Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Liquefaction potential of fine granular soils in Western Andalucía (Spain)

G.Armijo Palacio & P.Sola Casado
Geocisa, Spain

ABSTRACT: Shallow foundations on loose sandy sandy-silty soils under the water table have been studied in two points at "Bahía de Cádiz" in Western Andalucía. This study has found that these places can liquefy under the strongest seismic conditions given by the Spanish Seismic Norm Project (NSCE-90). This potential risk has been evaluated by means of field methods, which are based on the field tests-seismic behaviour correlation. These methods are considered to be the most adecquate among the existing ones for these soils and the local earthquakes. To ensure a proper static behavior in both places, two different ground improvement procedures have been used: dynamic compaction and vibro-replacement. The results obtained lead us to conclude that these procedures have also eliminated liquefaction susceptibility in these two particular cases.

1. INTRODUCTION

Even though no evidences of liquefaction phenomena have been registered in the last years in Spain, the historical background (Carreño, 1992) tell us that we should consider such a possibility at "Bahía de Cádiz" in Western Andalucía. In this place there is a coexistance of loose sandy-silty soils under the water table and remarkable intensities in the strongest foreseen earthquakes.

The evaluation methods of the liquefaction potential that are used have been developed from the revision of the existing ones, sorting out the most efficient according to the soil and seismic local conditions. These methods also allow us to prove that the ground improvement treatments-dynamic compaction and vibro-replacement (stone columns)-con avoid the liquefaction risk.

2. LIQUEFACTION POTENTIAL EVALUATION

2.1. Most adequate methods

The increasing need to know the liquefaction potential of fine granular soils has led to the development of a wide variety of evaluation methods in the last years. These methods can be divided into two main groups: 1. those in which the dynamic characterization of the soil is done by means of field tests, and 2. those in which it is done by means of cyclic laboratory tests.

The former are based on the experience of real cases, and they employ correlations of some soil characteristics (penetration resistance, grain size distribution, water table position) with their performance in previous earthquakes. The latter rely on the comparison between liquefaction resistance obtained in cyclic laboratory tests and the stress or strain conditions caused by the earthquake, which are usually evaluated using either simplified analytical methods or numerical response models.

The obtention of samples without changes in the structure and degree of saturation as well as the special laboratory tests for the reproduction of the stress and the "in situ" soil boundary conditions, is a difficult and rather expensive task. Therefore, the methods of the first group are the most advisable ones.

On the other hand, in spite of the historical background, we do not have reliable data to carry out a local verification of these field methods. Then it is convenient to use -within those having a wider experimental support- more than one method, taking into consideration the conditions of the soil and the seismic characteristics. Having this in mind, the two methods which are judged to be the most adecquate are based on empirical correlations with SPT N -values and they must be used regarding the considerations pointed out in this paper.

The first of these methods starts from the Seed-type charts (Figure 1) and it is convenient to consider the aspects from now on indicated.

The energy applied to the sampler during the realization of the SPT tests is far below the theoretical one. In Spain it only corresponds to about 45 % of the theoretical energy according to the Décourt (1988) correction factors.

In Figure 1 we represent the cyclic stress ratio (σ_{av}/σ'_{vo}) which causes liquefaction for earthquakes of magnitude $M = 6{,}5$ in terms of normalized corrected N-values for a reference energy of 60 %, $(N_1)_{60}$, and soils with fines content FC $\simeq$ 15 %. The dashed curve has been obtained multiplying the ordinates of the Seed et al. (1985) basic curve, for $M = 7{,}5$ and FC = 15, by a factor dependent on the number of equivalent cycles given to each M by such authours. At the same time the continuous line corresponds to the analytical expression given by Ambraseys (1988) for $6 \leq M < 7{,}5$ and FC $\simeq$ 13 %.

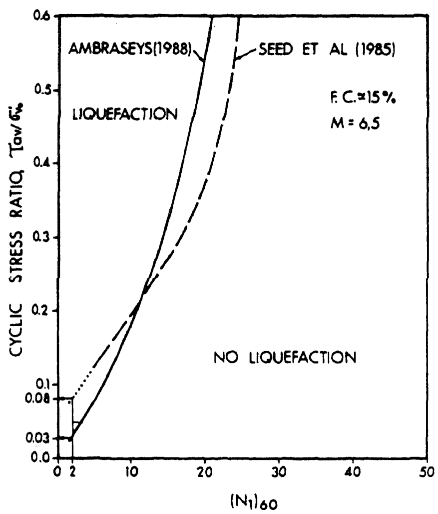


Figure 1. Relation Between stress ratios causing liquefaction and N_1 values for silty sands.

The cyclic stress ratio produced by the earthquake can be calculated using the well-known Seed et al (1983) simplified formula:

$$\frac{\tau_{av}}{\sigma'_{vo}} = 0{,}65 \cdot \frac{a_{max.}}{g} \cdot \frac{\sigma_{vo}}{\sigma'_{vo}} \cdot r_d \quad (1)$$

where a_{max} = maximum acceleration at the groung surface; σ_{vo}/σ'_{vo} = total and effective vertical stress ratio; r_d = stress reduction factor which equals 1 at the ground surface and 0,9 at a depth of 10 m.

In the potentially liquefiable areas of Western Andalucía the values which are normally considered are $M = 6\text{-}6{,}5$ and $(N_1)_{60} \leq 10$. So, the Ambraseys criterium is more appropiate because, appart from being based on more proximate European earthquakes, it is clearly a most conservative method.

A second method to have as a reference is the one based on the Chinese correlations (Taiping et al, 1984) which directly give the critical penetration resistance for an energy of about 60 %, N_{crit}, with the expression:

$$N_{crit} = N\,[1+0{,}125(d_s-3)-0{,}05(d_w-2)-0{,}07\,p_c] \quad (2)$$

where N = a function of the earthquake shaking intensity; d_s = depth to layer under consideration, in meters; d_w = depth of water table, in meters; and p_c = percentage of clay sizes.

The fact of considering the characteristics of the earthquake by means of the intensity entails a clear advantange in places like Spain, where there is in general a lack of instrumental data and, consequently, of M values.

The first of the given methods does not take into account the plasticity of fines, while the second does take it into account through the clay content, which is a parameter of uncomfortable determination and rare availability. Due to this situation and as a complement to the other aspects considered, it is convenient to bear in mind the indication of Armijo Palacio (1987) according to which *the liquefaction potential risk is very scarce* in soils with a liquid limit $\geq$ 35 % and a plasticity index $\geq$ 10 %.

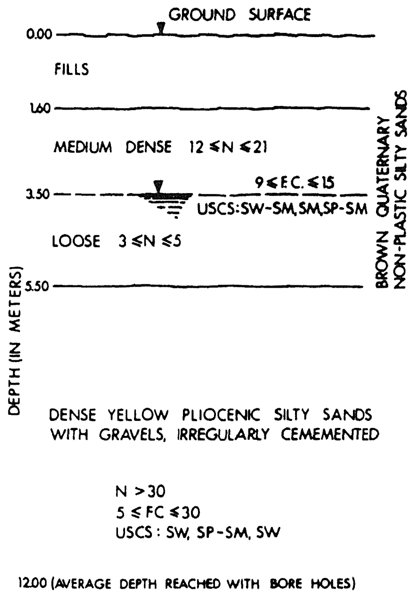
2.2. Application to two places in the "Bahía de Cádiz"

According to the Spanish Seismic Norm Project (NSCE-90) the corresponding values for this zone are: basic seismic acceleration $a_b = 0{,}06$; soil coefficient $C = 1{,}8$; and intensity I = VII. Consequently, for the average depths of the potencially liquefiable layers, we obtain, applying expression (1):

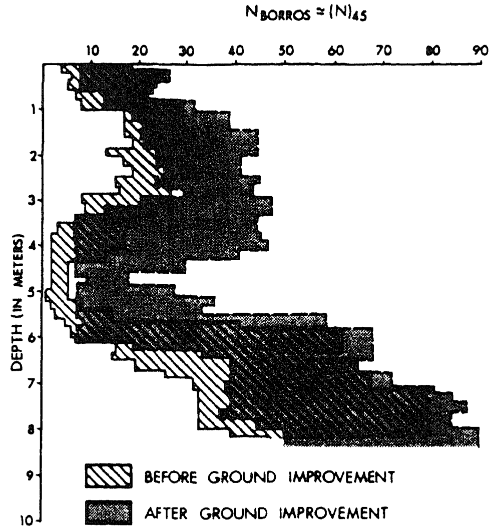
$$\frac{\tau_{av}}{\sigma'_{vo}} = 0{,}65 \times 0{,}06 \times 1{,}8 \times 1{,}13 \times 0{,}95 = 0{,}075$$

The first place to analyse is the "Polígono 8B" at Puerto Real, where the ground (Figure 2.a) includes a layer of loose silty sands inmediatly under the water table, with a FC = 9-15 % without plasticity, and $(N)_{45}$ = 3-5, deduced from Borros-type dynamic penetration tests.

Taking $(N_1)_{60} = 2$ as representative of these sands, the Seed and Ambraseys criteria (Figure 1) indicate a boundary cyclic stress ratio of 0,08 and 0,03 respectively, being these values similar or inferior to the ones that can be caused by the earthquakes in that



(a)



(b)

Fig. 2.a) Average soil profile at the "Polígono 8B" b) Envelopments of the penetration diagrams.

area. On the other hand, acknowledging a p_c ≃5 % the Chinese expression yields a N_{crit} = 5. Therefore, it must be concluded that these sands are potencially liquefiable.

A similar case can be observed in the "Factoría Off-Shore" of DYCSA in Bajo de la Cabezuela (Figure 3.a). Here the loose silty-sandy soils under the water table present a FC≃20 % without plasticity and an $(N)_{45}$ which varies between 2 and 7. So the analysis of the liquefaction risk shows similar results to the previous case.

3. RESULTS OF THE GROUND IMPROVEMENT

The improvement treatments can modify the liquefaction potential as a consequence of the densification (dynamic compaction, vibroflotation), of the increment of permeability or drainage (vibro-replacement, vertical drains), or of the cementation among particles (consolidation grouting).

At the "Polígono 8B", the foundation of buildings from 1 to 4 floors by means of continuous footings of 1,1-1,5 m wide and a pressure of 0,2 MPa, has led to a dynamic compaction, carried out in three phases with a net of 2,5-5 m, 1500 m.kN/m² of total energy and 600-1000 m.kN per impact.

The densification produced has caused an increase in the $(N_1)_{60}$ characteristic of loose sands (Figure 2.b) which has in most cases reached a value above 7. In this way the liquefaction risk has disappeared.

At the "Factoría Off-Shore" the foundation of some modules of 81000 KN with 4-5 m wide foundation blocks and a presure of 0,4 MPa, has required an improvement of the ground by means of vibro-replacement (Figure 3.b). The stone columns have been built having 0,6-0,8 m in diameter and 8-9 m in length and have been arranged at an average spacing of 1,68 m in a triangular grid.

These columns act as vertical drains in such a way that the improvement of the seismic behaviour can be analysed by means of the Seed and Booker (1977) method. Accepting a coefficient of compressibility $m_v \simeq 3 \times 10^{-5}$ m²/kN, a permeability coefficient $k \simeq 10^{-7}$ m/s and a safety factor not under 2 against the reduction of effective pressure, we obtain a spacing of about 2,30 m for the columns. This distance is greater than the one required by the "static" behaviour of the foundation. In this way, this last arrangement eliminates all liquefaction risks.

4. CONCLUSIONS

In Western Andalucía the liquefaction potential of non-plastic silty-sandy soils can be evaluated with sufficient aproximation by means of empirical correlations between the dynamic penetration resistance (SPT N-values)

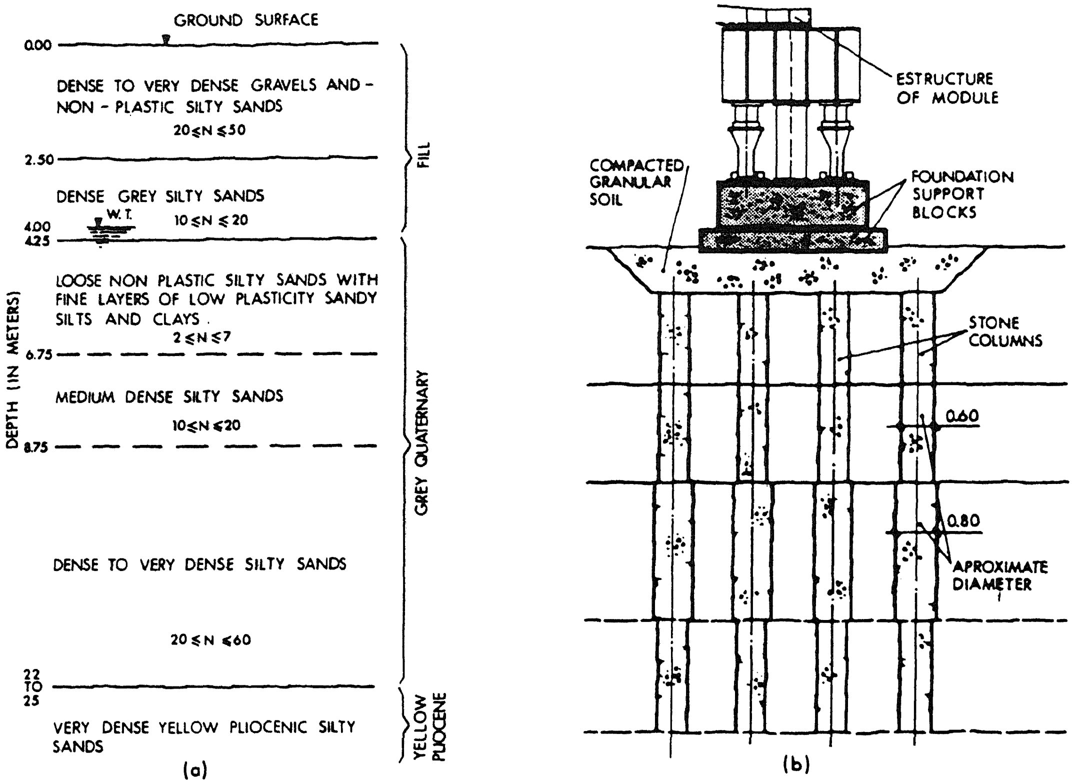


Fig. 3 a) Average soil profile at the DYCSA Factory, Bajo de la Cabezuela, and b) Cross section of the foundation on the improved ground.

and the seismic behaviour, such as Seed et al, Ambraseys and the Chinese expression.

The ground at this region with loose soils of the type mentioned above, located under the water table between 3 and 9 m deep, with N-values below 7, presents a very high liquefaction risk.

The improvement of the ground by means of dynamic compaction or vibro-replacement required by the "static" behaviour of shallow foundations is, in the cases considered, enough to eliminate all liquefaction risks.

The results obtained in this paper intend to be one more contribution to the analysis of the liquefaction potential, especially for relatively low values of the maximum surface acceleration and soils with a significant fines content.

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