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STRATEGIES FOR THE SEISMIC PROTECTION OF MONUMENTS: Issues of Geotechnical Earthquake Engineering and Soil – Monument Interaction

by
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EXTENDED SUMMARY

I. General

It is widely acknowledged that local soil and topography effects may prove detrimental for a structure's seismic vulnerability, as they may cause:

(a) Amplification of the seismic coefficient, in case that the bedrock is covered by "softer" soil strata or the topography is not flat but forms a slope, a hill or a valley.

(b) Permanent horizontal and vertical ground displacements due to slope failure or tectonic fault rupture.

(c) Settlements and large horizontal displacements, or even foundation failure due to liquefaction of non - cohesive saturated soil strata.

(d) Increase of a structure's fundamental frequency, due to dynamic soil – foundation – structure interaction

Such effects are even more likely to occur in the case of monuments, which differ from ordinary structures in that they have a significantly greater life expectancy, while they have been also built with less advanced construction techniques and materials. Consequently, even the "less frequent" among the above geo-actions (e.g. fault rupture), which are commonly ignored for contemporary structures, should be an inseparable part of the seismic studies which need to be performed for the protection of monuments.

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II. Contents

Chapter 2 of the present report, summarizes nine (9) case studies of monuments from Greece and other countries, having similar cultural heritage and comparable geotectonic background (e.g. Italy and Turkey), where the effects of soil and topography have been identified as the major factor in the development of the seismic damage. For each case study, information is provided about the seismicity and the dominant geological and geotechnical conditions of the area, whereas further evidence is provided substantiating the role of local soil and topography in the onset of seismic damage.

Chapter 3 presents seven (7) well documented geotechnical earthquake engineering studies that were performed, in Greece and abroad, as part of monument restoration and seismic protection projects. Emphasis is given to the associated geotechnical and geophysical investigations, the seismic ground response and failure analyses, as well as to the resulting evaluation of significance of the various geo-hazards in deciding a viable strategy for the monument protection.

Finally, chapter 4 summarizes the main findings of the above survey, in an effort to provide a general – still factual - framework for the type and the extent of geotechnical analyses and investigations which are required in order to account effectively for the role of ground in seismic studies related to monument restoration and protection. Namely, *Table 4.1* (or *Table I* of this Extended Summary) summarizes the case studies presented in previous chapters and provides a categorization of the main geo–hazards responsible for the onset of seismic damage. Furthermore, *Table 4.2* (or *Table II* of this Extended Summary) summarizes the means employed by the international engineering community for the analytical and experimental evaluation of the seismic geo-hazards and the design of appropriate seismic protection measures for monuments. The contents of these two Tables are summarized below.

III. Outline of Main Geo-hazards

The main geo-hazards which have been identified from the case studies of seismic damage to monuments, reviewed in Chapter 4, are the following;

(a) <u>Soil amplification of the seismic motion</u>.- It is attributed to the amplification of selected seismic frequencies, closely related to the fundamental vibration frequencies of a soil column extending from the bedrock up to the ground surface. The possible resonance between seismic action the soil column and the structure produces the most destructive effects. In practice, soil amplification effects are most commonly investigated with (numerical) non linear 1-D analyses of seismic wave propagation. Moreover, geotechnical and geophysical investigations (e.g. Crosshole, Downhole, SASW) are required for the exploration of the soil conditions prevailing in the area of interest.

(b) Topographic amplification of the seismic motion.- This effect is important for monuments situated on hilltops, at the crest of steep and high slopes (e.g. H > 30m, inclination > 15deg. according to EC – 8), or within alluvial valleys. It is attributed to the coupling of seismic waves which are independently transmitted (i) from the bedrock, (ii) from the inclined slopes after reflection and (iii) along the ground surface (Rayleigh & Love surface seismic waves). As a result, a significant aggravation of the horizontal acceleration component is commonly observed, accompanied by the appearance of a parasitic vertical acceleration component, independent from the vertical component of the initial vibration. To quantify these effects, 2 – D and 3 – D numerical analyses (Finite Elements or Finite Differences) are required, with the aid of specialized codes which incorporate appropriate constitutive models for the non – linear hysteretic soil response under cyclic–seismic loading, and "transparent" boundary conditions (free field or transmitting boundaries) for avoiding end effects. A detailed topographic survey, as well as extensive geotechnical and geophysical investigations become inseparable components of such investigations.

(c) Dynamic Settlement of the foundation soil.- They are attributed to the cyclic shear loading induced by the seismic waves propagating mainly through loose, non cohesive soil strata (sands, non plastic silts, or even gravels). In cases of high water table, soil settlement is preceded by soil liquefaction, which may lead to complete loss of soil strength and collapse of the monument. The relevant analyses rely mostly on empirical methodologies. Analytical tools are also available; however they require particular (not always commercial) codes as well as data from specialized laboratory tests (e.g. cyclic triaxial tests, simple or rotational shear tests) and consequently they are usually limited large scale projects.

(d) Slope failure.- It mainly concerns soil or soft rock slopes, as a result of the combined action of gravitational and seismic accelerations. The excess pore pressure build up mentioned in (c) above may also deteriorate the shear strength of the soil, thus contributing to failure. Dynamic slope failure is definitely milder than static failure, mainly because it is "instantaneous", i.e. the damaging up-slope seismic acceleration lasts for tenths of a second. Thus, it usually leads to relatively small (5–10 cm) permanent displacements of the sliding mass, or to the acceleration of already existing creep displacements of statically unstable slopes. Such issues are resolved with the aid of the seismic ground response analyses described in (a) and (b), as well as with detailed geotechnical and geophysical investigations accompanied by simple (pseudostatic) slope stability analyses and empirical determination of permanent down-slope displacements.

(e) Rock-falls.- They refer to the free fall of large rock blocks from fractured and weakly cemented rock slopes, hanging over archaeological sites. The volume of the sliding rock mass and the maximum covered possible distance are the main parameters incorporated in such analyses, which are carried out with sophisticated software. Topographic amplification analyses are initially required accompanied by detailed geological mapping of the rock mass which is susceptible to sliding.

(f) Faults.- The term refers to active tectonic ruptures emerging to the ground surface. They cause horizontal or/and vertical permanent differential ground displacements, which vary from a few centimeters to a few meters, depending on the size of the rupture (normal, reverse, strike slip). The above parameters and the characterization of a fault as active require a specialized tectonic and seismo-tectonic investigation including among others: review of aerial photographs, site observations and in situ measurements, trench excavation, etc.

IV. Required Geo – Investigations and Analyses

The following investigations, experimental measurements and (numerical) analyses have been employed in the geo-studies for the seismic protection of monuments reviewed in Chapter 4:

(a) Geo – investigations.- The majority of the studies involve a detailed set of: geological and geotechnical investigations – via exploratory boreholes, laboratory tests and in situ tests (CPT, SPT) - and geophysical inquiries for the direct measurement of the velocity of shear/primary waves (V_S, V_P). Among the usual geophysical tests, priority is given to Crosshole and Downhole tests that provide the greatest reliability. Specialized laboratory tests (resonant column, cyclic triaxial or torsional tests) can be additionally employed for the evaluation of the non linear soil behavior and the soil strength under seismic loading.

(b) Seismic Ground Response Analyses.- The majority of the reviewed special studies include non linear analyses for estimating the soil (1 – D) and topographic (2 – D or 3 –

D) amplification phenomena, despite the fact that the aforementioned analyses (especially the 2-D and 3-D) require significant specialization with regard to the involved personnel and the employed software. It is characteristic that in one special study, namely that for the ancient town of Tindaris in Italy, the 2-D seismic ground response analyses were combined with an elastoplastic soil model for direct computation of earthquake – induced permanent settlements.

(c) Ground Failure Analyses.- In a number of the specialized studies, the basic analyses of seismic ground response were supplemented by settlement and liquefaction hazard analyses, as well as analyses of soil – foundation – structure interaction. Despite that, slope failure and rockfall analyses were performed only in a limited number of the specialized studies (for ancient towns of Tindaris and Gerace in Italy), such analyses are considered as indispensable and should be carried out whenever the local geo–morphological conditions required it.

(d) Seismic Ground Response Measurements.- In two out of the reviewed specialized studies, the 1 – D seismic ground response was not evaluated numerically, but experimentally, using either strong seismic recordings (G.I. & HVSR) or microtremor measurements. Based on the expertise of this Group, even though the above methods have a clear advantage in terms of application cost and processing time, they lack in accuracy and thoroughness compared to numerical analyses based on detailed measurements of the dynamic soil properties.

V. Concluding Remarks

In concluding this Extended Summary, it is felt appropriate to repeat that monuments are much more demanding than common structures with regard to the studies required to assess their seismic vulnerability and also propose effective measures for their restoration and protection, for a number of reasons. For instance, their life expectancy is multiple than that of common buildings, they have accumulated considerable structural damage due to the seismic activity of the past years, while they have been built with materials and techniques which are inferior of these used for contemporary structures. As a result, it is internationally accepted that the related issues of Geotechnical Earthquake Engineering and Soil – Monument Interaction, which were identified before, are beyond the limits of conventional seismic codes (such as the Greek Seismic Code EAK or the European Seismic Code EC-8), but have to be the subject of specialized studies and field explorations.

Table I: Summary of case studies, with reference to the geological, geotechnical and geo – morphological causes of seismic damage aggravation [**1:** *observation data (O), analyses data (A) and seismic recordings(R),* **2:** *Ancient (A) or Later (L) years,* **3:** *parenthesis suggests Group's conclusions based on published evidence*]

	CASE STUDY	DATA	AGE	CAUSES OF DAMAGE					
				SOIL AMPLIF.	TOPOGR. AMPLIF.	DYNAMIC SETTLEMENT	SLOPE FAILURE	ROCK - FALL	FAULTS
1.	DELPHOI Archaeological site	O	A(2)		(X) (3)		X	X	X
2.	APOLLO Epikourieos Temple	O	A			X			
3.	TINDARI, Sicily	O, A	A	(X)	X	X			
4.	COLOSSEUM Rome	O, A	A		X				
5.	Trojan – Marcus Aurelius Columns, Rome	O,A	A	X resonance of soil & structure					
6.	DAFNI Monastery	O	L(2)			X	X		
7.	FATIH MOSQUE Turkey	O, A, R(1)	L	X resonance of soil & structure					
8.	UMBRIA, Italy	Π,Κ	N	X		X	X	X	
9.	CAMPOBASSO & FOGGIA, Italy	Π, Α	N	X	X				

Table II: Summary of Special Geotechnical Studies emphasizing in the geo – investigations and seismic response and ground failure analyses [**1:** *Ancient (A) or Later (L) years*]

	STUDY	AGE[1)]	INVESTIGATIONS			SEISM. RESPONSE ANALYSES		FAILURE ANALYSES			OTHER ANALYSES
			GEOL.	GEOT ECH.	GEOPH.	1-D	2-D & 3-D	Liquef.	Slope	Settl.	
1.	TINDARI, Sicily	A	X		X		X			X	
2.	COLOSSEUM Rome	A	X	X			X				
3.	FATIH MOSQUE Turkey	L	X	X	X	X					
4.	Cities of NICASTRO & GERASE, Calabria	A & L	X	X	X		X		X		
5.	Monuments of Thes/niki	A & L	X	X	X	X		X			
6.	LARNAKA aqueduct	L									Soil – Structure Interaction
7.	NAPOLI historic centre	L	X	X	X		X				
8.	UMBRIA & MARCHE, Italy	A & L	X	X	X						G.I. & HVSR
9.	City of BENEVENTO, Italy	A & L	X	X	X						MICROTREMORS