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Assessment of masonry structures subjected to foundation settlements using rigid block limit analysis

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ABSTRACT

In this paper, a three-dimensional rigid body model is implemented to investigate the behaviour of masonry block structures subjected to foundation settlements. The structural behaviour is investigated formulating a limit analysis problem for the calculation of the base reaction and the associated failure mode once the settlement is introduced in the model. The structural model is an assemblage of rigid blocks which interact at contact interfaces. The latter are modelled as concave-contacts, using contact points located at the corners of the interface to represent interactions. A no-tension and non-associative frictional behaviour with infinite compressive strength is considered for joints. The limit analysis problem is formulated as a second order cone programming problem (SOCP) and an iterative procedure is adopted to take into account non-associative frictional behaviour. A computer program has been developed for applications of the proposed procedure. Two simple numerical examples are presented with the aim to verify the obtained results against analytical solutions. Applications to a set of experimental tests and to a 3D building model are introduced for validation and to evaluate the computational efficiency of the model. Finally a dissipation index is defined in order to give a quantitative estimation of the consequences related to the foundation settlement.

1. Introduction

The assessment of the effects induced by foundation settlements on structures has been the subject of a wide literature in past decades which is related to geotechnical as well as structural engineering studies.

According to Negulescu and Foerster [1], different classification systems shall be adopted to describe the actual methods aimed at estimating the building damages related to foundation movements and settlements. These methods can be classified as follows: (i) '*empirical methods*' – such as the ones developed by Skempton and MacDonald [2]; Polshin and Tokar [3]; Sowers [4]; Bjerrum [5]; Rusch and Mayer [6]; Beeby and Miles [7] – which provide serviceability criteria comparing the settlement field observations – mainly weight induced settlement- to the structural damage; (ii) '*structural engineering based methods*' or analytical methods that, according to different and progressively refined assumptions, consider the building as an equivalent elastic beam [8–10], a laminate beam [11], or a thick plate [12] providing damage criteria based on limiting – maximum admissible – tensile strain and related crack development; (iii) '*numerical methods*' which can be uncoupled, if the settlements are just applied to the numerical model, or coupled in case of full modelling of soil–structure interactions (e.g. [13]).

In recent years there has been a renewed interest in modelling the effects of foundation settlements induced by excavation, tunnelling and subsidence or, generally speaking, ground movements on masonry structures.

From the structural perspective, different modelling approaches are used to assess the effects of foundation settlement on masonry structures. Most of these modelling approaches are formulated using the finite element method (FEM) and adopting both continuous (macro or micro-macro homogenized models, according to the classification given in [14]) and discontinuous-based models (such as micro-models using contact elements to represent discontinuities in the masonry texture).

A continuous finite element model, developed in the framework of the homogenization theory in [15,16], is applied in Amorosi et al. [17] to analyze tunnelling-induced deformation and damage on an historical masonry aqueduct.

Alessandri et al. [18] adopted a 2D non-linear finite element homogenized model firstly presented in [19] to verify that the actual structural damage of a historic masonry building was related to past foundation differential settlements. A 3D homogenized non-linear FE model presented in [20,21] was adopted in

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[22] for the evaluation of the non-linear behaviour of a masonry arch bridge subjected to pile foundation settlement.

A 2D semi coupled FE macro model, validated through comparison with experimental results, was presented in Giardina et al. [23] and adopted to carry out a sensitivity study to investigate the effect of openings, material properties, building weight and applied settlement profile [24]. With respect to coupled analysis, an application can be found in Giardina et al. [25], where a 3D model of a masonry building, foundation, soil, and tunnel is presented and used to investigate the main parameters governing the structural response to settlement.

FE models using macro-elements with nonlinear springs such as those developed in [26,27] have also been used to investigate the response of masonry structures subjected to differential settlement [28], as well as under combined effect of gravity and seismic loads [29].

A FE micro-model using contact elements to represent discontinuities is adopted in [30] to investigate the influence of architectural detailing on the damage prediction of unreinforced masonry structures subjected to excavation-induced subsidence.

As an alternative to FEM, applications of other modelling approaches can be also found in the literature for the assessment of masonry structures subjected to settlements, such as the distinct element method (DEM) and rigid body spring models (RBSM). Applications of DEM can be found in [31,32]. In [33] a 2D rigid body spring model is adopted to carry out non-linear analysis of masonry arches and trabeated colonnades subjected to spreading supports and settlements.

Despite the accuracy and the good prediction of the structural behaviour that can be achieved through the application of the above mentioned approaches, simplified methods such as those based on strut and tie models (STM) can be also conveniently used for investigating masonry structures subjected to settlements. In the framework of STMs [34], Palmisano and Elia [35,36] evaluated the effectiveness of the load path method (LPM) in the interpretation of the crack patterns of masonry panels subjected to landslide-induced settlements. Considering the reduced computational cost, the Authors found that this modelling approach is especially suitable for rapid diagnosis of crack patterns at the territorial scale. However, considering that the proposed model was applied for material linear behaviour and without including tensile resistance limits [37], the Authors also claim the need for further theoretical work to quantify the ultimate capacity of masonry walls also taking into account the nonlinear and anisotropic behaviour as well as laboratory tests.

Limit analysis (LA) is another modelling approach which can be effectively used to assess the damage induced by support movements on masonry structures, such as arches or domes [38,39].

Classical methods of LA such as static (thrust line) or kinematic (collapse mechanism) analysis, also taking into account the effects of gross displacements, have been adopted in [40–44].

Different numerical procedures based on theorems of LA, such as discontinuity layout optimization (DLO), could be also conveniently used to investigate soil–structure interactions and the effects of differential settlement on structures [45,46].

Another efficient computational modelling approach based on classic methods of LA is rigid block limit analysis (RBLA). In RBLA, the structure is discretized as an assemblage of rigid bodies interacting at contact interfaces for which a tensionless and frictional behaviour with infinite compressive strength is usually assumed. The calculation of the collapse load and failure modes can be cast as an optimization problem, formulated on the basis of the kinematic and static conditions governing the rigid block model, which can be efficiently solved using mathematical programming methods [47–54].

Most of applications of RBLA are concerned with response against lateral loads, such as those induced by seismic actions on portal frames or out-of-plane loaded facades [55–60].

Applications of RBLA to the assessment of masonry structures subjected to differential settlement can be found in [61] for the support movement analysis of masonry arch bridges.

In this framework, a novel modelling approach has been recently proposed for the limit analysis of large three-dimensional masonry block assemblages [62]. The model is based on a '*point-contact*' formulation, also known as '*concave contact*' formulation according to the definition given by Livesley [63], using contact points located at the corners of the interface to represent interactions. The limit analysis problem is formulated using second order cone programming (SOCP), for which very efficient solution algorithm exists [64], to allow direct modelling of the conic failure surface in sliding for spatial assemblages. A notable feature of the formulation is the ability to take into account non-associative behaviour in sliding according to an iterative procedure that provides accurate and stable solutions with significant CPU savings, if compared to classic approaches, even for problems with a large number of variables.

The above mentioned model, which has been originally formulated for in-plane and out of plane behaviour respect to seismic like actions, is herein extended to deal with the problem of masonry structures subjected to settlements.

With this aim, a simple modelling approach has been developed to introduce settlements in the 3D rigid block model presented in [62]. The key features of the proposed approach are related to the use of an additional rigid block for the simulation of the support movements and to the different use of the collapse load multiplier with respect to the static formulation developed so far.

The additional rigid block has degrees of freedom which are associated to the imposed movements. The collapse load multiplier, which in RBLA is usually adopted for lateral load in seismic assessment, is herein used to express variable loads applied to the movable support and to calculate the base reaction at collapse. The results obtained from limit analysis are the failure mechanism associated to the foundation settlement and the support reaction.

A set of experimental tests on dry-jointed masonry tuff walls was also carried out to validate the proposed modelling approach. With this purpose, a simple test set-up was designed to allow a comparison with numerical results in terms of failure mechanism and support reaction at collapse.

The paper is organized as follows. The modelling of foundation settlement, the relationships governing the behaviour of the rigid block model and the limit analysis formulation are introduced in Sections 2 and 3. The adopted iterative solution procedure to take into account Coulomb friction (non-associative) behaviour is described in Section 4. In Section 5 two verification examples are presented to illustrate the modelling procedure. To assess the accuracy and efficiency of the proposed model, in Section 6 the formulation is applied to two experimental case studies and in Section 7 an application to a 3D masonry building is presented. Sensitivity to algorithm parameters and computational efficiency of the proposed formulation are also discussed. Finally, a distribution index of the energy dissipated in the failure mechanism is defined in order to give a quantitative estimation of the consequences related to the foundation settlement.

2. The rigid block model

The numerical model is composed of rigid blocks i interacting at contact points k located at the vertexes of the interface j (Fig. 1).

A no-tension frictional behaviour with infinite compressive strength is assumed at contact interfaces.