BUILDING DAMAGE ASSESSMENT

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BUILDING DAMAGE ASSESSMENT

- Damage categories
- Basis of damage assessment
- Staged design approach and design assumptions
- Assessment of utilities

DAMAGE CATEGORIES

Three broad categories that affect:

1) Visual appearance or aesthetics;

2) Serviceability or function; and

3) Stability.

DAMAGE CATEGORIES

Category	Typical crack width (mm)	Effects
Negligible	0.1mm	Hairline cracks only
V. Slight	<1mm	Damage mainly to internal wall finishes.
Slight	<5mm	Doors & windows may stick slightly
Moderate	5 – 15mm or several >3mm	Doors and windows sticking. Service pipes may fracture. Weather tightness impaired.
Severe	15 to 25mm	Windows and door frames distorted. Walls leaning, some loss of bearing in beams. Service pipes disrupted.
V. Severe	>25mm	Beams lose bearing, walls require shoring. Windows broken with distortion. Danger of instability.

DAMAGE CATEGORIES

Category	Typical crack width (mm)	Repair
Negligible	0.1mm	Hairline cracks only
V. Slight	<1mm	Can be easily treated during normal decoration
Slight	<5mm	Can be easily filled. Some repainting may be necessary
Moderate	5 – 15mm or several >3mm	Patching by a mason. Repainting and replacement of a small amount of brickwork.
Severe	15 to 25mm	Extensive repair works involving breaking-out and replacing sections of walls.
V. Severe	>25mm	Major repairing work involving partial or complete rebuilding.

AS2870 DAMAGE CATEGORIES FOR WALLS

Description of typical damage and required repair	Approximate crack width limit	Damage category
Hairline cracks	< 0.1mm	0
Fine cracks which do not need repair	< 1mm	1
Cracks noticeable but **easily filled.** Doors and windows stick slightly.	< 5mm	2
Cracks can be repaired and possibly a small amount of wall will need to be replaced. Doors and windows stick. Service pipes can fracture. Weather tightness often impaired.	5mm to 15mm (or a number of cracks 3mm or more in one group)	3
Extensive repair work involving breaking-out and replacing sections of walls, especially over doors and windows. Window and door frames distort. Walls lean or bulge noticeably, some loss of bearing in beams. Service pipes disrupted.	15mm to 25mm but also depends on number of cracks	4

AS2870 - DAMAGE CLASSIFICATION FOR CONCRETE FLOORS

Description of typical damage	Approximate crack width limit in floor	Change in offset	Damage category
Hairline cracks, insignificant movement of slab from level.	< 0.3mm	<1/375	0
Fine but noticeable cracks. Slab reasonably level.	< 1mm	<1/300	1
Distinct cracks. Slab noticeably curved or changed in level.	< 5mm	<1/200	2
Wide cracks. Obvious curvature or change in level.	5mm to 15mm (or a number of cracks 3mm or more in one group)	1/200 to 1/120	3
Gaps in slab. Disturbing curvature or change in level.	15mm to 25mm but also depends on number of cracks	>1/120	4

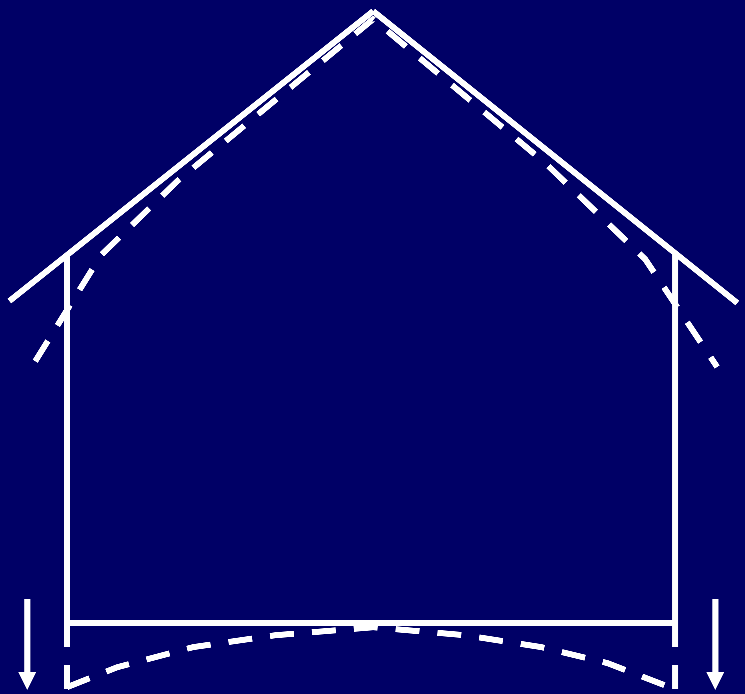
DAMAGE CATEGORIES

- Category 2: Results from within the structure itself or associated with ground movement.
- Category 3 and above: Usually associated with ground movement.

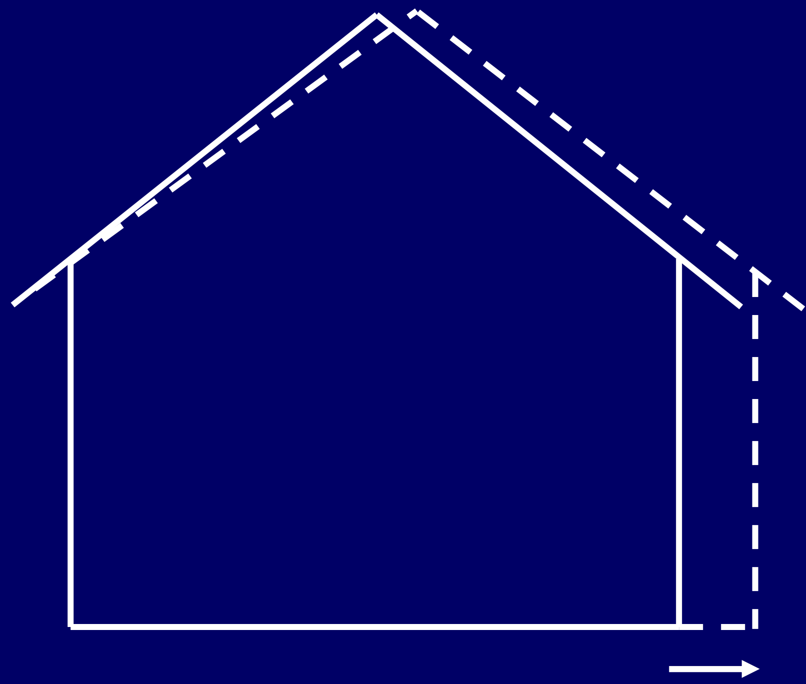
BASIS OF BUILDING DAMAGE ASSESSMENT

- Criterion for onset of visible cracking: Limiting tensile strain.
- Local strain at onset of cracking much smaller than limiting tensile strain.

MODES OF MOVEMENT - DAMAGING

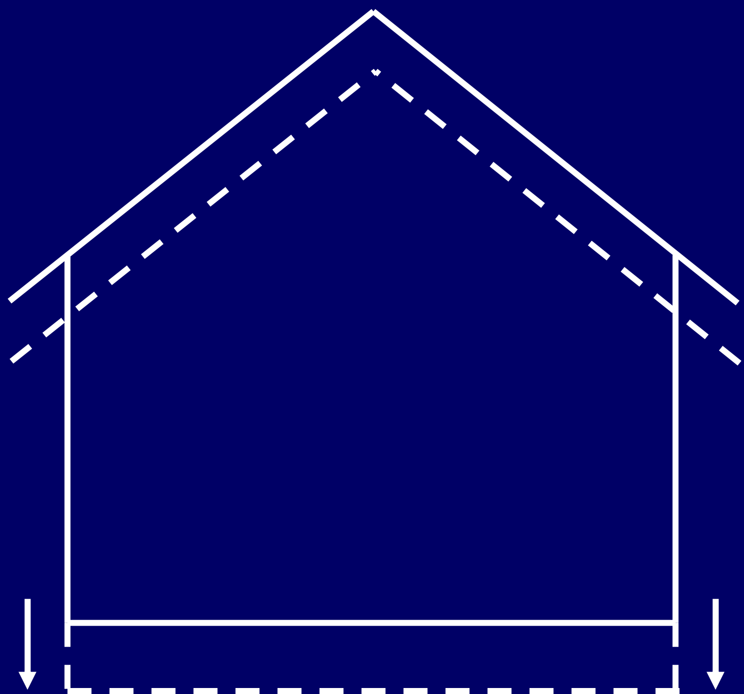


BENDING

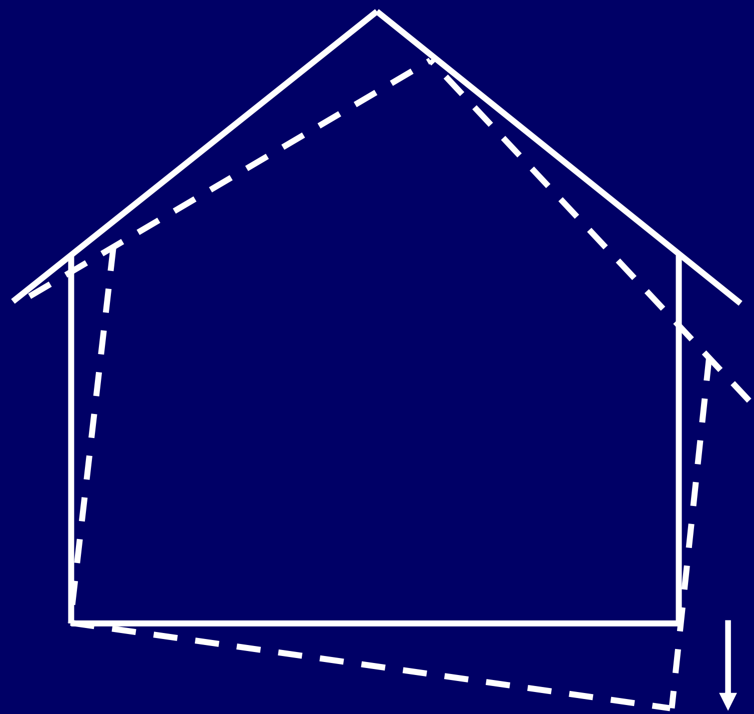


HORIZONTAL EXTENSION

MODES OF MOVEMENT
- NOT DAMAGING



UNIFORM SETTLEMENT



UNIFORM TILT

RIGID BODY TILT

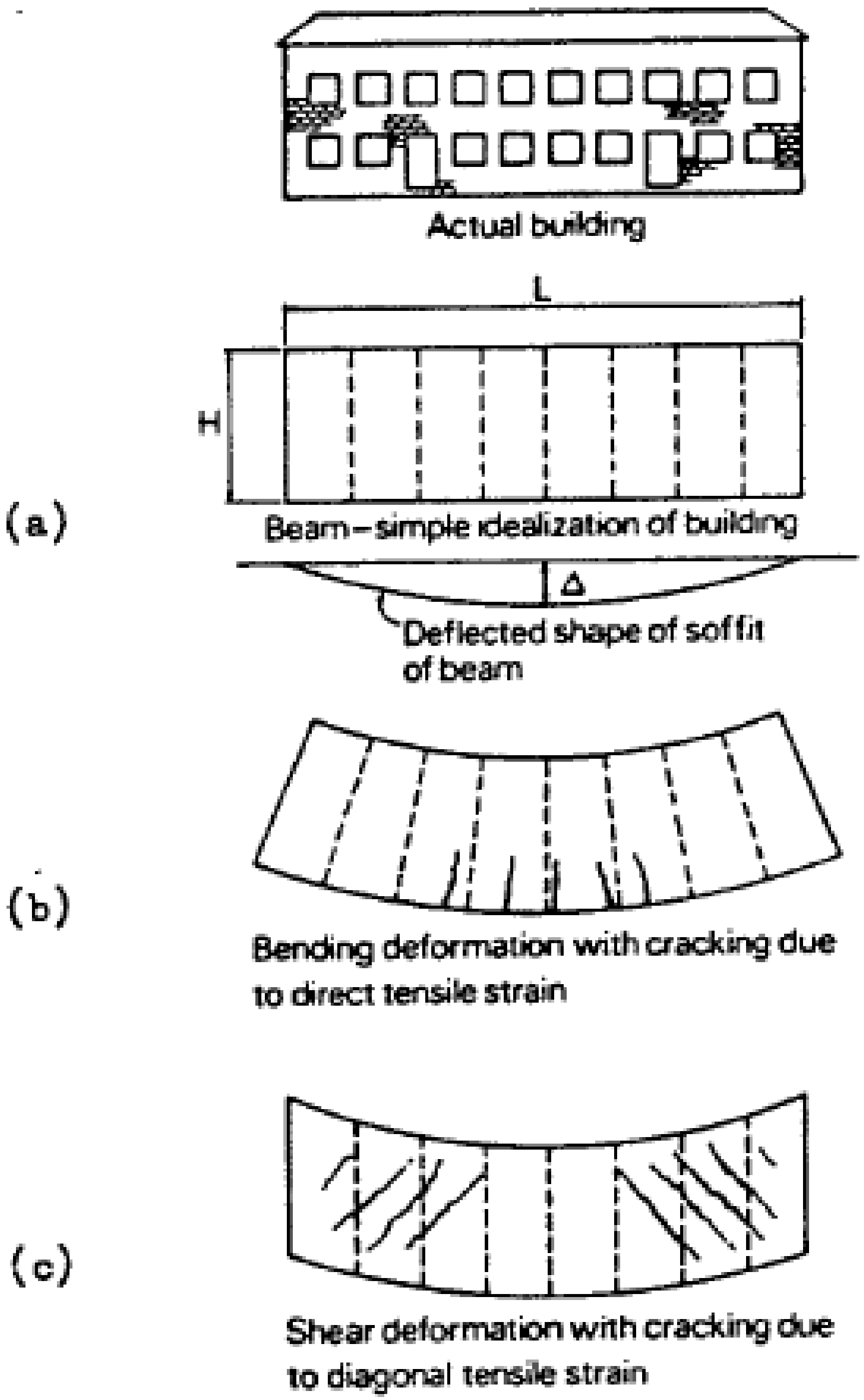
RIGID BODY TILT

LIMITING TENSILE STRAIN VS DAMAGE CATEGORIES FOR MASONRY BUILDINGS

Limiting tensile strain (%)	Damage Class	Typical crack width (mm)
0.0 - 0.05	Negligible	<0.1
0.05 – 0.075	Very Slight	<1.0
0.075 – 0.15	Slight	<5.0
0.15 – 0.3	Moderate	<15
>0.3	Severe to Very Severe	>25

USE OF LIMITS

- Not economic to restrict to no damage.
- Typically allow up to ‘slight damage’ for most structures.
- Restrict to ‘very slight damage’ for buildings of historical or architectural significance, such as heritage buildings.



BUILDING MODELLED AS A BEAM SUBJECTED TO BENDING AND SHEAR STRAINS

BENDING STRAIN

- The bending strain, $\varepsilon_{b\ max}$ can be calculated from:
- $\varepsilon_{b\ max} = \Delta / (L.\zeta_b)$
- Where $\zeta_b = (L / 12t) + [(3I/ 2tLH)*(E/G)]$
- L= length of segment of building
- H = height of building
- E/G is ratio of Young's modulus to shear modulus of building (use E/G of 2.6 for masonry buildings, 12.6 for RC framed structures)

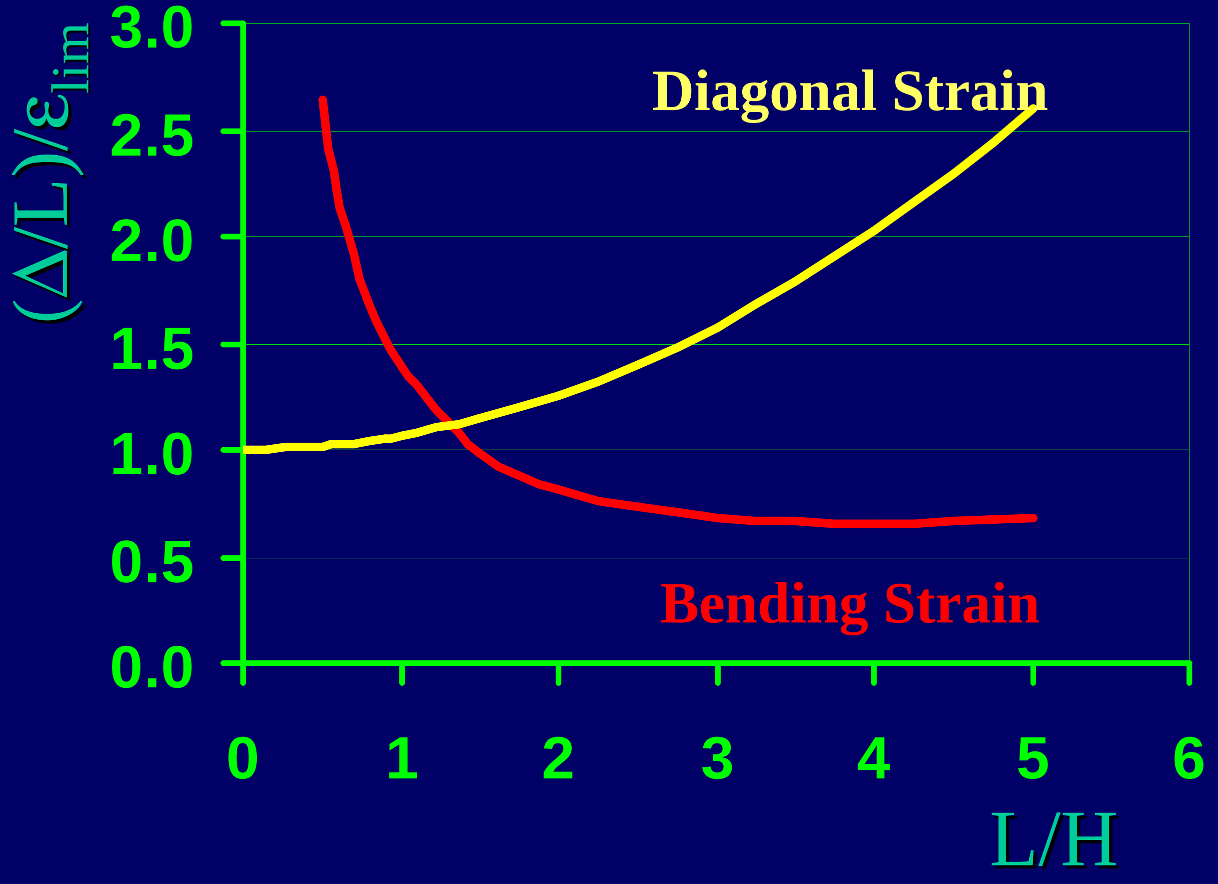
BENDING STRAIN (cont.)

- $I = H^3 / 12$ in sagging zone and $H^3/3$ in hogging zone
- $t = H / 2$ in sagging zone and H in hogging zone
- For a given Δ / L the bending strain is larger in the hogging zone than the sagging zone, i.e. hogging is more damaging than sagging.

DIAGONAL STRAIN

- The diagonal strain, $\varepsilon_{d\ max}$ can be calculated from:
- $\varepsilon_{d\ max} = (\Delta/L)(1/\zeta_d)$
- Where $\zeta_d = 1 + (HL^2/18I)(G/E)$

BENDING AND DIAGONAL STRAIN



Beam (E/G = 2.6) Undergoing Hogging with Neutral Axis at Bottom Edge

HORIZONTAL STRAIN

- Calculate horizontal strain from the extension of the segment of the building over the length of the segment.
- The horizontal movement, due to tunnelling, at each end of the segment can be calculated from:
- $S_h = x.S_x / z$
- Where x is the distance from the tunnel centre-line (in plan) and S_x is the settlement at x predicted from the assumed volume loss

COMBINATION OF CALCULATED STRAINS

- The horizontal strain and the bending strain can be added directly, so that :

$$\varepsilon_{bt}=\varepsilon_{h}+\varepsilon_{b\ max}$$

- Calculate the diagonal strain ε_{dt} by combining ε_{h} and $\varepsilon_{d\ max}$ using a Mohr's circle of strain.

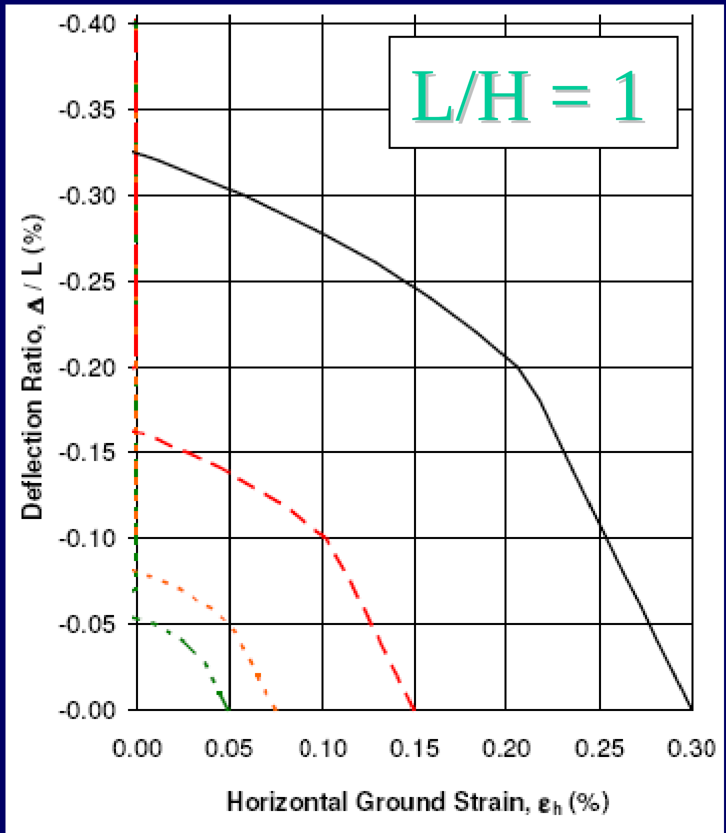
COMBINATION OF HORIZONTAL AND DIAGONAL STRAINS

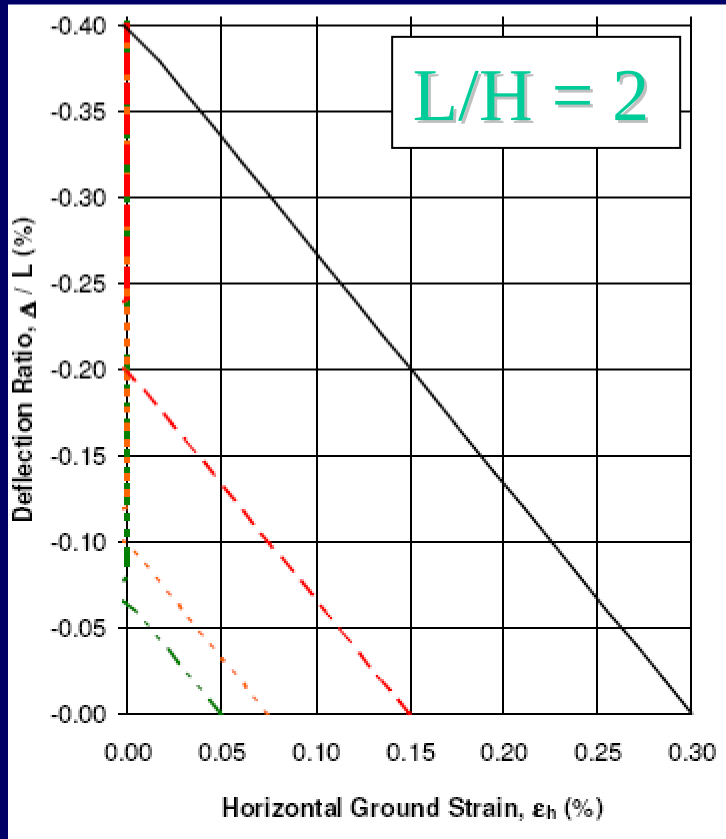
- For a Poisson's ratio of 0.3:

$$\varepsilon_{dt} = 0.35\varepsilon_h + [(0.65\varepsilon_h)^2 + \varepsilon_{d\,max}{}^2]^{1/2}$$

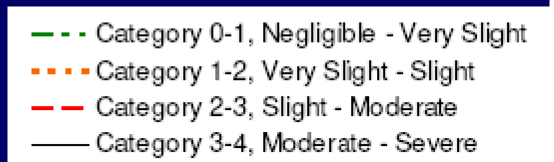
- Use the larger of ε_{bt} and ε_{dt} to assess building damage

INTERACTION DIAGRAM, Δ/L, ε_h & L/H





Relationship of damage category to deflection ratio and horizontal tensile strain for hogging



STAGED ASSESSMENT OF BUILDINGS

- **Stage 1 - if settlement <10mm,slope < 1:500**

  ➡ **Negligible damage**

- **Stage 2 - Assume 'green field conditions', building stiffness not considered, if tensile strain < 0.15%**

  ➡ **Slight damage ('very conservative')**

- **Stage 3 - Detailed assessment, considering stiffness of building and three dimensional effects of tunnelling and excavation**

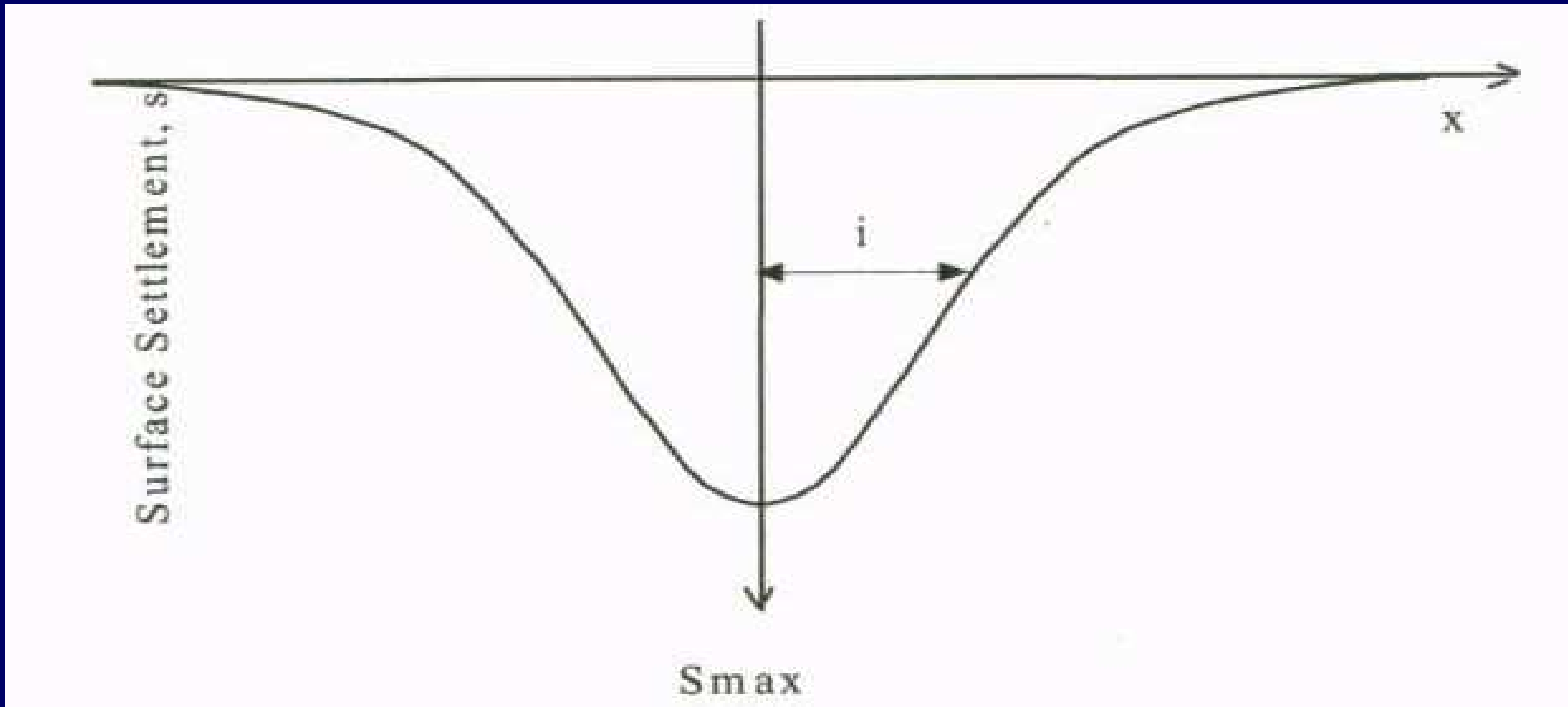
For settlements due to wall movement / tunnelling moderate damage (>5mm crack width) typically analysed as occurring at 40mm to 75mm maximum settlement

ASSUMPTIONS FOR STAGE 2 OF THE ASSESSMENT

- Building simply follows the 'green field' settlement
- Building is made of masonry
- Settlements due to consolidation are even, and do not induce bending or horizontal strain
- First two assumptions are considered 'conservative' i.e. they over-predict strain and damage

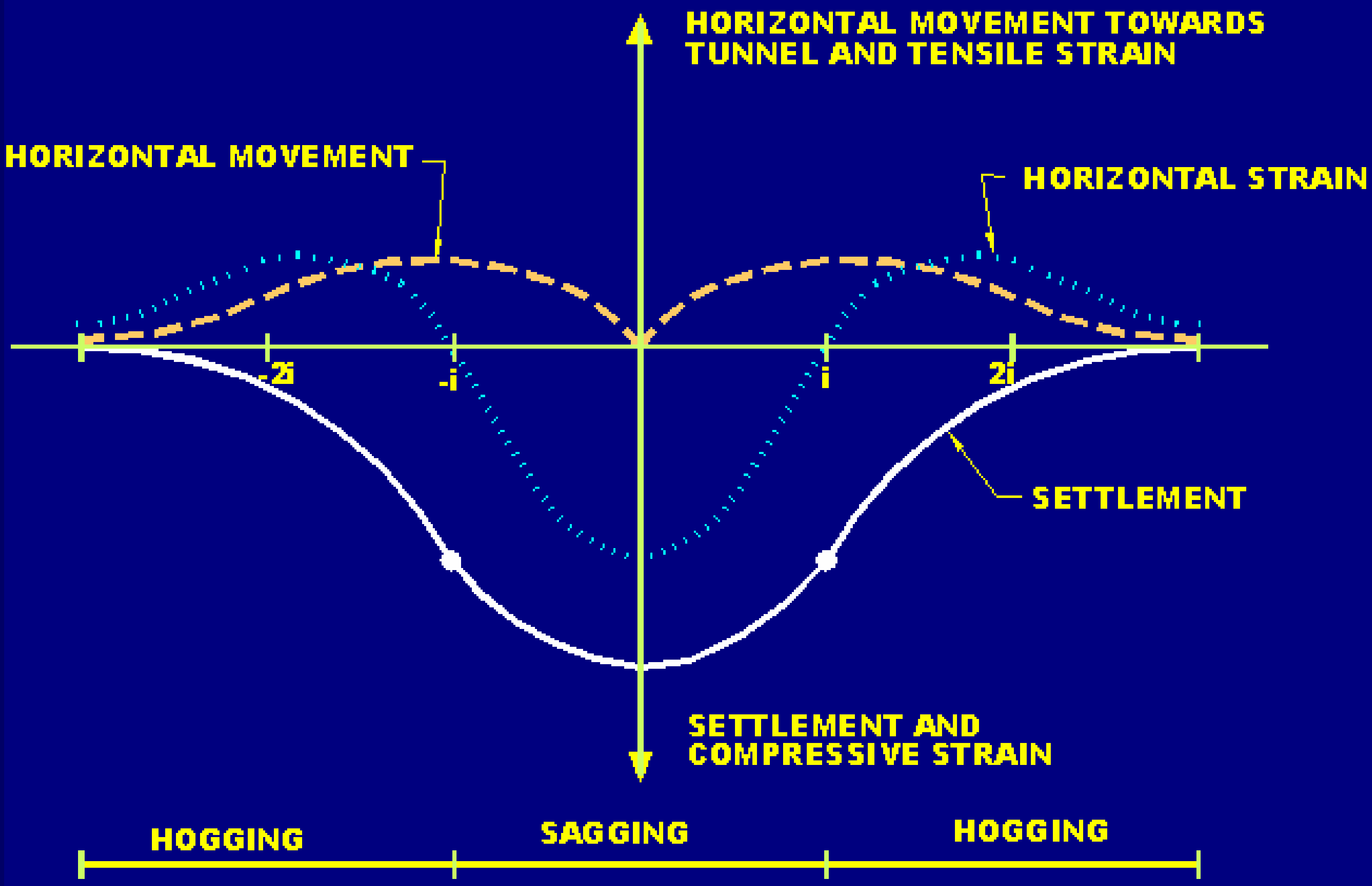
STEPS FOR STAGE 2 OF THE ASSESSMENT

1. Predict settlement trough, excluding consolidation.



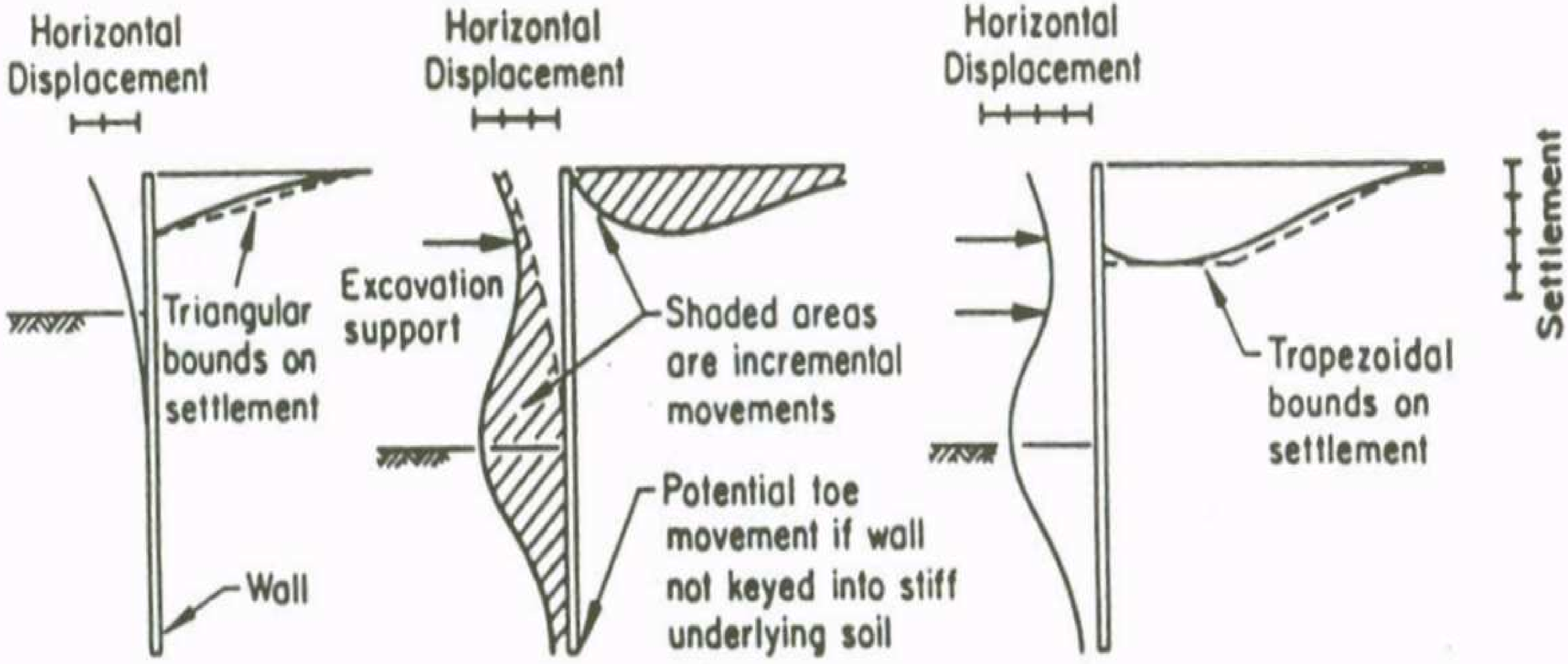
GREEN FIELD SETTLEMENT

3. Predict horizontal movement and strain



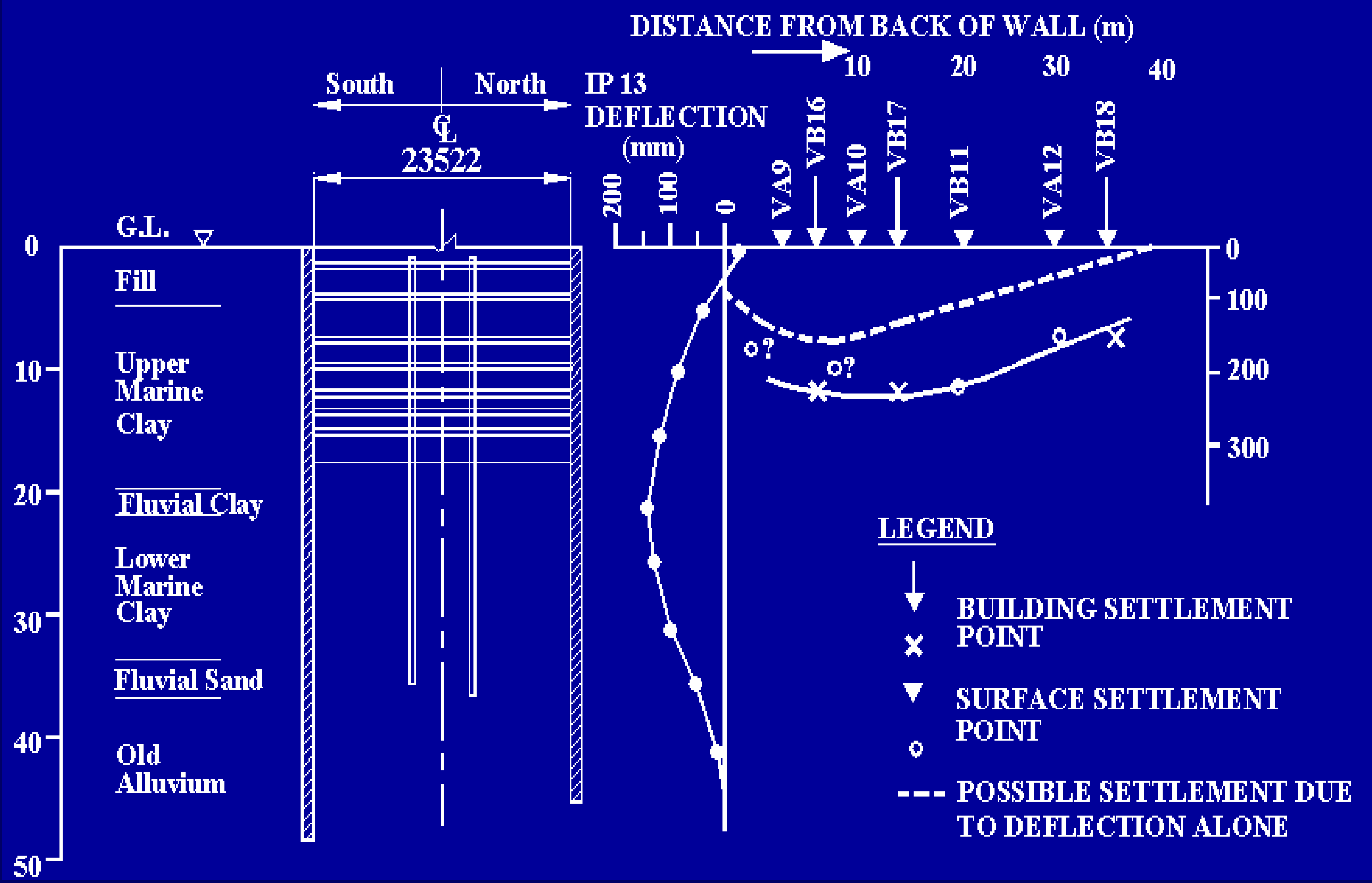
SETTLEMENT AND HORIZONTAL MOVEMENTS ABOVE TUNNEL

GROUND SETTLEMENTS DUE TO WALL MOVEMENT



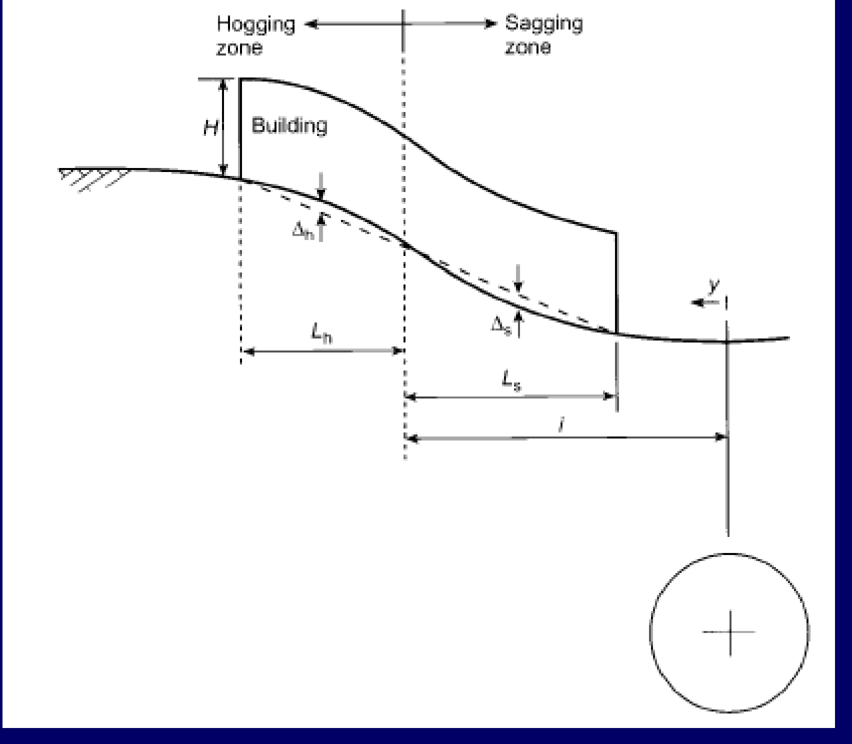
a) Cantilever Movement b) Deep Inward Movement c) Cumulative Movement

SETTLEMENT DUE TO EXCAVATION IN CLAY



STEPS FOR STAGE 2 OF THE ASSESSMENT

2. Separate the building into hogging and sagging zones because of different sensitivity to bending.



STEPS FOR STAGE 2 OF THE ASSESSMENT

3. Calculate the average horizontal strain in each zone
   - Calculate the bending strain ε_b (from Δ / L) in each zone
   - Calculate the diagonal strain ε_d (from Δ / L) in each zone
   - Calculate the horizontal strain, ε_h

STEPS FOR STAGE 2 OF THE ASSESSMENT

4. The horizontal strain and the bending strain can be added directly, so that :

$$\varepsilon_{bt}=\varepsilon_h + \varepsilon_b$$

5. Calculate the diagonal strain ε_{dt} by combining ε_h and ε_d using a Mohr's circle of strain

6. Use the larger of ε_{bt} and ε_{dt} to assess building damage

STAGE 3 ASSESSMENT

- Refinement of Stage 2 assessment.
- Foundation details are considered.
  - Ground beams will reduce horizontal extension to a negligible value.
  - Piles will reduce settlements and bending strains.
  - Continuous foundations, e.g. strip footings or rafts are less prone to damaging differential settlements.
- Effects of soil-structure interaction: Building stiffness will modify ‘Green Field’ settlements, typically making them wider and flatter.

STAGE 3 ASSESSMENT

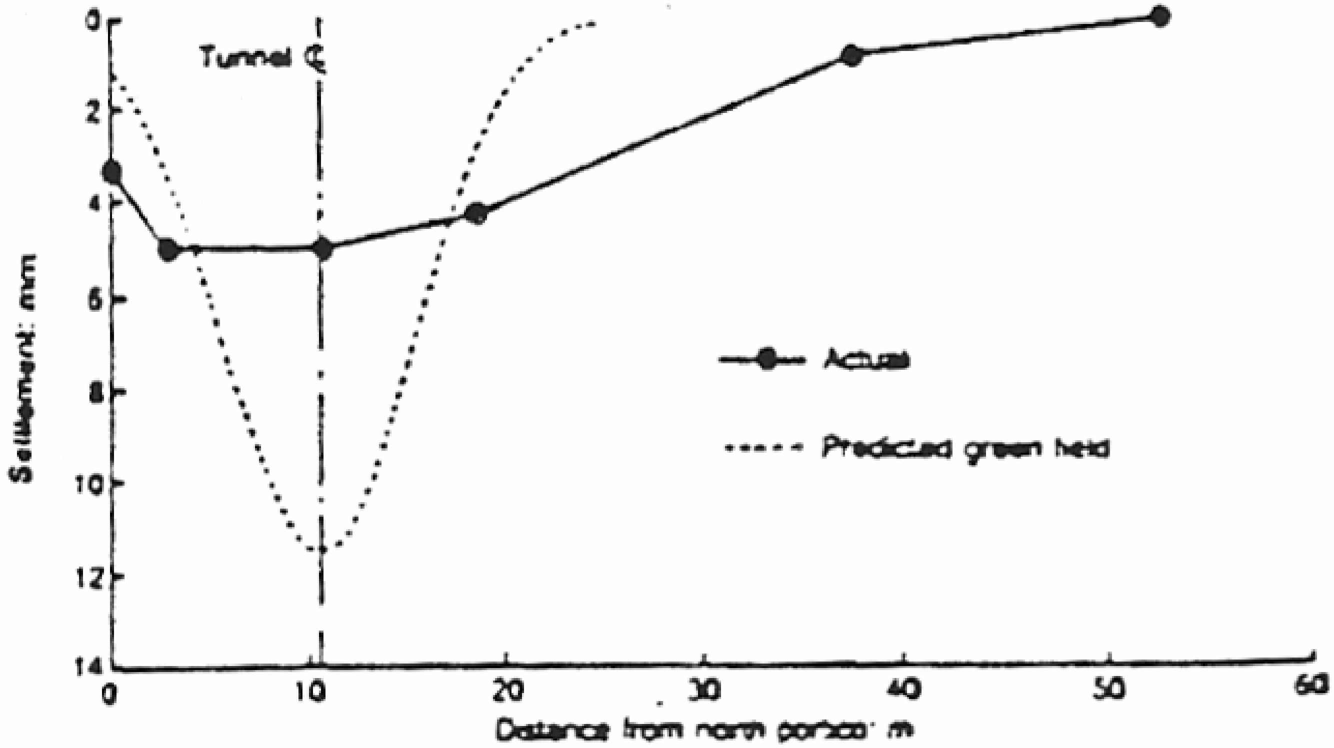
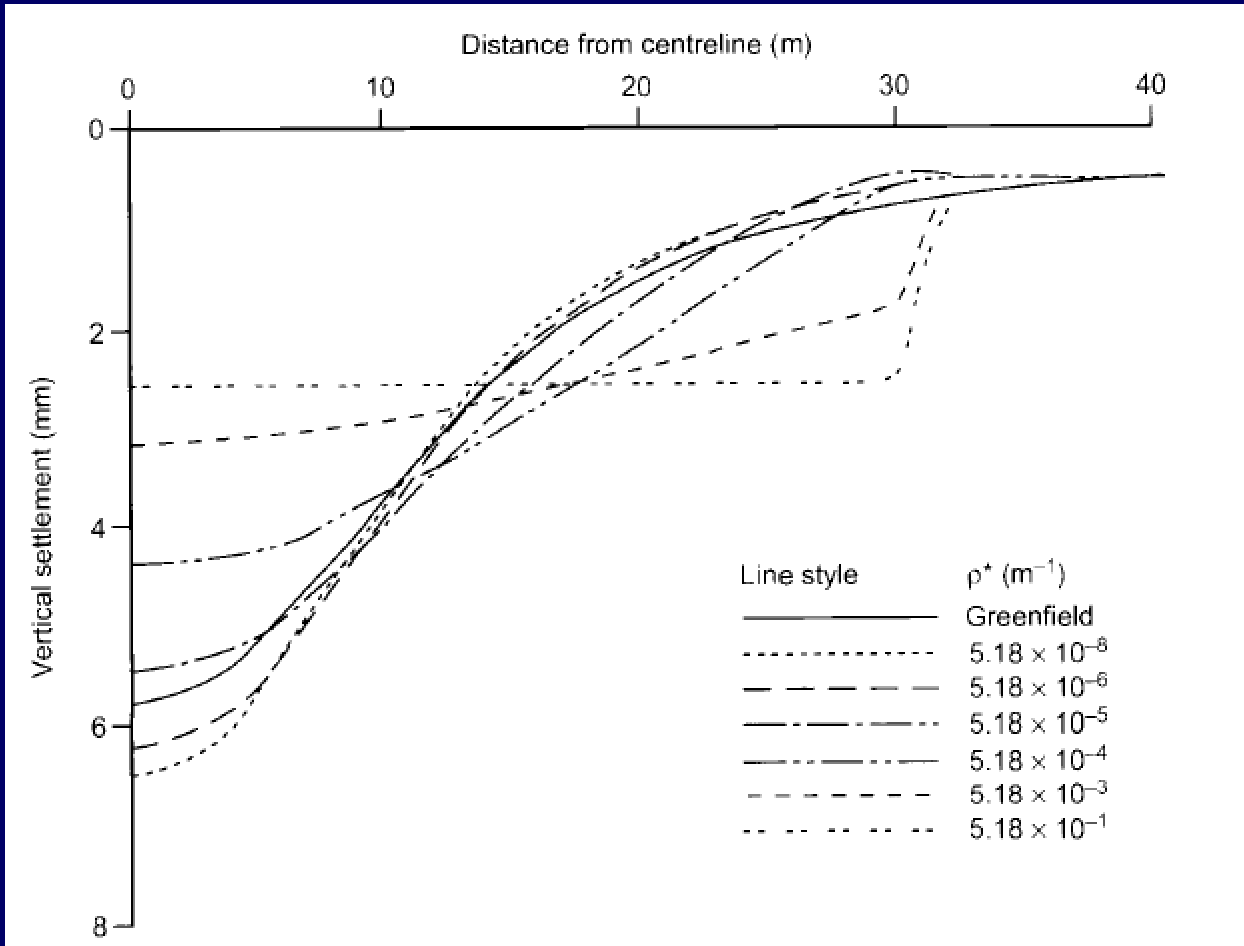


Figure 13. Influence of building stiffness on settlement profile associated with tunnel in London Clay (after Frischmann et al, 1994)

STAGE 3 ASSESSMENT



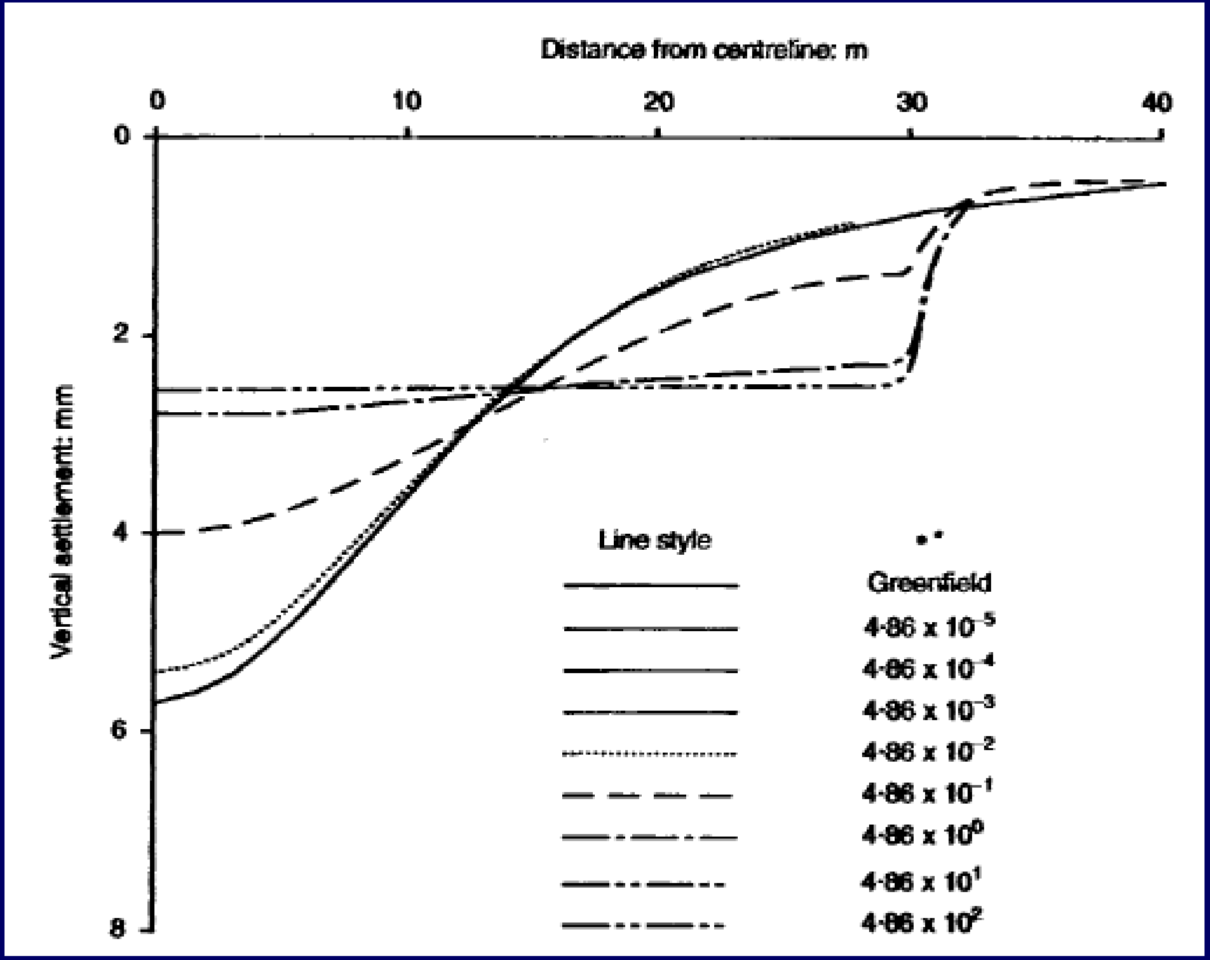
Effects of relative bending stiffness, ρ^* with a constant relative axial stiffness, $\alpha^* = 48.6$, where

$\rho^* = EI/E_sH^4$

$\alpha^* = EA/E_sH$

Potts & Addenbrooke (1997)

STAGE 3 ASSESSMENT



Effects of relative axial stiffness, α* with a constant relative bending stiffness, ρ* =0.518, where

$\rho^* = EI/E_sH^4$

$\alpha^* = EA/E_sH$

Potts & Addenbrooke (1997)

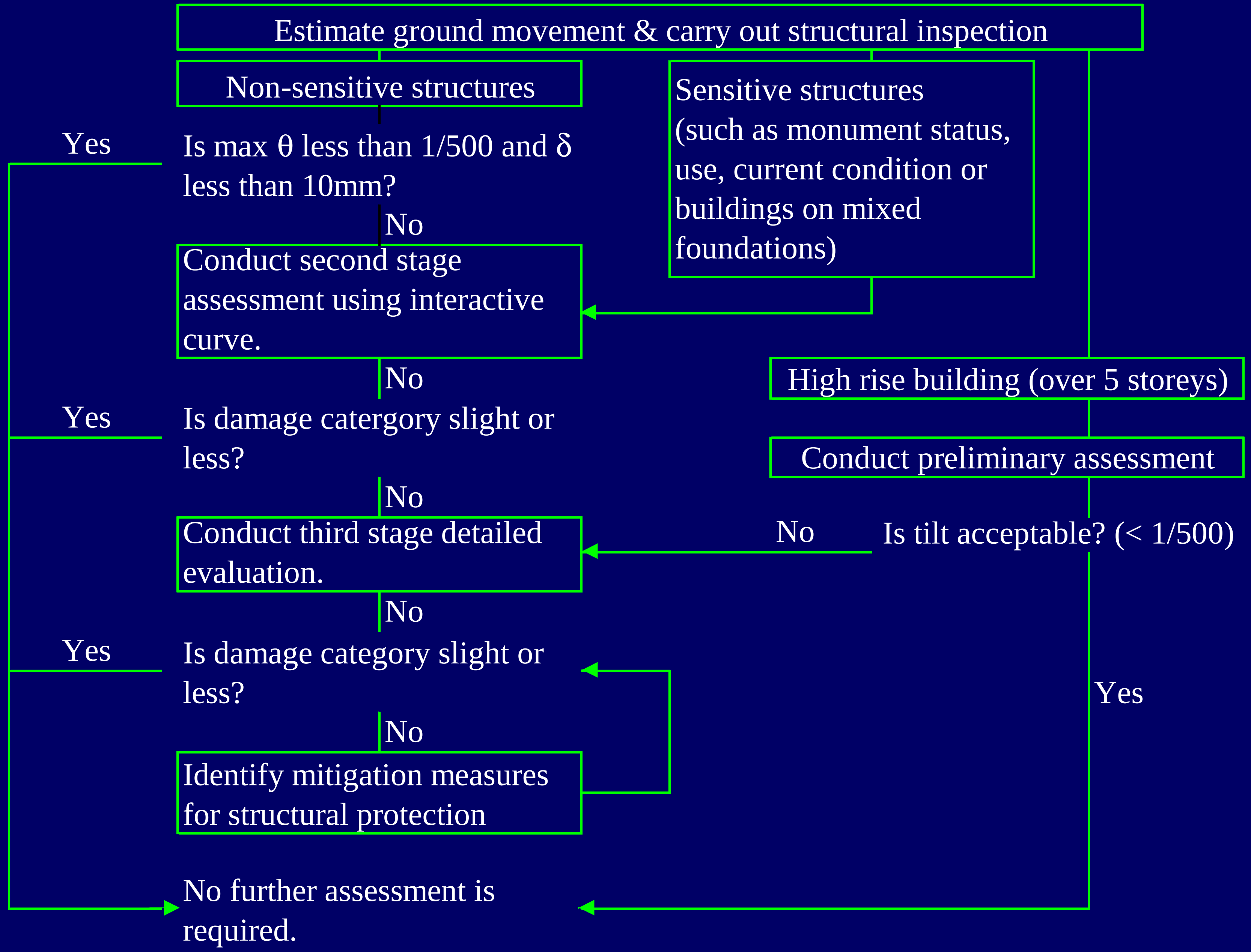
ASSESSMENT OF HIGH RISE BUILDINGS

Tall Buildings (Over 5 storeys)

- Large ratio of height to length.
- Predominately rigid body tilt under ground movement.
- Assessment on an individual basis to determine whether tilt affects the serviceability.

BUILDING DAMAGE ASSESSMENT

- The theory works well in buildings on uniform foundations
- Reliance should not be placed on theoretical assessment alone.
- Careful inspection of the buildings should be carried out. There would be Tell-Tale signs that indicate problems in buildings.
- Detailed structural assessment will be necessary for those buildings.


Estimate ground movement & carry out structural inspection
Non-sensitive structures
Sensitive structures (such as monument status, use, current condition or buildings on mixed foundations)
Is max θ less than 1/500 and δ less than 10mm?
Yes
No
Conduct second stage assessment using interactive curve.
No
Is damage catergory slight or less?
Yes
No
High rise building (over 5 storeys)
Conduct preliminary assessment
Is tilt acceptable? (< 1/500)
No
Conduct third stage detailed evaluation.
No
Is damage category slight or less?
Yes
No
Identify mitigation measures for structural protection
Yes
No further assessment is required.

BUILDING DAMAGE ASSESSEMENT SUMMARY SHEET

Project/ Contract Number

PHOTO

Name of Building:

Address:

Description of Structure:

Description of Foundations

Drawings available YES/NO

Result of Preliminary Assessment
Maximum settlement:
Maximum slope:

Second stage assessment required YES/NO

Result of Second Stage Assessment
Maximum settlement:
Maximum ground slope:
Maximum tensile strain:

Detailed evaluation required YES/NO

Detailed Assessment attached YES/NO
Protection measures needed YES/NO

Protection measures proposed:

ASSESSMENT OF UTILITIES

Three possible modes of failure:

- Pipe fracture (tensile strain)
- Joint rotation
- Joint slip (pull out)

The location of the pipe joints are critical to all three modes of failure. Either the worst location has to be assumed for analysis, or the joints exposed and checked.

Preliminary Assessment of the Effect of Ground Movement on a Buried Pipeline, Attewell, et al (1986)

Maximum surface settlement (mm)	Brittle materials (grey iron, asbestos cement, clayware)	Ductile materials (steel, ductile iron, polyethylene)
$w_{max} \leq 10$	Pipe stress increase is not significant compared with other causes of stress such as installation, traffic loading, seasonal movement.	
$w_{max} > 10$	The effect of movement should be assessed in detail.	-
$w_{max} > 25$	Significant stress increase is virtually certain; possible failure of small diameter pipes.	-
$w_{max} > 50$	Possible failure of large diameter pipes.	Significant stress increase likely; the effects of movement should be assessed in detail.

Allowable Joint Rotation and Pull-Out in Iron Distribution Mains for Tunnelling Induced Movement, Attewell, et al (1986)

Type of distribution main	Joint rotation from initial position (degree)	Joint pull-out from initial position (mm)
Lead-yarn joints in gas main with initial leaks	0.0	0
Lead-yarn joints in gas main initially sound	1.0	10
Lead-yarn joints in water mains	1.5	15
Rubber gasket joints in gas or water mains	2.5	25

Typical Pipe Material Properties for Short Term Static Loading in Direct Tension, Attewell, et al (1986)

Material	Elastic strain equivalent to design stress (microstrain)
Grey iron	400 to 500
Ductile iron	940
Grade 410 mild steel	450-660
UPVC (no creep)	7000
MDPE	10000
HDPE	9000

Typical Longitudinal Strain in 100mm Spun Grey Iron Pipeline, Attewell, et al (1986)

Cause of pipe strain	Pipe strain (microstrain) for different standards of pipeline construction		
	Very good (Granular bedding, densely compacted backfill)	Average (Trimmed trench bottom / compacted backfill)	Very poor (Uneven trench bottom/loose clay backfill)
“Lock-in” due to main laying and trench reinforcement	25	50	150+
“Lock-in” after consolidation of backfill due to traffic loading, etc. (up to 1 year after installation)	25	50	150+
Total “Lock-in” due to installation)	50	100	300+
Transient static load due to traffic on smooth road surface	50	100	250+

CRITICAL VALUES FOR UTILITIES

Rigid utilities - usually fail at joint

Values used for assessment in Toronto

Utility	Pipe Type	Rotation	Slip
General Purpose	Concrete	12.5/pipe diameter in mm	25mm
Gas	Cast or ductile iron, Steel	0.0075	10mm
Water	Cast or ductile iron, Steel	0.0075	25mm

CRITICAL VALUES FOR UTILITIES

Flexible utilities - usually fail by breakage

Values used for assessment in Toronto

Utility	Pipe Type	Tensile Strain
General Purpose	Steel	550×10^{-6}
General Purpose (<200mm)	Ductile Iron	820×10^{-6}
General Purpose	PVC	7000×10^{-6}

CONCLUSIONS

- Uneconomic to limit to “no damage”.
- Limiting tensile strain as assessment criterion.
- Staged approach to damage assessment.

Thank You