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Abstract: This paper presents a methodology that allows calculation of ground displacements behind corners of retained cut excavations. The increased stiffness of a retaining wall at the corner of an excavation normally leads to a corresponding reduction in ground movements behind the retaining wall. These 'corner effects' derived from retained cut excavations can only be assessed at present by using three dimensional numerical analysis or empirical methods. Significant cost and time can be taken carrying out three dimensional analysis, which, additionally, is not normally carried out at an early stage of the design of a project. Furthermore, numerical analysis must be undertaken by a competent person with appropriate training. An inappropriate analysis can yield misleading and counterproductive results. This constitutes an expensive requirement on practitioners that often resort to more conservative designs which ignore corner effects. The methodology of adjusting calculated ground movements around corners of excavations described in this paper is simple to use and easy to program into software or spreadsheets. It can be used in conjunction with two dimensional numerical analysis and also for calculating displacements in early stages of projects when numerical analysis has not yet been undertaken. This allows for more informed early discussion with third parties where approvals are sought on a given project.

Title: "Ground movements around corners of excavations – An empirical calculation method"

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ABSTRACT

This paper presents an empirical methodology that allows calculation of ground displacements behind corners of retained cut excavations. The increased stiffness of a retaining wall at the corner of an excavation normally leads to a corresponding reduction in ground movements behind the retaining wall. These 'corner effects' derived from retained cut excavations can only be assessed at present by using three dimensional numerical analysis or empirical methods. Significant cost and time can be taken carrying out three dimensional analysis, which, additionally, is not normally carried out at an early stage of the design of a project. Furthermore, numerical analysis must be undertaken by a competent person with appropriate training. An inappropriate analysis can yield to misleading and counterproductive results. This constitutes an expensive requirement on practitioners that often resort to more conservative designs which ignore corner effects. The methodology of adjusting calculated ground movements around corners of excavations described in this paper is simple to use and easy to program into software or spreadsheets. It can be used in conjunction with two dimensional numerical analysis and also for calculating displacements in early stages of projects when numerical analysis has not yet been undertaken. This allows for more informed early discussion with third parties where approvals are sought on a given project.

INTRODUCTION

Conventional non numerical geotechnical analysis is not able to cater for the effects of corners in excavations, yet observations of field measurements show that deformations of wall and ground movements are lower near the corners. The inclusion of this could lead to substantial savings in construction as stated by Gaba et al. (2003) by considering a reduced horizontal displacement of the wall, which, in turn, could result in reduction of reinforcement. In addition to these cost savings, a reduction of ground movements is observed around corners of excavations that will result in smaller displacements of nearby structures and utilities.

This paper considers a number of case histories and shows a relationship that calculates displacements around corners of excavations that closely matches the observed data. It also shows the limitation of this relationship and highlights the need for further work considering more ground conditions to calibrate the parameters required in the analysis technique.

Currently, ground movements around the corner of excavations are normally calculated using three dimensional (3D) numerical methods, or via empirical methods based on case history. Work has been carried out by multiple authors on the differences between plane strain, axisymmetric and 3D calculations in excavations (St John 1975, Simpson 1992, Zdravkovic et al. 2005). Some of this work also considers the effects at corners of excavations. Ou & Shiau (1998) showed a method to implement in finite element (FE) using the infinite element that gave promising results for one project.

An empirical method to calculate these movements has been recently presented by London Underground (2009). The method presented in this document does not accomodate internal excavation corner angles other than 90 degrees and it has not been calibrated against case histories outside London.

In order to be appropriate for wide application, empirical methods need to be calibrated against good case history data. The displacement reported in the case histories also needs to have been obtained from reliable and accurate monitoring data. Long (2001), presented a comprehensive list of case histories data and references which constitutes a useful source of information for any person interested in the design of retaining walls and associated ground movements in general. However, as far as the authors have been able to find, there is little case history data available based on field measurements that cover ground movements around corners. This leads to having to resort to other supplementary data for calibration purposes. This can be obtained from 3D FE analysis or model test data, such as centrifuge models. This paper considers only data from the former to complement the available field case histories.

The presented empirical method has two applications. First, it is considered to be appropriate to be used as a design tool in conjunction with 2D FE analysis. However, as shown later in this paper, its accuracy will depend on the accuracy of the 2D predictions. Secondly, it can be used as a quick and hence cost effective preliminary ground movement analysis method useful for instance at scheme or preliminary design. This allows early interaction with third parties to progress approvals before a detailed design is carried out.

This paper identifies plane strain conditions, as the area around excavations where displacements perpendicular to the wall are not affected by the presence of the corners of the excavation.

CASE HISTORIES

Table 1 shows the different case histories that have been used for this work, and the references these were taken from.

It is noticeable that the majority of the case histories consider excavations in London Clay. However, two more cases consider different ground conditions.

In the cases where FE results have been chosen for calibration purposes, two non-linear soil models were used. In the cases of BAS1 and BAS2, the BRICK model was used (Simpson, 1992). The authors who published the Moorhouse case history used the Jardine soil model (Zradvkovic, 2005). Both soil models are non-linear and account for small strain stiffnesses at small shear strains, and therefore, are considered adequate to model the behaviour of London clay.

Excavation depths, propping systems and construction methods also vary considerably between each case history.

Out of the seven cases covered in the paper, only two showed plane strain conditions: TNEC and BAS 1. In the case of the former, Ou et al (2000) showed that this occurs at approximately 34.4m away from the corner. In the case of BAS 1, the position was not relevant as predictions were made only at the corner, and not in intermediate sections between plane strain conditions (referred throughout this paper as 100%) and the corner.

METHOD BACKGROUND

An empirical method was developed over 15 years ago in Arup Geotechnics in London. This method has not been published and has only been used internally within the company as far as the authors know. The basis for this method is unknown and is not appropriately documented. However, it is known that it was calibrated using the information from the New Palace Yard Excavation (Burland and Hancock 1977). This original empirical method is shown in Figure 1.

Beadman & Cheng (2002) carried out some work to calibrate the method against four different excavations based on the following case histories:

- New Palace Yard car park, London (Burland and Hancock 1977)
- Moorhouse, London (based on results from Geotechnical Consulting Group).
- Immigration Building, Singapore (Lee et al. 1998)
- Taipei National Enterprise Centre (TNEC), Taiwan (Ou et al. 2000).

This work only verified the original method that used internally within Arup (see Figure 1). However, it did not improve on existing methods and had some limitations in the verification process.

Furthermore, the method was only developed and calibrated for 90° corners. Although this is the most common corner geometry, urban constraints often lead to other geometries which consist of acute or obtuse corner angles. A development of this approach to cater for this particular situation was therefore required.

Another limitation of the original method is that it was based on sketching contours of displacement by hand through displacements known at the 100%, 67% and (25 + 25)% lines. As the method is graphical it is not easy to implement in a computer program or spreadsheet.

Hence, it can be seen that there was a need for some improvements, both in the method formulation and the verification processes.

PROPOSED METHOD

The objectives in devising the new method were at the onset:

- Find equations that allow ground movements to be calculated at any point at the surface outside the excavation in order to provide the method with a mathematical basis;
- Generalise the method for any corner geometry;
- Assess its applicability to different ground conditions and construction methods;
- Calibrate the method's parameters to match, as practicably possible, the observations.

A representation of the main parameters and a generic corner geometry (for a non 90° angle, i.e. 65°) is shown on the left hand side of Figure 3. This shows that the plan space is divided into five different areas. Areas I and V, and II and IV share the same characteristics respectively. For any value of the angle $\varnothing$, up to 180 °, the sections shown in the figure must always remain perpendicular to the wall (see contour plans in the figure for two different angles). The exception is in Zone III, where the sections pass through the corner, as shown by the line that divides Zone III into two equal areas (see Section 2 in the figure).

Assumptions and simplifications

The following assumptions and simplifications have been made to develop the method, and therefore must be considered when applying it:

- The method does not distinguish between different sources of movement (e.g. wall installation, dewatering, soil improvement, excavation, etc). Therefore, it only looks at total movements, regardless of their origin.
- The method suggested works for all corner geometries except re-entrant corners ($\varnothing > 180°$, see Figure 3).
- Movements everywhere behind the wall are related to the ground movements at sections 100%A and 100%B. An assumption of the distance of the 100%A and 100%B sections from the corner must be made by the user.
- The ratio of ground movements behind the wall to the maximum or plane strain movements, varies linearly between the 100%A and p_1 lines (see Figure 3), with distance from the corner.
- Ground movements in Area III are to be calculated as a combination of ground movements behind walls (A and B). They may be calculated along Section 2 using the proposed formulae (Table 2). The percentage of both contributions is calculated as a function of the angle (α and β) that a given section forms with the p_1 sections. (See Figure 3)
- The distance behind the wall to zero movements is the same for all sections along the length of a wall. This is a consequence of calculating different sections as a percentage of 100%A or 100%B. This is considered to be a minor error that would normally only affect points that are well away from the wall, where the absolute displacement values are of lesser significance in most circumstances.

- Values of p_1^* and p_2^* should be found in advance for the ground conditions of interest, based on case histories. However, it will be shown in this paper that values of 67% and 25% have given a good agreement for all the cases considered.

Calibration

Calibration of the method was done against the observed data at the New Palace Yard Car Park as presented by Burland and Hancock (1977), which original data was presented by St John (1975).

Figure 2 shows the calibration process. A parametric study was carried out for the calibration of p_1^* (Figures 2a and 2b) and p_2^* (Figure 2c). The figure shows that the best match was obtained for values of 67% and 25%.

Using the method

The basis of the method is the calculation of percentage factors which are applied to the 100% movements in sides A and B in order to calculate movements elsewhere.

Table 2 shows what plots shown in Figure 3 need to be used for each zone (see figure for zone identification), and the mathematical equations to calculate the required percentage.

Given the values of $\varnothing$ and p_1^*, the value of p_1 can be calculated from PLOT 1 (see figure). Using the above and p_2^*, p_2 can be calculated using PLOT 2.

PLOT 3 is constructed from the values of p_1, p_2 and θ. It should be noted that $\theta = 180° - \varnothing$. Two angles are measured from both p_1 lines to the section that contains the point of consideration from walls A and B respectively (i.e. Section 2 in Figure 3). These angles are represented by α and β (see figure). Reading from the plot with these two values, two percentages, p_a and p_b can be found. These are then combined using the equations shown in Table 2 to calculate the total movement at a required section.

It should be noted that $p_1 = p_1^*$ when $\varnothing = 90°$. PLOT 3 is used only for points which fall within Zone III.

Example (Follow figure 3)

The figure shows an example where a corner angle of $\varnothing = 65°$ has been used. Values of p_1^* and p_2^* equal to 67% and 25% respectively, were assumed in this example.

Settlements at 100%A and 100%B are the input of the method. In this instance, they were artificially created, and both show the maximum settlement at the same distance from the wall. However, this would not be the case in general and it does not affect the calculation process.

The aim is to calculate the settlement at points located along Sections 1, 2 and 3 as shown in the figure.

The first step is to calculate p_1. This is done inserting the value of $\varnothing = 65°$ in PLOT 1 as shown in the figure, which gives a value of $p_1 = 48.4\%$. The second step is calculating p_2 using the calculated value of p_1 and PLOT 2. As shown in the figure, this gives a p_2 value of 18%.

Having done this, any section in Zones I, II, IV and V can be calculated.

Section 1 is located in Zone II. Using the equation shown in Table 2 for this zone, and the distances shown in the figure, the percentage that applies to this section can be calculated:

$\text{Section 1 } \%\text{A} = 48.4 + (100 - 48.4)\dfrac{19}{24} = 89.25\%\text{A}$, where $d_a = 19$ and $d_A = 24$

Similarly, for Section 3:

$\text{Section 3 } \%\text{B} = 48.4 + (100 - 48.4)\dfrac{23}{30} = 87.96\%\text{B}$, where $d_b = 23$ and $d_B = 30$

The calculated settlements for these two sections have been shown in the top right corner of the figure alongside the 100% values at both sides of the corner for comparison.

The calculation of Section 2 requires the use of PLOT 3. As it can be seen in the figure, the angles that the section forms with the two 100% lines are α = 37° and β = 78°.Inserting these two angles in PLOT 3, the values of p_a and p_b are shown to be 19.5% and 11.6% respectively. Section 2 is calculated using the equations given in Table 2:

$$\text{Section 2} = 19.5\%\text{A} + 11.6\%\text{B}$$

The results show that settlement can be calculated at any point located behind the wall by calculating a section that passes through that point. Similarly contour plots can be produced. In this case, Figure 3 shows contour plots that were produced using software called Surfer 8, and the Krigging technique to create the grid. It can be observed that the method is able to reproduce lower ground movements in the vicinity of the wall and the corner. The contours have been drawn up to the 100% sections.

A similar contour map was created for the case of an internal corner angle higher than 90° (135°) using the same geometry for the rest of the elements as well as the same settlement profiles at the 100% sections. It can be observed from comparison of the two contour maps that the settlement behind the corner for the more acute angle is lower than the ones obtained for a more obtuse angle, as expected.

VERIFICATION

The verification is based upon case histories and analyses. It followed the process shown in Table 3. This consisted in comparing the ‘observed’ movements with the ‘calculated’ movements using the method.

Figures 5 to 10 show the results for all the different case histories. The word ‘Observed’ in the figures corresponds to either the observed ground movements or those obtained from 3D FE analysis. The word ‘Calculated’ represents the displacements obtained using the method proposed in this paper.

DISCUSSION

Since the method is based on generic equations, the input parameters can easily be changed to adapt it to any ground conditions.

One of the input parameters is the location and magnitude of where the plane strain, or maximum ground movements occur, termed here as 100%A and 100%B. These ground movements occur at the mid section if no plane strain applies (or at the point where plane strain movement starts, if it does apply), and can be calculated using a 2D FE approach. This is less complicated and time consuming to obtain than a full 3D analysis. The validity of this approach depends on the accuracy of the 2D FE predictions. St John (1975) showed that 3D FE and 2D axisymmetric gave good agreement, but plane strain analysis overpredicted the horizontal movements using Mohr Coulomb. On the other hand, Simpson (1992) showed results where axisymmetric and plane strain analyses gave similar results. The above identifies the many uncertainties presented in 2D FE predictions. Recommendations on how to obtain accurate 2D FE predictions is outside the scope of this paper.

At an early stage of design, an alternative to using 2D FE calculations, could be to use a pseudo 2D FE program such as FREW or WALLAP that calculates wall deflections. Gaba et al (2003) suggested a method of rotating this profile to obtain vertical displacements at ground level. Caution is however expressed that this relationship is limited to similar conditions to those projects they used to calibrate the method.

An advantage of the proposed method over other empirical methods is that it allows calculating corner effects for corners that do not form 90°. The example of BAS 2 showed that, for a corner of 75°, the method gave good agreement with the observed results. This has only been demonstrated for a single back analysis and therefore should be used with caution on other projects.

The values of p_1^* and p_2^* may change for different ground conditions and should be calibrated for those for each particular predominant soil. This calibration should be made by comparing the calculated corner movements to the observed movements at the corner. However, as this paper shows, values of p_1^* = 67% and p_2^* = 25% are reasonable for the case histories considered. Please note that the TNEC and Immigration building basement case histories were constructed in clay with very different properties to London Clay, but still shows good agreement between observed and calculated results.

Ground conditions and geometry

Figures 5 to 10 show that although the total settlements for different ground conditions vary significantly among different sites, the ratio between ground movements at 100%A or 100%B and the corner movements is reasonably constant for all the case histories (i.e. a value of p_1^* = 67% applies), and therefore the percentage reduction is always 33%. Subject to verification with other case histories, this indicates that the ratio of movement occurring at the corner relative to plane strain conditions appears to be relatively independent of the ground conditions. Furthermore, the length of the wall also does not seem to affect this ratio. It also does not appear to be affected whether plane strain movements are reached at the centre section of an excavation. This can be observed in Figure 8. At the south wall, the wall is not long enough to reach a plane strain situation, but the ratio is the same as for other projects (i.e. 67%) with longer sides where plane strain has been reached, (e.g. TNEC). The above is further confirmed in the Immigration Building case history where Lee et al (1998) suggest that plane strain conditions do not apply in this excavation at mid span, but still the method's prediction at section D (Figure 6) is within 85% of the observed measurement in the worst case. In summary, although it is acknowledged that the length of the wall would affect the movements at the 100%A, 100%B and the corners in their total magnitude, it does not seem to affect their ratio.

Horizontal and sub-surface movements

Figure 9b shows the application of the above method to the calculation of horizontal movements in the corners. It can be seen that there is reasonable agreement between calculated and observed displacements. Further work is needed to consider against other case histories to further validate the proposed method for horizontal movements.

Figures 9c and 9d show results where the method was applied to the calculation of sub-surface vertical movements, for values of $p_1 = p_1^{*} = 67\%$ and 50% respectively. Results are shown at the surface (for reference), at 50% of the excavated depth and 100% of the excavated depth (i.e. formation level). Figure 9d showed a better match for points where $d/H > 1.5$, whereas Figure 9c showed a better match for points where $d/H < 1.5$. Further work needs to be completed to verify the method for subsurface displacements.

CONCLUSIONS

A new empirical method is proposed for the calculation of displacements around corners of retained cut excavations. It can be used as a design tool for quick and cost effective preliminary ground movement analysis (useful for instance for scheme or preliminary design). It may also constitute a useful design tool in combination with 2D FE. The latter would, when used properly, give indication of the movements at 100%A and 100%B sections.

The results presented suggest that the reduction of percentage of ground movements follows a linear relationship with the distance from the point of maximum ground movements along each side of the wall. It is also shown that this percentage reduction in ratio seems to be approximately 33% (100% - 67%) independently of factors such as; different ground conditions, support arrangements, construction sequences and retained heights, as covered on the verification processes.

This gives confidence in the extrapolation of the method to other sites, especially in clay soils. However, it should be used with care for different soil conditions and construction methods than the case studies used for comparison. The method also allows for acute and obtuse corners (no re-entrant, $\varnothing$>180°) effects to be calculated. A verification of the method for an acute corner angle has also been undertaken as part of this work, and the results showed good agreement.

It provides a simple way to calculate movements at any location by using only two ground movement profiles behind the retaining walls and their position. Furthermore, it has shown for one example that it also makes good predictions for horizontal and subsurface ground movements, although the authors are aware that it requires further calibration before more confident conclusions can be reached.

This method can be carried out using hand calculations, and it is also easy to include in software or program into spreadsheets.

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NOTATION (Please refer to Figures 3)

- Φ - angle that the corner forms inside the excavation.
- d_A and d_B - distance from the corner to the centre point of the wall in plan, or the distance to where plane strain movements start to occur, whichever is the lesser, at both sides of the corners A and B respectively.
- 100%A and 100%B – plane strain or maximum ground movements perpendicular and behind walls A and B respectively.
- p_1 - percentage (%) of the ground movements of d_A and d_B, in a section that passes through the corner and is perpendicular to the wall.
- p_1^* - calibrated value of p_1 for given ground conditions for corners that form a 90° angle.
- p_2 - percentage of 100%A and 100%B in a section that bisects the excavation at the given corner (i.e. divides it into two equal angles of values of θ/2, see Figure 3, where $\theta = 180 - \phi$).
- p_2^* – calibrated value of p_2 for a given ground conditions for corners that form a 90° angle.

Table 1
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Table 1. Summary of case histories

Project title	Reference	Predominant ground conditions (retained side)	Excavation depth (m)	Corner angle	Construction method	Wall type	Propping system	Data used	
								FE	Field measurements
New Palace Yard Car Park (NPYCP)	Burland and Hancock (1977)	London Clay	18.5	90°	Top down	D-wall	Permanent slabs	×	✓
Moorhouse (MOOR)	Zdravkovic et al (2005)	London Clay	40	90°	Bottom up	N/A	Multi-prop (7no prop levels)	✓	×
Immigration Building (IMM)	Lee et al (1998)	Marine Clay (soft, high plasticity)	17.3	90°	Bottom up	D-wall	Multiple level props	×	✓
Taipei National	Ou et al (2000)	Silty Clay (low plasticity and	19.7	90°	Top down	D-wall	Permanent slabs	×	✓

Enterprise Centre, (TNEC)		lightly overconsolidated)							
60 Victoria Embankment (60 VIC)	St John et al (1993)	Alluvium and London Clay	19	90°	Top down	Secant pile wall	Permanent slabs	×	✓
Basement 1 (BAS 1)	Arup FE LSDYNA results	London Clay	14.26	90°	Top-down	Secant pile wall	Horizontal temporary props in diagonal arrangement	✓	×
Basement 2 (BAS 2)	Arup FE LSDYNA results	London Clay	15	75°	Bottom up	Secant pile wall	Multi-level temporary corner props and horizontal prop	✓	×

Table 2
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Table 2. Plots and equations to be used for the different zones.

PLOT	INPUT	Zones I and V	Zones II and IV	Zone III
1	p_1^* and $\varnothing$	×	✓	✓
2	p_1^* and p_2^*	×	✓	✓
3	p_1^*, p_2^*, α and β	×	×	✓
Equations		$p = \%A$ OR $p = \%B$	$p = p_1 + (100 - p_1)\frac{d_a}{d_A}\%A$ OR $p = p_1 + (100 - p_1)\frac{d_b}{d_B}\%B$	$p = p_a \times \%A + p_b \times \%B$

d_a and d_b are the distances from the point where the ground movements want to be calculated to the position of d_A and d_B (see Figure 3). %A and %B represent the 100%A and 100%B sections.

Table 3
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Table 3. Verification process for each case history

Project	Verification process
New Palace Yard Car Park (see Figure 2)	The data was extracted from the observed ground movements contours. The values d_A and d_B were assessed from the contours. Using the given ground movements behind the centre of the excavation, the contours were reproduced to match the original. Good agreement was found.
Moorhouse (see Figure 5)	The reference gave movements at the centre of the excavation and at the corner. The movements at the centre points were used to calculate the corner movements and compared to those predicted by the FE calculations. Good agreement was found generally.
Immigration Building (see Figure 6)	Same process as followed in Moorhouse. Good agreement was found.
Taipei National Enterprise Centre – TNEC (see Figure 7)	The reference paper gave results of observed ground movements at various sections located every 6m far from the corner in one side of the wall. d_A was chosen to be 34.4m, and therefore it was assumed that plane strain movements had been reached at that distance. The different ground movements at different sections were calculated using the 30m section as input since it showed very similar movements in the corner to 34.4 and it was readily available. Good agreement was found.
60 Victoria Embankment (see Figure 8)	Data was extracted from the given ground movements contours at the centre of both sides of the wall forming the north-west corner. Using this input parameter the corner movements were calculated by comparing them to the extracted FE predicted ground movements.
Basement 1 (see Figure 9b)	Same process as followed in Moorhouse. For this basement the horizontal movements were also covered at both locations.

	Subsurface movements were also considered. Good agreement was found for vertical, horizontal and subsurface movements.
Basement 2 (see Figure 10)	Same process as followed in Moorhouse. This also includes a comparison between FE predicted ground movements at the section that bisects the excavation corner and the predictions from the method. Good agreement was found.

Figure
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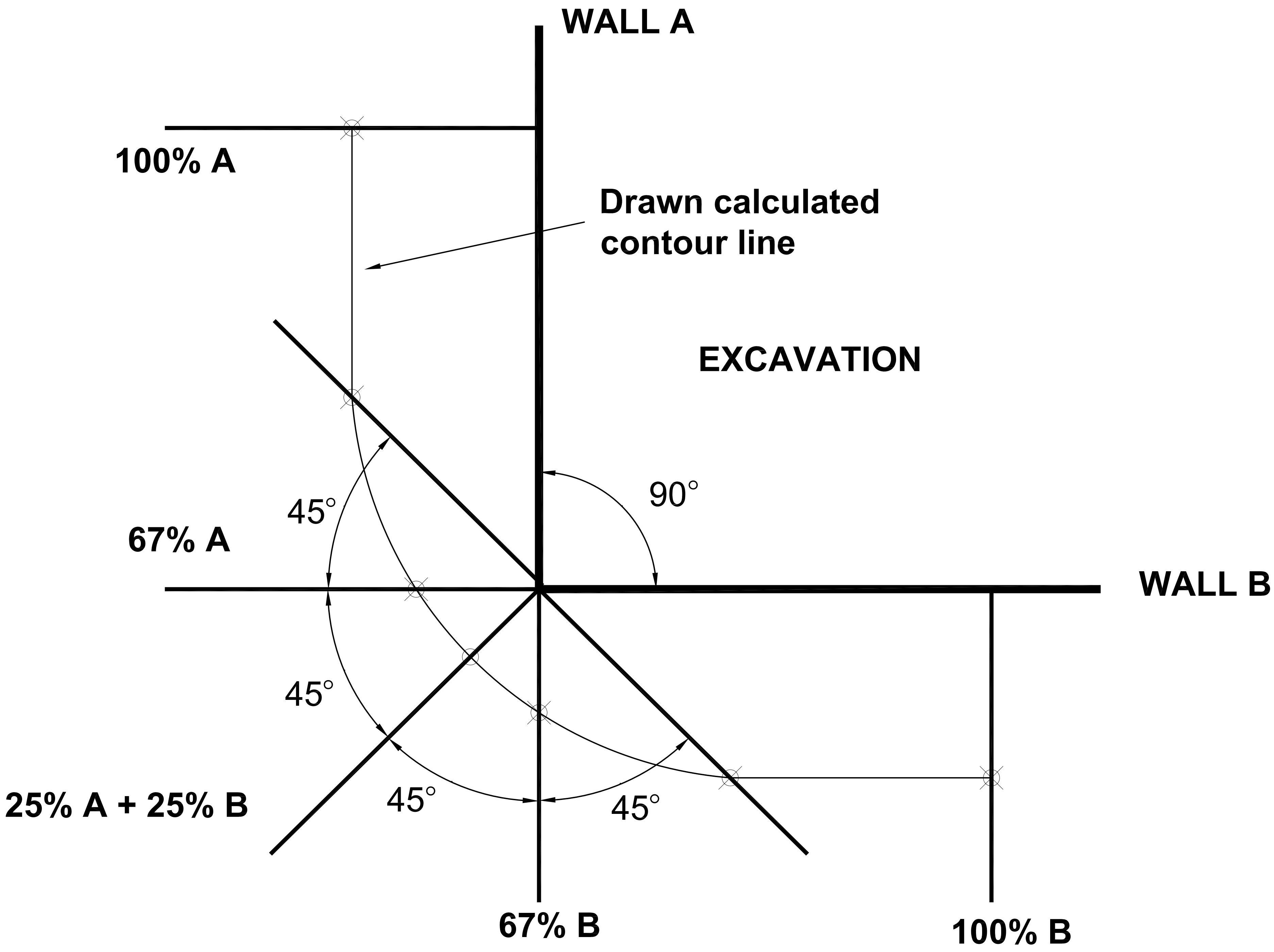

Figure 2a

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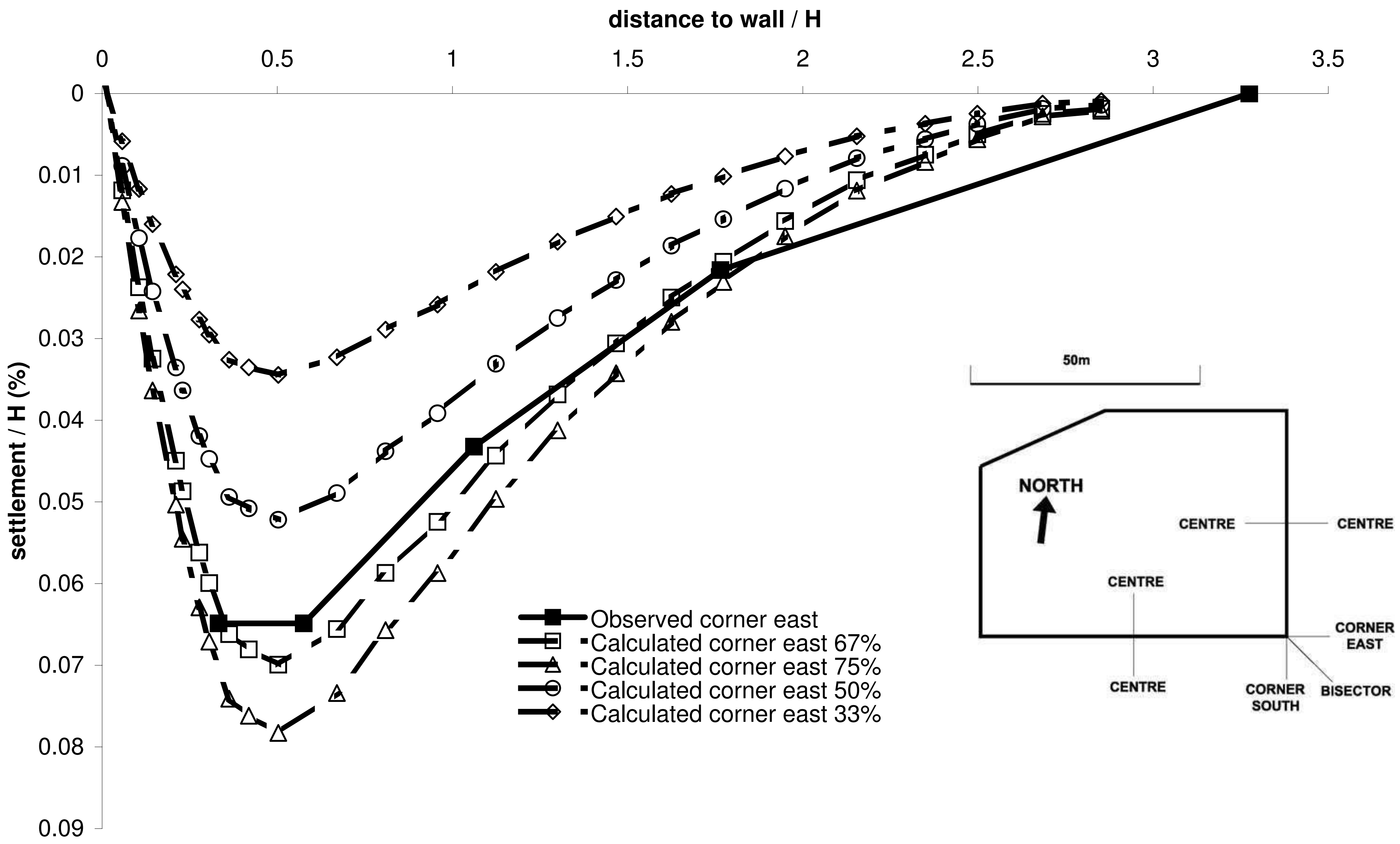

Figure 2b
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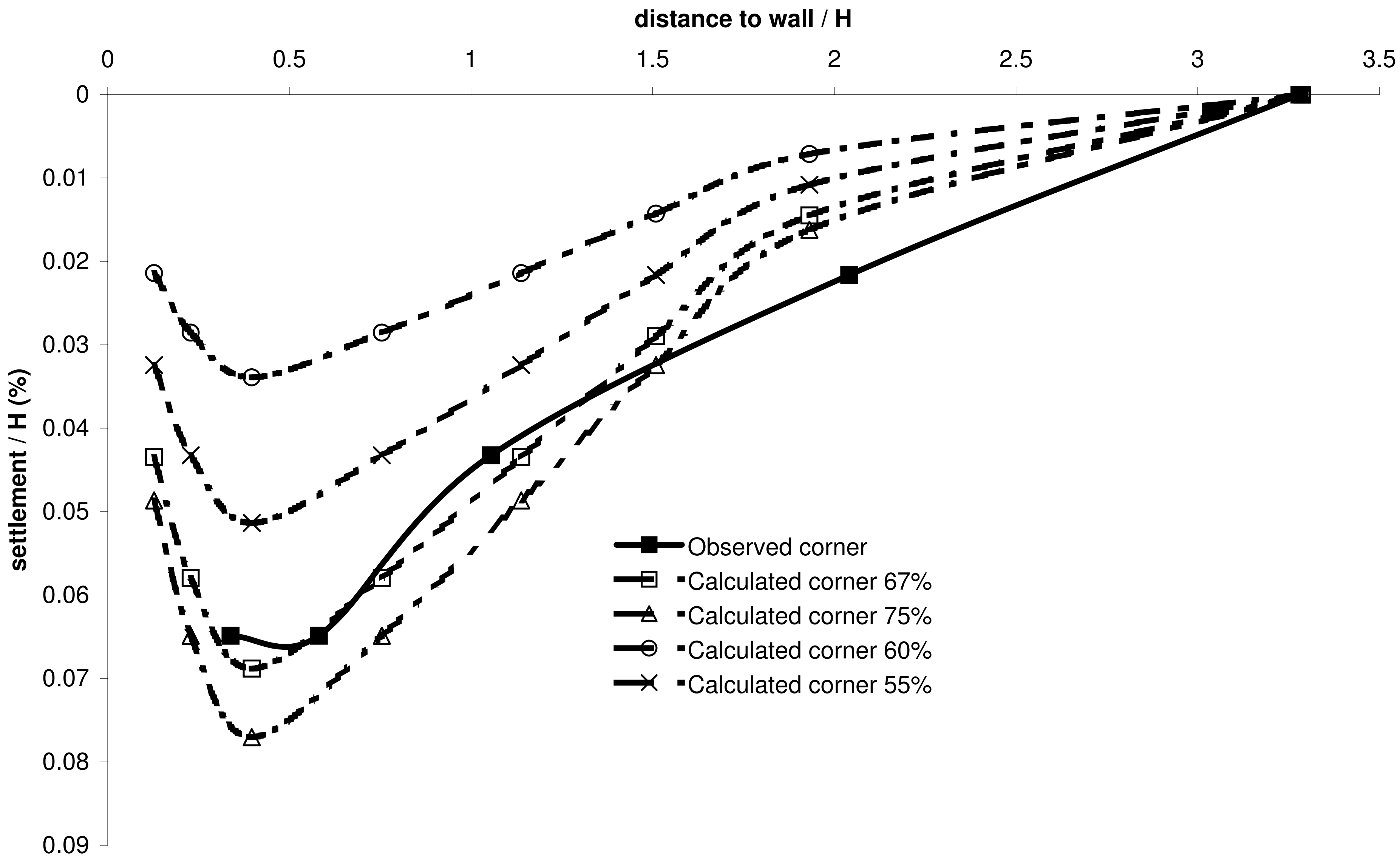

Figure 2c

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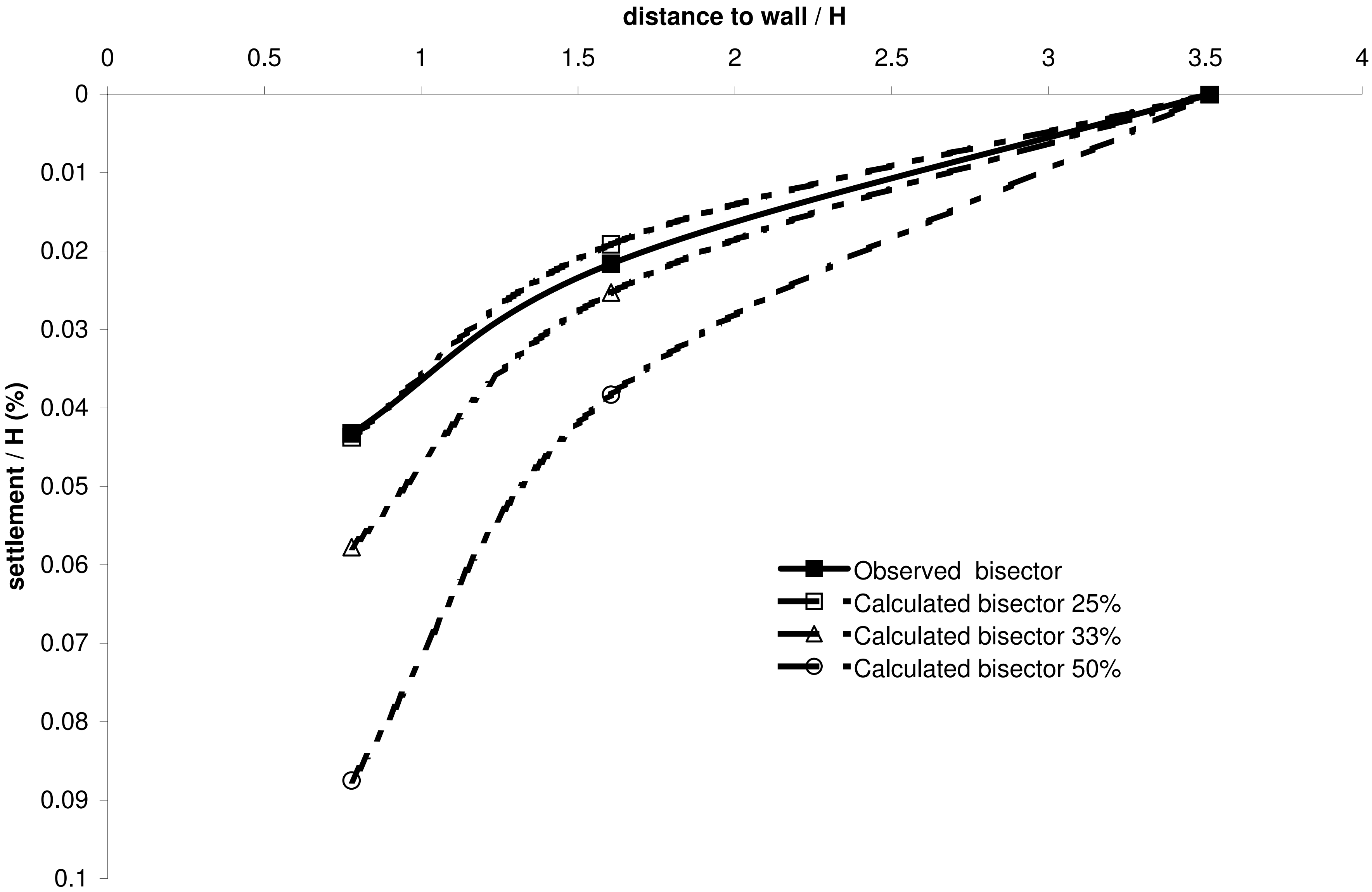

Figure 3
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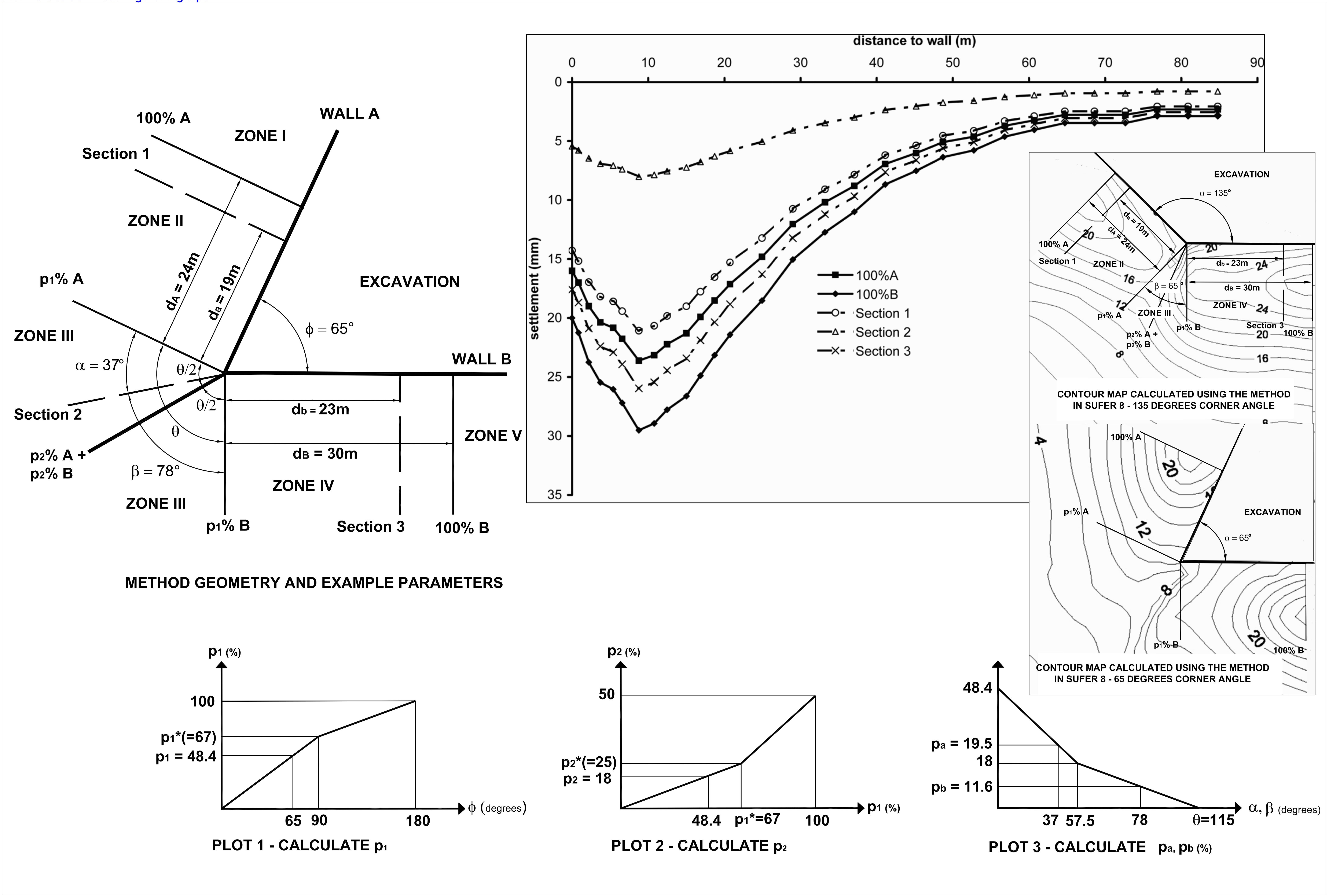

Figure 4a
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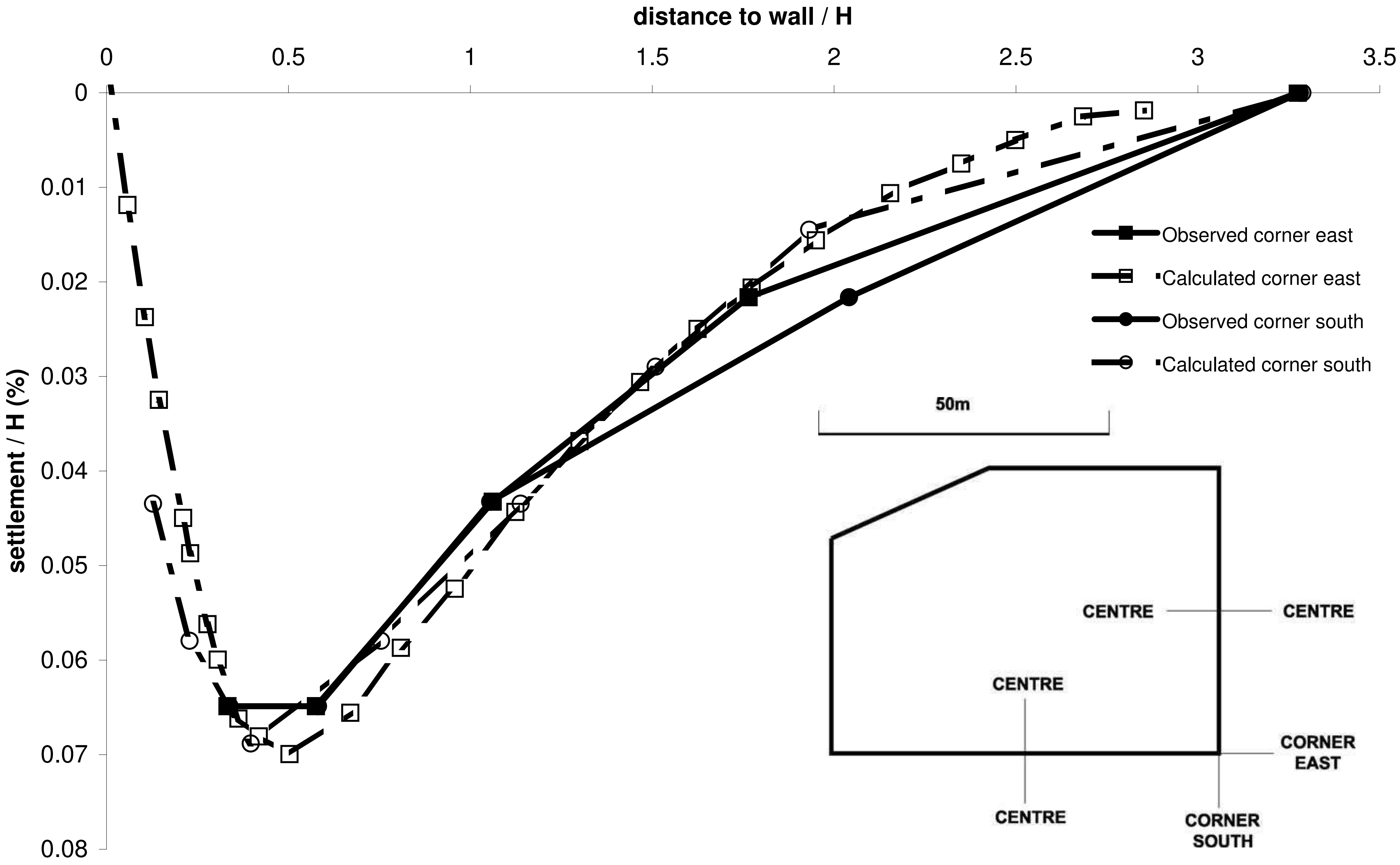

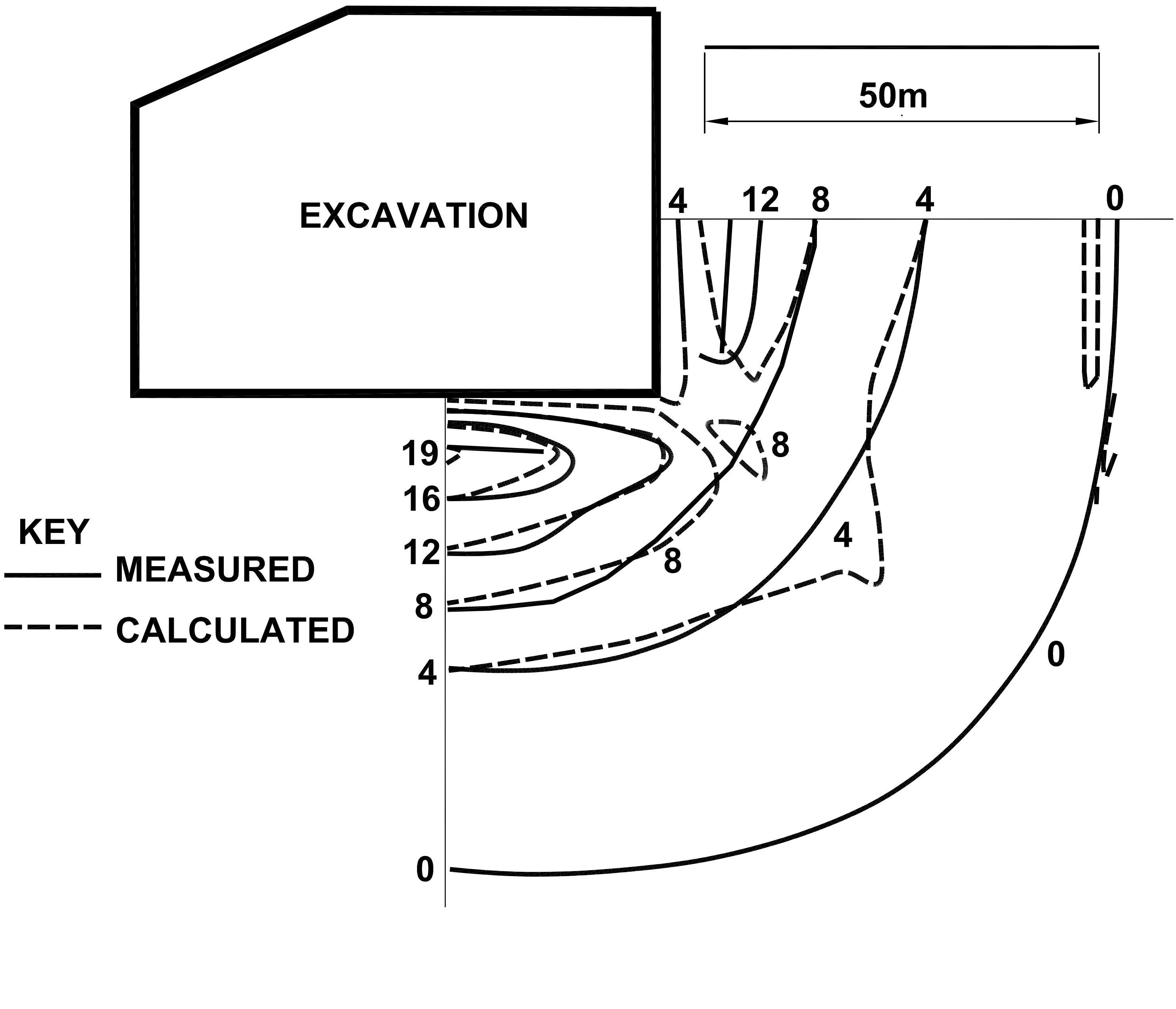
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12
8
4
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19
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12
8
4
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8
8
4
0
KEY
MEASURED
CALCULATED

Figure 5
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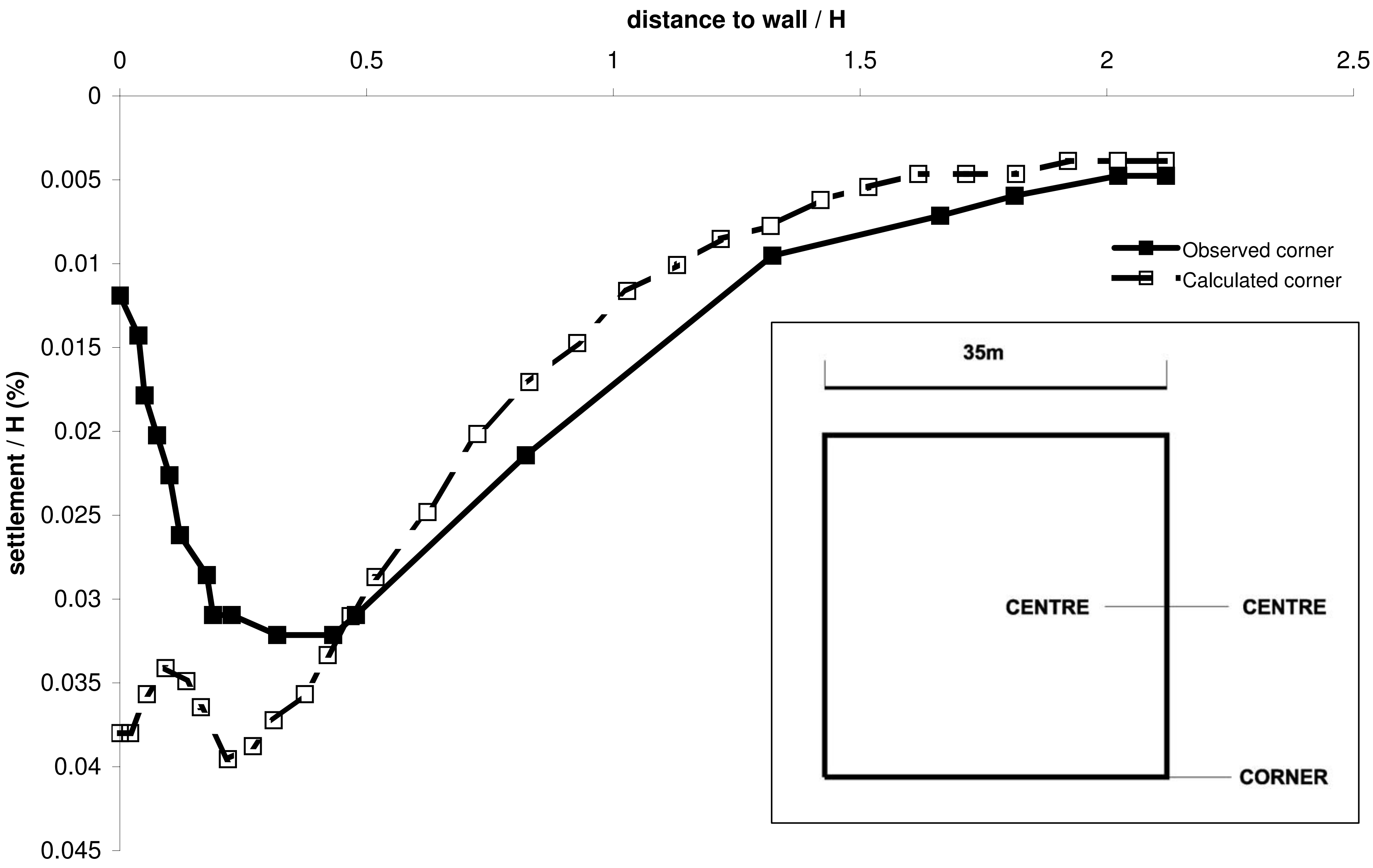

Figure 6

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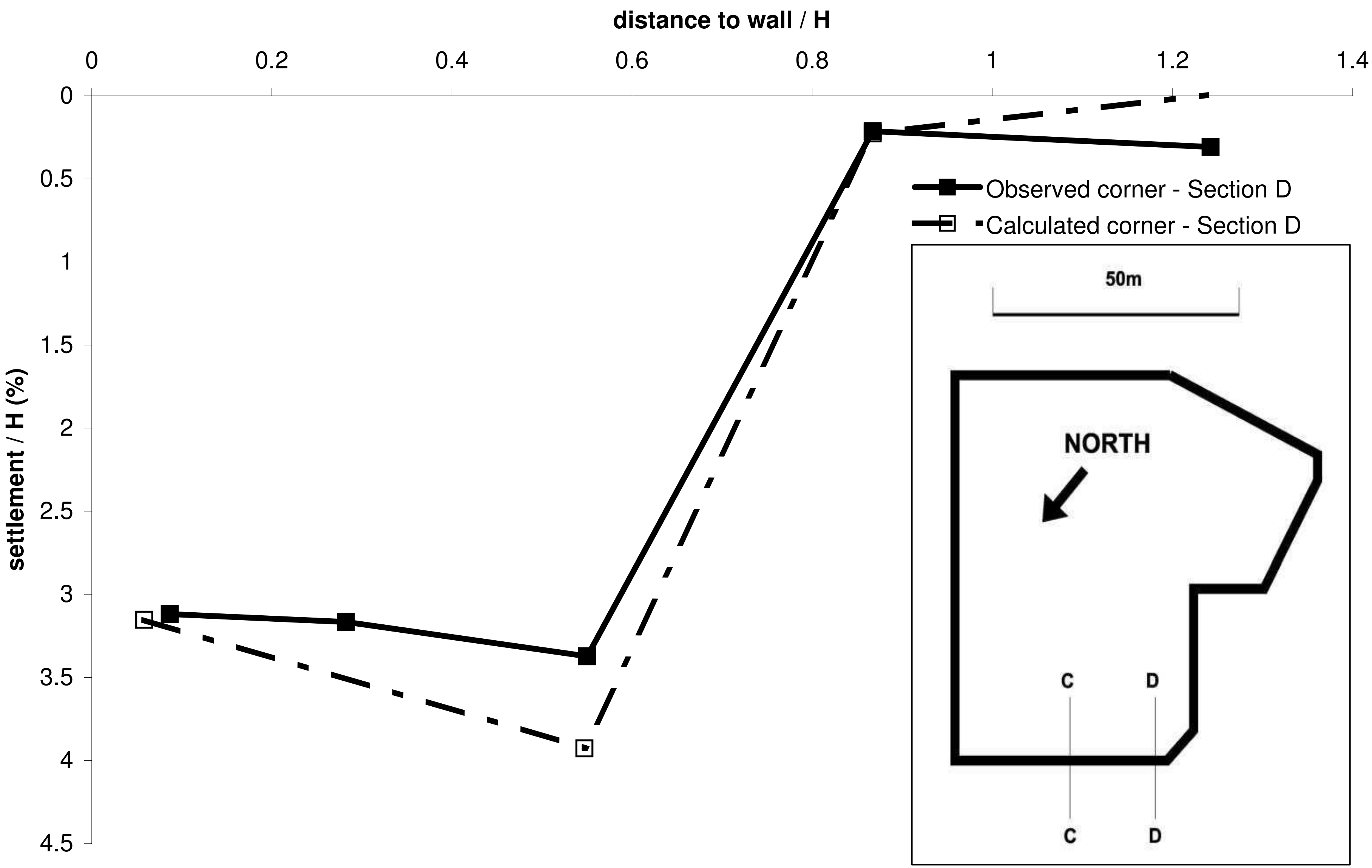

Figure 7
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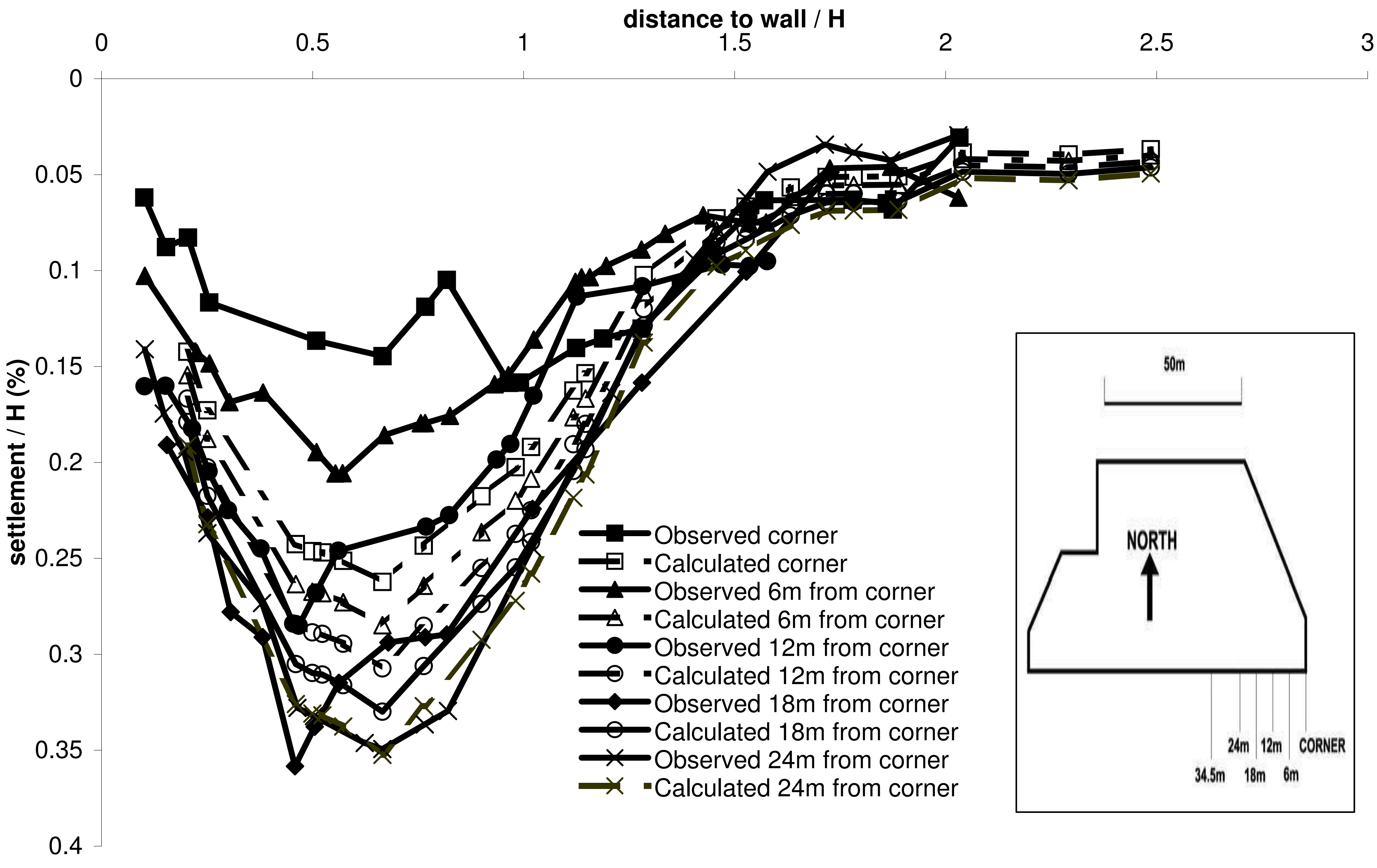

Figure 8
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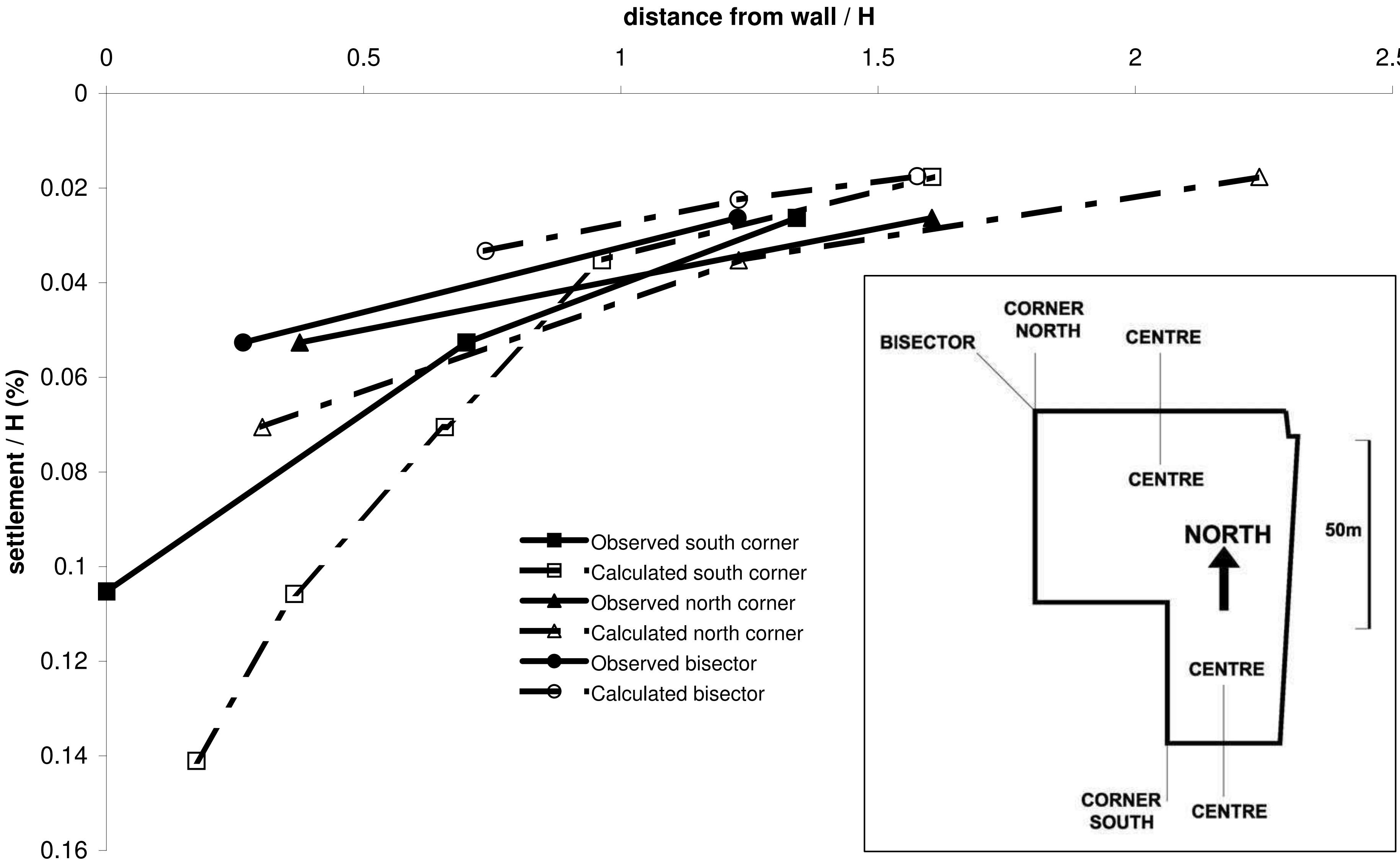

Figure 9a
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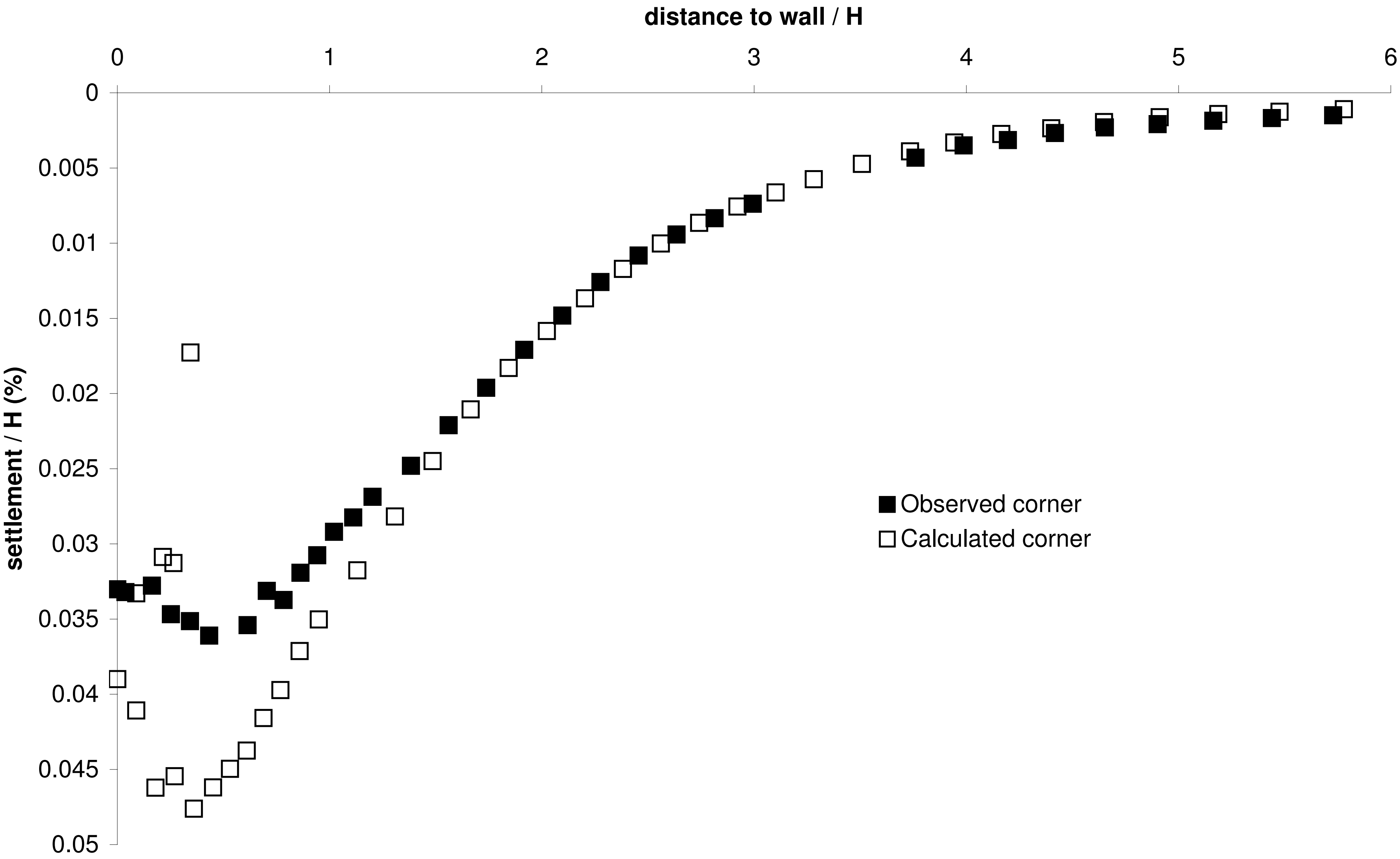

Figure 9b

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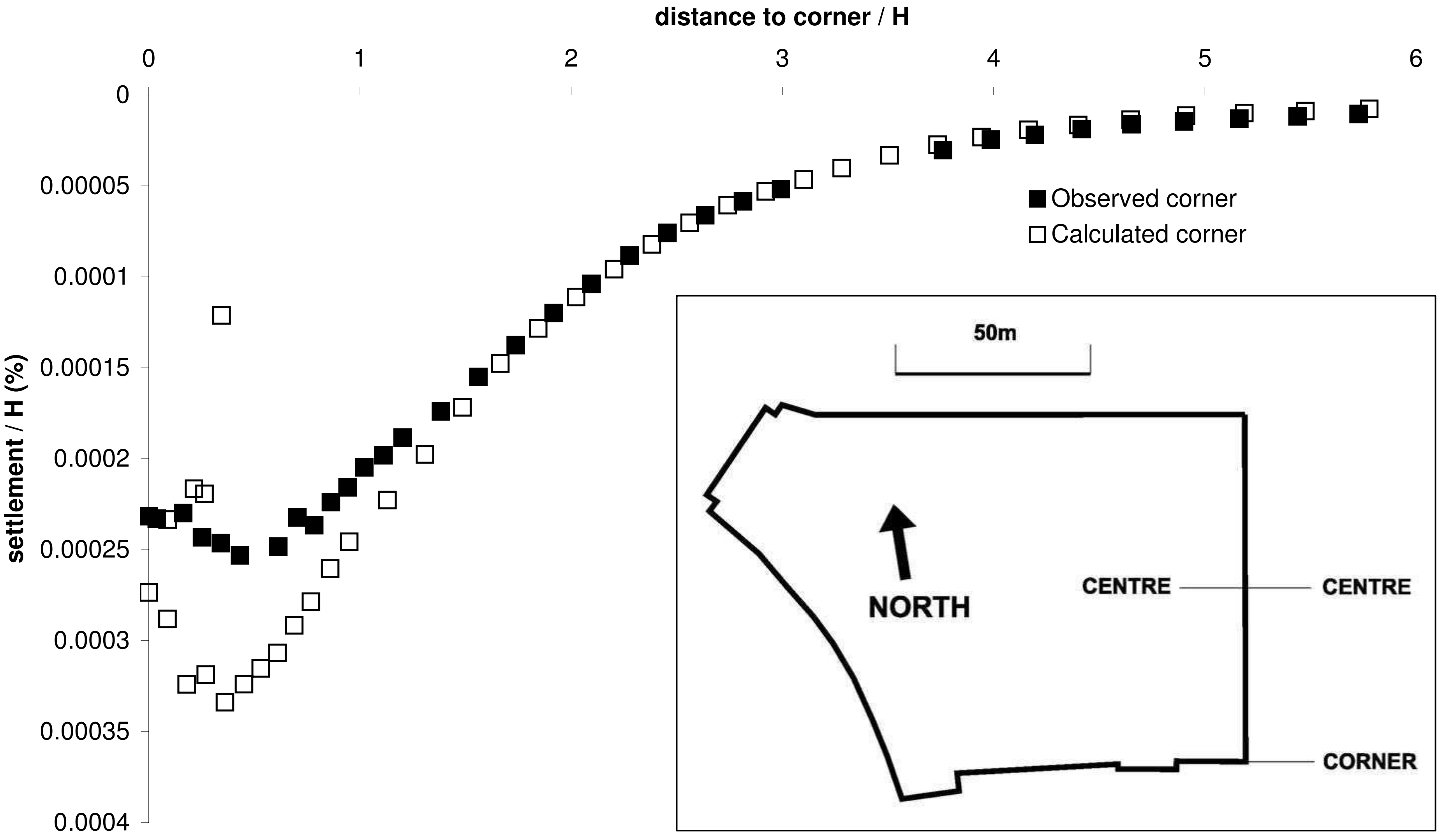

Figure 9c
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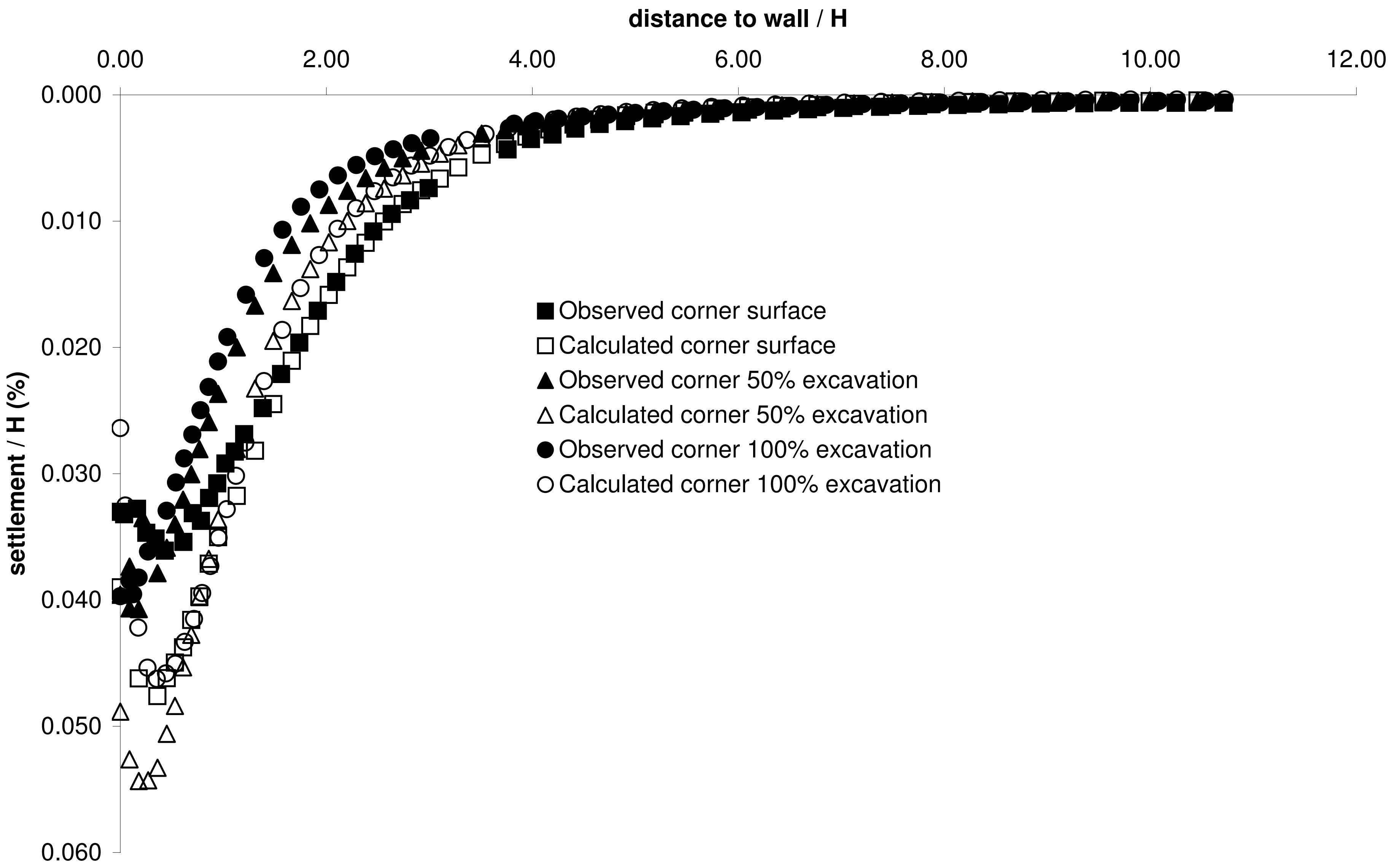

Figure 9d

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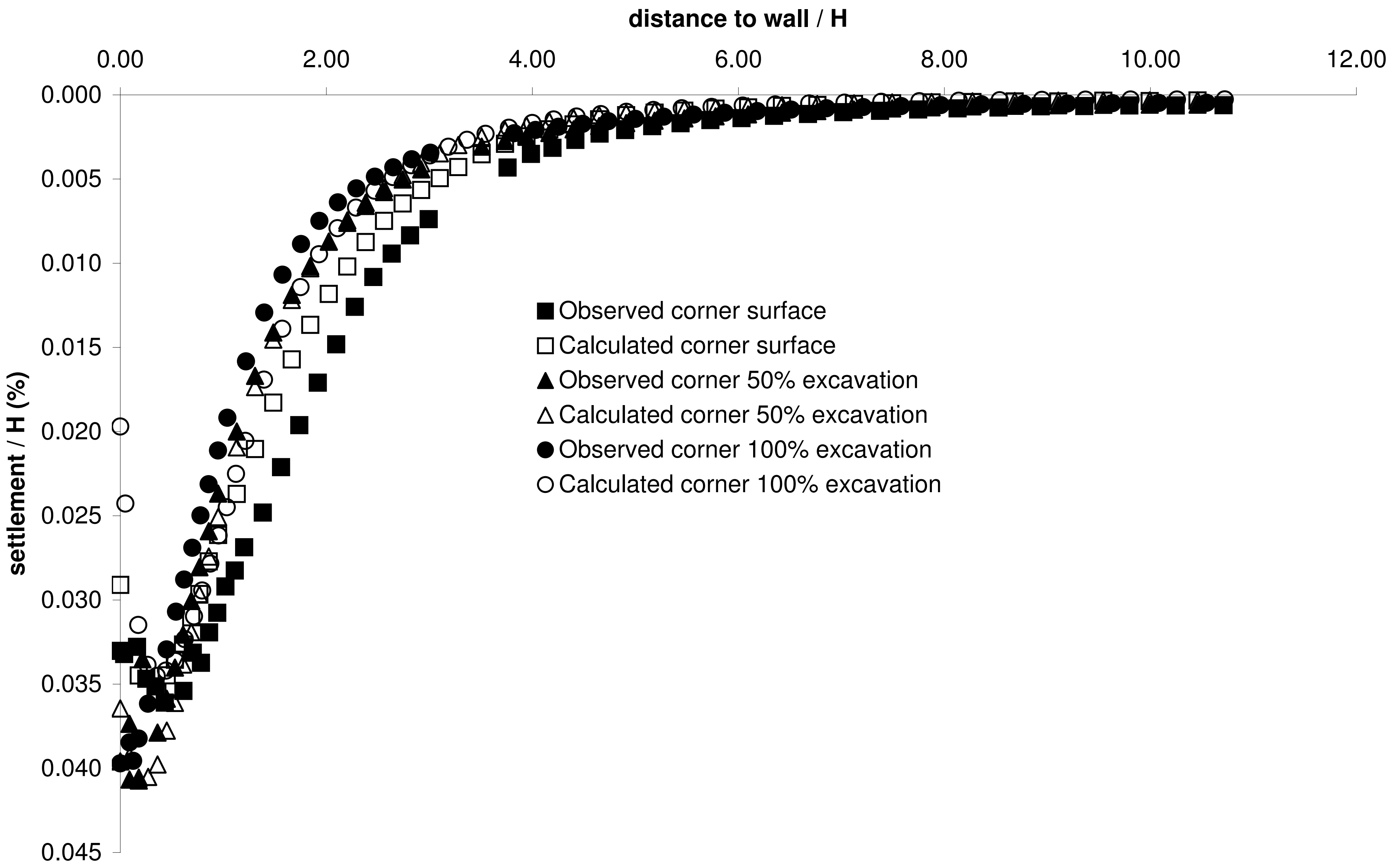

Figure 10
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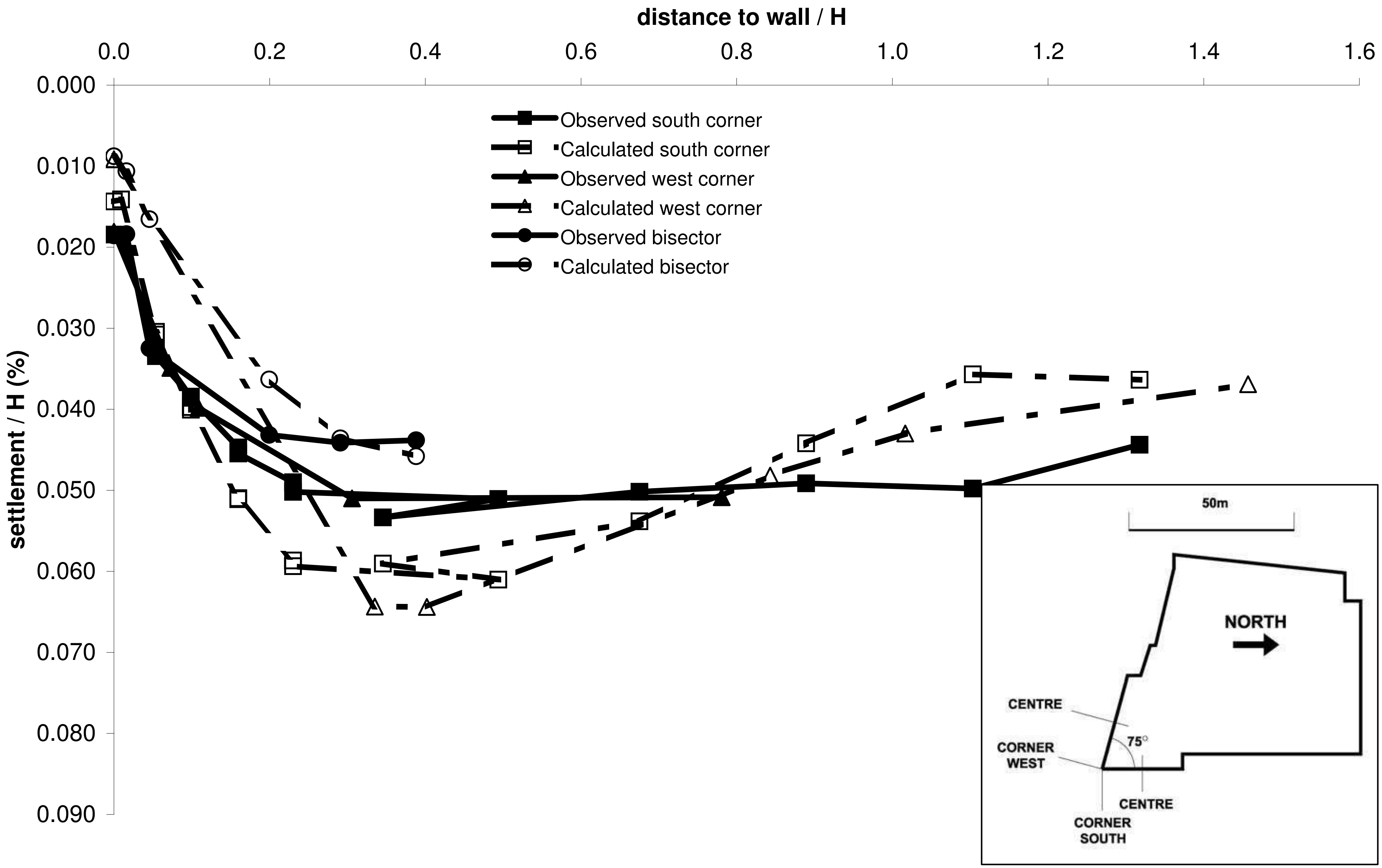

LIST OF FIGURES