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Numerical analysis of the behaviour of masonry buildings undergoing differential settlements

Analyse numérique du comportement des bâtiments en maçonnerie soumis à des tassements différentiels

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ABSTRACT: This paper presents the results of a numerical analysis – carried out by way of the academic version of the TREMURI software implementing the Equivalent Frame Method – that was aimed at generating fragility curves to be associated with existing masonry buildings resting on soils with different mechanical parameters and subjected to differential settlement scenarios. These numerical fragility curves, once validated on the basis of information concerning real cases, could represent a useful tool for decision makers and geotechnical engineers in planning/selecting/designing appropriate foundation repairing/replacing measures aimed at preventing the attainment of intolerable damage severity levels.

RÉSUMÉ: Cet article présente les résultats d'une analyse numérique – réalisée à l'aide de la version académique du logiciel TREMURI mettant en œuvre la méthode Equivalent Frame – visant à générer des courbes de fragilité à associer à des bâtiments de maçonnerie existants reposant sur des sols à paramètres mécaniques différents and soumis à des scénarios de tassement différentiel. Ces courbes de fragilité numérique, une fois validées sur la base d'informations concernant des cas réels, pourraient constituer un outil utile pour les décideurs et les ingénieurs géotechniciens dans la planification/sélection/conception de mesures appropriées pour réparer/remplacer les fondations afin d'empêcher l'atteinte des niveaux de gravité des dommages intolérables.

Keywords: settlement troughs; masonry buildings; damage; fragility curves

1 INTRODUCTION

The analysis and prediction of the damage that a building has undergone or may undergo, as a result of foundation settlements induced by natural (e.g. subsidence) or anthropogenic (e.g. excavation) events, represent key issues both in the management of urban systems and in the land use planning. However, addressing these issues is a difficult task since the attainment of a certain level of damage severity is the result of a complex interaction involving the superstructure-foundation-subsoil system as a whole. Consequently, in order to obtain reliable results, the availability of high quality and quantity data is required on the building (geometry, load distribution and mechanical properties of the constituting materials) and subsoil (stratigraphic assets, hydro-physical-mechanical properties of involved soils, groundwater regime) characteristics.

Since the collection and the systematic analysis of the aforementioned data is very costly both in

terms of time and economic resources, in the engineering practice the adoption of empirical (Skempton and MacDonald, 1956; Bjerrum, 1963) or semi-empirical (Burland and Wroth, 1974; Boscardin and Cording, 1989) criteria is preferred; in the latter case, the use of an "equivalent elastic beam" allows simulating the superstructure response to the ground movements by disregarding the foundation-subsoil interaction. More recently, the possibilities offered by advanced numerical tools have promoted the adoption of two-dimensional (Potts and Addenbrooke, 1997, Franzius et al., 2004) and three-dimensional (Burd et al., 2000) analyses useful to discriminate the role played by the different factors that contribute to the onset and development of the damage caused by foundation settlements.

Nevertheless, in all the methods mentioned above, the estimation of the settlement-induced damage severity level exhibited by the superstructure is generally based on a qualitative (Ferlisi et al., 2015) or semi-quantitative (Palmisano et al., 2018) description of crack patterns whose development is strongly influenced by uncertainties inherent to both the geometrical/mechanical characteristics of the superstructure and the mechanical parameters of the involved soils, as well as to the deformation mode of the foundation system.

To deal with these uncertainties, an interesting perspective is offered by the use of fragility curves (Mavrouli et al., 2014; Negulescu et al., 2014; Nicodemo et al., 2017; Peduto et al., 2017a, 2017b, 2019). These forecasting tools provide the probability that a building can reach or exceed a fixed damage severity level due to the occurrence of an event of given intensity.

In this regard, referring to a masonry building with shallow foundations, this paper shows the results of a numerical analysis aimed to generate fragility curves that take into account the variability of soil mechanical parameters and different settlement scenarios.

2 METHODOLOGICAL APPROACH AND SOIL-FOUNDATION-STRUCTURAL MODEL

The methodological approach adopted to analyze the response – in terms of attainment of a certain level of damage severity – of masonry buildings with shallow foundations resting on soils with different mechanical parameters and subjected to settlement scenarios includes: *i)* the definition of a soil-foundation-structural model that combines information on the (geometric and mechanical) characteristics of the superstructure with a suitable soil-foundation model; *ii)* the numerical analyses aimed to estimate the damage severity levels progressively attained by the superstructure as the imposed settlements increase (according to a given building deformation mode and for assigned soil mechanical parameters); *iii)* the generation, by way of an appropriate probabilistic model, of numerical fragility curves.

In this study, the structural model considered for analysis purposes (Fig. 1) corresponds to a three-storey building with a total height of 9 m (3 m per each storey) with a rectangular footprint having dimensions equal to 10 m × 14 m. The superstructure consists of masonry walls with openings on the various storeys not symmetrically distributed on the left and right side with respect to a central axis in the x direction (Fig. 1a). The thicknesses assigned to the walls are different for the exterior ones (60 cm for the first two storeys and 40 cm for the third one) and the interior ones (36 cm for the first two storeys and 24 cm for the third one). The floors are modelled as membranes (5 cm thick) having a linear-elastic orthotropic behaviour, reinforced by steel tie-rods placed at every floor level.

On the above masonry building model, the numerical analyses were performed using the academic version of the TREMURI software that allows simulating the global and non-linear behaviour of masonry buildings on the basis of the Equivalent Frame (EF) method (Lagomarsino et al., 2013).

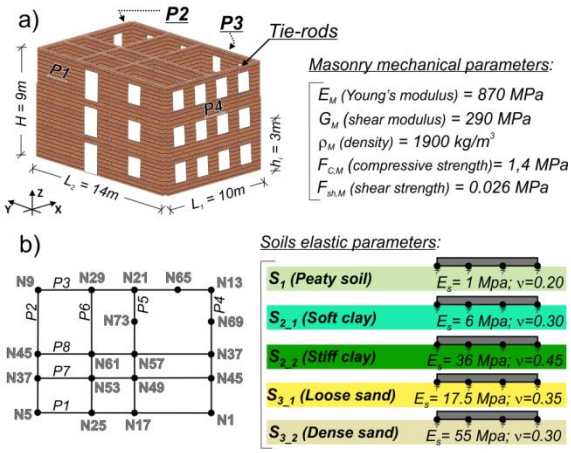

Figure 1. The soil-foundation-structural model: a) 3D view of the building model with adopted masonry mechanical parameters and b) distribution of computational nodes at the foundation level with considered soil elastic parameters.

In particular, masonry walls with openings subjected to in-plane loading are considered as idealized frames whose deformable elements (i.e. piers and spandrels – Fig. 2) are connected to each other by rigid nodes and may experience either a flexural or a shear failure mode. The mechanical parameters of the masonry adopted for numerical simulations (Fig. 1a) refer to the average values provided by the commentary of the Italian Technical Code (NTC, 2008) for existing buildings made of disorganized stones (pebbles, or erratic/irregular stones).

As for the soil-foundation interaction model, the foundation has a thickness equal to that of the exterior walls (60 cm) and rests on a subsoil model (Fig. 1b) simulating the behaviour of: peaty soils (S_1); clayey soils (S_2), in turn distinguished in soft clays (S_{2_1}) and stiff clays (S_{2_2}); sandy soils (S_3), categorised as loose sands (S_{3_1}) and dense sands (S_{3_2}). Their interaction with the building's foundation was simulated by putting springs, at the nodes at the base of the equivalent frame model generated by the TREMURI software (Fig. 1b), whose translational and rotational stiffness was estimated according to Gazetas (1991) on the basis of elastic parameters (Young's modulus E_s and Poisson ratio ν_s) associated with the type of interacting soil and the shape/size of the foundation base. The adopted values of soil elastic parameters (Fig. 1b) are consistent with information provided by the scientific literature (Kulhawy and Mayne, 1990; Berardi and Lancellotta, 1991; O'Kelly and Zhang, 2013).

On each of the five models deriving from the combination of the structural and subsoil model, numerical simulations were carried out by imposing – at the base of the foundation – differential settlements whose maximum value progressively increases from 0 to 50 cm according to four distinct scenarios (Fig. 3). In particular, the first two scenarios (Fig. 3a and 3b) allowed investigating the 3D behaviour of the masonry building model when the latter is subjected to settlements distributed with a linear trend whose maximum value corresponds to the node N1 (Fig. 3a) or the node N5 (Fig. 2b) of wall P1 (associated with the main façade); the third and fourth deformation mode aim to investigate the building's response when the minimum or maximum settlements are concentrated in the central part of the wall P1 according to, respectively, a hogging (Fig. 3c) or a sagging (Fig. 3d) deformation mode.

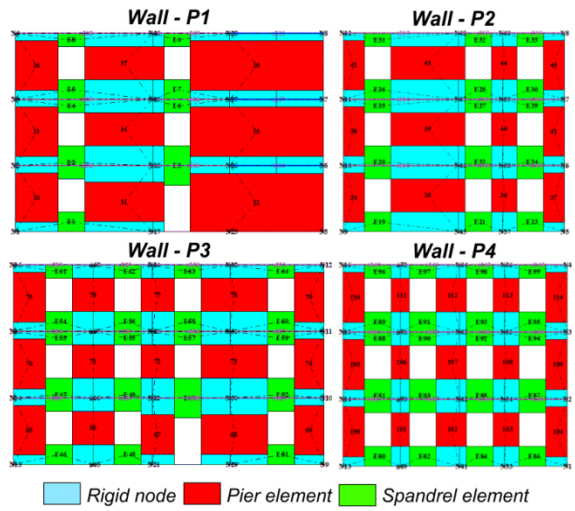

Figure 2. Sketch of the four exterior walls of the masonry building model.

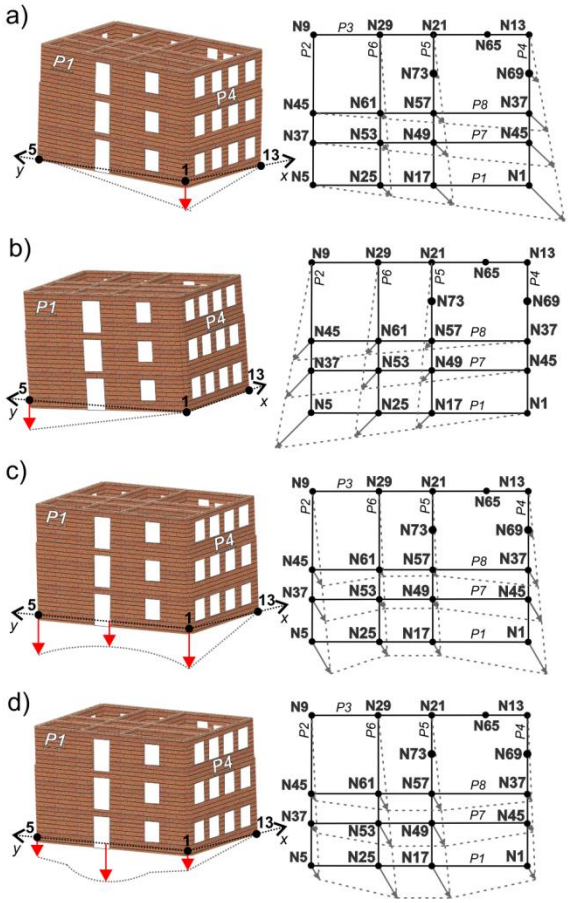

Figure 3. The four scenarios considered for the settlements imposed at the foundation level: a) linear-N1; b) linear-N5; c) hogging and d) sagging.

The results of the numerical analyses were used to analyze the global behaviour of the building in terms of attainment a certain damage severity level (Di) on the basis of a representative intensity measure IM (identified in the maximum differential settlement, Δ) and taking into account a well-defined damage criterion. In this regard, the damage severity was categorised into four classes (D2 – slight, D3 – moderate, D4 – severe, D5 – very severe) of the system proposed by Burland et al. (1977); whereas as engineering demand parameter (EDP), whose limiting values are associated with the attainment of given damage severity levels, the newly-defined *vertical drift* (VD) was assumed. More specifically, since in the case at hand the masonry walls are subjected to displacements whose main component develops along the vertical direction, the limiting values of VD were related to the relative vertical displacement (or vertical drift, dz) between two reference nodes located in the building roof as a consequence of the imposed settlements.

To this aim, it was considered an "elementary masonry building" (Fig. 4a) that, from a geometric/structural point of view, is representative of the building model corner in correspondence of the first bay (on the left) of wall P1 (Fig. 2). This elementary masonry building, which includes four walls (two of which with openings) having the same mechanical parameters used for the investigated building model (Fig. 1a) was subjected to linearly increasing settlements until the achievement of a maximum differential settlement equalling 50 cm in 200 steps. The relationship (Fig. 4b) between the incremental forces (ΔF_z) mobilized per each step (Δs) in correspondence of the two foundation nodes (b and c) undergoing the maximum absolute settlement and the relative vertical displacement (dz) between the nodes e (settling) and f (fixed) (Fig. 4a), allowed retrieving the yield (dz_y) and the ultimate (dz_u) values pertaining to dz. These values can be respectively associated with the achievement of the damage severity level D3 (corresponding to the loss of serviceability) and the damage severity level D5 (corresponding to the loss of stability). From the obtained F-dz curve (Fig. 4b), the limiting values of the vertical drift for each damage severity level (LVDi) were finally computed according to the heuristic equations proposed by Milutinovic and Trendafiloski (2003):

$$LVD2 = 0.7 \times dzy \quad (1a)$$

$$LVD3 = dzy \quad (1b)$$

$$LVD4 = dzy + 0.25 \times (dzu - dzy) \quad (1c)$$

$$LVD5 = dzu \quad (1d)$$

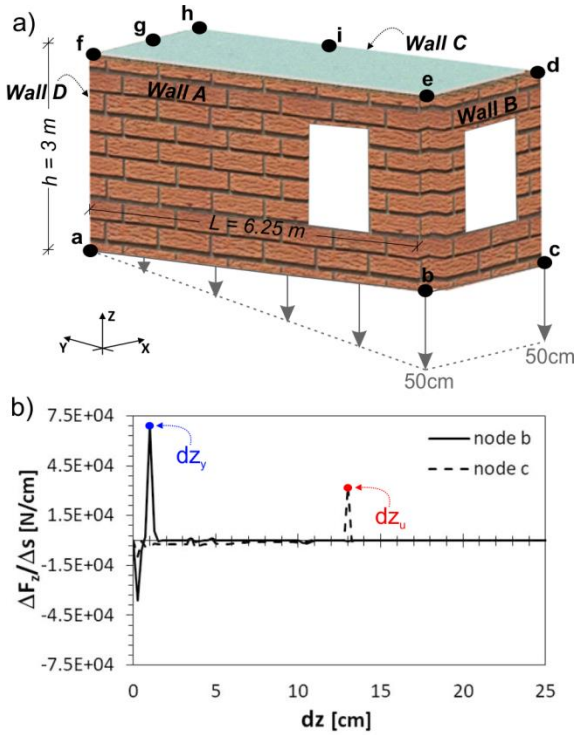

Figure 4. a) 3D view of the "elementary masonry building" and b) incremental force along the vertical direction per each step unit ($\Delta F_z/\Delta s$) - relative vertical displacement (dz) relationship with indication of the vertical drift values corresponding to the attainment of D3 (dz_y) and D5 (dz_u) damage severity levels (the showed example refers to a masonry made of disorganized stones and a S_{2_1} soil type).

For sake of completeness, the simulations were extended to another elementary building model having the same geometry but masonry mechanical parameters corresponding to buildings made of brick and lime mortar (NTC, 2008). Considering the results of all the computational schemes, it was assumed that the LVDi values normalised to the length (6.25 m) of the bearing wall A (Fig. 4a), namely the so-called limiting vertical drift ratios (LVDRi), are distributed log-normally about the median ($\overline{LVDR_i}$) with the standard deviation of the natural logarithm ($\beta_{ds,i}$). The obtained $\overline{LVDR_i}$ and $\beta_{ds,i}$ values are summarised in Table 1.

Table 1. Median ($\bar{\Delta}_i$) and standard deviation ($\beta tot,i$) values of the limiting vertical drift ratios corresponding to the attainment of a given damage severity level.

Damage severity levels	$\overline{LVDR_i}$	$\beta_{ds,i}$
D2 (Slight)	0.0019	0.424
D3 (Moderate)	0.0027	0.411
D4 (Severe)	0.0072	0.104
D5 (Very Severe)	0.0207	0.010

It is worth observing that the obtained limiting values are conservative estimates assuming that the building model schematised in Figure 1a attains the *i*-th damage severity level (Di) when at least one of the storeys of the (weakest) wall P1 reaches the $\overline{LVDR_i}$ value.

3 RESULTS

The results of numerical simulations carried out on a given masonry building model allowed evaluating its behaviour in terms of failure mode experienced by each of the elements (piers and spandrels) composing the walls of the superstructure. An example is shown in Figure 5 with reference to wall P1 of the masonry building model resting on the S_{2_2} soil (stiff clay) according to the four considered deformation modes (linear-N1; linear-N5, hogging and sagging) and for a Δ value equalling 16 cm.

For each masonry building model deriving from the combination of the structural and subsoil models and for each value of the maximum differential settlement imposed according to the four considered deformation modes, the corresponding vertical drift ratio values were estimated (as the ratio between the differential settlements exhibited by nodes 4 and 20 at the head of wall P1 in Figure 2 and their relative distance, equalling 6.25 m). Then, the latter were compared with the limiting values shown in Table 1 in order to individuate the Di attained by the building model.

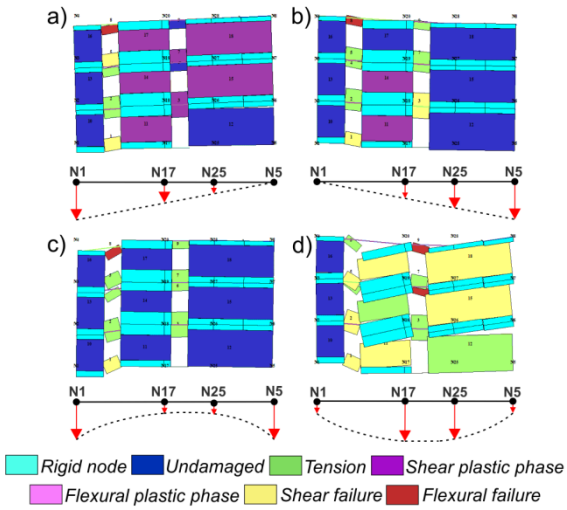

Figure 5. Damage development of the piers and spandrel elements of the P1 wall resting on stiff clay (S2_2) for a Δ value equal to 16 cm according to four considered settlement troughs: a) linear-N1; b) linear-N5; c) hogging; d) sagging.

The information so gathered was used to generate numerical fragility curves (Figure 6) by adopting a probabilistic log-normal distribution (NIBS, 2004; Shinozuka et al., 2000):

$$P\left(\text{Damage} \geq \text{Di} \middle| \Delta\right) = \Phi\left[\frac{1}{\beta_{tot,i}} \ln\left(\frac{\Delta}{\bar{\Delta}_i}\right)\right] \qquad (2)$$

where P (·) represents the probability of reaching or exceeding a certain damage severity level Di; Φ is the standard cumulative normal distribution function; $\bar{\Delta}_i$, is the median of the values of Δ; $\beta_{tot,i}$ is the standard deviation of the natural logarithm of Δ that can be computed by operating the convolution of the two log-normal cumulative distribution functions that are representative of the probabilistic relationships between either EDP and Di or EDP and IM. The median and standard deviation values pertaining to the latter relationship, which take into account the variability of the mechanical parameters associated with the soil type and the imposed failure scenario, were obtained by maximizing the likelihood function by way of a standard optimization algorithm (Shinozuka et al., 2000).

The generated fragility curves are shown in Figure 6; whereas the corresponding fragility parameters are synthesised in Table 2. The usefulness of these curves relies on the possibility of using them in preventing the occurrence of a serviceability limit state by quantifying the related uncertainties (in terms of fragility parameters). To these aims, considering credible scenarios of settlement troughs and soil types with a uniform probabilistic distribution, the maximum expected value of the IM should not be greater than a tolerable value; the latter might be determined at a specified probability of exceeding (e.g. the 5% according to Zhang and Ng, 2005) a given damage severity (e.g. the D3 level). Otherwise, suitable interventions (aimed to mitigate the effects of the external causes and/or restore/replace the existing foundations) should be designed and implemented.

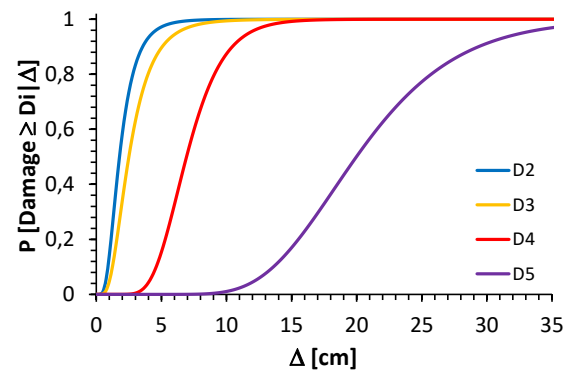

Figure 6. Numerical fragility curves generated for the analyzed masonry building model using the fragility parameters derived by way of the maximum likelihood estimation method.

Table 2. Median ($\bar{\Delta}_i$) and standard deviation ($\beta_{tot,i}$) parameters of the log-normal distribution function used for each damage severity level derived by adopting the maximum likelihood estimation (MLE) methods.

Damage severity levels	$\bar{\Delta}_i$	$\beta_{tot,i}$
D2 (Slight)	1.78	0.54
D3 (Moderate)	2.50	0.55
D4 (Severe)	6.93	0.32
D5 (Very Severe)	19.98	0.30

4 CONCLUSIONS

This paper showed the results of a numerical analysis aimed to investigate the response of masonry buildings, in terms of onset and development of the damage, to imposed settlement troughs. The same results were also used to generate fragility curves to be associated with masonry buildings, taking into account the uncertainties inherent to the mechanical parameters of soil and the deformation mode to which the foundation system might be subjected. The obtained curves, once validated on the basis of observations concerning real cases, could represent a useful tool for decision makers and geotechnical engineers in planning/selecting/designing appropriate foundation repairing/replacing measures aimed to prevent the attainment of intolerable damage severity levels.

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