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Vulnerability assessment of low-code reinforced concrete frame buildings subjected to liquefaction-induced differential displacements

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ABSTRACT

While liquefaction has been widely recognized as being one of the principal earthquake hazards resulting to significant economic and societal losses, research in the vulnerability assessment and quantitative evaluation of the expected physical damages to building structures is rather limited. In this respect, this study aims at the vulnerability assessment of typical low-code reinforced concrete (RC) frame buildings of various heights with shallow flexible foundations subjected to differential permanent displacements due to liquefaction. Nonlinear static analyses are carried out for each considered structural typology assuming different gradually increasing differential displacement patterns applied as quasi-static loads directly at its supports (footings). Different damage mechanisms are examined including a flexural damage of the building members and a shear failure of the columns. The proposed methodology results to the development of lognormally distributed fragility curves for different structural damage states as a function of the liquefaction induced differential displacements. It is shown that the height of the structure as well as the existence or not of a horizontal component of the differential displacements represent key factors affecting the vulnerability assessment. Vulnerability curves are also constructed to assess the expected direct losses in normalised cost terms. The whole approach is illustrated through a specific example.

1. Introduction

Experience gained from recent strong seismic events has demonstrated the high vulnerability of buildings and infrastructure to liquefaction-induced displacements resulting to severe physical damages and important economic and societal losses. Lai et al. [1] observed widespread liquefaction phenomena (lateral spreading and after-effects) on structures and infrastructures caused by the main shock that hit the Emilia-Romagna Region (2012) in Northern Italy. Bray and Dashti [2] have documented the performance of buildings at ground failure sites during recent earthquakes in Turkey (Kocaeli 1999), Chile (Maule 2010), New Zealand (Christchurch 2011) and Japan (Tohoku 2011) indicating that a considerable number of buildings on shallow foundations have settled differentially and slided laterally as a result of liquefaction causing extensive and substantial damage beyond economic repair. As an example, Cubrinovski [3] reported that liquefaction caused by the 2010–2011 Canterbury earthquake sequence in New Zealand seriously damaged 20,000 residential buildings in Christchurch (representing approximately one third of the total buildings), out of which about 8000 houses were considered uneconomic to repair.

Within an earthquake risk assessment framework, the evaluation of liquefaction demand in terms of permanent ground displacements is far from straightforward [4]. A number of methodologies are available for the prediction of absolute settlements and lateral movements due to liquefaction, most of which rely principally on empirical data e.g [5–8]. However, none of these methods have proved to be more reliable compared to the others. They are generally accepted to be accurate only to within a factor of 2 or 3 e.g [7] and their ability to predict displacements tends to reduce for small-to-moderate (0.3–0.75 m) deformations. Recently, physical tests and nonlinear dynamic soil-structure-interaction (SSI) effective stress analyses have provided valuable insights into the liquefaction-induced movements of buildings with shallow foundations proving that simplified empirical procedures are often inappropriate for estimating liquefaction-induced building settlements [2,9–11].

While methodologies for the assessment of ground and foundation deformation due to liquefaction have been the focus of research for many years, when it comes to determining the impact these deformations will have on existing structures and the subsequent liquefaction-induced structural damages, the published literature is generally rather poor. Methods for predicting structural damages due to liquefaction-induced ground displacements can be divided into three main

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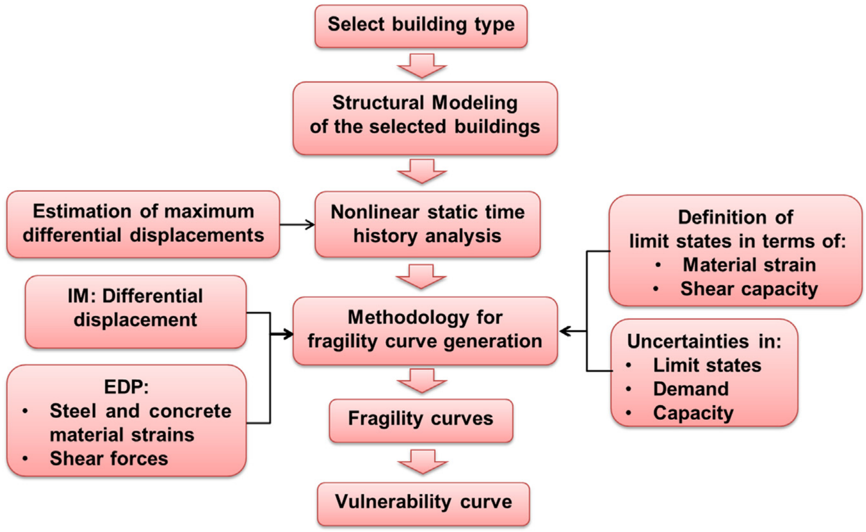

Fig. 1. Flowchart of the proposed framework for vulnerability assessment of RC frame buildings subjected to liquefaction-induced differential displacements.

categories: empirical/expert judgement methods e.g [12–14], mechanics-based methods [15] and methods based on numerical modelling e.g [16,17].

Regarding the first category, HAZUS [12] multi-hazard loss estimation methodology provides expert judgement fragility curves for buildings due to ground failure that relate the free field permanent ground displacement (PGD) to the probability of exceeding a certain damage state. Different fragility curves that distinguish between ground failure due to lateral spreading and ground failure due to ground settlement, and between shallow and deep foundations were proposed considering one combined Extensive/Complete damage state. Juang et al. [13] presented an empirical procedure for estimating the severity of liquefaction-induced ground damage at or near foundations of existing buildings. Cázares et al. [14] proposed vulnerability curves for buildings due to liquefaction, obtained through statistics of damage from a database of buildings affected by liquefaction during earthquakes.

As far as the second category is concerned, Bird et al. [15] made a significant contribution in this field by proposing analytical solutions to assess the expected damage of existing RC frame buildings due to liquefaction-induced differential ground movements (including differential vertical and/or horizontal displacements). Only representative cases of regular RC frame buildings with shallow, relatively flexible foundations were considered in this approach while the foundation deformation pattern was assumed to be equal to the free-field deformation.

In order to estimate the liquefaction-induced damages, more sophisticated methods based on numerical modelling can also be used. Two trends are generally used in the literature to estimate the liquefaction-induced damages using numerical analysis. The first is a "coupled approach", where the damages due to combined ground shaking and soil liquefaction effects are estimated in a single step e.g [16]. This approach is generally recommended for site specific applications where the degree of accuracy in the input data is high as it involves extensive computational effort. The second is an "uncoupled approach", where the soil and the structure are studied separately, and the soil displacements are imposed to a finite element model of the structure e.g [17]. The uncoupled approach yields to the evaluation of the structural damages due to liquefaction-induced permanent displacements ignoring possible initial damages due to ground shaking.

Numerical modelling techniques for estimating liquefaction-induced damages have also been applied for bridge systems e.g [17–20], quay walls [16,21] and other simplified soil-structure systems [22,23]. However their application to typical building structures has not received much attention and hence requires further investigation.

Under these considerations, the objective of this study is to propose a numerical methodology for the vulnerability assessment of typical RC frame buildings subjected to differential permanent ground displacements due to liquefaction (settlements and lateral spreading) based on an uncoupled numerical approach. Low-code RC moment resisting frame (MRF) buildings of various heights with surface flexible foundations are analysed using appropriate nonlinear constitutive models for the building materials. An extensive numerical parametric investigation of the selected building typologies is performed considering different combinations of statically applied differential displacements at the foundation level. The proposed vulnerability assessment method results to the construction of log-normally distributed fragility functions as a function of the liquefaction-induced differential displacement. Finally, a vulnerability curve is derived which allows the computation of the expected direct (structural and non-structural) losses of the buildings in cost terms.

2. Methodology

The layout of the proposed methodology for the vulnerability assessment of RC frame buildings subjected to liquefaction-induced differential displacements is illustrated in Fig. 1. It involves a comprehensive set of nonlinear parametric numerical computations and adequate statistical analysis. The conceptual features of the proposed methodological framework are outlined in the following paragraphs.

In the proposed vulnerability assessment method, the focus is on the differential component of liquefaction-induced ground deformation, which commonly occurs due to the heterogeneity in soil stiffness and stratigraphy both laterally and with depth. The differential settlements and differential lateral movements become the major cause of damage to buildings [4,15], as the absolute (uniform) displacements on their own are often insufficient to describe the main damage patterns of the structures. Thus, one may start with the quantification of the absolute free field ground deformations using one of the available empirical or numerical methodologies and continue with the evaluation of the corresponding differential movements beneath the foundation of a building.

The estimation of the differential ground movements entails an even greater uncertainty than the estimation of absolute movements. This is principally due to the soil heterogeneity and the lack of sufficiently detailed geotechnical data. Thus, unless an extensive geotechnical investigation at the building area is to be performed, the distribution of differential displacements over the footprint of the building in terms of