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ABSTRACT

A review is made of geotechnical factors that played an important role in three recent earthquake-induced failures, two of which were deadly. The first two catastrophes concern two five-storey hotels that collapsed during the "Alkyonides earthquake" of 24 February 1981 (M=6.7) and the "Egion earthquake" of 15 June 1995 (M=6.2). The third failure is the collapse of a multi-storey factory caused by the "Athens earthquake" of 7 September 1999 (M=5.9). In the first two catastrophes, ground subsidence was estimated by two different methods and was found to be of the order of 0.13 to 0.46 m. These estimates are based on tentative assumptions that should be reviewed and possibly revised. Considerable differential settlements must have existed before the earthquake, as there were no basements that would have attenuated vertical loading and so even a moderate additional differential settlement could cause failure. In the third case, the structure was built near the edge of a steep slope of clayey soil. The co-seismic shear displacement caused the footings resting on the sliding mass to settle, thus causing severe distortions to the structure.

INTRODUCTION

Several structural failures in Greece have taken place during recent earthquakes. The impact of geotechnical factors in such failures is overlooked by many investigators, mostly because these failures take place in populated areas, where it is not always possible to find visible evidence of ground movement.

This paper aims to emphasize the role of the ground in the performance of a structure during an earthquake, by presenting three cases where geotechnical factors contributed to the collapse of two five-storey hotels and a multi-storey factory.

The geotechnical factors which are being related to the three collapses are: a) the co-seismic and early post-seismic ground subsidence, contributing to the collapse of the two hotels, and b) the co-seismic shear displacement, contributing to the collapse of the factory.

GROUND SUBSIDENCE

Co-seismic and early post-seismic ground subsidence may have contributed to the collapse of the two hotels. Some important features that were common to both cases are the following: a) proximity to the sea coast, b) shallow footings and absence of basement, c) predominance of sandy soils in the upper 20 to 25 m of the subsurface.

The ground subsidence is evaluated with two methods: a) the *Tokimatsu and Seed (1987)* method for the evaluation of earthquake-induced settlements of saturated sands from SPT results and the cyclic stress ratio, b) a new tentative empirical method based on the statistical correlation of ground subsidence with seismic energy.

The relation between total and differential settlements of footings has been studied (for example, *Lambe&Whitman, 1968*) and it follows that differential settlements can be up to about one half of the total settlements.

Estimation of Ground Subsidence from SPT Results and the Cyclic Stress Ratio

Figure 1 below, shows the chart which is used for the estimation of the volumetric strain (ground subsidence ÷ layer thickness) of saturated sands, given the normalised $N_1(60)$ SPT value and the cyclic stress ratio *CSR* for an earthquake of magnitude M=7.5. The cyclic stress ratio *CSR* for an earthquake of magnitude *M* is given by the following expression:

$$(CSR)_M = \frac{0.65 \cdot \alpha_m \cdot \sigma_v \cdot r_d}{\sigma'_{v0} \cdot g} \qquad (1)$$

where: α_m is the peak horizontal ground acceleration at the ground surface, σ_v and σ'_{v0} are the total and effective overburden pressures at the depth considered, and r_d is a stress reduction factor.

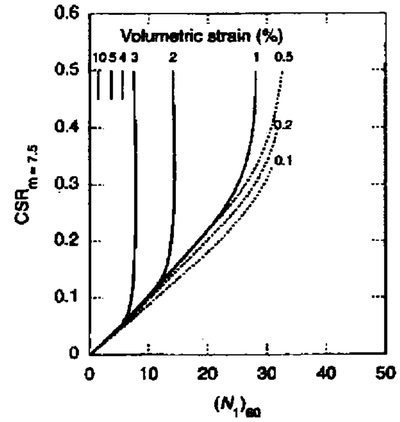

Fig. 1 Estimation of earthquake-induced settlements of saturated sands (Tokimatsu and Seed, 1987)

The cyclic stress ratios for magnitudes that are different from M=7.5 are obtained through a magnitude correction factor, $CSR_M/CSR_{M=7.5}$. For earthquakes with magnitude M=$5^1/_4$, 6, $6^3/_4$, $7^1/_2$, $8^1/_2$ the magnitude correction factor is 1.50, 1.32, 1.13, 1.00, 0.89 respectively.

The $N_1(60)$ value is the SPT N-value normalised to an effective overburden stress of 100 kPa (≈1 tsf) and to an effective energy delivered to the drill rods equal to 60% of the theoretical free-fall energy.

Estimation of Ground Subsidence from Seismic Energy

A database that has been formed as part of an ongoing project *"Seismic Ground Displacements as a Tool for Town Planning, Design and Mitigation" (ENV4-CT97-0392),* sponsored by DGXII of the European Commission, contains data from case histories of ground subsidence that has taken place as a result of densification, with or without liquefaction, during or shortly after an earthquake.

Figure 2 presents the correlation of the average volumetric strain (=representative observed ground subsidence ÷ layer thickness) with a measure of the seismic energy reaching a site $SE=[M+\log(1/d^2)]$, where M is the earthquake magnitude and d is the epicentral distance in km. As $M=\log(energy)$, $SE=\log[energy/d^2]$ where the expression in the brackets equals the energy reaching the circumference with radius d, assuming that the seismic energy emanates at the epicenter and propagates surficially all around.

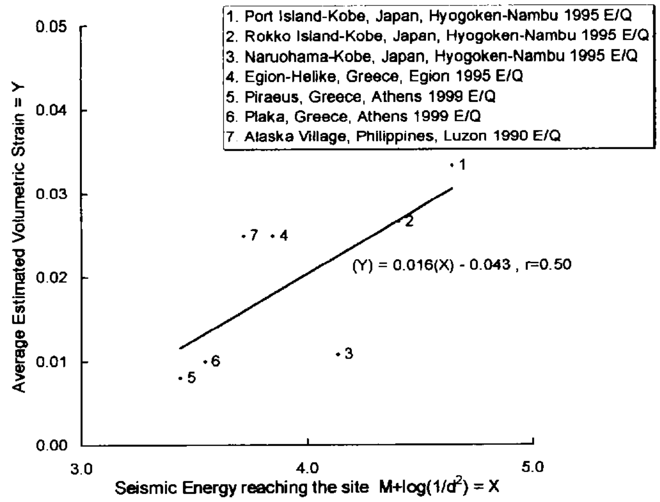

Fig. 2 Statistical correlation between ground subsidence and seismic energy, from case histories (Second Annual Report, ENV4-CT97-0392, DG XII, European Commission)

Each of the numbered points shown in Fig. 2 indicates a representative value of observed subsidence at the general location receiving the seismic energy. The locations included in the correlation are known to be underlain by geologically very recent granular deposits or by artificial fills. The coefficient of correlation of 0.5 allows the assumption that:

$$(Y) = 0.016(X) - 0.043 \qquad (2)$$

Clearly, eq.(2) should be used only for sites for which there is evidence that they are underlain by natural young sandy-silty deposits or by loose artificial fills.

Hotel Collapse at "Vrahati" - Earthquake of 24 February 1981

The collapse of this five-storey hotel at the "Vrahati" summer resort in the Peloponese was caused by the "Alkyonides earthquake" of 24 February 1981, with magnitude 6.7 and epicenter near the Islands of Alkyonides, 70 km west of Athens. The hotel epicentral distance was approximately 20 km. Fortunately enough it was off-season for tourists and there were no human casualties.

The hotel was constructed around 1969. It was built at a distance of about 75 m from the sea coast and did not have a basement. A subsurface investigation that preceded construction showed medium to dense sands down to the depth of 8 m, underlain by sands and silts of lower density down to the depth of 20 m. The ground water level was approximately 1 m below the ground surface. Figure 2 shows the results of the Standard Penetration Tests:

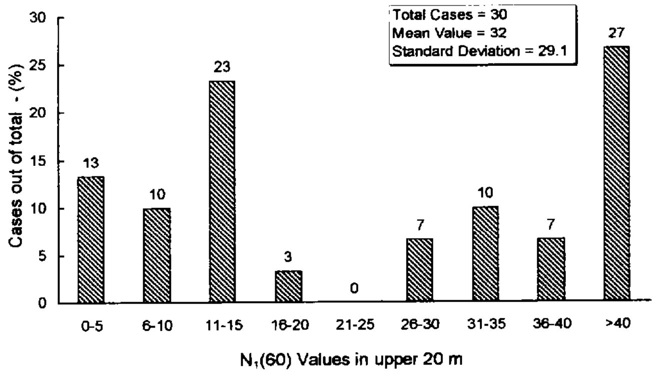

Fig. 3 Hotel site at "Vrahati". Pre-earthquake subsoil investigation. Water level depth = 1.0 m

Even though the ground water level was high and the subsoils were mostly sands, there was no evidence of liquefaction on site or in the nearby area.

Estimation of Ground Subsidence by the *Tokimatsu and Seed (1987)* Method. It is assumed that: a) only the upper 20 m of the soil profile contribute to subsidence, b) densification may take place in any non-adjacent layers with $N_1(60)$ values up to 15, c) since all SPT tests are taken at constant intervals, regardless of other considerations, the percentage of the thickness of the layers that densify can be taken equal to the percentage of the $N_1(60)$ values up to 15.

The peak horizontal ground acceleration α_m can be estimated from the following expression *(Ambraseys and Bommer, 1986)*:

$$log(\alpha_m) = -1.09 + 0.238 \cdot M_s - log(r) - 0.00050 \cdot (r) \quad (3)$$

where M_s is the earthquake magnitude measured from the surface waves and $r = \sqrt{(d^2 + 6.0^2)}$, d being the epicentral distance in km. For M=6.7 and d=20 km, eq.(3) gives $\alpha_m = 0.15g$.

The ground water level is 1 m below the surface, but for reasons of simplicity it may be taken at the surface, so that σ_v / σ'_{v0}=2. Finally, the stress reduction factor r_d is 0.92 for a depth of approximately 10 m, that is, at the middle of the upper 20 m of the soil profile that is considered. Therefore, according to eq.(1), the cyclic stress ratio *CSR* for the current earthquake of magnitude M=6.7 is $(CSR)_{6.7} = 0.18$. The magnitude correction factor for this earthquake is 1.13 and thus the equivalent cyclic stress ratio *CSR* for an earthquake of magnitude M=7.5 is $(CSR)_{7.5} = 0.16$.

Three virtual "layers" will be considered: one for each of the ranges of $N_1(60)$ values 0-5, 6-10 and 11-15. According to Fig. 3, the corresponding percentages of the $N_1(60)$ values are 13, 10 and 23%, therefore the presumed thicknesses - out of the total of 20 m - that densify are: 0.13x20 m = 2.6 m, 0.10x20 m = 2.0 m and 0.23x20 m = 4.6 m.

According to Fig. 1, the volumetric strain for $N_1(60)$ values of 2.5 and 7.5 and 12.5 (average values for the $N_1(60)$ ranges of 0-5, 6-10 and 11-15) are 7, 3 and 1.5% respectively. As a result, the subsidence of the first layer is 0.07x2.6 m = 0.18 m, of the second layer is 0.03x2.0 m = 0.06 m, and of the third 0.015x4.6 m = 0.07 m. Therefore, the total subsidence is 0.31 m.

Estimation of Ground Subsidence by the method of seismic energy. For this case M=6.7, d=20 and SE=6.7+log0.0025= =4.1=X. From eq.(2) Y=0.016x4.1-0.043=0.023. It follows that subsidence is 20mx0.023=0.46 m.

Hotel Collapse at "Valimitika" - Earthquake of 15 June 1995

The collapse of a part of this five-storey hotel at the "Valimitika" summer resort in the Peloponese, which resulted in the death of 15 people, was caused by the "Egion earthquake" of 15 June 1995, with magnitude 6.2 and epicenter near the city of Egion, 130 km west of Athens. The hotel epicentral distance was 15 km approximately.

Fig. 4 Hotel collapse at "Valimitika", 15 June 1995.

Ground Subsidence and Liquefaction in the General Area. Five days after the earthquake, the area was visited and photos were taken. Visible signs of ground subsidence and liquefaction were encountered. Sediments of sandy gravel subsided by 1 m or more, leaving young trees submerged to half their height (Fig. 5). The roads near the sea liquefied for about 1 km (Fig. 6).

That same area is believed to have experienced similar phenomena in old and ancient times. The repeated incidents of liquefaction and ground subsidence may be attributed to the loose state of the deposits of three rivers that feed the coastal area with sand and gravel *(Stamatopoulos and Stamatopoulos, 2000)*.

Fig. 5 Ground subsidence in the greater area of "Valimitika"

Fig. 6 Liquefaction in the greater area of "Valimitika"

The hotel was built at a distance of about 20 m from the sea coast and was founded on shallow footings without a basement. After the collapse, a geotechnical investigation with 5 borings showed that to a depth of 20 m subsoils consist mainly of sand and silt. The ground water level was about 1.5 m below the ground surface. Figure 7 shows the results of the Standard Penetration Tests normalised as $N_1(60)$.

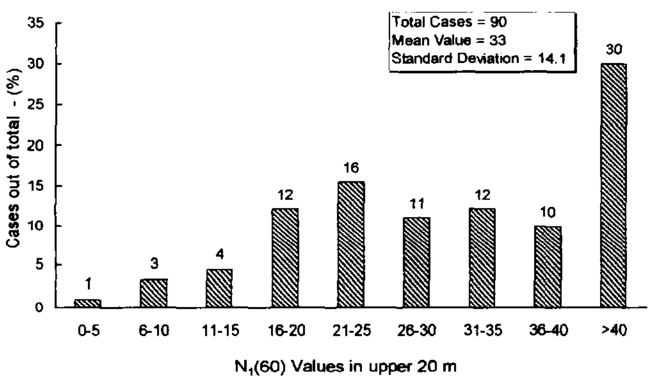

Fig. 7 Hotel site at "Valimitika". Post-earthquake subsoil investigation. Water level depth = 1.5 m

The investigation was carried out after the earthquake, so it is inferred that the pre-earthquake values were lower because of the densification that must have taken place as a result of the earthquake. As it is necessary to make an assumption for the pre-earthquake values, it does not seem unreasonable to accept that the earthquake caused the values of $N_1(60)$ to increase by 5. True, this assumption is arbitrary and can be easily contested, so for this reason it should be regarded only as a tentative "guess". On this basis the pre-earthquake percentages of cases for the $N_1(60)$ ranges of 0-5, 6-10, and 11-15, become 4, 4 and 12%.

Even though the ground water level was high and the subsoils were mostly sands, and despite the fact that liquefaction took place in the greater area, there was no evidence of liquefaction at the exact site of the hotel.

<u>Estimation of Ground Subsidence by the *Tokimatsu and Seed (1987)* Method</u>. It is assumed that: a) only the upper 20 m of the soil profile need to be considered b) densification may take place in any non-adjacent layers with $N_1(60)$ values up to 15, c) since all SPT tests are taken at constant intervals, it is considered that the percentage of the thickness of the layers that densify is equal to the percentage of the $N_1(60)$ values up to 15, d) the pre-earthquake values of $N_1(60)$ are smaller than those shown in Fig. 7 by 5.

For M=6.2 and d=15 km, eq.(3) gives $\alpha_m = 0.15g$. The ground water level is 1.5 m below the surface, but for reasons of simplicity it may be taken at the surface, so that σ_v / σ'_{v0}=2. Finally, the stress reduction factor r_d is 0.92 for a depth of approximately 10 m, that is, at the middle of the upper 20 m of the soil profile that is considered. Therefore, according to eq.(1), the cyclic stress ratio *CSR* for the current earthquake of magnitude M=6.2 is $(CSR)_{6.2} = 0.176$. The magnitude correction factor for this earthquake is 1.32 and thus the equivalent cyclic stress ratio *CSR* for an earthquake of magnitude M=7.5 is $(CSR)_{7.5} = 0.13$.

Three virtual "layers" will be considered: one with $N_1(60)$ values from 0 to 5, one with $N_1(60)$ values from 6 to 10 and another with $N_1(60)$ values from 11 to 15. The corresponding percentages of cases are 4, 4 and 12% and therefore the thicknesses - out of the total of 20 m - are: 0.04×20 m = 0.8 m, 0.04×20 m = 0.8 m and 0.12×20 m = 2.4 m.

According to Fig. 1, the volumetric strain for $N_1(60)$ values of 2.5, 7.5 and 12.5 (average values of the $N_1(60)$ ranges of 0-5, 6-10 and 11-15) are 7, 3 and 2% respectively. As a result, the subsidence of the virtual layers is 0.07×0.80 m = 0.056 m, 0.03×0.80 m = 0.024 m and 0.02×2.4 m = 0.048 m totalling 0.13 m. It is reminded that this calculation is based on a "guess".

<u>Estimation of Ground Subsidence by the method of seismic energy.</u> For this case M=6.2, d=15 and SE=6.2+log0.0044=

=3.8=X. From eq.(2) Y=0.016×3.8-0.043=0.018. It follows that subsidence is 0.018×20m=0.36 m.

SHEAR DISPLACEMENT

Collapse of the "Ricomex" Factory - Earthquake of 7 September 1999

The collapse of the multi-storey "Ricomex" factory resulted in 35 deaths. Earthquake had a magnitude of 5.9 and the epicenter was located on mount Parnes, 15 km north of Athens. The focal depth was 11 km and the factory epicentral distance was 5 km. Three analog accelerographs of *I.T.S.A.K., 2000,* recorded values of peak horizontal ground acceleration of 0.3g within distances of 15 km from the epicenter.

General Information. Contrary to the provisions of the Greek building code, one side of the structure was built on the edge of a steep slope. Surficial samples that were taken from the slope showed that the soils are mostly clayey silty sands. Figure 8 shows the collapsed factory a few hours after the earthquake while rescue operations were still in progress.

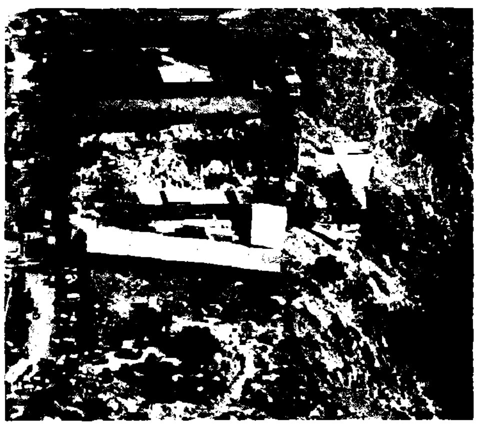

Fig. 8 Aerial view of the collapsed factory-7 September 1999

Fig. 9 The side of the slope where failure took place

Cause of Failure. From Fig. 8 it is clear that one side of the factory was resting on the edge of the slope. This fact can be seen more clearly in the photo of Fig. 9 that was taken 6 months after the earthquake.

Due to the inertial forces exerted on the slope by the high earthquake acceleration, and the surcharge of the structure, severe shear displacement took place. This displacement can be observed in the photo of Fig. 8 where the part of the building in the foreground is tilting towards the edge of the slope. A factor that must have added to the displacement is the accumulation of energy of seismic waves that takes place under the crest of a slope because of the direction of the reflected waves that hit the slope surface.

Also, the pattern of failure shows that a number of footings that may have rested on the surface of the prism that moved downward, followed the slope displacement and distorted the reinforced concrete structural frame. Had the factory not been built on the edge of the slope or had the soil in the slope not sheared, this structural failure might have been avoided; in Fig. 9, another factory can be seen in the background, which was located some tens of meters from the edge of the slope, and suffered minimal damage.

Estimation of Displacement and Shear Strength. It has been proposed *(Ambraseys and Srbulov, 1995)* that co-seismic displacements of slopes are mainly controlled by the value of the ratio of the critical acceleration α_c to the horizontal peak ground acceleration α_m, that is, $q=\alpha_c/\alpha_m$. Equation (4) below, expresses the attenuation of co-seismic downhill displacements as a function of the surface wave earthquake magnitude M_s, the epicentral distance d and the ratio q.

$$log(u) = -2.41 + 0.47 \cdot M_s - 0.01 \cdot r + log\left[(1-q)^{2.64} \cdot (q)^{-1.02}\right] + 0.58 \cdot p \quad (4)$$

where: u is the co-seismic displacement in cm, $r=\sqrt{d^2+h^2}$ (d and h being the epicentral distance and focal depth in km respectively), and p is the standard deviation. For M=5.9, d=5 km and h=11 km, eq.(4) is graphically presented in Fig. 10 that follows:

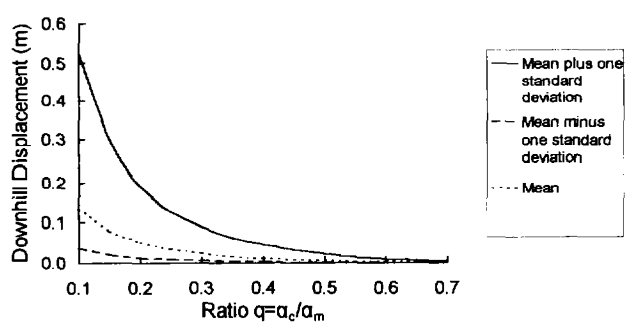

Fig. 10 Attenuation of downhill displacements in the area of the "Ricomex" factory

A pseudo-static analysis of the slope was carried out with the slope stability program LARIX-2S, which can estimate the Factor of Safety *FS* of a slope by applying the well-known Bishop's method of slices *(Bishop, 1955)*. Figure 11 that follows, presents a graph of the shear strength of the soil in the "Ricomex" slope, versus the critical acceleration α_c , that is, the horizontal acceleration for which FS=1.

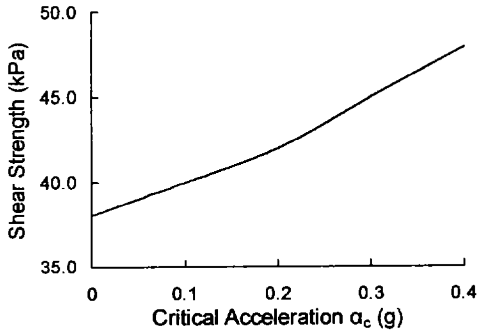

Fig. 11 "Ricomex" slope - Results of pseudo-static analysis with Bishop's method of slices - it is assumed the angle of internal friction of the soil φ=0.

A report by *I.T.S.A.K., 2000,* uses the attenuation relation of horizontal peak ground acceleration proposed for Greece by *Theodulidis and Papazachos, 1992,* and the accelerograms obtained at distances of 15 km, and estimates that the acceleration for the "Ricomex" epicentral distance of 5 km is α_m =0.60g.

It is reasonable to assume that seismic ground displacements of the order of 10 to 20 cm could have contributed to the collapse of the factory. Consequently, from Fig. 10 it is inferred that a probable value of q is in the order of 0.2 to 0.3. As $\alpha_c = q \times \alpha_m$, and the estimated value of α_m is 0.60g, it follows that α_c may have been of the order of 0.15g. Then from Fig. 11 it follows that the shear strength of the soil was about 41 kPa (≈0.41 tsf). Such a value of shear strength places the soil in the category of medium to nearly stiff clay, which appears to be reasonable.

CONCLUSIONS

Three structural failures caused by recent earthquakes in Greece are reviewed. These failures can be explained in terms of the geotechnical conditions prevailing at the three sites. It follows that geotechnical factors contributed or, perhaps, were the major cause of the failures.

The two hotels that were built on flat ground, may have failed due to high differential settlements caused by ground subsidence. The magnitude of subsidence was estimated by an existing credible method and also by a new tentative method, and was found to be of the order of 0.13 to 0.46 m. The factory that was built on the edge of a clayey slope, may have failed by a slope shear displacement which can happen if the shear strength of the soil is about 41 kPa or less.

ACKNOWLEDGEMENTS

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