1. Introduction

BATS-2BCW is a computer implementation of the analysis of building impact assessment due to tunnelling. The implementation follows the following references below:

i. J.B., Burland & C.P. Wroth, 1975. Settlement of Buildings and Associated Damage. *In* Building Research Establishment Report No. CP33/75.
ii. M.D. Boscardin & E.J. Cording, 1989. Building Response to Excavation-Induced Settlement. *Journal of Geotechnical Engineering*, Vol. 115, No.1, 1-23.
iii. J.B. Burland, B.B. Broms, V.F.B. de Mello, 1977. Behaviour of Foundations and Structures. *In* Proceedings of the 9th International Conference on Soil Mechanics and Foundation Engineering, Tokyo, July 1977, Session 2.
iv. J.B. Burland, 1995. Assessment of risk of damage to buildings due to tunnelling and excavation. *In* Proceedings of the 1st Earthquake Geotechnical Engineering International Conference, 1995, Tokyo, Vol. 3, 1189-1202.
v. R.J. Mair, R.N. Taylor & J.B. Burland, 1996. Prediction of ground movements and assessment of risk of building damage due to bored tunnelling. *In* Proceedings of Geotechnical Aspects of Underground Construction in Soft Ground.

The mathematics and mechanics in the references above were developed for masonry structures with shallow foundations due to tunnelling. This is the most widely adopted preliminary assessment in mega tunnelling projects, despite its simplified assumptions. The main gist of the calculation procedures are:

i. The settlement induced by tunnelling is expressed as a closed-form equation (see Figure 1)
ii. The position of the buildings in relation to the settlement troughs are analysed to calculate the building's deflection (see Figure 2)
iii. The limiting tensile strains are calculated and plotted into damage charts (see Figure 3) to find the corresponding damage categories (Tables 1-2)

By comparison to a MS Spreadsheet working environment, the computer program BATS-2BCW offers the following advantages:

- Automatic finding of settlement magnitudes at the inner and outer edges of the building
- Automatic searching of maximum *deflection* by comparing the calculated ground settlement profile against the building chord
- Automatic searching of point of inflection to separate the *hogging* and *sagging* spans of the building
- Automatic generation of damage charts which require iterative analyses for diagonal strains and takes into account the dimensions for each building

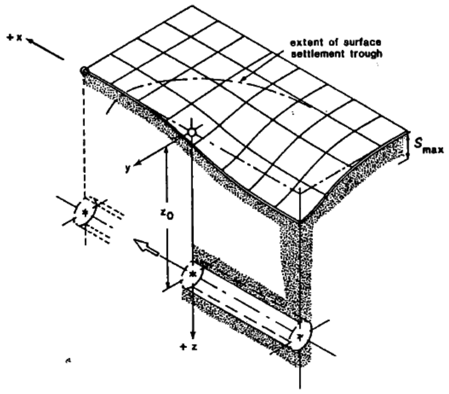


Figure 1. Settlement induced by tunnelling (after Mair et al., 1996)

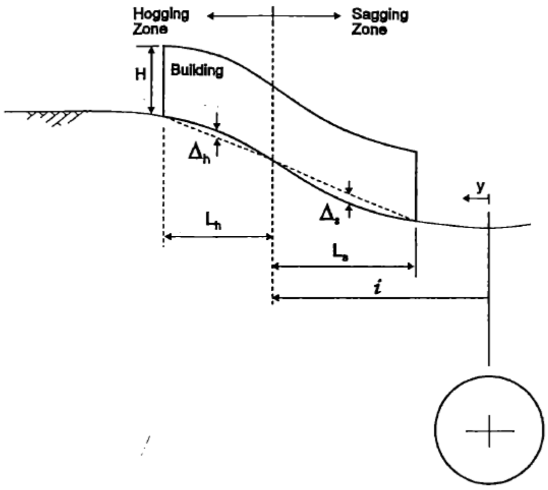


Figure 2. Sagging and hogging partitioning at point of inflection (after Mair et al., 1996)

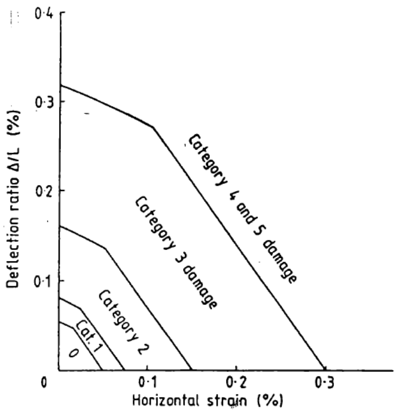


Figure 3. Example of damage chart (after Mair et al., 1996)

Table 1. Damage category in relation to limiting tensile strains (after Boscardin & Cording, 1989)

Category of damage	Normal degree of severity	Limiting tensile strain (ϵ_{lim}) (%)
0	Negligible	0 - 0.05
1	Very Slight	0.05 - 0.075
2	Slight	0.075 - 0.15
3	Moderate*	0.15 - 0.3
4 to 5	Severe to Very Severe	> 0.3

Table 2. Damage category and corresponding observations (Burland et al., 1977)

Category of damage	Normal degree of severity	Description of typical damage (Ease of repair is underlined) Note: Crack width is only one factor in assessing category of damage and should not be used on its own as a direct measure of it.
0	Negligible	Hairline cracks less than about 0.1mm.
1	Very Slight	Fine cracks which are easily treated during normal decoration. Damage generally restricted to internal wall finishes. Close inspection may reveal some cracks in external brickwork or masonry. Typical crack widths up to 1mm.
2	Slight	Cracks easily filled. Re-decoration probably required. Recurrent cracks can be masked by suitable linings. Cracks may be visible externally and some repointing may be required to ensure weathertightness. Doors and windows may stick slightly. Typical crack widths up to 5mm.
3	Moderate	The cracks require some opening up and can be patched by a mason. Repointing of external brickwork and possibly a small amount of brickwork to be replaced. Doors and windows sticking. Service pipes may fracture. Weathertightness often impaired. Typical crack widths are 5 to 15mm or several greater than 3mm.
4	Severe	Extensive repair work involving breaking-out and replacing sections of walls, especially over doors and windows. Windows and door frames distorted, floor sloping noticeably[1]. Walls leaning[1] or bulging noticeably, some loss of bearing in beams. Service pipes disrupted. Typical crack widths are 15 to 25mm but also depends on the number of cracks.
5	Very Severe	This requires a major repair job involving partial or complete rebuilding. Beams lose bearing, walls lean badly and require shoring. Windows broken with distortion. Danger of instability. Typical crack widths are greater than 25mm but depends on the number of cracks.

2. Theoretical background

The settlement trough due tunnelling is expressed using a Gaussian distribution curve:

$$S_v = S_{max} exp\left[\frac{-y^2}{2i^2}\right] \qquad (1)$$

where

- S_v is the vertical settlement
- S_{max} is the maximum settlement on the tunnel centreline
- y is the horizontal distance from the centre line

- *i* is the horizontal distance from the tunnel centre line to the point of inflection on the settlement trough defined below:

$$i = kz_0 \quad (2)$$

where *i* is the point of inflection, *k* is a trough width parameter.

The volume of the settlement trough (per metre of tunnel), V_S, can be evaluated as:

$$V_S = \sqrt{2\pi} i S_{max} \quad (3)$$

In practice, the volume loss is usually expressed as a percentage fraction, V_L, of the excavated area of the tunnel, i.e. for a circular tunnel

$$V_S = V_L \frac{\pi D^2}{4} \quad (4)$$

The vector of ground movement has vertical and horizontal components S_v and S_h respectively. Assuming that the vector is directed towards the tunnel axis, then

$$S_h = \frac{y}{z_0} S_V \quad (5)$$

where z_0 is the depth to the tunnel axis.

Tensile strains are distinguished as either bending strains or diagonal strains, both of which can be expressed as a function of the beam deflection, Δ/L, where *L* is the length of the building but limited by the affected span of the building, i.e. either sagging or hogging (Burland & Wroth, 1975):

$$\frac{\Delta}{L} = \left(\frac{L}{12t} + \frac{3EI}{2tLHG}\right)\varepsilon_b \quad (6)$$

$$\frac{\Delta}{L} = \left(1 + \frac{HL^2G}{18EI}\right)\varepsilon_d \quad (7)$$

where *H* is the height of the building, *E* and *G* are the Young's modulus and shear modulus of the building, *I* is the second moment of inertia of the building. The values for *H* and *I* are affected by the position of the neutral axis and is assumed to be at the centreline for the sagging and lower edge of the building for the case of hogging (Burland & Wroth, 1975).

With the influence of horizontal strains, the damage chart introduced by Boscardin & Cording, requires the calculation of contour lines of tensile strains as a function of (Δ/L - ε_h). That is to say, different combinations Δ/L and ε_h leading to the limiting tensile strain for each specific damage category have to be calculated. It is straightforward for bending strains, but requires transformations to calculate diagonal strains:

$$\varepsilon_{br} = \varepsilon_{bmax} + \varepsilon_h \quad (8)$$

$$\varepsilon_{dr} = \varepsilon_h \cos^2\theta + 2\varepsilon_{dmax}\cos\theta\sin\theta \quad (9)$$

Users can refer to Boscardin & Cording (1989) for the full calculation details.

Burland (1995) derived a simplified equation to calculate the resultant strains due to shear (diagonal strains), with the influence of horizontal strains:

$$\varepsilon_{dr} = \varepsilon_h \left(\frac{1-v}{2}\right) + \sqrt{\varepsilon_h^2 \left(\frac{1+v}{2}\right)^2 + \varepsilon_{dmax}^2} \qquad (10)$$

The *larger* of the bending or diagonal strain is adopted as the maximum tensile strain. The use of the Eq. (10) can directly give the maximum tensile strain, after making comparison with the bending strain, without the use of damage charts.

However, as damage charts can reveal the separate contribution of *horizontal strain* and *deflection*, the use of damage charts have been maintained to this date. In *BATS ©*, the calculation of strains and deflection adopt the affected sagging and hogging span. To maintain a unique damage chart for each building, the contour lines in the damage charts are calculated using the original length and height of the building. This is a preference adopted currently in *BATS*, and other options are being developed.

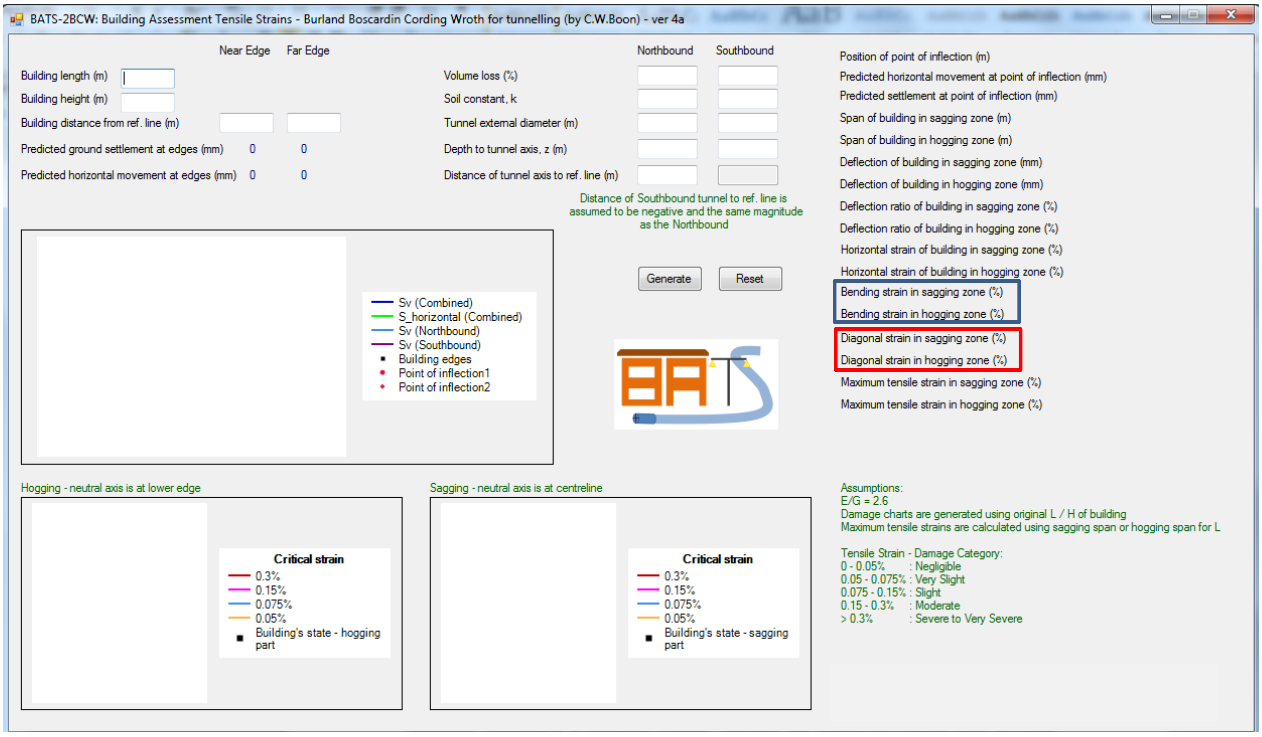


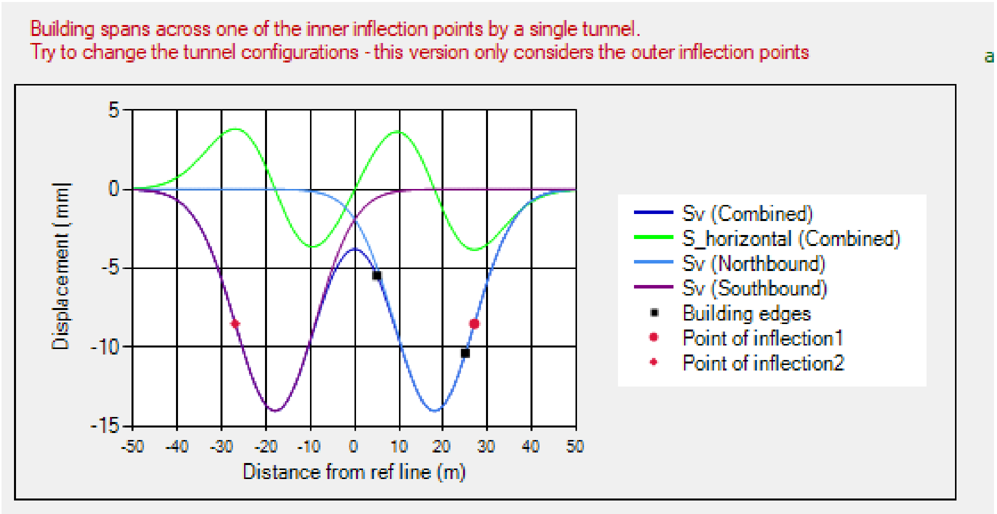
Figure 4. Both bending and diagonal strains are calculated at each sagging and hogging spans

3. Features/limitations:

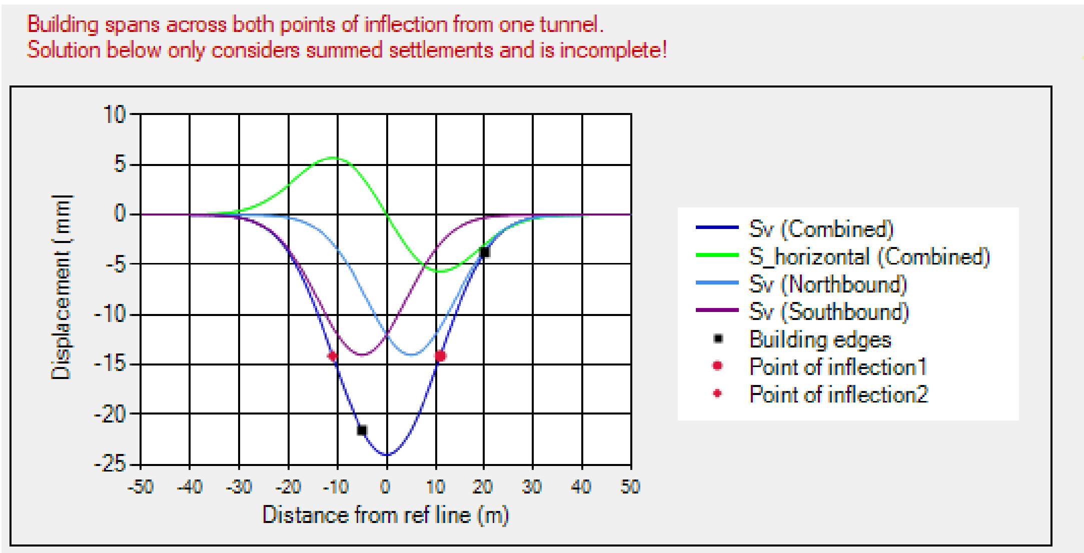
1. Distance of buildings are currently limited to -50m and + 50m from centreline
2. *E*/*G* of building is 2.6
3. Tensile strain of building is plotted into the damage chart using Δ/L and ε_h which are calculated from the settlement trough, where *L* is either the *sagging* span or *hogging* span.
4. The damage chart was generated using *L* and *H* of original building. An alternative is to assign *L* as the *sagging* span or *hogging* span based on position of *inflection point*, when generating the damage charts. This alternative was not pursued, so the damage chart here is unique to each building dimension independent of tunnelling position. However, the sagging and hogging spans are being used to calculate the tensile strains shown in the numbers in the lower right of the Window.
5. Does not consider effects of water drawdown
6. Does not consider effects of excess pore pressure or dissipation due to TBM mining
7. Does not consider elastic properties of soil or rock, effects of pressure grouting behind TBM tail skin, and elastic properties of tunnel lining
8. Solution is for circular twin tunnels
9. Solution is for masonry structures where building deforms compatibly with the ground
10. Building stiffness is ignored

4. List of bugs identified and fixed:

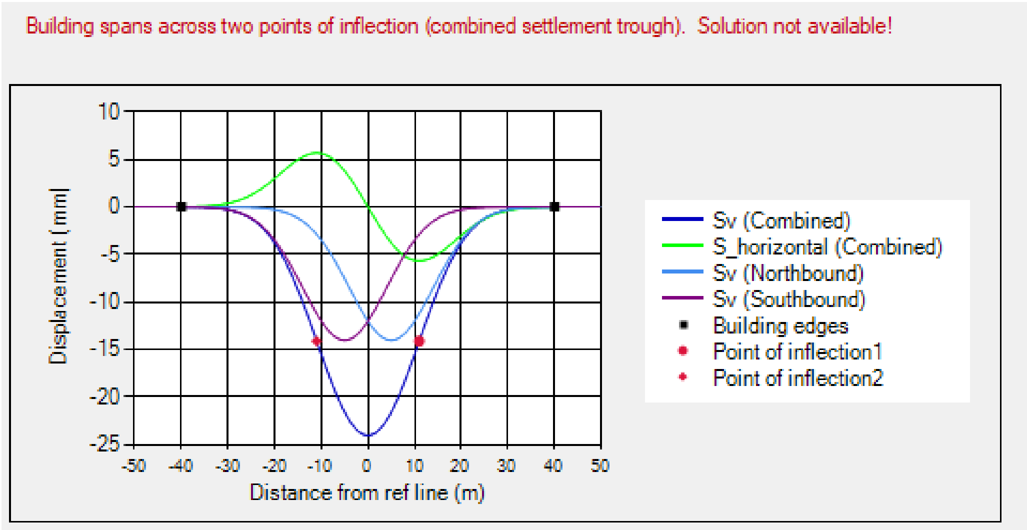
1. Made NB and SB tunnel distances from centreline symmetrical and avoid wrong input on distance from centreline
2. Give warning and avoids calculation when building spans across one of the inner inflection points (local minima/maxima in the horizontal strains) – happens when tunnels are far apart



3. Give warning when building spans across two inflection points of either single tunnel. Continues calculation with qualification, if there are no local minima/maxima in the horizontal strains (e.g. item 2 above)



4. Give warning and avoid calculation when building spans across both of the outer inflection points



5. When building is going across both positive and negative distances, to identify whether the left or right inflection points affected
6. Distance of 0.0 has no sign and was not computed correctly
7. Provide calculations to calculate maximum tensile strains for different spans depending on whether it is sagging or hogging

Disclaimer:

This is a Beta version computer program (trial). User's discretion is required. This is for educational purposes, and not to be used outside its intended purpose

Contact/ Report bugs to:

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Recognitions:

International Society for Rock Mechanics and Rock Engineering

https://www.isrm.net/gca/?id=288

American Rock Mechanics Association (ARMA)

https://armarocks.org/sample-page/future-leaders/

Member of the International Tunnelling Association Young Member Group

(Malaysian Representative)