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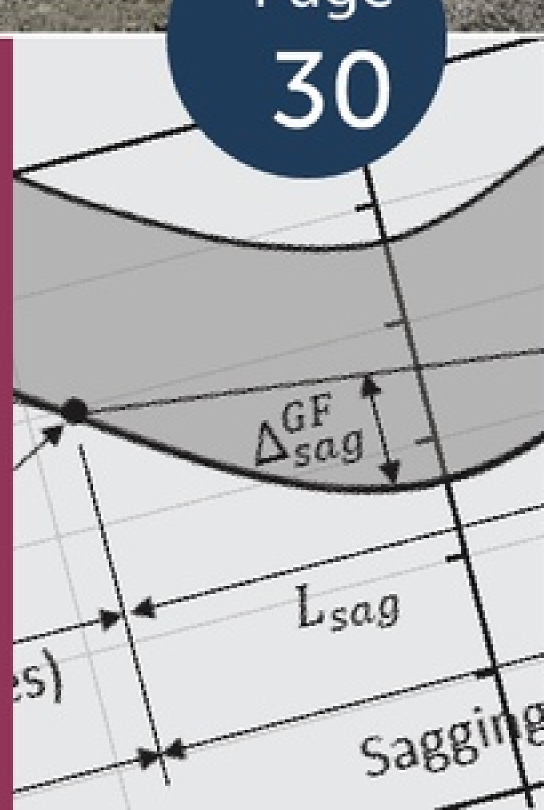

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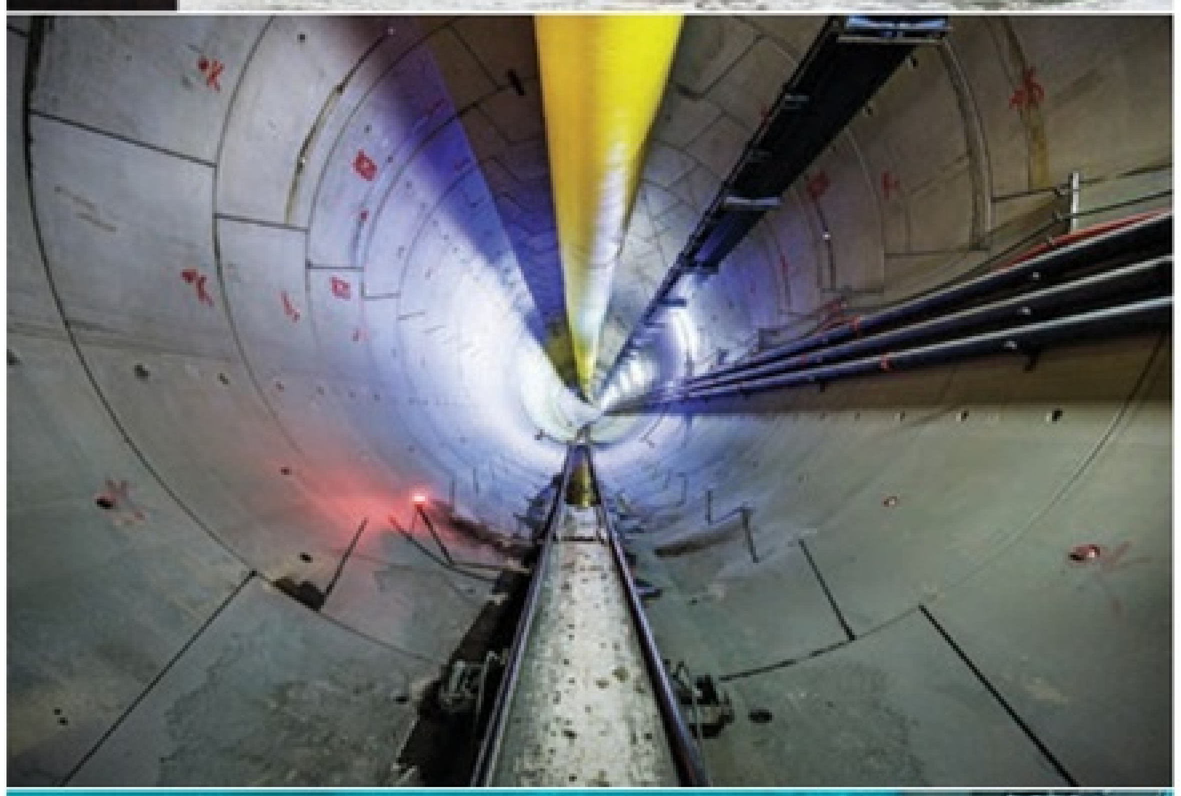

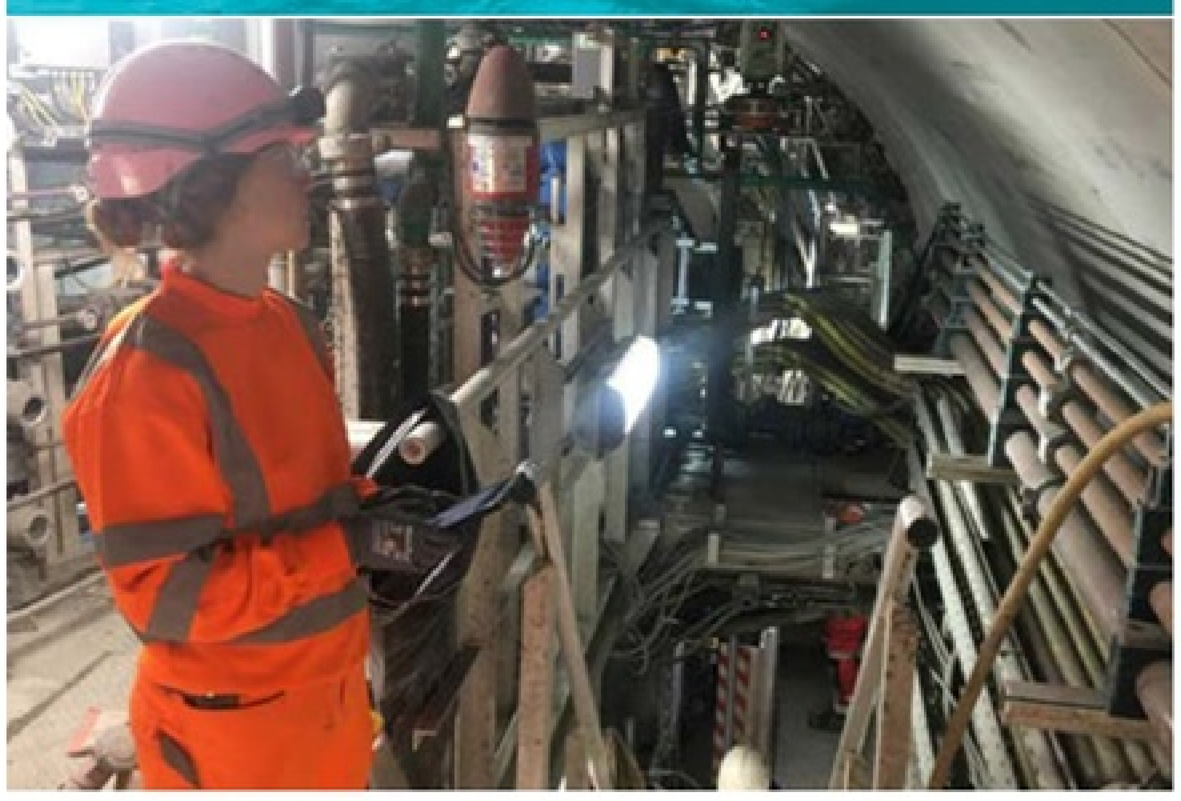

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Building damage assessment using the simple beam method – Part 2

In Part 1 the simple beam method equations were derived and several corrections and clarifications were made. In this second part, we will compare the corrected simple beam equations with the original equations from Burland & Wroth (1974). Then we will investigate some of the assumptions that need to be made when using this method, such as the length of the building in the hogging zone, and the effect of differences in whole-body tilt between hogging and sagging partitions. By Dr Benoît Jones, Inbye Engineering, and Dr Giorgia Giardina, Delft University of Technology

Comparison of corrected equations with Burland & Wroth (1974)

By setting either $\varepsilon_{bmax} = \varepsilon_{lim}$ or $\varepsilon_{dmax} = \varepsilon_{lim}$ we can plot equations 14 and 23 from Part 1 against L/H, as Burland & Wroth (1974) did. This is shown in Figure 1 for hogging and Figure 2 for sagging. Note that these do not include the interaction with horizontal strain and are not the resultant tensile strains, but they do give us an idea of where bending or diagonal strains are more important. The equations are reproduced here for convenience:

$$\varepsilon_{bmax} = \frac{\Delta/L}{\frac{L}{12d}\left[1 + \frac{72EI}{5L^2AG}\right]}$$

Equation 1

$$\varepsilon_{dmax} = \frac{\Delta/L}{\left[\frac{AGL^2}{18EI} + \frac{4}{5}\right]}$$

Equation 2

Figure 1 shows that the corrected equation for hogging gives lower values of $(\Delta/L)/\varepsilon_{lim}$ at all values of L/H and for both bending strains and diagonal strains. This is because at the same deflection ratio Δ/L the corrected equations will give higher values of ε_{bmax} and ε_{dmax}, demonstrating that the original equations underpredict maximum bending and diagonal strains. Figure 1 also shows that the corrected equations do not change the point (at exactly L/H=1.3) where diagonal strains cease to dominate and bending strains begin to dominate.

Figure 2 shows that the corrected equation for sagging gives lower values of $(\Delta/L)/\varepsilon_{lim}$ at all values of L/H and for both bending strains and diagonal strains. This was also the case for hogging, but here the difference is much more marked. The points at which diagonal strains cease to dominate and bending strains begin to dominate are not at the same value of L/H.

Length of building in the hogging zone

Referring to Figure 3, let us now consider a building that extends a long way from the point of inflexion. Mair et al. (1996) recommended cutting off the deflection ratio calculation at a transverse offset of ±2.5i, presumably to avoid deflection ratio being made smaller by considering a long building with a significant portion of its length far away from the tunnel, experiencing relatively little settlement. However, Netzel (2009) noted that considering the length of the building beyond the cut-off point can result in a significantly higher deflection ratio. There is also the effect of a longer building length L, which can increase the maximum

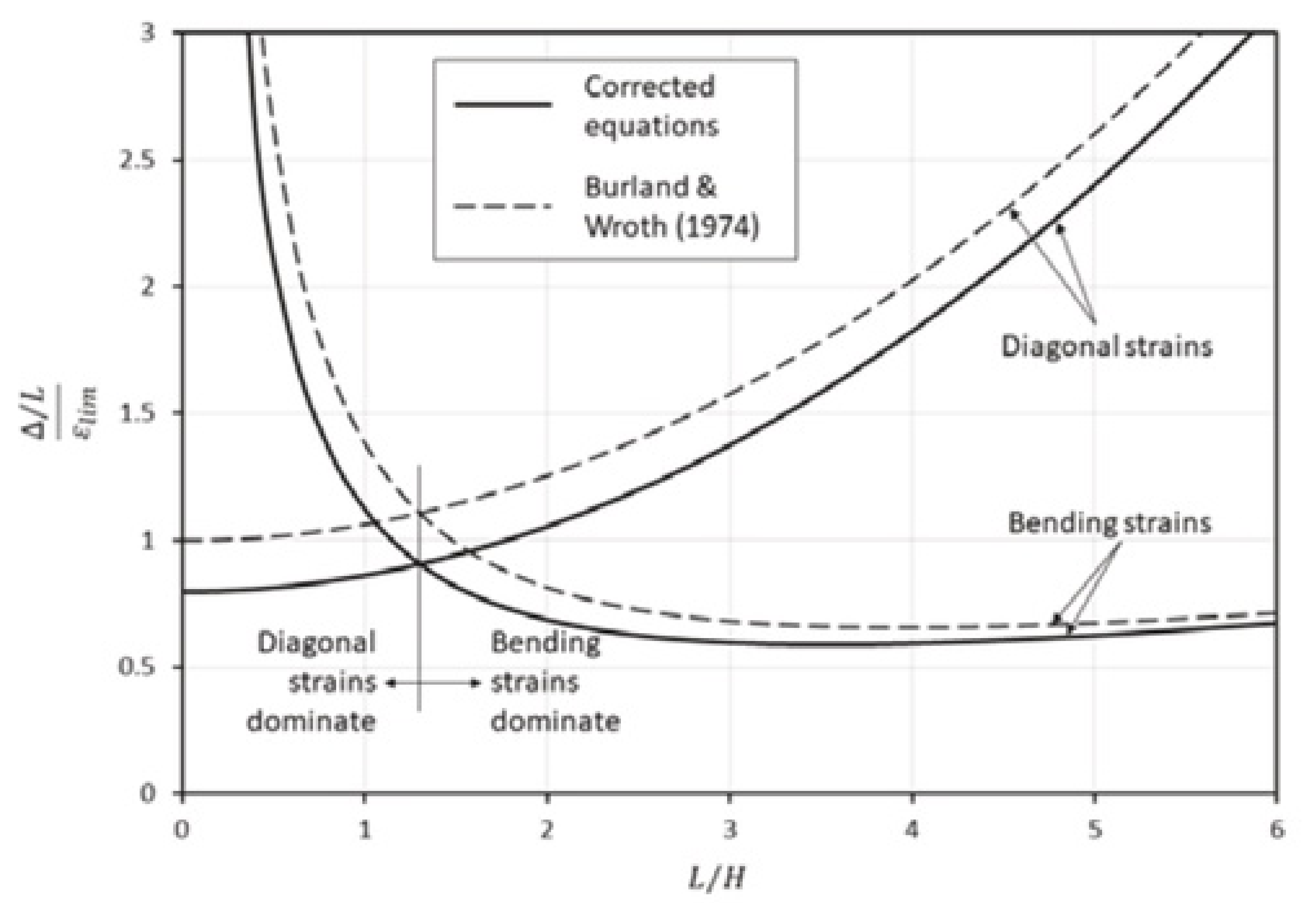


Figure 1: Relationship between $(\Delta/L)/\varepsilon_{lim}$ and L/H for buildings modelled as isotropic rectangular cross-section beams in hogging with the neutral axis at foundation level.

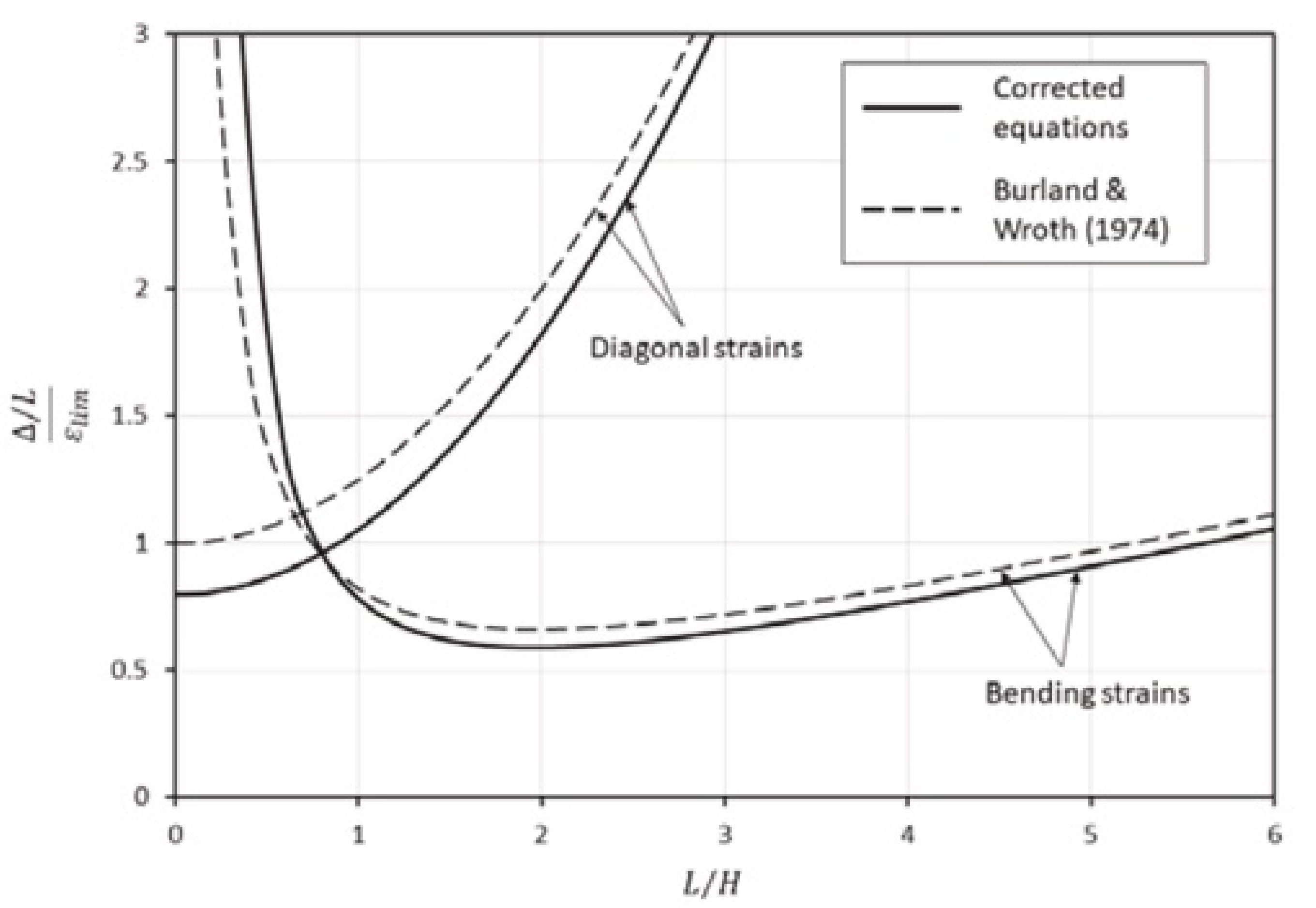


Figure 2: Relationship between $(\Delta/L)/\varepsilon_{lim}$ and L/H for buildings modelled as isotropic rectangular cross-section beams in sagging with the neutral axis at mid-height.

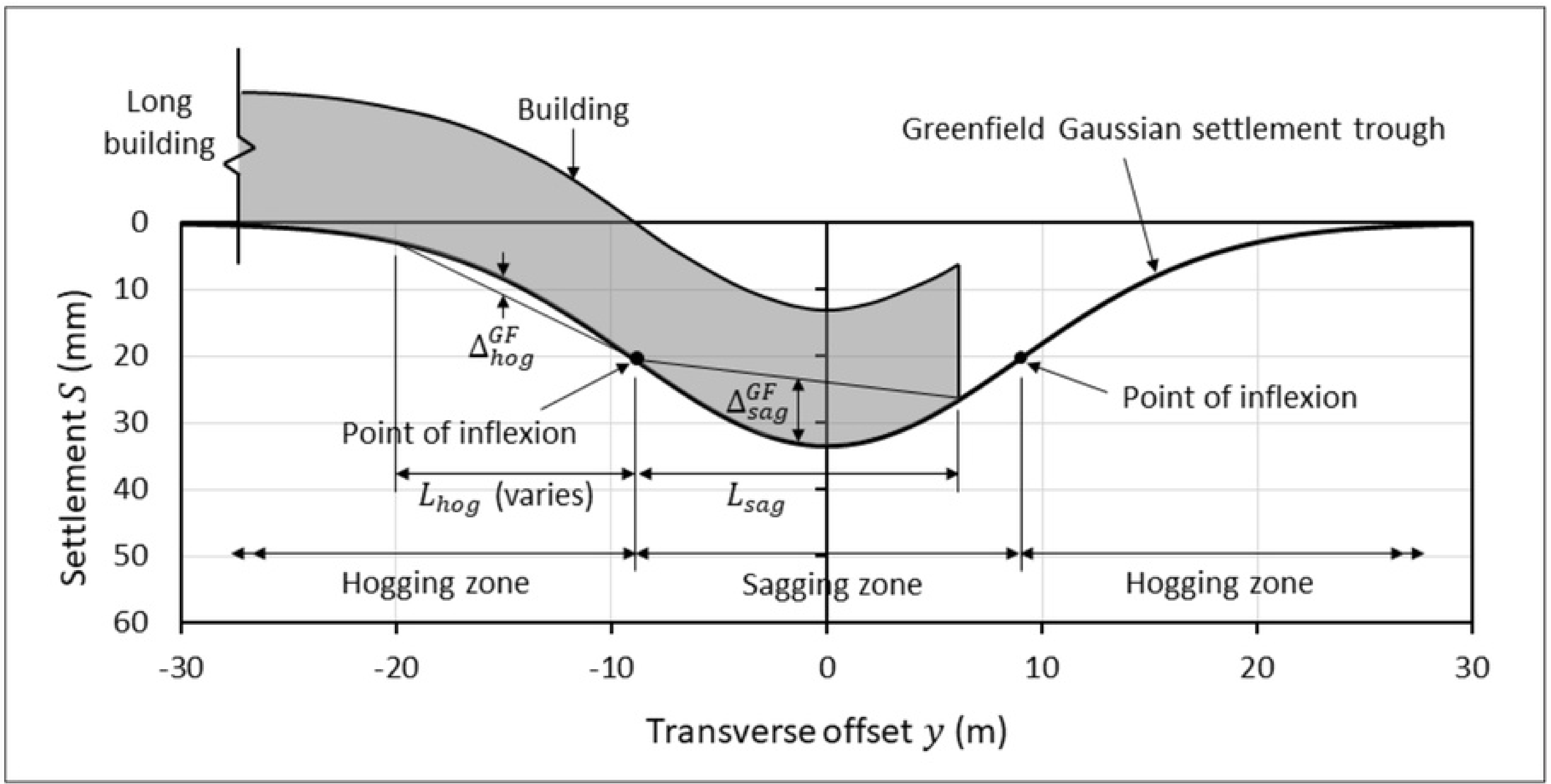


Figure 3: Idealisation of building deformation and definition of deflection ratio (vertical scale much exaggerated).

bending tensile strain in Equation 1. In a numerical example he showed that the maximum bending tensile strain may be increased by 75%.

If we do an example calculation for a settlement trough with volume loss of 1.5%, and trough width i of 9m, for a long building, the deflection ratio calculation can be visualised graphically as shown in Figure 4.

We can use these values of deflection ratio to calculate strains. As an example we will consider a long masonry wall extending at least 5i offset from the tunnel centreline, with height H of 5.5m and Poisson's ratio v of 0.3 (giving an E/G ratio of 2.6). Since L/H is large, we know that the resultant bending strain will be larger than the resultant diagonal strain. The calculation of bending strains is shown in Table 1.

Table 1 shows that maximum bending tensile strain may be significantly larger if we consider a longer building, as was shown by Netzel (2009). However, if we go on to calculate the resultant bending strain using the average horizontal strain along the hogging length of the building, which is standard practice, then using the 2.5i cut-off is a reasonable assumption, because longer building lengths result in a smaller average value of horizontal strain.

Note also that in Figure 4 the maximum deflection occurs at approximately the midpoint of L_{hog} when the length is 2.5i, but this becomes less and less true as L_{hog} increases beyond that. This means that the simple beam method, which assumes that the deformation of a building is similar to a beam loaded by a centrally-applied point load, would cease to provide a good approximation of strains.

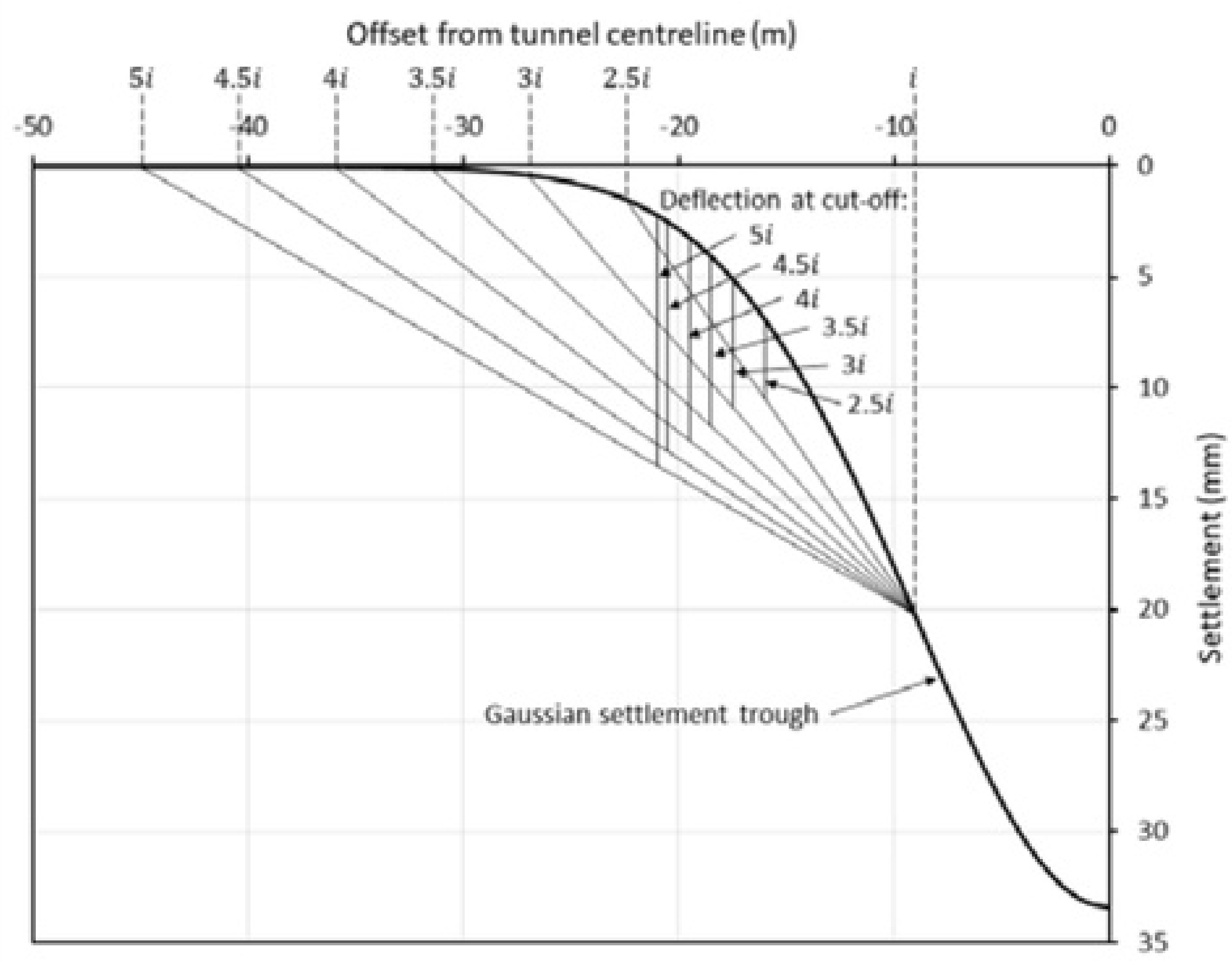


Figure 4: Deflection ratio with the building length cut off at various transverse offsets from the tunnel centreline.

Therefore, a cut-off of 2.5 or 3i is a sensible compromise.

Differences in whole-body tilt at the point of inflexion

The point of inflexion is used as a partition boundary, with the hogging and sagging partitions

Table 1: Example calculation of hogging deflection ratio with different cut-off distances.

Building length cut-off value (m)	Deflection ratio	Maximum bending tensile strain ε_{bmax} (Equation 1)	Average horizontal strain along L_{hog}	Resultant bending strain ε_{br}
2.5i	0.00026958	0.0429 %	0.0581 %	0.1010 %
3i	0.00032373	0.0548 %	0.0503 %	0.1051 %
3.5i	0.00034231	0.0575 %	0.0418 %	0.0994 %
4i	0.00034060	0.0549 %	0.0390 %	0.0938 %
4.5i	0.00032934	0.0500 %	0.0302 %	0.0802 %
5i	0.00031437	0.0446 %	0.0265 %	0.0711 %

on each side being considered separately in the simple beam method. As shown in Figure 1 in Part 1 and in Figure 3 here, we then assume that whole-body tilt of the building partition (the straight line drawn from one end of the partition to the other) does not induce strains and we only calculate strains from the deformation relative to that tilt (i.e. the deflection ratio). There are two extreme cases of this, as defined by Netzel (2009), and shown in Figure 5 and Figure 6. When the building ends near the tunnel centreline, then the difference in whole-body tilt between the hogging and sagging partitions is very small if the cut-off is taken at 2.5i. But when the building ends at the second point of inflexion as shown in Figure 6, the difference in whole-body tilt between the two partitions can be very large. By partitioning the building, we are allowing it to hinge at the first point of inflexion without inducing any bending or shear strains, which is not what happens in reality.

Netzel (2009) used finite element modelling to show that partitioning a building where there is a less than 15% difference in tilt between partitions (Figure 5) is valid, but where the tilt changes by more than 15% (Figure 6) partitioning will result in significant errors in predictions of bending moments and shear forces. Unfortunately the impact on resultant strains and damage categories was not calculated, but it seems clear that we should consider replacing the simple beam method with numerical models in these situations. They need not be complex and could be greenfield settlements imposed on a string of beam elements.

In fact, using simple numerical models may be a much better way of undertaking generic stage 2 assessments. They would only have a small number of elements and runtimes would be virtually instantaneous. It may even be quicker than spending the time programming spreadsheets to run the simple beam method. Comparisons between numerical models and the simple beam method, particularly with asymmetric deflections where the angular distortion at one end of a partition is significantly different to the other, show that the simple beam method can in some cases be highly inaccurate (Netzel, 2009).

Figure 5: Building ending at the tunnel centreline.

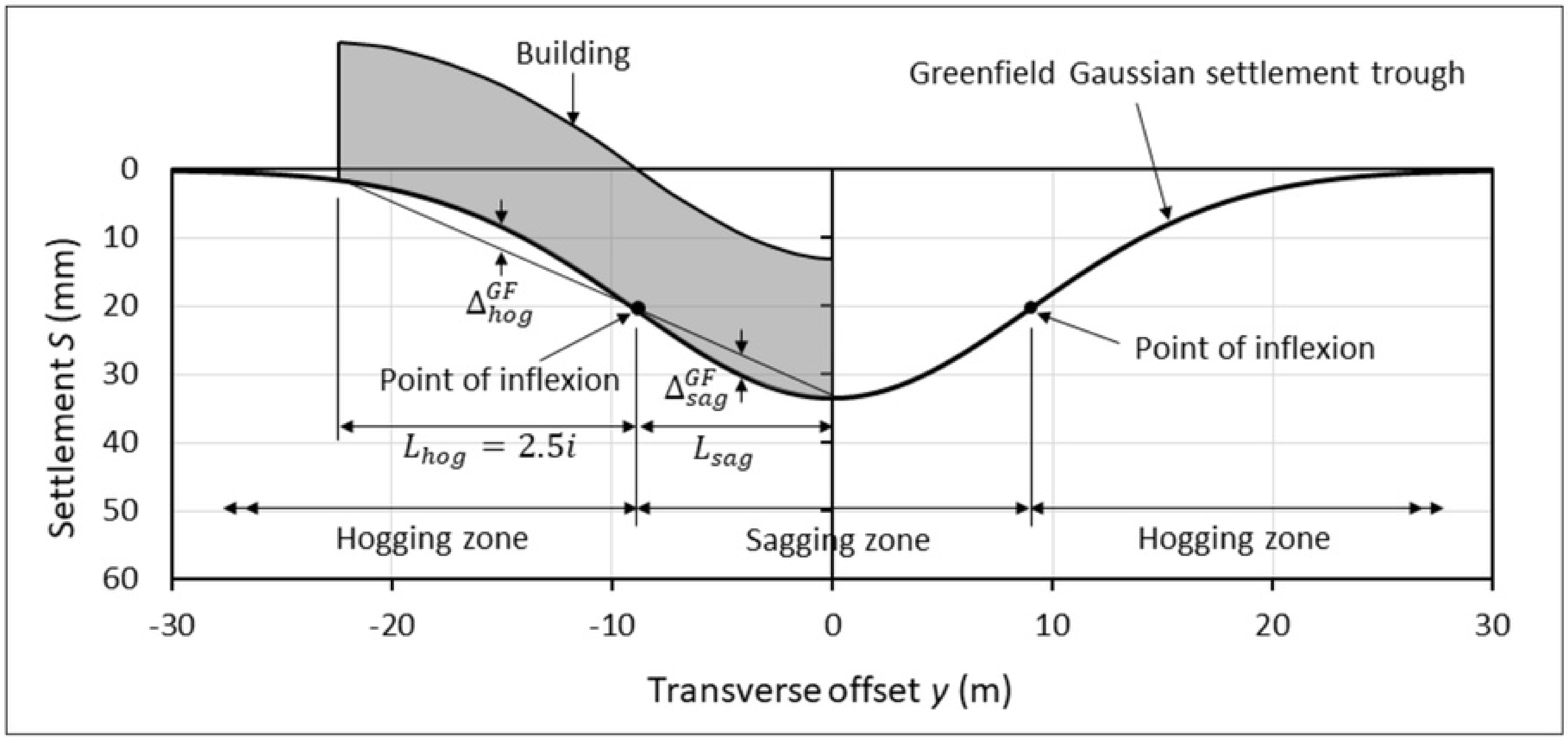
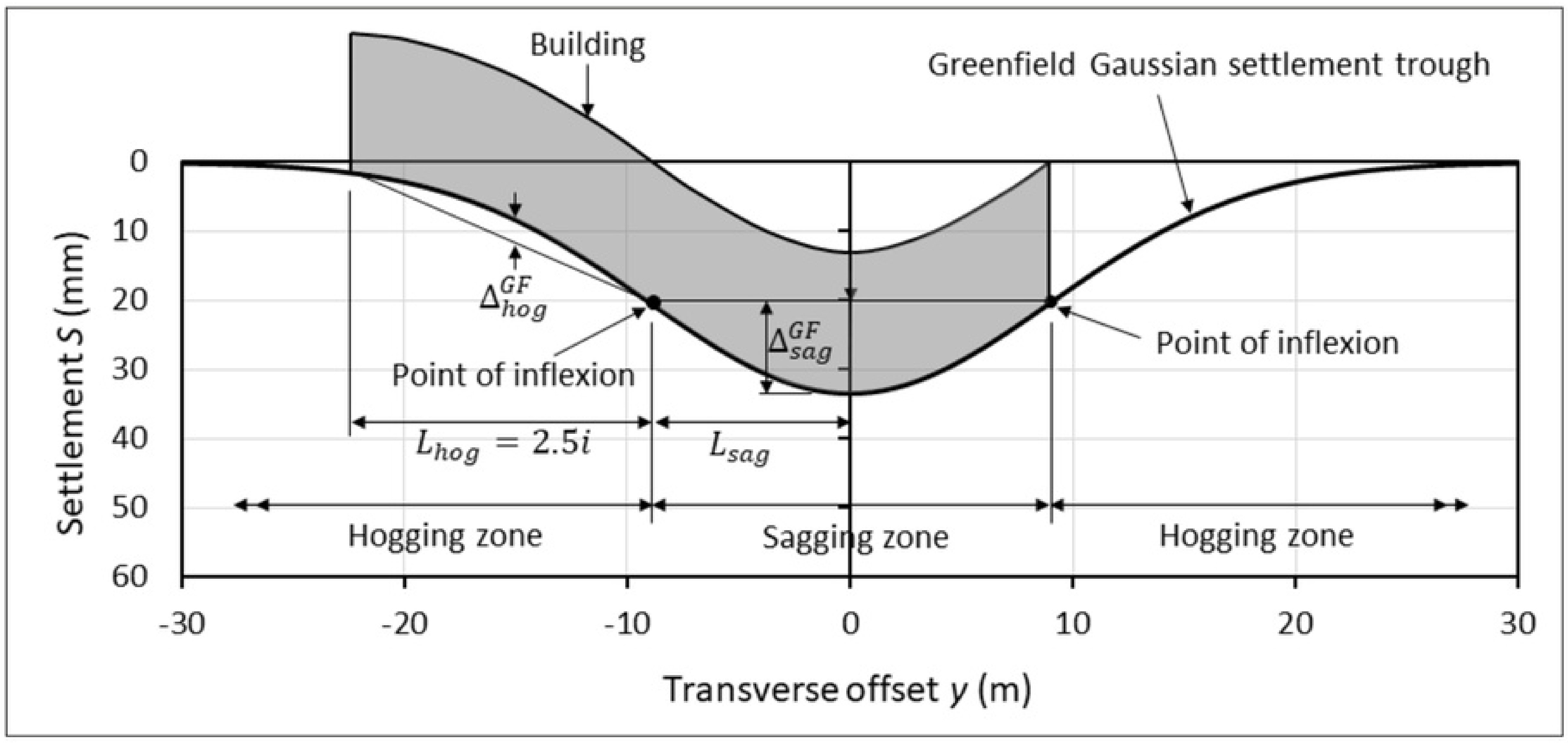


Figure 6: Building ending at the point of inflexion.



Summary

The simple beam method equations with the correct form factor for shear result in higher diagonal and bending tensile strains than the equations proposed by Burland & Wroth (1974).

The simple beam method has been used for at least 46 years with apparent success, and some may say that this is sufficient empirical proof of its usefulness. However, it is really only measured tensile strains that have been calibrated against crack widths – the prediction of the tensile strains using the simple beam method has not been widely validated. One exception is the comparison of predictions made by Mair & Taylor (2001) with actual strains measured in the foundations of Elizabeth House in London by Standing (2001), which found good agreement. However, the assumptions about the frame structure behaviour used in the simple beam method were quite arbitrary and other, just as reasonable, assumptions could have been made that would have led to different results.

The simple beam method must be used carefully. In particular, where the difference in tilt between partitions is more than 15%, it may not be applicable. Also, where the deflections within a partition are asymmetric, the deformation behaviour diverges from the assumption of a simple beam with a centrally-applied point load and the calculated strains will be less accurate.

The length of the building in the hogging zone can be cut-off at either $2.5i$ or $3i$ without introducing significant error.

It should always be remembered that the simple beam method is, at best, very approximate. The concept was always to provide a means of predicting strains so that buildings considered to be at risk could be analysed in more detail in a Stage 3 assessment. Nowadays, on large urban tunnelling projects, it is common practice to perform a generic Stage 2 assessment using the methodology proposed by Harris & Franzius (2006) rather than analysing individual buildings. It is likely that using simple numerical models for this purpose may not be more time-consuming than the simple beam method and will be more accurate.

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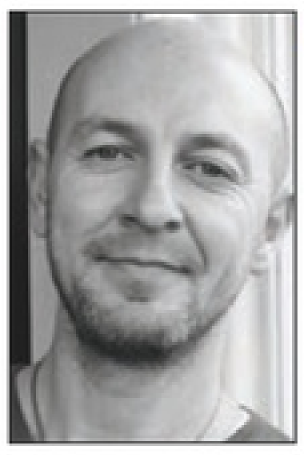

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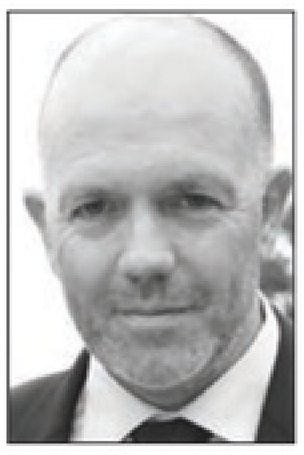

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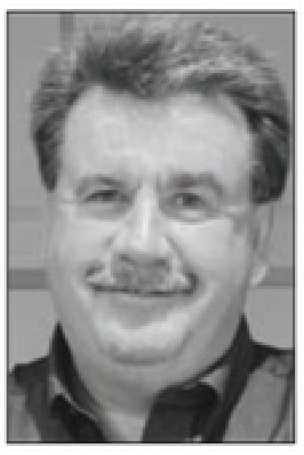

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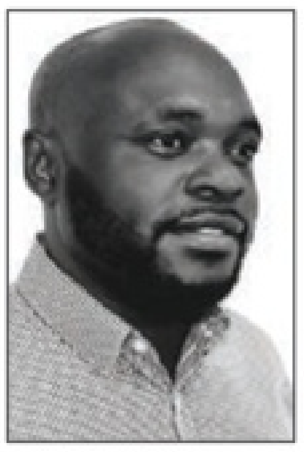

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