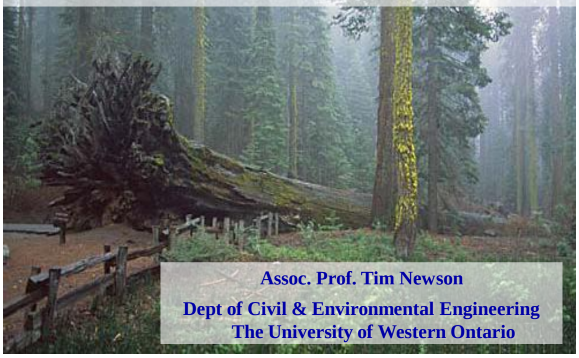
'Windthrow – a geotechnical engineer's perspective'



Assoc. Prof. Tim Newson

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The University of Western Ontario

Annual cost of storm damage

- The uprooting and overturning of trees by wind loads (*windthrow*) leads to significant losses for the forestry industry and extensive damage to domestic structures in North America.
- Millions of trees can be destroyed in single long period return storm events.
- Hurricane Katrina caused significant damage to 1.3 million acres of forest and the economic loss was estimated to be $1.3 billion.
- A further $1.1 billion damage also occurred to urban trees across the state of Mississippi.
- Between 1995 and 2007 estimated that 407 deaths occurred in US from wind related failures

Annual cost of storm damage

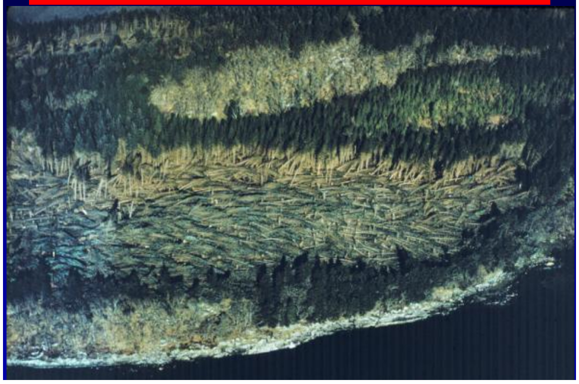
- Similarly, storm events in Canada have caused tremendous damage to structures and trees over the last 60 years, e.g. Hurricanes Hazel (1954), Gustav (2002) and Juan (2003), and the Windsor (1946) and Barrie (1985) tornadoes.
- Whilst separating damage exclusively due to wind loads from that related to trees is difficult, peak wind velocities often *do not exceed* design code values in many storms, and yet structural damage can be quite substantial.
- This implies that falling trees and projectiles striking structures and service infrastructure cause much of this destruction.

Damage to structures

Damage to utilities

Damage to vehicles

Damage to forestry



Damage to underground utilities

Less common damages….

Purpose of our interest?

- The Fujita scale is used for rating tornado intensity, based on the damage tornadoes inflict on man-made structures and vegetation.
- Category is determined by meteorologists (and engineers) after a ground/aerial damage survey; plus ground-swirl patterns, radar tracking, eyewitness testimonies, media reports & imagery.
- *The Fujita Scale is very subjective and varies according to the experience of the surveyor (requires good feel for 'cause and effect' of damage).*
- New 'enhanced' Fujita scale (2007) takes into account quality of construction and standardizes different kinds of structures (3 LPs)

NSERC CRD/ICLR Study

- Every year severe wind storms cause significant damage to Canadian residential structures and infrastructure.
- Detailed knowledge of wind damage is important to determine the performance of building and design codes, to develop of insurance risk or loss models, to improve the ability of meteorologists to forecast extreme events and to issue appropriate warnings, and validate laboratory test results.
- However, to achieve these goals quantitatively, it is imperative that reasonably accurate estimates of the peak wind speeds are available.

NSERC CRD/ICLR Study (cont.)

- Very rare to have direct wind speed measurements - damage observations must therefore be used to infer the wind speed.
- The study proposal addresses this issue, focusing on two particular aspects of storm damage, namely:

  (i) windthrow (or uprooting) of trees

  (ii) damage caused by, and the flight distances of, windborne debris,

  and how both of these sources can be used to estimate peak wind speeds.

Typical post-storm survey with Env. Canada

- Fujita Scale 2 tornado (low end of F2 scale: peak winds of 180-250 kph) touched down at about 1.30 pm for 10-12 minutes near Avon, Ontario (June 25th 2009).
- The tornadic damage started just north of Elgin Road near the community of North Dorchester, and traveled south east passing to the west of the town of Avon.
- The path length was 9 km, fairly erratic and only 10-12 m wide.

Tornado seen from Avon

June 25th 2009 – F2 tornado hits Avon

- Same afternoon survey damage teams from Western and Environment Canada were on site
- Significant damage had occurred along the track of the tornado:

  (i) Barn roofs were severely damaged.

  (ii) A bungalow was badly damaged – total roof removal and front wall knocked over.

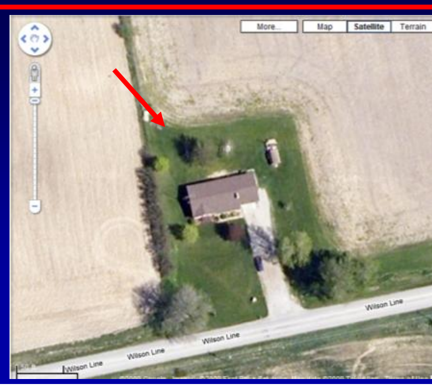
  (iii) Major damage to trees and crops.

  Some of the barn/shed/house debris was carried almost 1 km from original location.

Track of the tornado

Evidence of tornado touchdown

Bungalow on Wilson Line



Bungalow – roof and wall destruction

19

Tree damage around the bungalow

20

Tree damage around the bungalow (II)

21

Convergent pattern of windthrow: tornado

22

Divergent pattern of windthrow: microburst

23

Tree damage – Bornholm (2007)

24

Windthrow at the front of the same house

Topside of the 'Root Plate'

Bottom of the root plate

Example of windthrow

Critical Wind Speed Modeling

- **Winch/Pulley tests & empirical windthrow modeling: Published Values (Critical Wind Speed, CWS)**

Reference	Species	CWS
Smith et al. 1987	**Black Spruce**	28 - 53 m/s (101 - 189 km/hr)
Elie & Ruel 2005	**Black Spruce (mono cult. & mixed stands)**	9.5 -13 m/s (34 - 47 km/hr)
Achim et al. 2005	**Balsam Fir**	10 - 20 m/s (36 - 72 km/hr)

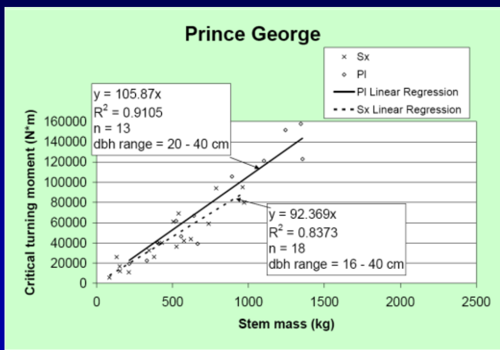
- **Immediate Problems**
  - **Some species *not* covered in the literature: red pine, eastern white pine**
  - **Critical wind speeds appear quite varied: investigate mechanistic model assumptions**

29

Static tree pull tests

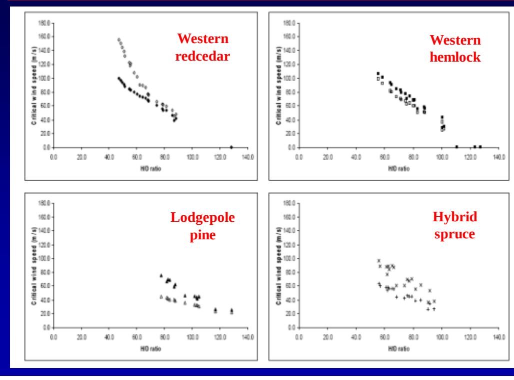
30

Static tree pull results



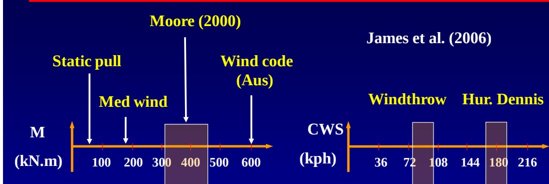
31

Relationship between tree and critical wind speed



32

Critical wind speed & overturning moments



- Forest GALES: CWS (Gardiner et al., 2000):

Overturning: $uh_{over} = \frac{1}{kD}\sqrt{\frac{C_{reg}SW}{\rho G d}}\sqrt{\frac{1}{f_{CW}}}\ln\left(\frac{h-d}{z_0}\right)$

Stem-break: $uh_{break} = \frac{1}{k.D}\sqrt{\frac{\pi.MOR.dbh^3}{32.G.(d-1.3)}}\sqrt{\frac{f_{knot}}{f_{edge}.f_{CW}}}\ln\left(\frac{h-d}{z_0}\right)$

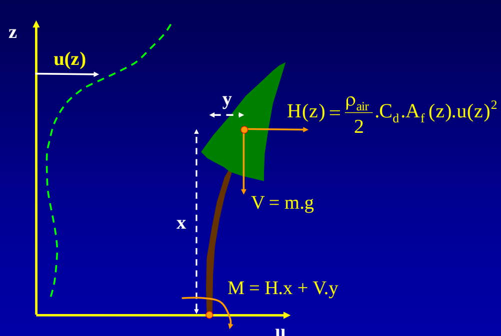
33

Trees: aims and aspirations

- **Biological system with a number of competing requirements for the elements of the tree:**
  - **Supply water**
  - **Photosynthesis**
  - **Reproduce**
  - **Structurally sound**
- **Therefore needs to optimise biomass, in competition with other trees.**

34

Applied loading from self-weight and wind



$$H(z) = \frac{\rho_{air}}{2}.C_d.A_f(z).u(z)^2$$

$$V = m.g$$

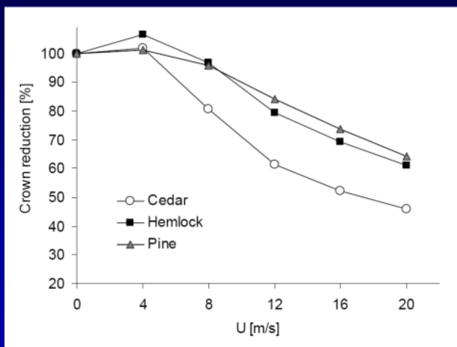
$$M = H.x + V.y$$

35

Are drag coefficient and frontal area constant?

36

Streamlining of trees during wind loading



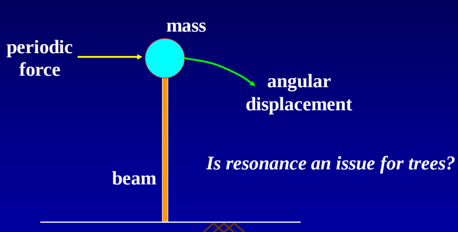
Axiom of 'uniform stress'

- How do trees respond to the loads placed on them?
- 'Axiom of uniform stress' (Mattheck and Breloer, 1994), states that growth of a tree is in response to the loads at a specific point.
- What does this really mean?

Trees are self-optimizing structures

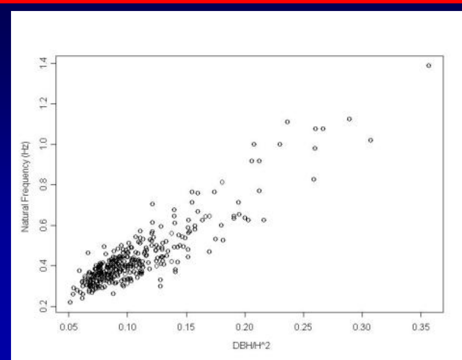
Are dynamic effects important?

Dynamic tree model = lumped mass and spring oscillator

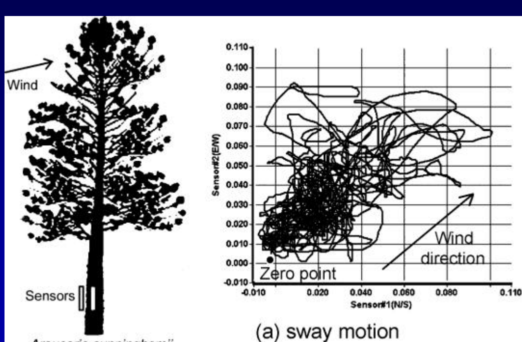


Dynamic motion of tree described by the following equation: $m\ddot{y}(t) + c\dot{y}(t) + ky(t) = F(t)$

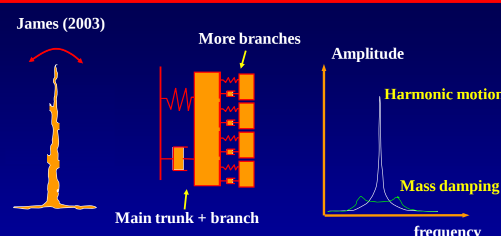
Natural frequency: relationship to tree size



Sway motion of a tree (Moore et al, 2000)



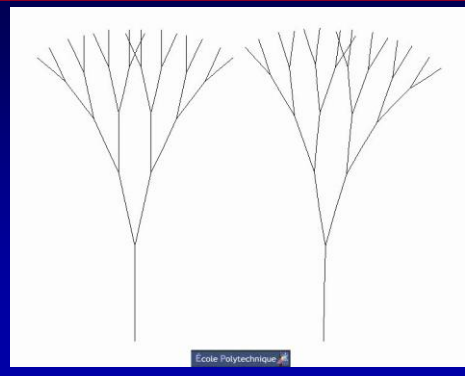
Multi-scale damping effects



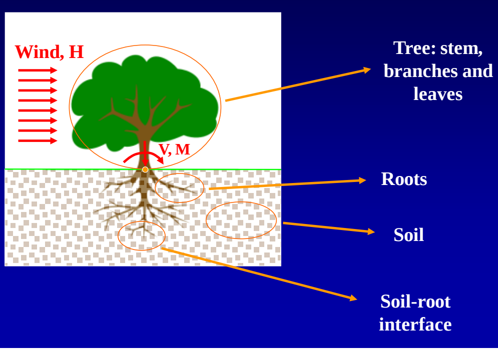
Damping: (i) aerodynamic drag (leaves)
(ii) visco-elastic damping (stem/root/soil)
(iii) mass damping (limb sway)

Susceptibility of stands and individual trees

Energy dissipation in stands

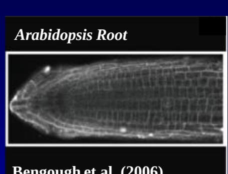


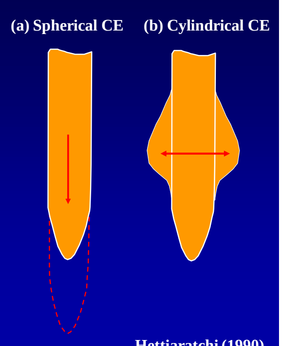
Resistance to environmental loads



Roots systems on trees

Root growth and extension

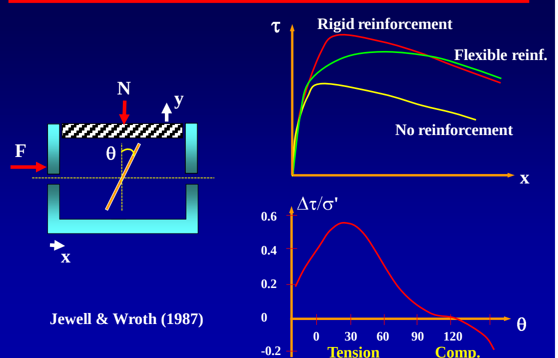




- Root cap, border cells, mucilage
- Spherical, cylindrical cavity expansion and nutation?

Hettiaratchi (1990)

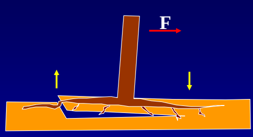
Soil & ‘reinforcement’ material behaviour



Jewell & Wroth (1987)

The 'root-plate' after windthrow

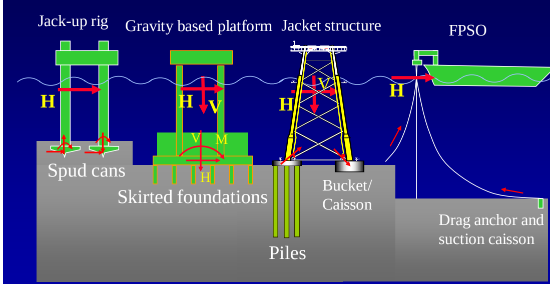
Windthrow resistance due to:



(1) weight of 'root-plate';
(2) tensile strength of roots on windward side;
(3) compressive and bending strength of roots on leeward side;
(4) frictional properties of soil along failure surfaces.

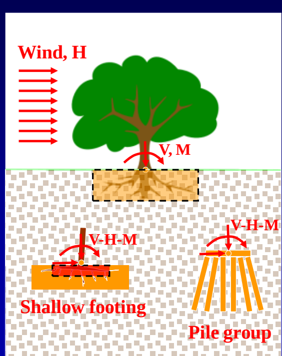
49

Offshore foundations and loadings



50

'Foundation' behaviour & complex loading



- **What type of loading is best for our analysis?**

  Pseudo-static or cyclic?

  Should we worry about dynamic effects?

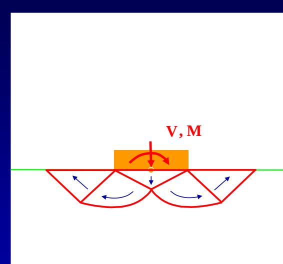
- **How do we model the soil-root interaction?**

  Can we homogenise the material behaviour for the soil and root-plate?

  Are explicit root and soil approximations better?

51

Shallow footing behaviour – vertical loading



Vertical capacity,

$V_f = A\, N_c\, d_c\, c_u$

c_u = undrained shear strength (modified for roots?)

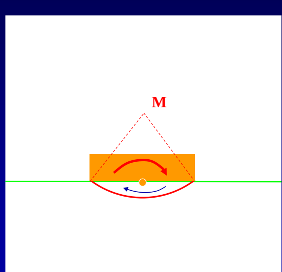
$N_c = 2 + \pi$, for strip footing
$N_c = 6.05$ for circular footing

Depth correction factor, d_c

A is the base area

52

Shallow footing behaviour – moment loading



Moment capacity,

$M_f = A\, D\, N_m\, d_m\, c_u$

Depth correction factor, d_m

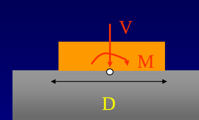
$N_m = 0.7$

A is the base area

D is the footing breadth

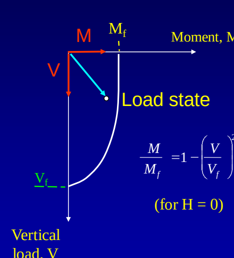
53

Combined vertical & moment load: failure envelope



At failure:

$$\left(\frac{V}{V_f}\right)^2 + \left(\left(\frac{M}{M_f}\right)^2 + \left(\frac{H}{H_f}\right)^2\right)^{\frac{1}{2}} = 1$$

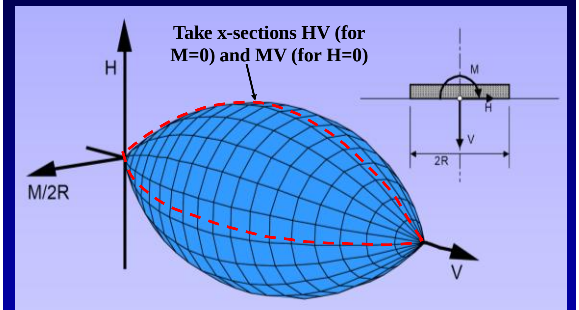


$$\frac{M}{M_f} = 1 - \left(\frac{V}{V_f}\right)^2$$

(for H = 0)

54

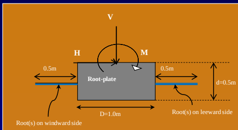
Interaction VHM diagrams



- Combinations of VHM causing failure bounded by surface – comparison with current load state indicates 'factor of safety'

55

Determining failure envelope shape



Assumptions:

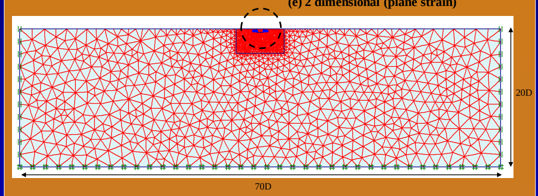
(a) Root-plate rigid and isotropic elastic

(b) Soil isotropic elastic-perfectly plastic (Mohr-Coulomb) and undrained

(c) 'Roots' rigid, thin isotropic elastic plates

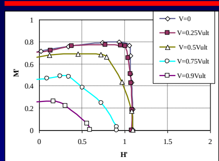
(d) Interfaces between roots, root-plate and soil allow detachment (gapping)

(e) 2 dimensional (plane strain)

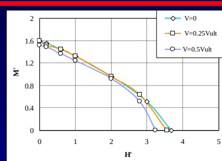


56

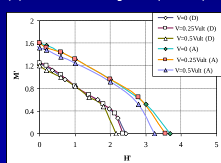
Failure envelopes for different scenarios



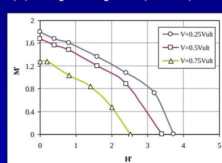
(a) Shallow root plate (D/d=5)



(b) Deep root plate (D/d=2) [No detachment]



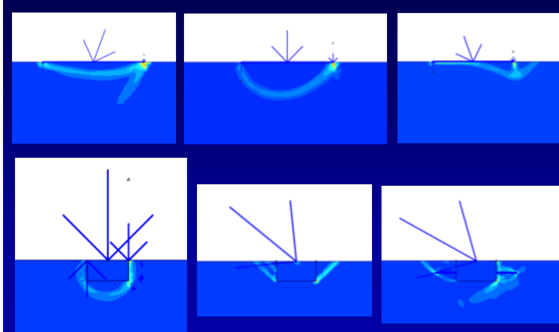
(c) Deep root plate (+/- detachm)



(d) Deep root plate (detachment, +/- roots]

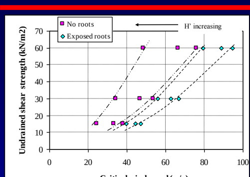
57

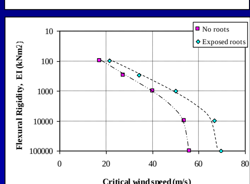
Soil failure mechanisms



58

Actual modeling of critical wind speeds…





- Bornholm, wind-speed of the order of 130-150 kph (from damage survey): 30 to 40 m/s
- VHM method:
  - L = 26m; DBH = 0.42m
  - Root plate = 2.5m square x 1.5m deep
  - Frontal area = 95m^2; C_d = 0.2
  - Trunk: uniform circular section cantilever loaded at 3L/4 from base
  - Soil assumed s_u = 15, 30, 60 kN/m^2
  - V' = 0.1; H' = 0.5, 1, 2
- Of course this is only a single estimate – the whole site provides better information of the entire wind field/history

59

The Fujita Scale

- The original scale developed around 1970 by Fujita who assigned wind speeds to expected damage produced by strong winds observed in tornadoes.
- Scale for rating for tornado intensity, based on damage tornadoes inflict on human-built structures/vegetation.
- In 2007, the original Fujita Scale, was replaced by the Enhanced Fujita Scale in US.
- Incorporates 28 damage indicators (DI), or types of structures and vegetation, varying number of degrees of damage (DoD), which are related back to the EF scale
- The new scale takes into account quality of construction and standardizes different kinds of structures (and includes trees!)

60

F to EF Comparison

FUJITA SCALE			DERIVED EF SCALE		OPERATIONAL EF SCALE	
F Number	Fastest 1/4-mile (mph)	3 Second Gust (mph)	EF Number	3 Second Gust (mph)	EF Number	3 Second Gust (mph)
0	40-72	45-78	0	65-85	0	65-85
1	73-112	79-117	1	86-109	1	86-110
2	113-157	118-161	2	110-137	2	111-135
3	158-207	162-209	3	138-167	3	136-165
4	208-260	210-261	4	168-199	4	166-200
5	261-318	262-317	5	200-234	5	Over 200

Wind speeds in the operational scale were rounded to avoid implying more accuracy than is justified. These winds are at the standard height of 10 meters.

61

More systematic tree damage surveys

- Often only plentiful information available is <u>tree data</u>
- No standardized, detailed reference relating tree damage to wind speed
- Important aspects for trees: *structural integrity, exposure, ground conditions, species*
- Difficult to estimate the effect of so many variables.
- Possible damage class for rating tornado intensity: *foliage tatter, foliage loss, small branch loss, large branch loss, stem break/uprooting*
- Thorough survey would involve number of trees on same site

62

Application to urban environments

63

Problems for urban trees

- Limiting root space causes problems: *curbs, sidewalks and pavements*
- Selection of trees that grow too large for their environment
- Selection of trees that are less wind resistant
- Inappropriate anthropogenic interventions:
  - *asymmetry*
  - *cutting back long branches*
  - *narrow branching angles*
  - *decay & disease*
- Poor drainage and soil conditions

64

Some general observations….

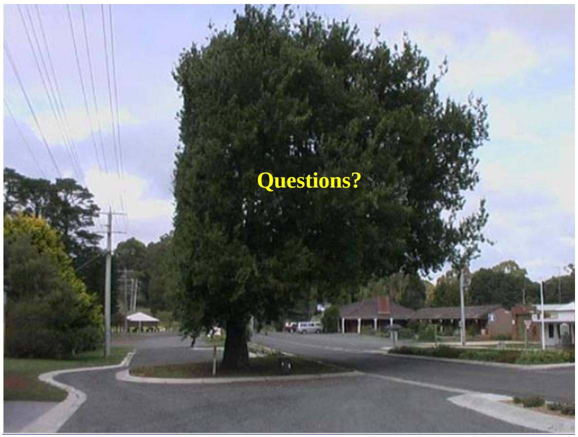
- We see alot of sub-fatal damage to trees (boughs and branches) - mechanical behaviour is optimized, but slow to respond (*<u>self-pruning system</u>*)
- Trees in groups fare better – isolated trees and trees in neat rows often fail
- Trees offer some protection to houses as wind-breaks
- Certain species fail more often (conifers and other shallow rooting species are common)
- Causes are often disease or 'manipulated' trees

65

Conclusions

- **Highly complex problem**
- **Dealing with a 'self-optimizing' structure, many features not found in man-made engineering works & design criteria very different from ours**
- **Number of 'engineering' approaches from structural and geotechnical fields that can enhance current knowledge - ultimately computer based methods may prove most useful**
- **Calibration will require WT testing, laboratory work and field testing for the requisite geographical species in Canada**
- **Development of new approaches to the Fujita Scale involving trees will take time, but could prove to be very useful**

66


Questions?