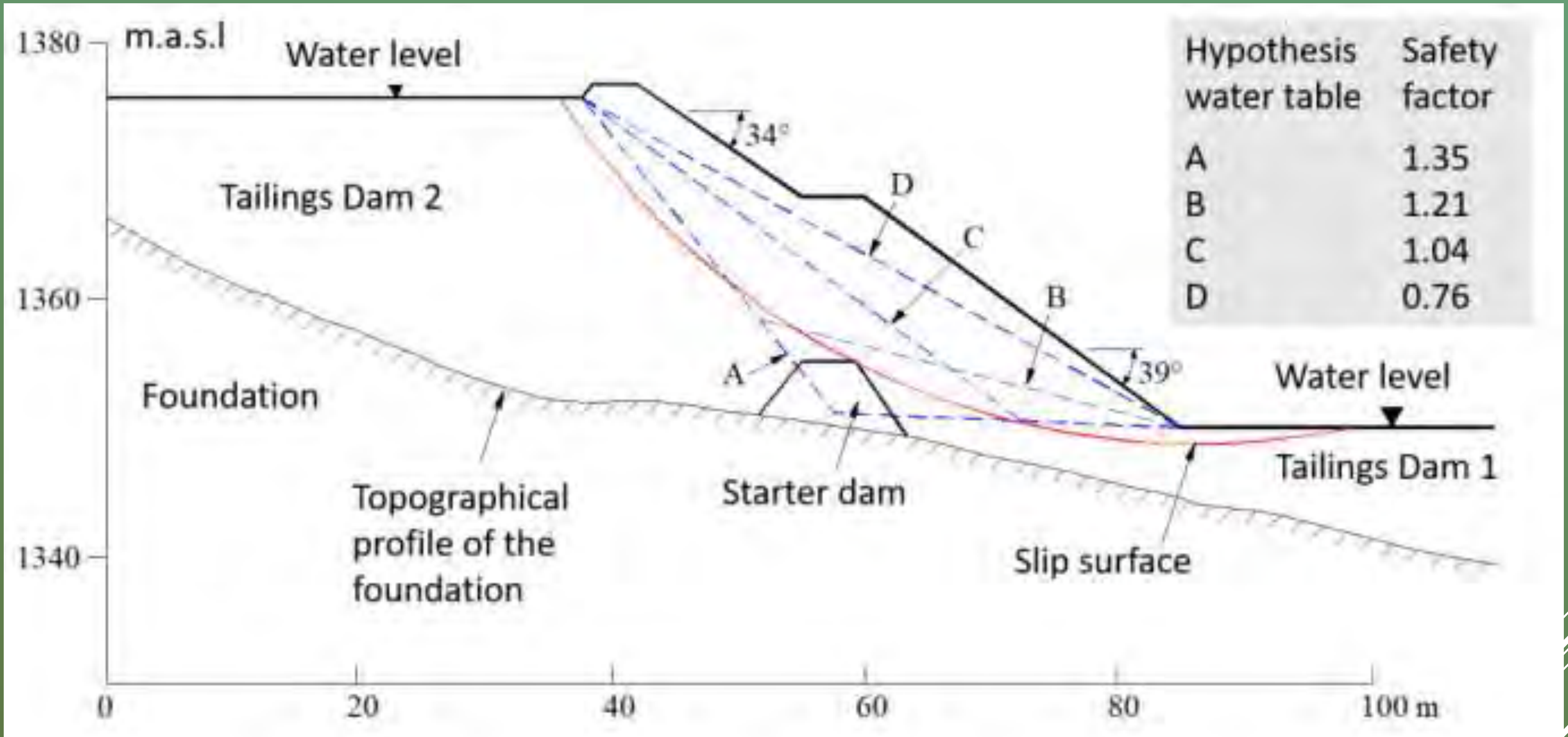
LONGITUDINAL CROSS-SECTION

Dickson Dam, Performance Data During Construction and Impoundment, after Alberta Environment (1986)




(a)
$\frac{\sigma_1 - \sigma_3}{2}$
Line K_f
2'$_a$
Failure envelope
Δu
u$_0$
Operation line
2'$_b$
S_u
1'
1'$_b$
1'$_a$
1
ESP
TSP
$\frac{\sigma_{1_0} - \sigma_{3_0}}{2}$
O''
C
B
A
Phreatic line rising
O'
O
$\frac{\sigma_1 + \sigma_3}{2}$
$\frac{\sigma'_{1_0} + \sigma'_{3_0}}{2}$
$\frac{\sigma_{1_0} + \sigma_{3_0}}{2}$
$\frac{\sigma'_1 + \sigma'_3}{2}$
u$_0$

Source: R.L. Rodriguez (2019). Static liquefaction in Tailings dam and flow Failure



Hypothesis water table	Safety factor
A	1.35
B	1.21
C	1.04
D	0.76

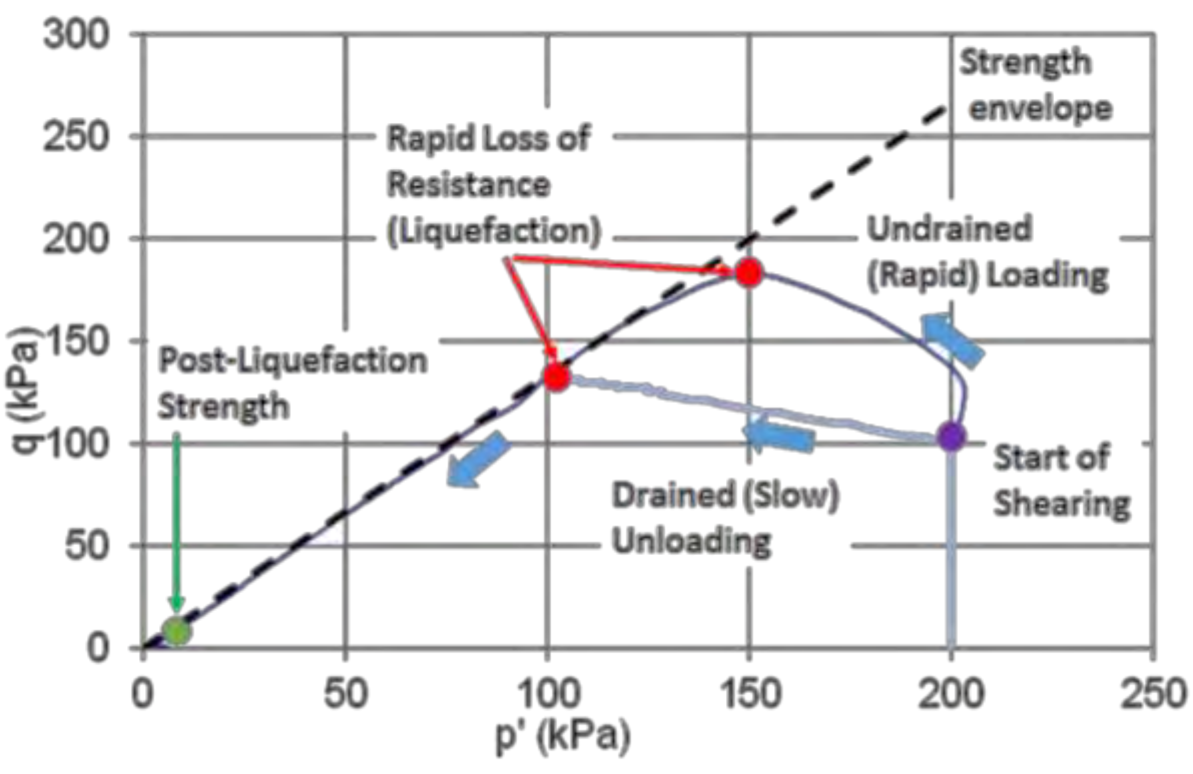
Influence of the water table on the safety factor in the case of static liquefaction and flow failure of the Stava tailings dam failure on July 19, 1985, Italy (modified from Chandler and Tosatti, 1995).

Tailings Sand Dams

Static liquefaction case

Stress paths for undrained loading and drained unloading triaxial tests on Fundão sand

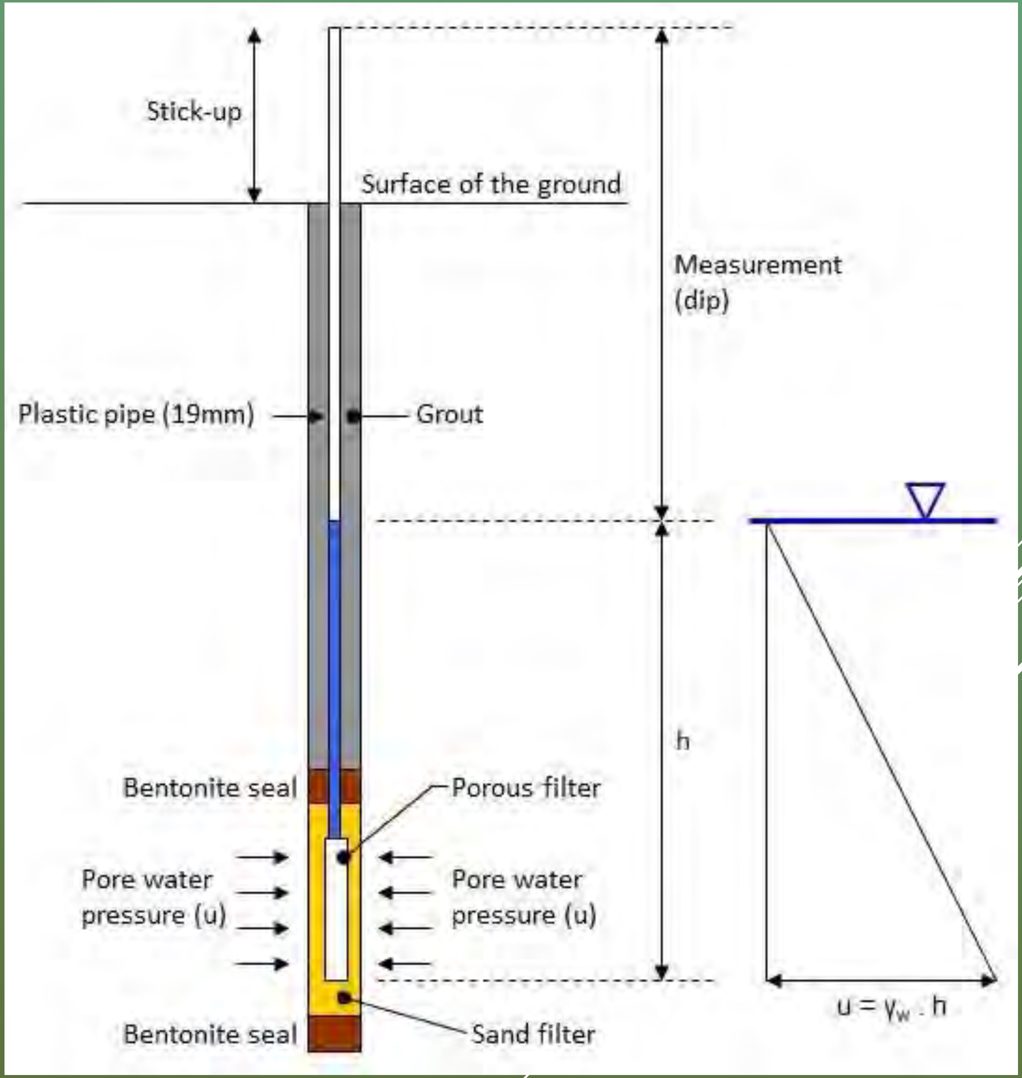
Fundão Tailings Dam Review Panel Report, 2016.



1931 1938 1940 1955 1959 1965 1967 1971 1974 1975 1978 1987 1990 1992 1996 2008 2010 2011 2016

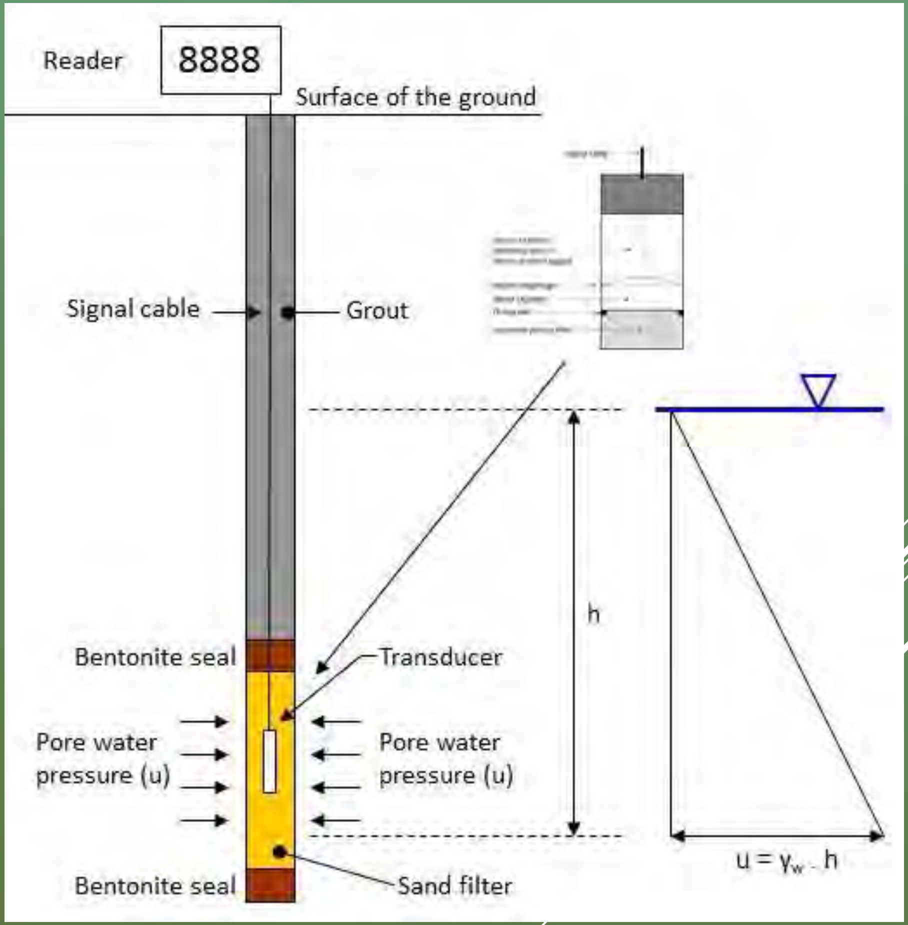
PIEZOMETER- OPEN TYPES

- Water in direct contact with atmosphere
- Plastic pipe provides access to water level
- Measuring instrument/device
  - Water level meter
  - (Pressure transducer in pipe.

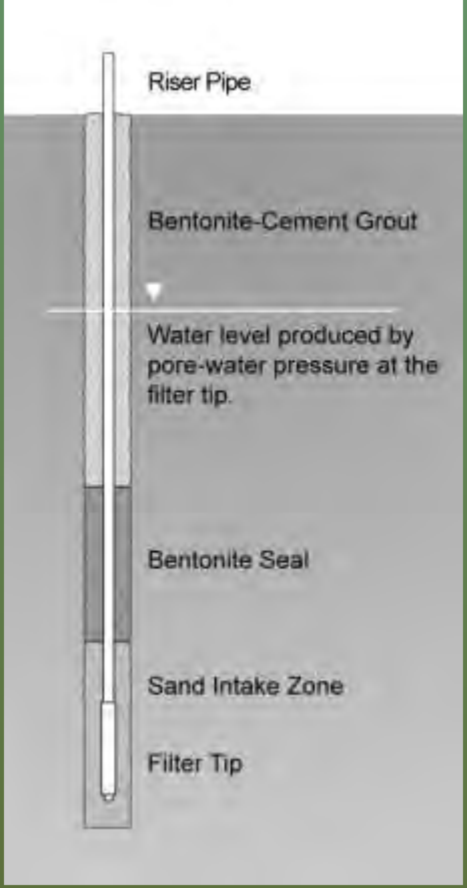


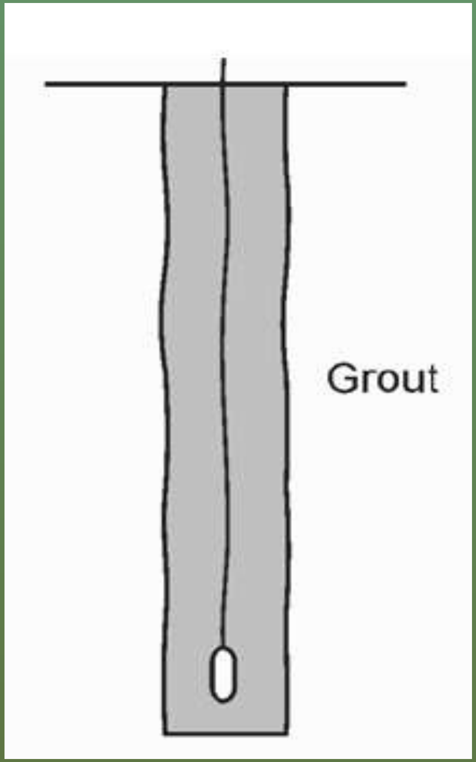
PIEZOMETER – CLOSED TYPES

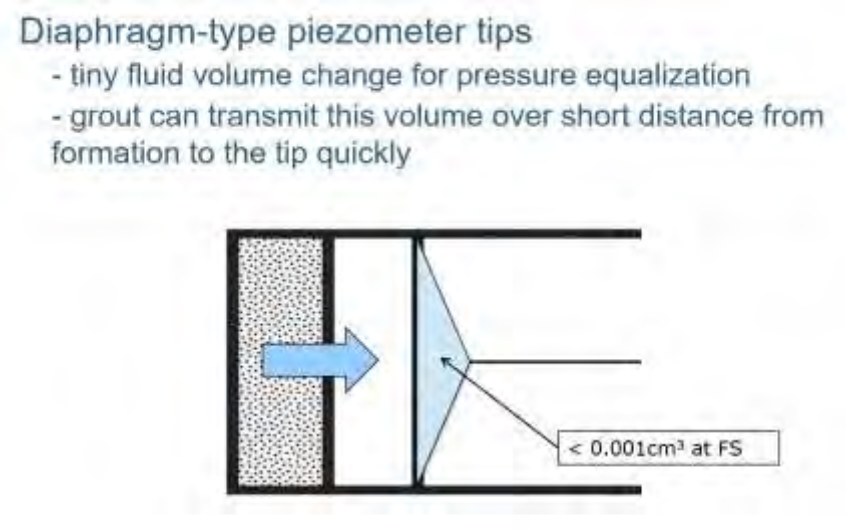
- Water not in direct contact with atmosphere
- Measuring device typically a pressure transducer buried in the soil
- The deflection of the pressure transducer diaphragm proportional to pore pressure
- Deflection measured by means of electric, pneumatic, fiber optic or hydraulic piezometer



INSTALLATION | BOREHOLE | FULLY GROUTED



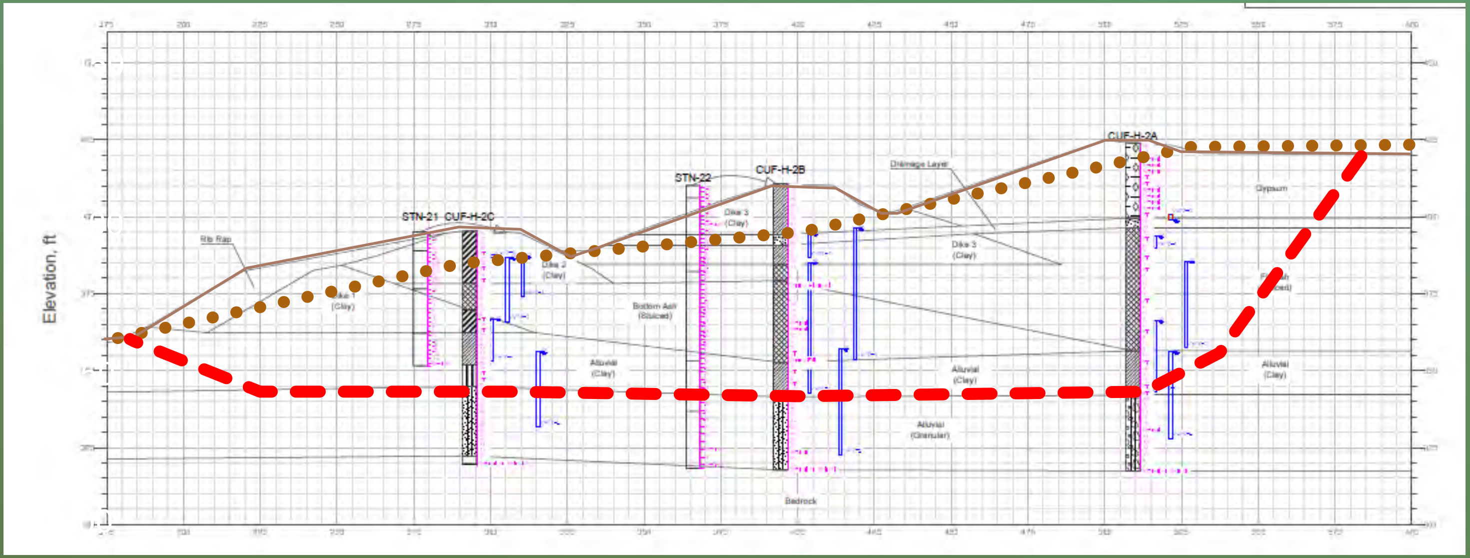




Diaphragm-type piezometer tips

- tiny fluid volume change for pressure equalization
- grout can transmit this volume over short distance from formation to the tip quickly

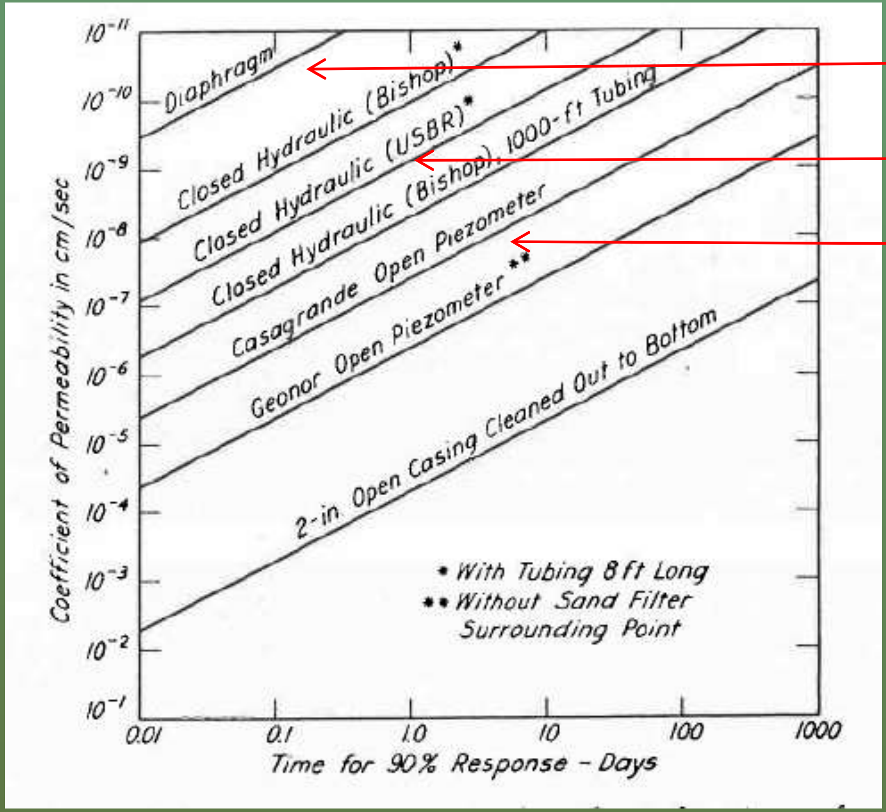
GROUTED IN-PLACE PIEZOMETERS MEASURE PORE PRESSURES AT SEVERAL DEPTHS



Pore pressures are almost never hydrostatic!

Using I-M-R to reduce uncertainty and unnecessary conservatism.

APPROX. RESPONSE TIMES (AFTER TERZAGHI & PECK, 1967)



Electrical, Pneumatic, Fibre Optic | Closed Type

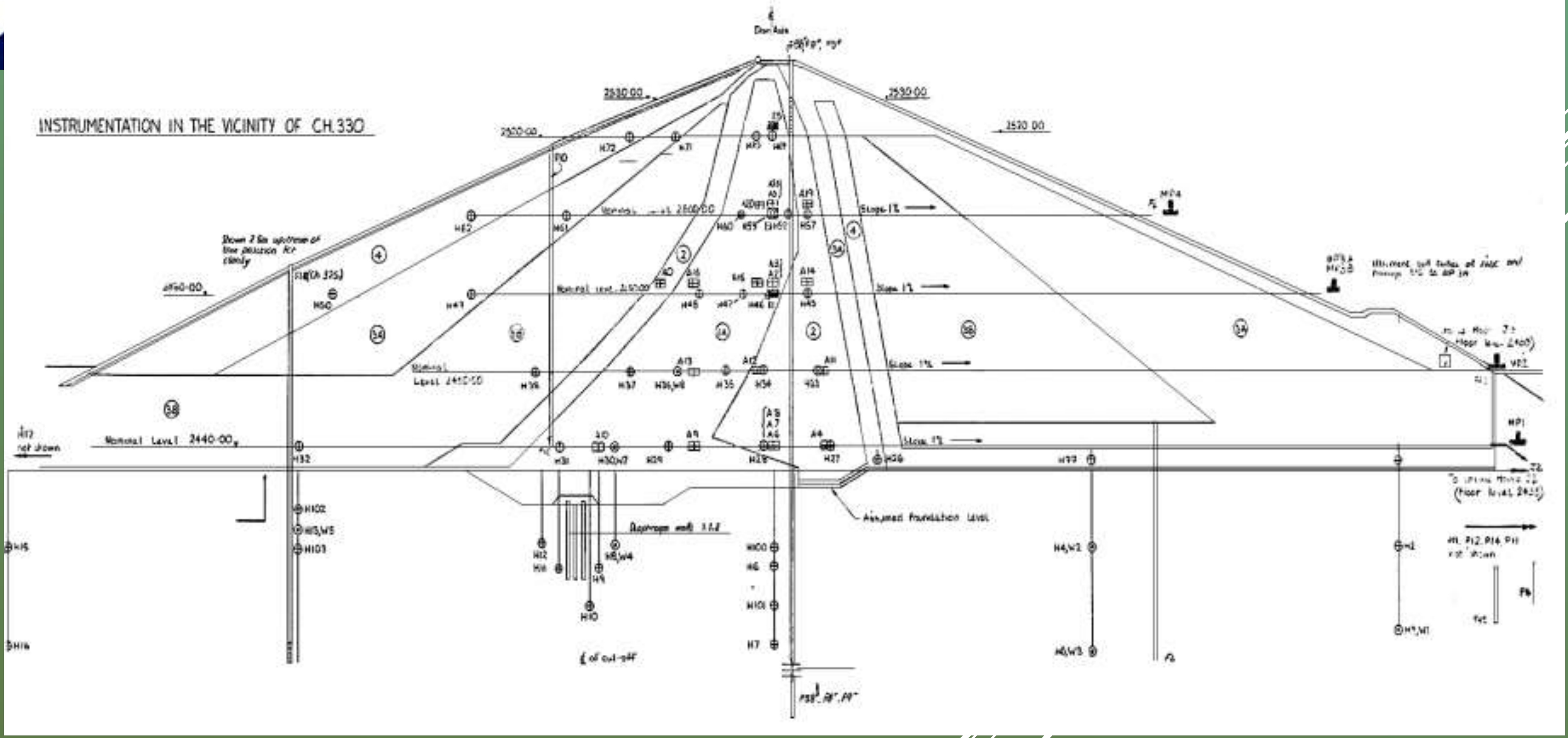
Hydraulic | Closed Type

Casagrande | Open Type

- Flow of water from soil into piezometer required for piezometer to record pressure changes
- Soil surrounding piezometer presents resistance to flow
- Time lag must exist between the groundwater pressure changes and the piezometer
- Time lag proportional to volume of water that must flow into the piezometer for given pressure change
- Is inversely proportional to the permeability of the soil surrounding the piezometer tip

MULTIPURPOSE LAR DAM - IRÃ

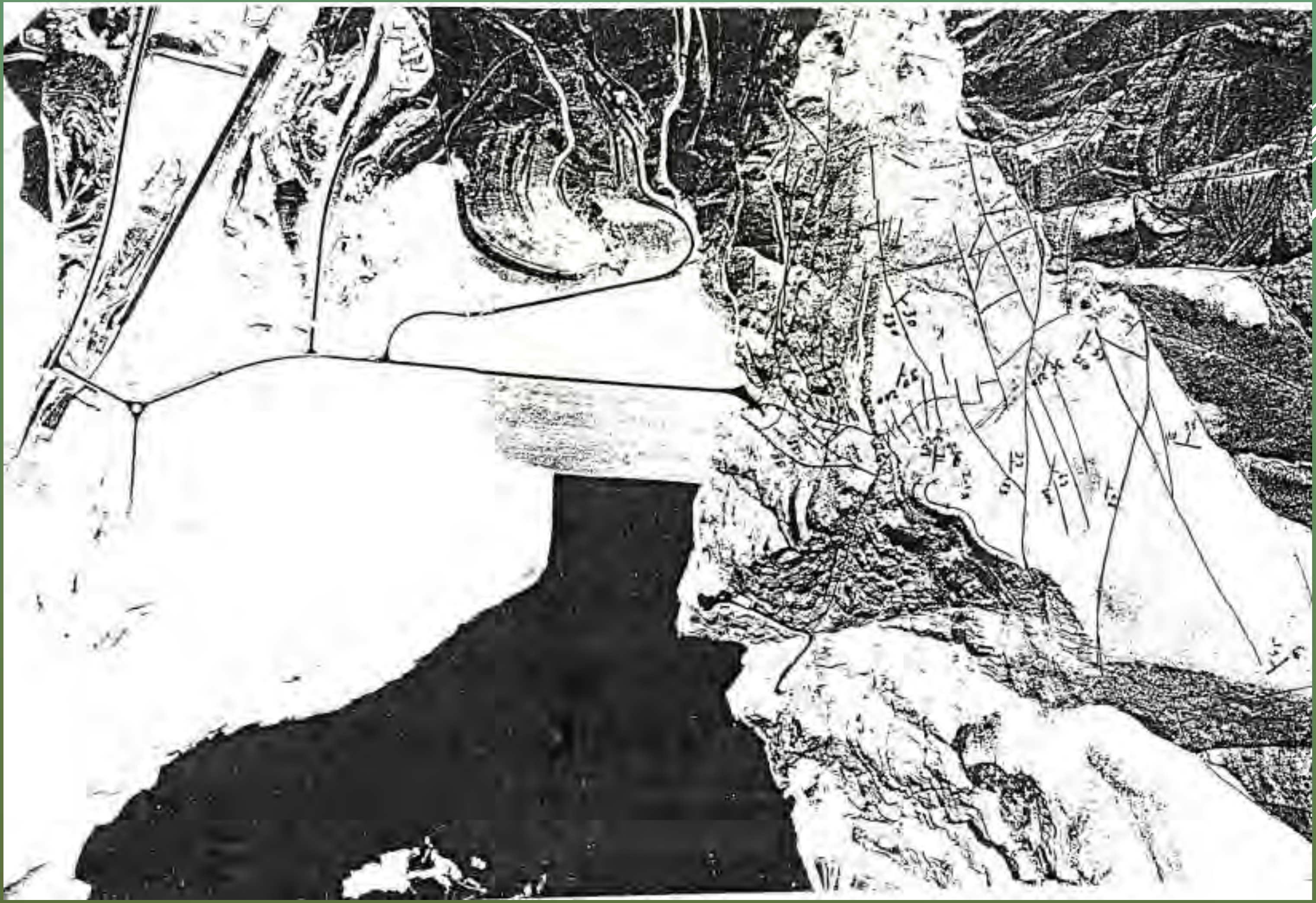
- BARRAGEM ZONADA C/ NUCLEO ARGILOSO.
- ALTURA MAXIMA 105m.
- COMPRIMENTO DA CRISTA 1170m.
- NIVEL DA CRISTA 2538m.
- NIVEL MAXIMO DO RESERVATORIO 2533m.
- OMBREIRA DIREITA: Lar limestone formation with significant tectonic activities. (Jurassic)
- OMBREIRA ESQUERDA: Damavand lavas from volcanic activities (quarternaly). The lava is underlain by old lake deposits.



LEGEND

⊕H	Hydraulic Piezometer	F	Deformation tube, tube length 2 to 3m.	HW	Hidraulic and Pneumatic Piezometer (Seperate boreholes)
	Standpipe Piezometer (P)		Deformation tube, tube length 1.5m.		Manometer Pillar (MP) (See notes 5 and 6)
A	Hydraulic Settlement cell (see notes)	E	Earth pressure cell	G	Gauge House

Tehran Water Board. Lar Dam Water Tightening- Consulting report. P Rocha Filho



Tehran Regional Water Board Lar Consulting Bureau – Lar Dam Water Tightening

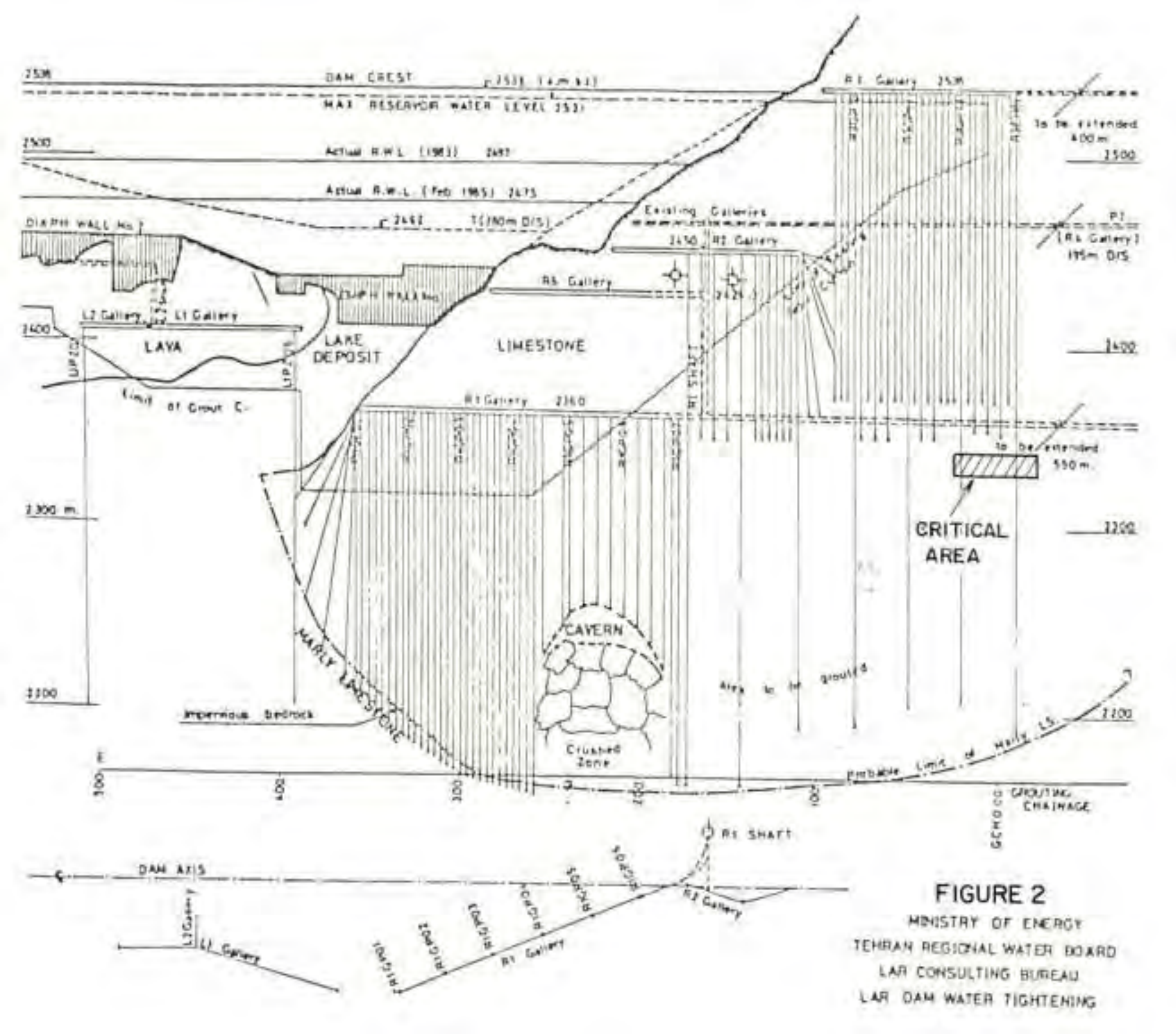


FIGURE 2

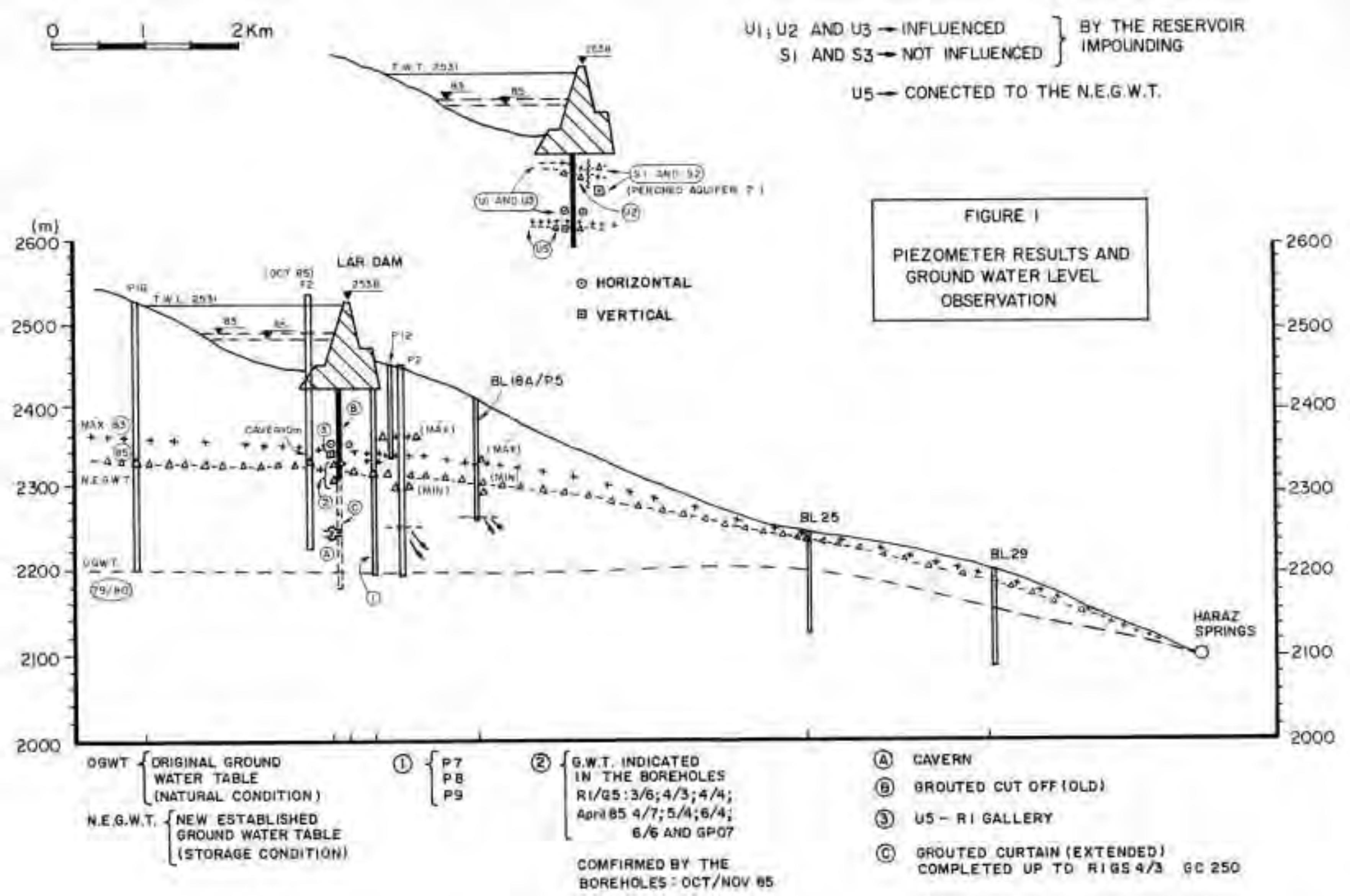
MINISTRY OF ENERGY

TEHRAN REGIONAL WATER BOARD

LAR CONSULTING BUREAU

LAR DAM WATER TIGHTENING

Piezometer results and Ground Water Level Observation



Tehran Regional Water Board Lar Consulting Bureau – Lar Dam Water Tightening

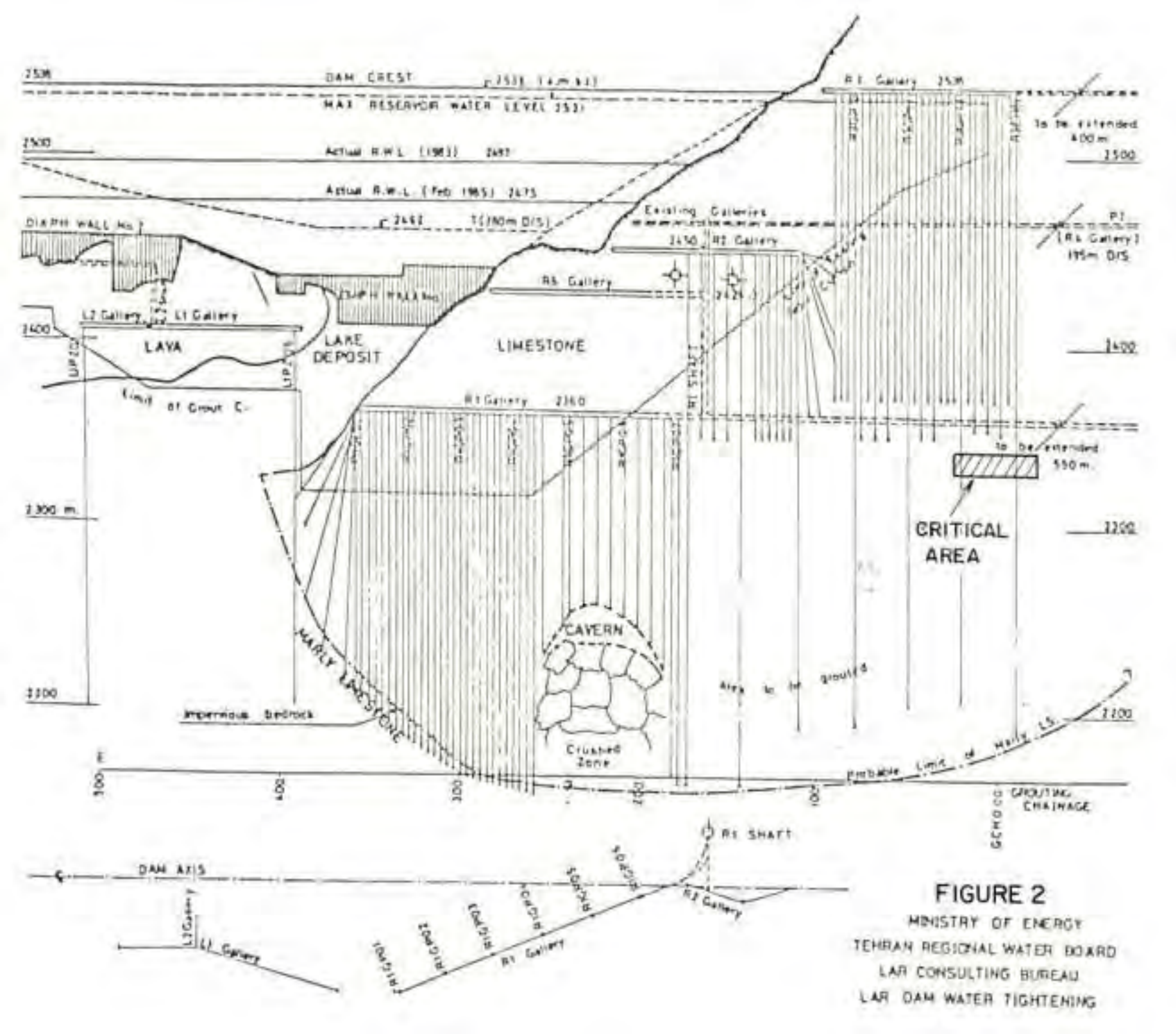


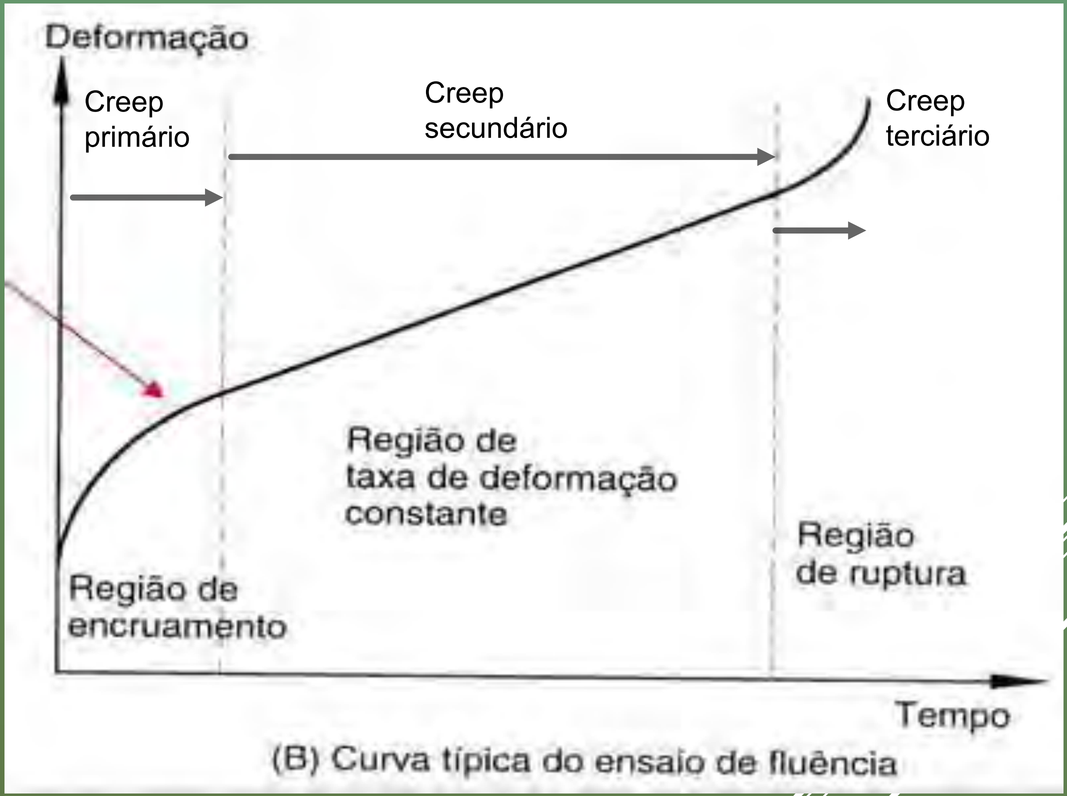
FIGURE 2
MINISTRY OF ENERGY
TEHRAN REGIONAL WATER BOARD
LAR CONSULTING BUREAU
LAR DAM WATER TIGHTENING

PREVISÃO DE TEMPO DE OCORRÊNCIA DA ROTURA EM FUNÇÃO DOS DESLOCAMENTOS/DEFORMAÇÕES MEDIDOS

CURVA ε x t

Estágio Primário:

Ocorre um decréscimo contínuo na taxa de fluencia (ε=dε/dt), ou seja, a inclinação da curva diminui com o tempo devido ao aumento da resistência por encruamento.



(B) Curva típica do ensaio de fluência

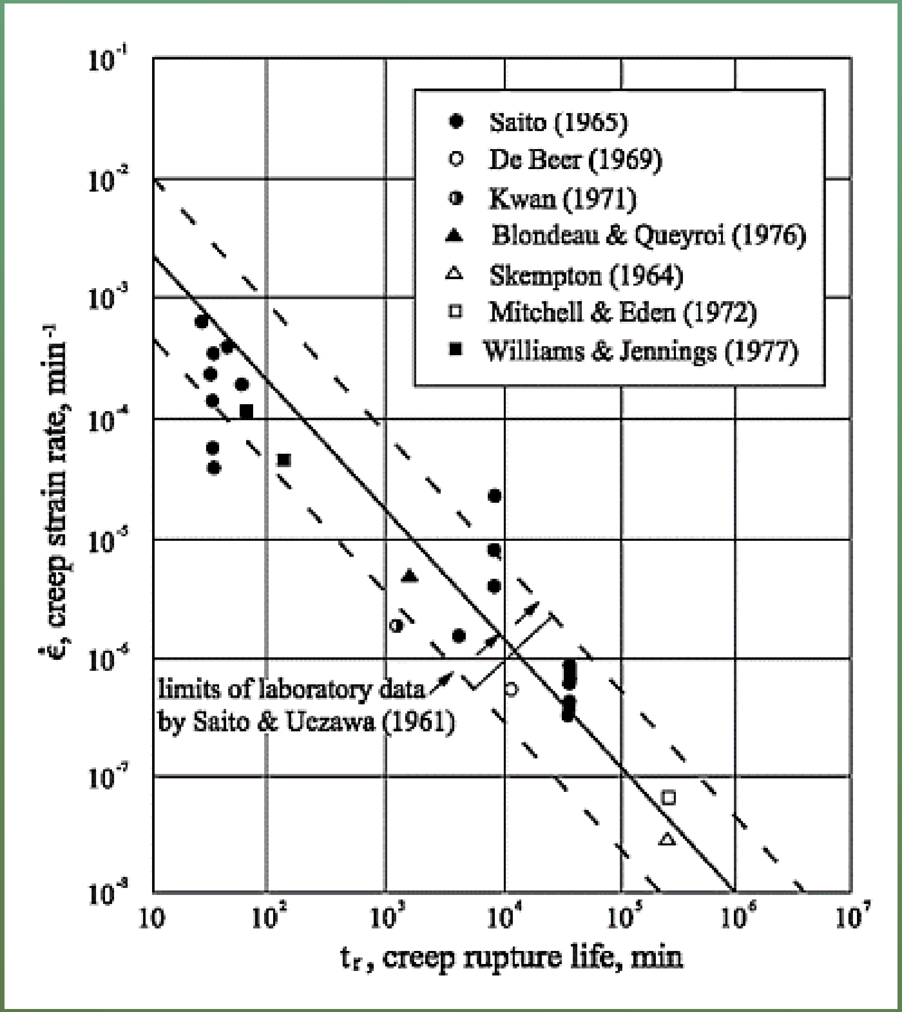


Figura: Relação entre Velocidade de Deformação e Tempo para a rotura em encostas (after Tavernas and Leroueil 1981)

1. **Equação 1**

$$(t_f - t)\,\dot{\epsilon} = a \tag{1.1}$$

$$(t_f - t)\,\frac{d\epsilon}{dt} = a \tag{1.2}$$

$$d\epsilon = a\frac{dt}{t_f - t} \tag{1.3}$$

Considerando $\epsilon_0 = 0$ e $t = t_0$

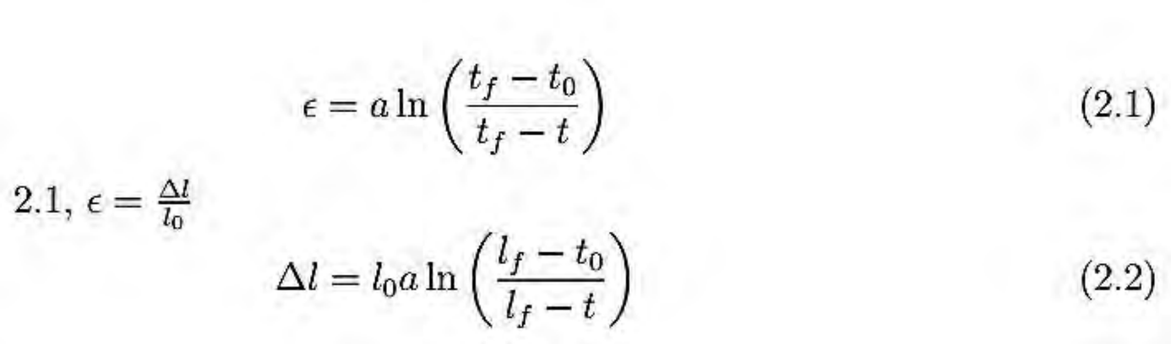
$$d\epsilon = a\frac{dt}{t_f - t} \int_{\epsilon_0}^{\epsilon} d\epsilon = a\int_{t_0}^{t} \frac{dt}{t_f - t} \tag{1.4}$$

$$\epsilon = -a\ln\left(t_f - t\right)\big|_{t_0}^{t} \tag{1.5}$$

$$\epsilon = -a\left[\ln\left(t_f - t\right) - \ln\left(t_f - t_0\right)\right] \tag{1.6}$$

$$\epsilon = a\left[\ln\left(t_f - t_0\right) - \ln\left(t_f - t\right)\right] \tag{1.7}$$

2. Equação 2



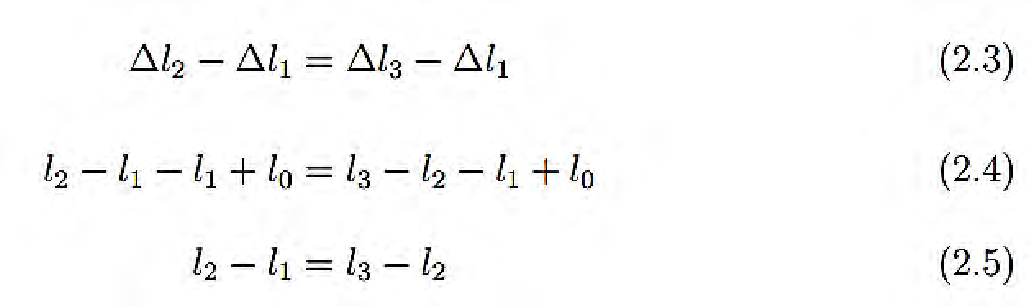
$$\epsilon = a \ln\left(\frac{t_f - t_0}{t_f - t}\right) \quad (2.1)$$

Da equação 2.1, $\epsilon = \frac{\Delta l}{l_0}$

$$\Delta l = l_0 a \ln\left(\frac{l_f - t_0}{l_f - t}\right) \quad (2.2)$$

Na equação 2.2, temos três constantes: $(l_0 a, t_0$ e $t_f)$.

Neste caso, estabelece três pontos sucessivos: $(\Delta l_1, t_1)$, $(\Delta l_2, t_2)$ e $(\Delta l_3, t_3)$ no trecho terciário da curva de crep, de modo a obter iguais diferenças de deslocamento.



$$\Delta l_2 - \Delta l_1 = \Delta l_3 - \Delta l_1 \quad (2.3)$$

$$l_2 - l_1 - l_1 + l_0 = l_3 - l_2 - l_1 + l_0 \quad (2.4)$$

$$l_2 - l_1 = l_3 - l_2 \quad (2.5)$$

Colocando os valores de cada ponto na equação 2.2

para $(\Delta l_1, t_1)$ teremos:

$$\Delta l_1 = l_0 a \ln\left(\frac{l_f - t_0}{l_f - t_1}\right) \tag{2.6}$$

$$\Delta l_2 = l_0 a \ln\left(\frac{t_f - t_0}{l_f - t_2}\right) \tag{2.7}$$

$$\Delta l_3 = l_0 a \ln\left(\frac{t_f - t_0}{l_f - t_3}\right) \tag{2.8}$$

Substituindo 2.6, 2.7 e 2.8 na equação 2.3

$$l_0 a \ln\left(\frac{t_f - t_0}{t_f - t_2}\right) - l_0 a \ln\left(\frac{t_f - t_0}{t_f - t_1}\right) = l_0 a \ln\left(\frac{t_f - t_0}{t_f - t_3}\right) - l_0 a \ln\left(\frac{t_f - t_0}{t_f - t_2}\right) \tag{2.9}$$

Onde $l_0 =$ Constante e a é um parâmetro empírico (Frederico et al., 2012)

$$\ln\left(\frac{t_f - t_o}{t_f - t_2}\right) - \ln\left(\frac{t_f - t_o}{t_f - t_1}\right) = \ln\left(\frac{t_f - t_o}{t_f - t_3}\right) - \ln\left(\frac{t_f - t_o}{t_f - t_2}\right) \qquad (2.10)$$

$$\ln\left(\frac{\frac{t_f - t_0}{t_f - t_2}}{\frac{t_f - t_0}{t_f - t_1}}\right) = \ln\left(\frac{\frac{t_f - t_0}{t_f - t_3}}{\frac{t_f - t_0}{t_f - t_2}}\right) \qquad (2.11)$$

$$\ln\left(\frac{t_f - t_1}{t_f - t_2}\right) = \ln\left(\frac{t_f - t_2}{t_f - t_3}\right) \qquad (2.12)$$

Utilizando $e^{\ln(x)} = x,$ a ultima equação estabelece

$$\frac{t_f - t_1}{t_f - t_2} = \frac{t_f - t_2}{t_f - t_3} \tag{2.13}$$

Reagrupando, temos a seguinte equação:

$$t_f = \frac{t_2^2 - t_1 t_3}{2t_2 - (t_1 + t_3)} \tag{2.14}$$

Subtraindo t_1, em ambos os termos de equação temos:

$$t_f - t_1 = \frac{t_2^2 - t_1 t_3}{2t_2 - (t_1 + t_3)} - t_1 \tag{2.15}$$

$$t_f - t_1 = \frac{t_2^2 - t_1 t_3 - 2t_2 t_1 + (t_1 + t_3)\, t_1}{2t_2 - (t_1 + t_3)} \tag{2.16}$$

$$t_f - t_1 = \frac{(t_2 - t_1)^2}{2t_2 - (t_1 + t_3)} \tag{2.17}$$

Dividindo por 2 no termo direito (numerador e denominador)

$$t_f - t_1 = \frac{\frac{1}{2}\left(t_2 - t_1\right)^2}{t_2 - \frac{(t_1+t_3)}{2}} \tag{2.18}$$

Subtraindo e adicionando t_1 no denominador do lado direito, temos:

$$t_f = \frac{\frac{1}{2}\left(t_2 - t_1\right)^2}{\left(t_2 - t_1\right) - \frac{1}{2}\left(t_3 - t_1\right)} + t_1 \tag{3.1}$$

Referências Federico, A., Popescu, M., Elia, G., Fidelibus, C., Internò, G., and Murianni, A. (2012). Prediction of time to slope failure: a general framework. Environmental

CONCLUSÕES

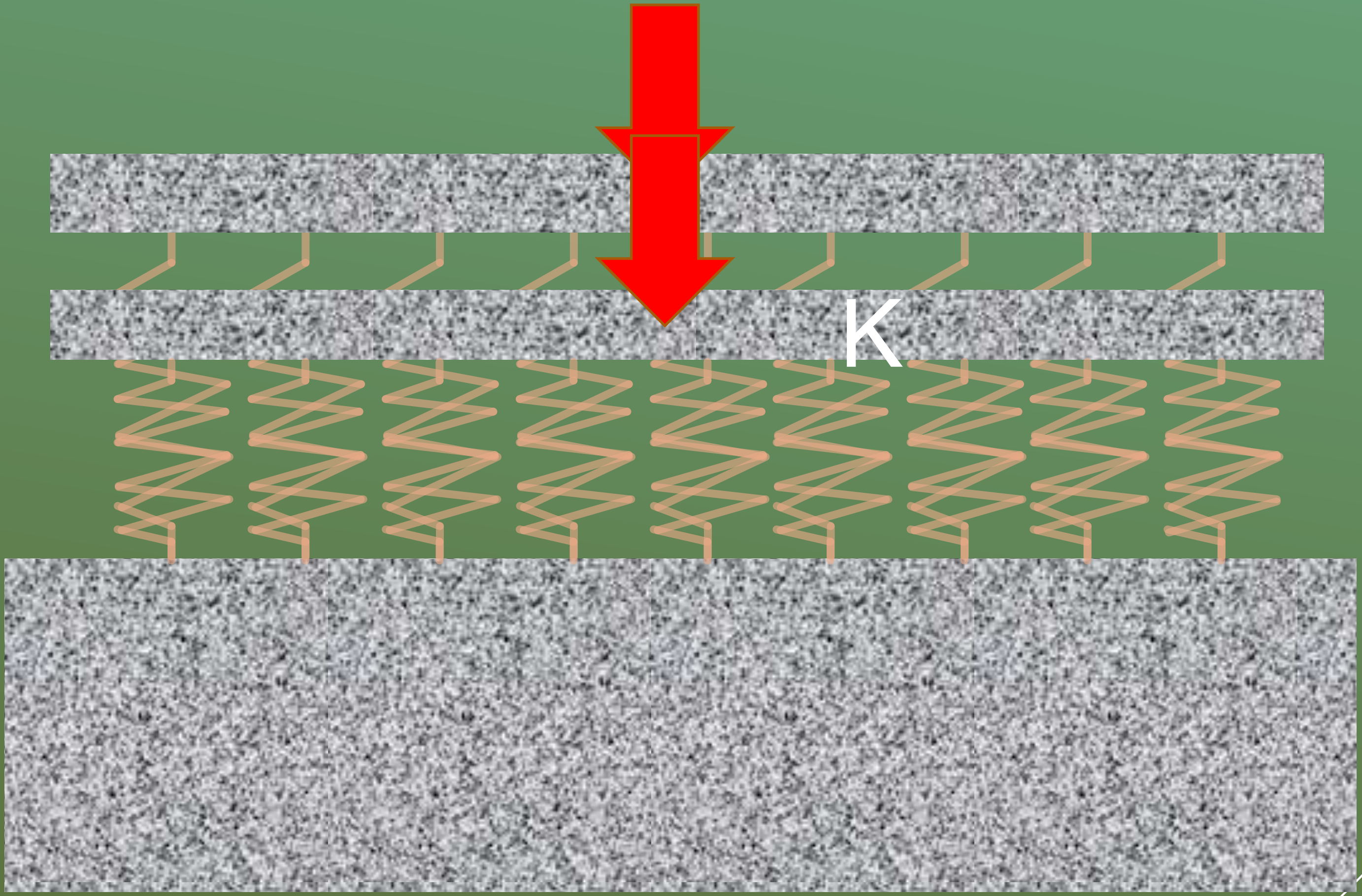
- IMPORTÂNCIA DA APLICAÇÃO DO PRINCIPIO DA TENSÃO EFETIVA NO PLANEJAMENTO E NA INTERPRETAÇAO DE UM PROGRAMA DE INSTRUMENTAÇÃO.
- CONTRIBUIÇÕES RELEVANTES ORIUNDAS DOS MÉTODOS OBSERVACIONAIS EM GEOTECNIA PARA O PROJETO E AVALIAÇÃO DO COMPORTAMENTO DE BARRAGENS DE TERRA E ENROCAMENTO.
- INDICAÇÃO DE ROTURA EMINENTE-AVALIAÇÃO DA ESTABILIDADE.
- IDENTIFICAÇÃO DE PROBLEMAS
- INDICACAÇÃO DE SOLUÇÕES MITIGADORAS PARA UM DETERMINADO PROBLEMA.
- AVANÇO NO ESTADO-DA-PRATICA.

CELULA TENSÃO TOTAL

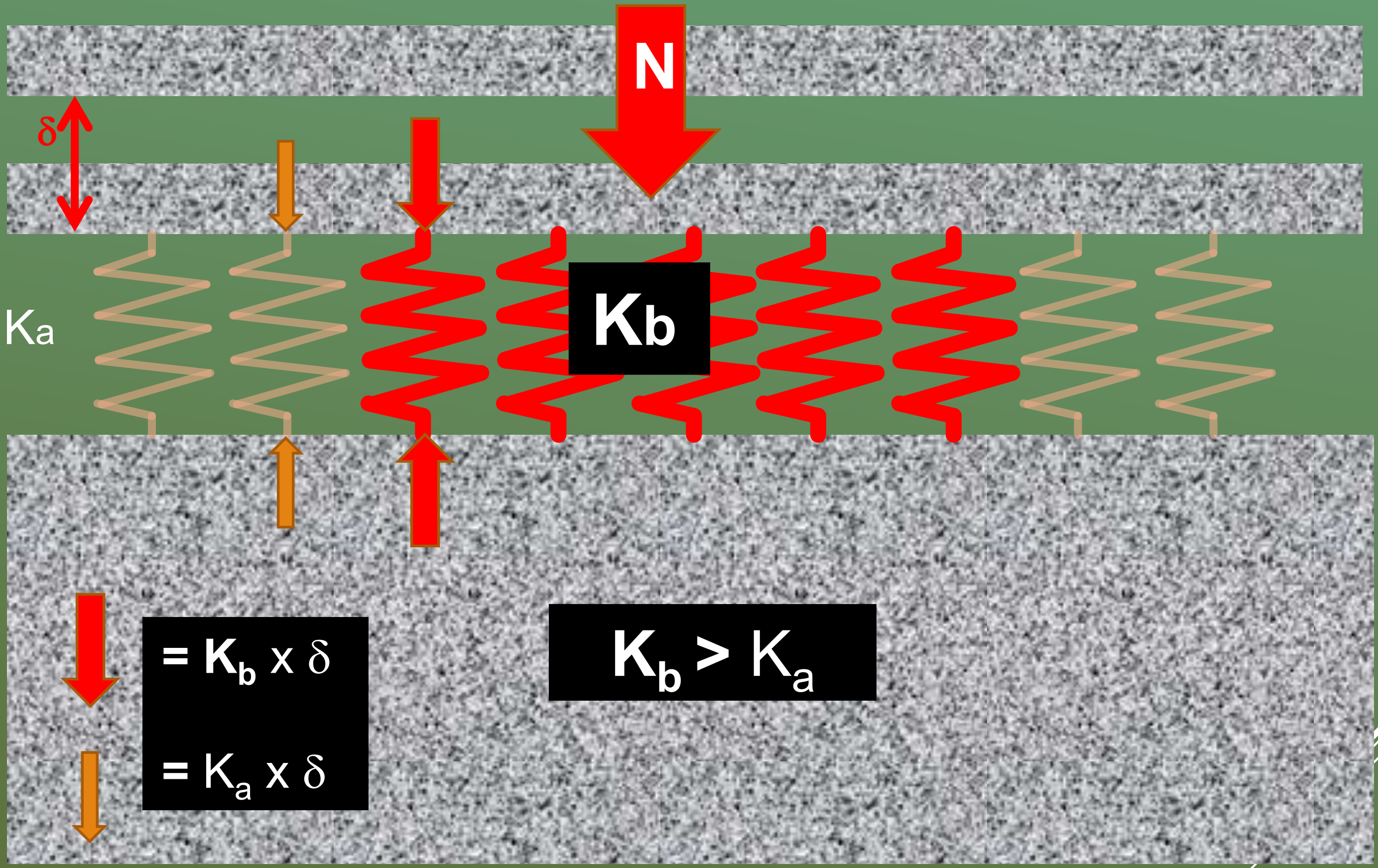
- U.S.Waterways Experimental Station- Soil Pressure Cell Investigation- Tec. Memorandun (1944).
- Hamilton (1960)- Earth Pressure Cells: Design, calibration and performance. Tech Paper NRC, Canada. Building Research, Ottawa.
- Thomas and Ward (1969)- The Design, Construction and Performance of a Vibrating-Wire Pressure Cell. Geotechnique. (Balderhead Dam)

Measurement Problems

- Stiffness



- Stiffness

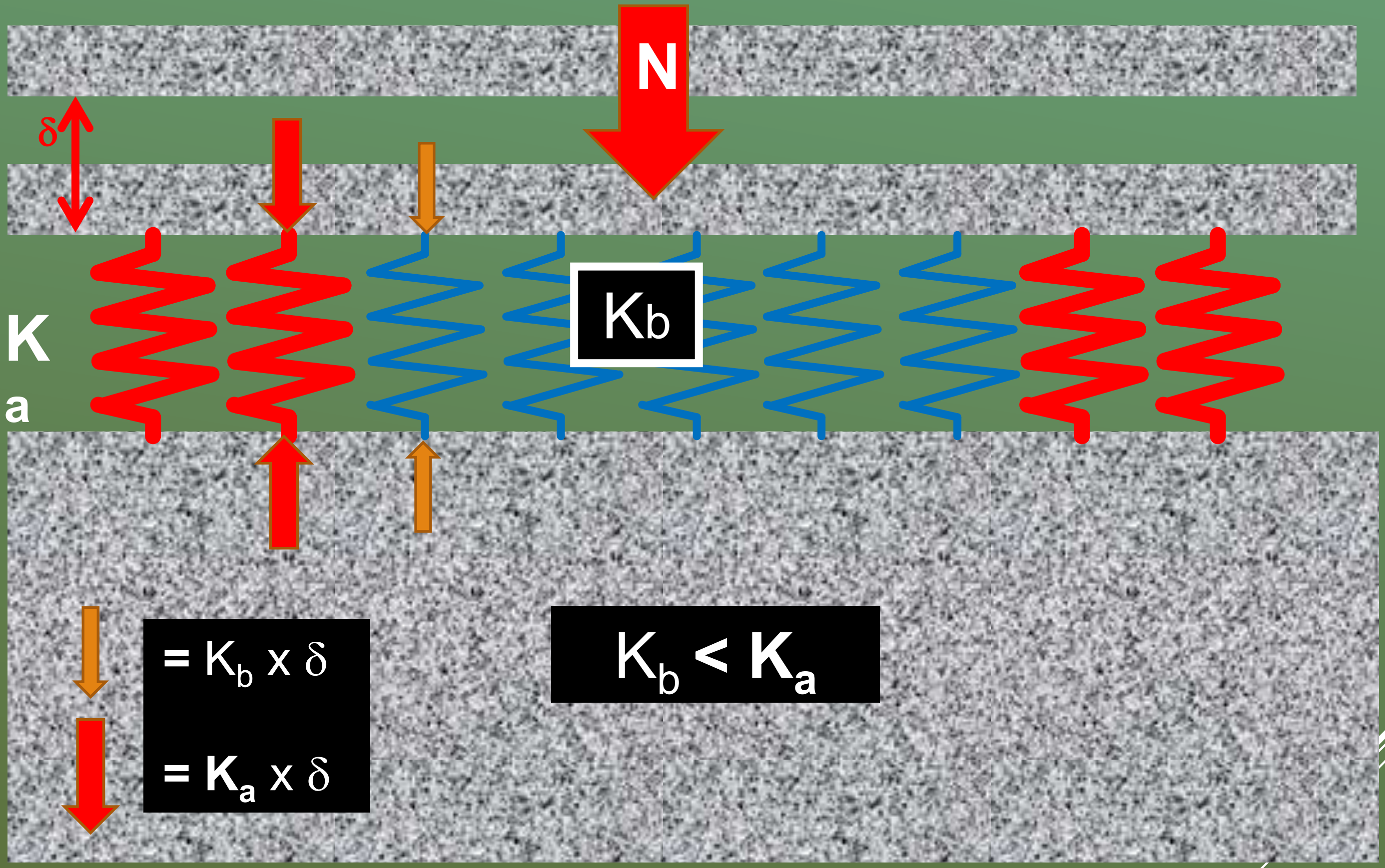


= K_b x δ

= K_a x δ

$K_b > K_a$

- Stiffness

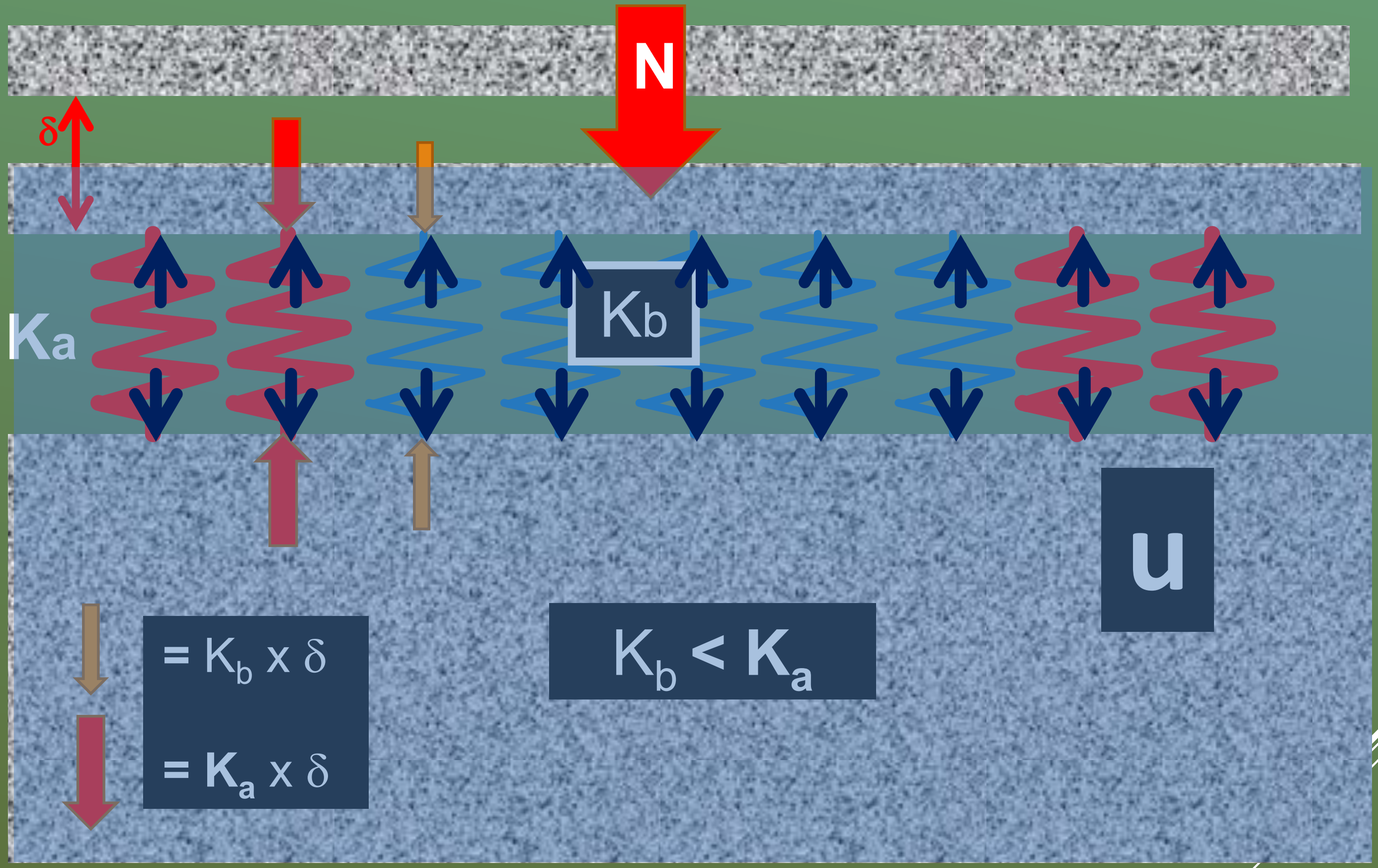


$= K_b \times \delta$

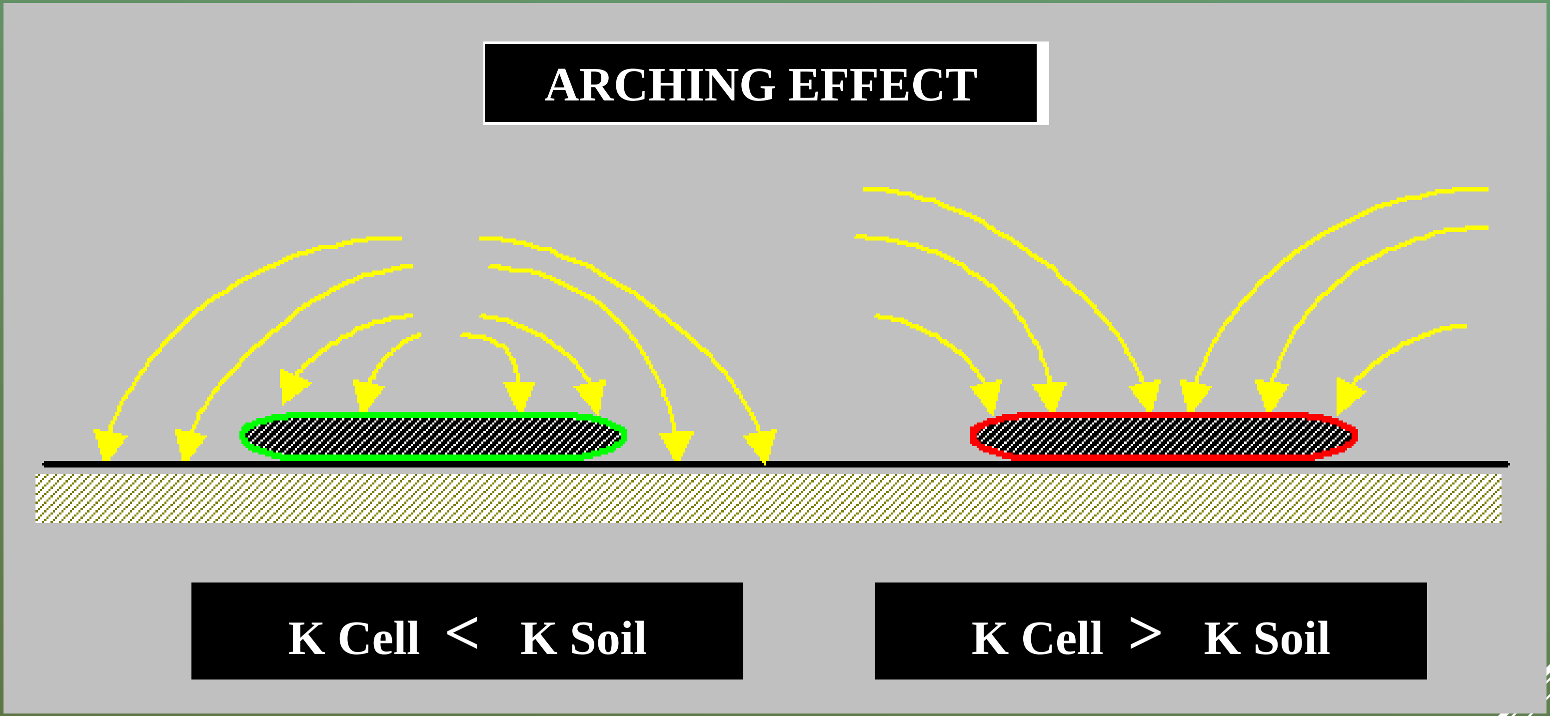
$= K_a \times \delta$

$K_b < K_a$

- Stiffness



- Arching effect

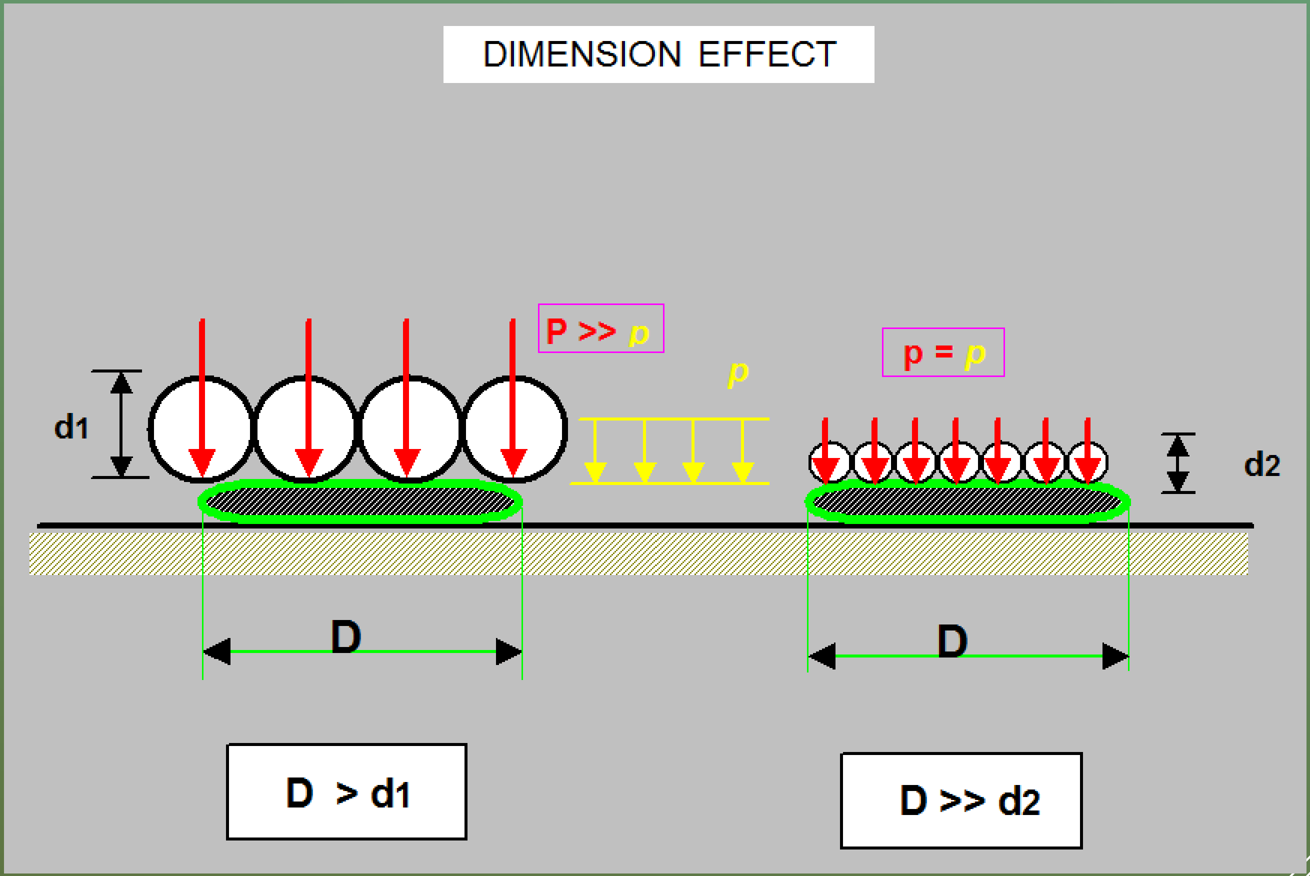


ARCHING EFFECT

K Cell < K Soil

K Cell > K Soil

- Dimensions



- - Soil: Registration Ratio
  (Efficiency Ratio)