MATHEMATICAL MORPHOLOGY

Application to Pavement Distress Assessment

Chakravarthy Bhagvati
Dept. of Computer & Information Sciences
University of Hyderabad

October 25, 2010

OVERVIEW

- Experiences with Mathematical Morphology
- Normalized Opening Distributions (pravda?)
  - matched and mis-matched geometries
  - normalized distributions
  - morphological algorithm for Texture Defect Analysis
  - application to pavement distress assessment
- Some other ideas
  - non-linear scale-spaces?
  - morphological Gabor filters?
  - colour morphological applications?

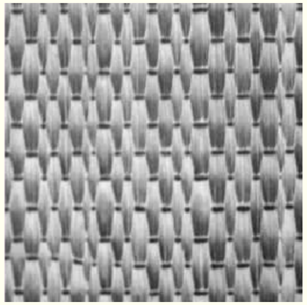
WHY SHOULD I BE HERE?

- 1988: First encounters with Mathematical Morphology at Rensselaer Polytechnic Institute
  - purchased my copy of Image Analysis and Mathematical Morphology
- 1989: Centroid movements induced by opening and closing operations as shape signatures
- 1990 – 1994: Normalized opening distributions for texture defect analysis
- 1992 – 1996: Application of normalized distributions to pavement distress assessment
- 1995 – 2002: Dabbling in crazy ideas!
- 2005 – 2006: Area morphology
- 2000 – present: Forensic applications

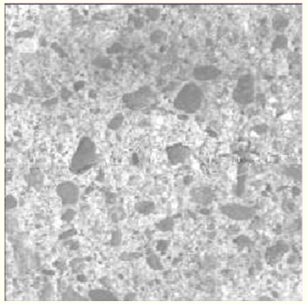
TEXTURE ANALYSIS

Texture:

- distribution of gray scales...
- repetition of elementary patterns...



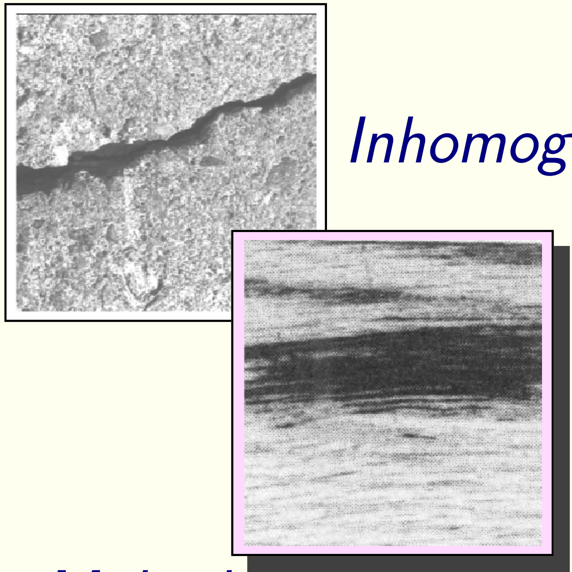
Common Uses of Texture:



Classification:	Types, Similarities, Differences
Description:	Characteristics
Segmentation:	Boundaries, Regions
Retrieval:	*Databases, Image Archives*

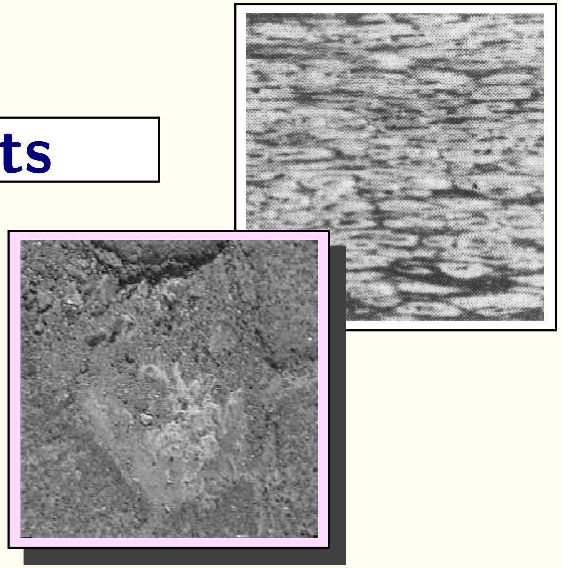
TEXTURE DEFECT ANALYSIS

Textures reflect variations in physical properties. . .
roughness, *graininess*, *porosity*, etc.



Inhomogeneities or regions of no texture

Texture defects



Multiple textures or regions of secondary texture

DEFECT ANALYSIS

Detection: Identifying the presence of a defect.
How *small* a defect can be detected?

Characterization: Classifying into different types

Measurement: Calculating areas, dimensions, aspect ratios and other geometric properties

Desirable to search for features that may be correlated to physical properties

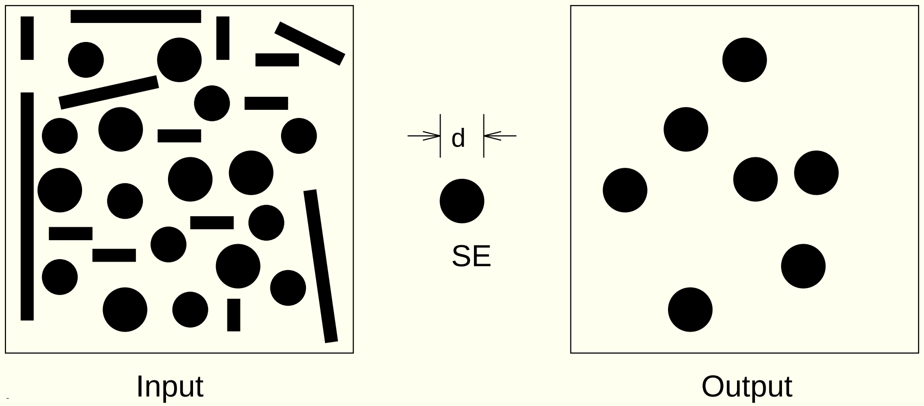
- *derive* texture features from physical properties
- *estimate* surface properties from image textures

Relationship between dolerite texture and porosity[*Serra82*]

MATHEMATICAL MORPHOLOGY

- Serra and Matheron (1967–1970)
- roots in materials analysis
- non-linear image processing technique

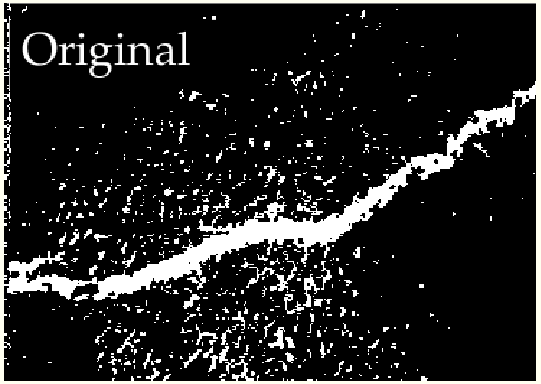
Morphological Opening

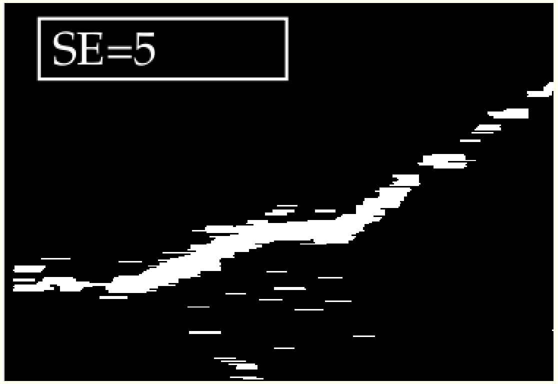


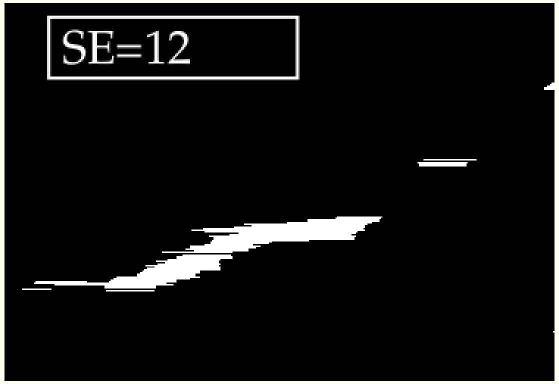
- basic elements — images and structuring elements (SE)
- non-linear operations —
  - hit-or-miss
  - minima or maxima
  - union or intersection
- Manipulates pixel coordinates and not intensities as in signal processing based techniques
- Operators:
  - Dilation ($\oplus$) and Erosion ($\ominus$)
  - Opening ($\circ$) and Closing ($\bullet$)

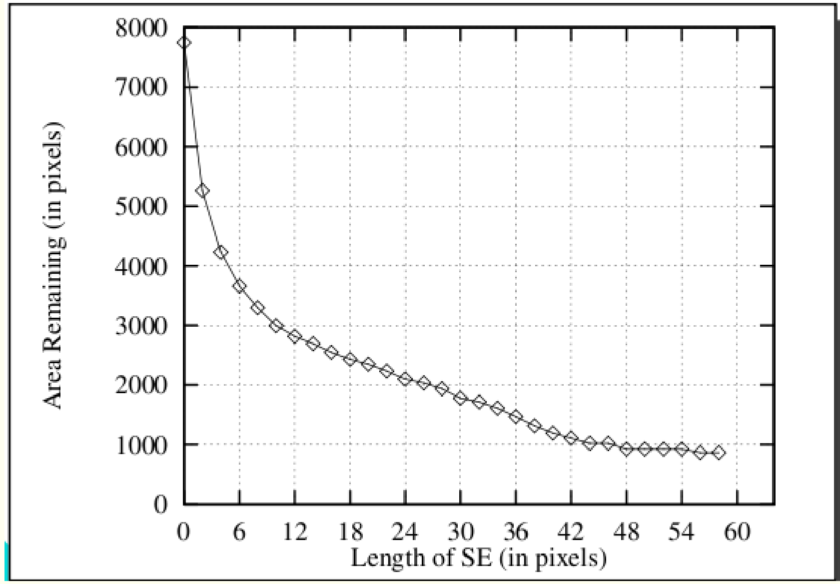
OPENING DISTRIBUTION

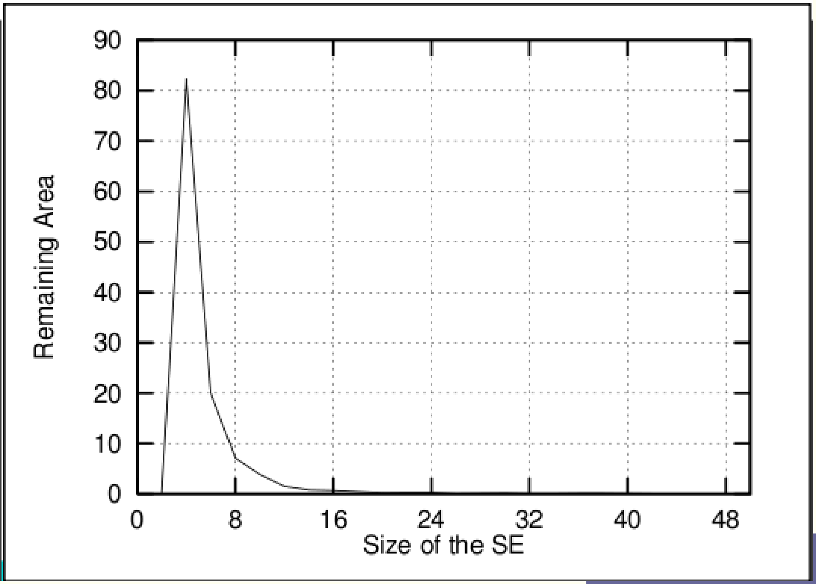
Measures particle size distributions — plot of the area remaining in the image after opening vs. size of structuring element



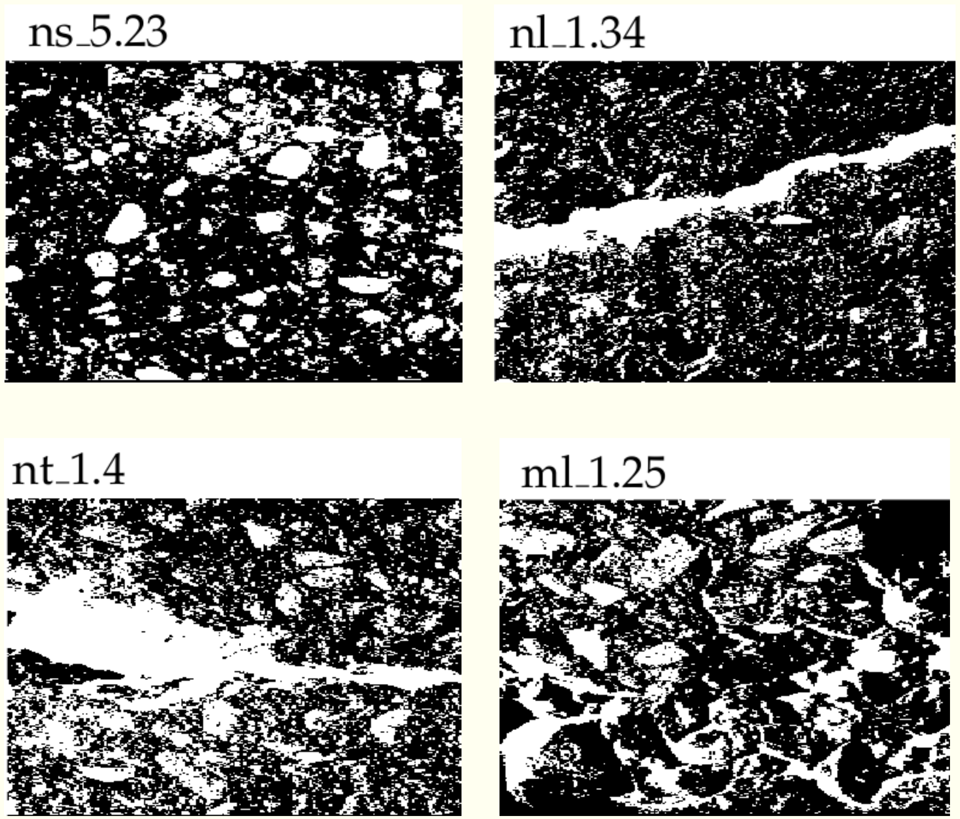


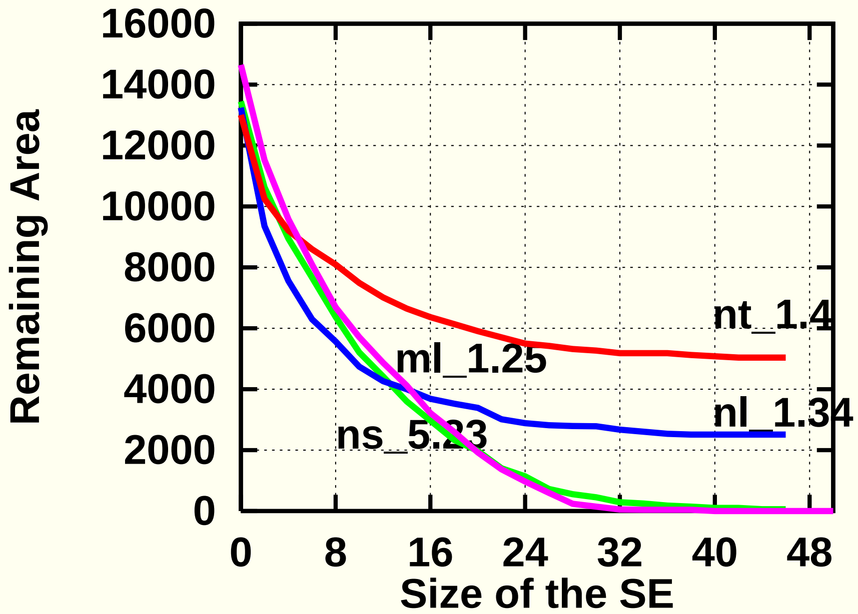






OPENING DISTRIBUTIONS (contd.)





The presence of cracks is revealed in the opening distributions with linear (horizontal) structuring elements

PROBLEMS WITH OPENING DISTRIBUTIONS

- Scales of defect and normal texture must be different
- Choice of structuring element is critical
  - Linear structuring element — highly sensitive to inhomogeneities
  - Circular structuring element — sensitive to multiple textures

Some proposed solutions in literature

- Battery of structuring elements
- Restrict domain of application
- Search for an optimal structuring element
- Use multiple approaches
  - Edge-detection for inhomogeneities
  - Texture analysis methods for multiple textures

NORMALIZED DISTRIBUTIONS

We explore a different approach

Basic Idea: Image texture = Ideal texture + Defective texture
$\Rightarrow$ Particle distribution = Ideal particle distribution +
Deviations due to defects

Normalized distributions *remove* ideal particle distributions – emphasize deviations due to defects

$$\eta = \frac{\text{Particle distribution from an image}}{\text{Ideal particle distribution}}$$
$$= \frac{\text{Ideal particle distribution} + \textit{Defects}}{\text{Ideal particle distribution}}$$

η is a flat-line$(= 1.0)$ if there are no defects
Undershoot, i.e., $\eta < 1.0$ indicates a deficiency of particles
Overshoot, i.e., $\eta > 1.0$ indicates an excess of particles

IDEAL PARTICLE DISTRIBUTION

Ideal particle distributions obtained in three ways:

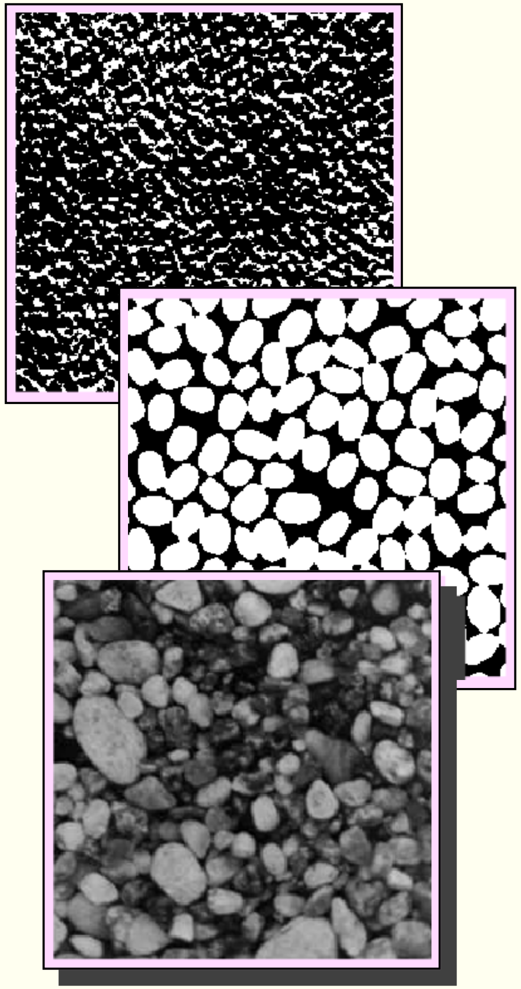
- A-priori or theoretical knowledge
  - specified or known from porosity, roughness, strength, etc.
  - e.g., highway materials, X-ray crystallography, materials engineering applications. . .
- Empirical measurements
  - computed from *known* non-defective images
  - results in *training* and *operational* phases
- Standard mathematical families of distributions
  - Several natural processes may be approximated by well-known mathematical distributions
  - e.g., Gaussian, Raleigh, Exponential, Weibull, etc.

GAUSSIAN NUMBER OF PARTICLES MODEL

Gaussian distribution describes several textures that have

- a specific scale
- large numbers of particles

Most of the particles are of a specific size and all the rest cluster around the *mean* size.



Number of particles at a scale x

$$N(x) = \mu_T e^{-\frac{(x-T)^2}{2\sigma^2}}$$

NORMALIZED DISTRIBUTIONS FOR GAUSSIAN MODEL

Area in the image at scale x for the Gaussian model

$$\begin{aligned} A_x &= \text{Number of particles at } x \times \text{Area of each particle} \\ &= \left(\mu_T e^{\frac{(x-T)^2}{2\sigma^2}}\right)\Phi(x) \end{aligned}$$

$\Phi(x)$ governs structuring element/texture interaction

For *matched geometry*,

$$\begin{aligned} \Phi(x) &= 0, \qquad \text{if } x \leq D \\ &= \text{Area of particle}, \qquad \text{if } x > D \end{aligned}$$

For *mis-matched geometry*,

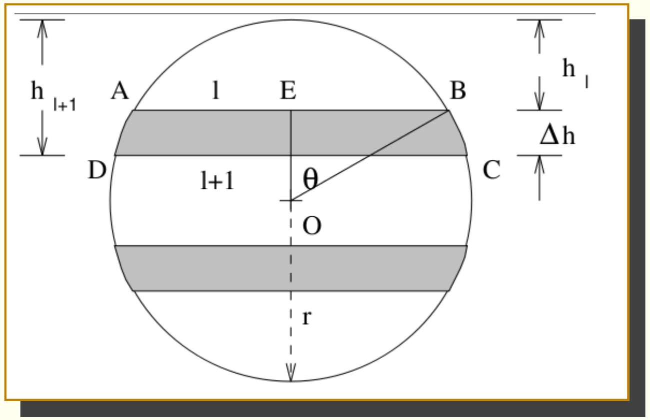
$$\Phi(x) = \mathcal{F}(\text{Particles of sizes } > x)$$

SQUARE particles and linear SEs

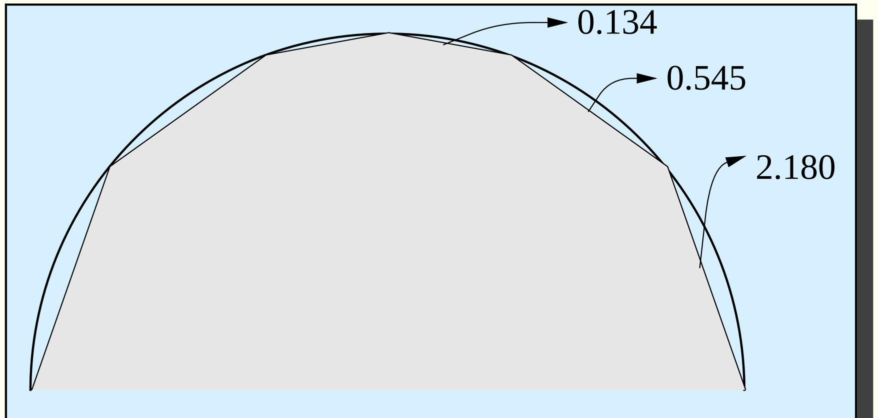
$$\eta_G(x) = \begin{cases} \dfrac{A(0)}{\sqrt{2\pi}\sigma\mu_T T^2}, & x = 0 \\[2ex] \dfrac{[A(x-1) - A(x)]}{\mu_T x^2 e^{-\frac{(x-T)^2}{2\sigma^2}}}, & T - 3\sigma \leq x \leq T + 3\sigma \\[2ex] \dfrac{[A(x-1) - A(x)]}{x^2} + 1, & \text{otherwise} \end{cases}$$

MIS-MATCHED GEOMETRY

$$A'(l) = \sqrt{2\pi}\sigma\mu_T{}^{\frac{2l+1}{2}} \Bigg[2.180\left\{\text{erf}\left(\frac{\frac{10l}{9}-1-T}{\sqrt{2}\sigma}\right)-\text{erf}\left(\frac{l-T}{\sqrt{2}\sigma}\right)\right\}+ 0.545\left\{\text{erf}\left(\frac{2l-1-T}{\sqrt{2}\sigma}\right)-\text{erf}\left(\frac{\frac{10l}{9}-T}{\sqrt{2}\sigma}\right)\right\}+ 0.134\left\{\text{erf}\left(\frac{3}{\sqrt{2}}\right)-\text{erf}\left(\frac{2l-T}{\sqrt{2}\sigma}\right)\right\}\Bigg]$$

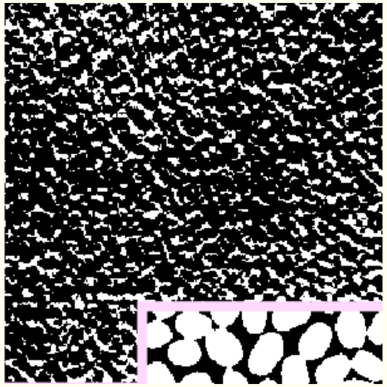


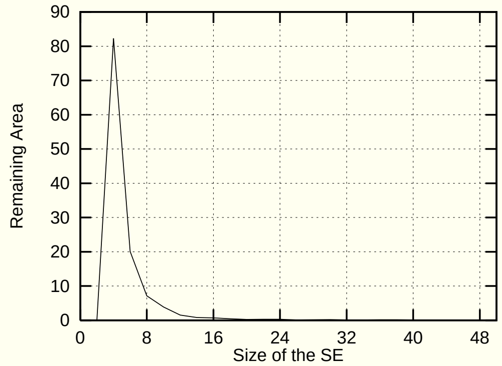
Area removed between successive openings $= \dfrac{(2l+1)\Delta h}{2}$

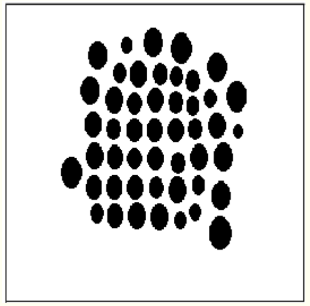


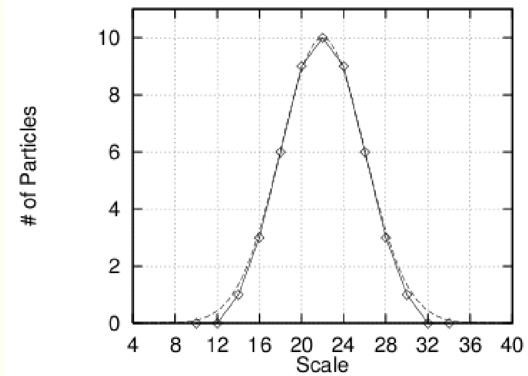
Circle as a duo-decagon

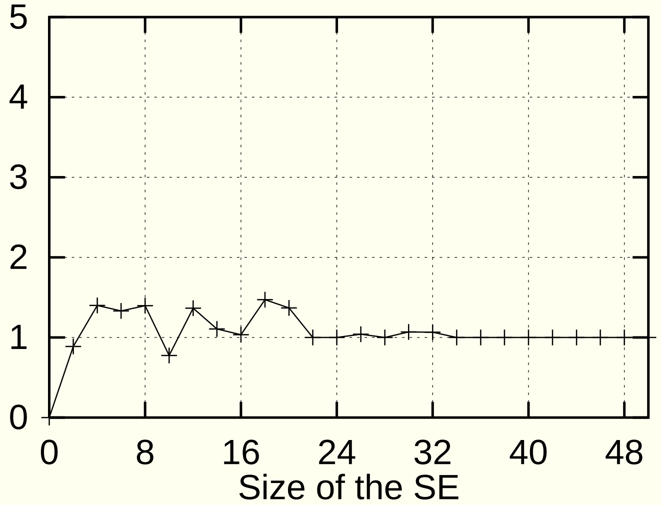
EXAMPLES OF NORMALIZED DISTRIBUTIONS



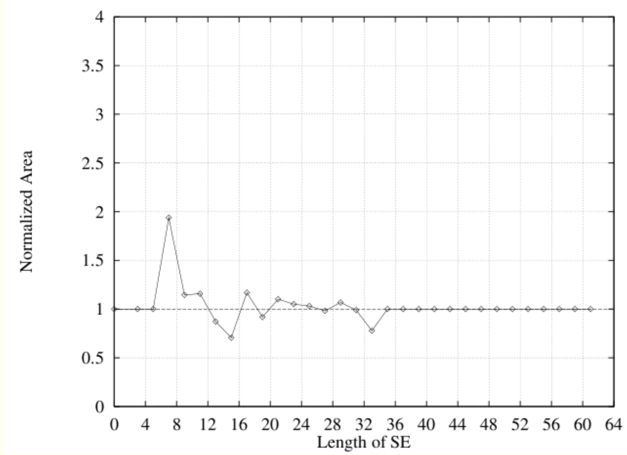






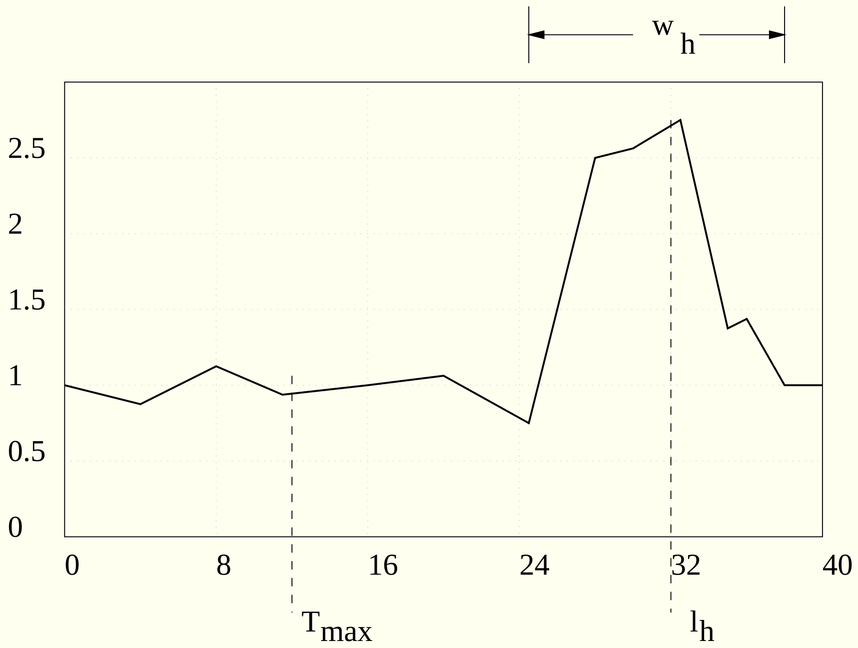


Matched Geometry Model



Mis-matched Geometry Model

FEATURES FOR TEXTURE DEFECT ANALYSIS



Location of overshoot/undershoot: l_h or l_v

Width of overshoot/undershoot: w_h or w_v

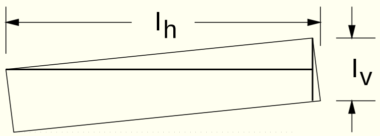
Height/width ratio of overshoot

Magnitude of overshoot/undershoot

DETECTING INHOMOGENEITIES

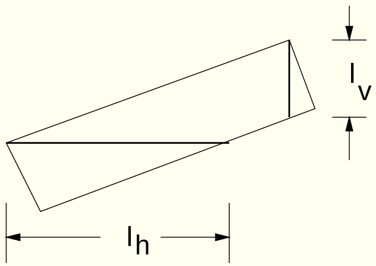
Dependent on orientation with respect to SE

Let l and w be the length and width of the inhomogeneity



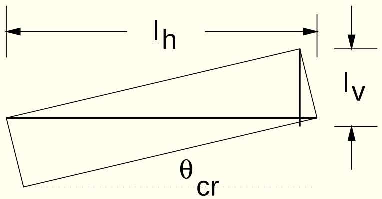
When θ is *small*

- θ is obtained from *normalized area*
- $l = l_h \cos(\theta)$
- $w = l_v \cos(\theta)$



When θ is *large*

- $\theta = \tan^{-1}(l_v/l_h)$
- $w = l_h \sin(\theta)$



Critical angle: θ_{cr} separates small and large

DEFECT ANALYSIS ALGORITHM

1. Compute $\eta(x)$ in horizontal and vertical directions
2. If the height-to-width ratio > 1, then *linear inhomogeneity*
3. – if $\theta < \theta_{cr}$
   - compute θ, l as $l_h \cos(\theta)$, w as $l_v \cos(\theta)$
4. – else
   - compute θ as $\tan^{-1}(l_v/l_h)$, w as $l_h \sin(\theta)$
5. Else
   - if l_h and $l_v > T_{max}$, then *circular inhomogeneity*
     - compute diameter as maximum scale of overshoot
6. – else
   - *multiple texture is present*
   - compute scales of multiple texture as scales of deviations
   - compute area of the defect from height of overshoot

APPLICATION: PAVEMENT DISTRESS ASSESSMENT

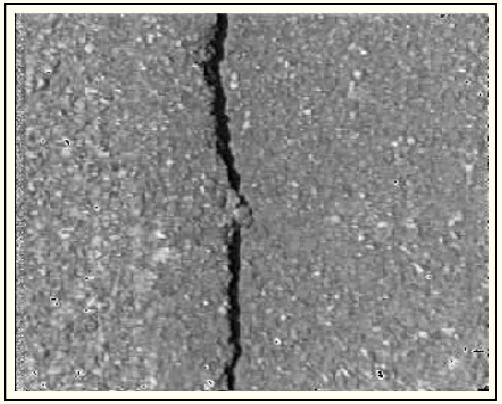
New York State Thruway Authority's distress classification scheme

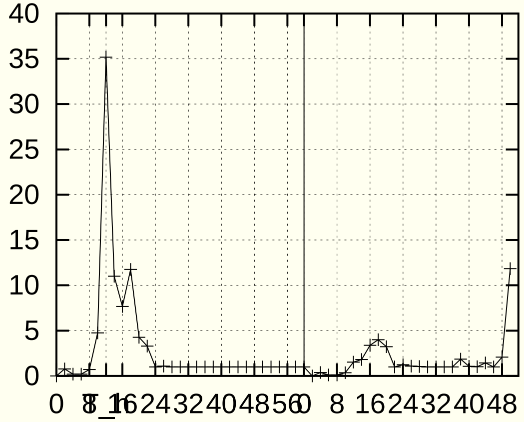
- detection of defects on pavement surfaces
- both inhomogeneities and multiple textures are present

DEFECT FEATURE	DESCRIPTION
Cracking	Separation of pavement surface
Pitting	A small region where material is lost from surface due to freeze-thaw action and aggregate expansion
Spalling	Breakdown of material especially along the sides of a crack
Material Loss	Wearing away of surface due to loss of asphalt or tar binder

Further classification based on pavement type and other non-visual factors

PAVEMENT CLASSIFICATION EXAMPLES



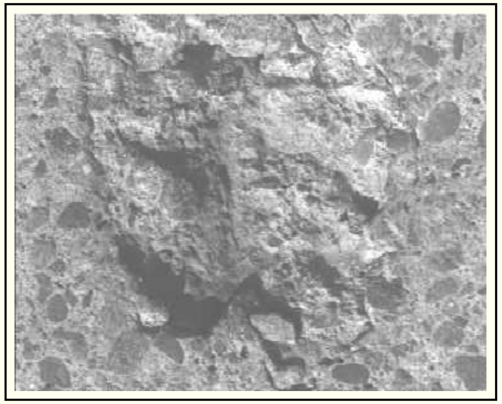


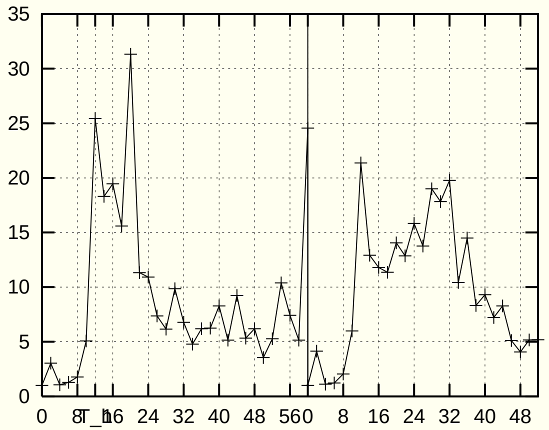
Length > 48 (256)

Width $= 12$ (12)

$\theta = 89^\circ$ (90°)

Ht/Wd ≈ 4.0



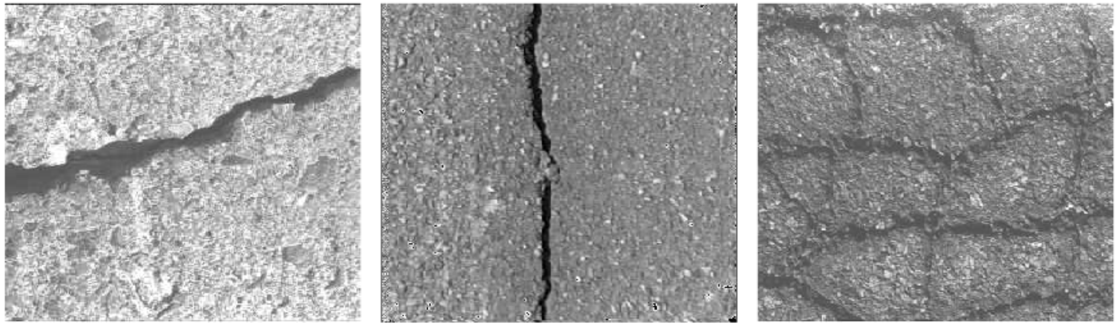


$l_h = 20$, $l_v = 32$

Height/Width ≈ 0.8

Area $= 24.72\%$

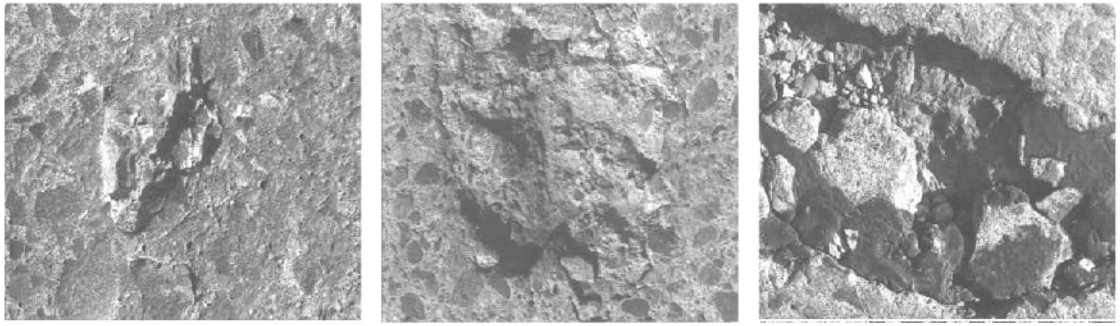
CRACKING DISTRESS EXAMPLES



(a) n_ml (b) e_sl (c) g_mg

Image	Horizontal			Vertical			Class
	l_h	w_h	Ht/Wd	l_v	w_v	Ht/Wd	
n_ml13	16	8	2.63	14	4	**11.25**	Linear Cracking
	22	8	2.25	16	10	1.40	
	>48	4	**13.75**	30	6	2.67	*Open*
				36	4	3.00	*Transverse*
e_sl15	12	6	**5.83**	16	12	0.33	Linear Cracking
	18	8	1.38	>48	4	**3.00**	*Open*
							Longitudinal
g_mg19	12	6	**7.33**	14	12	**4.16**	Linear Cracking
	18	4	**6.50**	26	4	**8.00**	*Alligator*
	28	6	**2.33**				Dominant direction:
	38	6	1.5				*Transverse*
	>48	4	**5.25**				

SPALLING DISTRESS EXAMPLES



(a) m_ml10 (b) m_ll04 (c) n_tg07

Image	Horizontal		Vertical		Area (%)	Rating
	l_h	Ht/Wd	l_v	Ht/Wd		
m_ml10	18	0.70	20 36	0.80 0.83	10.14	Circular Inhomoheneity *Medium Spalling*
m_ll04	20	<0.78	32	<0.50	24.72	Circular Inhomogeneity *Large Spalling*
n_tg07	24 >48	0.93 **8.87**	22 36	3.07 0.88	25.39	Circular Inhomogeneity + Horizontal cracking *Wide spalled crack*

CONCLUSIONS

- Introduced the idea of normalized opening distributions for texture defect analysis
- Showed results from a pavement distress assessment application
  - in reality, nearly 425 pavement images for the year 1993 – 1994 were analyzed
  - distress assessment matched human performance on 401 images (i.e., an accuracy of $\approx 92\%$)
- Opening distributions are powerful tools for texture as well as texture defect analysis
- The approach presented brings out the interplay between pravda and istina in a very interesting manner!