Evaluation of seismically induced ground settlements in four towns near the city of Granada (Spain)

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SUMMARY:
In the last fifty years, the population of Granada and its metropolitan area has doubled. This has led to an increase in built-up land of approximately 4650 ha. This research study focuses on differential vertical displacement assessment in four towns (Albolote, Atarfe, Fuente Vaqueros, Churriana) and La Chana district of Granada city for an earthquake similar to one that occurred in 1431 in Granada (Mw ~7). The evaluation of settlements in alluvial soils due to earthquake shaking was performed for sandy soils and fine soils (clay and/or silt), by applying a method based on Tokimatsu and Seed (1987), Pradel (1998), and Useng et al. (2010). The results obtained show predictable settlements ranging from 0.5 to 100 cm (Atarfe: from 6 to 100 cm; Fuente Vaqueros: 9-28 cm; Albolote: 1-6 cm; Churriana: 1.4-2.5 cm; and La Chana: 0.5-11 cm) for sandy layer thicknesses of 0.5-12 m.

Keywords: Ground settlement, dry sandy soils, building foundation, earthquake hazards, Granada (Spain).

1. INTRODUCTION

Soil deposits affected by seismic vibrations can undergo substantial changes in their resistance capacity which can cause considerable damage to buildings located over these deposits.

Soil stiffness conditions wave propagation velocity. In the event of a large magnitude earthquake, and depending on soil stiffness, strain can attain values of between 10-3 and 10-1 %. This can cause soil densification, if the soil drains rapidly, vary pore pressure in undrained conditions, or reduce strain resistance to a minimum. These behaviors lead to foundation settlement, subsidence or the floating of underground structures, the tilting of buildings, slipping of slopes and faults in unconfined flow deposits.

Silver & Seed (1969, 1971a, 1971b and 1972) studied the settlement of dry sands during earthquakes under single directional loading in the laboratory. Pyke et al. (1974, 1975) extended their work and investigated the effects of multidirectional shaking on the settlement of sands using a shaking table. Lee & Albaisa (1975) proposed a method applicable to saturated sandy soil. Martin et al. (1975) showed that the effect of the history of shear strain depends as much on the magnitude of the pulses as it does on the order in which they are applied. Cuellar et al. (1977) developed a method of calculating the densification of a granular material submitted to a dynamic load by applying the so-called "Endochronic" theory for the tenso-deformational behavior of viscoplastic materials with memory. Tokimatsu & Seed (1987), basing themselves on Seed & Silver (1972) and Pyke et al. (1974, 1975), proposed a simplified analytical method of predicting earthquake-induced settlements in both dry and saturated sandy soils. Pradel (1998) proposed a new method, based on Tokimatsu & Seed, which avoids numerous iterations or the use charts, tables and diagrams. Chen et al. (2009) adopted these methods and introduced new formulas to calculate the maximum shear modulus (G_{max}). Ueng et al. (2010) conducted shaking table tests on deposits of saturated clean sand concluding that, in the absence of liquefaction, settlements of these materials are generally very small. These methods are almost always based on the Standard Penetration Test (SPT) values.

In the last fifty years, the population of Granada and its metropolitan area has doubled. This has led to an increase in built-up land of approximately 4650 ha. Furthermore, the areas that have experienced the largest growth in population and built-up land are located less than 15 km from the city. Several phenomena related to seismically-induced ground liquefaction–such as ground settlement, lateral spreading or foundation support failure resulting in building damage–were observed in localized zones of this metropolitan area during moderate and strong historical earthquakes (e.g. the 1806 and 1431 events).

The present study focuses on differential vertical displacement assessment in land beneath urbanized areas in four towns (Albolote, Atarfe, Fuente Vaqueros, Churriana) and the La Chana district of Granada, for an earthquake similar to that which occurred in the city in 1431 (Mw ~7). To evaluate settlements due to earthquake shaking in alluvial soils and in sandy soils with different percentages of clays and/or silts, we applied a method based on Tokimatsu & Seed (1987), Pradel (1998) and Ueng et al. (2010). Moreover, we present a new formula to calculate maximum expected settlement due to densification in sandy soil layers by using a logarithmic correlation between the sandy soil layer thickness, $(N_1)_{60}$, and maximum expected settlement.

2. GEOLOGICAL SETTING AND ENGINEERING GEOLOGY OF THE STUDY AREA

The Granada basin is settled on the central part of the Betic Cordillera along a NE-SE belt separating the Sub-Betic domain, or External Zones, from the Betic domain or Internal Zones (Figure 1a). It is one of a set of intra-mountain basins developed in Neogene times during post-orogenic events of tectono-sedimentary deposits. The basin is composed of Miocene age deposits which are more than 2 km thick in some areas (Morales et al., 1990). The Vega de Granada is a predominantly Quaternary plain located in the NW part of the Granada basin, an area surrounding the Genil River between the villages of Cenes de la Vega and Láchar. This is a highly-irrigated alluvial plain recently deposited along the river and its subsidiaries (Cubillas, Fraile and Colomera streams, Darro River and Aguas Blancas, Monachil and Dilar streams), all descending from the surrounding hills and accumulating thick deposits of eroded material of which those dating from the Holocene are more than 200 m in thickness (Figure 2.1).

La Vega de Granada and its proximal edges present highly heterogeneous geotechnical conditions resulting from lithological, textural and hydro-geological variations. Seven zones and ten sub-zones were defined (Figure 2.1) for 22 areas with different lithologies.

The Quaternary alluvial formation is predominant in the study area. Three sub-zones have been distinguished: fine alluvial (CL and ML with intercalated–SM and SC–granular levels; alluvial fine-granular (alternation of CL-ML and SC, SM and GC, GM); and coarse alluvial (SM, GW-GM with silt intercalations–ML). These materials are located on a stretch running WNW-SSE from Láchar to Ogíjares (Figure 2.1 and Table 2.1).

The research and results obtained permitted the computing of a geotechnical database with more than 300 geotechnical foundation reports including 459 mechanical rotation borings with continuous undisturbed sampling, 691 dynamic penetration tests, 354 trenches and more than 5000 *in situ* and laboratory tests (Valverde-Palacios, 2010).

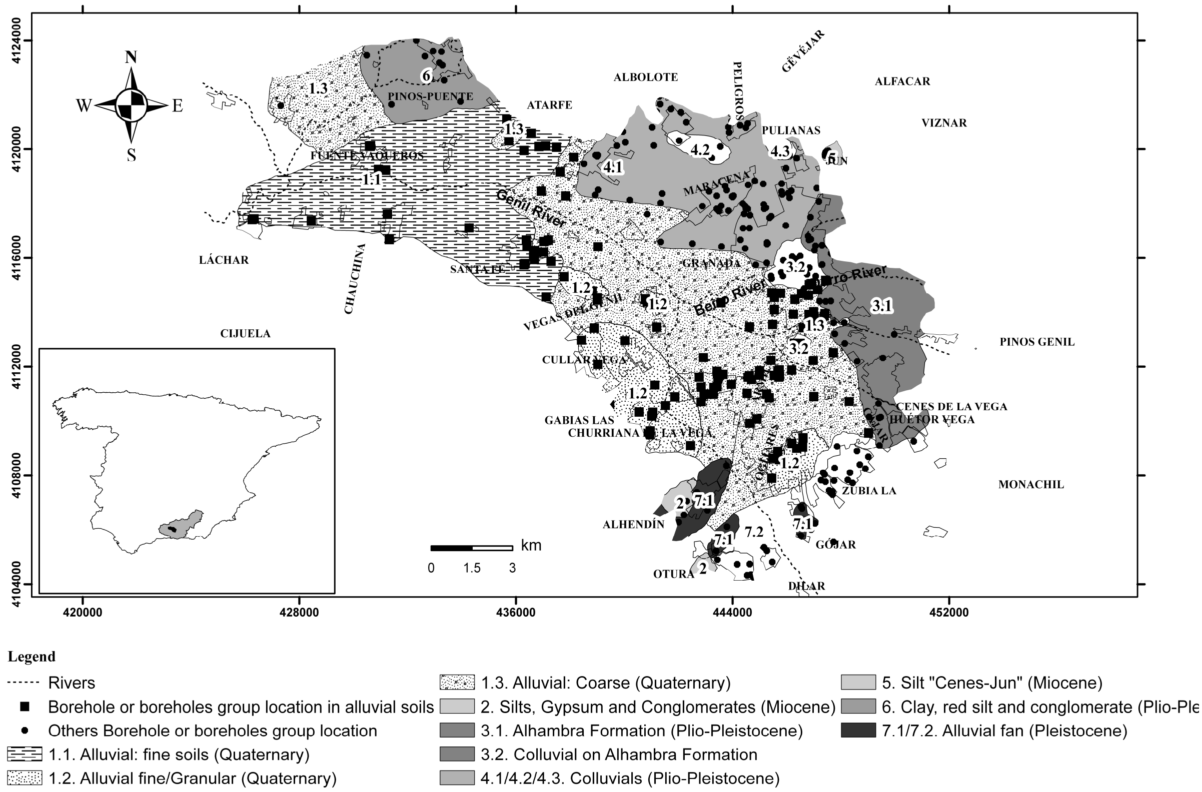

Figure 1. Spatial distribution of soil units, zones and subzones

Table 2.1. Summary of geotechnical parameters: σadm (kPa), admissible bearing capacity; c (kPa), cohesion; ϕ °, internal friction angle; Ks_1 (kN/m^3), coefficient of ballast; φ (kN/m^3), bulk density; NSPT , number N Standard Penetration Test; LL (%), liquid limit; LP (%) plastic limit; IP (%) plasticity index; #200(%), percentage of fine fraction passing sieve nº200 ASTM; D_{50}, soil grain size at 50%; USCS, Unified Soil Classification System.

Geotechnical parameters	Zone 1. Holocene: Alluvial	Zone 1.1. Holocene: Fine Soils	Zone 1.2. Holocene: Fine/granular soil	Zone 1.3. Holocene: Coarse granular soil
σ_{adm} (kPa)	40 - 300	40 - 100	50 - 250	70 - 300
c (kPa)	0 - 320	50 - 320	0 - 70	0
ϕ (º)	20 - 36	20 - 30	20 - 35	30 - 36
Ks1 (kN/m^3)	20 - 120	20 - 60	30 - 100	40 - 120
φ (kN/m^3)	16 - 20	16 - 20	16 - 20	18 - 19
$(N_1)_{60}$	5 - R	5 - 20	8 - 30	15 - R
LL (%)	NP - 54,8	23.5 - 47.4	21.4 - 54.8	NP - 23.2
LP (%)	NP - 22,4	13.8 - 22.4	16.9 - 22.0	NP - 16
IP (%)	0 - 32,8	4.5 - 27.0	2.5 - 32.8	NP - 7.2
#200 (%)	2,1 - 97,2	73.5 - 98.4	5.8 - 88.2	2.7 - 35.2
D_{50}	0,01 - 8	0.01 - 0.3	0.1 - 6	0.1 - 9
USCS symbols	CL, CH, ML, CL - ML, SW, SM, SC, GC, GM, GW, GP - GM, GW - GM, GP - GC	CL, ML, SC - SM	CH, CL, GM, GP - GM, ML	GW, GP, GM, GP - GM, GW - GM, GC, GP - GC, SW, SM

3. DATA

The sites and depths selected for the quantification of earthquake-induced settlements are those where the lithological column of the different probes, identified using the United Soil Classification System (USCS), show the presence of clean sandy soils (SW or SP) and sandy soils with fine clay or silt matrices (SC or SM). Moreover, unlike materials susceptible to liquefaction, where the ground should be saturated, densification can occur in sandy materials in the absence of water. Bearing in mind the established textural premise we have conducted a search of all the soil fraction layers between 4 and 0.08 mm in the previously determined sectors–i.e. Albolote, Atarfe, Fuente Vaqueros, Granada-La Chana and Churriana de la Vega (see Table 5.1)–to calculate the models. Finally, 17 points have been established to evaluate the settlements with sandy layer thicknesses of 0.5-12 m.

4. EVALUATION OF SEISMICALLY INDUCED GROUND SETTLEMENTS

When designing foundations, we need to know the maximum dynamic modulus of shear stress stiffness–also known as the maximum shear modulus (G_{max})–at the lowest point at which we want to estimate the deformation. This is essential in the simplified analytical methods of predicting earthquake-induced settlement in both dry and saturated sandy soils. Tokimatsu & Seed (1987) recommend an equation in which Gmax depends on the corrected SPT-N [$(N_1)_{60}$] and mean principle effective tension (σ'm). Kramer (1996) and Diaz Rodríguez (2006), following Ohta & Goto (1976), use a different formula to calculate Gmax, which makes no allowance for the material. In this case, Gmax depends on shear wave velocity (V_s) propagation, soil density (ρ) and the acceleration of gravity (g).

The most appropriate way to determine V_s is by drawing on seismic down-hole, up-hole or cross-hole field tests. However, these are not usually used in buildings even though, according to Spanish construction norm NCSE-02 for building types C-2 (constructions of between 4 and 10 floors, including basements), C-3 (constructions of between 11 and 20 floors, including basements) and C-4 (monumental buildings or exceptional constructions, or those of more than 20 floors, including basements), this type of test is obligatory when basic seismic acceleration exceeds 0.08 g. In fact, this norm should be applied throughout Granada province, except in the towns of Puebla de Don Fabrique and Alicún de Ortega where basic seismic acceleration is 0.08 g. Given that these seismic tests provide no information on V_s, we have drawn on the numerous existing empirically-established correlations (Ohta & Goto, 1978; Seed & Idriss, 1981; Hasancebi & Ulusay, 2007), in which V_s is obtained from $(N_1)_{60}$.

In current research being conducted by a research team of the Andalusian Institute of Geophysics (Navarro et al., 2010), V_s values measured using SPatial Auto-Correlation (SPAC) techniques, are similar to correlations reported elsewhere (Imai, 1981; Jafari et al., 2002) if applied to our study area. Among the V_S-$(N_1)_{60}$ correlations, a good approximation is that proposed by Imai (1981). Despite the fact that no empirical correlations exist for this area, we have adopted this formula in the present study, even though some V_s values may be below those measured *in situ*. In any case, adopting the Imai (1981) equation gives values that are to the side of safety. To calculate settlement due to densification, we have also used the method suggested by Tokimatsu & Seed (1987), which is another approximation with low uncertainties with respect to V_s measured in the field.

Accordingly, we have calculated V_s and G_{max} at each of the designated sites in the study area so as to use interpolations to prepare maps that characterize the Vega de Granada area in terms of V_s and G_{max}.

Having obtained G_{max}, we can determine effective earthquake-induced shear strain (γ_{eff} -(G_{eff}/G_{max})- using the Eqn. 4.1. proposed by Tokimatsu & Seed (1987).

$$\gamma\left(\frac{G_{eff}}{G_{max}}\right) = \frac{0.65 \cdot a_{max} \cdot \sigma_0 \cdot r_d}{g \cdot G_{max}} \tag{4.1}$$

On the basis of this, we determine the effective shear strain of the soil (γ_{eff}), using the table in Figure 3, to obtain γ_{eff} along the y-axis.

Volumetric strain (ε_v) is determined from the appropriate tables, when applying 15 cycles of cyclic shear stress (representing a seismic event of magnitude 7.5) and correcting for the volumetric strain ratio of 0.90 equivalent to M_w ~7. Cyclic shear stress (γ_{cyc}) is equivalent to the effective shear strain (γ_{eff}), except that γ_{cyc} is expressed as a percentage, hence γ_{cyc}=100 γ_{eff}. Notwithstanding, to determine volumetric strain (ε_v) we need to know *a priori* the corrected SPT-N value ($(N_1)_{60}$) or the relative density (D_r) of the soil *in situ*. Unidirectional volumetric strain (ε_v) is multiplied by two in order to take into account the multidirectional effect of earthquake-induced shaking. Unidirectional volumetric strain (ε_v) is multiplied by two to take into account the multidirectional effect of earthquake-induced shaking.

Finally, following Tokimatsu & Seed (1987), the settlement of each layer is calculated as volumetric strain, expressed as a decimal, multiplied by the thickness of each layer. Note that these authors use feet as their unit of measure.

Another method, based on the previous one and used elsewhere, is that of Pradel (1998). He only uses mathematical formulas analogous to Tokimatsu & Seed, without needing to resort to numerous iterations or the use of charts, tables and diagrams to obtain other parameters. Ueng et al. (2010) conducted shaking table tests on saturated clean sand deposits and concluded that settlements of these materials, in the absence of liquefaction, are generally very small. They established a relation between volumetric strain (ε_v) and relative density ($\varepsilon_v = -0.00055D_r + 0.0683$).

All these methods have been implemented using a spreadsheet in order to automate the process and make it easier to follow the protocol.

5. RESULTS AND DISCUSSION

According to the Spanish Technical Building Code (Ministerio de Vivienda, 2006) and recommended by different authors (e.g. Brinch Hansen, 1965; Meyerhof, 1976, 1982; Herndon, 1990), for reticular structures with partition walls, maximum angular distorsion (β) is established as β=1/500 of the mean distance between supports. If as usual, supports are 5 or 6 m apart, the maximum settlement allowable is in the order of 1 cm, and 1.2 cm, respectiely. Furthermore, β=1/150 is the limit at which fissures and damage to structural elements begin to appear, which means the maximum permitted settlements for these mean distances between supports range from 3.3 to 4.0 cm.

Table 5.1 shows results for expected earthquake-induced settlements in the five study area zones. We will now describe and comment on these results and recommend appropriate foundation depths and types.

a) Albolote sector. Expected settlements range between 1 and 6 cm, depending on the thickness of the sandy soil layer (0.5 to 2.5 m) with clays and/or silts. Settlements are expected to be greatest in the sector near to the right bank of the Juncaril River and NW of the town (Table 5.1).

Mean settlements can be estimated at some 2.5 cm, which is inadmissible for distances of both 5 and 6 m between supports. However, in static conditions in this sector, foundations with good load distribution and stiffness–such as strip footing, beam grid, or reinforced slabs with thicknesses of not less than 0.70 m–have been recommended; in the SE half of the Juncaril industrial estate deep foundations have even been recommended (Valverde-Palacios, 2010). However, the depths at which the sandy soil levels in which settlements can occur are located can mostly be avoided by the construction of a basement floor, bearing in mind that the water level is at around 3 m.

b) *Atarfe sector.* Expected settlements could measure between 6 and 100 cm as the sandy soil layer thicknesses–with varying proportions of fine clays and/or silts–range from 3 to 12 m. The largest expected settlements have been located along the Pinos Puente-Atarfe road (Table 5.1).

Even without considering seismic effects on the soil, we would recommend deep foundations based on pilings because of the presence of in-fill and, above all, of materials with very poor load-bearing capacity. These settlements should be taken into account in pile calculation because they can cause negative frictions potentially leading to increased axial load.

c) *Churriana de la Vega sector.* Expected settlements range from 1.4 to 2.4 cm, depending on the thickness of the sandy soil layer, well- or poorly-graded with silt matrix, which are found at between 1.0 and 1.5 m (Table 5.1).

Table 4.1. Summary of results and location and properties of sandy layers (#200(%), percentage of fine fraction passing sieve nº 200 ASTM; ϕ°, internal friction angle

Towns	Sandy layer thickness (m)	Depth of Sandy layer (m)	Maximum settlements (cm)	USCS symbol	Depth of water table	#200 (%)	$(N_1)_{60}$	Φ (°)
Albolote	1.0	1.50-2.50	2-3	SC	12.0	37.47	15	30
	1.0	3.50-4.50	2-3	SC-SM	6.3	38.51	20	15
	2.5	5.50-8.00	3-5	SM	6.3	19.11	30	30
	0.5	1.50-2.00	1-1.5	SC-SM	4.4	43.90	19	30
	1.5	4.50-600	4-6	SM	4.4	24.20	10	30
Atarfe	7.5	8.50-16.00	20-75	SM	3.9	30.22	11	28
	3.0	5.00-8.00	6-25	SW-SM	6.0	30.22	13	29
	12.0	4.50-16.50	28-100	SM	4.8	18.50	12	29
Churriana de la Vega	1.0	7.00-8.00	1.4-2	SM	70.0	16.20	30	33
	1.5	1.50-3.00	1.8-2.4	SP	70.0	16.20	30	30
Fuente Vaqueros	10.0	5.00-15.00	9-27	SW-SM SP-SM	2.0	6.80	15	28
	7.0	3.00-10.00	18-28	SM	1.5	15.50	11	28
Granada-La Chana	0.5	1.00-1.50	0.5-1	SC	15	47	14	28
	0.6	2.30-2.90	0.6-1.2	SC	15	42	14	28
	2.5	5.0-7.50	2-6.5	SP-SC	15	11.3	15	25
	0.5	1.0-1.50	0.5-1.2	SC	15	45	12	25
	5.5	4.50-10.00	5-11	SC	19	38	30	28

Any type of direct foundations can be used in this sector. While the maximum expected earthquake-induced settlements make the use of isolated footing type foundations inadvisable, the depths at which the sandy soil layers are to be found can be avoided by constructing a basement floor and/or increasing the depth to the foundation level.

d) Fuente Vaqueros sector Expected settlements are quite considerable, between 9 and 28 cm, as the thickness of the sandy soil layers, with different proportions of fine clays and/or silts, range from 7 to 10 m. Settlement is expected to be greatest in the materials found in the SSE sector.

In this sector, foundations with a good load distribution and stiffness–reinforced slabs of not less than

0.70 m thickness–are recommended. However, the depths at which the sandy soil layers which are susceptible to densification are located range from 3 to 15 m. They cannot, therefore, be avoided by constructing a basement floor and/or increasing the depth to the foundation level. Furthermore, we have to take into account the fact that the water level is at a depth of around 1.5 m. Consequently, we recommend the use of deep foundations on pilings. The expected settlements should be taken into account in pile calculation as they can produce negative frictions that increase the axial load.

e) Granada-La Chana sector Expected settlements due to densification range from 0.5 to 11 cm in sandy soils located at depths of between 1 and 10 m.

In this sector, *a priori*, we recommend using direct foundations with strip footing, and/or reinforced slabs with high stiffness. However, the levels susceptible to volumetric changes are depths of up to 10 m, which entails the construction of one to three basement floors, depending on the zones, or deep foundations on pilings.

6. CONCLUSIONS

The results obtained show important predictable settlements ranging from 0.5 to 100 cm in the studied zones. The great variation of this seismically-induced surface-permanent deformation shows us the importance of detailed studies in the Vega de Granada urban areas. In Atarfe town, we have found the most hazardous zones, due to the presence of a thick sandy layer with silt (3-12 m); settlements could reach from 6 to 100 cm, especially in the sector along the Pinos Puente-Atarfe road.

Near all the Fuente Vaqueros urban area is another hazardous zone because the thickness of the sandy-silt soil layers is substantial (7-10 m) and the water table level is at a depth of around only 1.5 m. Consequently, there could be settlements of 9 to 28 cm. The lowest expected settlements values are in the NW sector of the town. In Albolote, expected settlements are around 1-6 cm and the largest is located in the sector near to the Juncaril River and NW of the town.

The sandy layers underlying Churriana are thin and randomly distributed, with a thickness of 1 to1.5 m. Consequently, settlements could be of only 1.4 to 2.5 cm. In the La Chana district of Granada, the sandy layers have varying thicknesses of 0.5 to 5.5 m and expected settlements are therefore in the 0.5 to 11 cm range.

If we set the safety limit against fissures as $\beta=1/500$ of the separating distance and $\beta=1/150$ as the limit at which fissures and damage begin to appear in structural elements, we can conclude that:

- The depth and type of foundations recommended in static conditions can be modified when the seismic effect on soil densification is considered. This is even the case when shallow foundations with good load distribution and stiffness are recommended because the expected settlements surpass the limits established by Spanish regulations in terms of maximum angular distortion.

- If any given project includes no underground structures, or these are insufficient because the basement floors can be accommodated without the need to excavate layers that have been identified as being susceptible to densification, deep foundations based on pilings should be used.

This is of great importance in new urban development planning in order to establish construction type. To avoid making projects too expensive because of the foundation type, in areas where deep foundations based on pilings are needed, we recommend intensive residential property developments (multi-family dwellings) with extensive residential properties (single-family dwellings) being reserved for areas where shallow foundations, of no more than 4 m depth, are sufficient.

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