Engineering Geology 181 (2014) 58–70

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Simplified empirical method for predicting earthquake-induced settlements and its application to a large area in Spain

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ARTICLE INFO

Article history:
Received 9 January 2014
Received in revised form 1 August 2014
Accepted 10 August 2014
Available online 15 August 2014

Keywords:
Earthquake-induced ground settlement
Sandy soils
Empirical method
SPT
Maximum angular distortion
Granada (Spain)

ABSTRACT

Most of the commonly used existing empirical methods to predict earthquake-induced settlement (S) in sandy soils require numerous iterations or the use of charts, tables and diagrams. In general, these methods estimate the one-dimensional settlement of dry sandy soil on level ground by using a well-known step by step procedure based on Standard Penetration Test (SPT) values, which is particularly effective for practical applications. A review of the state-of-the-art methods shows that seismic settlement in all cases increases as the layer thickness (h) of sandy soils increases and corrected SPT blow count $(N_1)_{60}$ decreases. With that in mind, we propose a novel simple way to estimate S based on the $h/(N_1)_{60}$ ratio for a reference earthquake magnitude. This approach provides a tool that can rapidly obtain S in numerous sites and can be applied to large areas. In the last fifty years, the population of the Metropolitan Area of Granada (MAG) has doubled. The amount of developed land has increased by approximately 4650 ha and the areas with the greatest population and construction growth are located on sedimentary deposits. The land beneath the urbanized areas of the MAG is located on alluvial, colluvial, silt and clay deposits with different thicknesses of granular soils and varying water table depths. The MAG is acknowledged to be the most seismically active zone in Spain and seismically-induced phenomena such as liquefaction and ground settlement were reported in specific zones during moderate (1806) and strong (1431) historical local earthquakes. The present study focuses on differential vertical displacement assessment in this large area of Southern Spain for two earthquakes of magnitude Mw 6.6 and 7.0. The maximum expected settlement due to earthquake shaking of alluvial soils, sandy soils and fine soils (clay and/or silt) was obtained by correlating the mentioned $h/(N_1)_{60}$ ratio with the S predicted by two well-known methods. V_s values have been estimated from $(N_1)_{60}$ data using methods proposed in the literature and tested with V_s local data from SPAC and refraction profiles. The results from the new formula proposed here show predictable settlement ranging from 0.1 to 21.4 cm and up to 24.7 cm for the 6.5 and 7.0 earthquakes, respectively. These were greater than 2.0 cm and 3.3 cm in the north-central and north-western sectors of the study area, especially in the town of Atarfe and along the road between Pinos Puente and Atarfe, the same zones where settlements were observed in the 1806 earthquake. Zones where earthquake building damage may appear have been detected by comparing the maximum S and the maximum permitted settlements derived from different angular distortion values considering 5 and 6 m as typical distances between supporting structures.

1. Introduction

Soil deposits affected by strong seismic vibrations can undergo substantial changes in their resistance capacity which can cause considerable damage to structures built on these deposits. In the case of a large magnitude earthquake and depending on soil stiffness, strain can reach values of between 10^{-3} and 10^{-1}%. This can cause soil densification if the soil drains rapidly, a variation in pore pressure in undrained conditions, or it can reduce strain resistance to a minimum. This may lead to foundation settlement, subsidence or floating of underground structures, tilting of buildings, soil movements on slopes, and faults in unconfined flow deposits. It is important to understand that ground settlement is just one of the earthquake-related effects associated with large earthquakes, but densification can occur in sandy soils when no water is present, unlike liquefaction which only occurs when the ground is saturated.

Although early studies on the behavior of soils during vibration can be traced back to the early 1950s (e.g. Mogami and Kubo, 1953), extensive research on the calculation of earthquake-induced ground settlement began in the 1970s. Silver and Seed (1969, 1971a, 1971b) and Seed and Silver (1972) studied the settlement of dry sands during earthquakes under single directional loading in the laboratory and

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http://dx.doi.org/10.1016/j.enggeo.2014.08.009
0013-7952/

showed that cyclic shear strain, number of cycles, confining pressure and relative density affect the volume change of sandy soils. Pyke et al. (1974, 1975) extended this work and investigated the effects of multidirectional shaking on sand settlement using a shaking table, and concluded that settlement caused by multidirectional shear is twice that caused when it is unidirectional. Lee and Albaisa (1975) proposed a method that could be applied to saturated sandy soil. Martin et al. (1975) showed that the effect of the shear strain history depends as much on the magnitude of the pulses as on the order in which they are applied.

Tokimatsu and Seed (1987) based on Seed and Silver (1972) and Pyke et al. (1974, 1975), proposed a simplified analytical method for predicting earthquake-induced settlements which is widely used in both dry and saturated sandy soils. One of the main advantages of this method is that only the SPT-N value and some earthquake parameters must be considered, but unfortunately when there are multiple layers of soil with different properties a large amount of calculation is needed.

Pradel (1998) proposed a new method, based on Tokimatsu and Seed (1987), which avoids numerous iterations or the use of charts, tables and diagrams. It estimates the settlement of a sand layer subjected to seismic loading by directly using a set of equations. Lee (2007) proposed a simplified approach that consists of a set of equations to directly estimate the settlement of a saturated sandy soil layer subjected to earthquake loading. Chen et al. (2009) adopted these methods and introduced new formulas to calculate the maximum shear modulus (G_{max}). Useng et al. (2010) conducted shaking table tests on deposits of saturated clean sand and concluded that in the absence of liquefaction, settlements of these materials are generally very small.

The simplified methods mentioned above almost always use volumetric strain (ε_v) based on values for the cyclic stress ratio and normalized Standard Penetration Test, $(N_1)_{60}$. These methods estimate the magnitude of sandy soil settlement through empirical relationships, but are not practical when applied to multi-layered soil. An analysis of the state-of-the-art methods shows that earthquake-induced settlement (S) in all cases increases as the layer thickness (h) of sandy soils increases and the corrected SPT blow count $(N_1)_{60}$ decreases. Consequently, our proposal is a simple and practical approach to predict directly the maximum expected settlement due to densification in unsaturated sandy soil layers correlating it with the $h/(N_1)_{60}$ ratio.

To evaluate settlement (S) caused by earthquake shaking in sandy soil layers we first apply the three simplified procedures proposed by Tokimatsu and Seed (1987), Pradel (1998) and Useng et al. (2010) to different sites distributed in the study area and then we obtain a potential regression between S and the $h/(N_1)_{60}$ ratio for each of these methods. It is possible to apply one of these methods or a combination of them in this procedure. Once this relationship is obtained, the use of charts, tables and diagrams is not necessary. This approach provides a straightforward and quick estimate of S in large areas susceptible to earthquake hazard, such us Granada and its metropolitan area.

The Metropolitan Area of Granada (MAG) is located in the north-eastern part of the Granada basin (Figure 1a). Historical and instrumental seismic data indicate that it is the most seismically active area in Spain and it is classified as the most hazardous seismic zone in the Spanish Building Code (NCSE, 2002). From the 15th to the 20th centuries there have been several strong and destructive earthquakes in this basin, with the most important taking place in 1431 (June 27), and 1884 (December 25), with Io ≥ IX (EMS-98 scale). Others reached an intensity I_{EMS} ≥ VIII, such as those on April 24, 1431 (Io = VIII–IX), and October 27, 1806 (Io = VIII). The epicenters of these earthquakes are macroseismic and are located in the north-eastern part of the basin, our area of study, and are associated with the active NW–SE faults present in this area. The only exception is the 1884 event, which is

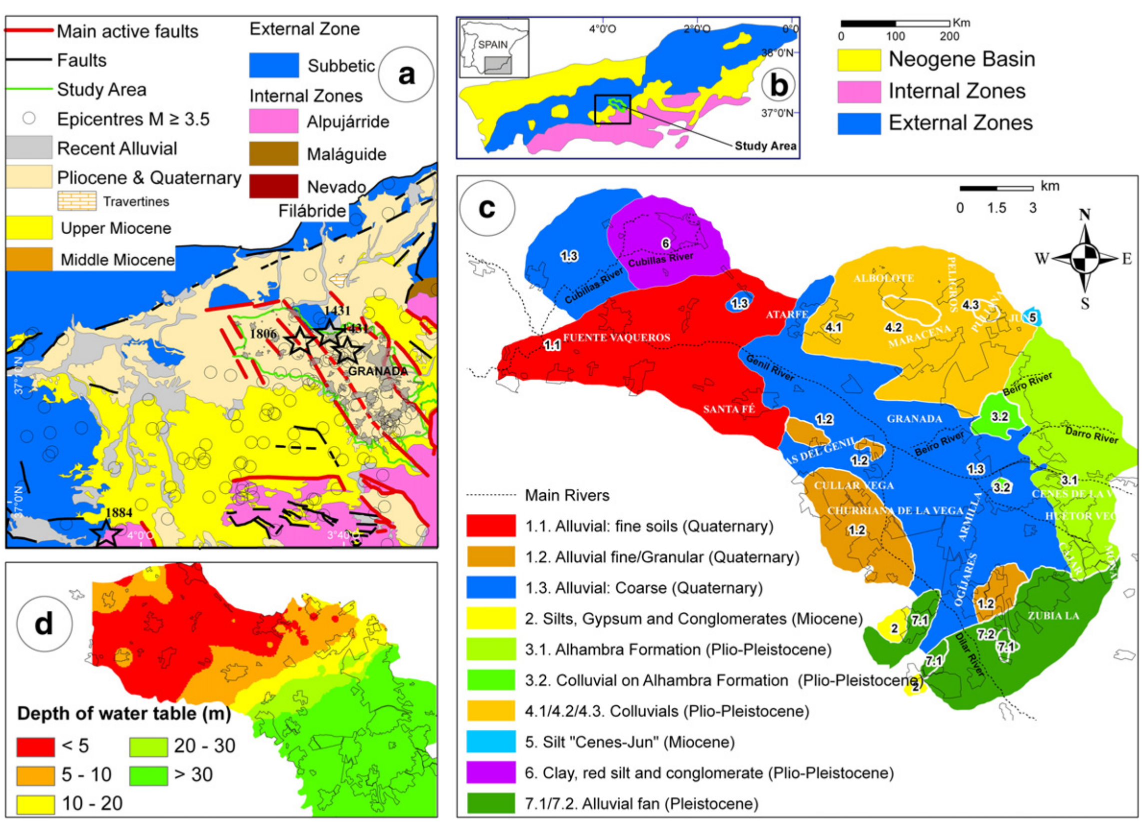

Fig. 1. Geological and hydrogeological features of the Metropolitan Area of Granada (MAG). (a) Geological and tectonic sketch of the Granada Basin showing the main active faults (modified from Sanz de Galdeano et al., 2012) and epicenters of instrumental (circle) and relevant historic (stars) shallow earthquakes. (b) General tectonic sketch of the central and eastern Betic Cordillera. The remarked zones show the location of Fig. 1a and 1c. (c) Spatial location of soil units (zones and sub-zones) of the study area. Town boundaries are shown with a thin polygonal line. (d) Map showing spatial distribution of water table depth.