NUMERO: 903 DATA: 12/03/2014

A P P U N T I

STUDENTE: Piccione

MATERIA: Sovrastrutt. Viarie,Ferroviarie,Aeroportuarie
(INGLESE) + Eserc.
Prof. Santagata

30/9/13

PAVEMENT AND TRACK ENGINEERING

INTRODUCTION

Goal = provide a basic knowledge for a performance related approach to the design and maintenance of pavements → use of models

PAVEMENTS AND TRACKS = civil engineering structures which constitute the upper part of infrastructures

- they require good materials,
- models (loadings, ...)

They have to ensure:
- comfort
- safety
- economic sustainability

3 principles to obey:

1. safety, comfort and "economy" of the users → depending on: kind of

2- Control structural response and performance

levels of stress, loading, ...

This may affect the functional response.

The 2 aspects are linked.
↓
FUNCTIONAL / STRUCTURAL

We want this 2 aspects change according to our needs

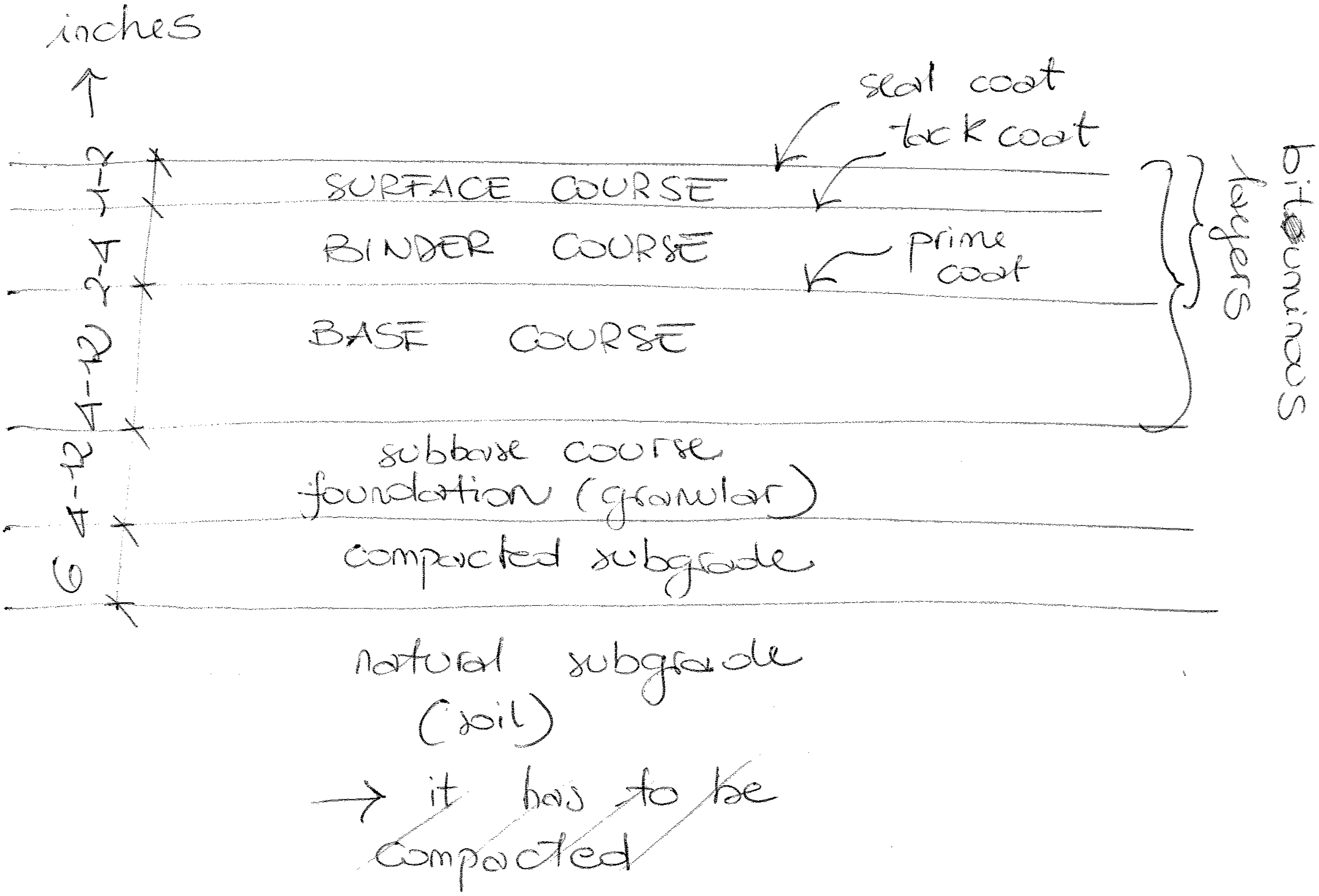
Approach:

- Non empirical models; theoretically based models to describe phenomena. with adequate parameters

they cannot be generalized

↳ this approach is more general (conclusions can be used in different situations)

- Mechanistic approach → materials characterization and in service experimental evaluation



Base course can be of 2 types: granular materials or bituminous mixture

Interface = separation between courses

Bituminous mixtures are also called asphalt (american term) es. open-graded → non continous curve (some classes are missing)

Functions:

- resist traffic distorsions caused by high normal and shear stress at the interface (local stress on the top is really high)
- waterproofing of the pavement
- provide skid resistance for safety purposes (micro and macro textures)
- provide specific functions, es. absorbing vibrations, reducing pollution, ...)

(3) BINDER COURSE

It has larger aggregates than those which constitute the surface course, and less bitumen

Functions:

- load distribution → structural function (stiffness and other mechanical properties)

Function: glue two layers → continous structure with no discontinuity → ensure bond between two courses

7) PRIME COAT

It has to ensure bond between a bituminous and a granular layer. It is thicker than tack coat. Emulsion or bitumen

8) SUBGRADE

It has to support the pavement. This support should be uniform (same stiffness on the entire layer) to avoid localized distresses. The top of this layer has to be compacted.

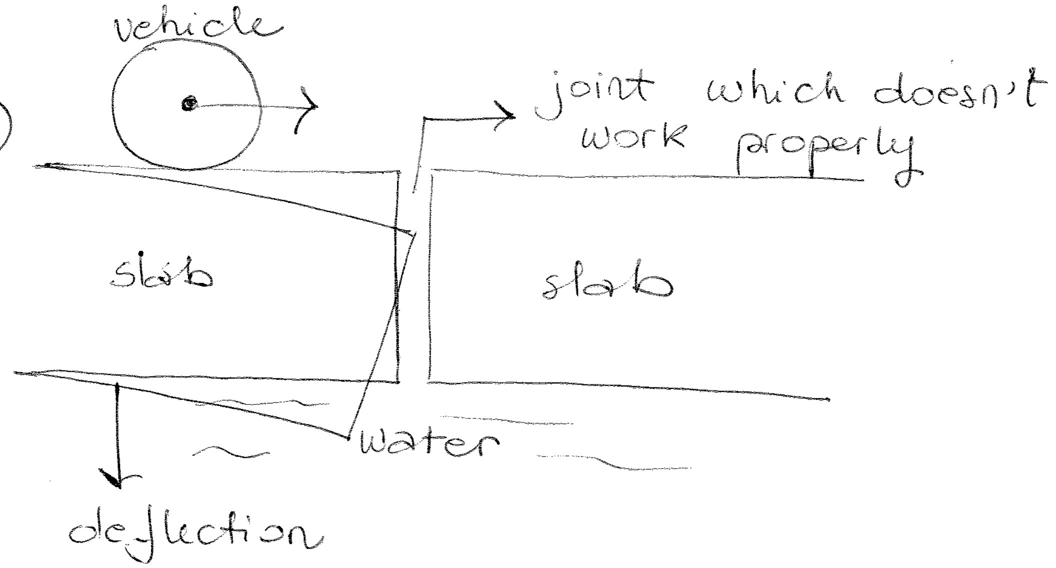
1 SUB-BASE COURSE

Composed by granular or stabilized (to enhance stiffness) material

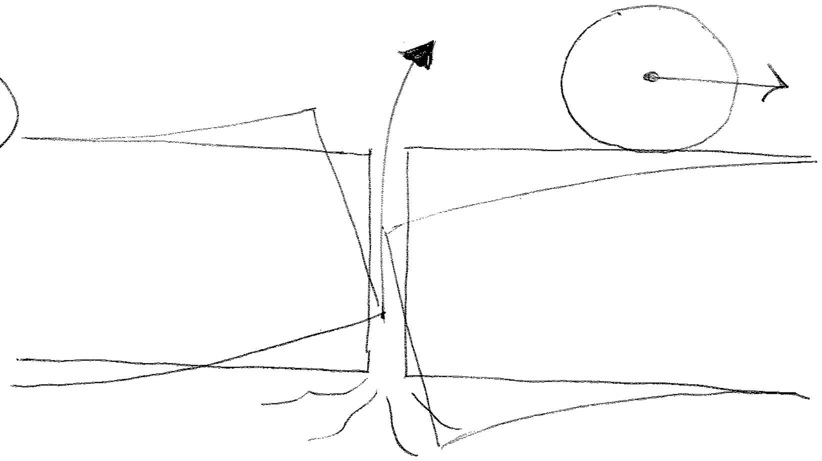
Functions:

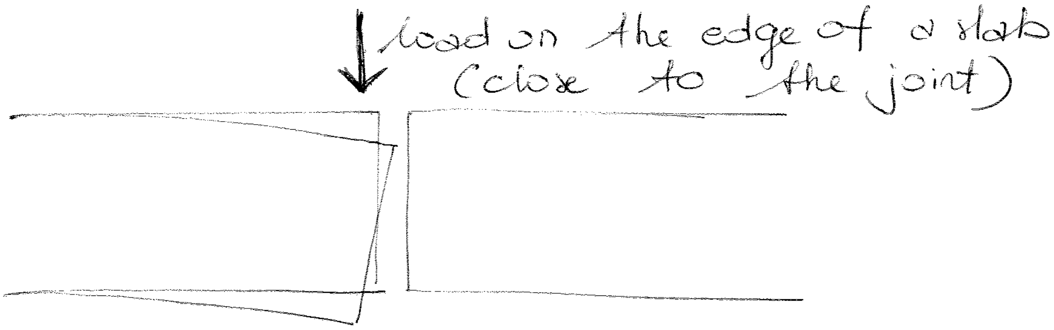
- load distribution
- control of pumping = water trapped in the subgrade is sucked up (because of pressure) though the joints and goes on the surface

a)

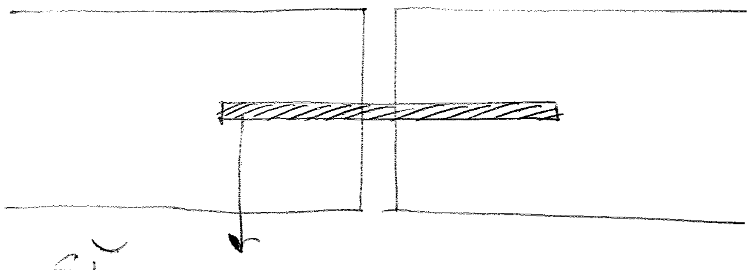


b)





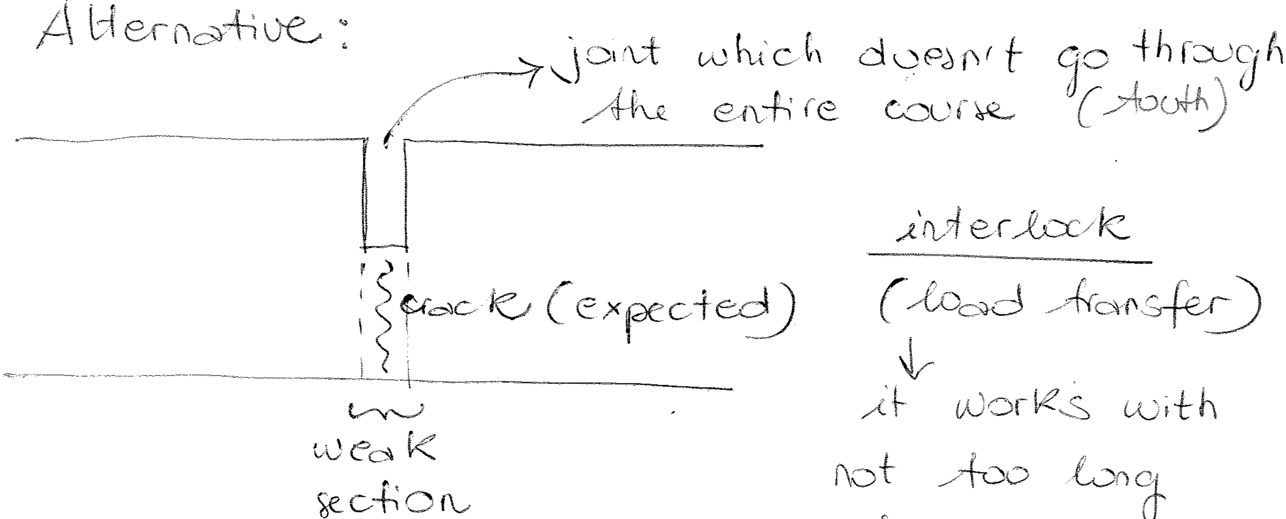
↳ NO → I want also the following slab to support the load



Sì

<u>dowel</u> with a shear action transfers part of the load to the following slab

Alternative:



<u>interlock</u>

(load transfer)
↓
it works with not too long slabs

long slabs → movimenti relativi maggiori

b) <u>jointed reinforced concrete pavements</u>

Steel reinforcement to increase joint spacing → 30 ÷ 100 ft

13

3/10/2013

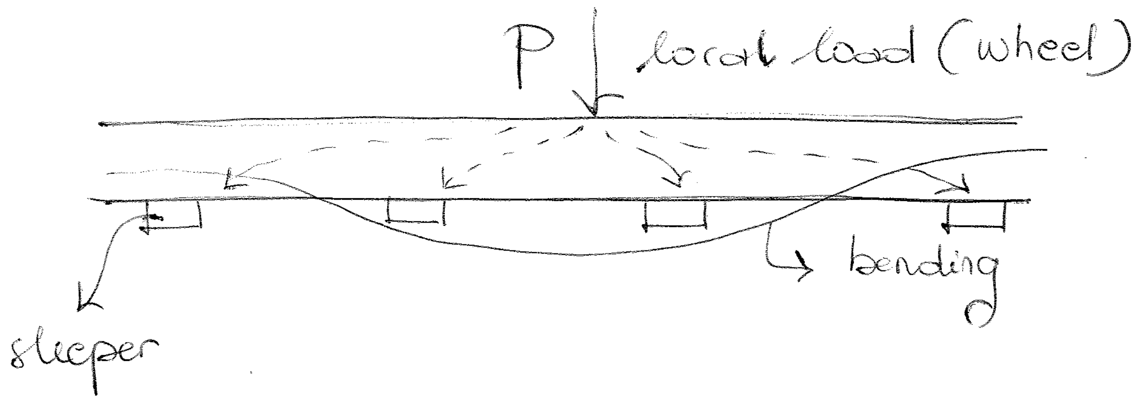
RAILWAY TRACKS

Beginning of 19th century → 1st railway tracks → railway construction tecniques ~~are~~ were not so different from nowadays

rigidity
Rails are connected to sleepers (or ties), which are transverse elements, through fastenings supplemented with resilient pads (elastic elements)
Sleepers are included in a layer composed by granular material called ballast; under ballast it can be present another layer, called subballast.
Finally there is subgrade.

Ballasted track (or ⟺ flexible track)
↳ Rails and sleepers are supported by ballast. Alternative: rigid support (concrete slab)

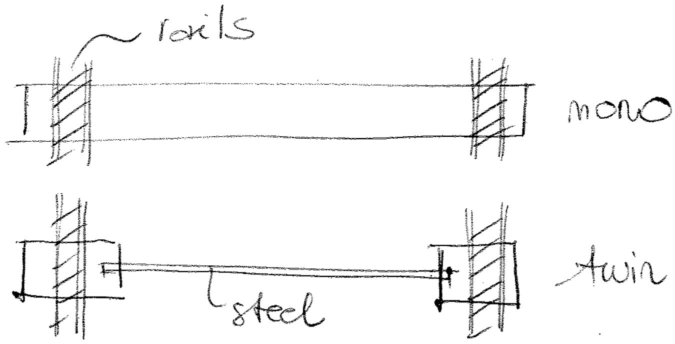
-15



② SLEEPERS

- Wood (in the past)
- Reinforced concrete (monoblock / twin block)
- Steel

stiffer than wood



Functions:

- Load distribution
- Keep the rails at a constant spacing → rigid grid to keep rails in a fixed position

gage "scartamento"

Loads < vertical / horizontal (chance of sliding on the ballast)

5 SUB-BALLAST

Additional layer which is tipically made of gravel sand, recently bituminous mixtures or cement stabilized material

Functions:

- load distribution
- protect the subgrade top made of fine soil from the penetration of big stones from ballast
  → separation of ballast / soil
  (alternative: phisical barrier es. reti geo)
- fast drainage of water
- damping effect → dissipation of part of the energy

2 layer structure: ballast / sub-ballast

reduce the consumption of the selected material (crushed stone) which constitute ballast, using another layer of less selected material (aiuto in load distr.)

ASPECTS

Structural and functional behaviour change in time

STRUCTURAL

load distribution leading to minimum damage to all materials

- stresses σ
- strains ε
- displacements δ

↳ this things affect structural behaviour

FUNCTIONAL

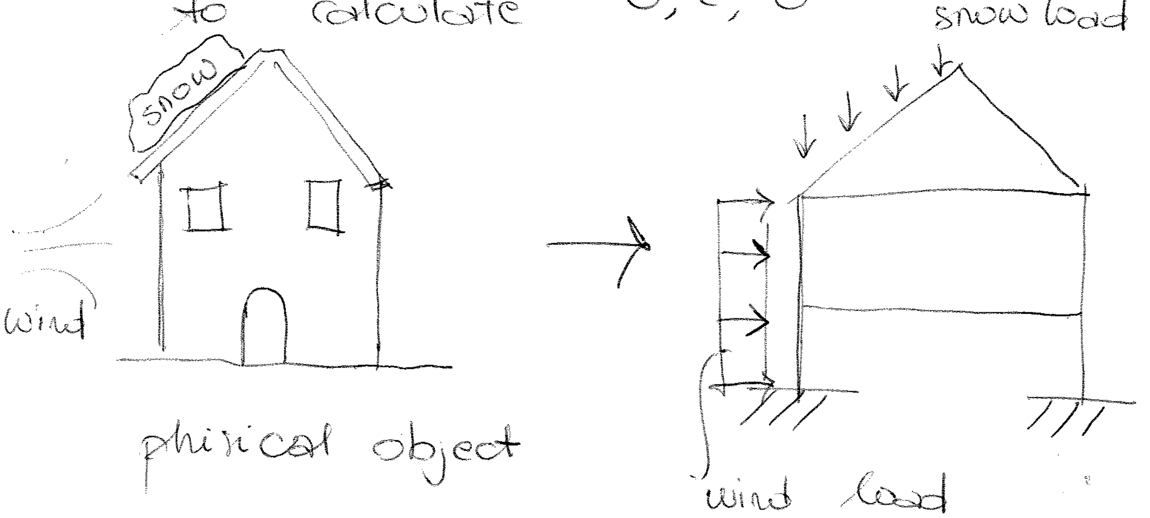
perceived by users

- traction / skid resistance → maximum available traction

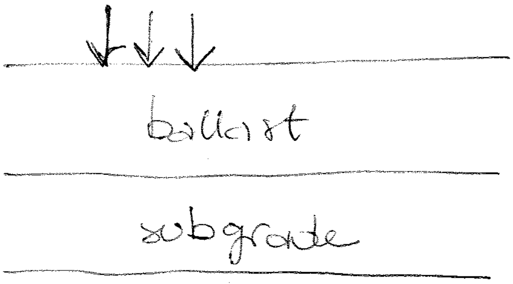
(comfort, safety)
↓
- roughness
- noise

DISTRESSES

(1) A Model of the structure is needed to calculate $\sigma, \varepsilon, \delta$



→ loadings and structure models



multilayer element

Assumptions on materials behaviour
→ elastic, visco-elastic, ... models
it depends on the tool I use

Moreover, we have to do assumption on interactions between layers

Input values are function of, for example, temperature, humidity or other parameters
↓
T. model is very important also for actions (expantions, reductions → stresses)
↳ environmental model (T, U)

Materials properties
→ materials models or direct measurements

ENVIRONMENTAL MODEL → MATERIALS MODELS → STRUCTURAL MODEL

Then I need transfert functions: $\sigma, \varepsilon, \delta$ → → performance in term of distresses

23

In concrete shear effects are very small → we will focus on <u>vertical loads</u>

(N.B.) <u>liquid</u> <u>foundation</u> → hp) subgrade is a set of <u>independent</u> springs

Techniques:

- analytical (formulas)
- graphical / tabular

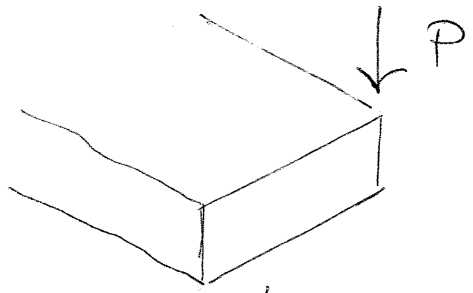
} these methods are applicable only to a large slab on a liquid foundation

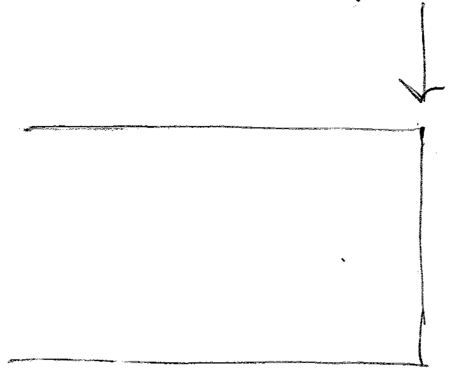
- FEM (finite element method), DEM

↳ numerical → this method can be used if the loads are applied to multiple slabs on a liquid, solid or layer foundation

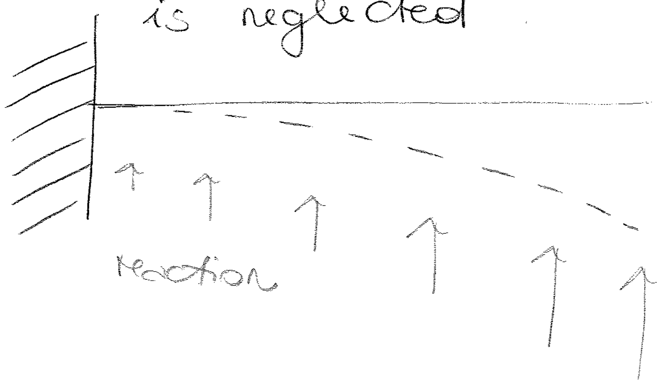
- GOLDBECK'S FORMULA (1919)

Load applied at the corner of a slab (vertical load)





model: cantilever beam; the subgrade support is neglected



The bending moment is overestimated

The stress is constant, independent from x

This solution is exact only for $x \to \phi$ (*)

This is a good tool for a first evaluation of:

- thickness required
- tensile stress on the slab

- **WESTERGAARD'S FORMULAS (1919 - 1948)**

Rigorous approach

- behaviour of the slab: plate subjected to <u>plane</u> bending (cross sections remain plane under bending effect → no distorsions)
- support → Winkler elastic support

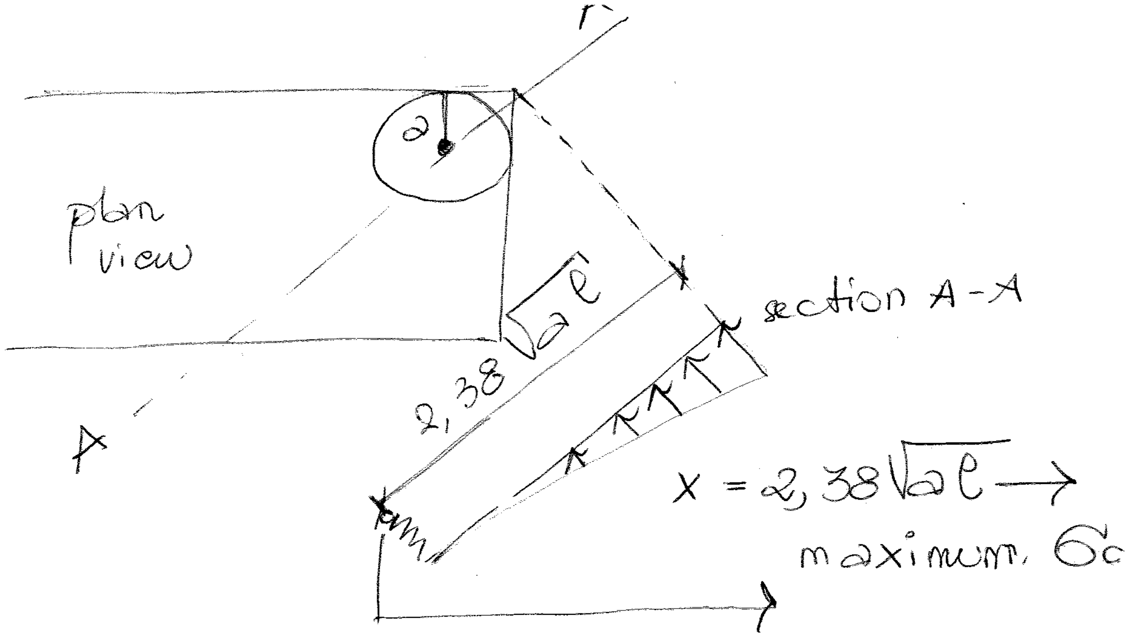
$$p = k\,z$$

p → reactive pressure

k → modulus of subgrade reaction

z → deflection of the slab

1.



Reactive forces are not neglected

$$\sigma_c = \frac{3P}{h^2}\left[1 - \left(\frac{a\sqrt{2}}{\ell}\right)^{0,6}\right]$$

a = radius of the circular print

ℓ = radius of relative stiffness

$$\rightarrow \boxed{\ell} = \left(\frac{E h^3}{12(1-\nu^2)K}\right)^{0,25}$$

$K \rightarrow$ stiffness of the foundation

$\rightarrow$ related to the bending stiffness of the structure

$$\Delta_c = \frac{P}{K\ell^2}\left[1,1 - 0,88\left(\frac{a\sqrt{2}}{\ell}\right)\right]$$

the maximum displacement under loading is proportional to the loading P

invers. prop. to ℓ^2

Limitations of W. formulas:

- Are pavement slabs isolated?

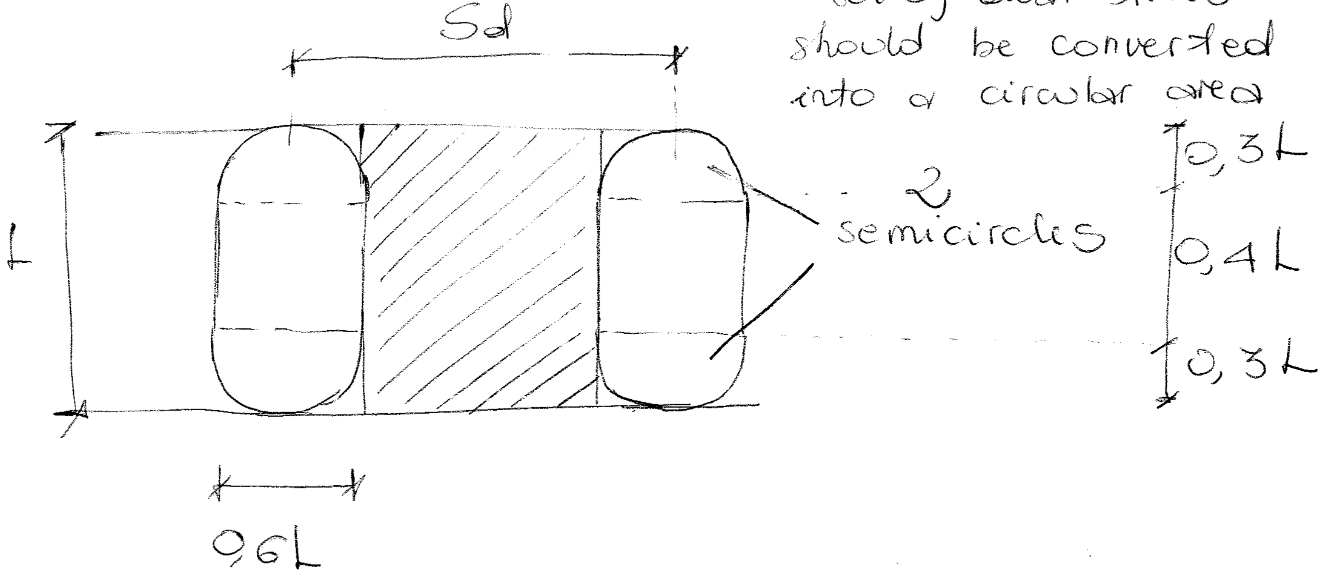
- Winkler foundation is a realistic behavior?

- Is the single wheel load realistic?

→ multiple loading → biggest limitation

↓

2 tireprints → a load applied over a set of dual tires should be converted into a circular area



How can I use W. solution?

→ sum of loading areas → single circular area → too large stresses and deflections
NO

a- Determine ℓ (SCALE of the graph)

b- Use the scale to draw the configuration of contact areas → we position the prints according to our needs

c- Count the number of blocks covered by tire imprints (N)

d- Calculate the bending moment:

$$\boxed{M_n = \frac{q \cdot \ell^2 \cdot N}{10'000}}$$

n = direction in which I calculate the moment

$\longmapsto$ longitudinal direction

$O \longrightarrow n$

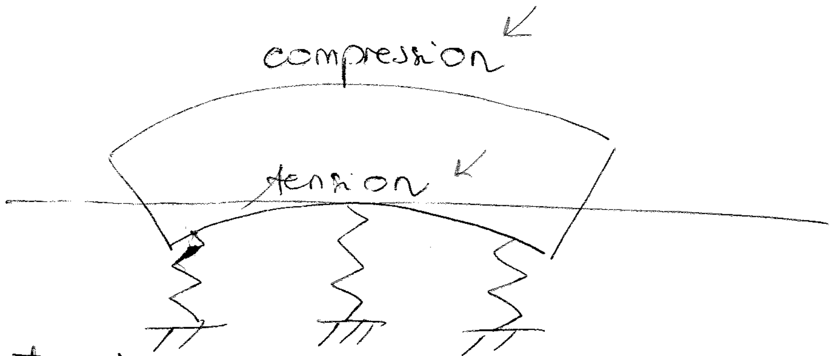
If I want the moment in the other direction, I can rotate the imprints

16/10/2013

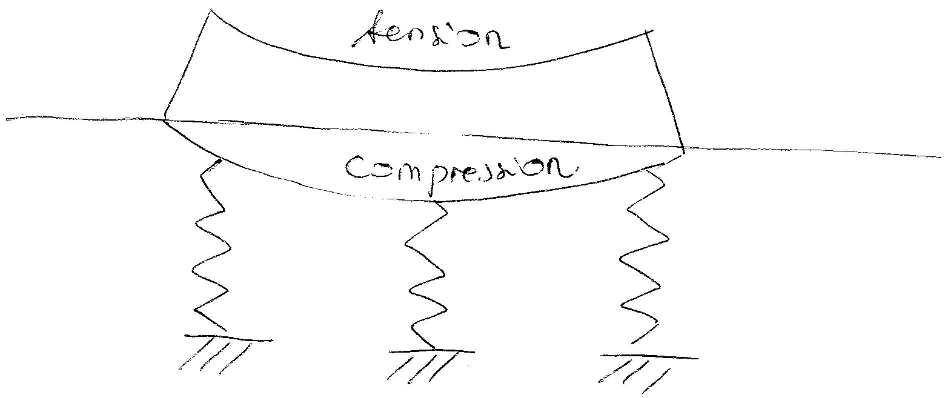
TEMPERATURE - INDUCED STRESSES IN RIGID PAVEMENTS

State of stress induced in slabs by temperature variations

Day → T on the top of the pavement is greater then the T on the bottom → DOWNWARD CURLING



Night → UPWARD CURLING



The weight prevents this phenome-non → the dead weight mantains

- Bending in one direction ex_ x

→ no strain in the perpendicular direction y (the plate is very wide and well restrained)

$$\varepsilon_y = \emptyset \rightarrow \quad \sigma_y = \nu \cdot \sigma_x \qquad \sigma_x = \frac{\varepsilon_x \cdot E}{1-\nu^2}$$

$$\varepsilon_x = \emptyset \rightarrow \quad \sigma_x = \nu \cdot \sigma_y \qquad \sigma_y = \frac{\varepsilon_y \cdot E}{1-\nu^2}$$

- Bending in both directions

→ stress superposition

hp) the temperature distribution is linear throughout the depth of the slab

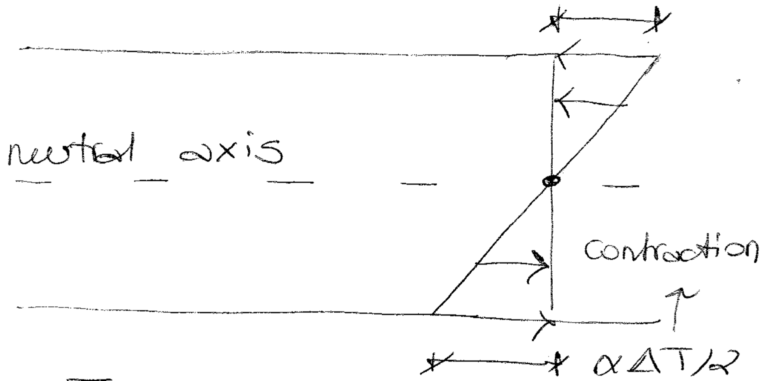
Actual case: strain (expansion)

$T_{top} > T_{bottom}$

$\alpha\Delta T/2$

α = coefficient of thermal expansion

ΔT = temperature differential between the top and the bottom of the slab



ΔT occurs with a linear distribution

$$\varepsilon_x = \varepsilon_y = \frac{\alpha_T \Delta T}{2}$$

2) Case of a finite plate (L_x, L_y)

The slab has a finite lenght and width

We have an approximative solution

We start from the expressions of σ_x and σ_y for the infinite slab and we introduce correction factors which refers to the contribute of bending in x dir. and in the y dir. → different dimentions x and y

in the center

$$\begin{cases} \sigma_x = \dfrac{C_x E \alpha \Delta T}{2(1-\nu^2)} + \dfrac{C_y \nu E \alpha \Delta T}{2(1-\nu^2)} \\[2ex] \sigma_y = \dfrac{C_y E \alpha \Delta T}{2(1-\nu^2)} + \dfrac{C_x \nu E \alpha \Delta T}{2(1+\nu^2)} \end{cases}$$

The point which is most far from the edges of the slab is the center (in this point we have the best approximation of a point in an infinite slab)

$C_{x\,y} = 1 \rightarrow$ case of infinite plate

$\downarrow$

when $L/\ell = 6,7$

In the finite slab the stresses are lower than the stresses in the infinite slab → the finite plate is capable of moving

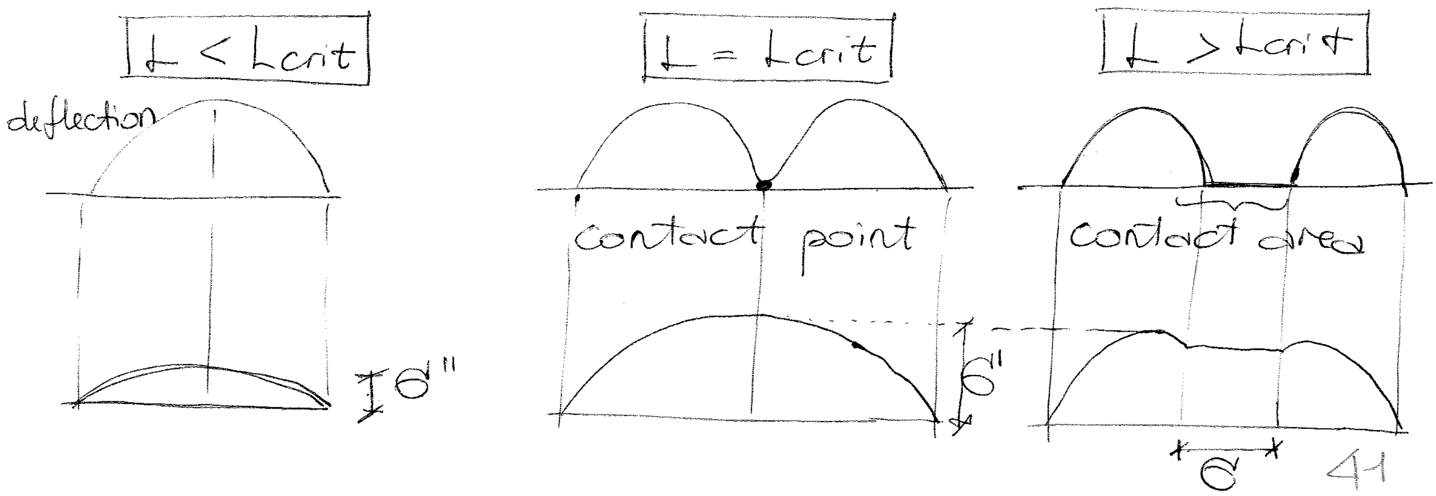
High L/ℓ (long slab) $\Rightarrow C \rightarrow 1$

$C > 1 \rightarrow$ very long slab: the subgrade reaction reverses the curvature

Other solutions:

EISENMANN (1970)

Case of $+\Delta T$ → concept of critical lenght L_{crit}



Most general case of ΔT → ?

<u>Uniform</u> temperature variation:

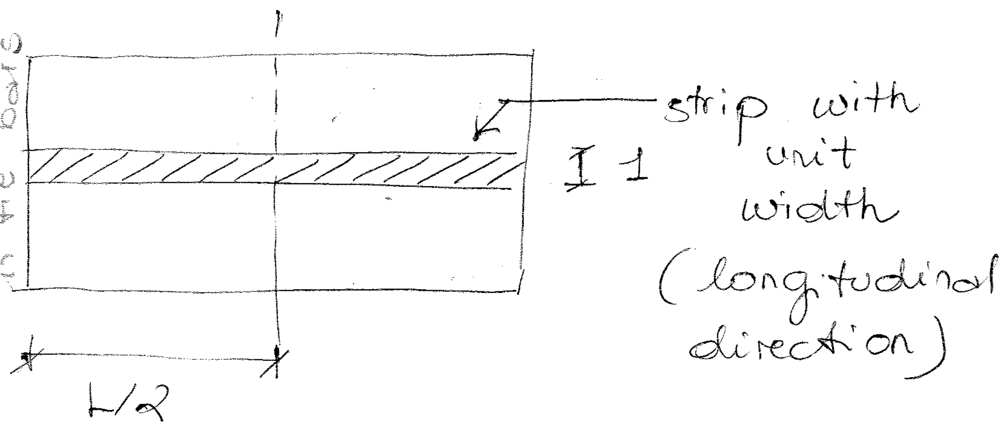
cooling → contraction

heating → expansion

↳ Partially hindered movement: the slab is not totally free to contract and expand because of the support $\boxed{\text{friction}}$

In fact it is the friction to induce stresses; if the slab is free to move (no support, unreal situation), cracks will never occurr

the friction between the slab and its foundation causes tensile stresses in the concrete, in the steel reinforcements and in tie bars



In order to have friction, you need relative movement → the amount of friction depends on the relative movement:

Stresses in :

wire fabric or bar mats

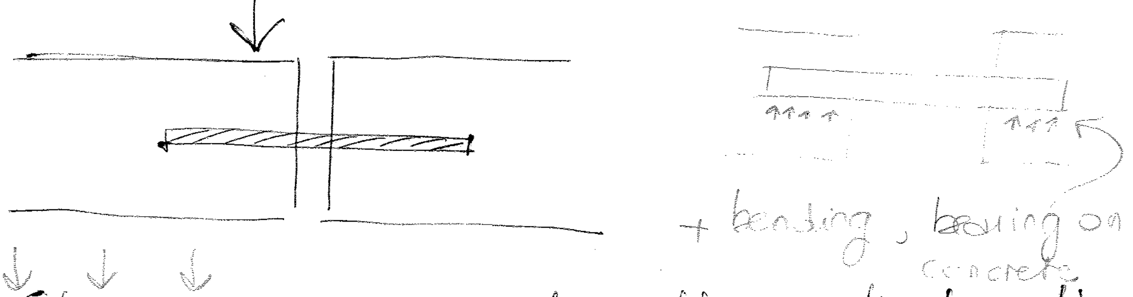
1 - distributed steel controls the width of crack opening (temperature cracking)
no structural function

2 - dowel bars transfer loads ; they have to be heavy and closely spaced to provide sufficient resistance; they must be smooth → they have to respond to shear stresses

3 - tie bars tie 2 slabs together to ensure load transfer

In detail :

2 Stresses in $\boxed{\text{dowel bars}}$



Shear response to the vertical action

Timoshenko's approach, Friberg's developments, numerical analyses (FEM)

N.B. Concrete is weaker than steel → size and spacing required are governed by the bearing stress between dowel and concrete

© Proprietà riservata dell'autore - Digitalizzazione e distribuzione a cura del CENTRO APPUNTI - Corso Luigi Einaudi, 55 - Torino / Pagina 47 di 318

deflection

$$y = \frac{e^{-\beta x}}{2\beta^2 EI}\left[P_t \cos\beta x - \beta M_\phi(\cos\beta x - \sin\beta x)\right]$$

β = relative stiffness of the bar

$$= \sqrt[4]{\frac{K b}{4 E_d I_d}}$$

K → modulus of bar support

$4E_dI_d$ → stiffness of the bar

$I_d = \frac{1}{64}\pi b^4$

b = diameter of the bar

M_ϕ = bending moment on the bar

17/10/13

- FRIBERG'S ANALYSIS (1940)

Solution of elastic line y

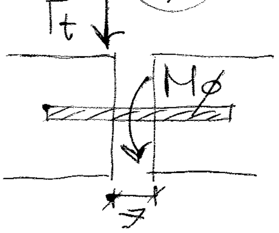
$$-EI \cdot \frac{d^2y}{dx^2} = M = -\frac{e^{-\beta x}}{\beta} \cdot \left[P_t \sin\beta x - \beta M_\phi \cdot (\sin\beta x + \cos\beta x)\right]$$

$$\frac{dM}{dx} = T = -e^{-\beta x} \cdot \left[(2\beta M_\phi - P_t) \cdot \sin\beta x + P_t \cos\beta x\right]$$

$$M_\phi = \frac{P_t \cdot z}{2}$$

z = joint opening

2 → not the entire load is transferred to the following bar



47

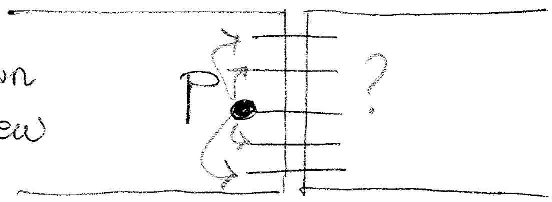
there is greater deflection and reactive forces under the loaded slab.

(Large) ?
High loads → loseness is almost not perceived → no reduction

In order to have a satisfactory perfor= mance, the dowel should be long enough
→ calculus of lenght → second point of counterflexure ($M = \phi$) is ok

Dowel group action

plan view



series of dowels

How is the load P distributed on dowels?

→ for interior and edge loadings

Point at 1,8 ℓ from the load → maximum negative moment → zero shear force

© Proprietà riservata dell'autore - Digitalizzazione e distribuzione a cura del CENTRO APPUNTI - Corso Luigi Einaudi, 55 - Torino / Pagina 51 di 318

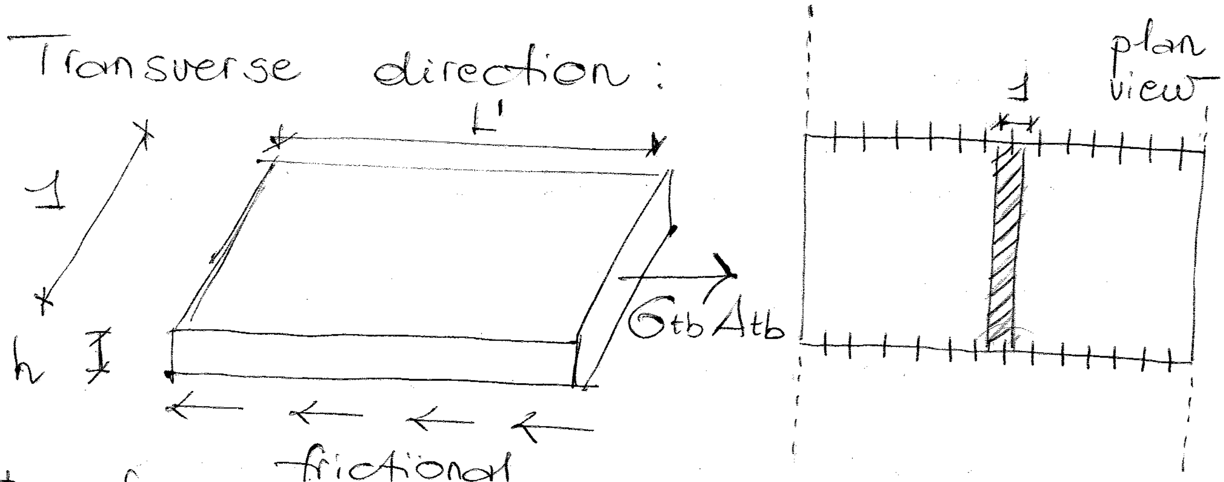
There are not temperature effects on dowels → they are free to move

3_ Stresses in $\boxed{\text{tie bars}}$ → they are placed along the longitudinal joint

Tie bars tie the 2 slabs together

Stresses in tie bars should be compatible with their resistance

Transverse direction:



distance from free edge

total cross section area of tie bars included in the unith width

$$\underbrace{\gamma_c h L' f_a}_{\text{resultant of frictional stresses}} = \underbrace{\sigma_{tb}}_{\text{resultant of normal stresses}} A_{tb} \quad \text{(equilibrium)}$$

$$\rightarrow \sigma_{tb} = \frac{\gamma_c h L' f_a}{A_{tb}}$$

allowable stress in steel

hp) all tensile stresses are taken by the steel alone

54

Once the pavement is cracked, this steel acts like a tie bar

$$\gamma_c \, h \, \frac{L}{2} \, f_a = \sigma_s A_s$$

$L \rightarrow$ lenght of the slab ($\neq L'$)

Formally is the same equation of tie bars

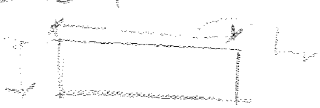
$$\sigma_s = \frac{\gamma_c \, h \, L \, f_a}{2 \cdot A_s}$$

design: Imposing a certain stress on steel, we can design the amount of steel A_s

σ_s can be reduced by increasing the cross section of the steel, or by reducing the slab lenght L: the last one is the most practical solution.

the calculus should be done also for the other direction L_y

Pre-fabricated wire:



if there is a big difference between L_x and L_y $\rightarrow$ waste of steel in the tranverse direction

c'è bisogno di meno acciaio

It is more convenient to design a

but in this case (railways) the factors are applied directly con dynamic loads

- longitudinal → traction, braking, acceleration, thermal loads, wave action under wheels
  ↳ as a result of a non perfect geometry of wheels and rails
  → roughnesses
  or because of the train movement → carico sulle ruote "dinamico"

  thermal loads → instability of rails → lose of gage

- transverse → centrifugal effects, wind, conical wheel and inclination, dynamic impact

All of these components are very important

- STRESSES IN $\boxed{\text{RAILS}}$

Bending stresses : vertical component of wheel loads

Bending stresses due to the lateral components of wheel loads, thermal forces, braking and acceleration

Contitutive equation:

$$p = -U \cdot y$$

U = modulus of track stiffness (elasticity)

high values of U → the rail is well supported (small deflection)

U depends on:
- number of ties
- geometry of ties
- ballast thickness
- ballast materials (angular, ...)
- subgrade
- type of rail

Equation of the elastic line:

$$E I \cdot \frac{d^4 y}{dx^4} + U \cdot y = \emptyset$$

I → inertial modulus of the track

solution →

$$y(x) = \frac{P}{(64 E I U^3)^{1/4}} \cdot e^{-\lambda x} (\cos \lambda x + \sin \lambda x)$$

Increasing E, I, U, the deflection will be reduced

$$EI \frac{d^3y}{dx} = \text{shear}$$

$$EI \frac{d^4y}{dx} = \text{unit pressure}$$ (identical to $y(x) = \dots$

Maximum values of those parameters:

$$y_\phi = -\frac{P}{(64\, EI\, U^3)^{3/4}}$$ under the loading point

$$M_\phi = P \cdot \left(\frac{EI}{64\, U}\right)^{1/4}$$ " "

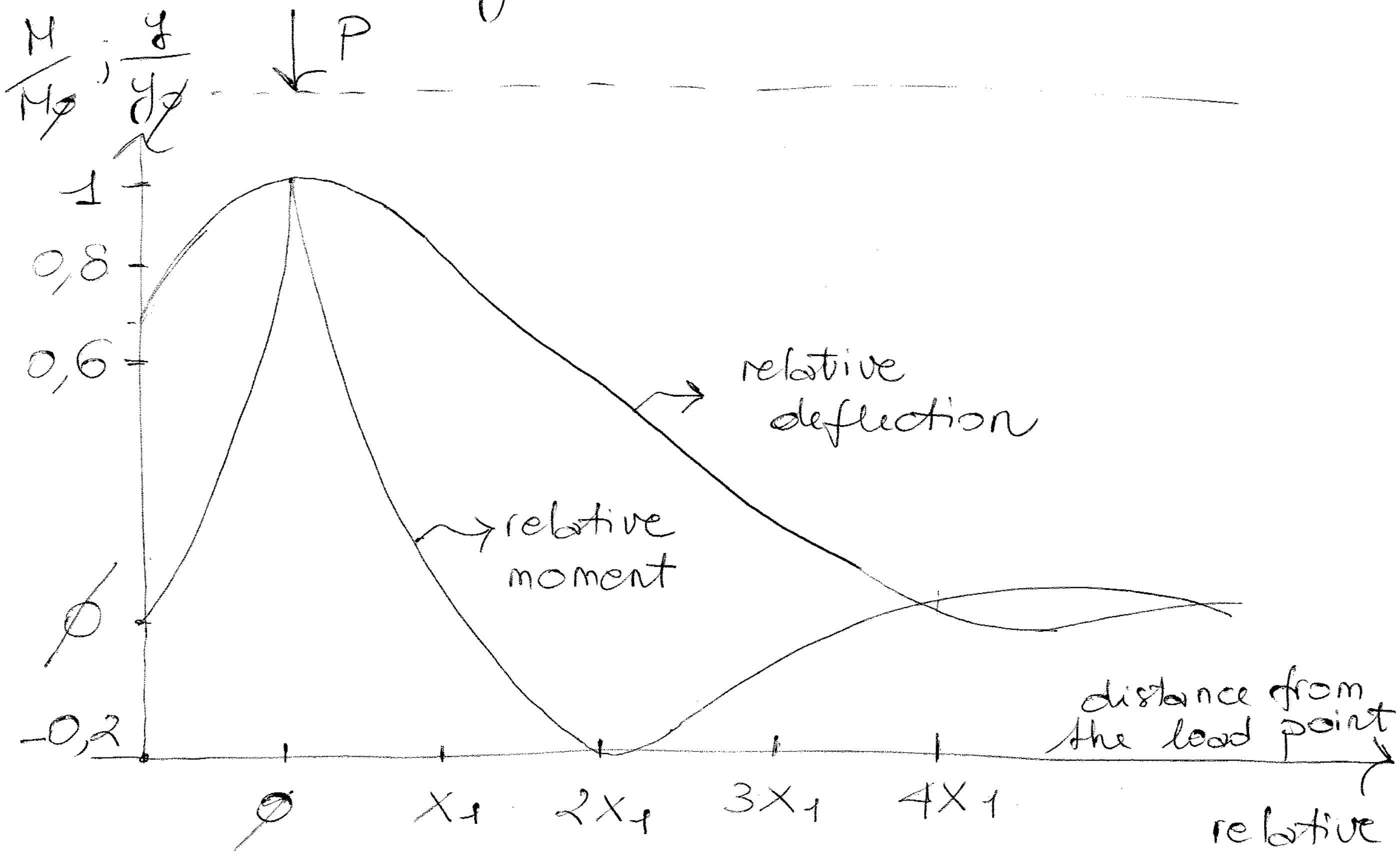
$$T_\phi = -\frac{P}{2}$$ " "

$$p_\phi = P \left(\frac{U}{64\, EI}\right)^{1/4}$$ " "

Under the loading point, the slope is zero.

© Proprietà riservata dell'autore - Digitalizzazione e distribuzione a cura del CENTRO APPUNTI - Corso Luigi Einaudi, 55 - Torino / Pagina 61 di 318

Master diagrams (Talbot)



relative scale (function of X_1)

Non dimentional representation (very useful) → it is good for every railway track.

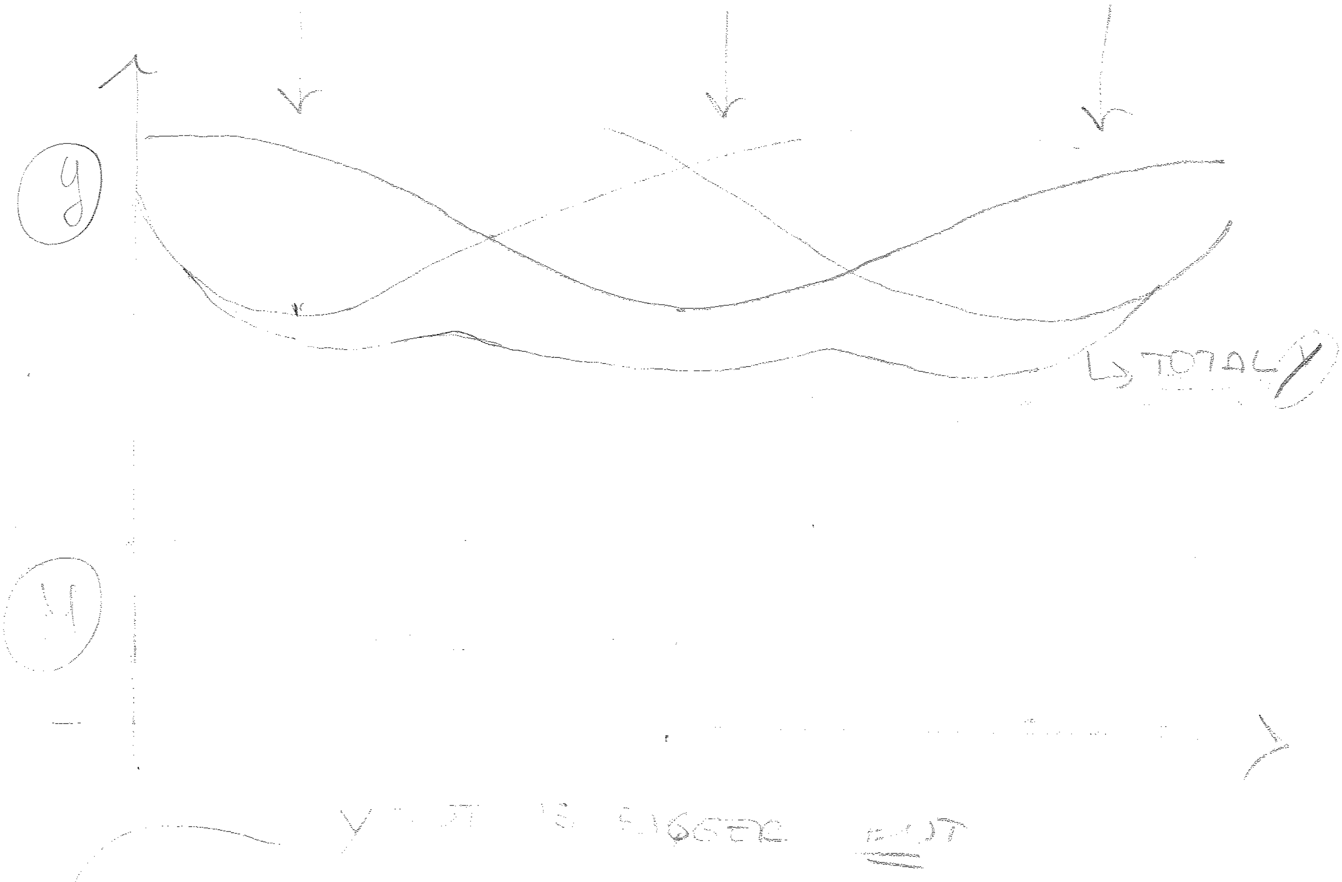
How much is the system sensitive? I try to change some parameters

1) 100 pounds rail (weight)

μ = 1500 pounds per inch per inch
modulus of track support

Multiple loading

The system is linear → superposition

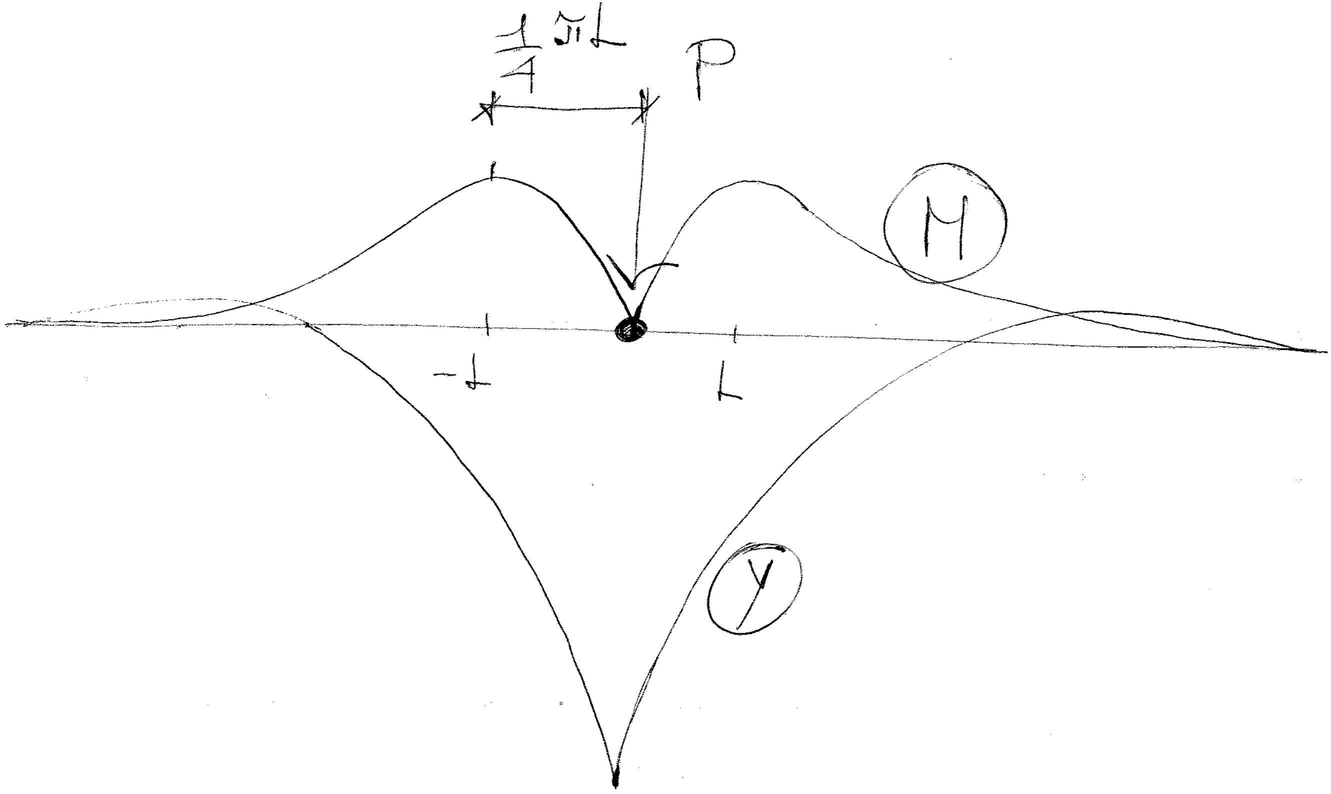


Flatter distribution of total deflection → the total moment is smaller

There is a more realistic description of the system?

- beam theory → good approximations
- infinite beam → there are points of discontinuity → non continuous rails

© Proprietà riservata dell'autore - Digitalizzazione e distribuzione a cura del CENTRO APPUNTI - Corso Luigi Einaudi, 55 - Torino / Pagina 65 di 318



Dynamic effects

Dynamic amplification factor (DAF)

$$P_d = DAF \cdot P_s$$

P_d → dynamic load

P_s → static load

→ statistical value

DAF depends on:

- speed
- contact patch (it depends on the weight)
- roughness of rails (level of maintenance)
- acceleration

© Proprietà riservata dell'autore - Digitalizzazione e distribuzione a cura del CENTRO APPUNTI - Corso Luigi Einaudi, 55 - Torino / Pagina 67 di 318

- ORE (European Organisation of Railways)

	DAF_{min}	DAF_{max}
Accele-ration	1,15	1,28
Decele-ration	1,07	1,11

The travel regime (change of speed) affects dynamic amplification

- Eisenmann

$$\begin{cases} DAF = 1 + t \cdot \varphi & \text{for } V < 60\,km/h \\ DAF = 1 + t \cdot \varphi \left(1 + \dfrac{V-60}{140}\right) & \text{for } 60 \leq V \leq 200\,km/h \end{cases}$$

$t = 1$ (68,3% rel.); $= 2$ (95,4% rel.);

reliability factor $= 3$ (99,7% rel.) (*)

level of maintenance track in:

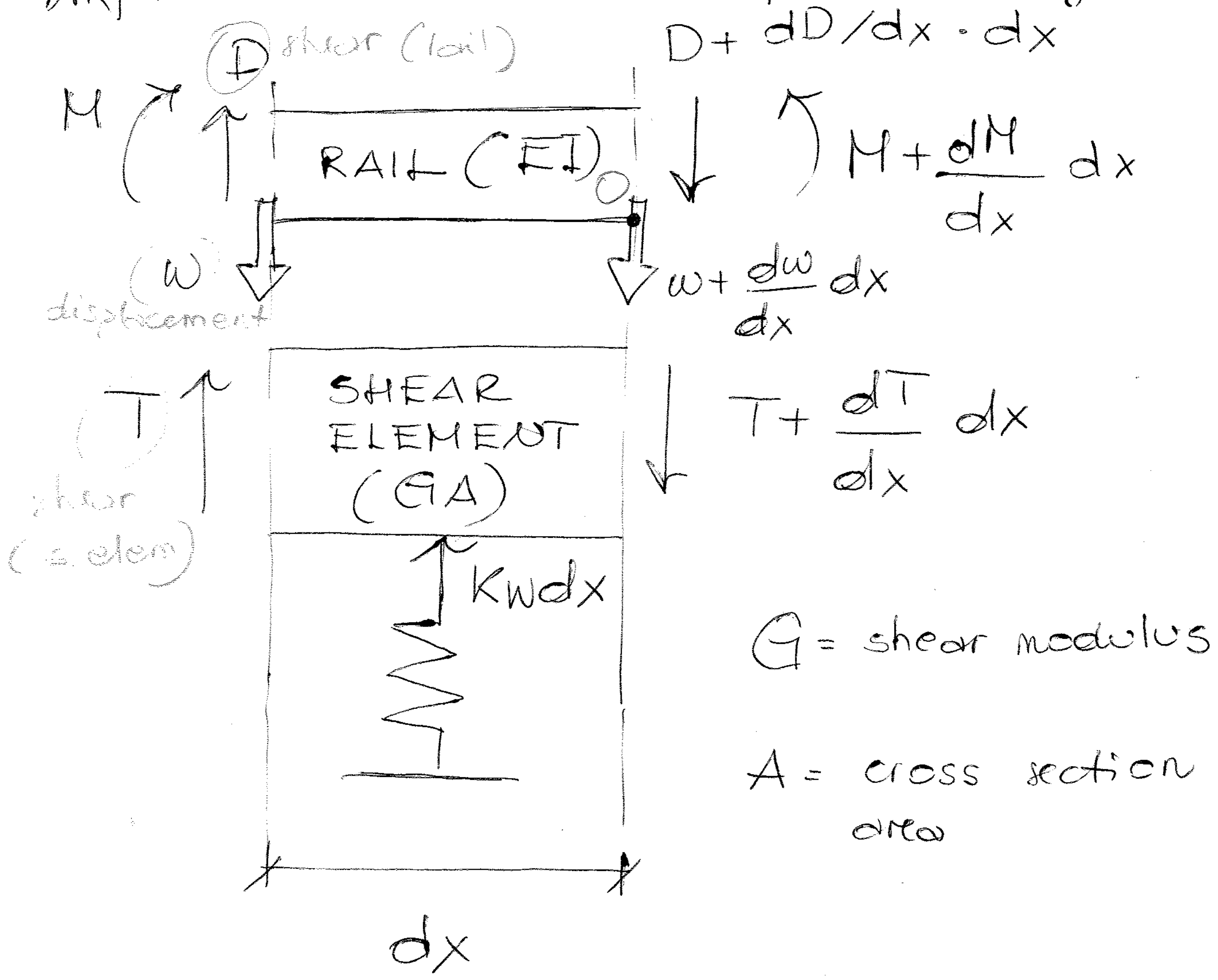
$\varphi = 0,1$ good conditions

$\varphi = 0,2$ standard conditions

$\varphi = 0,3$ bad conditions

67

Infinitesimal element of dx lenght :



Equilibrium equations:

↑

+ constit. equations $M = -EI \frac{d^2y}{dx^2}$

+ $T = GA \frac{dy}{dx}$

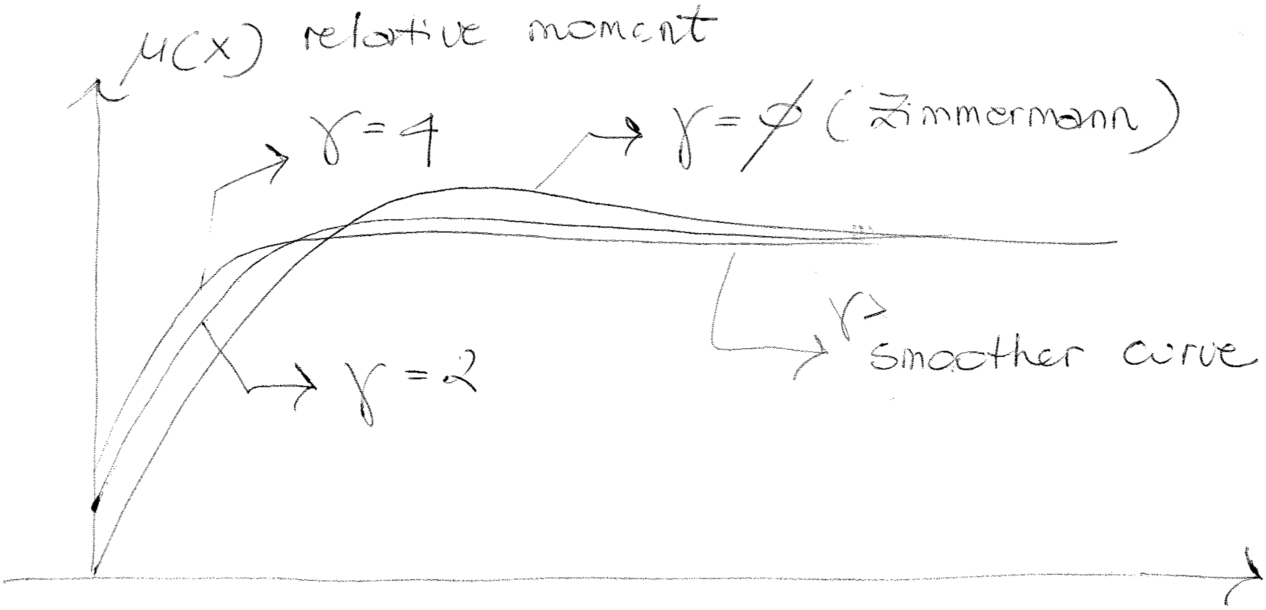
If $\gamma = \emptyset \rightarrow a = b = \beta$

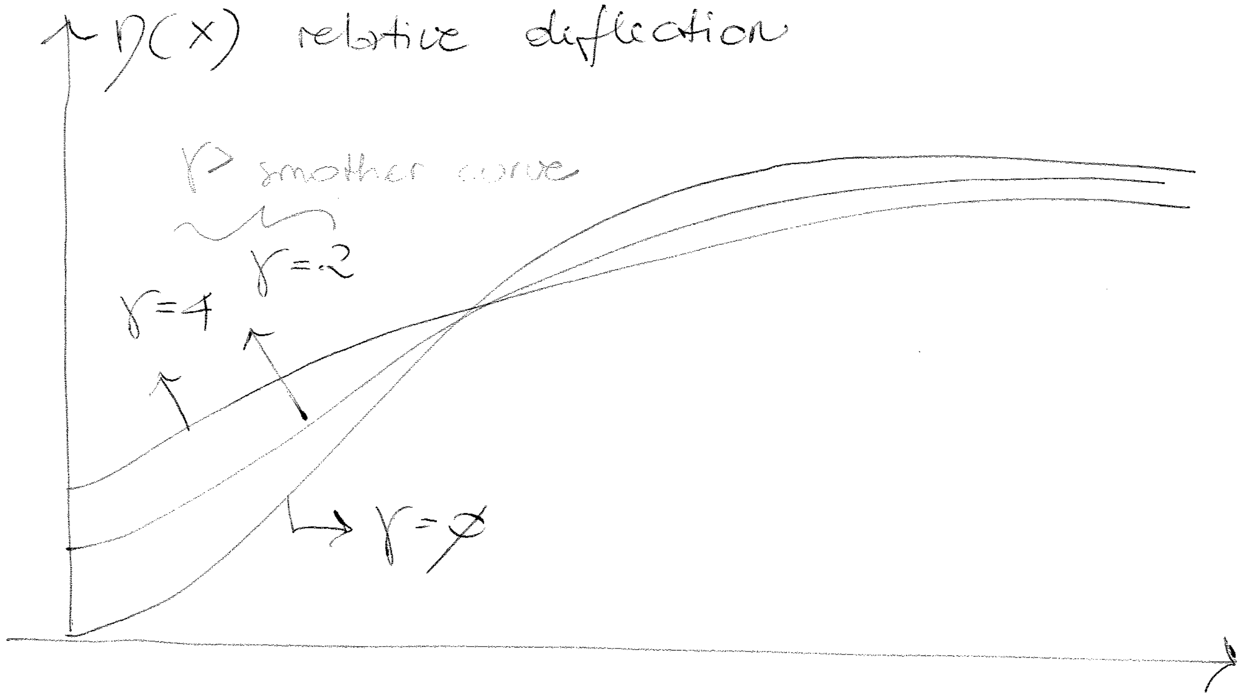
↳ solution = Zimmermann case

Equation of the bending moment:

$$M(x) = \frac{P}{4ab} e^{-bx} (a\cos ax - b\sin ax)$$

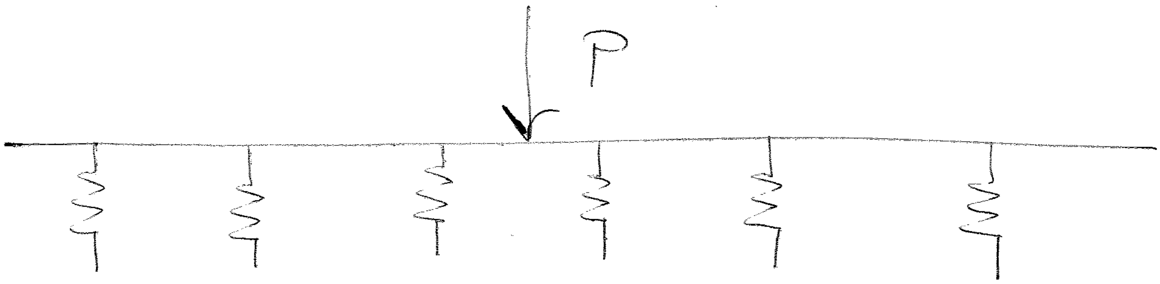
$= EIy''$





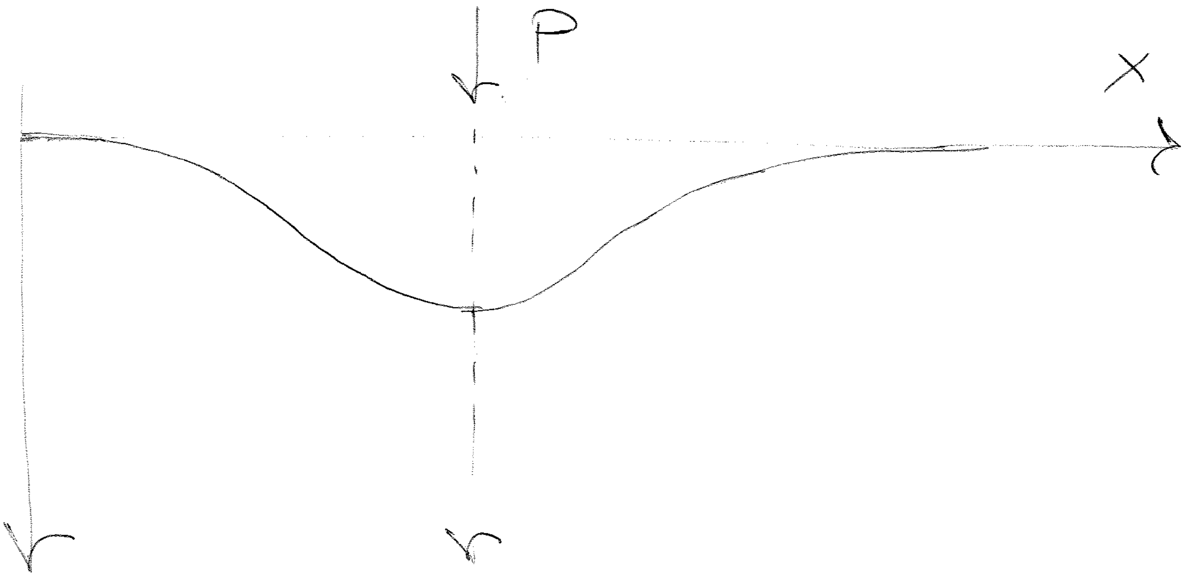
Scheme:

infinite beam, Winkler model (or Pasternak model, more complex)



The beam deflects under loading

$p = cy$ unit pressure



$$\int_{-\infty}^{+\infty} p(x)\,dx = P$$

$\rightarrow Q = 0,391\, P \simeq 40\%\, P$

order of magnitude of the seating load

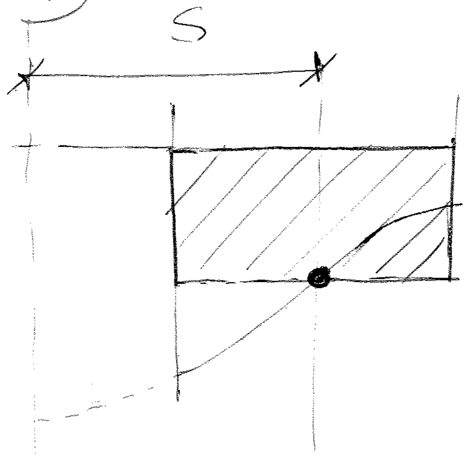
Moving away from the load, the values of P_i are smaller and in the end $\rightarrow \phi$

How can I calculate P_i?

1) $P_1 = \int_{-S/2}^{3S/2} p(x)\, dx$

...

2)

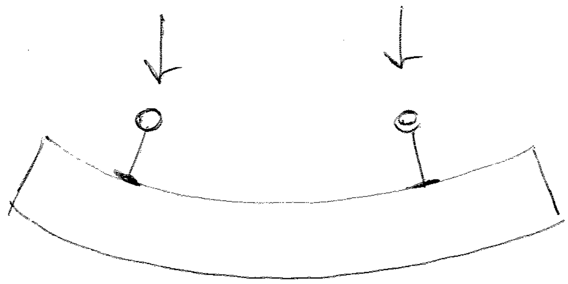


$y(s) \cdot u = p(s)$

point for s from the origin

SUPPORT MODEL → full support / end support

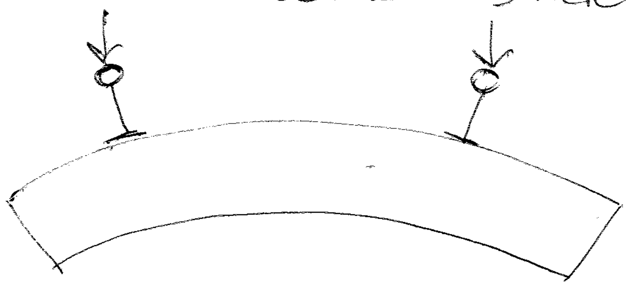
At the beginning:



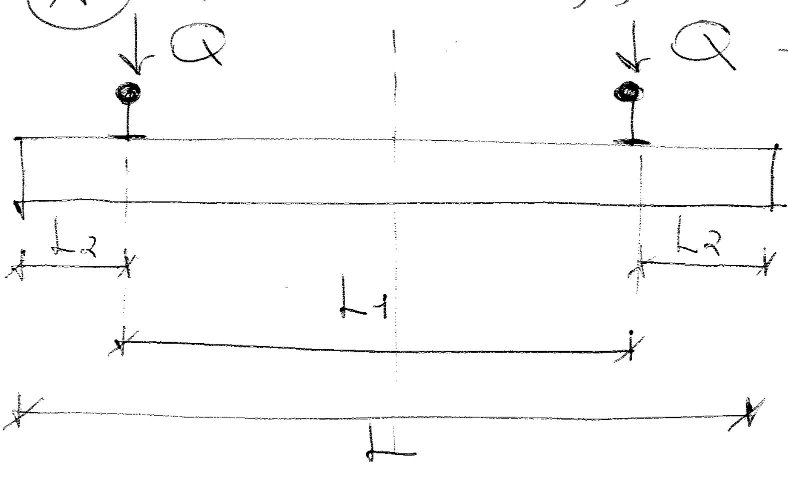
The system is supported by the ballast area under the tie → the centre is not supported → "free bending"

In time things change → looseness, compaction

center bound track



CASE (A) → RIGID BODY, FULL SUPPORT

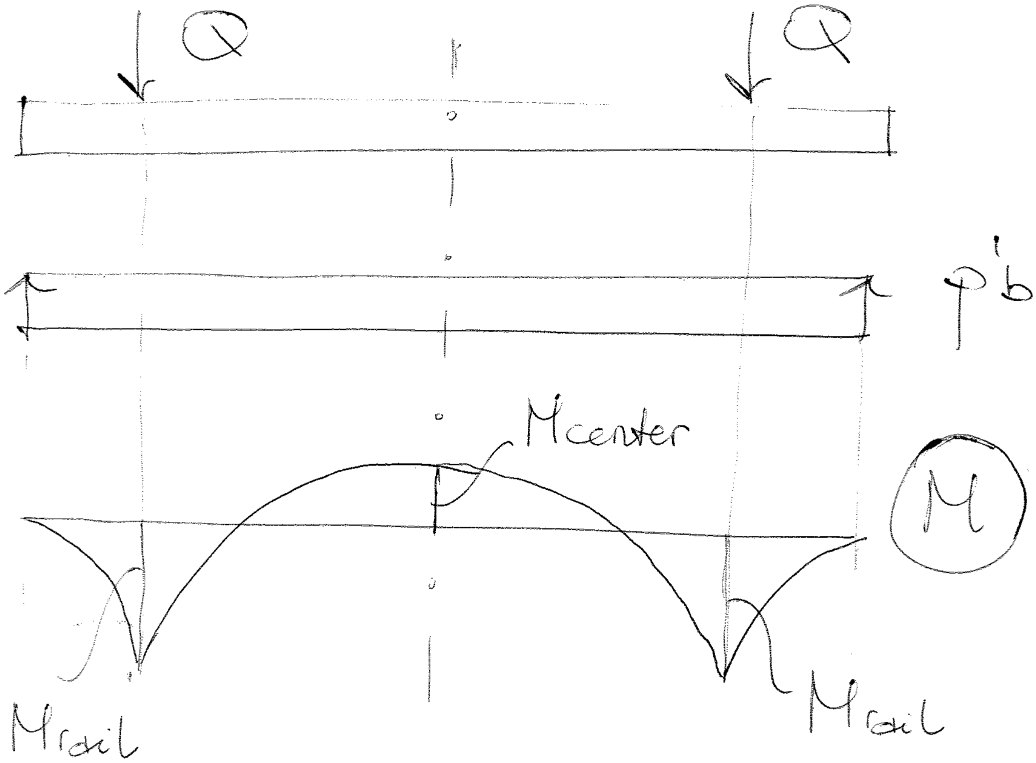


→ $Q_1 = Q_2 = Q$

↓

symmetrical loading

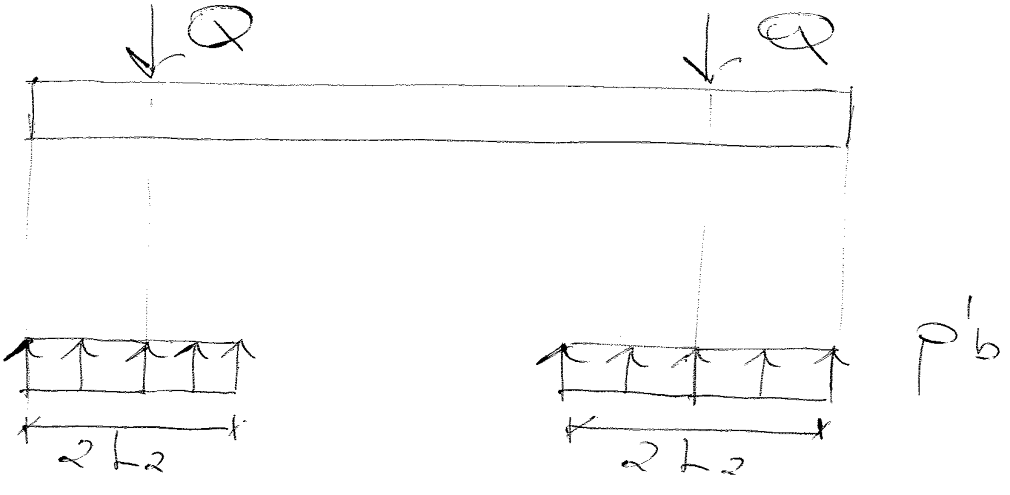
Section by section I can calculate the bending moment (rigid body)



$$\boxed{M_{rail}} = Q\frac{L_2^2}{L} = \frac{Q}{4}\frac{(L-L_1)^2}{L}$$

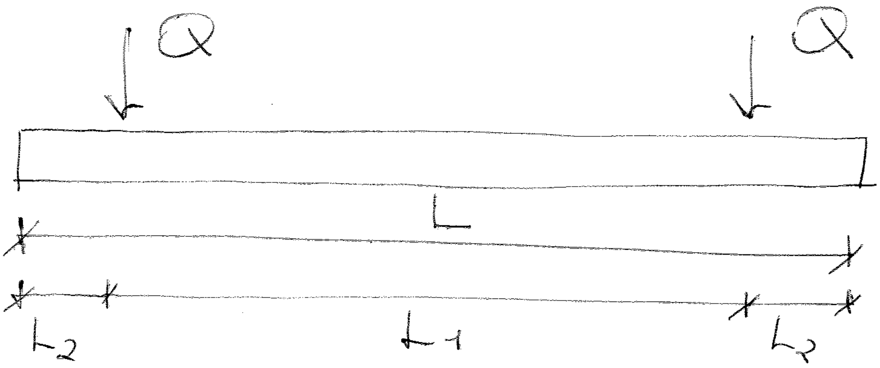
$$\boxed{M_{center}} = Q\left(\frac{L}{4}-\frac{L_1}{2}\right) = \frac{Q}{4}(L-2L_1)$$

CASE B → RIGID BODY, END SUPPORT



-79

CASE C → ELASTIC BEAM, FULL SUPPORT



We need to introduce constitutive models:

$$M = -EI \frac{d^2y}{dx^2}$$

$$p' = -uy \quad \text{(Winkler model)}$$

$$\frac{d^4y}{dx^4} + 4\alpha^4 y = 0 \quad \text{differential equation}$$

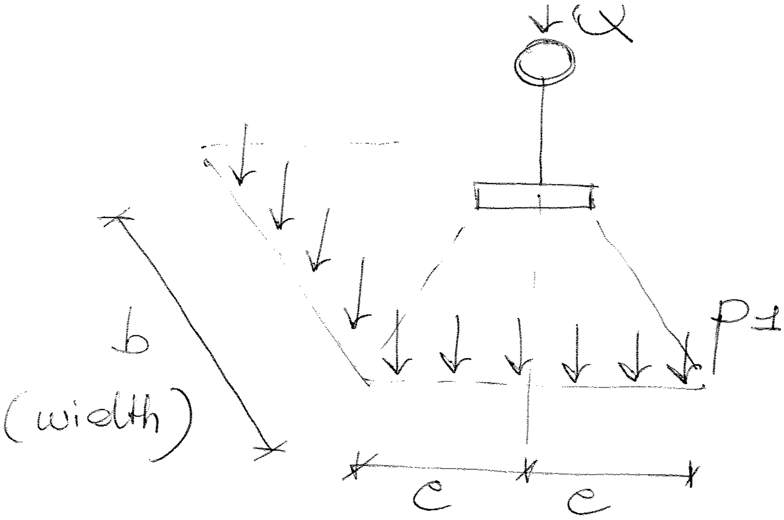
$$\alpha = \sqrt{\frac{kb}{4E_t I_t}}$$

b = width of the tie

E_t = modulus of elasticity of the tie

I_t = m. of inertia of the tie

81



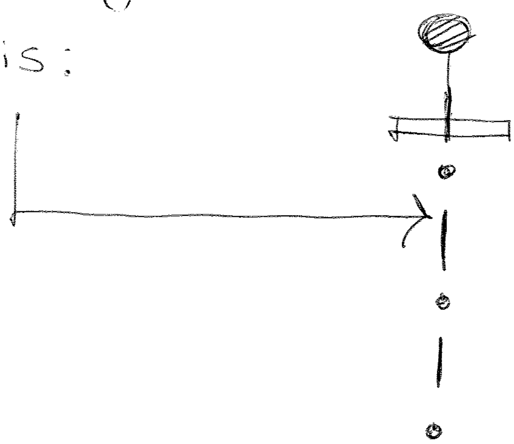
$$p_1 = \frac{Q}{2c \cdot b}$$

$$p_b = p_2 = \frac{Q}{2L_2 b}$$

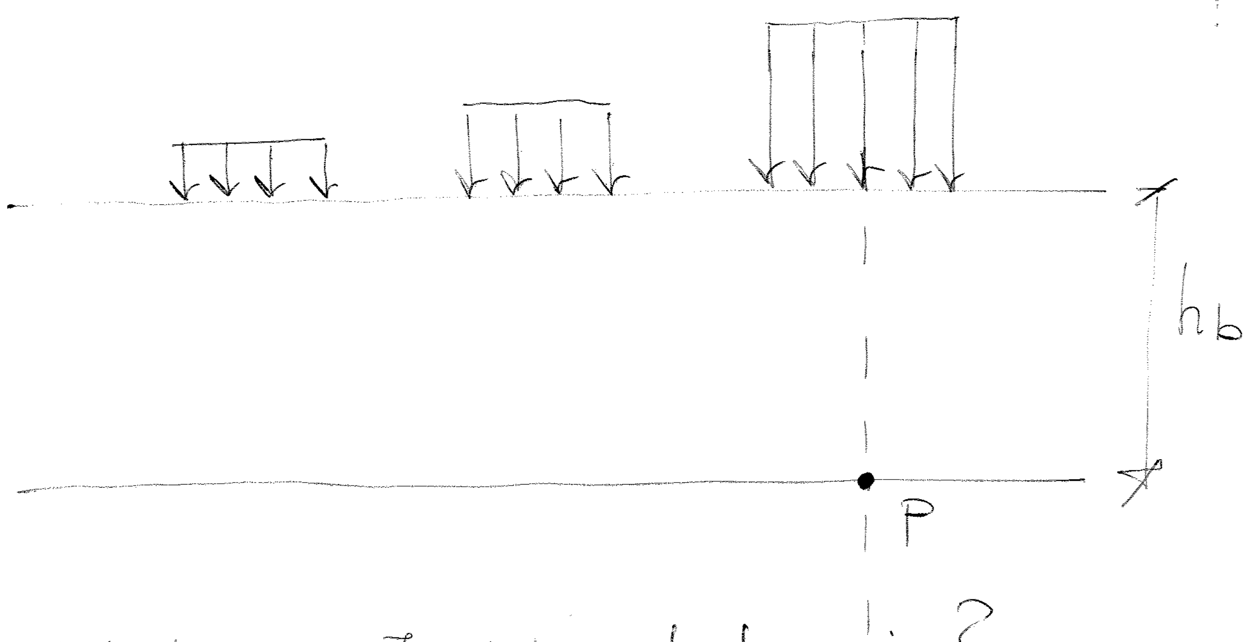
$$\boxed{M_{rail}} = \left(\frac{Q}{2L_2 b}\, b\, \frac{L_2^2}{2}\right) - \left(\frac{Q}{2eb}\, b\, \frac{e^2}{2}\right) =$$

$$= \frac{Q}{4}\left(L_2 - e\right)$$

bending moment calculated on the rail axis:



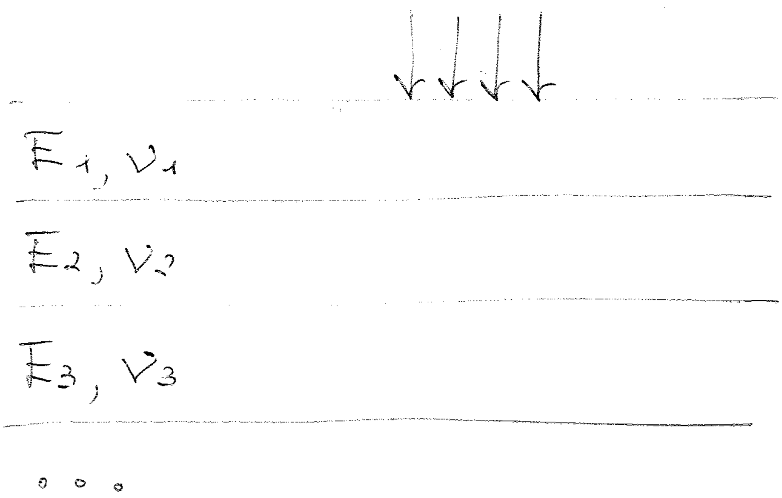
83



What am I interested in?

- stress in a generic point on the top of the subgrade (P)
- stresses distribution

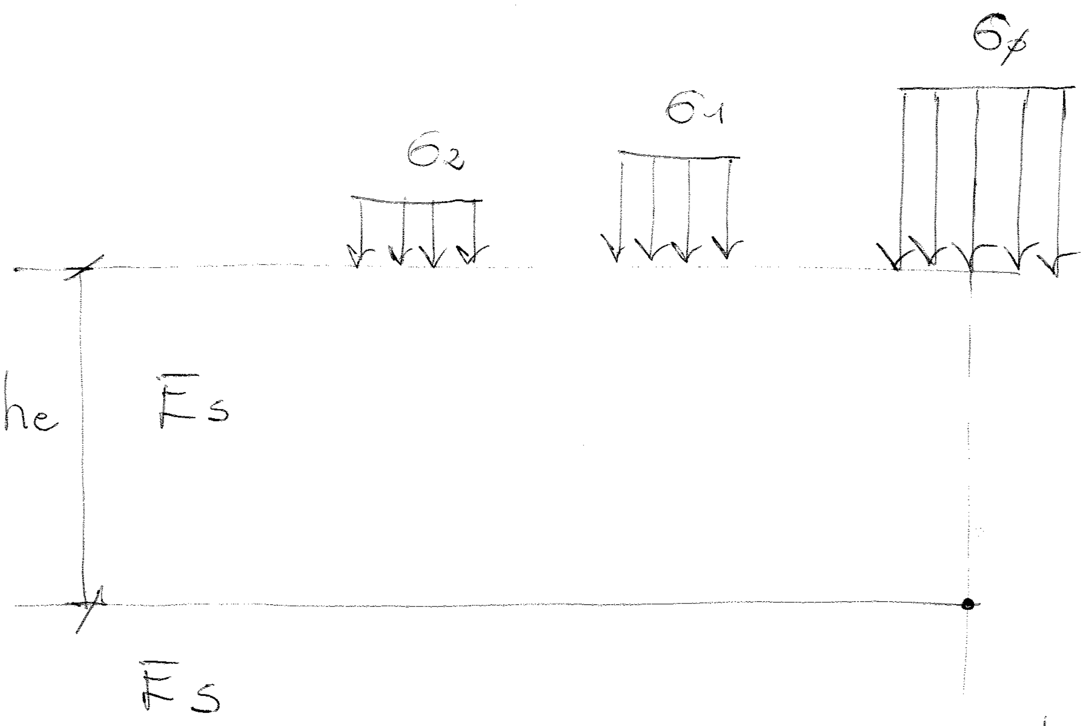
Multi layer elastic system



Cases:
- point load
- circular area
- strip

→ loading areas

Boussinesq (first solution), then extensions of this theory



physical thickness

h_e = equivalent thickness > h_b

because $E_b > E_s$

$$h_e = 0{,}9\, h_b \sqrt[3]{\frac{E_b}{E_s}}$$

The equivalent layer and real layer have the same bending stiffness

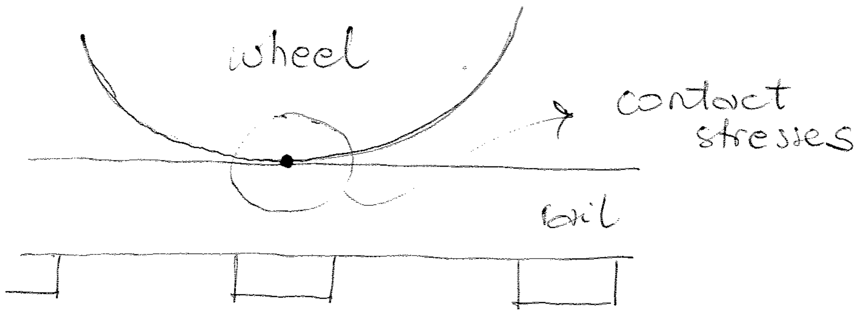
$\sigma_i \rightarrow$ surface pressure

$i = 0, 1, \ldots, n$

© Proprietà riservata dell'autore - Digitalizzazione e distribuzione a cura del CENTRO APPUNTI - Corso Luigi Einaudi, 55 - Torino / Pagina 89 di 318

CONTACT STRESSES

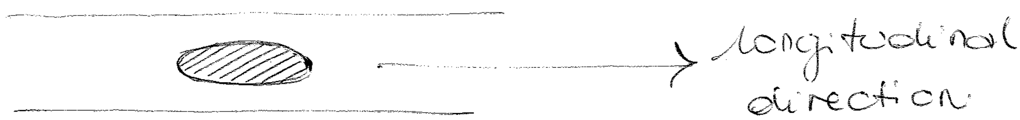
Small contact patch with very high stresses



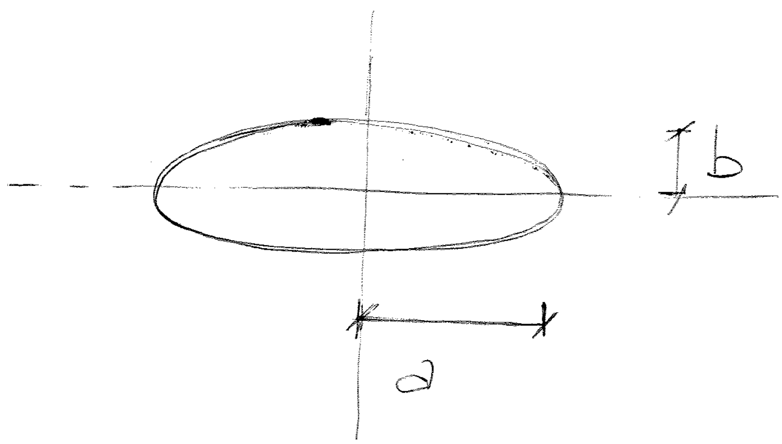
What is the actual shape of this contact area?

→ contact between 2 curved rigid bodies

The contact patch is elliptical

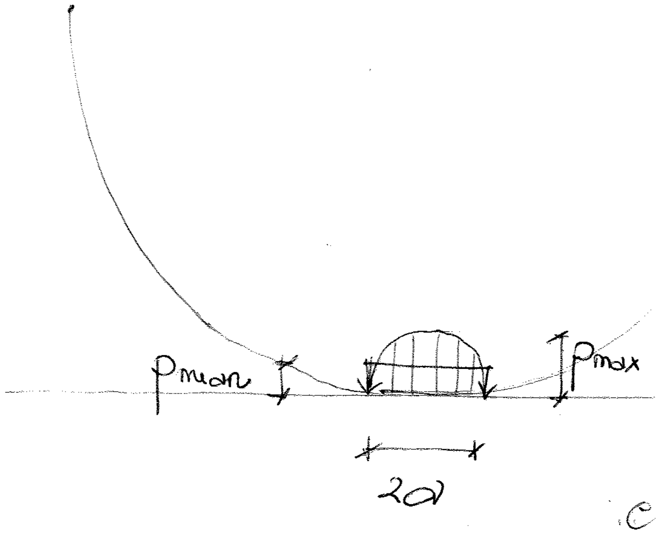


N.B The actual shape can change in time because of ... ?



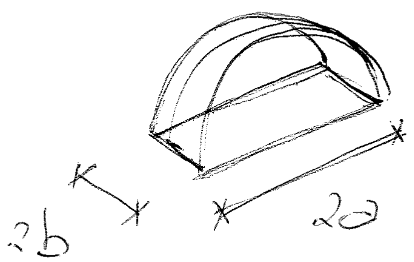
© Proprietà riservata dell'autore - Digitalizzazione e distribuzione a cura del CENTRO APPUNTI - Corso Luigi Einaudi, 55 - Torino / Pagina 91 di 318

$R_w \neq \emptyset$

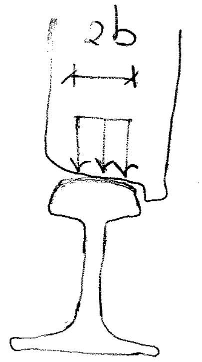


longitudinal direction: elliptical distribution

Transvers direction: uniform pressure



3D shape

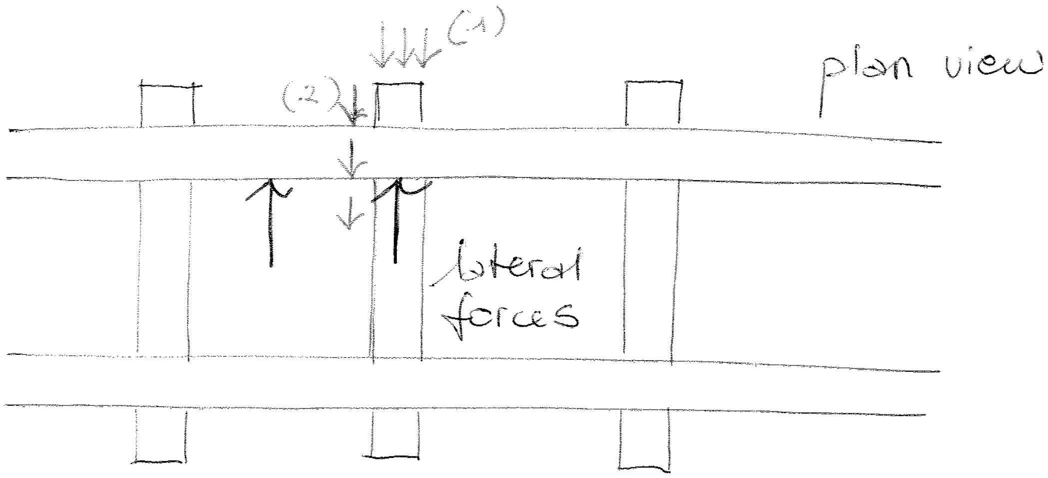


$$p_{mean} = \frac{P}{2a \cdot 2b} = \frac{P}{4ab}$$

Those pressures may lead to fractures

TRANSVERSE LOADING

Track response under transverse (lateral) loading



Rails are not free to move → resistance to lateral displacement → ties are incapsulated into ballast (1): shear stresses (friction) on the base and on the side (2) What model can we use

→ discrete resistent effect
(~ analogia discrete support described with springs for vertical loading)
↓
same model

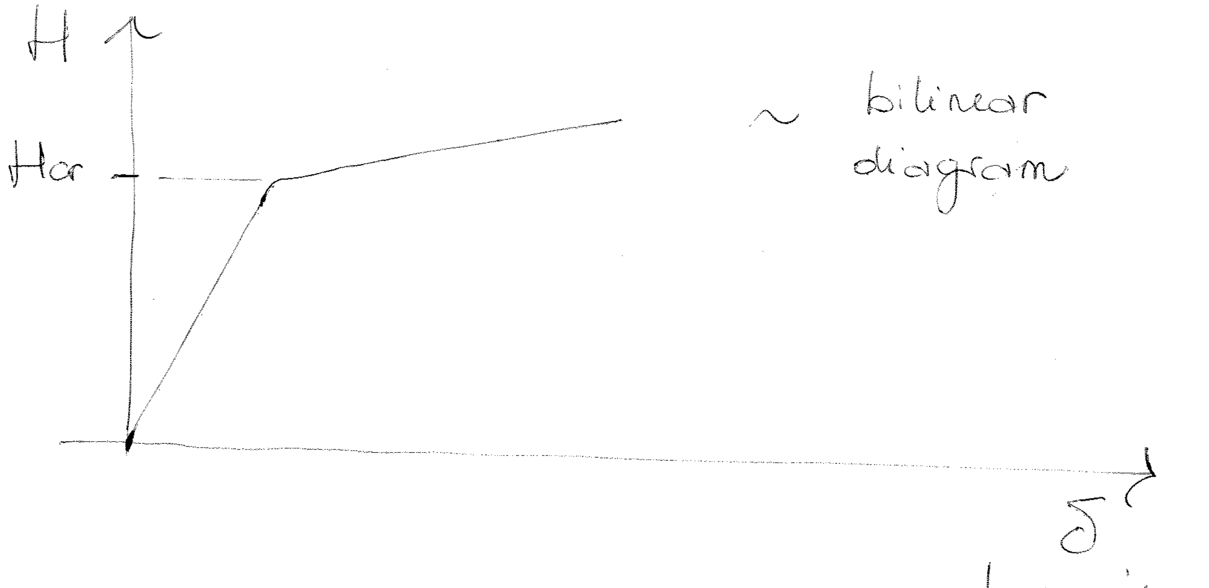
Resistance proportional to lateral displacement

$$EI \frac{d^4 z}{dx^4} - \frac{dc}{dx} + \tau = \emptyset$$

↓ Same theoretical approach of the response under vertical loading

PRUD'HOMME STUDIES

Response of a track under an increasing horizontal loading H



~ bilinear diagram

For $H < H_{cr}$:

The ballast is overcompacted → stiffer response from the system

$$\boxed{H_{cr}} = 1 + \alpha P$$

↳ vertical loading applied to the system

97

LONGITUDINAL LOADING

Thermal stresses cause longitudinal loading

Ties cannot freely move in the longitudinal direction and offer restraints to expansions and contractions

change in length → original rail length

$$\Delta l = \alpha \Delta T l$$

$$\varepsilon = \frac{\Delta l}{l} = \alpha \Delta T$$

↓ impedito

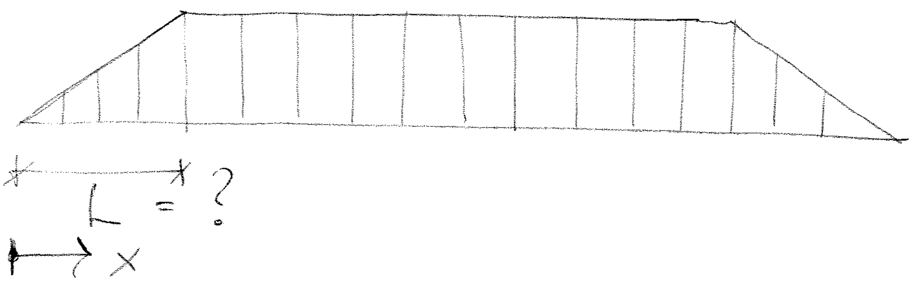
Birth of normal forces

$$N = A_{rail}\,\sigma_{rail} = A_{rail}\,\underbrace{E\,\alpha\,\Delta T}_{\sigma_{rail}}$$

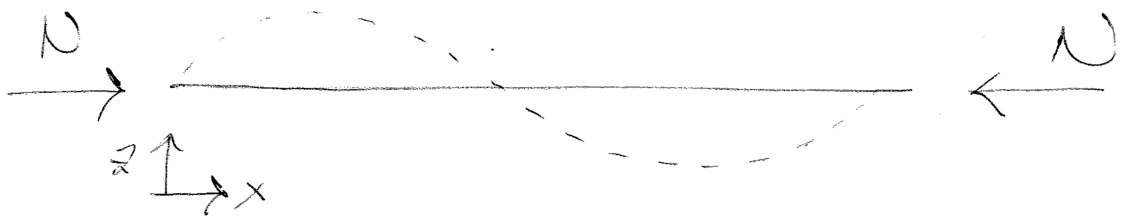
$$N_x = \frac{1}{2} r_a x$$

N_x ↓ for one rail

r_a ↓ total resistance (expressed for the entire track → 2 rails)



$$\frac{1}{2} r_a L = \alpha E \Delta T A_{rail}$$



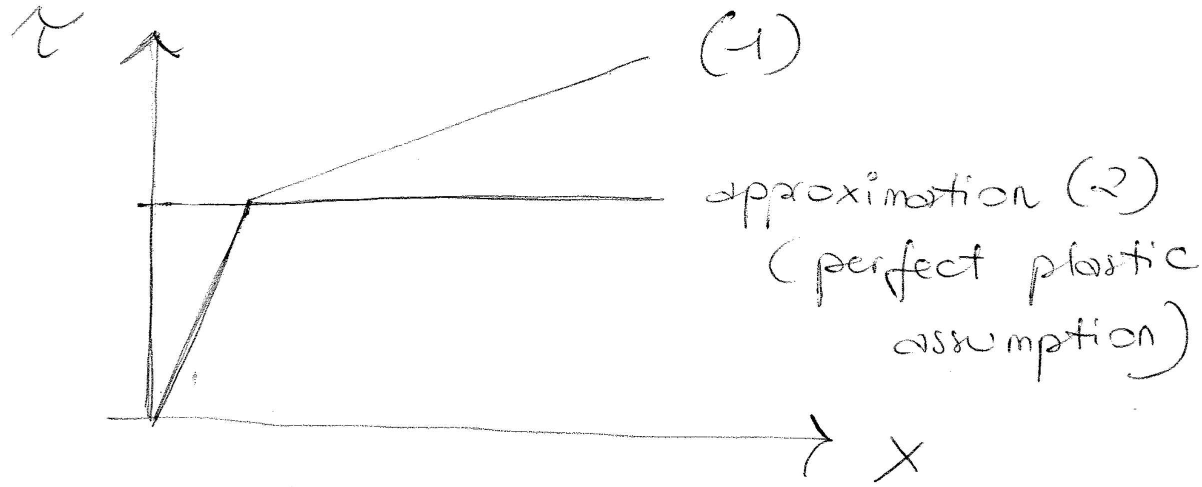
We need a function to describe the system

(*) $z(x) = z_\phi \sin \frac{2\pi x}{L}$ (buckling effect)

imposed displacement

(1) $\tau = -\beta z(x)$ (Winkler)

(2) τ = constant



Rail = beam

$$M = -EI \frac{d^2 z}{dx^2}$$

Impose equilibrium:

$$\frac{\partial W_{TOT}}{\partial z_\phi} = \phi \quad \text{(first derivative = zero)}$$

$$\hookrightarrow N = \frac{4\pi^2 EI}{L^2} + \frac{\beta L^2}{4\pi^2}$$

Is the system in a stable or in an unstable situation?

$$\frac{\partial^2 W}{\partial z_\phi^2} \overset{\text{stability}}{>} \phi \rightarrow N < \frac{4\pi^2 EI}{L^2} + \frac{\beta L^2}{4\pi^2}$$

$$\frac{\partial N}{\partial L} = \phi \rightarrow L_{cr}^2 = 4\pi \sqrt{\frac{EI}{\beta}}$$

first der. of N with respect to L

define the critical lenght

$$\rightarrow \boxed{N_{cr} = 2\sqrt{\beta EI}}$$

Imposing $\beta = \phi \rightarrow$ no lateral restrain $\rightarrow$ Euler's case

Stability:

$$\frac{\partial^2 W}{\partial z^2} > 0 \longrightarrow N < \frac{4\pi^2 EI}{L^2}$$

Critical condition:

$$\frac{\partial N}{\partial L} = 0 \longrightarrow L_{cr}^2 = 2\sqrt{\frac{\pi^5 f_0 EI}{\tau_0}}$$

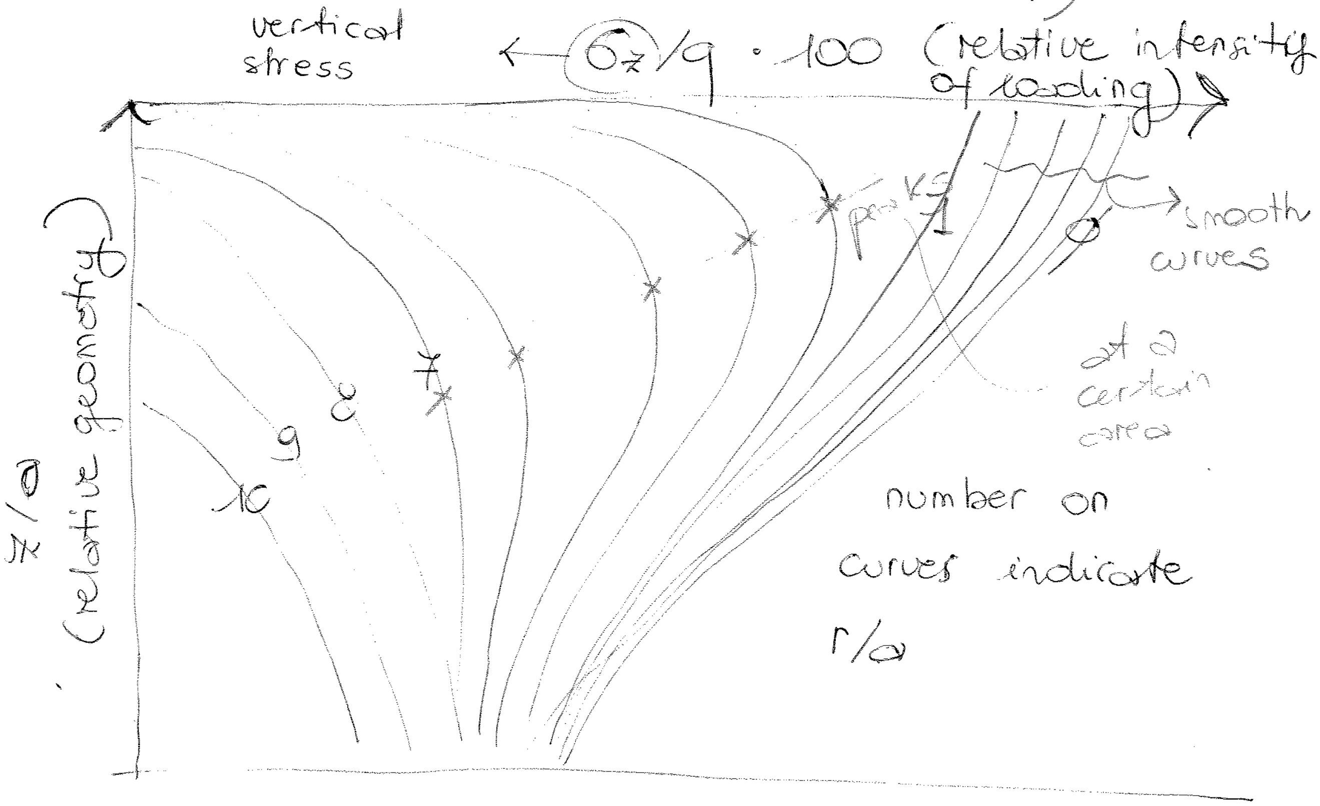
In the reality, when we have misallinements,
We need to have good DATA to extimate $\underline{\underline{f(x)}}$

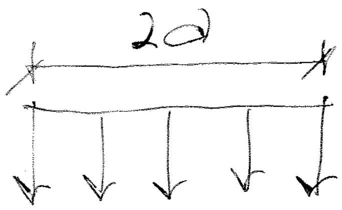
No point loading → extension of the theory

Distributed loading → circular area → integration of Boussinesq's formulas

Close solution only for center line

Charts solutions, equations and tables which provide solutions for points which are away from the center line (Foster and Alvin, 1954)



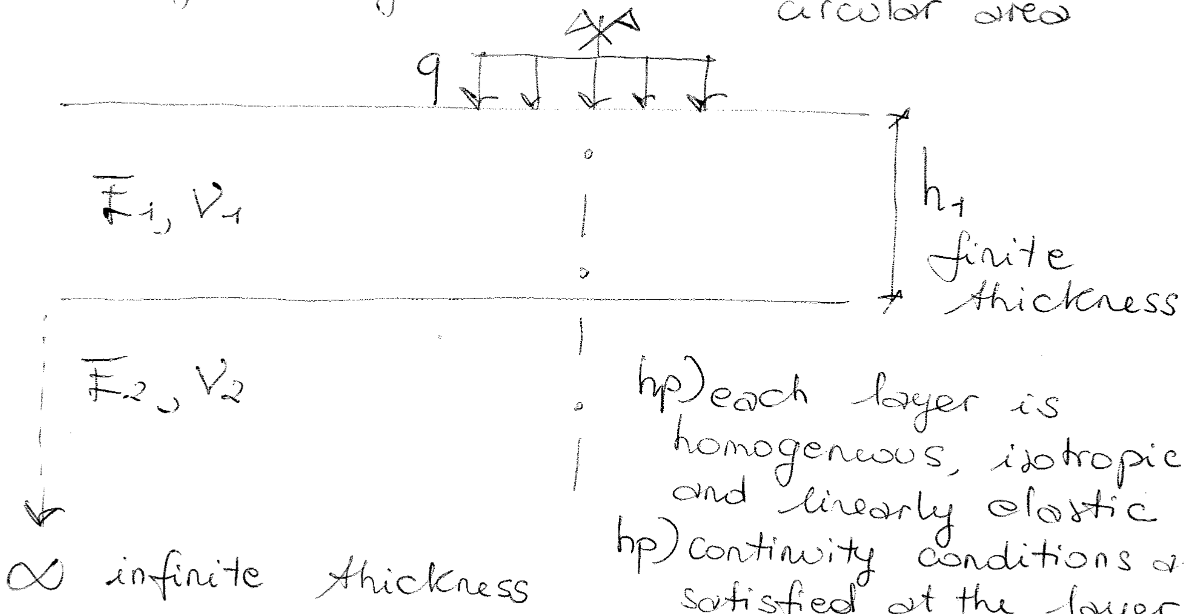


z = depth
r = distance from the axis

© Proprietà riservata dell'autore - Digitalizzazione e distribuzione a cura del CENTRO APPUNTI - Corso Luigi Einaudi, 55 - Torino / Pagina 107 di 318

- BURMISTER (1943)

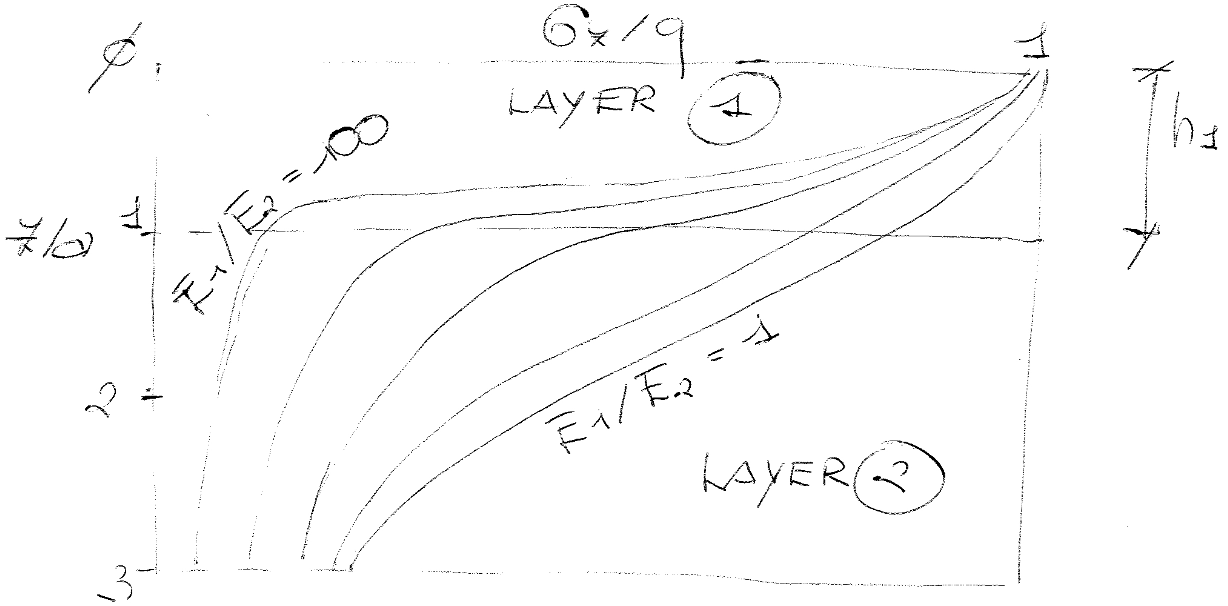
2 - layer system



hp) each layer is homogeneous, isotropic and linearly elastic

hp) continuity conditions are satisfied at the layer interfaces

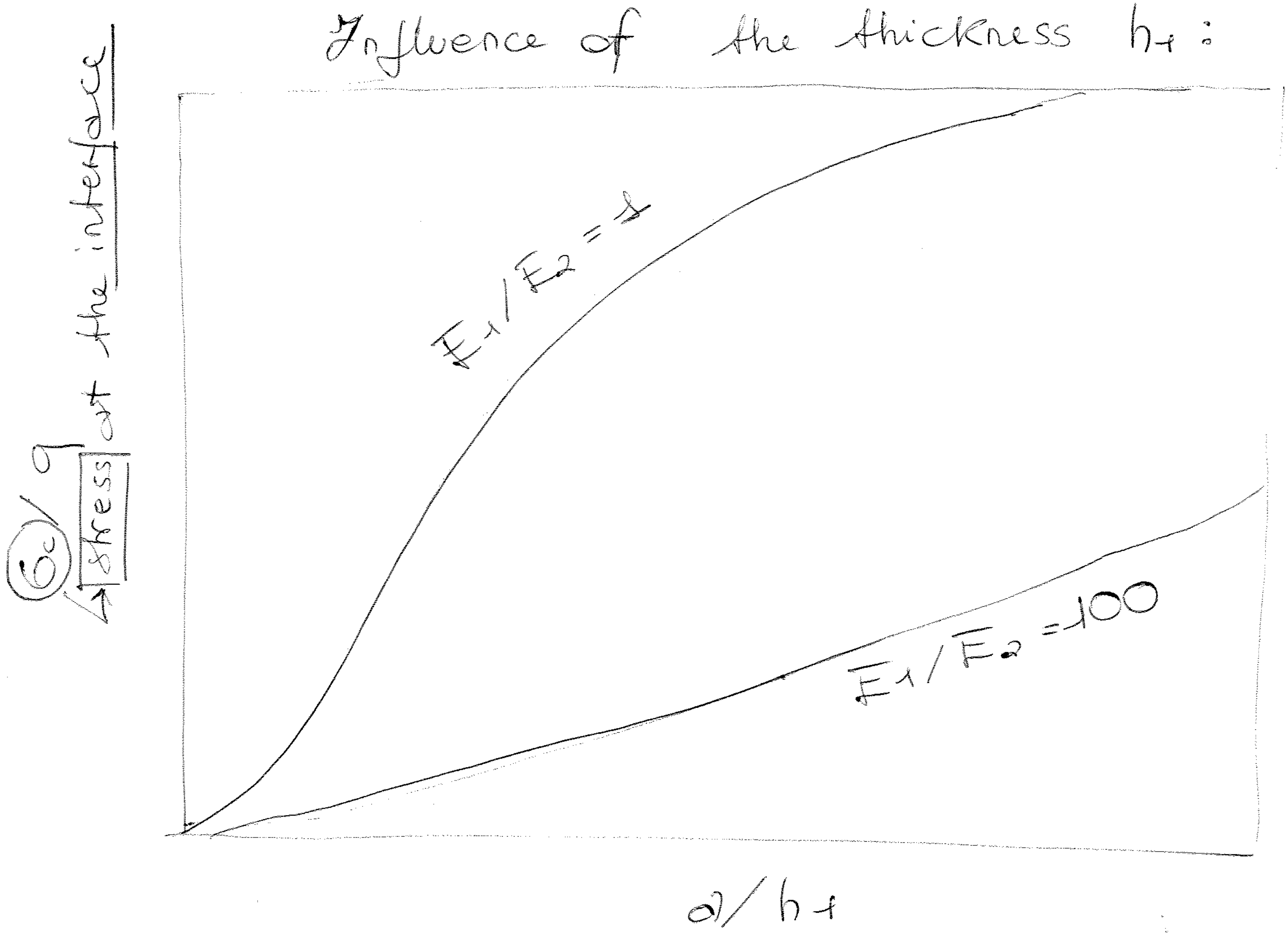
The relative stiffness of the layers controls the response of the system



ε_z is used most frequently as design criterion: this is valid for highway and airport pavements, because ε_z is caused mainly by σ_z, the effect of the horizontal stress is small ≠ railways

109

Influence of the thickness h_1:



The system is sensitive in different ways (depending on the value of $\frac{E_1}{E_2}$) to thickness variation

E_1/E_2 high (the material on top is very stiff) → < slope of the curve (I need very high variation of the thickness to have variations on the distribution of stresses)

E_1/E_2 variation → Δ thickness → different in case of the study of stresses or displacements

$$\sigma_{z2} - \sigma_{r2} = q\,(ZZ2 - RR2)$$

Tabular solution:
ZZ1, ZZ2, RR1, RR2 are numbers function of K_1, K_2, A, H (input values)

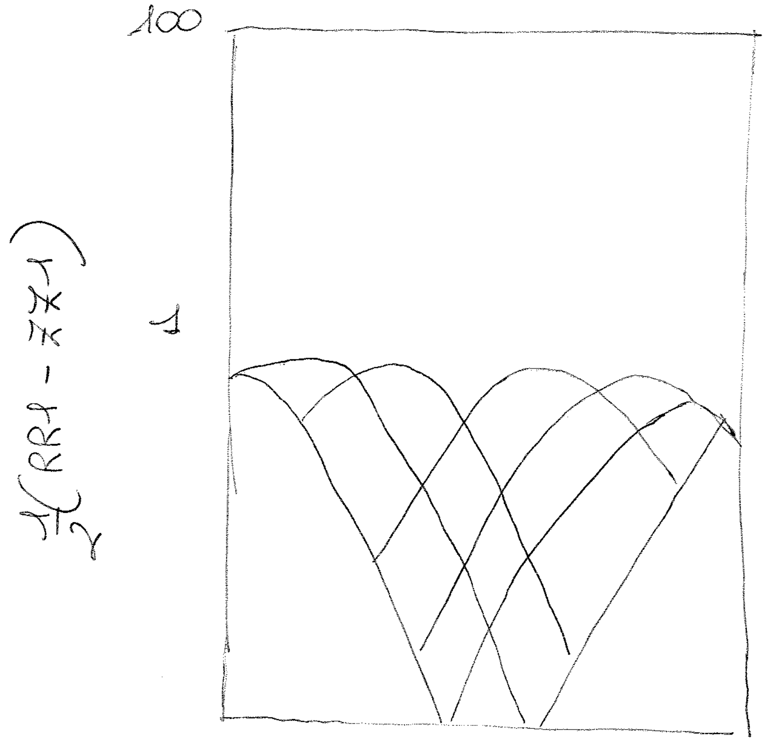
- PEATTIE (1962)

$$\varepsilon_r = \frac{q}{E}\left(\underbrace{\frac{RR1 - ZZ1}{2}}_{\text{horizontal strain factor}}\right)$$

radial stress (at the bottom of layer 1)

4 sets of K_1 and K_2

4 Charts for the evaluation of $(RR1 - ZZ1)/2$



© Proprietà riservata dell'autore - Digitalizzazione e distribuzione a cura del CENTRO APPUNTI - Corso Luigi Einaudi, 55 - Torino / Pagina 113 di 318

Limitations of the multi-layer elastic theory:

1- Is the pavement system indefinite in width?
This assumption is quite realistic - in case the load is applied at more than 0,6 m from the edge (because flexible pavements are not as stiff as rigid pavements)

2- Constant thickness of layers
NO there are thickness variation

3- Is the surface pressure vertical and uniform over a circular area?
NO we have shear stresses, the loading area is not circular

4- Are pavement layers perfectly bonded to each other? NO

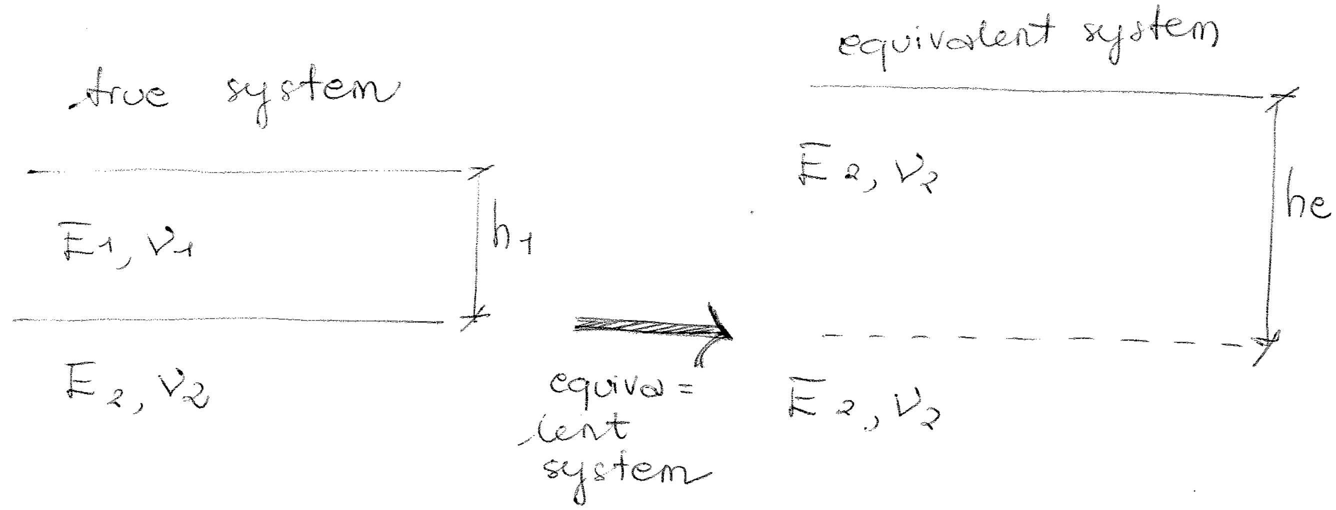
© Proprietà riservata dell'autore - Digitalizzazione e distribuzione a cura del CENTRO APPUNTI - Corso Luigi Einaudi, 55 - Torino / Pagina 115 di 318

30/10/13

Alternative method (multi-layer systems):

METHOD OF EQUIVALENT THICKNESS (MET)

We've seen it for tracks



→ Stresses and strain below the top layer

$$\frac{h^3 E}{1-\nu^2}$$ → flexural bending stiffness of the top layer is proportional to this quantity

$$\frac{h_1^3 E_1}{1-\nu_1^2} = \frac{h_e^3 E_2}{1-\nu_2^2}$$

This method can be applied to a multi-layer system by iteration

$$\boxed{h_{e,n}} = f \times \sum_{i=1}^{n-1} h_i \sqrt[3]{\frac{E_i}{E_n}}$$

→ homogenize the system by progressive iteration

Calculus of displacements (total deflection):

tot. deflect. = sum of the compressions which occur in every layer + the deflection on the top of the subgrade.

When does this method work properly?

Hypotesis:

1) $E_1 > E_2 > E_3 > \dots$ the modulus E must decrease with depth

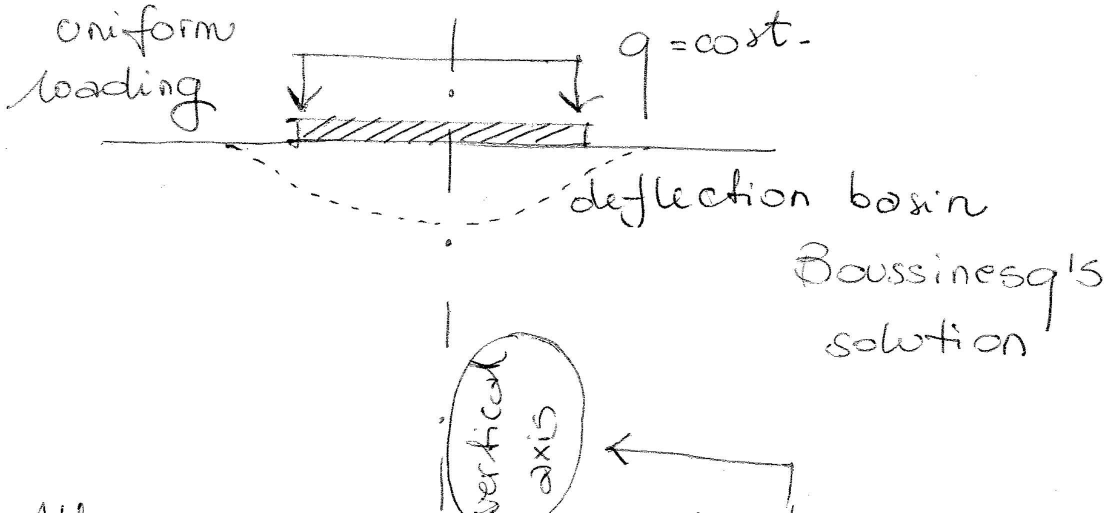
2 cases:

1) flexible plate → constant pressure distribution

2) rigidid plate → parabolic distribution of vertical stresses

In detail:

1_ flexible plate



All quantities are calculated here

$$\sigma_z = q\left[1 - \frac{z^3}{(a^2+z^2)^{1,5}}\right] \xrightarrow{f} \begin{cases} \text{loading } (q) \\ \text{geometry } (a) \\ \text{depth } (z) \end{cases}$$

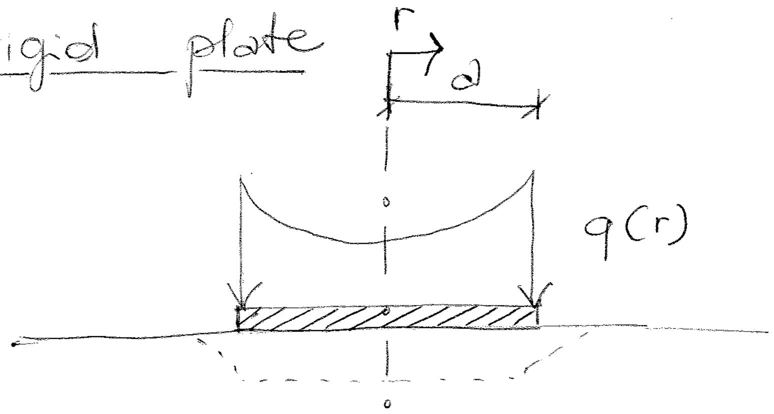
vertical stress

$$\sigma_r = \frac{q}{2}\left[1+2\nu - \frac{2(1+\nu)}{(a^2+z^2)^{0,5}} + \frac{z^3}{(a^2+z^2)^{1,5}}\right]$$

radial stress

$$\xrightarrow{f} \begin{cases} \text{loading } (q) \\ \text{depth } (z) \\ \text{geometry } (a) \\ \text{Poisson's ratio } (\nu) \end{cases}$$

2- rigid plate



Ollitz (1987)

$$q(r) = \frac{q a}{2(a^2 - r^2)^{0,5}}$$ pressure distribution

Boussinesq's solution for this particular distribution:

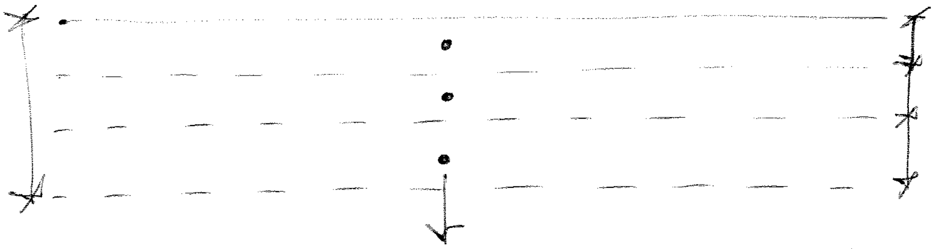
$$w_\phi = \frac{\pi (1 - \nu^2) q a}{2E}$$

↳ the displacement for the same radius and pressure is slightly smaller than the one which occurs in case of flexible plate

© Proprietà riservata dell'autore - Digitalizzazione e distribuzione a cura del CENTRO APPUNTI - Corso Luigi Einaudi, 55 - Torino / Pagina 123 di 318

The axial deformation depends on the magnitude of confining pressures.

hp) $E_{hp,i}$ initial modulus, assumed for each layer



sublayers

- calculate stresses in those points

$E = (\theta)$

$E = (\sigma_d)$

these functions are known (stress dependency)

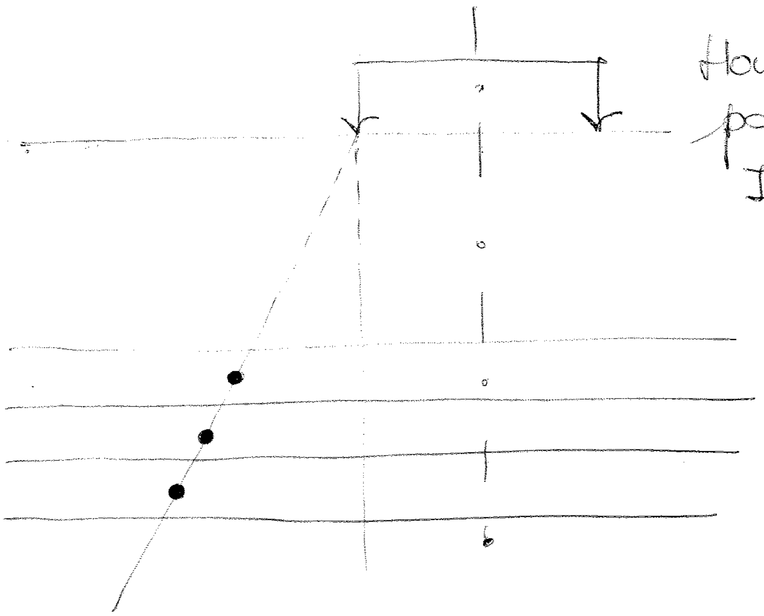
θ = stress invariant $(\sigma_1 + \sigma_2 + \sigma_3)$

↳ new modulus $E_i = E_\emptyset (1 + \beta\theta)$

$E_\emptyset$: modulus when $\theta = \emptyset$

...

→ convergence $E \simeq E_{hp}$



How can I choose points in which I calculate stresses?

4/11/2013

DISTRESS MANUAL

This manual is divided in sections

1. Distresses for pavements with asphalt concrete surfaces

- CRACKING
- PATCHING AN deterioration POTHOLES (formation)
- SURFACE DEFORMATION
- SURFACE DEFECTS
- MISCELLANEOUS DISTRESSES

2. Distresses for pavements with jointed cement concrete surfaces

- CRACKING
- JOINT DEFICIENCIES
- SURFACE DEFECTS
- MISCELLANEOUS DISTRESSES

fatigue failure of asphalt surface / stabilized base

As the severity of cracking increases, you will have multiple cracking

- **Fatigue cracking** → series of interconnecting cracks caused by repeated traffic loadings

  Low, moderate and high severity level

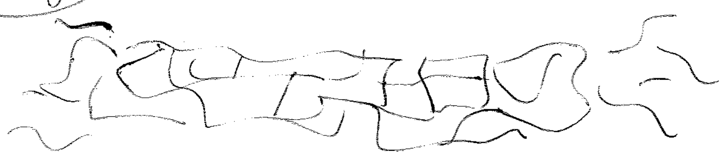
  Unit of measure:
  square meters of affected area

low

isolated cracks (non interconnected)

medium

high



big area, lot of interconnections

© Proprietà riservata dell'autore - Digitalizzazione e distribuzione a cura del CENTRO APPUNTI - Corso Luigi Einaudi, 55 - Torino / Pagina 129 di 318

- Edge cracking

Different support
on confined area

Crescent - shaped cracks

~ 0,6 m of the pavement edge

Different severity levels based
on the loss of material degree:

- low: no loss of material
- moderate: < 10 %
- high: > 10 %

- Longitudinal cracking — record separately

Positions:
- in the wheel path (inner + outer)
- outside the wheel path

The width of the cracks defines
the severity level.

© Proprietà riservata dell'autore - Digitalizzazione e distribuzione a cura del CENTRO APPUNTI - Corso Luigi Einaudi, 55 - Torino / Pagina 131 di 318

- Transverse cracking

They occur as a result of prevented contractions

Severity levels based on the width of the cracks

Record number and lenght of cracks → cracks frequency

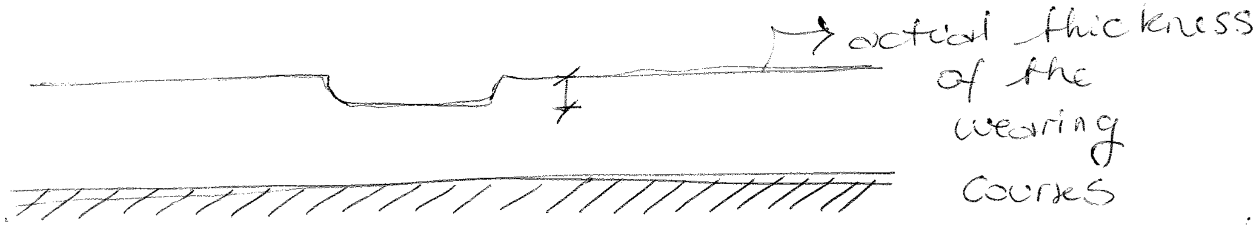
PATCHING & POTHOLES

Potholes → loss of material (area > 0,1 m²)

caused by? 2 layers not well glued

Patches → replaced material

Depth of potholes → severity levels



SURFACE DEFECTS

- **Bleeding**

Bitumen is sipped through the mixture and goes on the pavement surface

Causes
- excessive binder content
- ΔT
- associated to rutting
- low void content

→ loss of texture

Square meters of affected area

- **Polished aggregate**

Smoother surface → loss of skid resistance

Caused by high shear stresses

Square meters of affected area

6/11/13

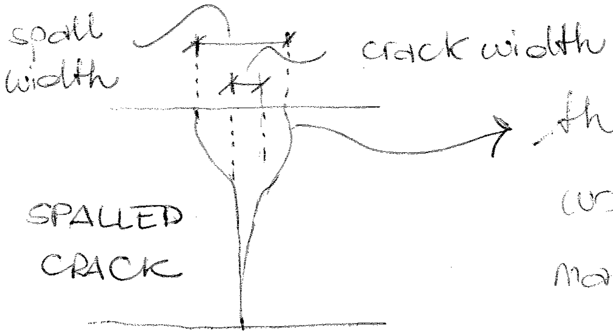
(2) No permanent deformations, no distorsions

A cumulated permanent deformation may occurr in the subgrade and, if it is not uniform, it may lead to pavement cracking

CRACKING

Crack occurs in different types and forms

spall width ≠ crack width



→ the edges has worn out (loss of material) → spalling

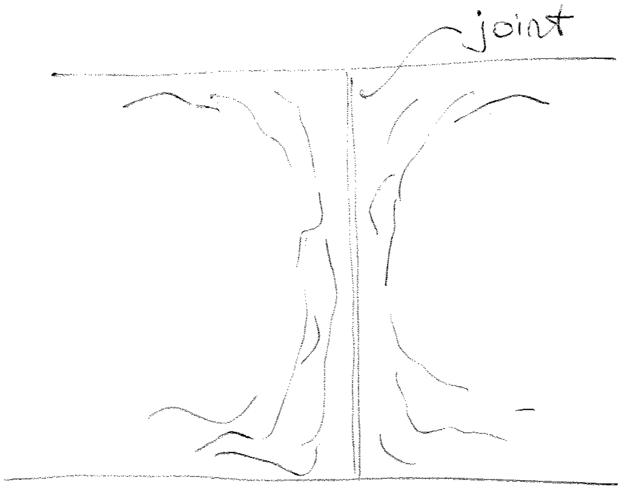
Small opening → there is still load transfer

- Corner breaks

A crack which usually has a 45° angle with respect to the horizontal

- D - Cracking -

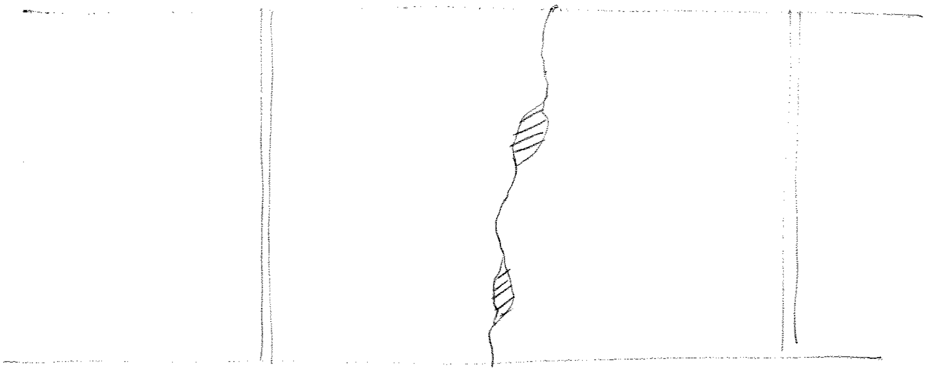
It occurs close to joints, cracks and free edges.
Cracks are small, thin and close to each other
This cracking is a function of the properties of concrete (curing conditions, mix design,...)
It will lead to loss of material and could promote other distresses
Record the extension in term of square meters
Severity levels based on the presence of missing pieces,



© Proprietà riservata dell'autore - Digitalizzazione e distribuzione a cura del CENTRO APPUNTI - Corso Luigi Einaudi, 55 - Torino / Pagina 139 di 318

- Transverse cracking

Due to temperature effects → prevented contraction



Severity levels based on:

- crack width
- spall width
- presence of faulting

Record the n° of cracks per slab or unit lenght and their lenght

- <u>Transverse joint seal damage</u>

Severity levels are
function of the extent of joint which
as been damaged

- <u>Longitudinal joint seal damage</u>

Record the n° of sealed joints
and the n° of the damaged ones

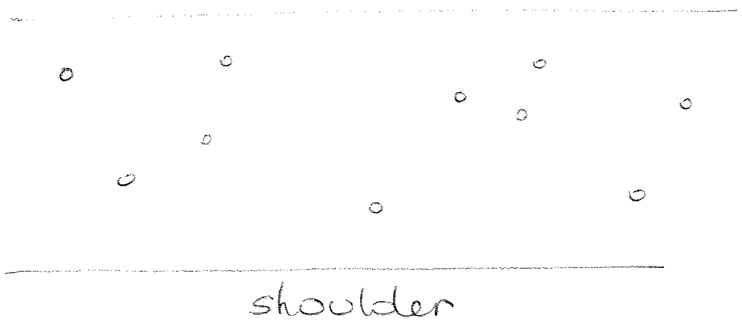
- <u>Spalling of longitudinal joints</u>

Record the spall width
Spalling increases very quickly, expecially
in airports

- <u>Spalling of transverse joints</u>

© Proprietà riservata dell'autore - Digitalizzazione e distribuzione a cura del CENTRO APPUNTI - Corso Luigi Einaudi, 55 - Torino / Pagina 143 di 318

Small depth, circular imprint

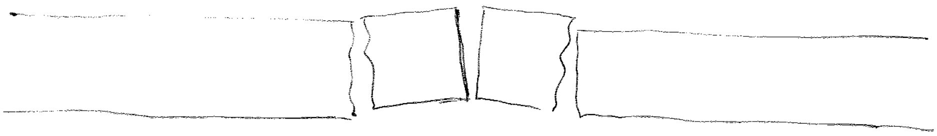


This is not a structural problem

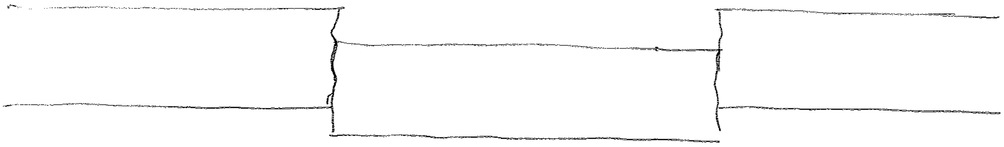
MISCELLANEOUS DISTRESSES

- **Blowups**

The pavement tries to expand and if the joint has not a sufficient width, the edges of the slabs touch each other and go in compression



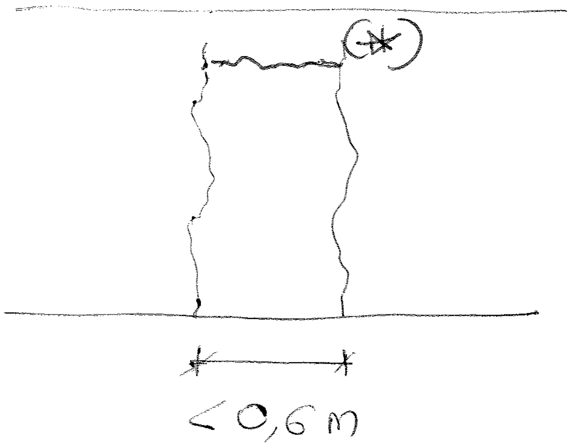
- **Faulting**



3 Pavements with no joints

- **Punchouts**

2 transverse cracks closed to each other (< 0,6 m)



This part acts as a cantilever beam and bends ; in fine there will be a longitudinal crack (*) on the top as a result of the excessive tensile strenght

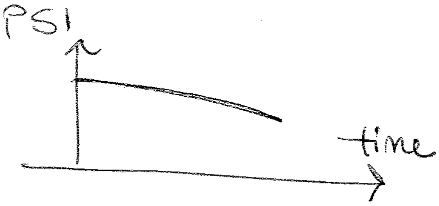
Severity levels based on the quantity of spalling and faulting

This parameter (PSI) links the subjective evaluation to a more objective evaluation

→ Data-base of the pavement conditions (measurements), linked with users' ratings

$$PSI = 5,03 - 1,91 \log(1+\overline{SV}) - 0,01\sqrt{C+P} + - 1,38\,\overline{RD}$$

PSI decreases in time



Measurements:

- $\overline{SV}$ = average of the slope variation of the longitudinal profile
  time ∅) constant slope for every single section (variation = ∅)
  time t) dynamic loads → SV increases
- P = area in which there are potholes and patches
- C = " " " damages (cracks, ...)

(for $\underbrace{1000\ ft'}_{\text{lenght}}$)

SN = structural number associated to the thickness of the pavement; it quantifies the "structural capability" of the pavement

$$SN = \underbrace{a_1 \cdot h_1}_{HMA} + \underbrace{a_2 \cdot h_2}_{base} + \underbrace{a_3 \cdot h_3}_{foundation}$$

a_i = layer coefficients (AASHTO road test materials: $a_1 = 0{,}44$ / $a_2 = 0{,}14$ / $a_3 = 0{,}11$)

h_i = thicknesses of layers

Stiffer material → greater a_i

N = number of load applications

L_1 = load on one single axle or on a set of tandem axles

L_2 = n° axles (1 for single axle, 2 for tandem axles)

$(PSI)_{initial} = 4{,}2$ typical value

N which leads to $(PSI)_f$ (n° of allowable loadings)

$$\log N_{18} = 9{,}36 \log\left(\frac{SN}{2{,}5}+1\right) - 0{,}20 + \left(\log \frac{4{,}2-(PSI)_f}{2{,}7}\right) \Big/ \left(0{,}40 + \frac{1094}{\left(\frac{SN}{2{,}5}+1\right)^{5{,}19}}\right)$$

N_{18} = n° of 18-kip single axle load applications

Observations:

- Total damage is given by the sum of every damage caused by a given axle (i)

$$(\text{damage})_{TOT} = \Sigma_i (\text{damage})_{ax,i} \quad \left(\begin{matrix}\text{additivity} \\ \text{of damage}\end{matrix}\right)$$

- $(\text{damage})_{axle} = k \, W^4_{axle}$

  $W \to$ mass

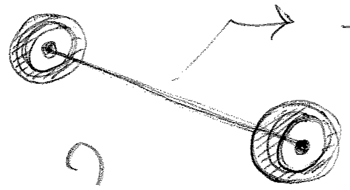
↳ <u>equivalence law:</u>

$$(\text{damage})_{\substack{gen.\\axle}} = n \cdot (\text{damage})_{\text{reference axle}}$$

$$n = \begin{matrix}\text{proportionality factor} \\ (\text{equivalency factor})\end{matrix} = \left(\frac{W_{gen.}}{W_{ref}}\right)^4$$

AASHTO STANDARD AXLE: 18'000 pounds = = 8,2 t = 80 kN

ES.



→ 100 kN 22'400 lb

$n = 2,4$ ref. ax.

(n)

TOT

n° of trucks
weighted

→ opening of traffic

$T_\emptyset$) n° equivalent loadings per year =
= 1 millions

20 years (design life of the pavement)

↳ 20 millions

BUT I need to take into account the traffic growth

2% per year of traffic increase
typical value

↳ IMPORTANT predictions of traffic levels

$(N) = G \cdot (N)$

periodo di progetto

↓ growth factor

annuale attuale

adjusted version of the equation:

$$\log \overline{N}_{8,2} = \log N_{8,2} + 0,372\,(S_i - S_\phi)$$

- <u>environmental conditions</u>

R = environmental coefficient

$R_\phi = 1$ (AASHTO test)

$R_i = f(T, \text{humidity}, \ldots) \rightarrow$ tables

$$\overline{N}^{(R)}_{8,2} = \frac{\overline{N}_{8,2}}{R}$$

- <u>different materials</u>

a = layer coefficients

$a_1 = 0,44$ / $a_2 = 0,14$ / $a_3 = 0,11$
(AASHTO test)

$a_i \rightarrow$ tables

Final expression:

$$\log \overline{N}_{8,2} = 9,36 \;\ldots$$

© Proprietà riservata dell'autore - Digitalizzazione e distribuzione a cura del CENTRO APPUNTI - Corso Luigi Einaudi, 55 - Torino / Pagina 157 di 318

Once the level of reliability is chosen:

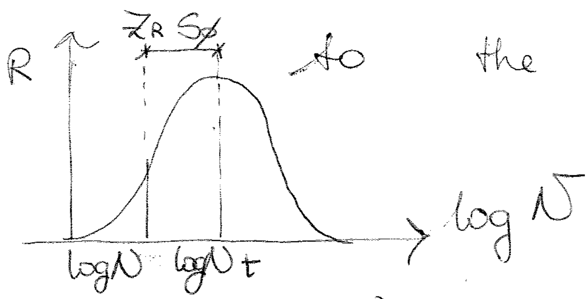
it depends on the level of importance of the road

$Z_R \times S_\phi$

S_ϕ = standard deviation of the variable $\delta_\phi = \log N_t - \log N_T$

→ the variability of both factors is taken into account

Z_R = value of δ_ϕ which corresponds to the probability R



$$\log(N_{ESAL}) = 9{,}36 \cdot \log_{10}(SN+1) - 0{,}20 + \frac{\log_{10}[\quad}{0{,}40 + \quad}$$

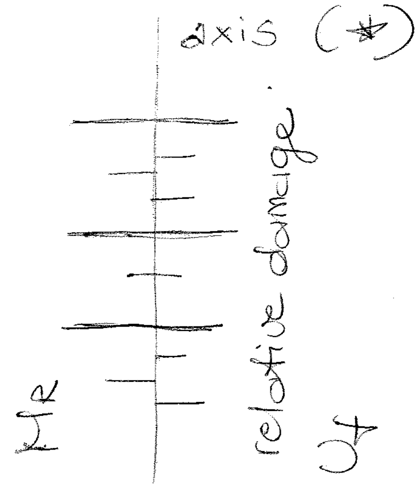
RESILIENT MODULUS

M_R = resilient modulus → measurement of the elastic response of the subgrade

The resilient modulus test is performed on a soil sample

© Proprietà riservata dell'autore - Digitalizzazione e distribuzione a cura del CENTRO APPUNTI - Corso Luigi Einaudi, 55 - Torino / Pagina 159 di 318

spring / summer → dry soil



Once I have $\sum U_{fi}$:

average $\overline{U_f} = \frac{\sum U_{fi}}{n}$ $n \to$ 12 months

On (*) axis I can read $\overline{M_R}$ which corresponds to $\overline{U_f}$

$\overline{M_R}$ → weighted average → equivalent modulus (effective resilient modulus)

DRAINAGE CONDITIONS

m_j = coefficient which takes into account the drainage quality and the availability of moisture

→ added in the expression of SN:

$$SN = a_1 \cdot h_1 + a_2 \cdot h_2 \cdot m_2 + a_3 \cdot h_3 \cdot m_3$$

EXAMPLE

LEVAN - TEPELENE ROAD PROJECT (Albania)

Analysis of the pavement structure

Problem: very soft subgrade soil
→ CBR = 3% (low bearing capacity)

1. Design traffic

Data on traffic → annual average daily traffic

2400 vehicles (AADT)

annual traffic growth 8% - 7%

distribution of vehicles → % cars, % trucks, % buses, ... → values adopted for pavement design

equivalency factor = 2,1 (for heavy vehicles

10,4 millions ESAL's considered in the design

2. Pavement evaluation and design

Given design cross section: given layers with given thicknesses

Reliability level = 85 %
Standard deviation = 0,49
$P_\varnothing$ = 4,2
p_f = 2
ESAL'S = 26 million

Even small changes in embankment thickness are significant → significant increase of the design life (ESAL'S)
Small improvements in the quality of the sub-base (> $h_{sub\text{-}base}$) also increase significantly the design life

4- Field validation of design calculations

Simulations take into account the non-linearity of the response

$M_R = k_1 \cdot \theta^{1/2}$ (granular materials)

↳ k-θ model

with θ = 5 psi

k_1 = 6,385 (sub-base course)
K_2 = 9,215 (base course)

Now we have a 3-layer system
(natural soil, embankm., sub-base)

→ simulations of plate loading test

ES. Plate loading test on the sub-base (h_{sub} = 15 cm)

h_{emb} (cm)	$E_{sub-base}$ (MPa) initial value of E	d (mm)	M_d (MPa)	θ (psi)	value of E from k-θ model
125	116	...		7	→ 141
	141	...			→ 142
	142		$\boxed{66,8}$		→ 142 OK CONVERGENCE
100	116				
	...				
	...				
	...				
75	116				
	...				
	...				
	...				
50	116				
	...				
	...				
	...				

The test is carried out for different values of CBR and h_{sub}
↓
> CBR → more selected material

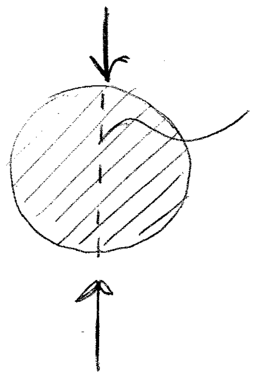
Study: SENSITIVITY of the model

FATIGUE CRACKING MODEL

Fatigue cracking occurs as a result of repetitive loadings (positive and negative signs → tension / compression)

We can define limiting condition according to different criteria.

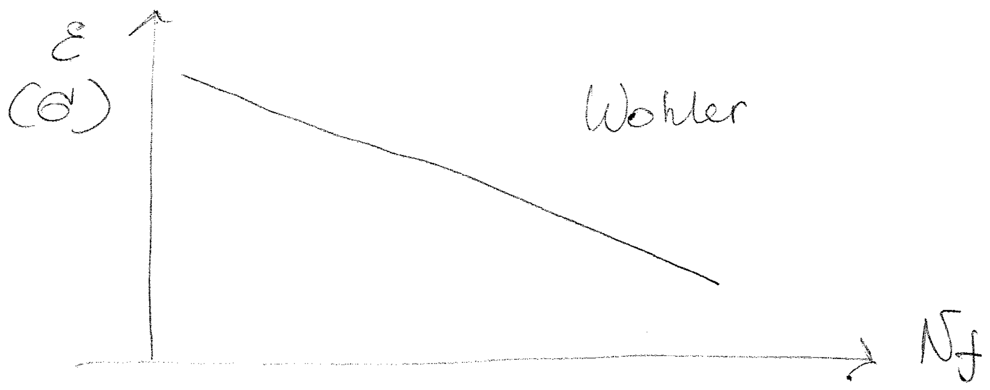
The problem is studied by carring out different tests in laboratory



vertical diameter tensile forces develop in the horizontal direction

<u>Repeated loading indirect tensile test</u>

The magnitude of loading affects the magnitude of stresses and the number of loadings which leads to fatigue failure.

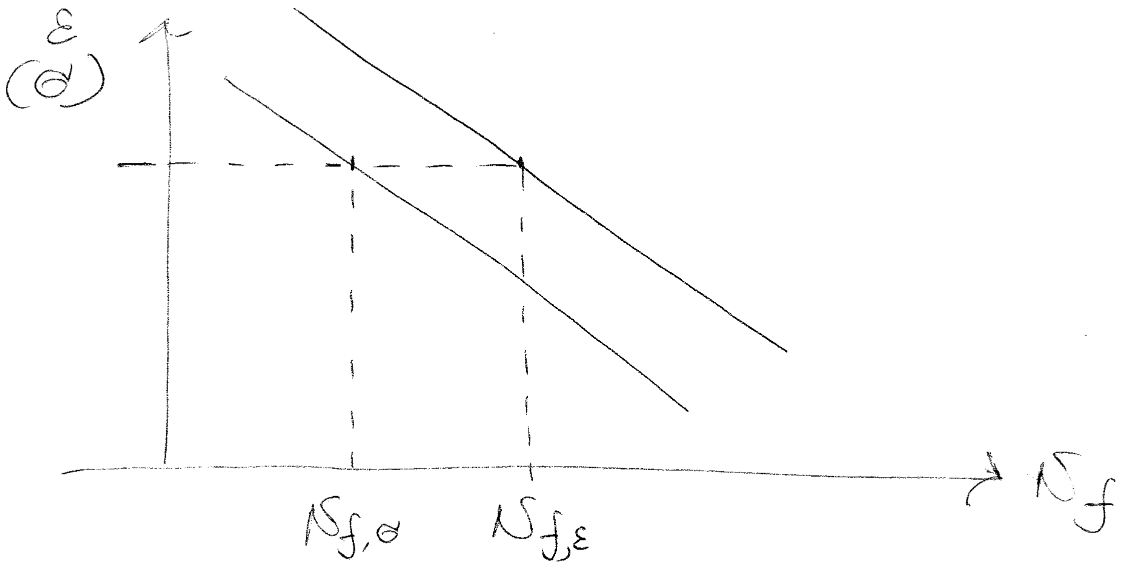


pavement

Laboratory test modes:

- controlled stress → crack progress really fast due to high local stress

- controlled strain → maximum magnitude of the imposed strain = costant
  As cracks depelop, we need to reduce the level of stress to mantain the strain constant



The mode of loading affects the estimation of number of loadings

© Proprietà riservata dell'autore - Digitalizzazione e distribuzione a cura del CENTRO APPUNTI - Corso Luigi Einaudi, 55 - Torino / Pagina 171 di 318

The negative exponent ($-f_2$) means that if we increase the strain, the number of loadings decreases: this is coherent with Wohler's curve (negative slope)

E also has a negative exponent: as we make the material stiffer, this is not always good. This is related to the fact that the material is brittle. But, if we increase E, ε_t decreases → positive effect

negative effect

influence of (III)

$f_1, f_2, f_3 = ?$ laboratory / field data

f_1 is a factor which correlates laboratory data with field data → calibration of f_1

f_2, f_3 depends upon the material carachteristics

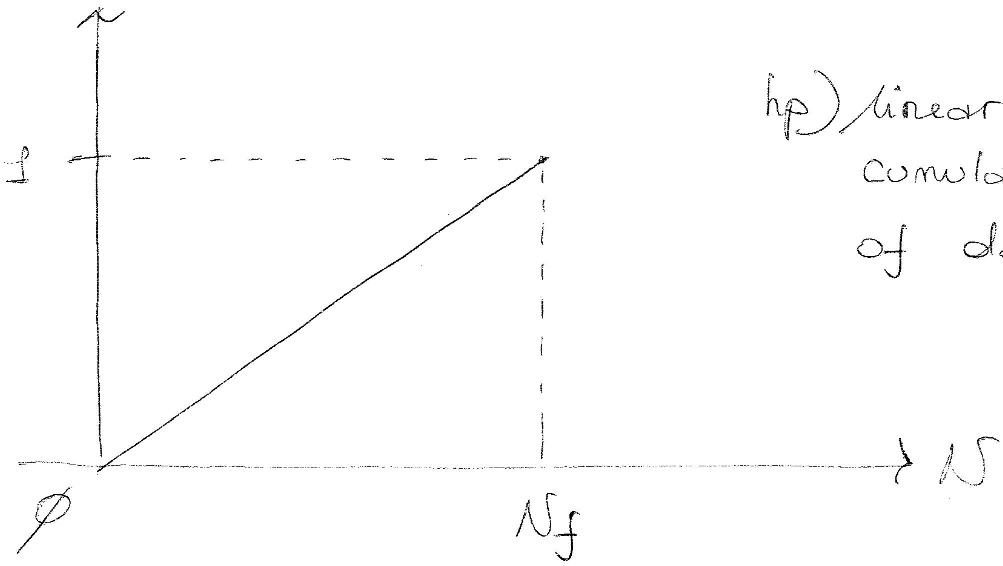
$$D_{(1)} = \frac{1}{N_f}$$

$$D_{(2)} = \frac{2}{N_f}$$

$i = \emptyset \div N_f$
number of applied loadings

...

$$D_{(N_f)} = \frac{N_f}{N_f} = 1 \text{ (limiting conditions)}$$



hp) linear cumulation of damage (*)

(*) This is not realistic → the damage rate increases in time, as the pavement becomes weaker

© Proprietà riservata dell'autore - Digitalizzazione e distribuzione a cura del CENTRO APPUNTI - Corso Luigi Einaudi, 55 - Torino / Pagina 175 di 318

The 2 values of ε_t are different

$\varepsilon_{t,A} \neq \varepsilon_{t,B}$

n° of applications (N_i)

A) $N_A = 1$ million
B) $N_B = 200'000$ } traffic prediction

A) $N_{f,A} = f_1 (\varepsilon_{t,A})^{-f_2} (E)^{-f_3}$

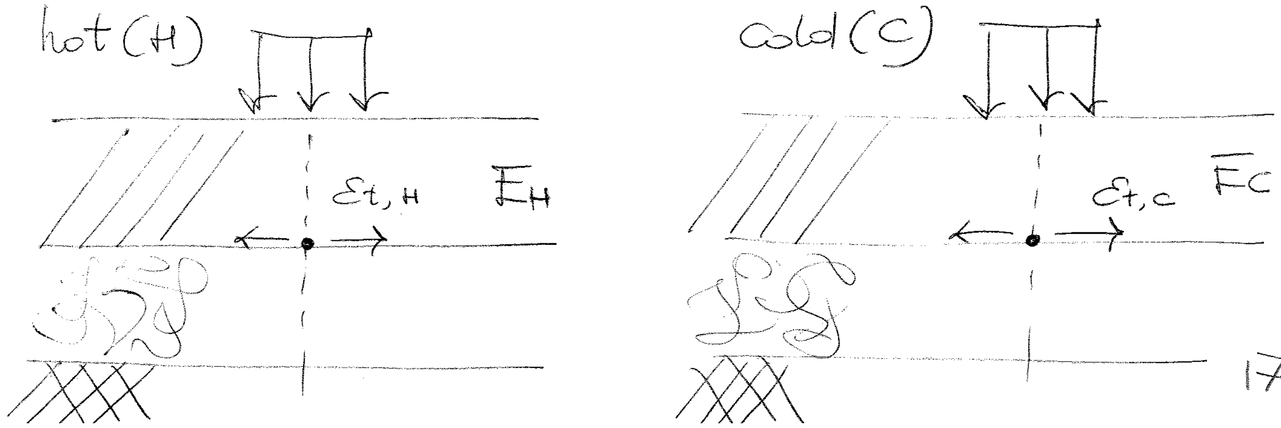
B) $N_{f,B} = f_1 (\varepsilon_{t,B})^{-f_2} (E)^{-f_3}$

We need to do a global evaluation:

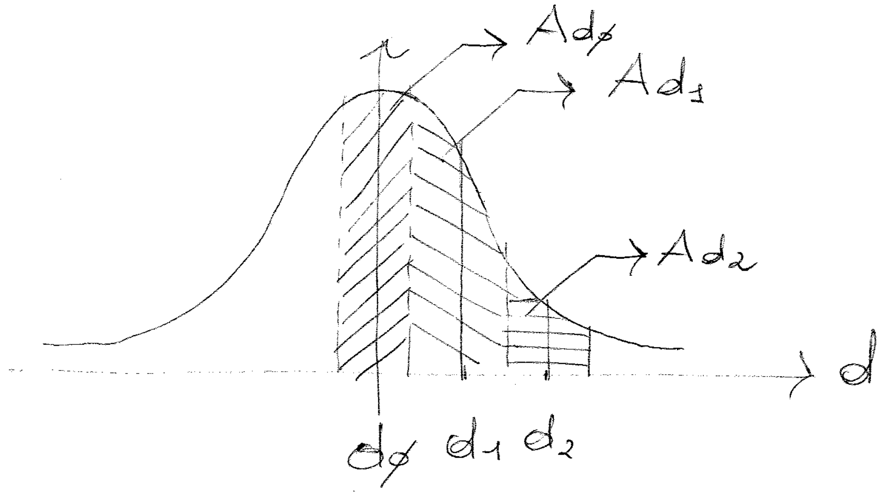
Miner's law $\sum_i D_i < 1$

$$\sum_i D_i = \underset{\displaystyle \frac{N_A}{N_{f,A}}}{\underset{\parallel}{D_{f,A}}} + \underset{\displaystyle \frac{N_B}{N_{f,B}}}{\underset{\parallel}{D_{f,B}}}$$

- Different environmental conditions:



N_{TOT} total number of loadings distributed in different positions
→ statistical distribution



↳ most frequent condition (axis of aircraft = centerline)

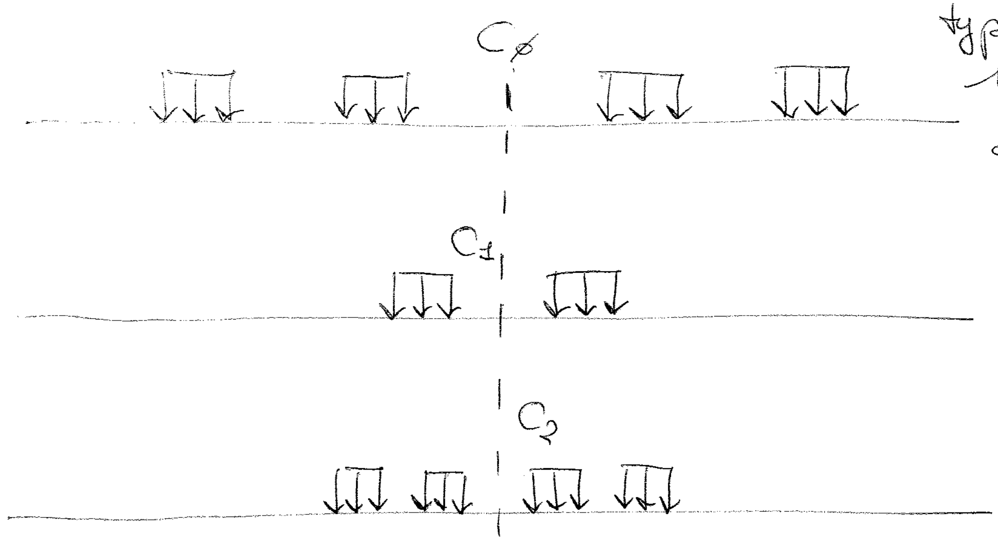
$$\frac{A_{di}}{A_{TOT}} \cdot 100 = P_{di} \qquad i = \emptyset, \dots, n$$

$$\left.\begin{aligned} & N_{TOT} \cdot \frac{A_{d\emptyset}}{A_{TOT}} \\ & N_{TOT} \cdot \frac{A_{d1}}{A_{TOT}} \\ & \dots \\ & N_{TOT} \cdot \frac{A_{di}}{A_{TOT}} \end{aligned}\right\} \text{number of loadings which occurs in each position}$$

© Proprietà riservata dell'autore - Digitalizzazione e distribuzione a cura del CENTRO APPUNTI - Corso Luigi Einaudi, 55 - Torino / Pagina 179 di 318

- Different loading configurations

(different types of trucks / aircrafts)



...

Same procedure

So, D is really useful to combine together all these effects

$\boxed{EALF}$ equivalent axle load factor

Ex. Generic axle $X \rightarrow x$ kN

Standard axle STD $\rightarrow$ 80 kN

(reference axle)

N_{STD} number of applications of the std axle

$$EALF = \frac{\cancel{f_1} (\varepsilon_{t,STD})^{-f_2} \cancel{(E)^{-f_3}}}{\cancel{f_1} (\varepsilon_{t,x})^{-f_2} \cancel{(E)^{-f_3}}} = \left(\frac{\varepsilon_{t,x}}{\varepsilon_{t,STD}} \right)^{f_2}$$

$$f_2 \simeq 4$$

$$\frac{\varepsilon_{t,x}}{\varepsilon_{t,STD}} = \frac{\sigma_{t,x}}{\sigma_{t,STD}} = \frac{N_x}{N_{STD}}$$

coherent with AASTHO road test

25/11/2013

EXAMPLE of PAVEMENT DESIGN

New motorway in Italy; given information:

- Preliminary design with a given cross section (no calculations)
  Several section types:
  - embankments, excavations
  - tunnels
  - viaducts
  - service roads
- Geographic position → useful for environmental conditions
- Mobility study → daily traffic

Limiting functions for fatigue and rutting:

$$N_f = f_1 \cdot \varepsilon_t^{-f_2} \cdot E^{-f_3}$$

$$N_d = f_4 \cdot \varepsilon_c^{-f_5}$$

(permanent deformation)

ε_c → max compressive strain on the top of layer underneath the bitumen bound layer

$$D_{f,j} = \frac{N_j}{N_{f,j}}$$

N_j → j-th period

(fatigue cracking)

$$D_{d,j} = \frac{N_j}{N_{d,j}}$$

(rutting)

$$D_{f,tot} = \sum_j D_{f,j}$$

$$D_{d,tot} = \sum_j D_{d,j}$$

total damage < 1 ok

lane)

Annual growth rate = 2%

% heavy vehicles = 30% (high value)

F_r = 0,4

Homogenization:

Standard axle = 80 kN

vehicle equivalency factor = Σ axle eq. factor

average equivalency coefficient = 2,52

(from AASHTO road test tables)

N.B.

Typical spectrum of traffic for each road category (da tabelle date o se si hanno surveys)

vehicle type	axle [kN]	% vehicle type
		100

→ N_{vp} = 58 172 765

design value (N_j)

- FOUNDATION LAYER

- CEM. STAB.

after 90 days of curing → elastic modulus =

= 4'000 ÷ 12'000 MPa (cem. stabilized f.)

→ conservative choice: modulus ≤ 4'000

↳ ~ 3'000 MPa (safe assumption)

in time stiffness may decrease as a result of microcracking due to thermal variations, ..

$\nu = 0{,}25$

- GRANULAR FOUND. 27/11/13

$$E_{mg} = 0{,}2 \cdot h^{0{,}45} \cdot E_s$$

→ h: thickness of the foundation

(unbound granular foundation)

↳ E_s: elastic modulus of the subgrade

This is an "indirect way" to consider the non linear behaviour of a granular material (2 layer system)

vedi "Shell Pavement Design Manual"

Sensitivity of the model:

Variable thickness h, given E_s elastic modulus of subgrade soil (= 100 MPa) → $\bar{E}$ = of foundation = 191 ÷ 313 MPa

I can do the same thing with

189

Hp on volumetrics:
- %v (void content)
- binder content

→ V_a, V_e, %v

Hp on reological properties of binder:
(polymer modified binder)
↳ data from literature (Round Robin study)

$E^* = a \cdot e^{-b \cdot T}$ → obtained by fitting the available experimental data of this study (at 10 Hz) (*)

↓
complex modulus

$$\rightarrow B^* = \frac{E^*}{E_g}$$

↳ glossy modulus ≃ 1 GPa (shear mode)
3 GPa (tensile compressive mode)

(*) loading frequency is related to the speed of loading

$f = 0,4 \cdot V$ ↳ speed of vehicles [km/h]

actual frequency of loading [Hz]

Asphalt Institute: limiting condition for fatigue = 20% of cracking on the surface

↳ $N_f = 0{,}0248 \cdot C \cdot \varepsilon_t^{-3{,}291} \cdot |E^*|^{-0{,}854}$

$C = 10^M$ M is a function of volumetrics

$\uparrow \%V \rightarrow \downarrow N_f$ (fatigue life decreases)

$\uparrow V_e \rightarrow \uparrow N_f$ (" " increases)

The polymer modified binder provides 30% of increase of fatigue life:

$N_f = 1{,}3 \cdot 0{,}0248 \cdot C \cdot \varepsilon_t^{-3{,}291} \cdot |E^*|^{-0{,}854}$

Asphalt Institute: limiting criterion for rutting = depth of ruts = 1,27 cm

↳ $N_d = 1{,}365 \cdot 10^{-9} \cdot \varepsilon_c^{-4{,}477}$

conditions of interfaces

1 → full adhesion (between 2 bit. mix. layers)

∅ → full slip (between 2 granular layers or 1 granular layer and 1 bit. layer)

© Proprietà riservata dell'autore - Digitalizzazione e distribuzione a cura del CENTRO APPUNTI - Corso Luigi Einaudi, 55 - Torino / Pagina 193 di 318

Asphalt Institute:

$f_4 = 1,365 \cdot 10^{-9}$

$f_5 = 4,477$

Shell:

$f_4 = 1,05 \div 6,15 \cdot 10^{-7}$

$f_5 = 4$

TRL:

$f_4 = 6,18 \cdot 10^{-8}$

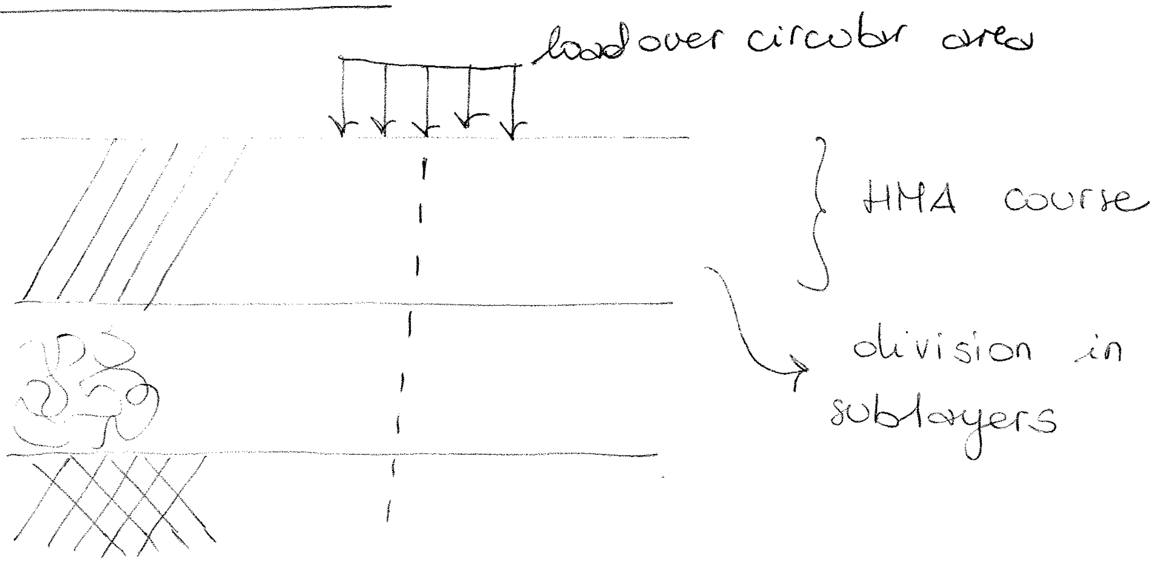
$f_5 = 3,95$

f_4 very different values: from empirical observations (different ways to calibrate the model using this data)

Ruts are limited by an adequate choice of materials

Metods to compute rut depth:

<u>Direct method</u>

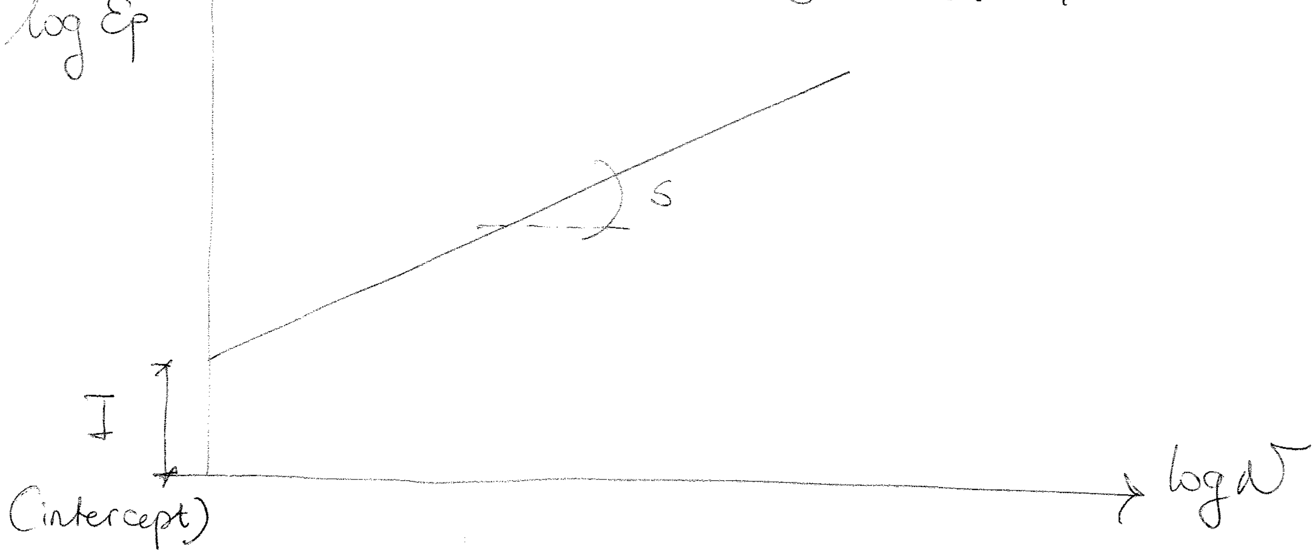


Logaritmic form:

$$\log(\varepsilon_p) = \log\left(\frac{\varepsilon\mu}{1-\alpha}\right) + (1-\alpha)\cdot \log N$$

If I plot the values of $\log \varepsilon_p$ and $\log N$ I find a linear relationship between ε_p and N, with $(1-\alpha)$ slope

$S = 1-\alpha \rightarrow \alpha = 1-S$



$$I = \frac{\varepsilon\mu}{1-\alpha} \rightarrow \mu = \frac{I S}{\varepsilon}$$

But we have a system (different layers; we need to discretize the system)

Additional assumption: $\varepsilon = \varepsilon_p(N) + \underset{\substack{\uparrow \\ \text{reversible deformation}}}{\varepsilon_r}(N)$

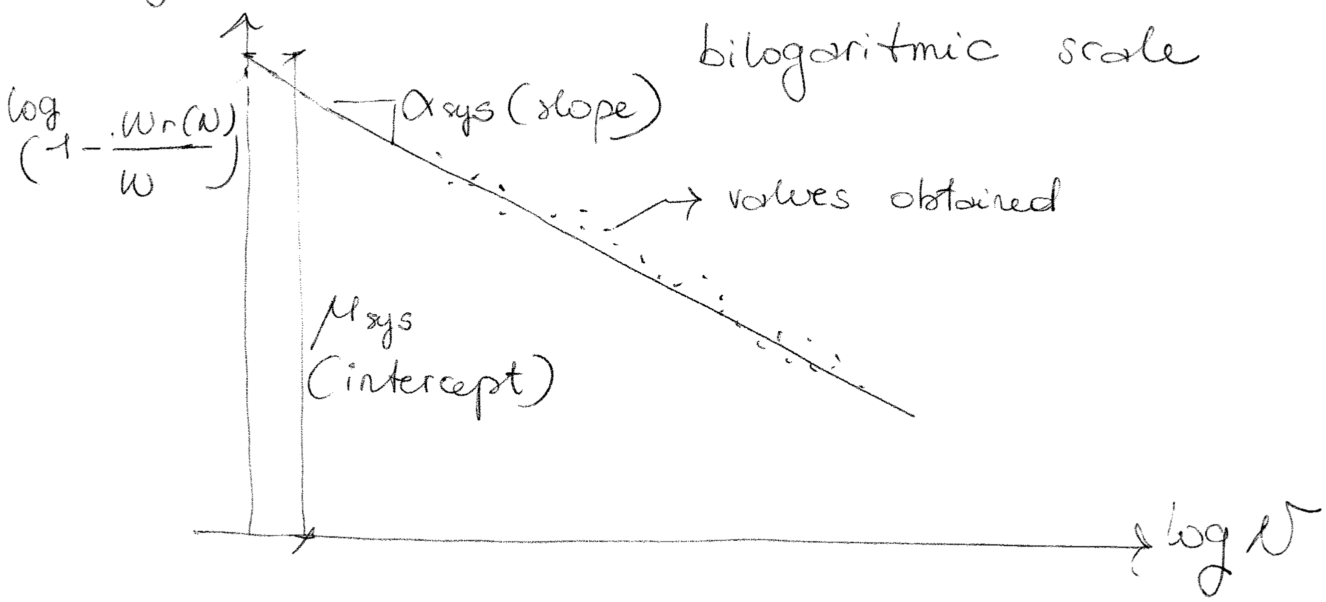
(after the 200-th load repetition)

197

$$1 - \frac{W_r(N)}{W} = \mu_{system} N^{-\alpha_{system}}$$

↓

Now we can represent data on a simple graph:



Summarizing:

1) $1, 10, 10^2, 10^3 \dots 10^7$ = various values of N

↳ $E_r(N)$ for each layer

$$= \frac{E N^{\alpha}}{N^{\alpha} - \mu}$$

2) By using those unloading moduli (E_r) I can calculate $W_r(N)$ for each value of N (number of loadings)

3) I compute $1 - \frac{W_r(N)}{W}$ for all

© Proprietà riservata dell'autore - Digitalizzazione e distribuzione a cura del CENTRO APPUNTI - Corso Luigi Einaudi, 55 - Torino / Pagina 199 di 318

(*) It takes into account <u>dynamic</u> effects

$1 \div 2$ = typical values of C_m

This method works well if you manage to homogenize well loadings and temperatures

loadings → ESAL

temperatures → characteristic T of pavement

Effect of irregularities:

$$f = \frac{V}{L}$$

L → wave lenght of irregularity

f → frequency

$\boxed{\text{CORRUGATIONS}}$

The rail in time will change its shape: the surface will corrugate

2 main aspects:

- appereance
- mechanism by means of which the corrugation appear

6 types:

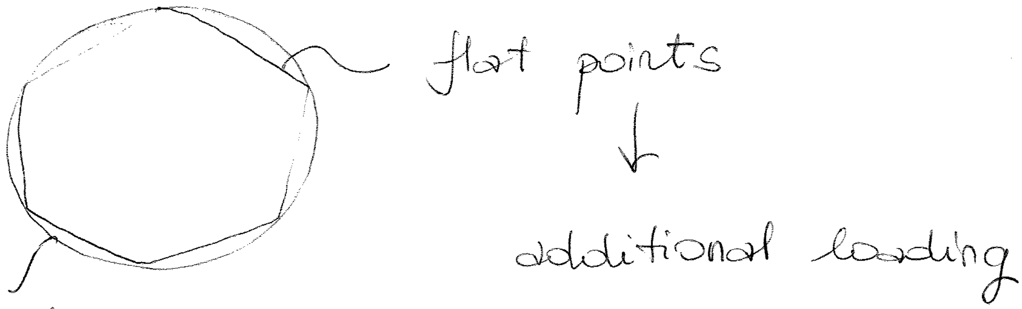
1) Heavy rail corrugation
2) Light rail corrugation
3) other P2 resonance
4) rutting corrugation
5) pinned-pinned resonance
6) track-form specific

Typical wave-lenght ~ 200mm

1-2) related to the unsprung mass, directly in contact with the rail

6) Other types of corrugations, caused by specific defects

WHEEL OUT OF ROUNDNESS



RAIL MANUFACTURING

The corrugation is not $\not\exists$ at the beginning

Sleepers spacings

They affect initial corrugation and its developement in time

CRACKS

Internal defects

Monitoring of the internal structure of steel → voids, inclusions

Internal / External cracks

Politecnico di Torino –Corso di Laurea Magistrale in Ingegneria Civile

Pavement and Track Engineering - 02IODMX

A.A. 2013/14

PRACTICAL APPLICATION #1 - 31/10/2013

Example #1 PLAIN CONCRETE SLAB

A plain concrete slab (geometrical and mechanical characteristics in **Table 1**) is supported by a subgrade whose modulus of subgrade reaction is 100 MN/m³.

Table 1.

E	[GPa]	30
ν	[-]	0.15
γ	[kN/m³]	25
α	[1/°C]	9.E-06

h	[m]	0.25
L_x	[m]	8.00
L_y	[m]	3.75

coefficient of thermal expansion

1.1 Given a circular load (P=30 kN, q=650 kPa),

Using closed-form formulas (**Appendix 1**) determine:

- maximum stress and deflection due to corner loading;
- maximum stress and deflection due to interior loading;
- maximum stress and deflection due to edge loading (both circular and semicircular).

Using influence charts (**Appendix 2**) determine: PICKETT AND RAY

- maximum stress and deflection due to corner loading; edge
- maximum stress and deflection due to interior loading;

1.2 Given a temperature differential of 12°C determine:

- curling stresses in the interior and at the edge of the slab according to the Westergaard and Bradbury approach (**Appendix 3**);
- curling stresses according to the Eisenmann approach.

1.3 Given a coefficient of friction of 1.5, determine stress in concrete due to friction.

Example #2 JOINTED REINFORCED CONCRETE PAVEMENT

A reinforced slab (geometrical and mechanical characteristics in **Table 2**) is supported by a subgrade whose modulus of subgrade reaction is 100 MN/m³.

Table 2.

E	[GPa]	30
ν	[-]	0.15
γ	[kN/m³]	25
h	[m]	0.25
L_x	[m]	8.00
L_y	[m]	3.75
A_x	[mm²/m]	280

A_y	[mm²/m]	100	
A_{tie}	[mm²/m]	140	
ϕ_{dowel}	[mm]	30	0,03 m
z	[m]	0.005	
E_d (dowels)	[GPa]	200	
k_{ds}	[GN/m³]	400	
s	[m]	0.300	

Appendix #2

0,8 m

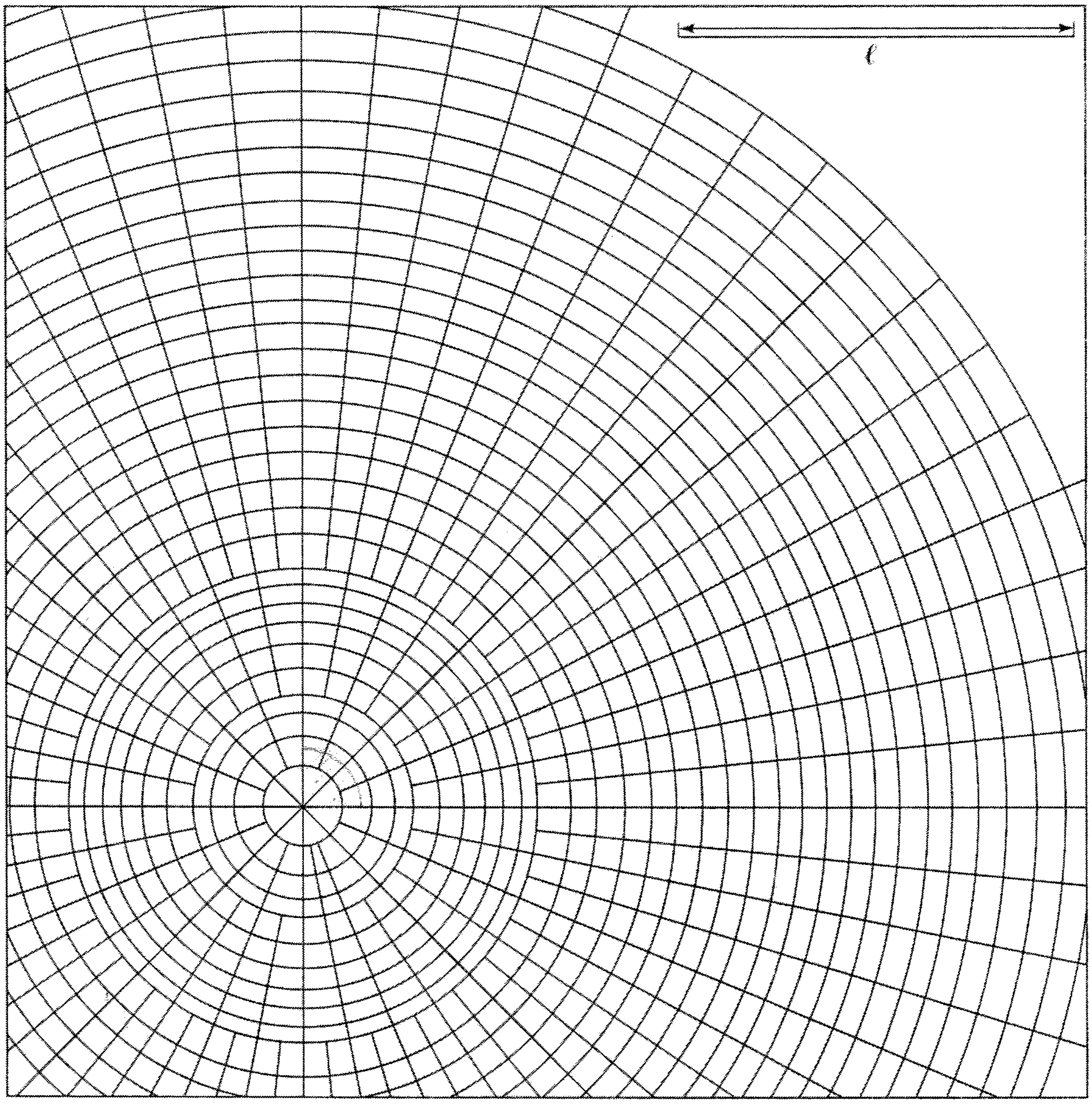


FIGURE 4.13

Influence chart for deflection due to interior loading. (After Pickett and Ray (1951).)

m : cm

0,8 : 5,7 = 0,12 : X

X = 0,855 raggio scalato

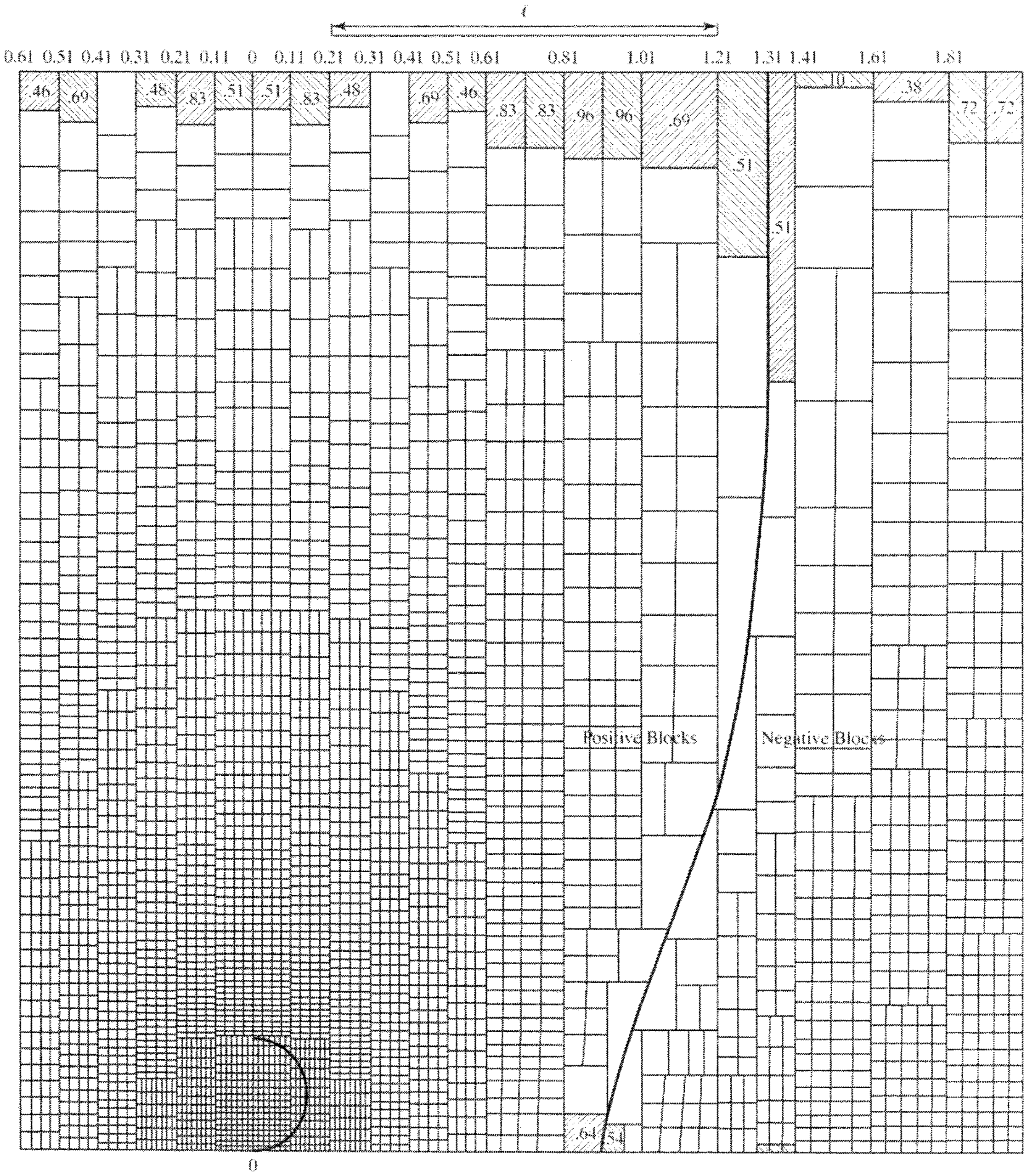


FIGURE 4.15

Influence chart for moment due to edge loading. (After Pickett and Ray (1951).)

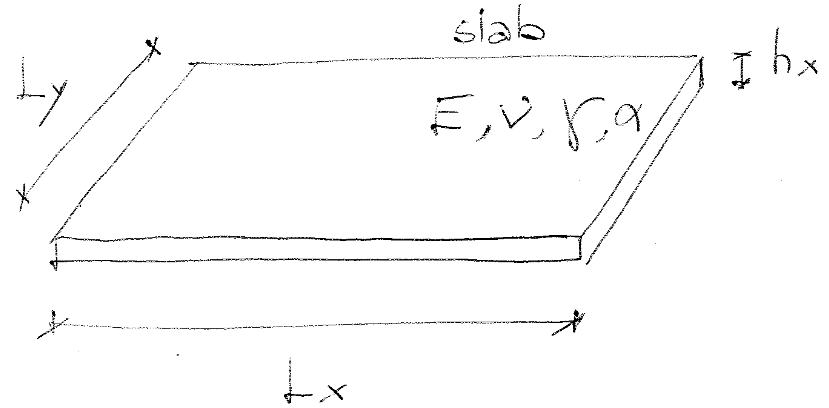
© Proprietà riservata dell'autore - Digitalizzazione e distribuzione a cura del CENTRO APPUNTI - Corso Luigi Einaudi, 55 - Torino / Pagina 211 di 318

31/10/2013

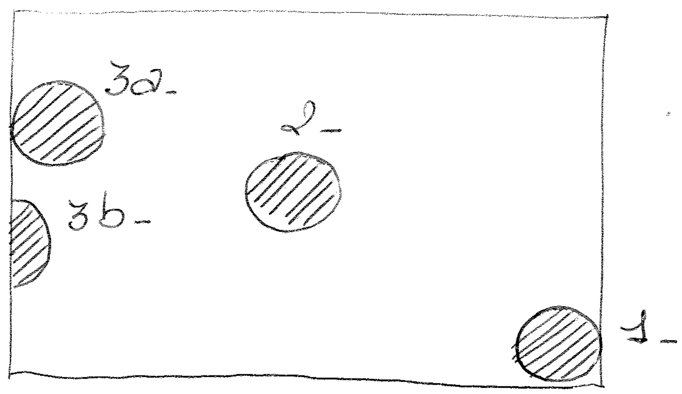
PRACTICAL APPLICATION 1

EXERCISE 1

$k = 100 \ MN/m^3$



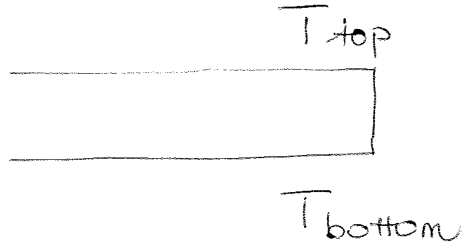
1-1) Cases:



Hp)
2- The load is sufficiently distant from any edge
3- The load is sufficiently distant from any corner

a = radius of the loading area (circular load)

1.2) Temperature differential:



$$\Delta T = -12\,°C$$

The slab tends to curl, but this movement is prevented → stresses

stresses in x dir.

$$\sigma = \frac{E \alpha \Delta T}{2(1-\nu^2)}(1+\nu)$$

due to M in y direction

Case of a finite slab (Bradbury):

$$\sigma_x = \frac{E \alpha \Delta T}{2(1-\nu^2)}\left(C_x + \nu C_y\right)$$

$$\sigma_y = \frac{E \alpha \Delta T}{2(1-\nu^2)}\left(C_y + \nu C_x\right)$$

C_x, C_y correction factor, determined by using Bradbury's chart

$C_x \rightarrow$ I have to use L_x / ℓ

$C_y \rightarrow$ " " L_y / ℓ

3

$$L' > 1{,}1\, L_{crit} \rightarrow \sigma_w = \frac{E \alpha \Delta T}{2(1-\nu^2)} (1+\nu)$$

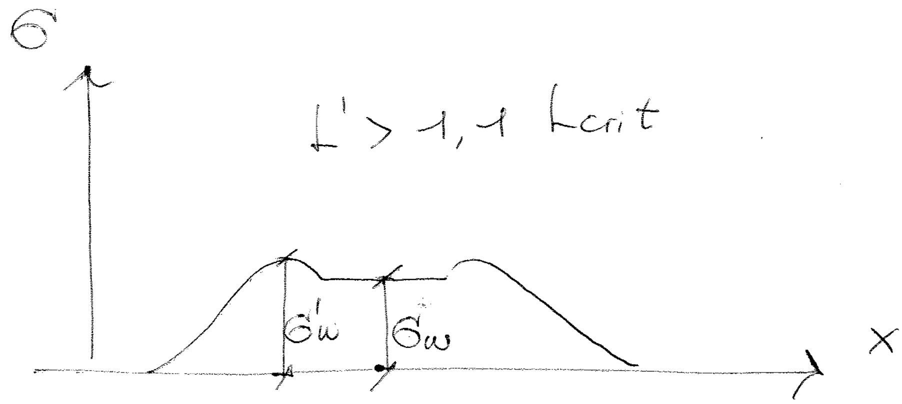
stress
at the centre
of the slab

$$\sigma'_w = 1{,}2\, \sigma_w \quad \text{maximum stress}$$

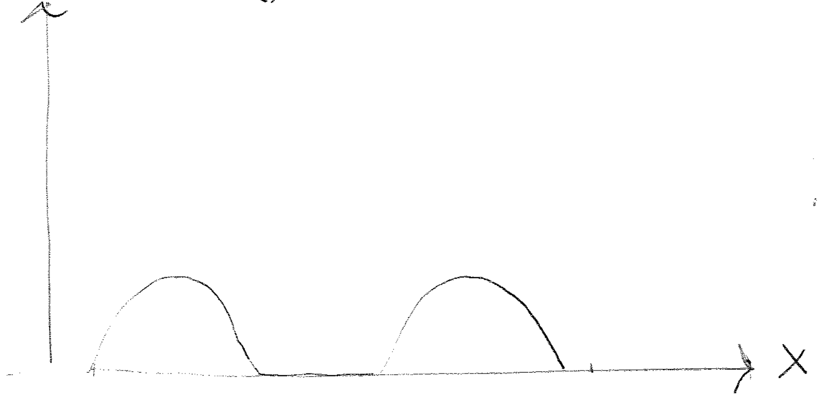
$$L' = L_{crit} \rightarrow \sigma_w = \sigma'_w \quad \text{in the centre}$$

L' → distance between the 2 supports

$$L' < 0{,}9\, L_{crit} \rightarrow \sigma''_w = \left(\frac{L'}{0{,}9\, L_{crit}}\right)^2 \cdot \sigma_w$$

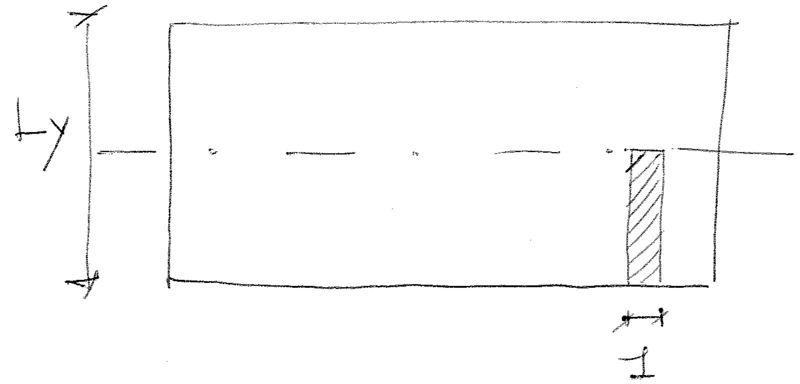


vertical deflection



$$f_a \cdot \gamma_c \cdot \frac{L_x}{2} \cdot h \cdot 1 = \sigma_{cx} \cdot h \cdot 1$$

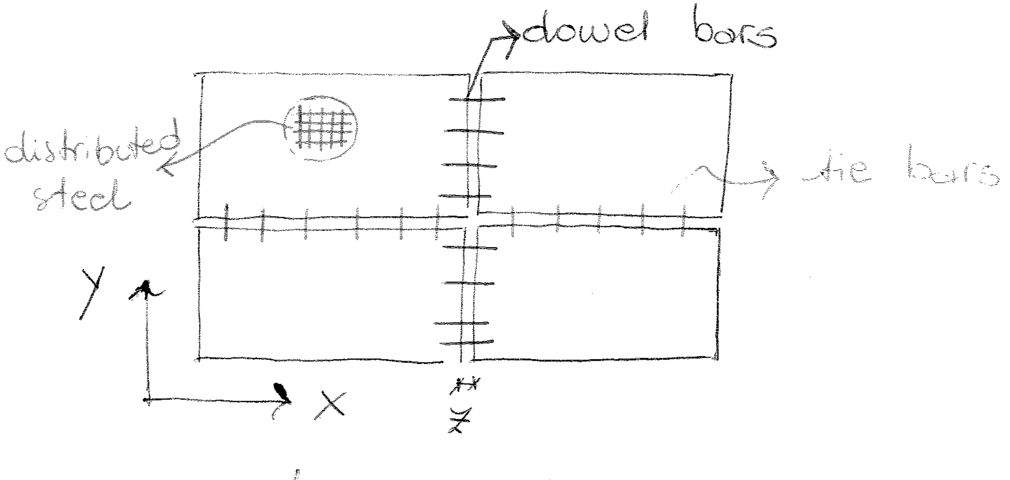
We assume an average friction coefficient f_a



stresses in y direction

$$f_a \cdot \gamma_c \cdot \frac{L_y}{2} \cdot h \cdot 1 = \sigma_{cy} \cdot h \cdot 1$$

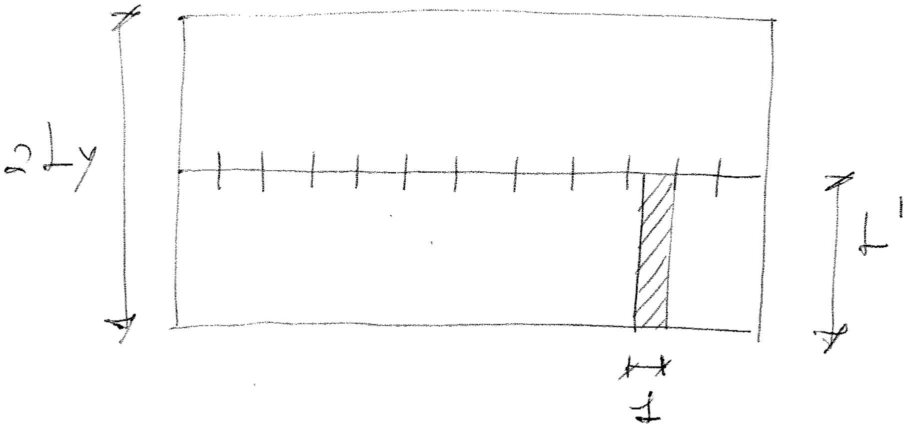
EXERCISE 2



z = transverse joint width

K_{ds} = modulus of dowel support = concrete

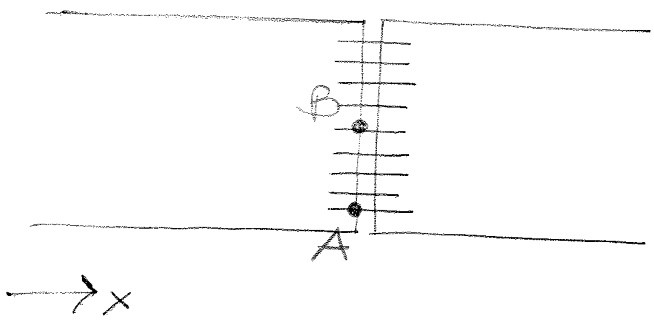
7

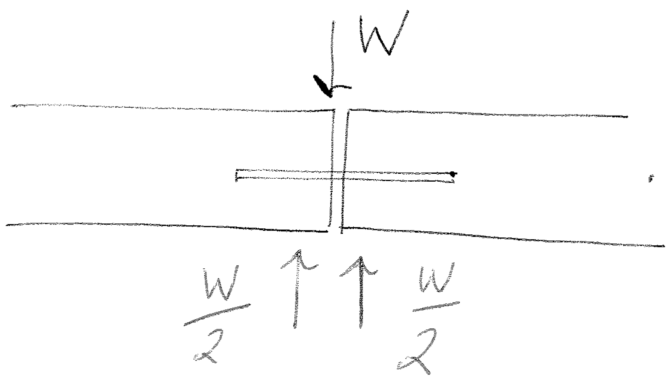


tie bars:

$$f_a \cdot \gamma_c \cdot h \cdot 1 \cdot \underbrace{L'}_{= L_y} = \sigma_{tie} \cdot A_{tie}$$

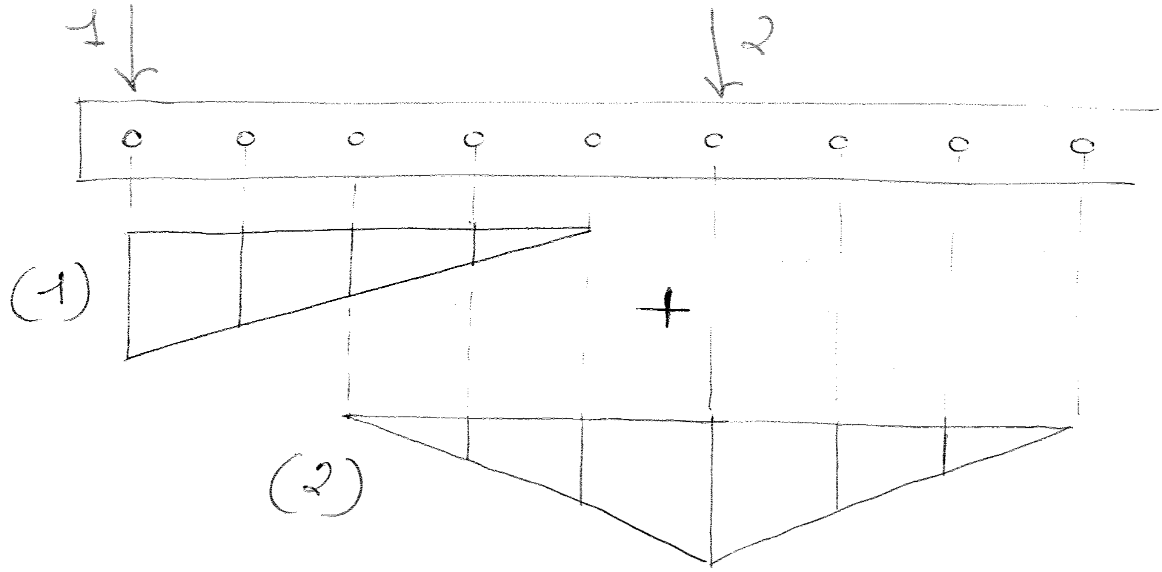
2.3)





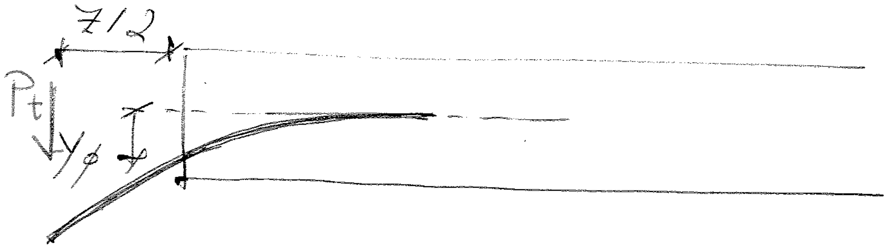
efficient dowel

Now I can superpose the effects of the 2 loadings:



$\sigma_b = y_\phi \cdot K_{ds}$ bearing stresses between dowel and concrete

y_ϕ ↓ maximum deflection of the dowel (at the joint)



P_t = load applied to the dowel = max load carried by dowels

We consider:

- the dowel as a beam
- concrete as a Winkler foundation

© Proprietà riservata dell'autore - Digitalizzazione e distribuzione a cura del CENTRO APPUNTI - Corso Luigi Einaudi, 55 - Torino / Pagina 223 di 318

Politecnico di Torino – Corso di Laurea Magistrale in Ingegneria Civile

Pavement and Track Engineering - 02IODMX

A.A. 2013/14

PRACTICAL APPLICATION #2 - 07/11/2013

Example #1 HOMOGENEOUS HALF-SPACE

Two circular loads, having radius 15 cm each and spaced at 60 cm on centers are applied on a homogenous half-space. The pressure on circular area is 250 kPa, the half-space has elastic modulus 70 MPa and Poisson's ratio 0.5. Determine vertical load stress, strain and deflection at point A, which is located 60 cm under the center of one circle.

Example #2 TWO-LAYER SYSTEM

x 2.1 A plate bearing test using a 30 cm diameter rigid plate, was performed on a subgrade. A load of 100 kN was applied to the plate, and a deflection of 5 mm was measured. Considering the subgrade as a homogenous half-space with Poisson's ratio 0.5, determine the elastic modulus of the subgrade.

x 2.2 Assuming that this deflection is too high, a cement treated base will be placed on top of the subgrade. To know mechanical parameters of the new material, a layer of 15 cm thick was realized over the subgrade and a new plate bearing test was conducted. A deflection of 3 mm was measured. Assuming Poisson's ratio equal to 0.5, determine the elastic modulus of the treated base.

2.3 Design the required thickness of the cement treated base course to sustain a 40 kN tire with a contact pressure of 700 kPa over a circular area to comply with all the requirements indicated in **Table 1**. ricavo 3h → prendo il max

Table 1. Requirements

Maximum vertical surface deflection (mm)	w_0	1.5
Maximum vertical stress at the interface (kPa)	σ_{z1}	200
Maximum horizontal strain at the interface (strain)	ε_{r1}	0.001

ottimi 2 grafici

E_1 σ_z E_2

Example #3 THREE-LAYER SYSTEM

A flexible pavement is composed of the following layers:

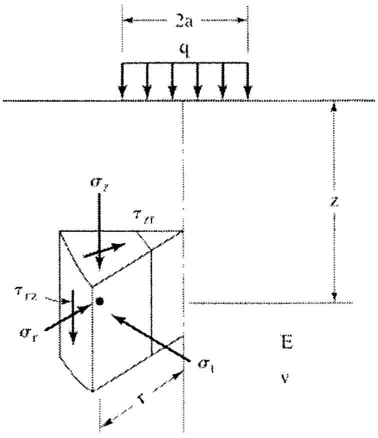
- a HMA course 15 cm thick with elastic modulus 3 GPa;
- a granular foundation 30 cm thick with elastic modulus 150 MPa;
- a subgrade with elastic modulus ~~50~~ MPa. 75

All layers are assumed to be incompressible. The asphalt pavement is subjected to a single-wheel load having contact radius 12 cm and contact pressure 700 kPa. Determine all stresses and strains at the interfaces on the axis of symmetry.

$$\varepsilon_r = \frac{1}{2E}(\sigma_r - \sigma_z) \rightarrow \sigma_r\ (E_1) \qquad \sigma'_r\ (E_2)$$

$$\sigma_r = \varepsilon_r \cdot 2E + \sigma_z$$

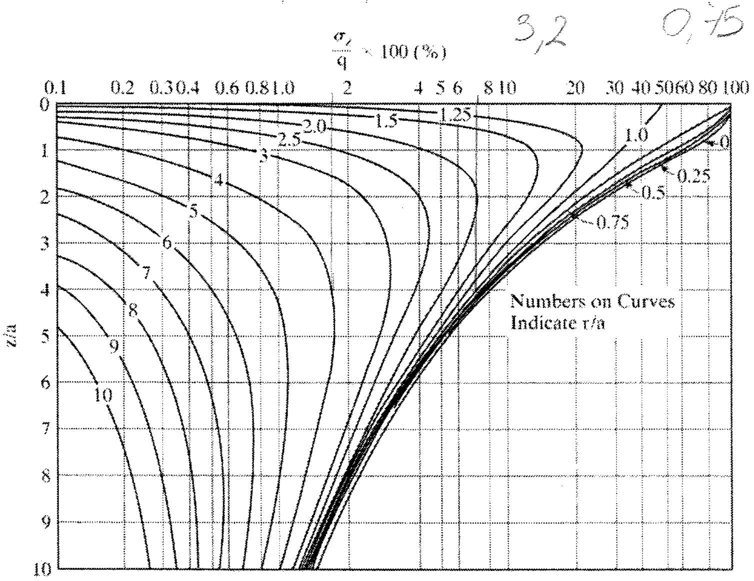
Foster and Ahlvin charts for determining stresses and vertical deflection. (After Huang, 2004)



2,75

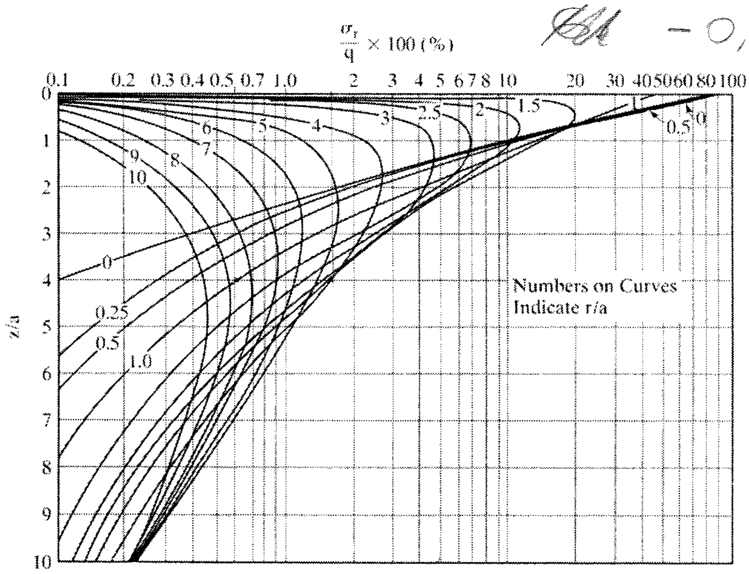
3,2 0,75

6,3



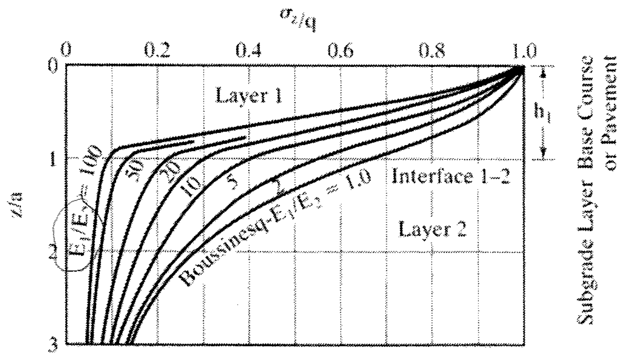
−0,7

0,65



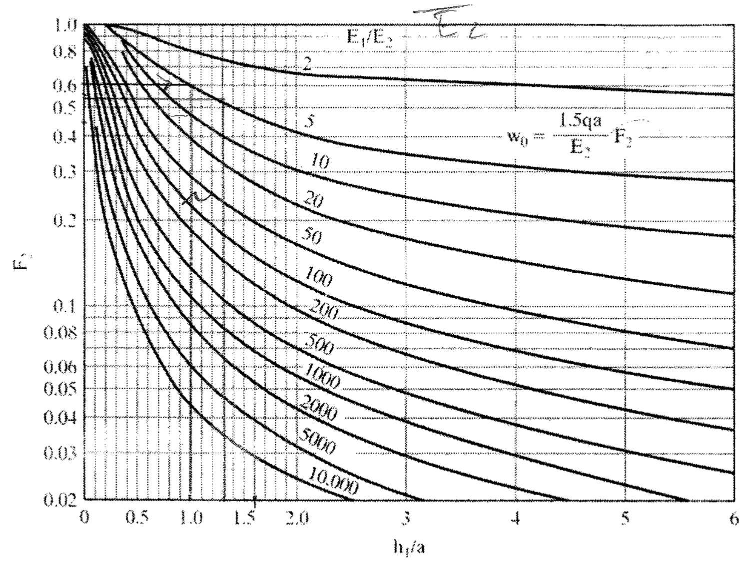
Appendix #2

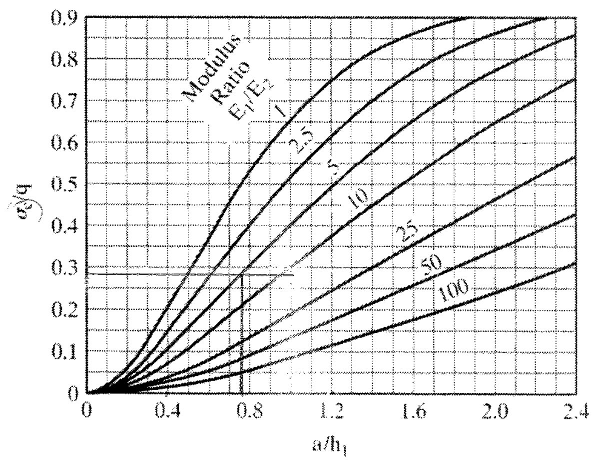
Two-Layer System (Huang, 2004)

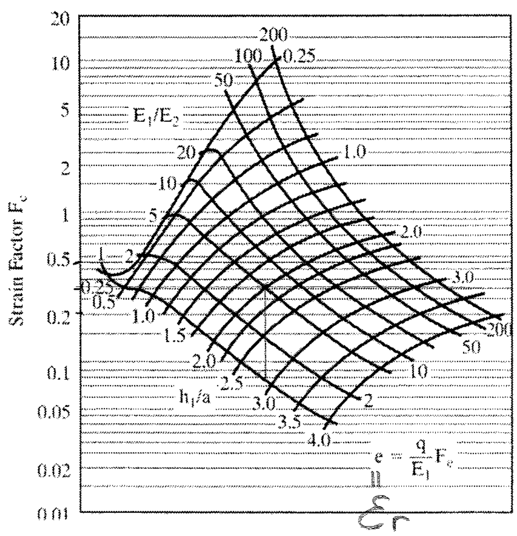


(non da usare)

$\frac{E_1}{E_2} = 5$







ε_r

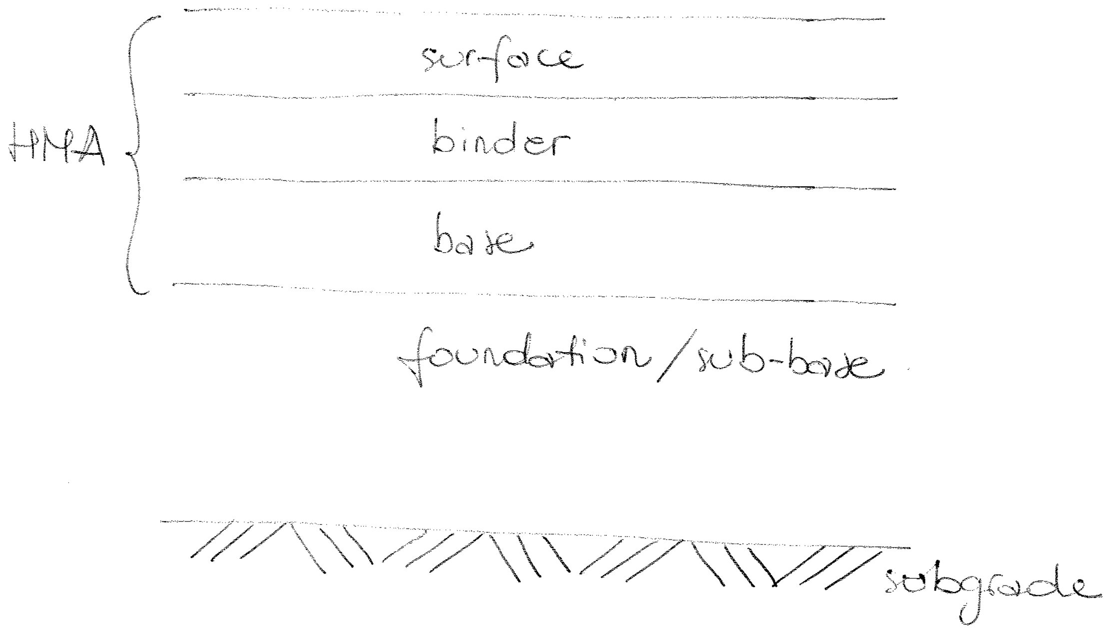
$\frac{a}{h_1} = x \qquad \frac{1}{h_1} = \frac{x}{a} \qquad h_1 = \frac{a}{x}$

7mm

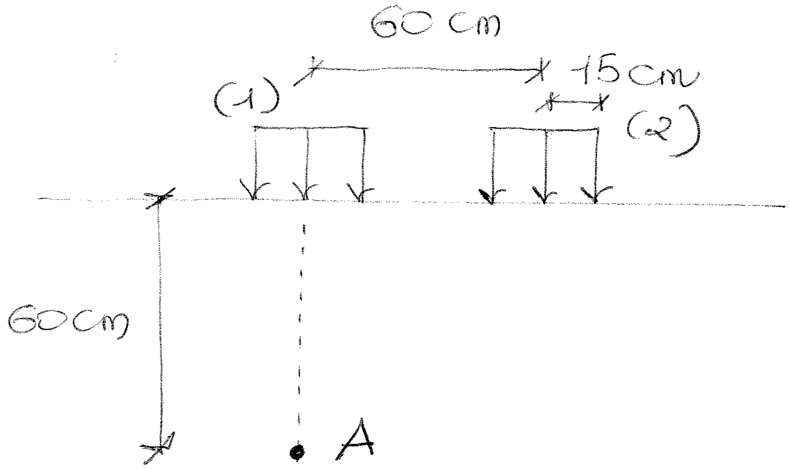
7/11/2013

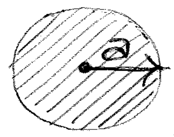
PRACTICAL APPLICATION 2

Behaviour of flexible pavement under wheel load → σ, ε, w



EXERCISE 1





$$q = \frac{P}{\pi a^2}$$

σ_A, ε_A, d_A = ?

$$\frac{y}{x} = z$$

$$10^{z} = n$$

→ value of $\frac{\sigma_z}{q}$ in point P

$$\sigma_z = \frac{\sigma_z}{q} \cdot q$$

For the deflection, I have to determine the factor F

$$w = \frac{qa}{E} \cdot F$$

ε is determined by Hooke's law:

$$\varepsilon_z = \frac{1}{E}\left[\sigma_z - \nu\left(\sigma_r + \sigma_t\right)\right]$$

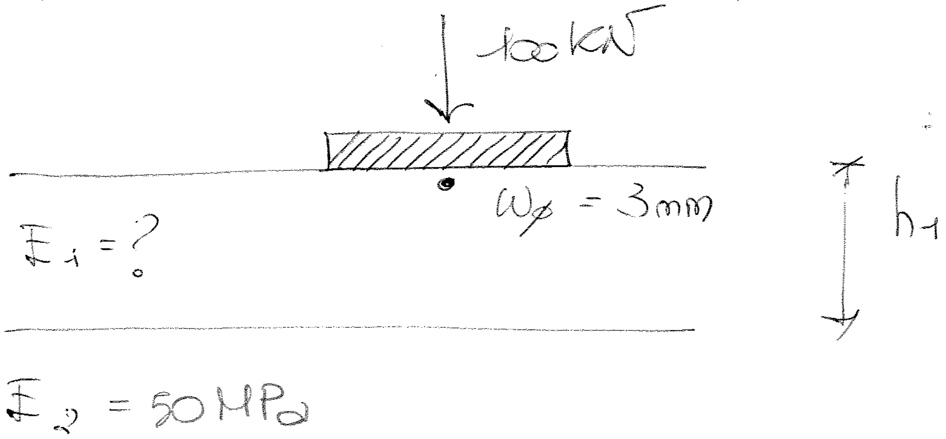
$$\varepsilon_r = \text{〃} \quad \sigma_r - \sigma_z \text{〃} \; \sigma_t$$

$$\varepsilon_t = \text{〃} \quad \sigma_t - \sigma_z \text{〃} \; \sigma_r$$

© Proprietà riservata dell'autore - Digitalizzazione e distribuzione a cura del CENTRO APPUNTI - Corso Luigi Einaudi, 55 - Torino / Pagina 233 di 318

We have determided E_2, the modulus of the subgrade

2 layer system → no homogeneous halfspace



E_1 can be determined using the graphics (appendix 2)

Design h_1 (thickness of the cement treated base course)

wheel → flexible plate

© Proprietà riservata dell'autore - Digitalizzazione e distribuzione a cura del CENTRO APPUNTI - Corso Luigi Einaudi, 55 - Torino / Pagina 235 di 318

Jones' table

$$K_1 = \frac{E_1}{E_2} \qquad K_2 = \frac{E_2}{E_3}$$

$$A = \frac{a}{h_1} \qquad H = \frac{h_1}{h_2}$$

→ stress factors ZZ1, ZZ2, RR1, RR2

$$\sigma_{z1} = q\, ZZ1$$

$$\sigma_{z1} - \sigma_{r1} = q\,(ZZ1 - RR1)$$

ε determined using Hooke's law ($\sigma_r = \sigma_t$)

$$\frac{\sigma_{z1} - \sigma_{r1}}{2E_1} = \frac{\sigma'_{z1} - \sigma'_{r1}}{2E_2}$$

$$\sigma_{z1} - \sigma'_{r1} = \frac{E_2}{E_1}(\sigma_{z1} - \sigma_{r1}) = \frac{\sigma_{z1} - \sigma_{r1}}{K_1}$$

© Proprietà riservata dell'autore - Digitalizzazione e distribuzione a cura del CENTRO APPUNTI - Corso Luigi Einaudi, 55 - Torino / Pagina 237 di 318

$$h_{2,eq} = f \cdot (h_{1,eq} + h_2) \sqrt[3]{\frac{E_2}{E_3}}$$

use it for the second transformation

$f = 0,8$ (general case)

$f = 0,9$ (2-layers system at the 1° interface)

$f = 1$ (3-layers system at the 1° interface)

use it for the first transformation

1.6 Determine bending moment in ties according to the following approaches:

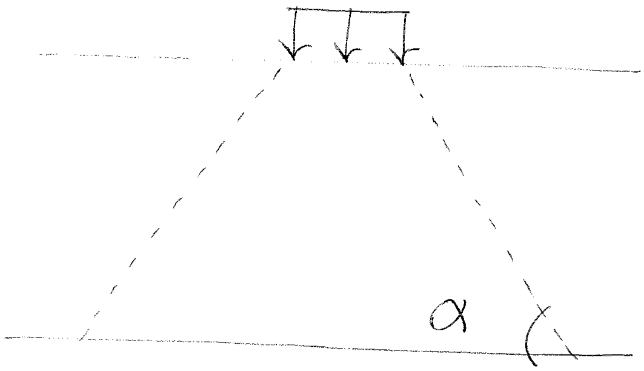
- rigid body with full support;
- rigid body with end support;
- ORE empirical method (ϕ = 1.375; B = 0.5; χ = 1.35).

1.7 Determine pressure on ballast and on subgrade caused by an isolated tie according to the following approaches:

- rigid body with full support;
- rigid body with end support;
- ORE empirical method (ϕ = 1.375; B = 0.5; χ = 1.35).

1.8 Determine pressure on subgrade by means of the combined use of the Odemark's method and of the infinite strip theory.

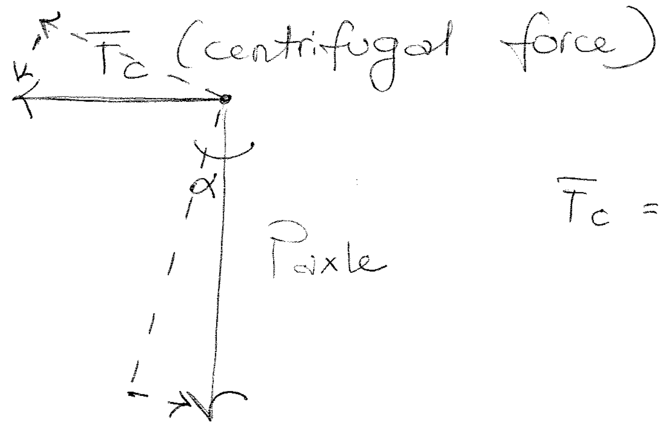
α describes the distribution of loadings through the ballast



ballast E_b

subgrade, E_s

1.1)



$$F_c = \frac{P_{axle}}{g} \cdot \frac{V^2}{R}$$

2 components:

$$N = P_{axle} \cdot \cos\alpha + F_c \cdot \sin\alpha = P_{axle} + F_c \cdot \frac{h}{s}$$

$$H = F_c \cdot \cos\alpha \mp P_{axle} \cdot \sin\alpha = F_c \mp P_{axle} \cdot \frac{h}{s}$$

(hp) α small $\rightarrow \cos\alpha \simeq 1$; $\sin\alpha \simeq tg\alpha \simeq \simeq \frac{h}{s}$)

© Proprietà riservata dell'autore - Digitalizzazione e distribuzione a cura del CENTRO APPUNTI - Corso Luigi Einaudi, 55 - Torino / Pagina 243 di 318

$(DAF)_{ORE} = 1,11$ (braking conditions)

$$P_{dyn} = P_{static} \cdot (DAF)_{dis.} \cdot (DAF)_{ORE}$$

1.2) $H_{TOT} = H_{(static)} \cdot \beta + H'$

H' → abnormal movements

β → non uniform distribution of the load among the connected axles

with $H' = \dfrac{P_{axle} \cdot V}{1000}$

1.3) $N_{\ell} = E_{rail} \cdot \alpha_{rail} \cdot \Delta T \cdot A_{rail}$

N_{ℓ} → longitudinal force

$+ \Delta N = 15\% \, N$ (increase)

$$N_{\ell, tot} = N_{\ell} + 15\% \, N$$

4

© Proprietà riservata dell'autore - Digitalizzazione e distribuzione a cura del CENTRO APPUNTI - Corso Luigi Einaudi, 55 - Torino / Pagina 245 di 318

$$M(x) = \frac{P}{4a \cdot b} e^{-bx}(a \cos ax - b \cos ax)$$

(Pasternak)

$\gamma = \emptyset \rightarrow$ Zimmermann

$\gamma \neq \emptyset \rightarrow$ Pasternak

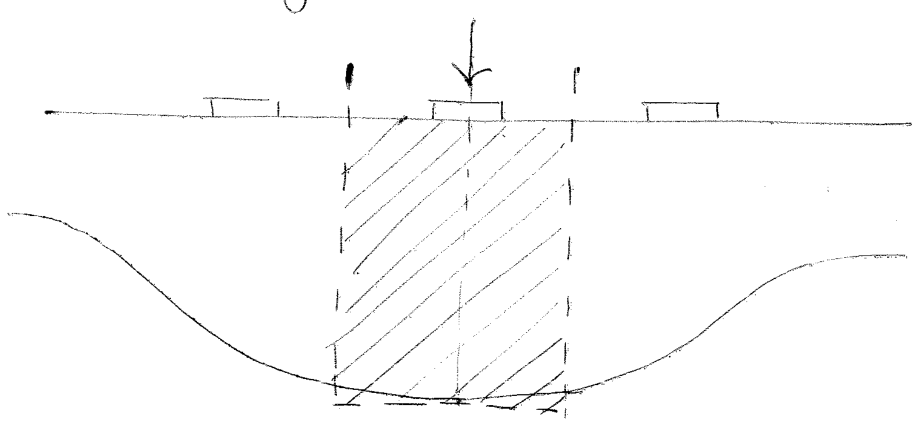
1.5) Talbot

$$y_{max} = 0,391 \frac{P}{u \cdot x_1}$$

with $x_1 = \dfrac{\pi}{4\lambda}$

$$M_{max} = 0,318 \cdot P \cdot x_1$$

Seating loads:



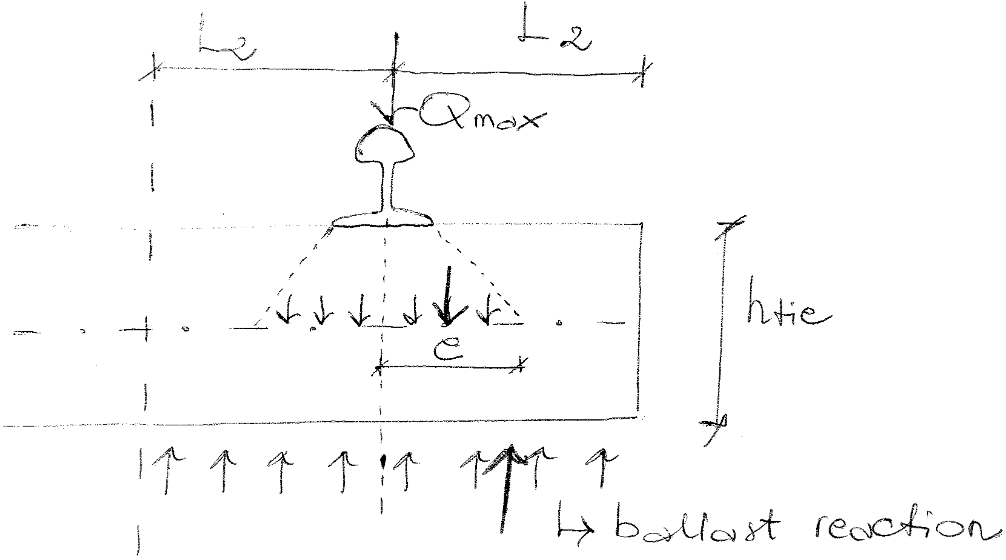
$$p_z(x) = \frac{P \cdot u}{\sqrt[4]{64 E I u^3}} \cdot e^{-\lambda x}(\cos \lambda x + \sin \lambda x)$$

- ORE empirical method

Evaluation of the maximum seating load:

$$Q_{max} = \varphi \cdot \frac{P_{axle}}{2} \cdot \beta \cdot \gamma$$

$\varphi \rightarrow f(V)$ $\qquad \beta \rightarrow 0{,}4 \div 0{,}5$



$$e = \frac{c}{2} + \frac{h_{tie}}{2}$$

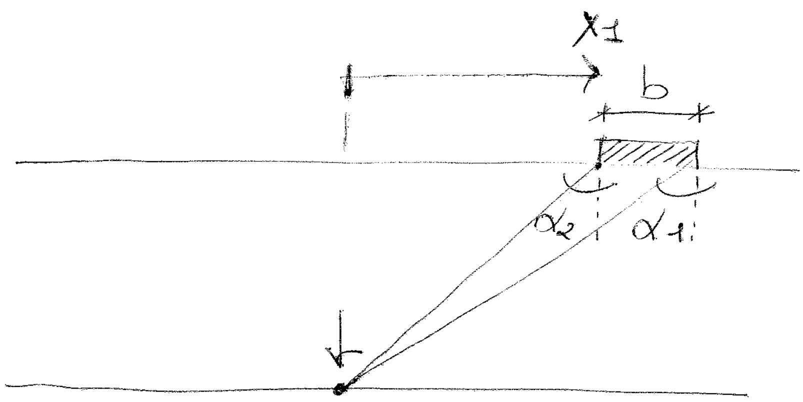
$$M_{rail} = 1{,}6 \cdot \left(\frac{Q_{max}}{2} \cdot \frac{L_2}{2} - \frac{Q_{max}}{2} \cdot \frac{e}{2} \right) =$$

$$= 1{,}6 \, \frac{Q_{max}}{4} \left(L_2 - e \right)$$

$$M_c = 1{,}2 \, M_{rail} \cdot \frac{(EI)_{center}}{(EI)_{rail}} = 1$$

$E_{sleeper}$, $I_{sleeper}$ $\qquad$ the section doesn't change

$$h_e = 0{,}9 \cdot h_b \cdot \sqrt[3]{\frac{E_b}{E_{sub}}}$$



$$\alpha_1 = \operatorname{arctg}\left(\frac{x_1 + \frac{b}{2}}{h_e}\right)$$

$$\alpha_2 = \operatorname{arctg}\left(\frac{x_1 - \frac{b}{2}}{h_e}\right)$$

$$\sigma_{zi} = \sigma_i \cdot f(x_1)$$

pressure acting on the ballast for each sleeper $= \dfrac{2Q}{A_{bs}} \cdot s$

↳ contact area between sleepers and ballast)

$$f(x_1) = \frac{1}{\pi} \cdot \left[\alpha_1 - \alpha_2 + \frac{1}{2} (\sin 2\alpha_1 + - \sin 2\alpha_2) \right]$$

10

Politecnico di Torino – Corso di Laurea Magistrale in Ingegneria Civile

Pavement and Track Engineering - 02IODMX

A.A. 2013/14

PRACTICAL APPLICATION #4 - 28/11/2013

Example #1 ACCUMULATED ESAL ON THE DESIGN LANE

A six-lane two-way highway has an average annual daily traffic (AADT) in both direction of 11000 during the first year of traffic. Traffic composition and axle loads are reported in **Table 1**. It is assumed that they will remain constant over the analysis period of 30 years. Traffic volumes for all vehicle types is expected to increase at a rate of 2.5 percent per year. The pavement has a terminal serviceability index (p_t) of 2.5 and a structural number (SN) of 5. The directional distribution factor (D_D) is 0.5 and the percent of traffic on the design lane (D_L) is 65 percent. Determine the design ESAL and the traffic versus time relationship.

Table 1.

Vehicle Types	Percentage (%)	Axle loads Distribution (kN)
Passenger cars	50	total weight < 30
2-axle single-unit trucks	25	↓10 ↓20
3-axle single-unit trucks	10	↓40 ↓80 ↓80
5-axle multiple-unit trucks	15	↓40 ↓100 ↓80 ↓80 ↓80

Example #2 EFFECTIVE ROADBED RESILIENT MODULUS

Figure 2.4 shows the 12 monthly subgrade resilient moduli (M_r) estimated by means of a laboratory relationship between resilient modulus and moisture content of soil beneath the pavement. Determine the effective roadbed resilient modulus (M_R).

Example #3 LAYER THICKNESSES

Calculate the required layer thicknesses for a new flexible pavement consisting of an asphalt concrete surface, a crushed-stone base, and a granular subbase. The subbase has a resilient modulus (E_3) of 20 ksi, resilient modulus of the base (E_2) is 40 ksi, and resilient modulus of asphalt concrete (E_1) is 400 ksi. It is estimated that water drains out of the pavement within a period of one day and the pavement structure will be exposed to moisture levels approaching saturation for 20 percent of the time. As cumulative ESAL in the design lane, consider the traffic versus time relationship developed in example #1 and a performance period of 15 years. As effective roadbed soil consider the result obtained in example #2. Assume a reliability level of 95 percent and an overall standard deviation of 0.45. The initial serviceability index (p_i) is 4.2 and the terminal serviceability index (p_t) is 2.5.

→ ESAL = 3.2 millions

SN (= 5,8) da (★)

(1) using $E_3 = M_R \rightarrow SN_1 \rightarrow D_1$

$D_1^* \geq SN_1 / a_1$

(2) using $E_3 = M_R \rightarrow SN_2 \rightarrow D_2$

$D_2^* \geq \frac{SN_2 - SN_1}{a_2 m_2}$

(3) using $M_R \rightarrow SN^* \geq 5,8$

NOMOGRAPH SOLVES:

fundamental equation

$$\log_{10} W_{18} = Z_R \cdot S_o + 9.36 \cdot \log_{10}(SN+1) - 0.20 + \frac{\log_{10}\left[\frac{\Delta PSI}{4.2-1.5}\right]}{0.40 + \frac{1094}{(SN+1)^{5.19}}} + 2.32 \cdot \log_{10} M_R - 8.07$$

(*)

Table 2.2. Suggested Levels of Reliability for Various Functional Classifications

Functional Classification	Recommended Level of Reliability: Urban	Rural
Interstate and Other Freeways	85–99.9	80–99.9
Principal Arterials	80–99	75–95
Collectors	80–95	75–95
Local	50–80	50–80

NOTE: Results based on a survey of the AASHTO Pavement Design Task Force.

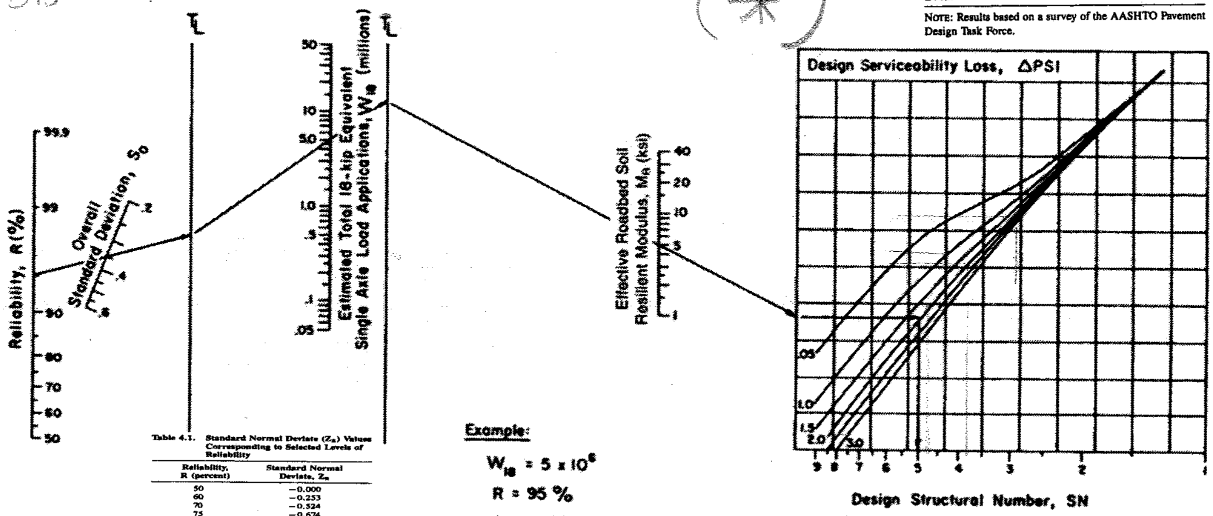


Table 4.1. Standard Normal Deviate (Z_R) Values Corresponding to Selected Levels of Reliability

Reliability, R (percent)	Standard Normal Deviate, Z_R
50	−0.000
60	−0.253
70	−0.524
75	−0.674
80	−0.841
85	−1.037
90	−1.282
91	−1.340
92	−1.405
93	−1.476
94	−1.555
95	−1.645
96	−1.751
97	−1.881
98	−2.054
99	−2.327
99.9	−3.090
99.99	−3.750

Example:

$W_{18} = 5 \times 10^6$

$R = 95\,\%$

$S_o = 0.35$

$M_R = 5000$ psi

$\Delta PSI = 1.9$

Solution: $SN = 5.0$

Figure 3.1. Design Chart for Flexible Pavements Based on Using Mean Values for Each Input

relative r. modulus

Month	Roadbed Soil Modulus, M_R (psi)	Relative Damage, u_f
Jan.	20,000	0,0124
Feb.	20,000	
Mar.	2,500	
Apr.	4,000	
May	4,000	
June	7,000	
July	7,000	
Aug.	7,000	
Sept.	7,000	
Oct.	7,000	
Nov.	4,000	
Dec.	20,000	

Summation: Σu_f = ______ danno tot

Average: $\bar{u}_f = \frac{\Sigma u_f}{n} =$ ______ = media danno → Mr equivalente

n = 12 mesi

Effective Roadbed Soil Resilient Modulus, M_R (psi) = ______ (corresponds to $\bar{u}_f$)

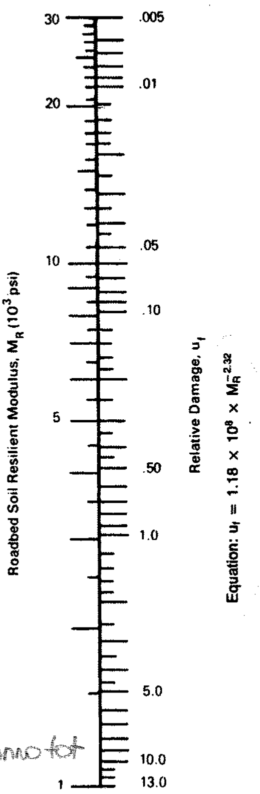


Figure 2.4. Chart for Estimating Effective Roadbed Soil Resilient Modulus for Flexible Pavements Designed Using the Serviceability Criteria

Table 4.1. Suggested Seasons Length (Months) for the Six U.S. Climatic Regions

U.S. Climatic Region	Season (Roadbed Soil Moisture Condition): Winter (Roadbed Frozen)	Spring-Thaw (Roadbed Saturated)	Spring/Fall (Roadbed Wet)	Summer (Roadbed Dry)
I	0.0*	0.0	7.5	4.5
II	1.0	0.5	7.0	3.5
III	2.5	1.5	4.0	4.0
IV	0.0	0.0	4.0	8.0
V	1.0	0.5	3.0	7.5
VI	3.0	1.5	3.0	4.5

*Number of months for the season.

Table 4.2. Suggested Seasonal Roadbed Soil Resilient Moduli, M_R (psi), as a Function of the Relative Quality of the Roadbed Material

Relative Quality of Roadbed Soil	Season (Roadbed Soil Moisture Condition): Winter (Roadbed Frozen)	Spring-Thaw (Roadbed Saturated)	Spring/Fall (Roadbed Wet)	Summer (Roadbed Dry)
Very good	20,000*	2,500	8,000	20,000
Good	20,000	2,000	6,000	10,000
Fair	20,000	2,000	4,500	6,500
Poor	20,000	1,500	3,300	4,900
Very poor	20,000	1,500	2,500	4,000

*Values shown are Resilient Modulus in psi.

Table 4.3. Effective Roadbed Soil Resilient Modulus Values, M_R (psi), That May be Used in the Design of Flexible Pavements for Low-Volume Roads. Suggested values depend on the U.S. climatic region and the relative quality of the roadbed soil.

U.S. Climatic Region	Relative Quality of Roadbed Soil: Very Poor	Poor	Fair	Good	Very Good
I	2,800*	3,700	5,000	6,800	9,500
II	2,700	3,400	4,500	5,500	7,300
III	2,700	3,000	4,000	4,400	5,700
IV	3,200	4,100	5,600	7,900	11,700
V	3,100	3,700	5,000	6,000	8,200
VI	2,800	3,100	4,100	4,500	5,700

*Effective Resilient Modulus in psi.

REGION	CHARACTERISTICS
I	Wet, no freeze
II	Wet, freeze – thaw cycling
III	Wet, hard-freeze, spring thaw
IV	Dry, no freeze
V	Dry, freeze – thaw cycling
VI	Dry, hard freeze, spring thaw

Figure 4.1. The Six Climatic Regions in the United States (12)

$$U_f = 1{,}18 \cdot 10^8\, M_r^{-2{,}32} \qquad \frac{1}{M_r^{2{,}32}} = \frac{U_f}{1{,}18 \cdot 10^8} \qquad M_r = \sqrt[2{,}32]{\frac{1{,}18 \cdot 10^8}{U_f}}$$

28/11/2013

PRACTICAL APPLICATION (4)

1993 → last version of AASHTO method

Structural number: describes the performance of the pavement.

W_{18} → ESAL which cause a reduction of the level of serviceability ΔPSI

Z_R → standard normal deviate

S_ϕ → standard deviation

SN → structural number

M_R → resilient modulus

Performance period = "life" of the pavement before mainteinance