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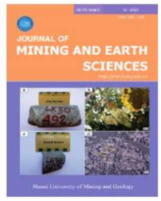

Twin-tunnelling: Case studies in clay

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ABSTRACT

New developments in the theory and practice of tunnel construction are essential for the industry to progress but it is the relationship between these two areas that is equally as important. Tunnelling practice has greatly benefited from laboratory research; specifically, centrifuge modelling linked with field measurements. The wide body of work on the construction of single tunnels has led to the identification of parameters and techniques that are widely accepted for predicting and assessing the magnitude and extent of tunnelling ground movements. However, the usage of twin tunnels in urban areas for transportation purposes have increased and better understanding on the associated ground displacements are required. This paper firstly provides background to ground displacements due to single tunnel, twin tunnel constructions and common prediction methods used in practice. Then, it introduces recent technological advancements in centrifuge modelling, applied to the complex geotechnical events of twin-tunnelling, that has led to further insight. The tunnelling induced ground displacements obtained from twenty four case studies in clay around the world and eighteen centrifuge tests are presented for further analyses. From that, a comparison between the recent theories of proximity-dependent tunnelling-induced ground movements with case histories has been carried out to establish their validity and limitations. Published field measurements have been reanalysed taking into account newly discovered relationships between the tunnels' proximity and the magnitude and extent of ground movements, reflected via volume loss and the settlement trough width, respectively. The applicability to field measurements of the additional volume loss prediction method (derived from consideration of the experiment work) for tunnelling in clay is assessed.

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1. Introduction

Any tunnelling process causes ground movements towards the cavity as a consequence of stress relief before a permanent lining is installed. These ground movements manifest at the surface as a transverse settlement trough and for an undrained tunnelling event, the volume of this trough is assumed to equal to the volume of 'lost ground' from around the tunnel cavity. This is termed volume loss and is generally expressed as a percentage of the excavated area of the tunnel. The transverse settlement trough apparent immediately following tunnel construction has been shown to be well represented by a Gaussian curve (Peck, 1969). These settlements are governed by two parameters, trough width (extent) and maximum settlement (magnitude). The maximum settlement has been shown to be highly dependent on the magnitude of volume loss which is influenced by a number of factors such as ground type, groundwater conditions, tunnelling method and quality of workmanship.

In their review of the state-of-the-art of bored tunnelling developments in the urban environment, Mair and Taylor (1997) presented a comprehensive overview of how ground movements could be predicted. However, in their discussion of multiple tunnels, it was merely noted that significant interaction effects were evident. These effects are apparent as increased volume loss compared to the first tunnel during the second tunnel drive (implicitly due to the presence of the first tunnel) as well as asymmetry of surface settlement observations. It is clear, that when tunnels are very closely spaced, the ground in the region where the second tunnel is to be constructed will already have been subjected to considerable shear strains associated with the construction of the first tunnel and hence a higher volume loss is likely for the second tunnel. Standing and Burland (2006) stated that establishing the reasons for these unexpected volume losses was considered essential for future tunnelling proposals. Since most modern metropolises make use of pairs of tunnels for their transportation systems the accurate predictions of twin-tunnelling-induced ground movements, specifically volume loss, are essential for realistic assessments of potential building and services damage (Standing & Burland, 2006).

Field measurements of the volume loss arising specifically as a result of the construction of a second, closely spaced, tunnel are comparatively rare. The majority of projects monitor each tunnel as an individual event (for the purposes of warning of excessive movement) and monitoring often ceases soon after completion. Results that are presented in the literature usually take the form of overall settlements for the entire scheme.

The particular focus of the work presented here is to use published settlement data from case studies and compare with the results from the laboratory tests of Divall and Goodey (2015). In that work (following on from Divall, 2013) a series of centrifuge model tests demonstrated a significant effect on movements of a second tunnel construction event. These results are presented here in the context of enabling better predictions of ground movements resulting from a twin-tunnel construction project in clay.

2. Current practice for predicting movements and volume loss

2.1. Single tunnel prediction method

An accepted procedure for prediction of surface settlement arising from single tunnel construction largely follows that detailed in O'Reilly and New (1982) and New and O'Reilly (1991). Site measurements from these studies and the centrifuge tests described by Mair et al. (1993) have demonstrated that tunnelling-induced ground settlements can be represented by a Gaussian distribution curve. At the surface, these settlements, S_v, can, therefore, be estimated by:

$$S_v = S_{v\,max} exp\left(-\frac{x^2}{2i^2}\right) \qquad (1)$$

$$S_{v\,max} = \sqrt{\frac{\pi}{32}}\frac{V_L D^2}{i} \qquad (2)$$

Where: $S_{v\,max}$ - the maximum settlement that normally occurs above the centre-line of the tunnel; D - the tunnel diameter; V_L - the volume of the transverse surface settlement trough x - the distance from the tunnel centre-line; i - the horizontal distance to the point of inflexion.

In order to make a prediction, the practising engineer would, therefore, need to assess values of i (primarily controlling the extent of settlement) and V_L (primarily controlling the magnitude).

O'Reilly and New (1982), based upon a review of published tunnelling data, first proposed the relationship:

$$i = Kz_0 \qquad (3)$$

Where: z_0 - the depth from the ground surface to tunnel axis level.

The value of K (the trough width parameter) for tunnels in clay was shown to be 0.5 for most practical cases and the validity of this relationship has been demonstrated by several subsequent authors (Rankin, 1988).

The prediction or estimation of volume loss was proposed to be related to load factor (Mair, 1989). The load factor considers the stability ratio of the tunnel compared with the stability ratio at failure.

The concept of a stability ratio was introduced by Broms and Bennermark (1967):

$$N = \frac{(\sigma_v - \sigma_T)}{S_u} \qquad (4)$$

And therefore the Load Factor is given by:

$$LF = \frac{N}{N_{TC}} \qquad (5)$$

Where: N - the stability ratio or stability number; σ_v - the total vertical effective stress at the tunnel axis level; σ_T - the internal support pressure of the tunnel; and S_u - the undrained shear strength of the clay; N_{TC} - stability number at collapse state.

Macklin (1999) presented data for measured volume loss from a significant number of published case histories of tunnels in stiff overconsolidated clay. For each site, the geometry was assessed in terms of the cover to depth (C/D) and the unlined length (P/D) ratios and the load factor calculated using values for N_c taken from the design curves of Kimura and Mair (1981). The majority of these cases had the ratio C/D larger than 1. These data were plotted on the semi-logarithmic scale shown in Figure 1 and thus, a relationship between load factor and volume loss was defined by:

$$V_L\,(\%) = 0.23e^{4.4(LF)}\ for\ LF \geq 0.2 \qquad (6)$$

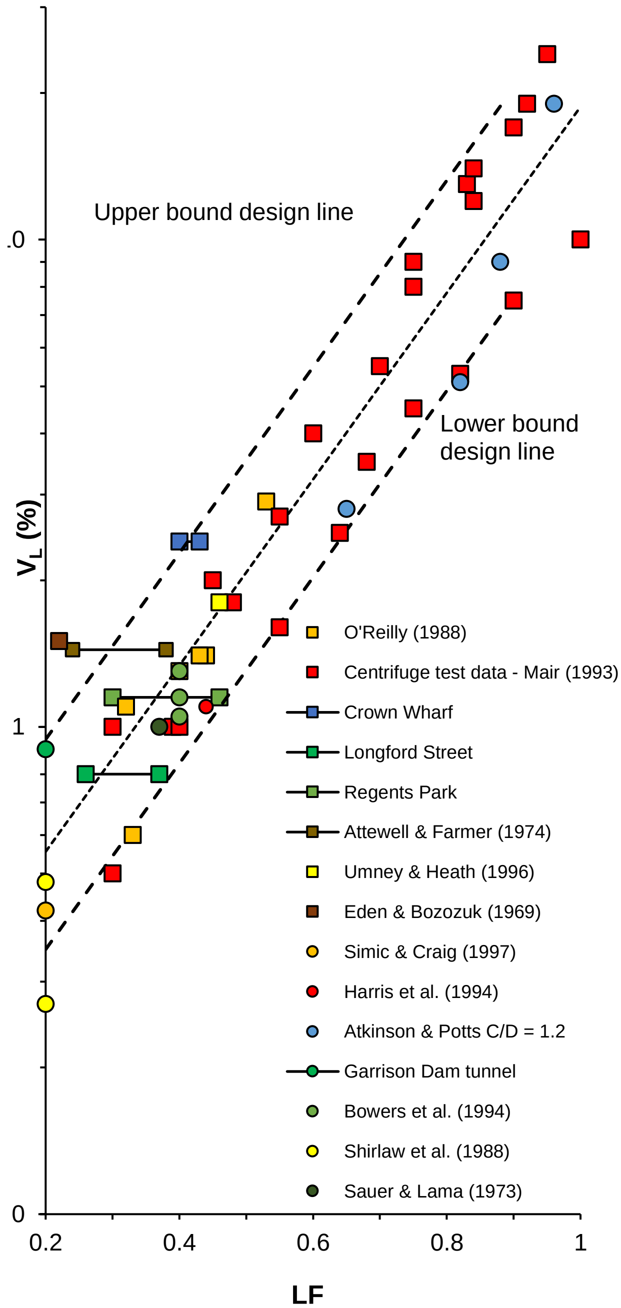

Figure 1. Upper and lower bound design lines for a relationship between volume loss and load factor for field monitoring data from overconsolidated clay sites (Divall, 2013 after Macklin, 1999).

Therefore, for a given load factor LF, for C/D ratios in excess of 1, an estimate for volume losses in clay can be undertaken for single tunnels which are essentially related to the tunnel support pressure (σ_T).

2.2. Twin-tunnelling induced settlement prediction method

It is generally assumed that superposition is the method applied for predicting surface settlement above any twin-tunnel arrangement. Using the Equations 1 to 3, a Gaussian distribution of each tunnel's settlements is positioned over each tunnel's respective centre-line. The summation of these two overlapping curves describes the total settlement. The centre-line above the first tunnel is often used as a fixed point of reference for describing lateral distances.

New and O'Reilly (1991) provided a formula for the prediction of the settlements above twin-tunnels by superposition:

$$S_v = \sqrt{\frac{\pi}{32}} \cdot \left[\frac{V_{L\,A} D_A^2}{K_A Z_A} \cdot exp\left(-\frac{x^2}{2K_A Z_A}\right) + \frac{V_{L\,B} D_B^2}{K_B Z_B} \cdot exp\left(-\frac{(x-d)^2}{2K_B Z_B}\right)\right] \quad (7)$$

Where: subscripts A and B - refer to the first and second tunnels respectively; d - the distance between the tunnel centre-lines.

Utilising this method, different tunnel diameter or volume loss parameters can easily be taken into account but often there is little or no guidance given to engineers to enable them to account for possible effects arising from the presence of any existing infrastructure (in this case, the first tunnel construction).

3. Case studies: Historic data analysed

3.1. Experimental

This paper incorporates results from centrifuge tests investigating the tunnelling-induced ground movements. Simply put, centrifuge modelling is a technique involves creating small scale models and subjecting them to acceleration forces much stronger than Earth's gravity, g. By doing so, the effects of gravity on the prototype, including dimensions and soil stresses, are accurately replicated. With the well-established centrifuge scaling laws, researchers can design realistic models that allow them to interpret observations from these small scale models in relation to full scale prototypes. More details on centrifuge modelling can be found in Taylor (1995).

Divall (2013) conducted a series of 18 plane strain centrifuge tests investigating the ground movements arising from twin-tunnel constructions in clay. All of the models consisted of preformed circular cavities in overconsolidated clay and the influence of the lining was not taken into consideration. The tunnels were bored equally spaced from the model centre-line with varying centre-to-centre spacing. All models had a cover to diameter ratio equal to 2 and the tunnel axis level was approximately 80 mm above the base of the model. These tests were conducted at 100g and utilised the apparatus described in Divall and Goodey (2012). During this study, the delay between the construction of each tunnel was 3 minutes at model scale and therefore analogous (in terms of consolidation) to the second tunnel face passing the monitored section three weeks after the first. This period remained fixed in these tests to ensure that any observed effect was not influenced by changes in consolidation time but it should be acknowledged that, in practice, this time period is highly variable.

Divall and Goodey (2015) proposed a relationship between tunnel spacing and the additional volume loss, ΔV_L, (over that generated by the first tunnel) during the second tunnel construction from the experimental data. Based upon these results, Divall and Goodey (2015) suggested the following for determining modified values of the volume loss for the second tunnel dependant on their proximity to the first tunnel.

$$\Delta V_L \big/ V_{Lg} = 0.441\left(d/D\right)^{-1.062} \quad (8)$$

for $1.5 \le d/D \le 4.5$

Where: V_{Lg} - the "Greenfield" volume loss; d - the horizontal distance between the two tunnels'centre-lines.

Substituting the modified values of volume loss into Equation 7 generates predicted total settlements as the summation of the unaltered first tunnel and the modified second tunnel settlements.

Divall and Goodey (2015) also present a comparison of the trough width parameter with depth for each half of the second tunnel's settlement trough. The tunnelling-induced settlement troughs were divided into "limbs" near (or towards) the existing tunnel and far (or away) from the existing tunnel. The centrifuge tests indicated that the far limbs were minimally affected by the presence of the first tunnel and fit well within the framework proposed by Mair et al. (1993) for a single tunnel. That can be explained by the fact that the longer the distance from the first tunnel, the lesser the effect it has for the trough shape induced by the second tunnel. All spacings show the half-trough settlements for the limb near to the existing tunnel are wider in shape than previously reported.

3.2. Case history dataset

Reports of twin-tunnelling in clay are reasonably rare. This is perhaps because each tunnel is considered as a single geotechnical event and therefore are reported as such. However, many tunnelling projects are twin bored running tunnels and careful interpretation of case studies can allow for the validation of current models. Similar to the approach of Macklin (1999), Table 1 summarises published case studies of twin-tunnelling in clay, eleven of which were in London, UK. In addition, data was also obtained from projects in China, Taiwan, India, Thailand, USA, Turkey, and Japan. Included in Table 1 are the important values relating to the geometry for each project (e.g. tunnel diameter, depth and centre-to-centre spacing) and any details given about the strength or stiffness of the clay strata the tunnels were constructed in. In cases where the volume loss for each tunnel was not directly reported, values were calculated for the individual tunnels by fitting Gaussian curves through the settlement data, subtracting first tunnel settlements from the total to obtain second tunnel settlements or a combination of these techniques.

A limitation of extracting data from case studies is that often when undesired volume losses have occurred during the construction of the first tunnel, changes are made to the construction method for the second. Either the face pressure is increased, or the rate of construction is slowed. For example, at St James Park westbound was 45 m/day or 1.9 m/hour and eastbound was 21 m/day or 0.9 m/hour (Dimmock, 2003). The case studies, where possible, are from those where these factors were not too dissimilar.

3.3. Magnitude of settlement plot

Figure 2 shows the results from the centrifuge tests undertaken by Divall (2013) along with the values of increases in Volume Loss from Table 1. Similar to Divall (2013) the y-axis assumes the first constructed tunnel as the "Greenfield" scenario. The values are therefore the difference between the first and second tunnel's volume loss divided by the "Greenfield" volume loss.

Despite differences in construction method, there is a clear relationship between spacing and the observations of an increased volume loss associated with the second tunnel construction. The error banding of 7% (from Divall & Goodey, 2015) could largely be due to the huge variability in the soil such as shear strength properties, and tunnelling methods. Figure 2 would indicate that the closer the spacing, d/D, shows a much greater variation in potential increases in Volume Loss than Divall and Goodey (2015) first indicated (20÷55% at approximately 1.8D spacing). Figure 2 would also indicate that at a spacing of approximately 7.5D, there would be minimal or no interaction between the two tunnel constructions regardless of the stiffness of stratum. Because the case studies are sourced from many different nations, this would imply that patterns in the phenomenon are not unique to London Clay (i.e. the Jubilee Line Extension; Nyren, 1998). In addition, it is worth noting that the observed pattern is only applicable to tunnelling in clay and there have been a few case studies of tunnelling in sand where the 2nd tunnel induced smaller volume losses (Le et al., 2023).

3.4. Extent of settlement plot

Figure 3 presents the results of the centrifuge tests by Divall (2013), the framework by Mair et al. (1993) and the Case Studies from Table 1 where the K data of the settlement trough at surface and subsurface could be obtained. It is worth noting that for most of the cases, for the second tunnel the trough near the first tunnels, i.e. near limbs, are wider, reflected by larger K values, than that for the first tunnels (Table 1).

Table 1. Summary of published case studies of twin-tunnelling in clay.

No	Ref	Location	Soil Description	Method	Depth to instrumentation	Tunnel (1st or 2nd)	Tunnel diameter D	Depth, z_0	Spacing, d	Cover to depth C/D	Volume loss, V_L (%)	Trough width parameter, K	d/D	Additional volume loss, V_L incr.
1	Viggiani & Standing (2001)	The Treasury, London, UK	Very **stiff** grey brown fissured very silty CLAY (**London Clay**). Twin running tunnels, offset arrangement.	Tunnel Boring Machine	"From St James's Park instrumented section"	1st	4.85	32	13.0	6.1	3.00	0.50	2.7	0.10
						2nd	4.85	23		4.2	3.30	0.50		
2	Standing & Selman (2001)	Bakerloo Line northbound (a), London, UK	Weathered "brown" and intact "blue" CLAY (**London Clay**). Twin running tunnels, side-by-side.	Tunnel Boring Machine	measure at z = -11.1m (Figure 29.32)	1st	4.85	18.5	25.5	3.3	0.83	0.77	5.3	0.17
						2nd	4.85	18.5		3.3	0.97	0.79		
2	Standing & Selman (2001)	Northern Line northbound (c), London, UK	Weathered "brown" and intact "blue" CLAY (**London Clay**). Twin running tunnels, offset arrangement.	Tunnel Boring Machine	measured at z = -7.8m	1st	4.85	15.6	32.5	2.7	1.03	0.61	6.7	0.08
					measured at z = -11.5m	2nd	4.85	20.1		3.6	1.11	0.82		
3	Withers (2001a) and Dimmock (2003)	Southwark Park, London, UK	Weathered "brown" and intact "blue" CLAY (**London Clay**). Twin running tunnels, side by side.	Tunnel Boring Machine	measured at surface (Figure 37.6)	1st	4.85	21	27.5	3.8	0.39	0.39	5.7	0.15
						2nd	4.85	21		3.8	0.45	0.45		
3	Withers (2001b)	Niagara Court, London, UK	Weathered "brown" and intact "blue" CLAY (**London Clay**). Twin running tunnels, side by side.	Tunnel Boring Machine	measured at surface (Table 43.3)	1st	4.85	17	19.5	3.0	0.55	0.53	4.0	0.13
						2nd	4.85	17		3.0	0.62	0.53		
4	Sugiyama et al. (1995)	DLR Lewisham Extension (St Alfege Passage Building), London, UK	WRB is Laminated **silts and sands**, Lower Shelly Clay (**Su>200kPa**), Lower Mottled Clay (**Su>250kPa**)	Slurrry Shield	measured at surface (Table 2)	1st	5.85	13.83	15.0	1.9	0.57	0.62	2.6	0.12
						2nd	5.85	13.83		1.9	0.64	0.62		

			and Pebble Beds (Su=20-140kPa). Twin running tunnels side by side.											
4	Lee (2002)	DLR Lewisham Extension (MS7 Roan Street), London, UK	WRB is Laminated **silts and sands**, Lower Shelly Clay (**Su>200kPa**), Lower Mottled Clay (**Su>250kPa**) and Pebble Beds (Su=20-140kPa). Twin running tunnels side by side.	Slurrry Shield	measured at surface (section 4.2)	1st	5.85	16.42	15.0	2.3	0.79	0.61	2.6	0.32
						2nd	5.85	16.42		2.3	1.04	0.66		
5	Suwansawat & Einstein (2007)	Bangkok MRTA (Section D), Thai Land	**Soft** dark grey Bangkok CLAY (OCR = 2-6). Twin running tunnels side by side (Su = 15kPa)	EPM Shield	measured at surface (Fig. 21)	1st	6.30	22.2	20.0	3.0	1.78	0.59	3.2	0.17
						2nd	6.30	22.2		3.0	2.09	0.77		
6	Bartlett & Bubbers (1970)	Victoria Line: Case 2 & 3, London, UK	**Stiff** blue-grey fissured silty London **CLAY.** Su 1.7kg/sq.cm (166.713kPa) Moisture Content 25%	Cut and Cover	measured at surface	1st	3.81	22	25.0	5.3	1.40	0.36	6.6	0.07
						2nd	3.81	22		5.3	1.50	0.36		
7	Cording & Hansmire (1975)	Lafayette Park, Washington DC, USA		Cut and Cover	measured at surface (Hunt, 2005; Table 8.1)	1st	6.40	14.6	11.0	1.8	3.00	0.50	1.7	0.21
						2nd	6.40	14.6		1.8	3.63	0.60		
9	Hunt (2005)	Heathrow Express Tunnel, London, UK	Weathered "brown" and intact "blue" CLAY (**London Clay**). Twin running tunnels, side by side.	NATM	measured at 13m (Hunt, 2005; Table 8.1)	1st	9.00	26	20.9	2.4	1.30	0.80	2.3	0.15
						2nd	9.00	26		2.4	1.50	1.20		
10	Perez Saiz *et al.* (1981)	Plaza de Morelos (section IV), Mexico	Medium to coarse **sand** with **weathered schist**	"Excavator Shields"	measured at various levels (Table II)	1st	5.60	11.2	11.2	1.5	0.90	0.42	2.0	0.56
						2nd	5.60	11.2		1.5	1.40	0.38		
11	Barrat & Tyler (1976)	Regent's Park, London, UK	**London Clay** with **Su = 200kPa**	"hand driven with the aid of a shield"	measured at surface (Fig. 24)	1st	4.15	34.1	22.6	7.7	1.30	0.41	5.4	0.08
						2nd	4.15	20.1		4.3	1.40	0.54		
12	Ou et al. (1998)	CH218 Taipei (Section	CL Sungshan (IV) is **silty clay** with **Su =**	Earth Pressure	measured at surface (Fig. 14)	1st	6.05	19	18.0	2.6	1.60	3.21	3.0	0.25

		B-B), Taiwan	**81kPa**. Twin running tunnels - side by side	Balance shield		2nd	6.05	19		2.6	2.00	3.21		
13	Hanya (1977)	Case B-1, Japan				1st	7.06	27.5	10.0	3.4	3.08	NA	1.4	0.32
						2nd	7.06	27.5		3.4	4.07	NA		
14	Som & Narayan (1985)	Calcutta, India	Soft CLAY. Grey **silty Clay**/Clayey silt with Decomposed Wood (Su = 17.652kPa). Bluish Grey **Silty Clay** (Su = 35.304kPa).	Cut and Cover; Shield Tunnelling	measured at surface	1st	5.10	10.5	11.0	1.6	5.40	0.40	2.2	0.43
						2nd	5.10	10.5		1.6	7.73	0.53		
15	Chen et al. (2011)	Hangshou Metro, China (section G2)	Silt (**Su = 9kPa)** and "Lean Clay" (**Su = 7.8kPa**).	Earth Pressure Balance shield	measured at surface (Fig. 6)	1st	6.20	19	12.0	2.6	0.75	0.39	1.9	0.17
						2nd	6.20	19		2.6	0.87	0.39		
16	Dimmock & Mair (2007) and Nyren (1998)	St James' Park, London, UK	Weathered "brown" and intact "blue" CLAY (**London Clay**). Twin running tunnels, side-by-side.	Tunnel Boring Machine	measured at surface (Fig 8.1)	1st	4.85	31	21.0	6.4	2.80	0.43	4.3	0.14
						2nd	4.85	20.5		4.2	3.20	0.53		
17	Ocak (2013)	Istanbul Metro, Turkey	Clay (Gungoren fr.) SPT = 60.	Earth Pressure Balance shield	measured at surface	1st	6.30	35.75	14.3	5.2	NA	NA	2.3	0.37
						2nd	6.30	35.75		5.2	NA	NA		
18	Cooper *et al.* (2002) and Hunt (2005)	Heathrow Express Tunnel, London, UK	Weathered "brown" and intact "blue" CLAY (**London Clay**). Twin running tunnels, side-by-side.	NATM	measured at 12.7m (Hunt, 2005; Table 8.1)	1st	9.00	25.9	15.900	2.4	1.20	0.80	1.8	0.50
						2nd	9.00	25.9		2.4	1.80	1.20		
19	Ou et al. (1998)	CH218 Taipei (Section A-A), Taiwan	CL Sungshan (IV) is **silty clay** with **Su = 81kPa**. Twin running tunnels - side by side	Earth Pressure Balance shield	measured at surface (Fig. 14)	1st	6.05	19	18.0	2.6	2.06	0.45	3.0	0.25
						2nd	6.05	19		2.6	2.58	0.48		
20	Shirlaw et al. (1988) from Dimmock (2003)	Singapore Mass Rapid Transit, Singapore	**Stiff** to hard **clay**	Sprayed concrete lining		1st	6.00		7.7		1.00		1.3	1.00
						2nd	6.00				2.00			
21	Koukotas & Sofianos (2015)	Thessaloniki Metro Project, Greece	**Stiff**, brown to light brown **sandy clay**. Low plasticity. E = 43MPa, Su = 7kPa	EPBS	measured at surface (Fig. 12)	1st	6.19	27	12.2	3.9	0.83		2.0	0.31
						2nd	6.19	27		3.9	1.09			

22	Elwood & Martin (2016)	City of Edmonton's Light rail Transit expansion, Canada	Hard, fissured cohesive till	SCL	measured at surface	1st	6.50	10.5	11.6	1.1	0.07		1.8	0.57
						2nd	6.50	10.5		1.1	0.11			
23	Elwood & Martin (2016)	City of Edmonton's Light rail Transit expansion, Canada	Hard, fissured cohesive till	SCL	measured at surface	1st	6.50	10.5	8.0	1.1	0.16		1.2	0.06
						2nd	6.50	10.5		1.1	0.17			
24	Wan (2014)	Crossrail, Hyde Park, UK	Very **stiff** grey brown fissured very silty CLAY (**London Clay**). Twin running tunnels, offset arrangement.	EPBM	many depths	1st	7.10	34.5	16.2	4.4	0.80	0.5	2.3	0.36
						2nd	7.10	34.5		4.4	1.09	0.4		

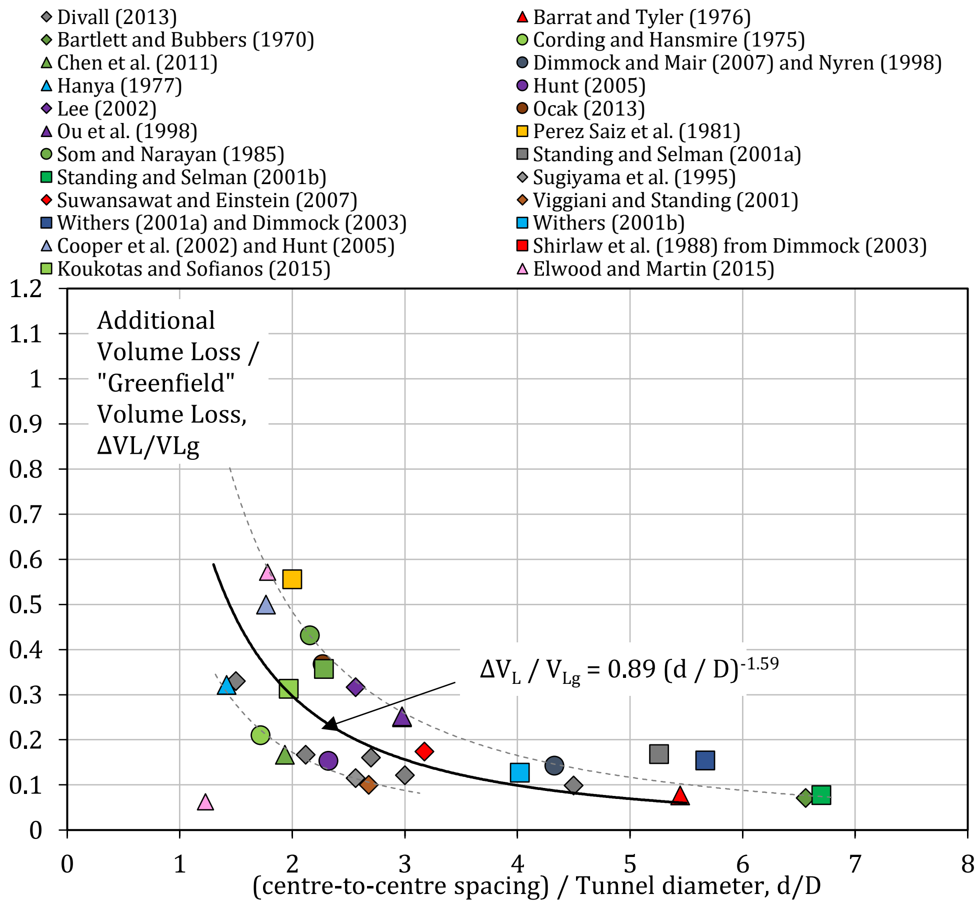

Figure 2. Centrifuge tests from Divall and Goodey (2015) with field monitoring data from clay sites presented to show a relationship between tunnel spacing and the observed increases in Volume Loss associated with the second tunnel construction.

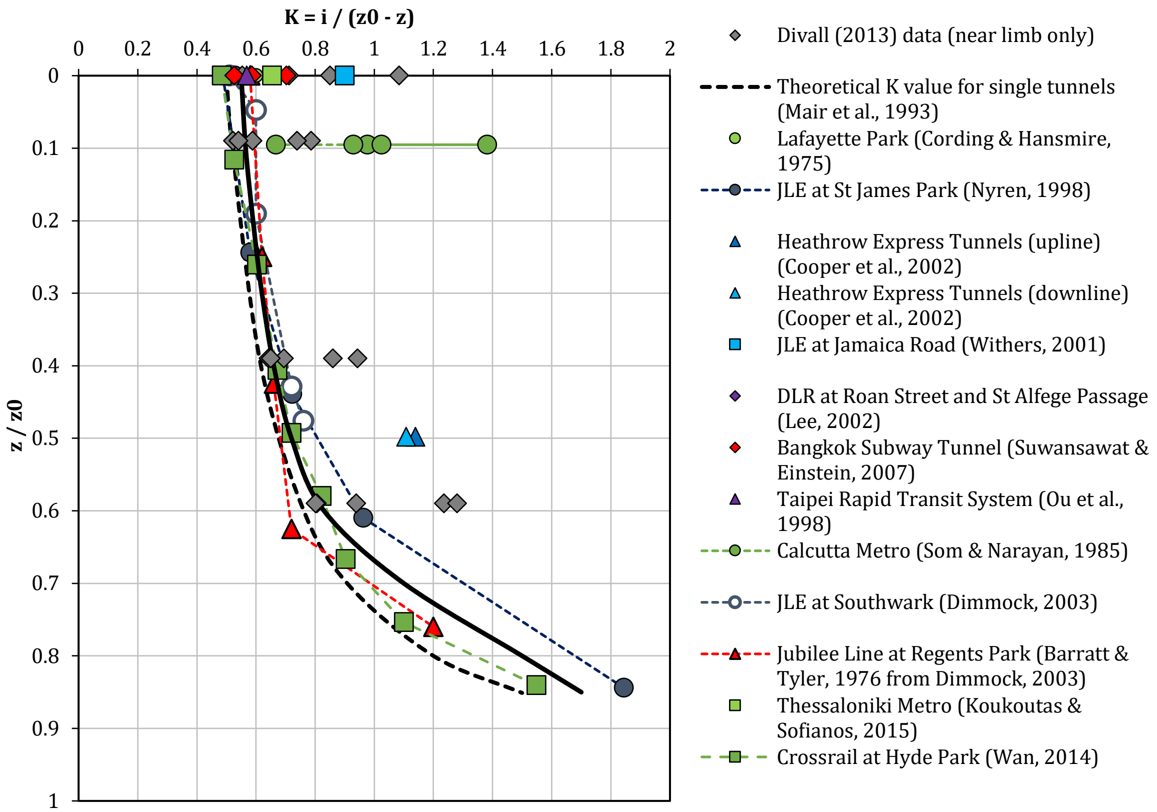

Figure 3. Centrifuge tests from Divall and Goodey (2015) with field monitoring data from clay sites presented to show a relationship between tunnel spacing and the observed increases in Trough width parameter with depth associated with the second tunnel construction.

The K data at the surface for tunnelling in clay is concentrated between 0.5 and 0.7 and this offset continues with depth. The K values for clay is considerably wider than those for tunnelling in sand in which K ranges between 0.25 and 0.45 (Le et al., 2023; Mair, 2008; Mair & Taylor, 1997).

4. Conclusion

The findings from eighteen centrifuge tests and twenty-four case studies of twin-tunnelling have been described in this paper. The results show clear relationships regarding the magnitude and extent of tunnelling-induced ground movements above a second, closely spaced, bored tunnel in clay. The main findings are summarised as:

1. Relative increases in Volume Loss of the second tunnel are influenced by proximity to the first tunnel, the stratum stiffness and are evident in many projects across the globe.

2. Wider than previously predicted trough width parameters for 'limbs' near the existing tunnel are also evident.

3. These increases apply to both the surface and with depth.

4. Twin-tunnelling settlement predictions could benefit from modifying the second tunnel construction in-line with the two design lines presented in this paper before adding to the "Greenfield" or first tunnel prediction. This is a modified version of the classic superposition and the one presented in Divall and Goodey (2015).

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Contribution of authors

Sam Divall - Formal analysis, Validation, Investigation, Writing - Original Draft, Funding acquisition; Richard James Goodey - Conceptualization, Writing – review & editing; Michael. C. R. Davies - Conceptualization, Validation; Binh Thanh Le - Writing – review & editing, Funding acquisition; Tra Thu Thi Nguyen - Formal analysis, Writing – review & editing.

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