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The Search for Suitable Lab Test Procedures and Materials Models for Mechanistic Design



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Pavement materials characterization

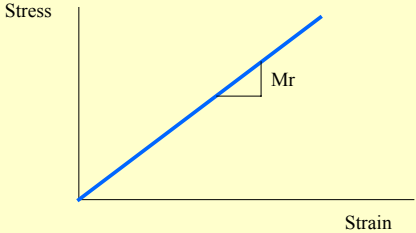
Involves ...

- laboratory testing procedures to determine M_r
- equations that relate resilient modulus to stress conditions (constitutive models)
- analytical methods for mechanistic pavement design

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Linear elastic material



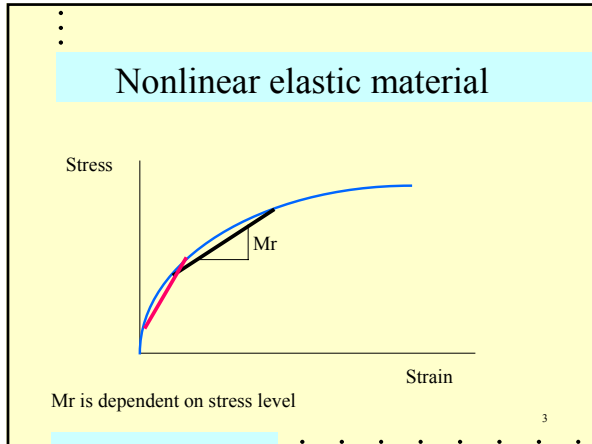
Stress

Strain

M_r

M_r is independent of stress level

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Models in current use

Linear elastic model : $M_r = \text{constant}$

Bulk stress model : $M_r = k_1 \Theta^{k_2}$

Deviator stress model : $M_r = k_3 \sigma_d^{k_4}$

Octahedral shear stress model :

$$M_r = k_5 \tau_{oct}^{k_6}$$

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Models in current use

Uzan model: $M_r = k_1 \Theta^{k_2} (1 + \tau_{oct})^{k_3}$

$$\sigma_d = \sigma_1 - \sigma_3$$

$$\Theta = \sigma_1 + \sigma_2 + \sigma_3$$

$$\tau_{oct} = \frac{1}{6} \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}$$

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Scalar invariants

The bulk stress, Θ , and the octahedral shear stress, τ_{oct} , are “scalar invariants.” That is, their magnitude is not a function of direction.

This is particularly useful when transferring a materials characterization from the laboratory into the field.

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Log-log bulk stress model

$M_r = k_1 \Theta^{k_2}$

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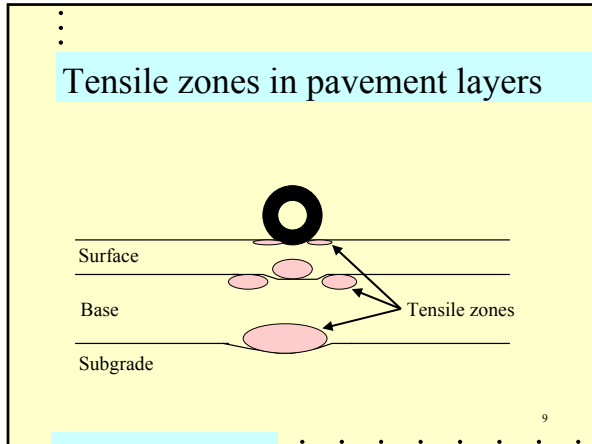
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Problem ...

Log-log models have limited applicability to pavements because ...

- Pavements under load are in bending.
- Layers in bending have zones of tensile (e.g., negative) stress.
- The logarithm of a negative number is undefined.

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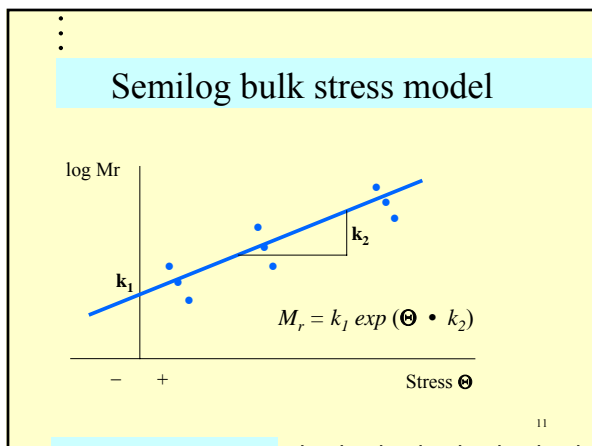
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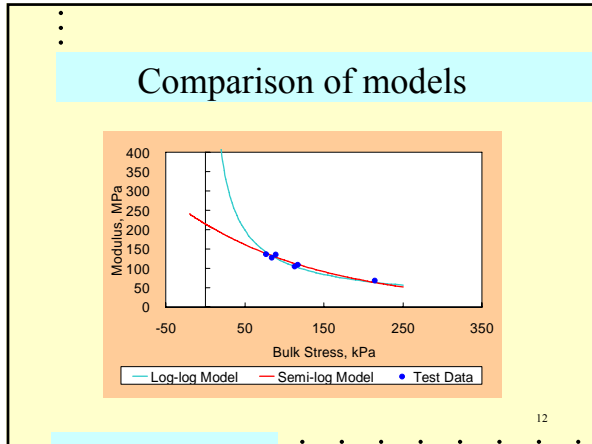
Solution ...

Semilog models will work better because ...

stresses can be either tensile or compressive without any discontinuity.

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Comparison of models

- Results of regression with the data:
 $E = 4181 \theta^{-0.779}$
(log - log model, $r^2 = 0.96$)
 $E = 214.8 \exp(-0.00567 \theta)$
(semi - log model, $r^2 = 0.95$)

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Conclusion

- Using statistics (r^2) or visual evaluation, one cannot say which is the better model
- However, the semi-log model behaves more reasonably for negative bulk stresses

There is a need to improve the state-of-the-art regarding constitutive models

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Question ...

- Why do we not get the same results (M_r) from laboratory repeated-load triaxial tests and from backcalculation of FWD data?

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Answer ...

The initial confining pressure condition in the **field** is NOT the same as it is in the **laboratory** ...

Due to compaction, the horizontal stresses are bigger under a pavement than would be predicted from the unit weight of the materials.

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Geostatic stresses

$$\sigma_v = \gamma \cdot h$$
$$\sigma_h = k_0 \cdot \sigma_v$$

where γ = unit weight of material
 k_0 = at rest pressure coefficient

$0.4 < k_0 < 0.6$ for uncompacted materials
 $0.6 < k_0 < 2$ for compacted materials

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Confining pressures

- We do not know what the field value of k_0 is to any degree of precision.
- The confinement influences the M_r value
- The large confining pressure acts like a pre-stress that enables the pavement layer to resist tensile stresses due to load.

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Confinement in the field

Surface

Base

Subgrade

$\sigma_v \neq \sigma_h$
 $0.6 < k_0 < 2$

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Confinement in the lab

$\sigma_v = \sigma_h$
 $k_0 = \sigma_h / \sigma_v = 1.0$

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Research at Cornell has found that ...

$$M_r = k_1 \Theta^{k_2} (1 + \tau_{oct})^{k_3} k_0^{-0.7}$$

Note: k_0 is also present in Θ and τ_{oct} since they are total stresses.

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Problem ...

Since we normally have $k_0 = 1$ in the laboratory, we cannot detect its influence.

Since k_0 in the field is seldom 1.0, it always has an influence on materials behavior.

Therefore, comparisons between laboratory test results and back-calculated moduli will inevitably be unfavorable.

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Conclusion ...

We need to develop better laboratory repeated-load triaxial test procedures to be more representative of the field conditions.

We need to use better constitutive models that are more applicable to pavements.

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Problem ...

We tend to use different constitutive models for coarse-grained soils and fine-grained soils.

Most materials in the field are a mixture of the two. How do these materials know which model to follow?

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Research at Cornell has found that ...

$$M_r = k_1 \Theta^{k_2(1-P_{200})} (1 + \tau_{oct})^{k_3} P_{200} k_0^{-0.7}$$

- Combined results of four materials (311 tests)
- P_{200} ranged from 5 to 55 percent
- k_1 is a function of moisture content, density, gradation and plasticity index.
- **Unbound base course and subgrade materials all follow the same model.**

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Laboratory testing procedure

- Similar to SHRP P-46 and AASHTO T 307.
- Uses anisotropic consolidation.
- Uses kneading compaction rather than double-plunger static compaction.
- Verifies that a uniform density is achieved in the specimen.

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Laboratory testing procedure

- Confines the specimen during transfer to the triaxial cell.
- Covers a range of anisotropic confining conditions ($0.3 < k_0 < 1.0$)

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Confinement in the lab

$\sigma_v \neq \sigma_h$
 $0.3 < k_0 < 1.0$

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Specimen loading

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Loading sequence (psi)

Step	σ_{cell}	σ_{static}	K_0	$\sigma_{dynamic}$	$(\sigma_1, \sigma_3)_{peak}$
1	4	0	1.0	1	1.25
2	4	1	0.8	2	1.75
3	4	2	0.67	3	2.25
4	2	0	1.0	3	2.5
5	2	1	0.67	2	2.5
6	2	2	0.5	1	2.5
...					

A total of 24 steps are used.

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- ### Details of the test procedure
- Run a 24-step sequence.
 - Initially condition the specimen with 1000 load repetitions at Step 1.
 - Measure the dynamic and permanent strain response after 200 load cycles.
 - Allow 5 minutes for consolidation at the start of each step.
 - Stop the test if the permanent strain exceeds 5 percent.
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Tentative constitutive model

$$\log M_r = k_1 + k_2 \Theta + k_3 (1 + \tau_{oct}) + k_4 k_0$$

$$k_2 = k_2^* (1 - P_{200})$$

$$k_3 = k_3^* P_{200}$$

∴

$$M_r = k_1 \cdot \exp(k_2^* \cdot \Theta \cdot (1 - P_{200})) \cdot \exp(k_3^* \cdot (1 + \tau_{oct}) \cdot P_{200}) \cdot \exp(k_4 \cdot k_0)$$

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Summary

In order to apply laboratory materials test results to the field we must ...

- Modify lab test procedures to include anisotropic confinement
- Define semilog constitutive models to accommodate pavement tensile stresses
- Develop a better understanding of in situ k_0 values

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