INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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SMR.705 - 28

COLLEGE ON SOIL PHYSICS

(6 - 24 September 1993)

"Concepts of Soil Hydrology"

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These are preliminary lecture notes, intended only for distribution to participants.

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CONCEPTS OF SOIL HYDROLOGY

FROM SOIL PORES TO LANDSCAPE SCALE

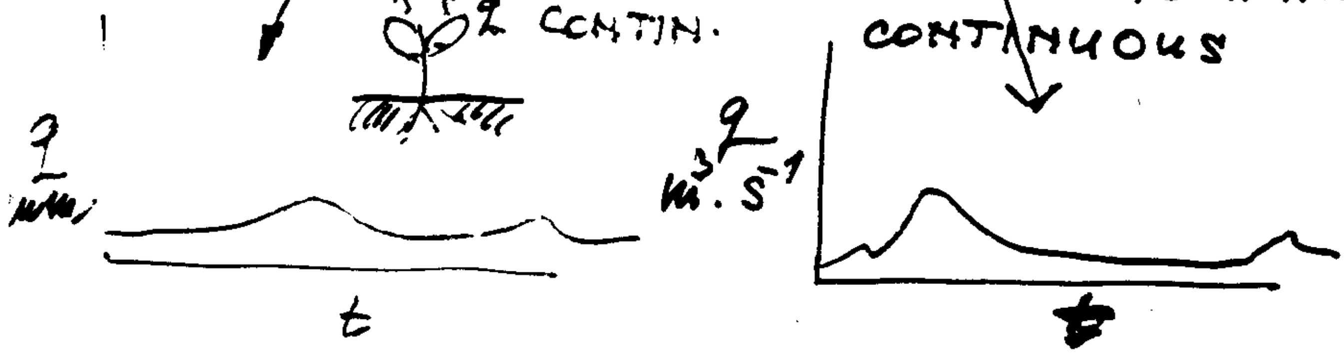
SOILS IN HYDROLOGY – IMPORTANCE – – OR JUST OUR RESEARCH HOBY?

RAIN DISCONTINUITY

SOIL → TRANSFORMATION OF DISCONTINUITY TO CONTINUITY

PLANTS CONSUMPTION — q CONTIN.

RIVERS DISCHARGE CONTINUOUS



WATER IN SOIL = 1/3 WATER IN LAKES

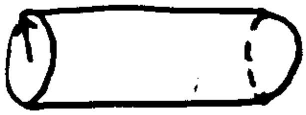
CAPACITY TO RETAIN RAINWATER

SOILS = LAKES

SOIL & GROUNDWATER = $10^2 \times$ SURFACE FRESH WATER

SCALE ① SINGLE PORE SCALE

SINGLE PORE:

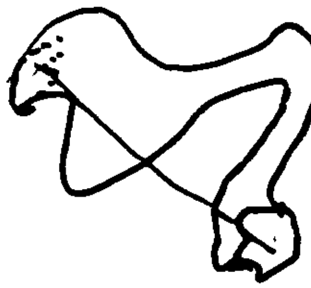
① r_e 

IF r_e IS KNOWN:

NAVIER–STOKES EQ.

FOR LAMINAR FLOW IN THE TUBE HAGEN – POISEUILLE EQ.

SOIL



TORTUOSITY τ

SHAPE CHANGE σ_c

UNKNOWN τ, σ_c, r_e

② n – PORES SCALE

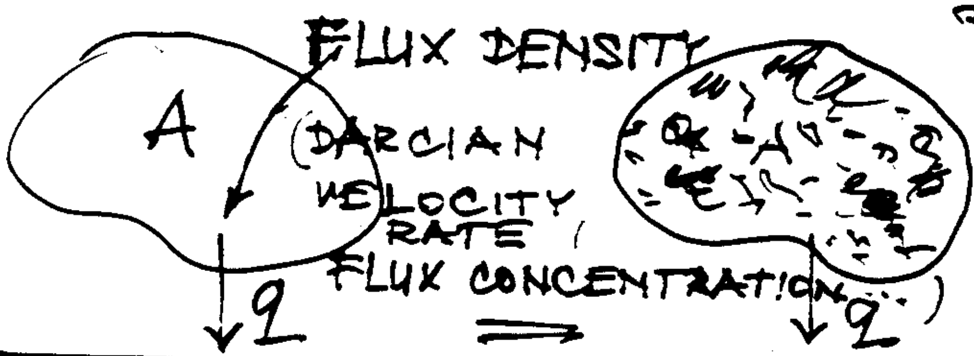
MICROSCALE – n PORES

UNKNOWN $\tau_i, \sigma_{ci}, r_{ei}, n$

WHAT IS Σ ?

~~n – PORES SCALE~~

DARCIAN SCALE



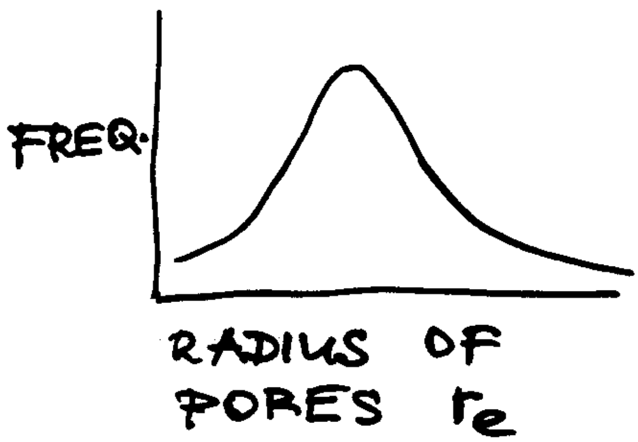
FLUX DENSITY (DARCIAN VELOCITY RATE / FLUX CONCENTRATION ...)

⟹

PORES WHERE THE FLUX IS REALISED

DARCIAN SCALE – IF A ≥ REV

(α) LABORATORY D.S., THEORETICAL STUDIES, LAB. COLUMNS ...
HOMOGENEOUS POROUS SYSTEM

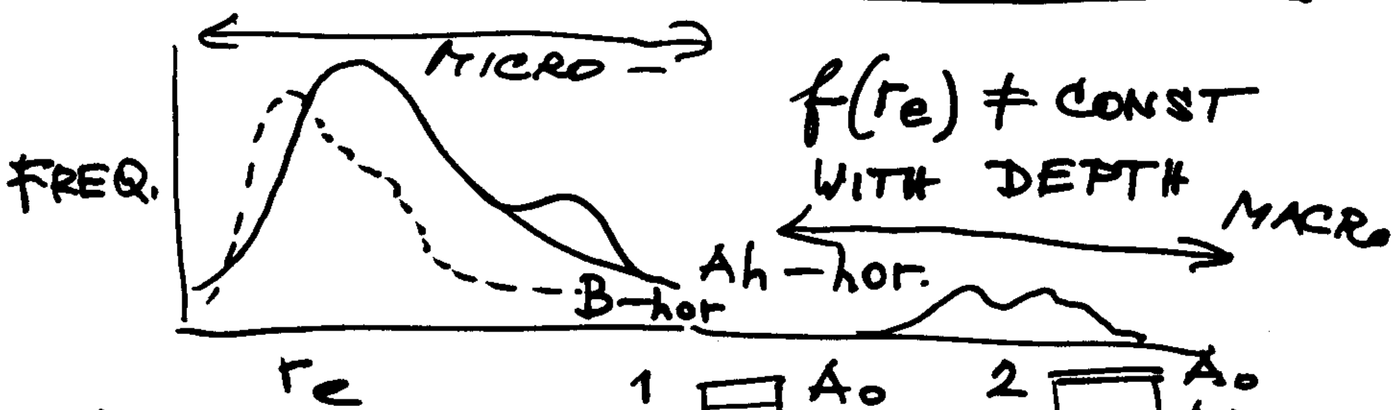


IN ALL SECTIONS,
IN ALL DEPTHS

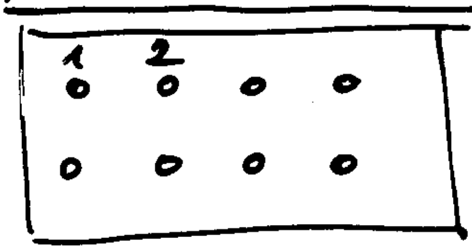
$f(r_e) = \text{CONST}$

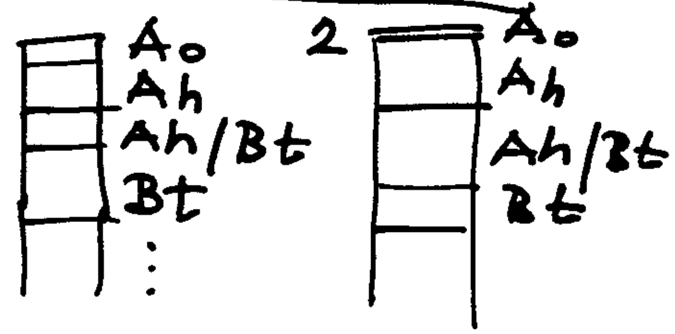
(β) FIELD D.S. = PEDON SCALE

$f(r_e) \neq \text{CONST}$
WITH DEPTH



(γ) PEDOTOP SCALE

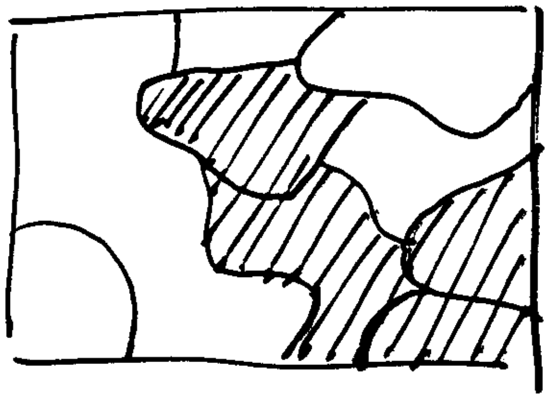




ALL PEDONS – ONE PEDOTOP
BUT: AREAL HETEROGENEITY – STOCHASTIC

PEDOCHOR – PEDOCOMPLEX SCALE (4)
(REGIONAL SCALE) – SMALL CATCHMENT

MOSAIC PEDOTOPS – UNITED INTO HIGHER CLASSIFICATION UNITS



DETERMINISTIC HETEROGENEITY OVER STOCHASTIC HETEROGENEITY

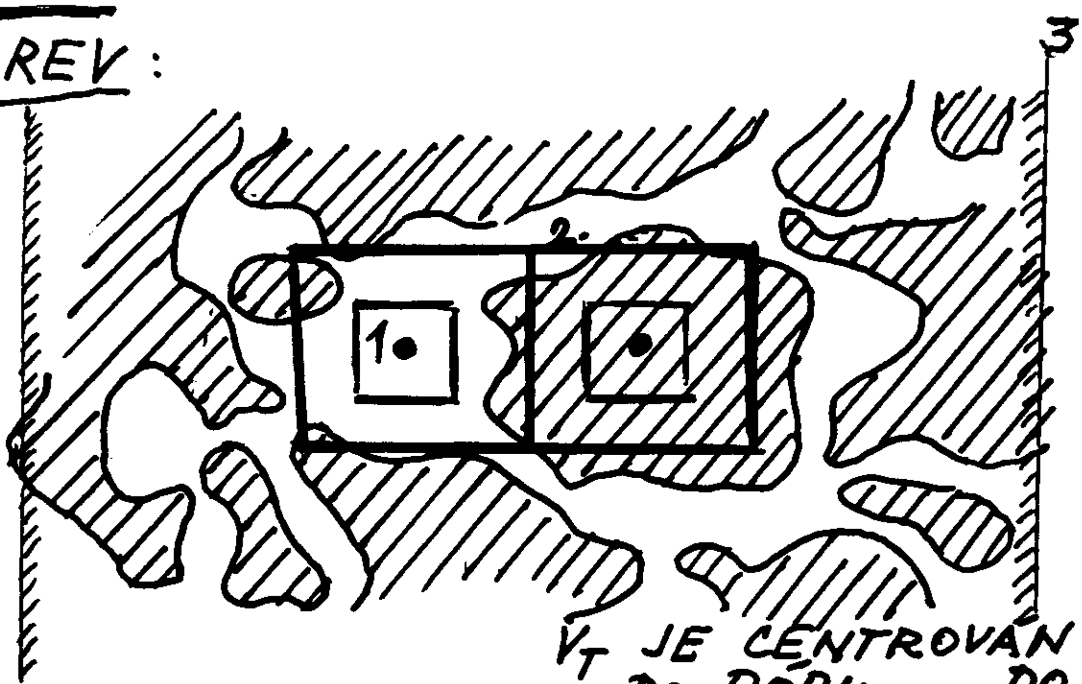
?

OUR DISCUSSIONS

DARCIAN SCALE
(α) LABORATORY D.S.
(β) PEDON D.S.
(γ) PEDOTOP D.S.

REO :

REV :



1. $V_T \leq V_P$

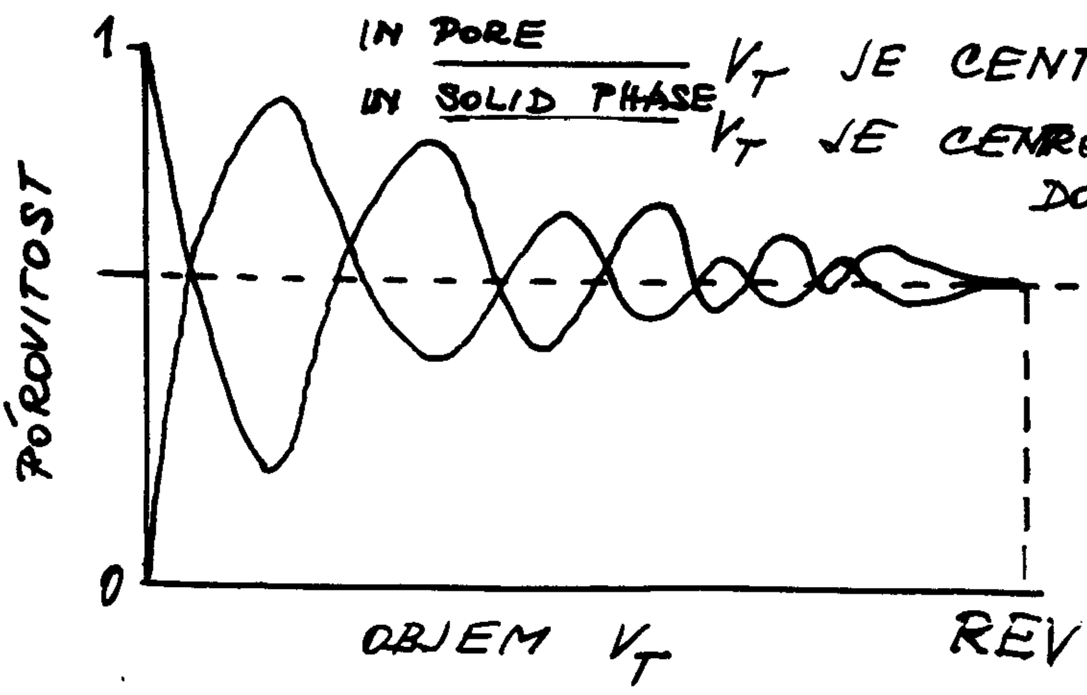
   $V_T \leq V_F$

2. $V_T = V_P + \delta V_F \qquad p = 1 - \dfrac{\delta V_F}{V_T} \qquad p = \dfrac{\delta V_P}{V_T}$

   $V_T = V_F + \delta V_P \qquad p < 1 \qquad p > 0$

3. $V_T = V_P + n\,\delta V_F \qquad p = 1 - n\dfrac{\delta V_F}{V_T} \qquad p = n\dfrac{\delta V_P}{V_T}$

   $V_T = V_F + n\,\delta V_P$



II. 4. PŮDNÍ HYDRODYNAMIKA

HYDRODYNAMICS OF SOIL WATER

4.1. NASYCENÉ PROUDĚNÍ – SATURATED

THEORY – IDEAL MODEL
TEORETICKY : $\theta_S = P$, FIELD V TERÉNU „ $\theta_S^{"} = P - \delta P$

DARCYHO ROVNICE – PLATNOST : 1) REO – REV („DARCYOVSKÉ MĚŘÍTKO) ; 2) LAMINÁRNÍ PROUD.
(DARCYAN SCALE)
(ZANEDBÁNÍ SETRV. SIL)

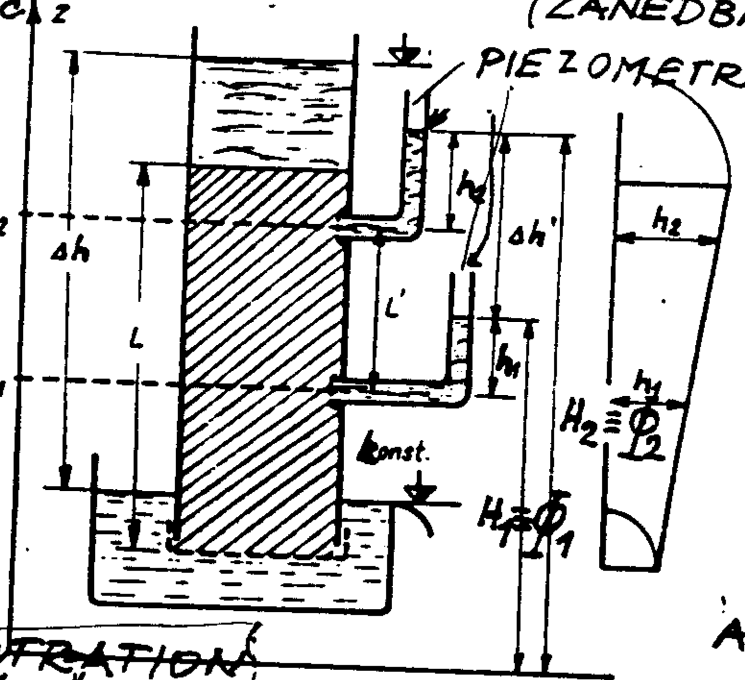
MACROSCOPIC
MAKROSKOPICKÁ (DARCYOVSKÁ v

$$v = \frac{V}{At}$$

$[LT^{-1}]$

$$q = \frac{V}{At}$$

TOK, R. TOK
KONCENTACE TOKU
FLUX CONCENTRATION



DARCY (1856)

$$v = K_S \frac{\Delta h}{L}$$

$$= K_S \frac{\Delta h'}{L'} \text{ (PIEZ)}$$

$$= K_S \frac{\Phi_2 - \Phi_1}{z_2 - z_1}$$

$$= -K_S \operatorname{grad} \Phi$$

ANALOGY:

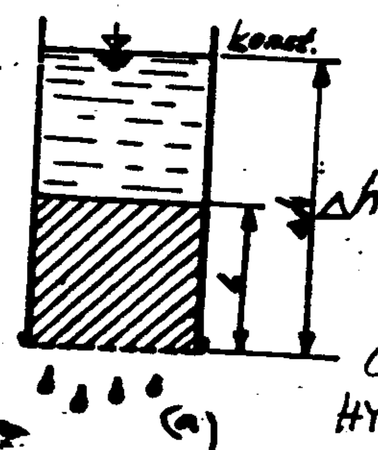
$$q = -D \frac{\partial c}{\partial x}$$

$$q = -\lambda \frac{\partial T}{\partial x}$$

STŘEDNÍ PÓROVÁ RYCHLOST $\boxed{v_p = \frac{v}{P}}$

$P < 1$, $v_p > v$

MEAN PORE VELOCITY

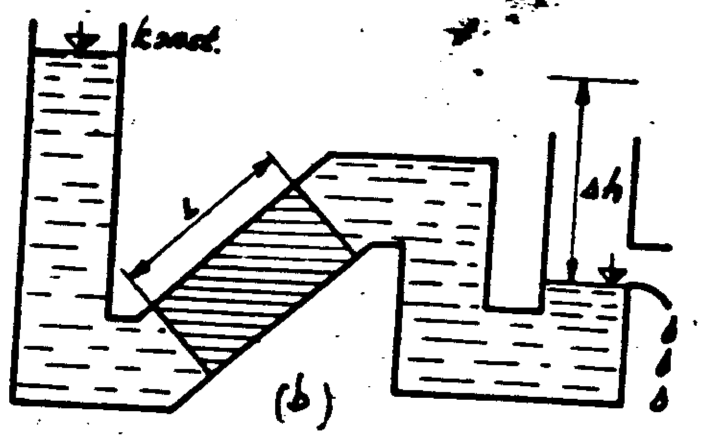


GROUND WATER HYDRAULICS:
V PODZEMNÍ HYDRAULICE

$$\varphi^* = K_S \Phi$$

$$v = -\operatorname{grad} \varphi^*$$

$\varphi^* [L^2 T^{-1}]$



Φ	grad Φ	K_S
$J.kg^{-1}$ $[L^2 T^{-2}]$	$J.kg^{-1}m^{-1}$ $[LT^{-2}]$	$[s]$ $[T]$
Pa $[ML^{-1}T^{-2}]$	$Pa.m^{-1}$ $[ML^{-2}T^{-2}]$	$m.s^{-1}(\rho_w g)^{-1}$
cm $[L]$	BEZDIMENZION.	$cm.s^{-1}$ $[LT^{-1}]$

PROPUSTNOST K_p — VODIVOST (HYDR.), NASYCENÁ K_S

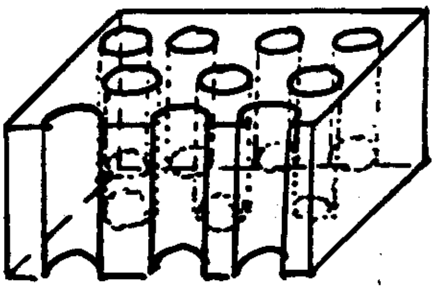
K_S SATURATED HYDRAULIC CONDUCTIVITY

K_p PERMEABILITY

$$K_p = K_S\,\nu \qquad [T.L^2T^{-1}] = [L^2]$$

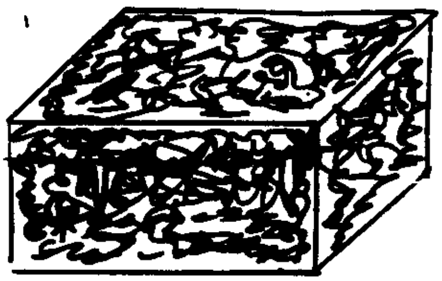
1 DARCY = 1 μm^2

MODEL



VÝŠKA = 1
HEIGHT

PŮDA SOIL



$n\pi r^2$	PÓROVITOST / POROSITY	P
$2n\pi r$	VNITŘNÍ PLOCHA PÓRŮ / SURFACE AREA OF PORES	A_m (MĚRNÁ)

$$r = \frac{2P}{A_m}$$

HAGEN-POISSEUILLE — LAMINÁR. PROUDĚNÍ — LAMINARY FLOW

$$q \equiv v = P.\,v_p = P\,\frac{r^2}{8\nu}\,I_h = \frac{P^3}{2\nu A_m^2}\cdot I_h \approx$$

$$\approx \frac{cP^3}{\tau A_m^2}\,\frac{1}{\nu}\cdot I_h$$

$\frac{cP^3}{\tau A_m^2}$: PERMEAB. PROPUSTNOST

$\frac{cP^3}{\tau A_m^2}\frac{1}{\nu}$: HYDRAULICKÁ VODIVOST / HYDR. CONDUCTIVITY

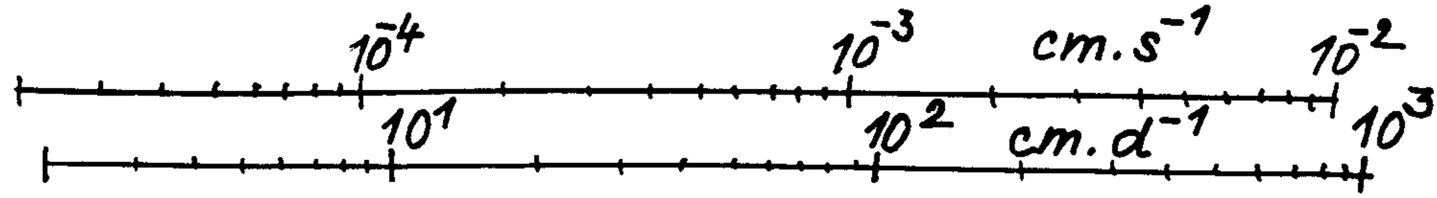
KOZENY

⋮

KOZENY-CARMAN

$$K_p = \frac{P^3}{\tau A_m^2 (1-P)^2}$$

HYDRAULICKÁ VODIVOST – HYDR. CONDUCTIVITY



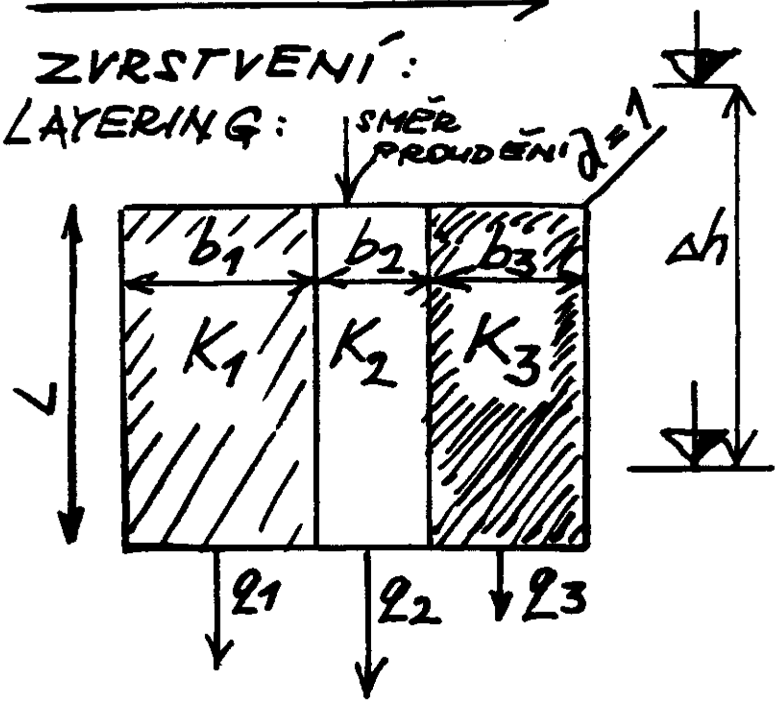
PROPUSTNOST – PERMEABILITY μm^2

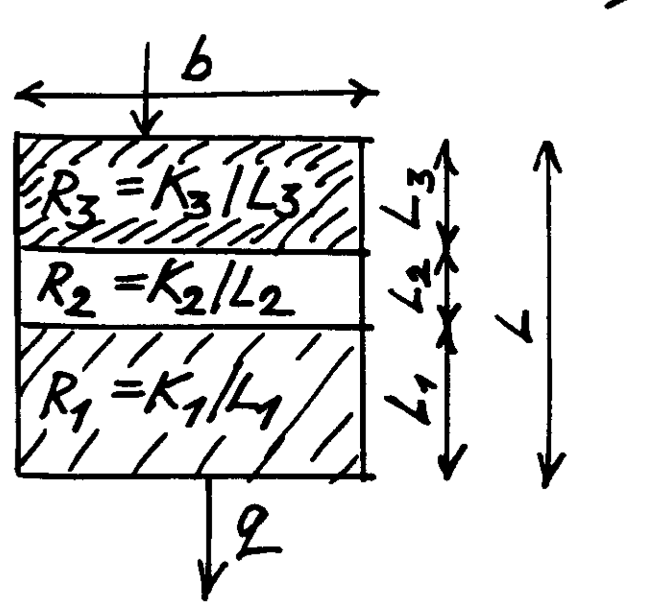
HLINITÉ P. LOAMY S.

JÍLOVITÉ P.–CLAYS

PÍSČITÉ SANDS

ZVRSTVENÍ: LAYERING:

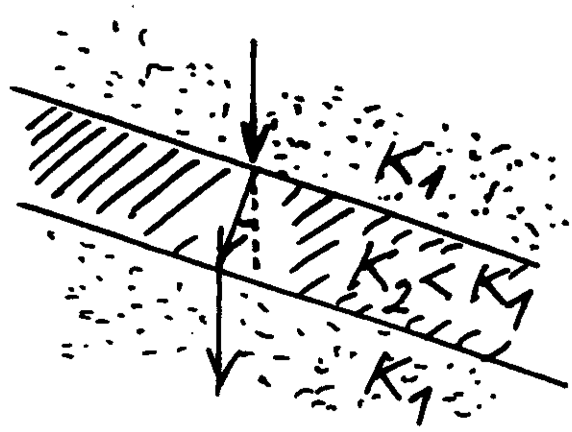




$$q = q_1 + q_2 + q_3 = \frac{\Delta h}{L}\left(K_1 b_1 + K_2 b_2 + K_3 b_3\right)$$

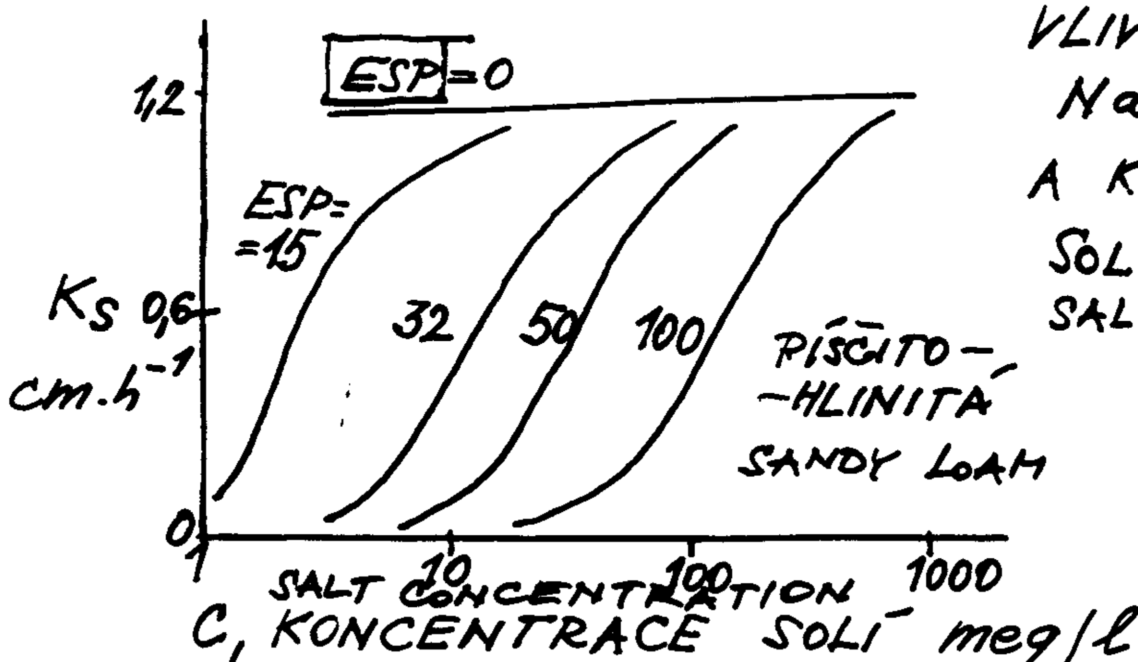
$$q = \frac{\Delta h}{R_1 + R_2 + R_3} \cdot b$$

! $R\,[T]$!



VLIV VÝMĚNNÉHO Na (ESP) A KONCENTRACE SOLÍ

SALT CONCENTR.



IF ESP IS HIGH

VYSOKÉ ESP

- NÍZKÉ C ⟶ PEPTIZACE
- LOW C ⟶ PEPTIZATION
- VYSOKÉ C ⟶ (KOAGULACE)
- HIGH C ⟶ COAGULATION

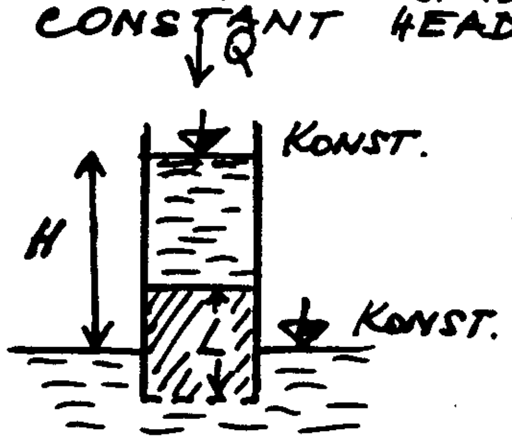
STANOVENÍ K_S — MEASURING K_S

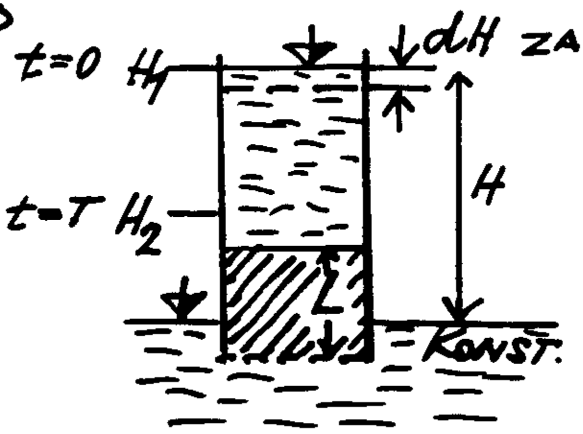
a) V LABORATOŘI — NEPORUŠENÉ VZORKY

LABORATORY

KONSTANTNÍ SPÁD / CONSTANT HEAD

FALLING HEAD / PROMĚNNÝ SPÁD





H = KONST.

$$v = \frac{Q}{A} = K_S \frac{H}{L}$$

$$v = -\frac{dH}{dt} \qquad v = K_S \frac{H}{L}$$

$$-\frac{dH}{dt} = K_S \frac{H}{L}$$

$$K_S = \frac{L}{T} \ln \frac{H_1}{H_2} \quad \Longleftarrow \quad \int^{H_1} \frac{dH}{H} = \frac{K_S}{L} \int^{T} dt$$

4.2. NENASYCENÉ PROUDĚNÍ $\vartheta < \vartheta_S$

UNSATURATED FLOW

$h < h_V < 0$

PŘI DOSAŽENÍ STACIONARITY:

$$v = K \frac{\Delta h}{L}$$

$$K(\vartheta) < K_S$$

KOZENY

$$K_S = \frac{c\, P^3}{\tau A_m^2 \nu}$$

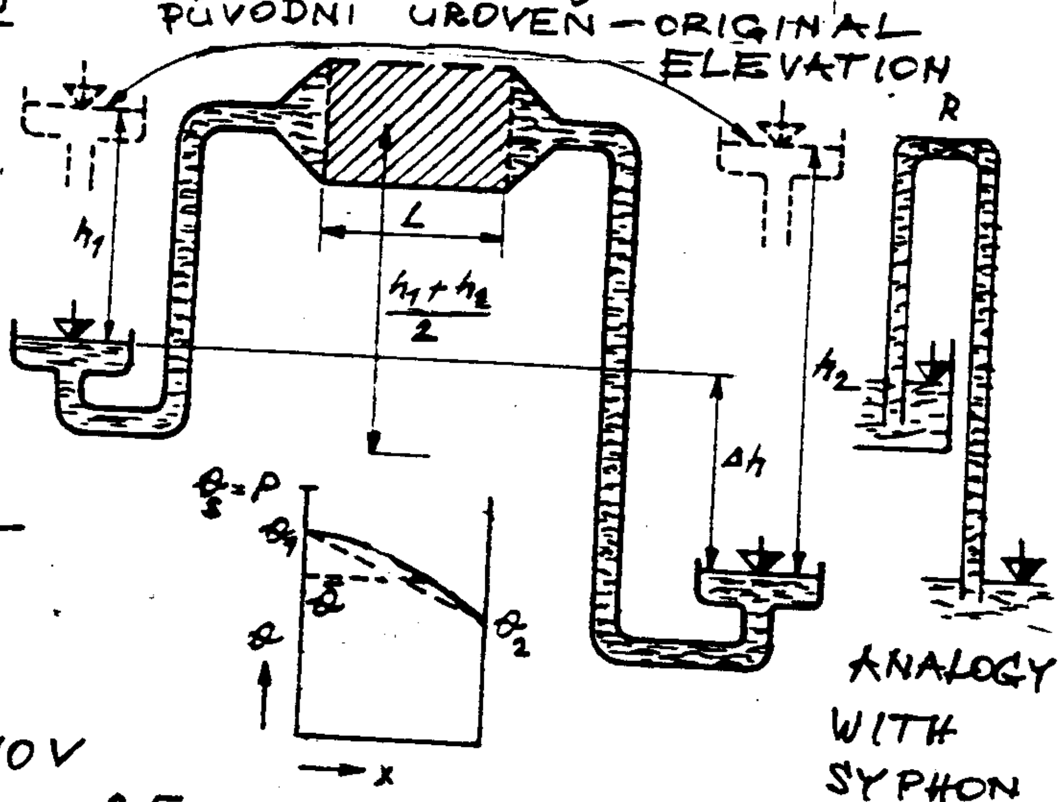
$$\vartheta < P$$

$$K = \frac{c_x\, \vartheta^3}{\tau_x A_m^2 \nu}$$

$$\tau_x > \tau$$

SMĚR PROUDĚNÍ PŘI Δh

DIRECTION OF FLOW

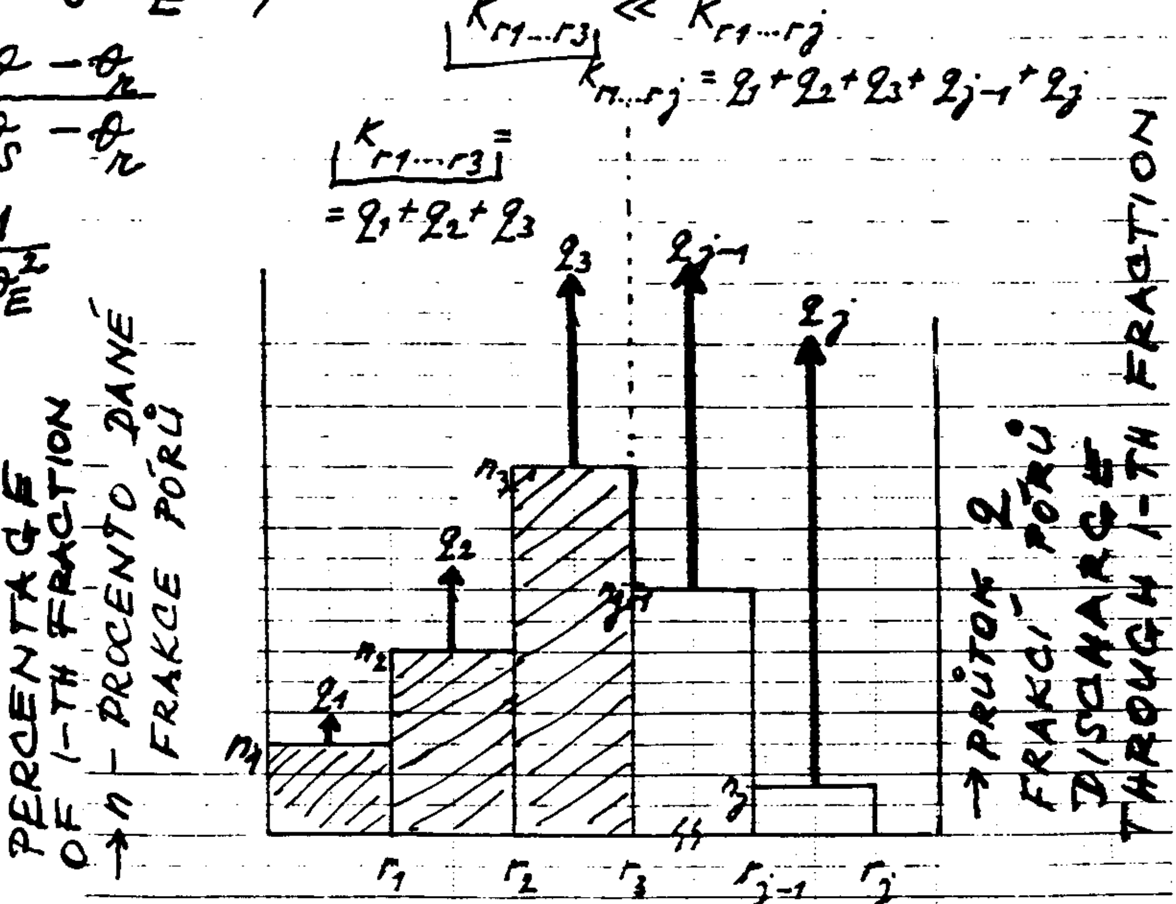


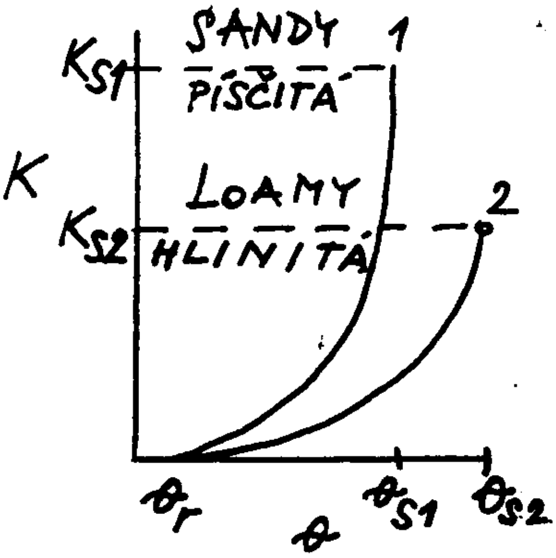
AVERJANOV

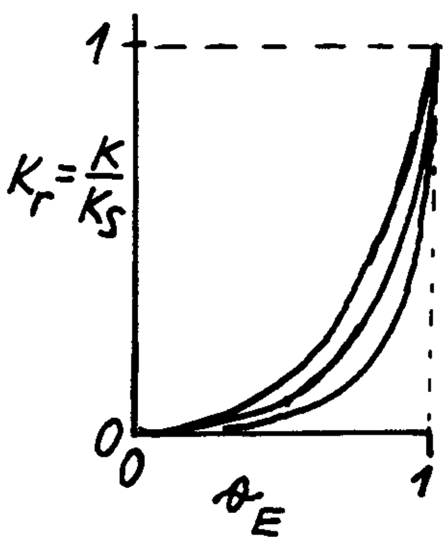
$$K = \alpha K_S \vartheta_E^{3,5}, \quad \alpha \sim 1$$

$$\vartheta_E = \frac{\vartheta - \vartheta_r}{\vartheta_S - \vartheta_r}$$

$$\frac{\tau(\vartheta)}{\tau_S} \approx \frac{1}{\vartheta_E^2}$$





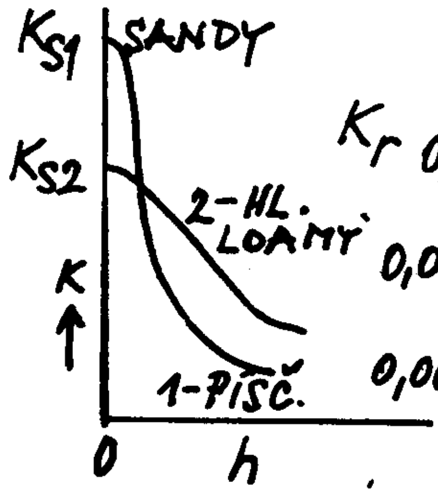


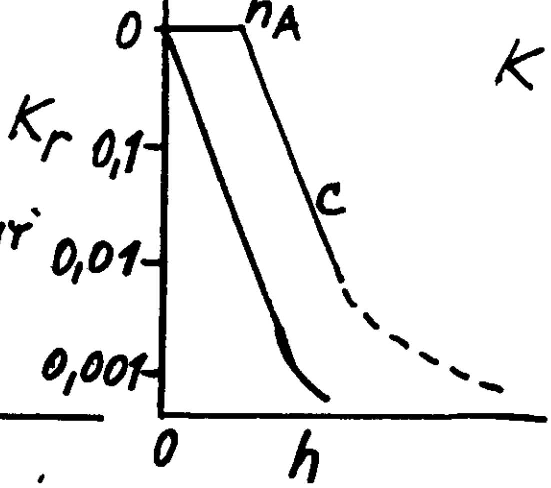
$K_r \approx \theta_E^{3,5}$

POMOCÍ $h(\theta)$

$K(\theta)$ …. FYZIKÁLNÍ

- - - → $K(h)$





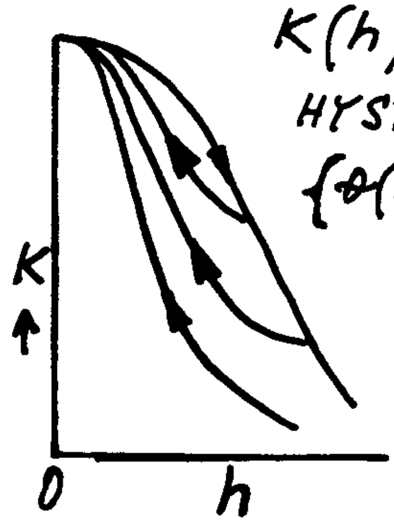
$K = K_S \exp(ch)$

$K_S \exp[c(h - h_A)]$

$(ch) < 0$

$c \ [cm^{-1}]$

$\langle 0,1 ; 0,01 \rangle$



$K(h)$ JE HYSTEREZNÍ

$\{\theta(h)$ —"— !!$\}$

K_r SE KALIBRUJE NA REÁLNÉ K

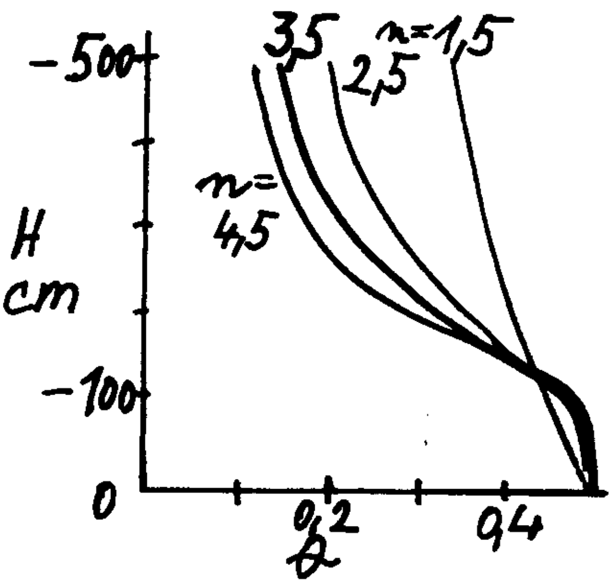
a) BUĎ POMOCÍ K_S V PŮDÁCH S HOMOGENNÍ PÓROVITOSTÍ (= PÓROVÝM SYSTÉMEM)

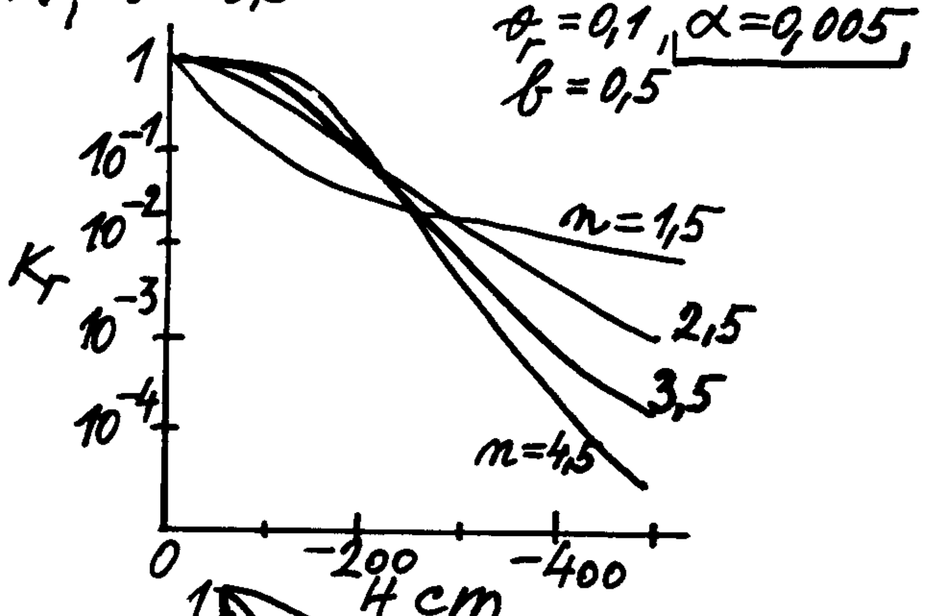
b) POMOCÍ 1 PŘÍMO MĚŘENÉ $K(\theta_E)$

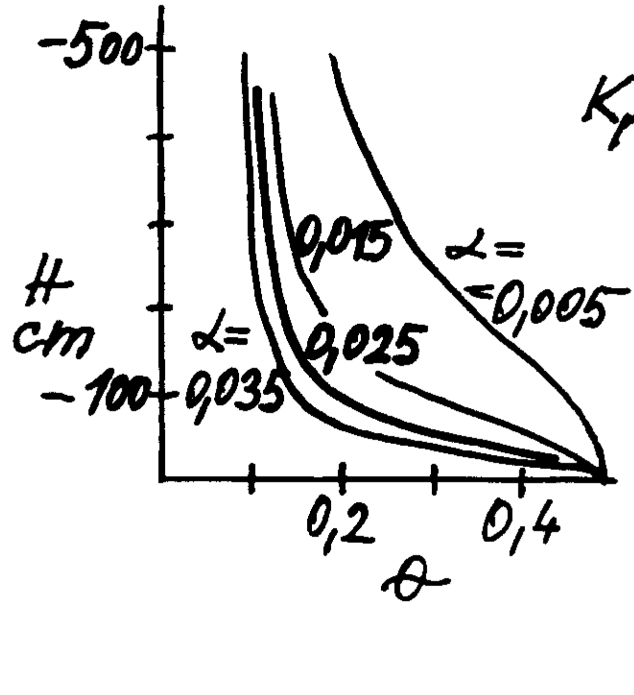
V PŘÍPADĚ α) MAKROPÓRŮ } HETERO-

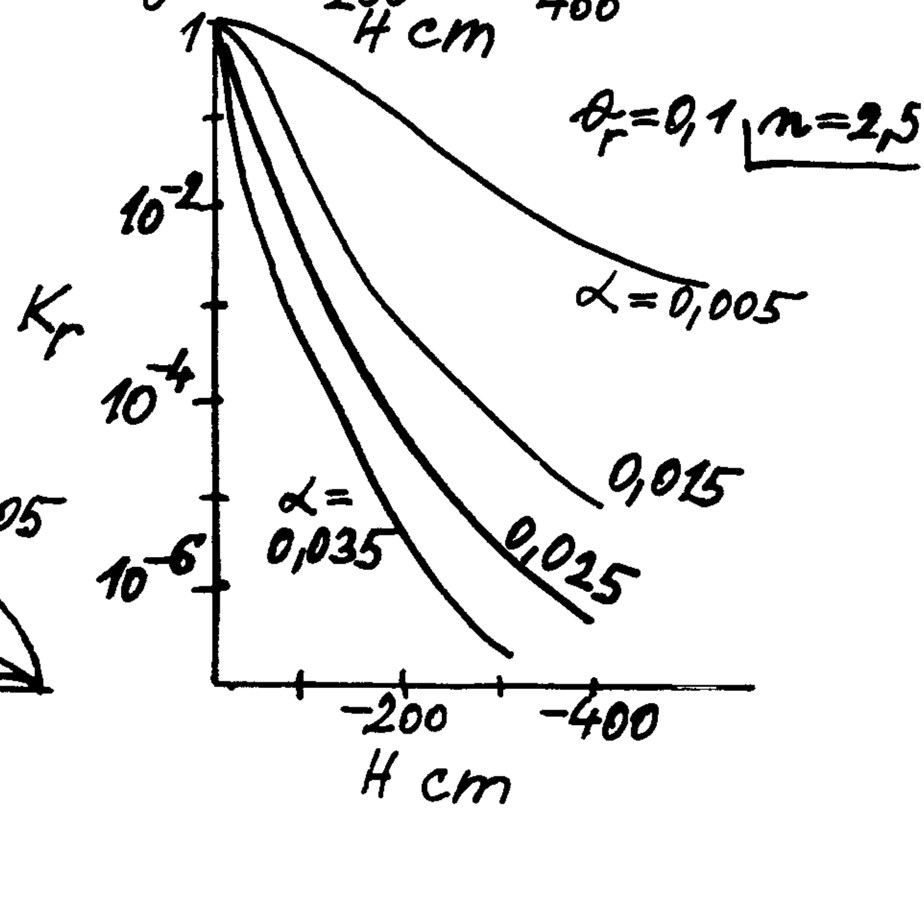
β) BI-MODÁLNÍ PÓR. } GENNÍ PÓR. SYSTÉM

→ MUALEM, $b = 0,5$









ELEMENTARY HYDROLOGIC PROCESSES

- INFILTRATION — I
- REDISTRIBUTION — R
- DRAINAGE TO GW — D
- EVAPORATION — E
- EVAPOTRANSPIRATION — ET

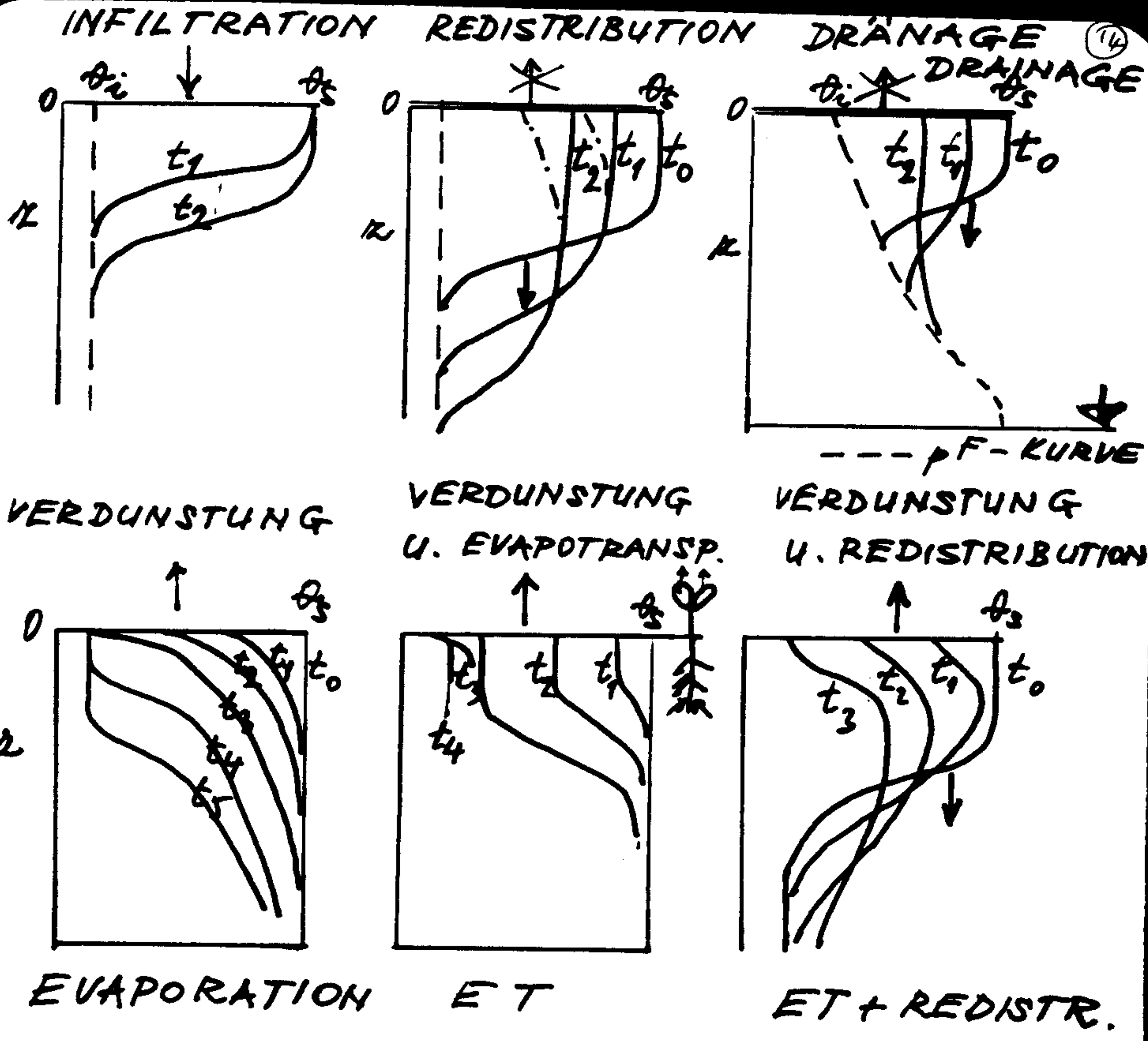
IRDEET ($t_{SEAZON,\ YAR}$) = SOIL HYDROLOGY

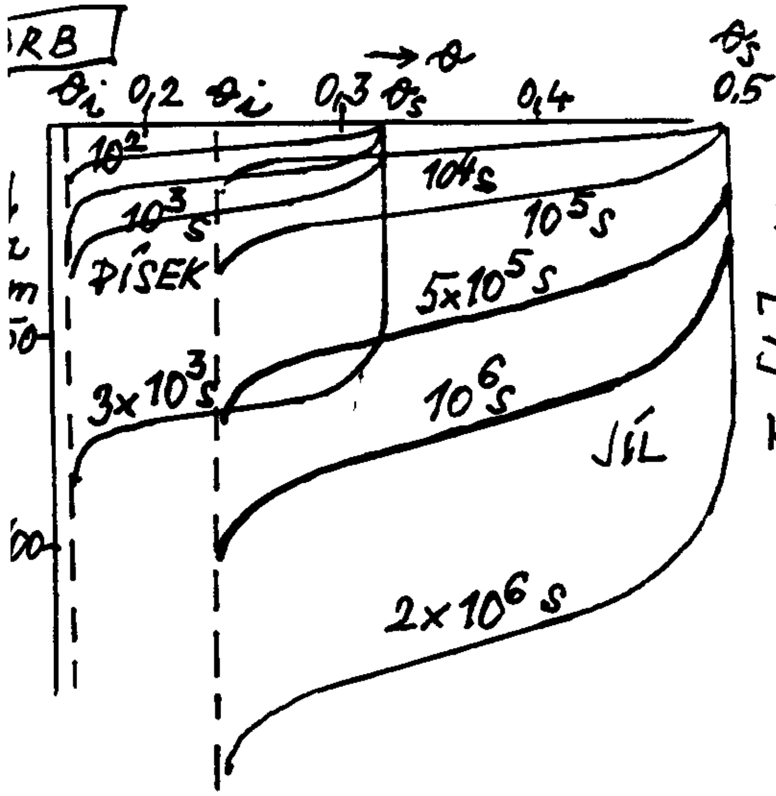
SOLUTIONS:

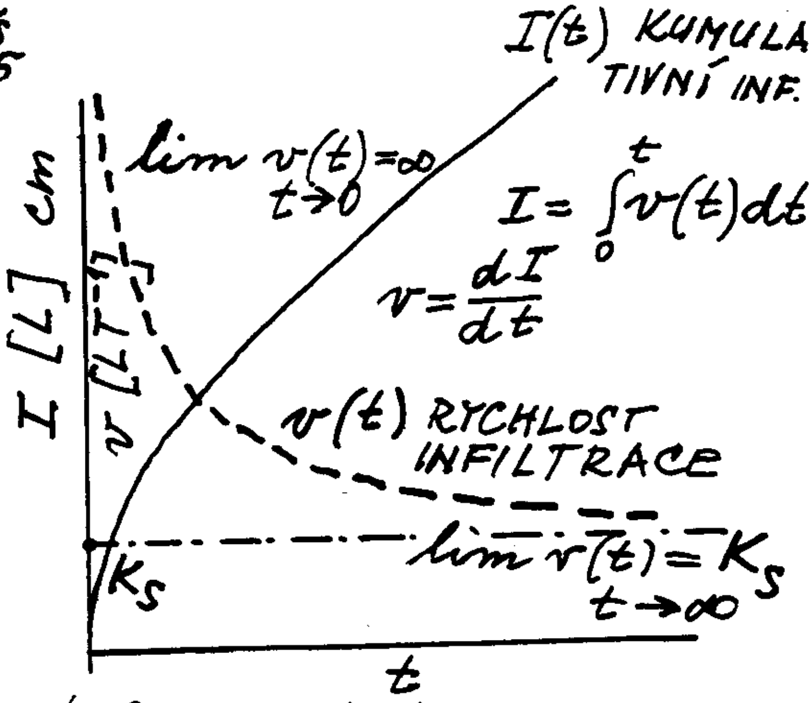
ANALYTICAL
APPROXIMATIVE
NUMERICAL
PHYSICAL LAB &/OR FIELD EXPER.

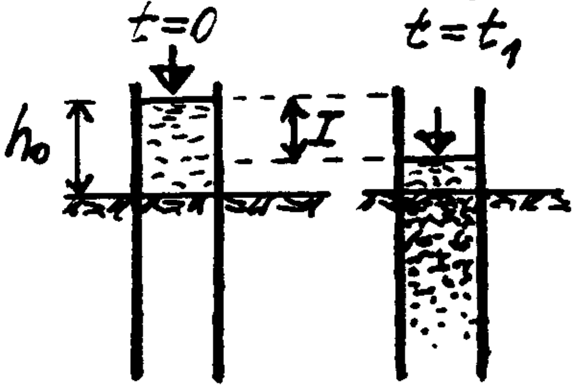
STEADY — DARCY-BUCKINGHAM EQ
ONLY B.C. — NEUMAN C.

UNSTEADY — RICHARDS' EQ
I.B.C.
B.C. < NEUMAN / DIRICHLET

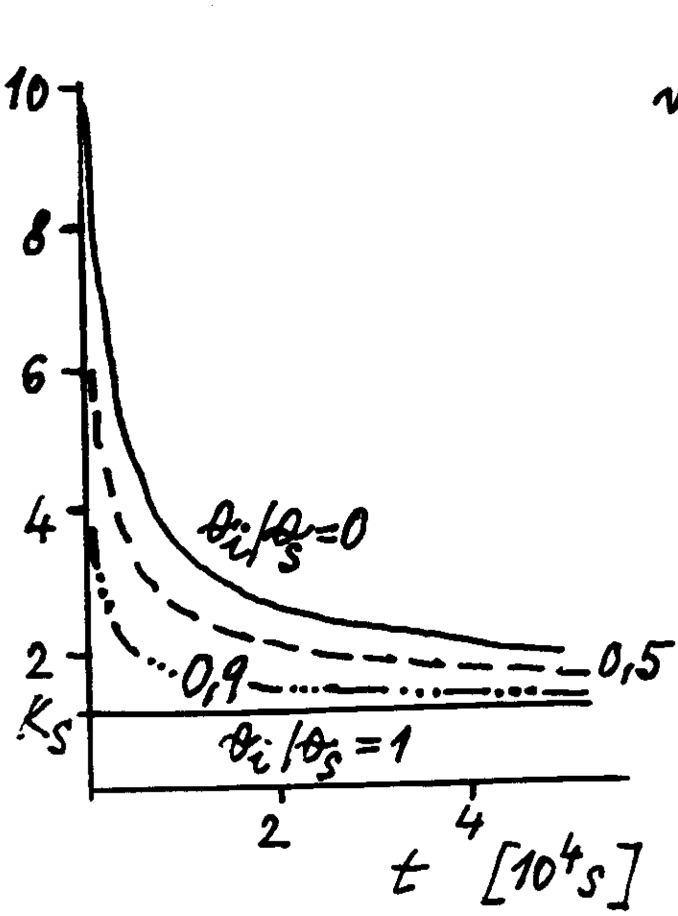

INFILTRATION
REDISTRIBUTION
DRÄNAGE
DRAINAGE
0
θi
θs
t1
t2
t0
z
- - - pF-KURVE
VERDUNSTUNG
VERDUNSTUNG
U. EVAPOTRANSP.
VERDUNSTUNG
U. REDISTRIBUTION
t3
t4
t5
EVAPORATION
ET
ET + REDISTR.



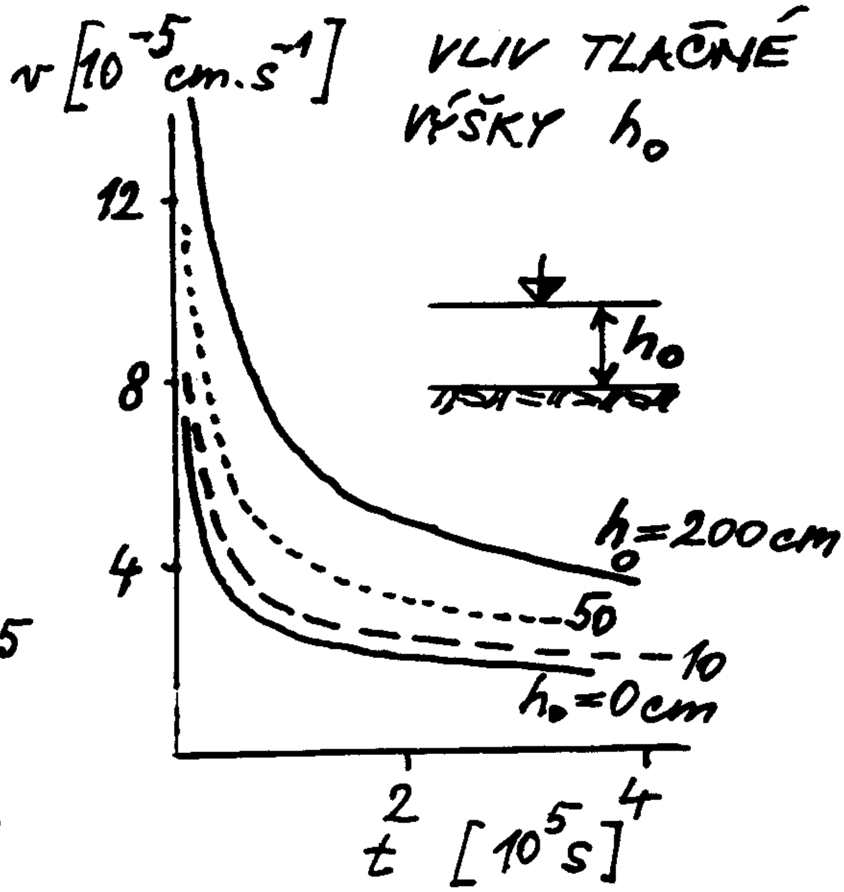




VLIV POČÁTEČNÍ VLHKOSTI θ_i



VLIV TLAČNÉ VÝŠKY h_0



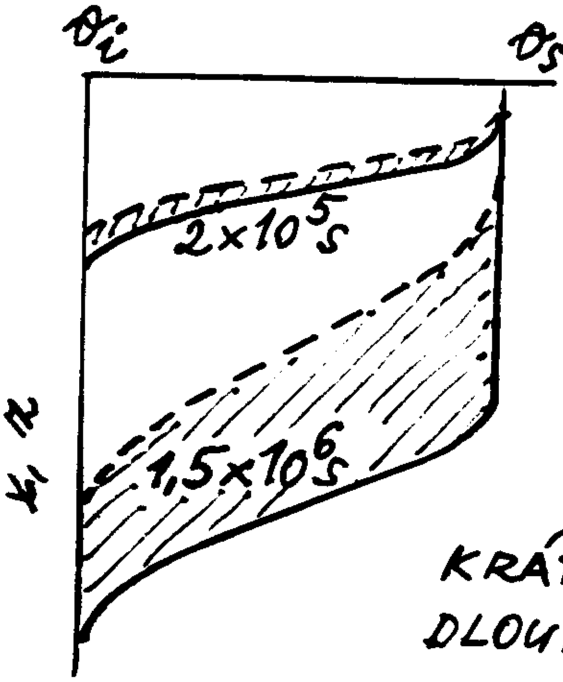
ŘEŠENÍ

1. FYZIKÁLNÍ – ANALYTICKÉ
2. APROXIMATIVNÍ – FYZIKÁLNÍ
3. EMPIRICKÉ

FYZIKÁLNÍ – ANALYTICKÉ

VLIV GRAVITACE

(ABSORPCE)
– – – – HORIZONTÁLNÍ INF.
——— VERTIKÁLNÍ –"–



R.R. – VERTIKÁLNÍ INF

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[D(\theta)\frac{\partial\theta}{\partial z}\right] - \frac{dK(\theta)}{d\theta}\frac{\partial\theta}{\partial z}$$

HORIZONTÁLNÍ = ROV. DIFÚZE

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x}\left[D(\theta)\frac{\partial\theta}{\partial x}\right]$$

KRÁTKÝ ČAS t ~ HORIZ.
DLOUHÝ ČAS $(t\to\infty)$ ~ JEN GRAVITACE

ŘEŠENÍ PHILIPOVO (1956, 57)

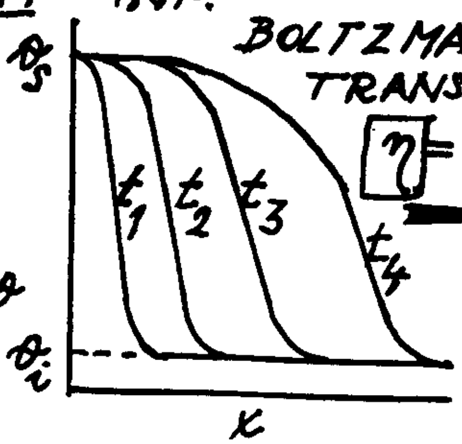
1. KROK – HORIZONTÁLNÍ INF.
2., 3. ... KROKY – OPRAVY 1. KROKU NA GRAVITACI
   x ... z

HORIZONTÁLNÍ INF.

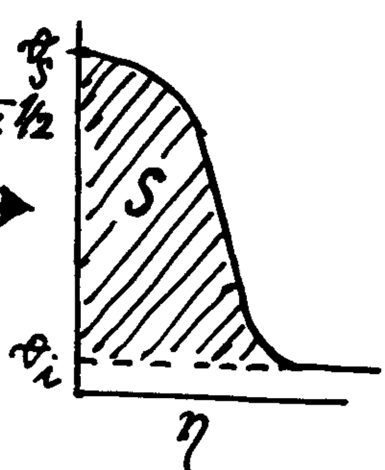
ŘEŠENÍ R.R.

$$x(\theta,t) \equiv \eta(\theta)$$

$$I(t) = \int_{\theta_i}^{\theta_s} x(\theta,t)\,d\theta$$



BOLTZMAN. TRANSF.
$\eta = x t^{-1/2}$



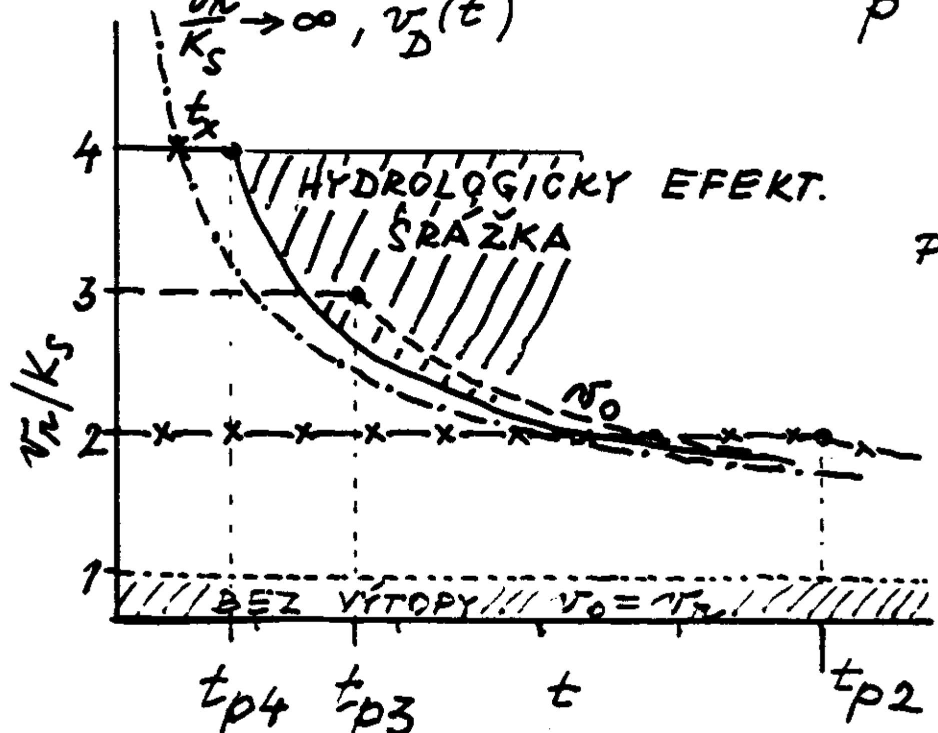
SORPTIVITA

$$S = \int_{\theta_i}^{\theta_s} \eta(\theta)\,d\theta$$

R.R. $$\frac{\eta}{2}\frac{d\theta}{d\eta} = -\frac{d}{d\eta}\left[D(\theta)\frac{d\theta}{d\eta}\right]$$

b) NEUMANOVA O. P. (SRÁŽKA)

b1) $v_r = \text{KONST.}$, $\frac{v_r}{K_S} \to \infty$, $v_D(t)$



t_p

1. $\int_0^{t_p} v_r(t)\,dt = \int_0^{t_x} v_D(t)\,dt$

2. $v_r(t_p) = v_D(t_x)$

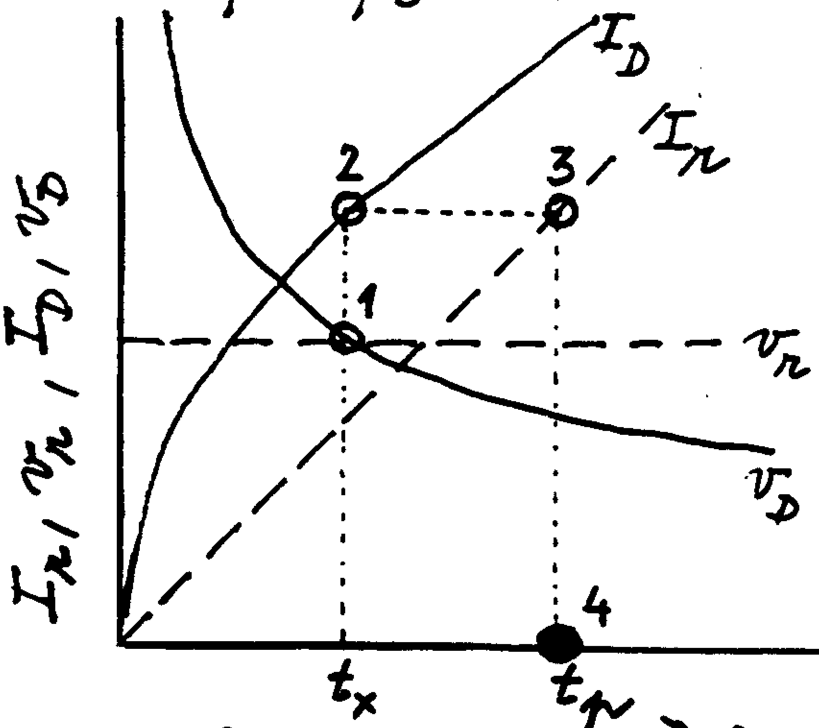
PRO $v_r = \text{KONST.}$

$$t_p = \frac{1}{v_r}\int_0^{t_x} v_D(t)\,dt$$

v_D (PHILIP)

$$t_p \approx \left(\frac{S}{A}\right)^2 \frac{2Q_r^* - 1}{4Q_r^*(Q_r^* - 1)^2}$$

$$Q_r^* = v_r / A$$

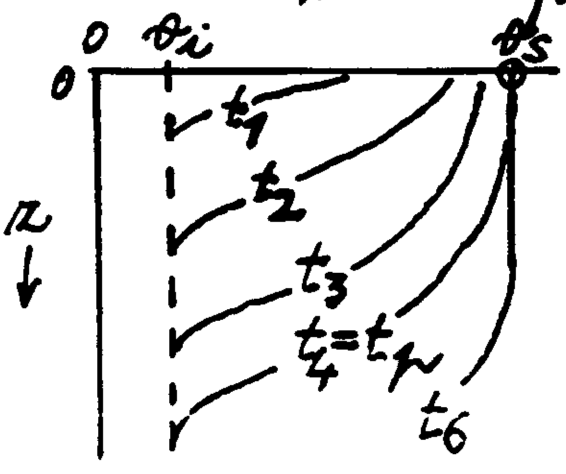


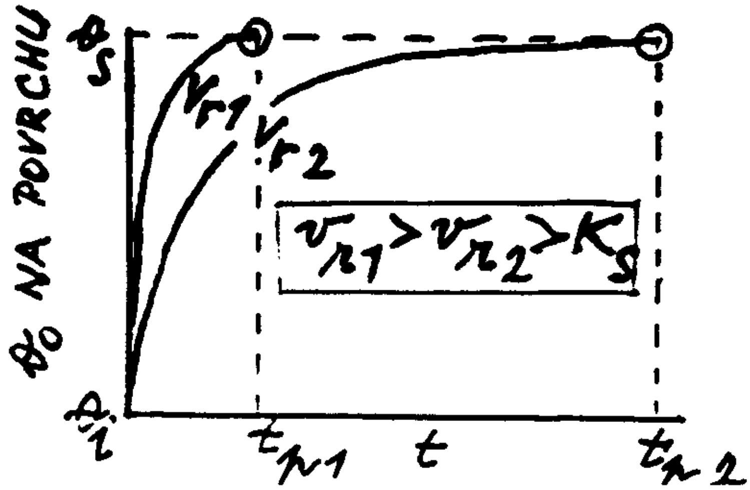
$v_0 = v_r \quad t \le t_p$

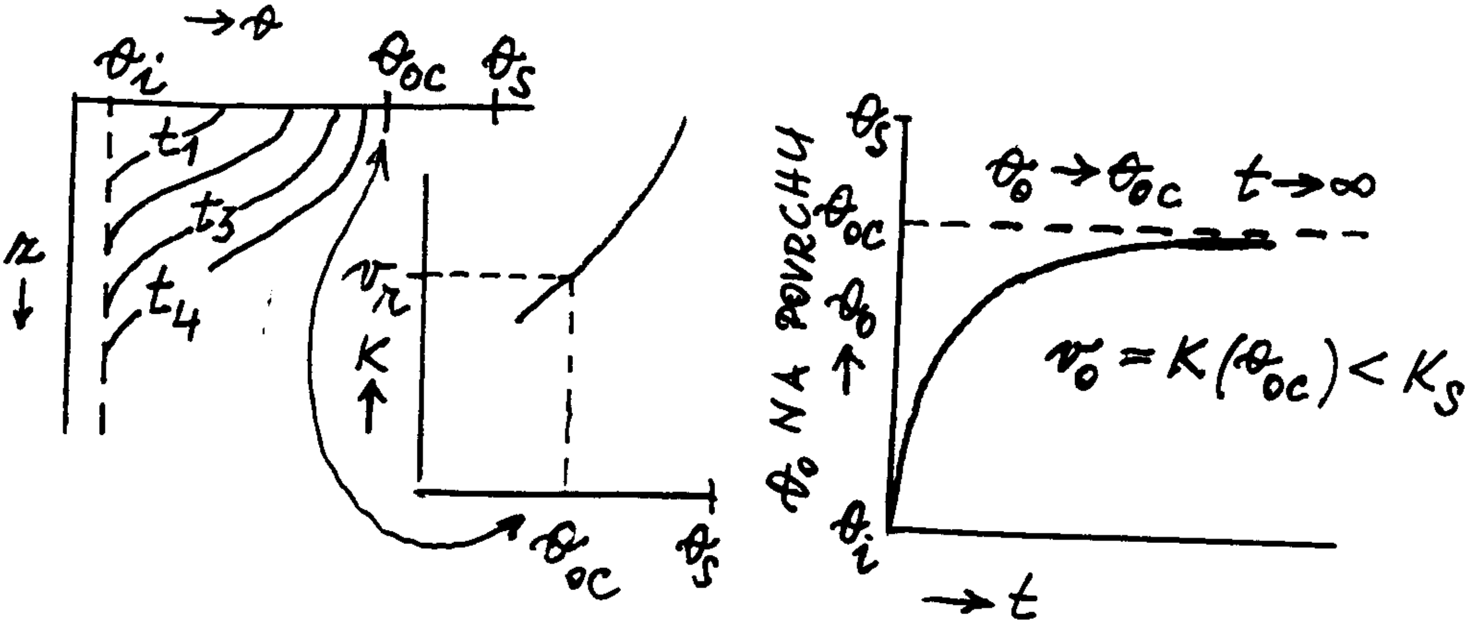
$t > t_p$

$$v_0(t) \approx v_D[t - (t_p - t_x)]$$

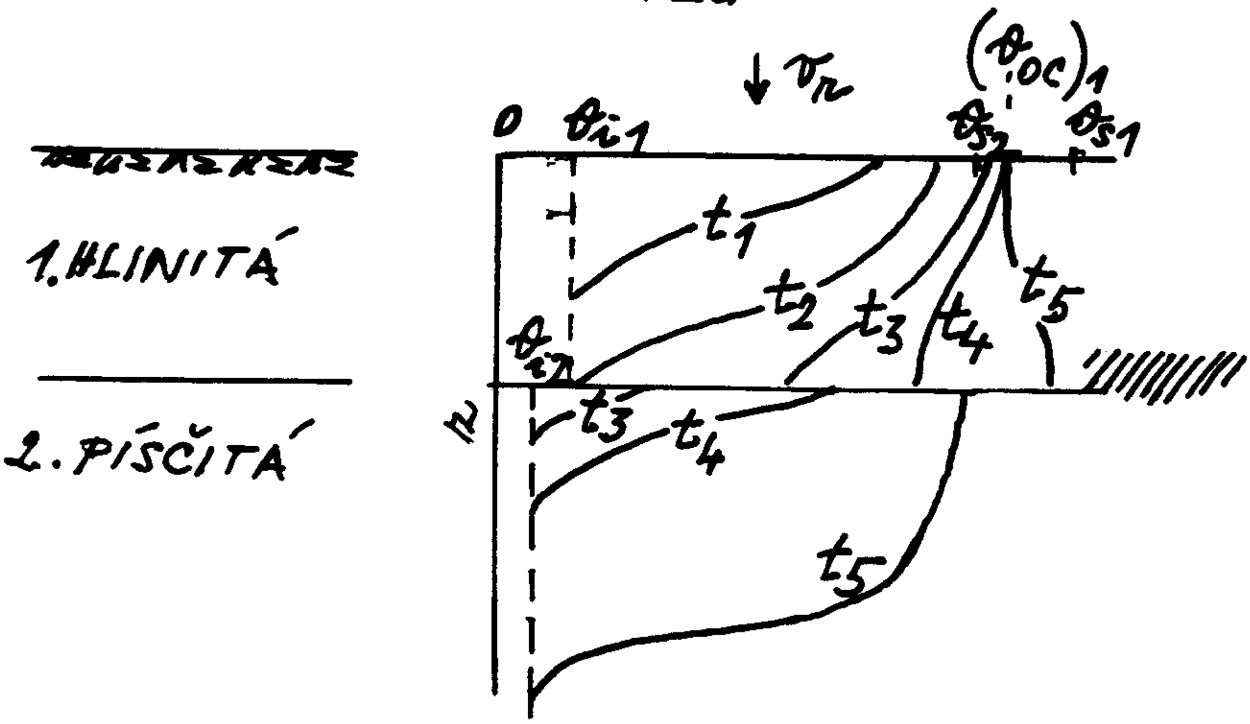
$$v_0 = \frac{1}{2} S \left[t - \frac{S^2}{4A^2 Q_r^*(Q_r^* - 1)}\right]^{-\frac{1}{2}} + A$$







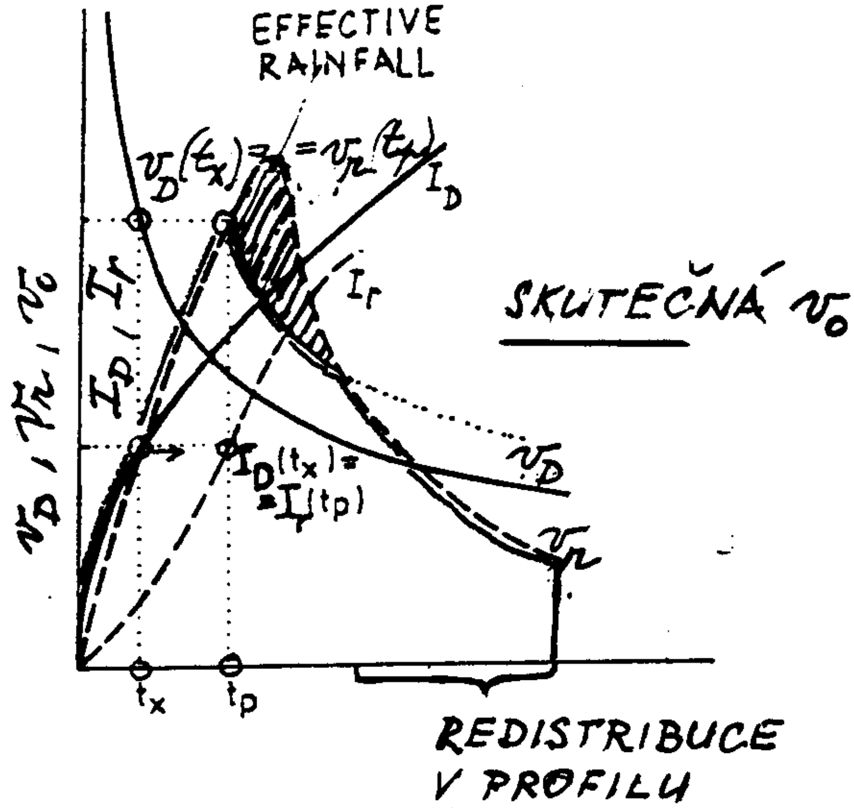
INFILTRACE ZE SRÁŽKY v_r = KONST. DO ZVRSTVENÉHO PROFILU

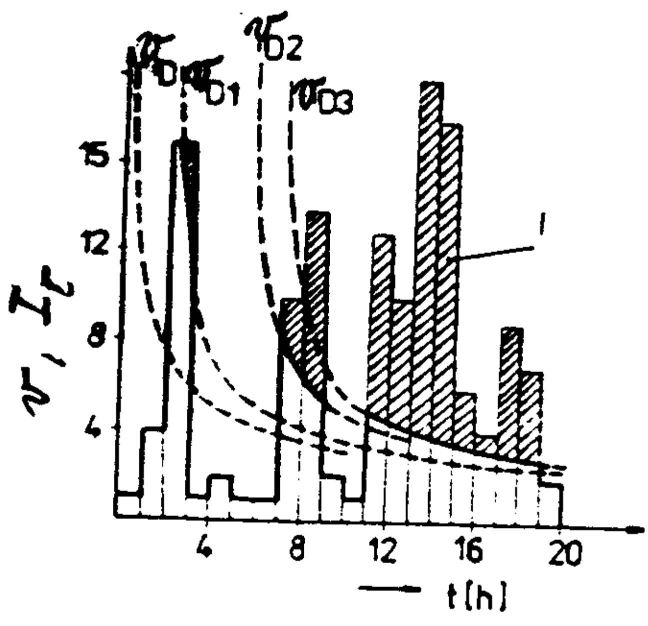


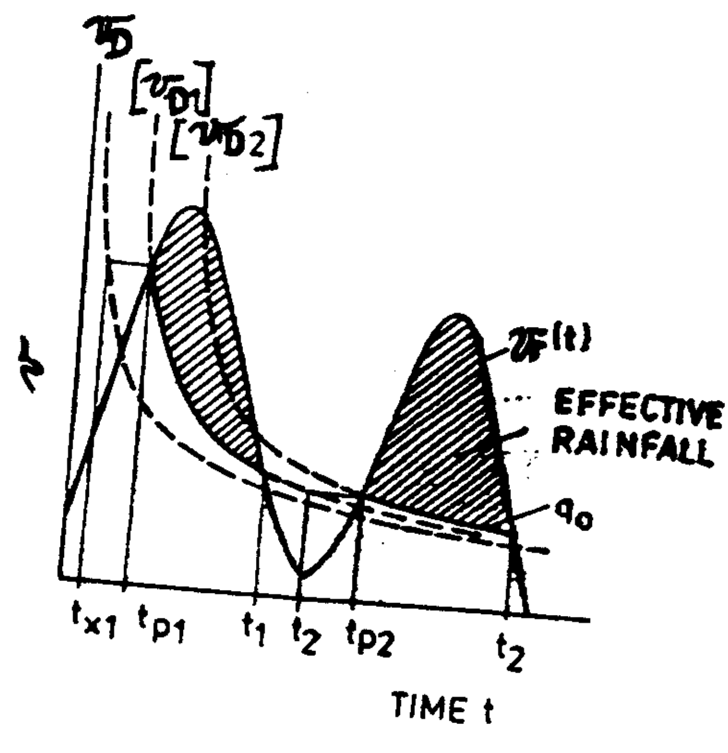
b2) SRÁŽKA O PROMĚNNÉ INTENZITĚ $v_r(t)$

$$\int_0^{t_p} v_r(t)\,dt = \int_0^{t_x} v_D(t)\,dt$$

$$v_r(t_p) = v_D(t_x)$$

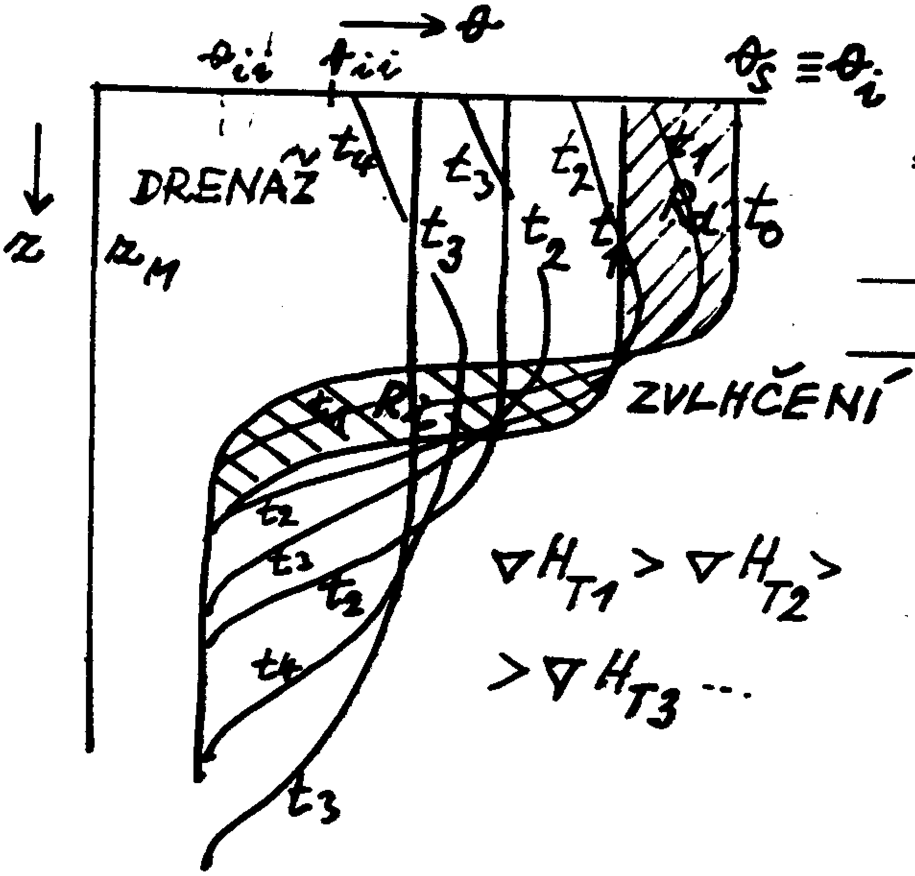






PO SKONČENÍ VÝTOPOVÉ INFILTRACE (20)

ČAS t_0 VÝPAR = 0 !

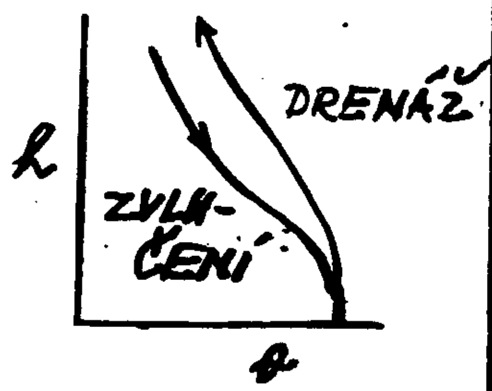


$R_d = R_i$

——— BEZ HYSTEREZE

——— S HYSTEREZÍ

$\nabla H_{T1} > \nabla H_{T2} > \nabla H_{T3} \ldots$



MĚŘENÍ POLNÍ KAPACITY : θ PŘI $\frac{\Delta\theta}{\Delta t} \to 0$

θ_{PK} FIELD CAPACITY