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Finite Element modelling of tunnelling-induced displacements on framed structures

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ABSTRACT

The construction of tunnels in urban areas inevitably entails the interaction with existing structures. While the effect of tunnel excavation on masonry structures has been thoroughly studied, the response of framed buildings has not been widely investigated in the past. In this paper, a parametric study of the response to tunnelling of reinforced concrete framed structures founded on strip footings is carried out using the Finite Element method. The foundations and the structural members of the building are modelled with a sufficient detail and a realistic contact law is employed to simulate the interaction between the foundation and the adjacent soil. Results are summarised in terms of deflection ratios and modification factors for horizontal strains. It is shown that the structural stiffness, mainly provided by the foundation, on average reduces the differential settlements and the horizontal displacements of the frame as compared to greenfield conditions. However, in contrast with what discussed in previously published papers, while the deflection ratio in sagging reduces as the number of floors becomes larger, it increases in hogging, which always occurs at the ends of the foundation. This evidence appears to be related to the non-uniform contact pressure at the soil-foundation interface and to the peculiar load distribution associated to the frame geometry.

1. Introduction

The construction of tunnels in urban areas inevitably entails the interaction with existing structures. Current design approaches for the evaluation of tunnelling induced damage on buildings are based on semi-empirical evaluations of the deflection ratios and horizontal tensile strains at foundation level, assuming that the structure will conform to the greenfield displacements (Peck, 1969; Burland and Wroth, 1974; Burland et al., 1977; O'Reilly and New, 1982; Boscardin and Cording, 1989; Burland, 1995). If the stiffness of the structure is deemed significant, coupled numerical analyses should be performed including a model of the building. The latter can be simulated using either an equivalent solid (e.g.: Potts and Addenbrooke, 1997; Franzius et al., 2004, 2006; Pickhaver et al., 2010; Maleki et al., 2011; Rampello et al., 2012; Farrell et al., 2014; Losacco et al., 2014), for which appropriate equivalence criteria have to be defined, or using a detailed structural model (e.g.: Burd et al., 2000; Liu et al., 2000; Giardina et al., 2010; Son and Cording, 2011; Amorosi et al., 2012; Liu et al., 2012; Sebastianelli et al., 2013; Amorosi et al., 2014; Boldini et al., 2014; Fargnoli et al., 2015a, 2015b; Boldini et al., 2016; Franza et al., 2017).

Numerical studies on the effects of tunnel excavation on pre-existing buildings have been carried out by many Authors in recent years. However, only a limited number of them focused their attention on the response of concrete framed structures. The strong dependency of the building response on the structural type (i.e. brick-bearing structures, open-frame and brick-infilled frame structures) was highlighted by Son and Cording (2011). Goh and Mair (2014) presented a numerical study, also corroborated by field data, centred on the behaviour of framed structures founded on continuous or individual footings behind a multi-propped excavation. Fargnoli et al. (2015a, 2015b) developed a detailed structural-geotechnical three-dimensional model aimed at back-predicting the response of a multi-storey reinforced concrete building underpassed by a metro tunnel in Milan.

This paper focuses on the soil-structure interaction due to mechanised tunnel excavation, with special reference to reinforced concrete framed buildings. The study is aimed at investigating the role of building stiffness and weight in altering the settlement trough induced by the excavation as compared to greenfield conditions.

The research was carried out by performing parametric Finite Element analyses with reference to ideal single frame structures

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Nomenclature

ε_h	horizontal strain
ε_{hc}	maximum horizontal compressive strain
$(\varepsilon_{hc})_{gf}$	maximum horizontal compressive strain in greenfield conditions
γ	structure unit weight
γ_s	soil unit weight
ν	structure Poisson's ratio
ν_s	soil Poisson's ratio
φ	soil friction angle
ψ	soil dilatancy angle
ρ^*	relative bending stiffness
Δ_{hog}	relative deflection in hogging
Δ_{sag}	relative deflection in sagging
c	soil cohesion
e	eccentricity of the frame with respect to tunnel axis
h	storey height
l	span length of the frame bay
n	number of storeys
z	depth
z_t	depth of tunnel axis
A	area of the beam
D	tunnel diameter
DR_{hog}	deflection ratio in hogging
DR_{sag}	deflection ratio in sagging
E	structure Young's modulus
E_s	soil Young's modulus
G_0	soil small-strain shear modulus
K	settlement trough width parameter
K_0	coefficient of the earth pressure at rest
L	frame width
$M_{\varepsilon hc}$	modification factors for horizontal strains
N	concentrated loads at the base of the columns
N_{calc}	hand-calculated concentrated loads applied at the foundation in correspondence of the columns
L_{hog}	building length in hogging
L_{sag}	building length in sagging
S_h	horizontal displacement
S_v	settlement
V_L	volume loss

founded on a strip footing. The influence of varying the number of storeys, the eccentricity with respect to the tunnel centreline and the length of the frame was investigated to outline the typical response of this class of structures to the excavation of a tunnel. The geotechnical conditions and tunnel geometry are inspired by the case-history of the Milan metro line 5 (Fargnoli et al., 2013, 2015b).

This paper demonstrates the major role of the self-weight of the framed structure in determining the response to the excavation of a tunnel. Also, the relative contributions of the frame and of its foundation to the overall structural stiffness are highlighted. Those features were often disregarded in previously published works that focuses on similar problems (e.g.: Potts and Addenbrooke, 1997; Goh and Mair, 2014).

2. Statement of the problem

The general layout of the investigated problem in shown in Fig. 1. It consists of a single-frame structure oriented perpendicularly to the axis of a shallow circular tunnel. The scope of this study is the evaluation of the displacement pattern induced by the excavation of the tunnel at the base of the structure, i.e. at the foundation level. For this reason, the construction of the tunnel was not modelled in detail, since the focus of the work is on the soil-structure interaction phenomena occurring near the ground surface. As discussed later, the excavation was simulated in a rather simplistic way, by adopting a displacement controlled technique, already tested in a number of previously published studies, able to reproduce a realistic displacement field for this class of engineering problems (e.g. Rampello et al., 2012; Amorosi et al., 2014), while completely disregarding the installation of the lining. Also, the progressive advancement of the tunnel face is not simulated in the analyses: the excavation is carried out simultaneously throughout the length of the FE domain, thus rendering the problem essentially bi-dimensional. Nevertheless, a three-dimensional FE mesh was used in order to avoid the uncertainties related to the coexistence of plane stress elements, for the frame, with plane strain elements, for the soil, in the same 2D analysis (Amorosi et al., 2014).

In order to adopt realistic geotechnical conditions and geometry layout for the tunnel, reference was made to a real case, the excavation performed by an EPB machine of the metro line 5 in Milan (Fargnoli et al., 2013, 2015b), whose typical subsoil mainly consists of sands and gravels. The tunnel has a circular section, with external diameter $D = 6.7$ m and axis depth $z_t = 25$ m from the ground surface. The average volume loss observed at the ground surface was 0.5%.

The examined structure is a reinforced concrete frame founded on a strip footing. The frame has a variable width L, with 4 m long bays; all the beams and columns have the same square cross section of 0.4 m side; each storey is 3.2 m high. The strip footing is 0.7 m high and 1.2 m wide, while being 1.2 m longer than the frame. Various frame layouts were investigated, varying the number of storeys n (from 1 to 20), the width of the frame L (20 and 36 m) and the eccentricity e (from 0 to 12 m) with respect to the tunnel, this latter defined as the horizontal distance between the tunnel axis and the centre of the structure. Floors were not explicitly simulated in the model but their weight, calculated considering typical composite RC-masonry floors, was applied to the beams. The details of the analyses in terms of n, L and e are provided in Table 1, together with an estimation of the structural equivalent stiffness as calculated following Finno et al. (2005).

In order to isolate the relative contribution of the foundation and the frame to the global stiffness, the analyses were repeated using the sole foundation, properly loaded to account for the weight of the frame, in place of the original structural model. The relative influence of the weight, instead, was probed by removing the weight of the frame and comparing the results with those obtained with the original model.

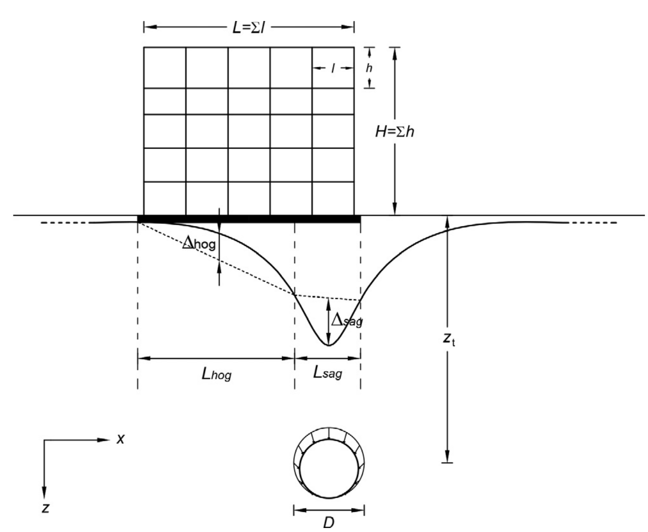

Fig. 1. Problem layout.