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Response of framed buildings to excavation-induced movements

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Abstract

This paper presents a study of the influence of frame action on the response of buildings to deformations induced by deep excavations in soft clay. Using the finite element method, a building was modelled as a framed structure adjacent to a multi-propped excavation, firstly as a frame with continuous footings and then as a frame with individual footings. The geometry, location, and structural elements forming the frame models were varied to investigate the response of various frames. Using a structural analysis, parameters representing the stiffness of the frames in reducing deflection ratios and horizontal strains were derived. The influence of the frame action on the building stiffness can be quantified using the results from the finite element models. This makes it possible to estimate building modification factors from the relevant design charts so that induced deflection ratios and horizontal strains, caused by adjacent excavation and tunnelling activities, can be calculated. The approach gives a more realistic estimate of the tensile strains for assessing the potential damage caused to buildings.

Keywords: Building response; Excavations; Frame action

1. Introduction

1.1. Background

Buildings vary so much in structural concept and detail that it is difficult to lay down general guidelines for the influence of settlements on building serviceability and performance. Nevertheless, from full scale model tests conducted by the Building Research Station, in which masonry walls and infill frames were forced to deflect like simple beams, Burland and Wroth (1974) noted that the onset of visible cracking was related to the induced tensile strains. They proposed using the deflection of a centrally loaded simple beam as an idealised representation of the deflection of actual buildings, and used Timoshenko's beam theory to derive equations relating the deflection ratio to tensile strains using the beam's geometric and stiffness properties. These were supported using observations of the damage to a number of buildings together with the observations from full-scale model tests (Burland et al., 1977). Since then, these equations have been re-written and are now the basis for estimating the potential building damage caused by tunnelling- and excavation-induced deformations.

The procedure for building damage assessment, outlined by Mair et al. (1996), was based on deflection ratios and horizontal strains in the *greenfield* condition. This ignores the inherent stiffness in buildings and is conservative. To include

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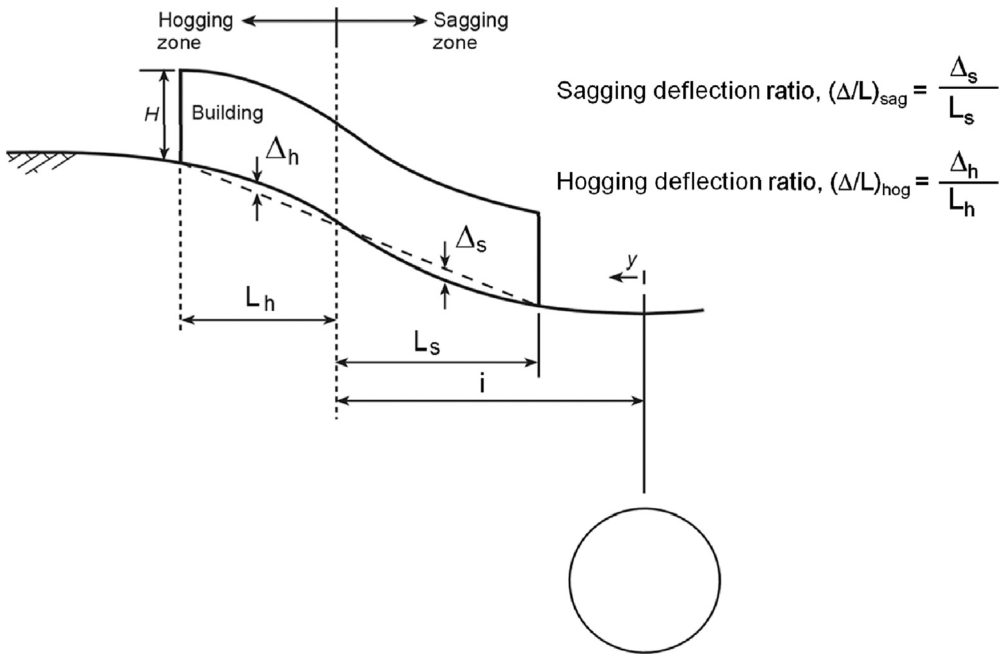

Fig. 1. Deformation of building above tunnelling (after Mair et al., 1996)

the influence of building stiffness, Potts and Addenbrooke (1997) pioneered the use of the modification factor approach to estimate the deflection ratios and horizontal strains caused by tunnelling deformations. In their finite element study, a building was modelled as an elastic beam with bending and axial stiffness properties, and was in full contact with the ground surface. By changing the building's geometry and location or eccentricity in relation to the tunnel, design charts were developed so that the influence of the building stiffness in modifying the response from that of the *greenfield* condition could be estimated.

The use of an elastic beam to estimate a building's stiffness would be appropriate if the building response were dominated by the wall behaviour, such as the masonry houses at Moodkee Street in London, described by Mair and Taylor (2001b). However, it is unclear how the stiffness of framed buildings can be related to the elastic properties of a simple beam. For example, when estimating the realistic bending stiffness of buildings up to 5-storeys for their numerical study, Potts and Addenbrooke (1997) employed the parallel axis theorem to define the stiffness in bending about the neutral axis for a rigidly framed structure, namely,

$$EI_{frame} = \sum E*(I + AH^2)_{\text{ith}\,floor} \quad (1)$$

Essentially, the stiffness of the 'beam' increases depending on the distance H between the beam's neutral axis and the structure's defined neutral axis, similar to that of composite materials. Nevertheless, Potts and Addenbrooke acknowledged this to be an overestimate of building stiffness. On the other hand, in Mair and Taylor (2001a)'s estimate for the bending stiffness of Elizabeth House, a 10-storey reinforced concrete frame structure with two basement levels, the influence of the frame action was ignored as the effects of any shear walls or moment connections were judged to be minor. The building stiffness was estimated for the 'Class A' prediction (Lambe 1973) by algebraically summing the individual bending stiffness of all the floor slabs, so that

$$EI_{frame} = \sum (EI)_{\text{ith}\,floor} \quad (2)$$

It is not clear which method would give a better estimate of the bending stiffness of frame structures (although the approach by Mair and Taylor in the case of Elizabeth House led to the Class A prediction being in close agreement with the subsequent field measurements). Moreover, previous studies have been based on buildings on continuous footings that are in full contact with the ground. Using a centrifuge modelling of a simple frame model on separate footings behind an excavation supported by a cantilever wall, Elshafie (2008) observed the beam dislodging from the column-footing due to ground movements during the excavation. The behaviour of framed buildings on individual footings could be quite different from that of a simple beam model.

1.2. Building modification factor approach

The building modification factor approach introduced by Potts and Addenbrooke (1997), which will be used in this paper, is a valuable tool for studying the response of buildings. Essentially, building modification factors describe the maximum deflection ratios and horizontal strains in a building in relation to the *greenfield* condition. The definition of deflection ratio (Δ/L) is given in Fig. 1. To calculate the deflection ratio modification factors, the following steps are undertaken: (i) the deflection ratios are calculated in the sagging and hogging zones corresponding to the building's geometry and location using the *greenfield* settlement trough, i.e., $(\Delta/L)_{\text{sag,GF}}$ and $(\Delta/L)_{\text{hog,GF}}$; (ii) for the settlement trough for the building