



Title	The Effect of Uncertainty on the Prediction of Building Damage Due to Tunnelling-Induced Settlement
Authors(s)	Clarke, Julie, Moradabadi, Ehsan, Laefer, Debra F.
Publication date	2015-09-17
Publication information	Clarke, Julie, Ehsan Moradabadi, and Debra F. Laefer. "The Effect of Uncertainty on the Prediction of Building Damage Due to Tunnelling-Induced Settlement," September 17, 2015. https://doi.org/10.1201/b16058-74 .
Conference details	XVI ECSMGE 2015, Edinburgh, UK, 13 - 17 September 2015
Item record/more information	http://hdl.handle.net/10197/7335
Publisher's version (DOI)	10.1201/b16058-74

Downloaded 2026-05-01 23:48:07

The UCD community has made this article openly available. Please share how this access benefits you. Your story matters! (@ucd_oa)



© Some rights reserved. For more information

The effect of uncertainty on the prediction of building damage due to tunnelling-induced settlement.

L'effet de l'incertitude sur la prévision de dommages aux bâtiments causée par la subsidence induite par effet tunneling.

J. A. Clarke*, E. Moradabadi, and D.F. Laefer

School of Civil, Structural and Environmental Engineering, University College Dublin, Ireland.

* Corresponding Author

ABSTRACT Prediction of the response of buildings to tunnelling-induced settlement for the extent of a tunnel route is a complex task due to the heterogeneous nature of ground conditions, variable tunnelling operations, and unknown building parameters. Consequently, there are generally uncertainties associated with building damage predictions. This paper presents a probabilistic numerical methodology to investigate the effect of uncertainties for the damage prediction of masonry buildings due to tunnelling-induced settlement. The methodology is employed to provide a Class C1 prediction for a previously documented case history. The results demonstrate the uncertainties that have a significant influence in terms of the building response prediction and, furthermore, provide a quantitative risk assessment for masonry buildings due to nearby tunnelling.

RÉSUMÉ Prédiction de la réponse des bâtiments à la subsidence induite tunnel pour l'étendue d'un tronçon de tunnel est une tâche complexe en raison de la nature hétérogène des conditions du sol, les opérations de tunneling variables et les paramètres de construction inconnus. Par conséquent, il est généralement d'incertitude associé à des dommages de bâtiments prédictions. Cet article présente une méthodologie numérique probabiliste pour étudier l'effet des incertitudes pour la prédiction de l'endommagement des bâtiments de maçonnerie en raison de la subsidence induit tunnel. La méthodologie est utilisée pour fournir une prédiction de classe C1 pour une histoire de cas précédemment documenté. Les résultats démontrent les incertitudes qui ont une influence significative en termes de prédication de réponse de la construction et, plus-plus, fournir une évaluation quantitative des risques pour les bâtiments de maçonnerie en raison de proximité tunneling

1 INTRODUCTION

Tunnelling through soft ground generates surface settlement, which may damage existing buildings. Load-bearing masonry buildings are particularly vulnerable to settlement-induced cracking damage due to the low tensile capacity of these structures. To avoid building damage and, consequently, to minimise project losses, an accurate risk assessment is required for surface structures due to nearby tunnel excavation.

Numerical methods may be employed to predict building response to tunnelling-induced settlement and these methods have distinct advantages over alternative empirical and analytical methods (e.g. Burland & Wroth 1974), especially if the ground and building are considered simultaneously in a 'coupled' model to simulate the important soil-structure interaction effects (Potts & Addenbrooke 1997). However, there may be uncertainties associated with the choice of model input parameters due to the heterogeneous nature of ground conditions and

variations in workmanship during tunnelling. In addition, building material properties are generally not known with certainty, particularly for historic structures.

To provide a reliable risk assessment for buildings due to tunnelling-induced settlement, the effect of uncertainty must be examined. To do so, a probabilistic numerical analysis is conducted in this paper to provide a Class C1 risk assessment (Lambe 1973) for a previously documented case history, for which the results were known. The case history is documented by Withers (2001a) and describes the response of a group of three masonry buildings to tunnelling-induced settlement. The probabilistic numerical analysis considers the associated uncertainties and is used to quantify the impact in terms of the predicted building damage due to tunnelling-induced settlement. The analysis is focused upon short-term ground settlement following tunnel excavation and is limited to the consideration of load-bearing masonry buildings on shallow foundations.

2 BACKGROUND

The shape of a surface settlement trough due to tunnelling has been shown to be accurately represented by an inverted Gaussian curve in the transverse direction to the tunnel axis (Peck 1969). To predict the damage response of surface buildings, Burland & Wroth (1974) outlined an analytical method, in which the surface structure was idealised as an elastic beam and the surface settlements were imposed onto the beam to determine the maximum building tensile strain value. For the classification of visible building damage due to settlement-induced deformation, Burland et al. (1977) proposed a categorisation according to crack width and ease of repair, as outlined in Table 1.

Table 1. Classification of visible building damage (Burland et al. 1977)

Degree of damage	Approximate crack width (mm)
Negligible	<0.1
Very Slight	0.1-1
Slight	1-5
Moderate	5-15 or a number of cracks greater than 3.
Severe	15 – 25 but also depends on number of cracks.
Very Severe	Greater than 25 but depends on number of cracks.

More recently, numerical methods have been employed to simulate the soil-structure interaction effects that occur during tunnelling in the vicinity of surface structures, resulting in a modified surface settlement trough in comparison to a greenfield site (an area that is free from structures) (Frischmann et al., 1994) and relative movement at the soil-structure interface (Farrell, 2010). For example, Potts & Addenbrooke (1997) demonstrated according to a parametric study, for which a coupled numerical model was employed, that the surface settlement modification was dependant on the relative building stiffness. Boonpichtvong & Rots (2002) applied fracture mechanics to accurately simulate the brittle response of masonry buildings to settlement-induced deformation. Furthermore, Franzius et al. (2006) implemented a contact region at the soil-structure interface to provide an accurate representation of the strain transmission to surface structures during tunnelling.

In terms of the uncertainties associated with the prediction of building response to tunnelling, Schweiger et al. (2007) demonstrated that the stiffness of the soil stratum in which the tunnel was excavated impacted the magnitude of surface settlements. Mollon et al. (2013) highlighted the impact of machinery operations on the extent of ground loss during shield tunnelling. Furthermore, Son (2003) demonstrated that the mechanical tensile strength of the building masonry significantly impacted the onset of settlement-induced cracking damage.

For a reliable risk assessment of existing buildings along the proposed route of a tunnel, it is important to

consider the effect of uncertainties. To do so, a probabilistic methodology is adopted in this paper.

3 METHODOLOGY

To consider the effect of uncertainties associated with building response due to tunnelling, a probabilistic numerical analysis was conducted. The numerical model was generated using ANSYS Mechanical finite element (FE) software and considered the ground and surface buildings simultaneously in a coupled model. To conduct the probabilistic analysis, a Monte Carlo simulation method with Latin Hypercube sampling was employed (see Ang & Tang 2006). The methodology was applied to provide a risk assessment for a documented case history, as described by Withers (2001a), which consisted of a group of three masonry buildings that underwent settlement-induced deformation due to nearby tunnel excavation. The uncertainties considered in the analysis related to the volume loss during tunnelling, as well as properties of the surface buildings. The objective was to investigate the influence of the uncertainties in terms of the building damage classifications and to provide a quantitative risk assessment for the buildings due to tunnelling-induced settlement.

3.1 Moodkee Street Case History

The case history described by Withers (2001a) consisted of a group of three buildings, Neptune, Murdoch and Clegg Houses located on Moodkee Street in London, UK, which underwent deformation as a result of nearby tunnelling as part of the Jubilee Line Extension. Two parallel tunnels, each 5m in diameter, were excavated at a depth of 17m below the ground surface using an Earth Pressure Balance Machine (EPBM). In this paper, the effect of the first tunnel excavated in the vicinity of buildings, the westbound tunnel, was examined (see Figure 2). The buildings consisted of load-bearing brickwork and were founded on strip footings.

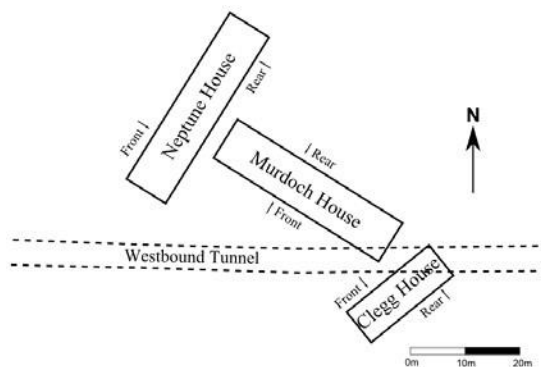


Figure 2. Plan view showing Moodkee Street case history

Ground conditions in the vicinity of the buildings were described by Withers (2001b) and consisted of Made Ground, overlying Terrace Gravels, which were overlying Lambeth Group soils, in which the tunnels were excavated. These soil stratum were underlain by Thanet Sands, and dewatering of the soils prior to tunnel excavation was reported.

Several nearby greenfield sites to the Moodkee Street Houses are described by Withers (2001b), for which surface monitoring due to tunnelling was conducted. The monitored readings at these sites provided values of volume loss (V_i) and trough width parameter (K) for the westbound (W) and eastbound (E) tunnel respectively, as outlined in Table 2.

Table 2. Values of V_i and K for nearby greenfield sites (Withers 2001b)

Site	V_i (%)		K	
	W	E	W	E
Old Jamaica Road	0.5	0.71	0.5	0.5
Southwark Park	0.39	0.45	0.45	0.46
Niagara Court	0.62	0.53	0.55	0.53

3.2 Parametric Model

A coupled FE model was generated using ANSYS commercial software version 14.5, as outlined in Figure 3. The model consisted of a 3D soil mass and the three masonry buildings at ground surface. Soil behaviour was modelled according to a linear-elastic, perfectly plastic material model and the excavation of

a 5m diameter tunnel was simulated at a depth of 17m below ground level.

The building displacements examined (as reported by Withers 2001a) were measured following the completion of tunnel excavation beneath the buildings. Therefore, the developing settlement trough in the longitudinal direction to the tunnel axis was neglected and tunnel excavation was simulated according to a plane strain assumption (e.g. as a single excavated volume in the longitudinal direction).

The ground was represented according to four distinct soil strata to represent the ground conditions in the vicinity of the Moodkee Street Houses and the effective stress properties outlined in Table 3 were adopted, based on Kovacevic et al. (2001).

Table 3. Geotechnical soil properties (Kovacevic et al. 2001)

Soil Type	E' MPa	ν'	γ kN/m ³	ϕ' °	c' kPa	ψ °
Made Ground	20	0.2	18	25	0	0
Terrace Gravels	60	0.2	20	38	0	0
Lambeth Group	100	0.3	22	30	15	0
Thanet Sands	<u>200</u>	<u>0.3</u>	<u>22</u>	<u>38</u>	<u>0</u>	<u>0</u>

The Moodkee Street Houses were modelled according to the external solid masonry walls at the ground surface with openings to represent the location of doors and windows. The walls were fixed in the horizontal direction at the roof level and at assumed floor levels. To represent the masonry material, a macro-modelling approach was adopted, in which the masonry was idealised as a continuum and homogenised mechanical properties were applied (see Lourenço 1996). The onset of cracking was simulated according to the William-Warke failure criterion using a smeared crack model.

At the region between the soil and the overlying buildings, a contact interface was implemented. The material behaviour of the interface was defined according to a Coulomb friction yield criterion. Gravitational loading vertical building loads were applied to the model in the initial load step to establish the initial stress state. Tunnel excavation was

simulated in the subsequent load step according to the ‘volume loss control’ method (Potts & Zdravković 2001), whereby the forces acting along the tunnel boundary were reduced incrementally until a prescribed volume loss was achieved.

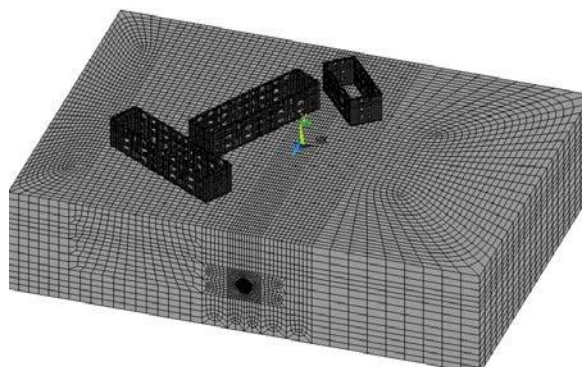


Figure 3. Coupled FE model to represent Moodkee Street case history

3.3 Probabilistic Analysis

To conduct the probabilistic numerical analysis, a Monte Carlo simulation (MCS) method was performed using the Probabilistic Design System in ANSYS software (ANSYS 2012). MCS is a sampling-based procedure that develops a mapping from analysis inputs to analysis outputs. The method requires significant computational resources since a large number of simulation loops are generally required (Rubinstein 1981). Therefore, to reduce the number of sampling loops required, Latin Hypercube sampling (LHS) was employed, which ensures that the random variables are each sampled across their entire range (McKay et al. 1979). For the probabilistic numerical analysis, 100 MCS simulation loops were performed.

To consider the associated uncertainties for the prediction of building response to tunnelling-induced settlement, several model parameters were defined as random input variables in the analysis. The volume loss due to tunnelling was considered as an uncertainty, since this parameter has been shown to vary depending on local ground conditions, as well as tunnelling operations (Leca & New 2007). A uniform range varying between 0.2% and 0.8% was considered

for the volume loss based on Table 2 and values commonly encountered during shield tunnelling (Mair and Taylor 1997). Figure 4 illustrates the predicted greenfield surface settlement trough for a volume loss (V_1) equal to 0.8%. The calculated trough width parameter (K) corresponded to approximately 0.55, which was assumed to be appropriate for the soil conditions in the vicinity of the Moodkee Street Houses (O'Reilly and New 1982).

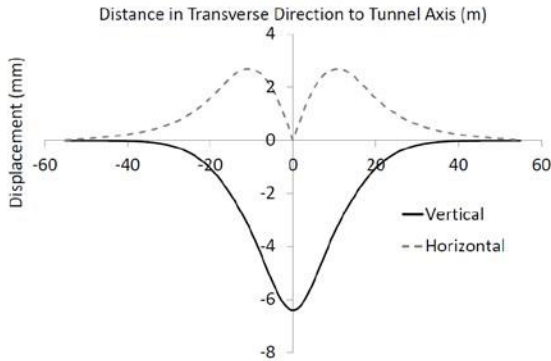


Figure 4. Numerically predicted greenfield surface settlement trough ($V_1 = 0.8\%$, $K = 0.55$)

The uncertainty relating to the properties of the masonry buildings was also considered in the analysis since the masonry mechanical properties were unknown for the Moodkee Street Houses and details of the building foundations were uncertain. The buildings were described by Withers (2001a) as loadbearing brickwork structures that were constructed in the early 20th century. Therefore, a review of the current literature relating to the experimental testing of brickwork samples was conducted to establish parameter ranges for the masonry material (see Table 4). A normal probability distribution function (PDF) was defined for each variable, as commonly adopted for material properties. The exception to this was the masonry tensile strength which was considered to be related to the masonry compressive strength and was assumed to vary uniformly between 2% and 10% of the compressive strength value (Hossain et al. 1997). The frictional coefficient to define the material behaviour at the soil-structure contact interface was also defined as a uniformly varying random input variable based on NCHRP (2010).

Table 4. Random input variables (SD = Standard Deviation, N = Normal, U = Uniform)

Parameter	Mean	SD	Lower	Upper	PDF
Volume Loss, V_1	-	-	0.2	0.8	U
Young's Modulus, E (MPa)	3130	1509	1260	6140	N
Density, ρ (kg/m^3)	2000	100	1630	2200	N
Poisson's Ratio, ν	0.2	0.04	0.13	0.25	N
Comp. Strength, f_c (MPa)	7.4	4.5	1.1	14	N
Tensile Strength, f_t (MPa)	-	-	0.02 f_c	0.1 f_c	U
Frictional Coefficient, μ	-	-	0.3	0.6	U

For each simulation loop in the probabilistic analysis, the maximum building deflection ratio due to tunnelling was recorded for the Moodkee Street Houses, as defined by Burland & Worth (1974). Additionally, the occurrence of cracking damage was recorded. To estimate the crack widths (w_{cr}), the product of the crack strain (ϵ_{cr}) and the characteristic element length (h) was calculated since a smeared crack model was employed in the analysis. In addition, the number of cracking locations was determined, whereby adjacently cracked elements were considered as a single crack location. To categorise the building damage due to tunnelling, a damage classification was conducted according to Burland et al. (1977) (see Table 1).

4 RESULTS

To determine the effect of the uncertainties in terms of the predicted building response due to tunnelling-induced settlement, a sensitivity analysis was performed based on the results of the probabilistic analysis. For each of the random input variables considered, a Partial Rank Correlation Coefficient (PRCC) was calculated, to provide a measure of the influence of the input variable in terms of the predicted model output. A PRCC value may range between -1 and 1 according to the parameter correlation (negative or positive), and the calculated values exclude the influence of the other input variables (see Oberguggenberger et al. 2009).

The calculated values of PRCC for each of the random input variables considered are presented in Figures 6 – 8 for Murdoch House in terms of the maximum building deflection ratio, the maximum

crack width and the number of crack locations due to tunnelling, respectively. The volume loss had a positive correlation approximately equal to 0.5 with the building deflection ratio, which indicated that as the volume loss due to tunnelling increased, the extent of the building deformation also increased. A negative correlation equal to 0.34 was evident in terms of the masonry Young's modulus. This indicated that for higher values of Young's modulus (e.g. increased building stiffness), the building deformation due to tunnelling-induced settlement was less severe. For the remaining random inputs, the correlation was less than 0.1 and, therefore, these parameters did not have a significant influence in terms of the building deformation response to tunnelling-induced settlement.

In terms of the maximum building crack width due to tunnelling, the most significant uncertainty was the Young's modulus of the building masonry, which had a negative correlation equal to 0.54 (see Figure 7). Therefore, the maximum building crack width due to tunnelling decreased with increasing Young's modulus (or building stiffness). None of the other variables had a significant influence in terms of the maximum building crack width.

With respect to the number of crack locations due to tunnelling for Murdoch House, Figure 8 demonstrated that the Young's modulus of the masonry had a positive correlation equal to 0.5. Therefore, the distribution of cracking damage due to tunnelling increased with increasing building stiffness. Additionally, the tensile strength of the masonry had a significant influence in terms of the number of crack locations due to tunnelling and had a negative correlation equal to 0.45. Therefore, as the tensile strength of the masonry increased, the number of building cracks due to tunnelling-induced settlement decreased.

Figure 5 illustrates the results of the probabilistic analysis according to the damage classification (Burland et al. 1977). For each of the Moodkee Street Houses examined, a 'Negligible' damage classification was the most likely outcome due to tunnelling-induced settlement. For Murdoch House, there was a low probability (less than 0.25) that a

damage classification defined as 'Very Slight', 'Slight' or 'Moderate' would be encountered due to tunnelling. For the Neptune House, there was also a low probability that a 'Very Slight' damage classification would be encountered. Meanwhile, for the Clegg House, it was almost certain that a damage classification of 'Negligible' would not be exceeded due to the adjacent tunnelling. The damage probabilities relate to the building positions relative to the tunnel axis and the building geometries (see Figure 2).

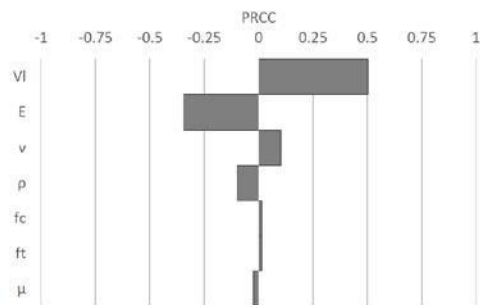


Figure 6. PRCC values in terms of maximum deflection ratio for Murdoch House due to tunnelling

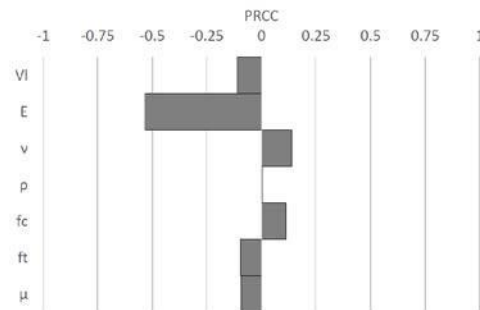


Figure 7. PRCC values in terms of maximum crack width for Murdoch House due to tunnelling

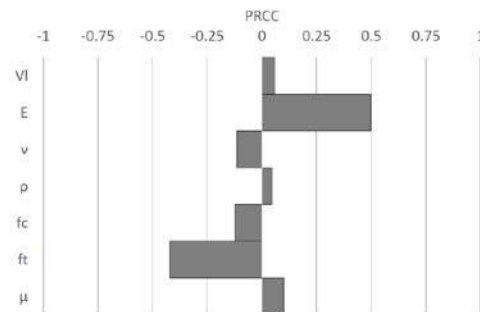


Figure 8. PRCC values in terms of the number of crack locations for Murdoch House due to tunnelling

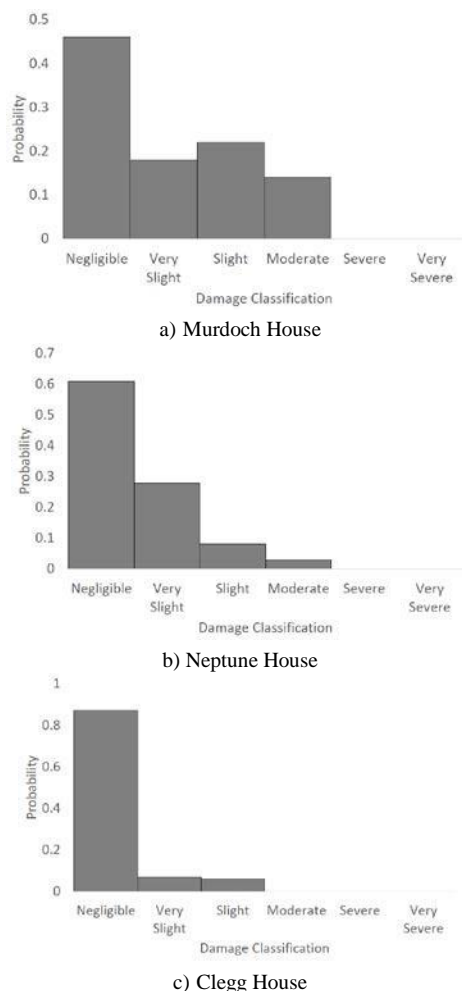


Figure 5. Risk assessment for the Moodkee Street Houses

5 DISCUSSION AND CONCLUSIONS

A probabilistic analysis was conducted for a case history documented by Withers (2001a) and, therefore, provided a quantitative risk assessment for the surface buildings due to tunnelling-induced settlement, which considered the associated uncertainties.

A sensitivity analysis of the results demonstrated that the volume loss during tunnelling and the building stiffness have a significant influence in terms of the building deformation response due to tunnelling-induced settlement. With respect to building cracking due to tunnelling, the Young's modulus and the tensile

strength of the masonry each had a significant influence. Therefore, to provide a reliable risk assessment for masonry buildings due to tunnelling-induced settlement, these uncertainties must be considered.

In terms of the damage classification for the Moodkee Street Houses due to tunnelling, a 'Negligible' classification was predicted as the most probable outcome for each building. Notably, Withers (2001a) reported no settlement-induced building damage following tunnel excavation for the Murdoch, Neptune and Clegg Houses.

ACKNOWLEDGEMENTS

This research was generously supported by the Irish Research Council (IRC) through an Embark Initiative Scholarship and the European Research Council (ERC), through research grant number 307836 (RETURN).

REFERENCES

- Ang, A.H-S. & Tang, W.H., *Probability Concepts in Engineering: Emphasis on Applications to Civil and Environmental Engineering*, Wiley, 2006.
- ANSYS Academic Research Release 14.5. 2012. *Theory Reference for Ansys*.
- Boonpichetvong, M. & Rots, J.G. 2002. Settlement damage of masonry buildings in soft-ground tunnelling. *Finite Elements in Civil Engineering Applications, Proc. of the 3rd DIANA World Conf., Tokyo* (Eds: Hendriks, A.N. & Rots, J.G.) 285-293.
- Burland, J.B. & Wroth, C.P. 1974. Settlement of buildings and associated damage. *Proc. of the 9th Int. Conf. on Soil Mechanics and Foundation Eng., Cambridge*, 611-654. Pentech Press, London.
- Burland, J.B., Broms, B.B. & de Mello, V.F.B. 1977. Behaviour of foundation and structures. State of the Art Review, *Proc. of the 9th Int. Conf. on Soil Mechanics and Foundation Engineering, Tokyo*, Vol. 2, 495-546. Balkema.
- Farell, R. P., 2010. Tunnelling in sands and the response of buildings. *PhD Thesis*, University of Cambridge.
- Franzius, J.N. Potts, D.M. & Burland, J.B. 2006. The response of surface structures to tunnel construction, *Proc. of the Institution of Civil Engineers, Geotechnical Engineering* **159**, 3-17.
- Frischmann, W.W, Hellings, J.E., Gittoes, G. & Snowden, C. 1994. Protection of the Mansion House against damage caused by ground movements due to the Docklands Light Railway extension, *Proc. of the Institution of Civil Engineers, Geotechnical Engineering* **107**, 65-76.

- Hossain, M.M, Ali, S.S. & Rahman, M.A. 1997. Properties of masonry constituents, *Journal of Civil Engineering, The Institution of Civil Engineers, Bangladesh* **25 (2)**, 135-155.
- Kovacevic, N., Mair, R.J. & Potts, D.M. 2001. Finite element analyses of ground movement from tunnelling below Southwark Park. *Building response to tunnelling: case studies from construction of the Jubilee Line Extension, London*, CIRIA and Thomas Telford, 2001.
- Lambe, T.W. 1973. Predictions in soil engineering, *Géotechnique* **23 (2)**, 142–202.
- Leca, E. & New, B. 2007. Settlements induced by tunnelling in soft ground, *Tunnelling and Underground Space Technology* **22**, 119-149.
- Lourenço, P.B. 1996. Computational strategies for masonry structures, *PhD Thesis*, Delft University of Technology.
- Mair, R. J. and Taylor, R. N. 1997. Bored tunnelling in the urban environment. *Proc. of the 4th Int. Conf. on Soil Mechanics and Foundation Engineering*, Hamburg, 2353-2385.
- Mollon, G., Dias, D. & Soubra, A-H. 2013. Probabilistic analyses of tunnelling-induced ground movements, *Acta Geotechnica* **8**, 181-199.
- McKay, M.D., Beckman, R.J.. & Conover, W.J. 1979. A comparison of three methods for selecting values of input variables in the analysis of output from a computer code, *Technometrics* **21**, 239–245.
- National Cooperative Highway Research Program (NCHRP): Report 651. *LRFD Design and Construction of Shallow Foundations for Highway Bridge Structures*. Transportation Research Board, 2010,
- Oberguggenberger, M., King, J. & Schmeizer, B. 2009. Classical and imprecise probability methods for sensitivity analysis in engineering: A case study, *International journal of approximate reasoning* **50**, 680-693.
- O'Reilly, M. P. and New, B. M. 1982. Settlements above tunnels in the United Kingdom: their magnitude and prediction. *Proc. of Tunnelling '82 Symposium*, London, 173-181.
- Peck, P.B. 1969. Deep excavations and tunnelling in soft ground. *Proc. of the 7th Int. Conf. on Soil Mechanics and Foundation Engineering, Mexico City*, 225-290.
- Potts, D.M. & Addenbrooke, T.I. 1997. A structure's influence on tunnelling-induced ground movements, *Proc. of the Institution of Civil Engineers, Geotechnical Engineering* **125 (2)**, 109–125. Potts, D.M. & Zdravković, T.I. 1997. *Finite element analysis in geotechnical engineering: theory and application*, Thomas Telford, 2001.
- Rubenstein, R.Y. *Simulation and the Monte Carlo Method*, John Wiley & Sons, 1981.
- Schweiger, H. Peschl, H. Potter, R. 2007. Application of the random set finite element method for analysing tunnel excavation. *Georisk*, 1(1), 43-56.
- Son, M. 2003. The response of buildings to excavation-induced ground movements. *PhD Thesis*, University of Illinois at UrbanaChampaign.
- Withers, A.D. 2001a. Murdoch, Neptune and Clegg Houses in Moodkee Street, Rotherhithe. *Building response to tunnelling: case studies from construction of the Jubilee Line Extension, London*, CIRIA and Thomas Telford, 2001.
- Withers, A.D. 2001b. Surface displacements at three reference sites above twin tunnel through the Lambeth Group. *Building response to tunnelling: case studies from construction of the Jubilee Line Extension, London*, CIRIA and Thomas Telford, 2001.