#### Estimation of the Seismic History of the City of Thessaloniki through back analysis of its Byzantine Land Walls

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ABSTRACT: This paper aims at developing the tools and strategy for assessing the dynamic and seismic performance of the Byzantine Walls of the city of Thessaloniki in order to evaluate the seismic history of the city as a whole. The particular Walls have been constructed at the end of the 4th century A.D. in the reign of Theodosius the Great and as such, their structural integrity and record of damage reflects to a certain degree the level of seismic forces that has developed during the centuries. Moreover, the fact that they are extending in kilometers within the civil grid of the modern city allows the study of the role played by the local soil conditions for a given earthquake scenario. It is worth noting that despite their relatively simple structural system, their foreseen seismic behavior as a 3D body has not been thoroughly studied so far, primarily due to the lack of efficient numerical tools and the high computational cost related, especially towards the study of their response in the time domain. Along these lines, a refined dynamic analysis approach is proposed and the structural performance of particular parts of the Walls complex is examined for a number of realistic earthquake scenarios, accounting for the site specific soil conditions, the spatially variable nature of the incident seismic waves, as well as the overall geotechnical/geotectonic environment of the area. Through this advanced simulation scheme, an upper bound of the historical level of seismic forces for the city of Thessaloniki is traced (through back analysis), while the overall refined approach can be also used as a guide for the direct assessment of the existing seismic capacity of monuments as a whole.

#### **1 INTRODUCTION**

#### 1.1 Scope

The impact of earthquakes on monumental heritage is a critical issue that has attracted growing scientific interest during the last decades. Monuments however, are most often complex structures, whose preservation and/or seismic strengthening heavily relies on the clear understanding of all factors affecting their vulnerability as well as on the accurate study of the effects of past earthquakes. Until recently, the investigation of the seismic performance of important and extended monuments was restricted by the inherent limitations of numerical analysis thus preventing the engineers from the study of their dynamic response in the time domain under realistic (recorded or artificial) ground motion scenarios. This problem was further stressed in the case of (Classical, Roman, Byzantine or Medieval) city (Sea or Land) Walls whose dimensions were normally significantly large, hence the complexity of the analytical or numerical procedures to be followed, (as well as the subsequent computational cost) were considerably high. Along these lines, it was deemed interesting to focus on the city Walls of Thessaloniki, utilizing state-of-the-art numerical tools and the experience gained from the seismic study of other historical structures of the Byzantine Era throughout the city, in order to attempt to shed some light not only on the structural history of the Walls through the centuries, but if possible, to back analyze and evaluate the reliability of the seismic scenarios developed for the Metropolitan City of Thessaloniki as a whole.

The Walls, still surrounding partially the old town of Thessaloniki were initially built in 315 B.C. by the king Kassandros and were completed at the time of Great Theodosius (379-395 A.D.). Nowadays, the Walls extend in kilometres within the civil grid of the modern city but their continuity has been disrupted due to partial or complete collapse at numerous locations. Historically, due to their dynamic nature, in the sense that they could be adapted in accordance with civilian needs, thus being repaired after sieges and following rules of economy and functionality where the art of war was concerned, the Walls of Thessaloniki (as those of Constantinople, Nicaea and others), did in fact changed considerably over the centuries (Bouras, 2002) following the heavy fortification requirements that arose. From the overall Byzantine Walls complex which extends in kilometres within the city, two sections (Figure 1) were chosen to be studied, particularly: (a) a simple relatively small, essentially stand-alone part of the Walls located approximately in

the center of the modern city and (b) the Walls circuit in the northern part of the Byzantine fortification. This part, which due to its size is studied more thoroughly, forms a statically independent structural system, extending from the beginning of the West Gate (namely "Pyrros Gate") to the main East Gate along the Eptapygriou street, near the Trigonion Tower, inclusive of the two twin gates at the East section (widened and named thereafter by Anna Palaiologina) up to the circle tower (Figures 2-5) constructed later. The particular Walls Section was encircling the Byzantine acropolis (Velenis, 1998) thus separating it from the Ancient Acropolis and it consists of numerous rectangular (primarily) and triangle defensive towers. This is essentially a monolithic and straight complex with its main axis being parallel to the East-West direction. The superstructure was constructed of masonry made by alternate bands of stones and bricks (Velenis, 1998). The masonry displays a mixture of construction methods as can be seen in Figure 3.

From the two locations selected to be studied, the small, free-standing masonry wall illustrated at the bottom of Figure 1 was chosen on the basis of the well controlled study environment which was ensured by its clear geometry and structural system, its proximity to the unique location where the 1978 earthquake was recorded and the good knowledge of the underlying soil.

On the other hand, the extended Land Walls Section in the upper part of the city (illustrated at the top of Figure 1) was selected to be studied primarily for three reasons: (a) due to its structural integrity which has remained almost intact within the centuries thus allowing to assume that its seismic capacity must have not been exceeded for the last 1600 years, (b) due to its overall length (reaching approximately 500m) that forms one of the most extended preserved parts of the fortification and (c) due to the additional opportunity that this length provides, to further investigate (in contrast to what is commonly performed) the potential effect of the (typically neglected) traveling nature of the incoming seismic waves to the dynamic response of the system.

The scope of this research effort is therefore, to utilize state-of-the-art knowledge and numerical tools for the pilot study of the seismic performance of the selected Thessaloniki city Land Walls in order to:

- a) verify the good seismic performance of the specific Walparts during the 20/6/1978 Thessaloniki severe earthquake (M<sub>s</sub>=6.5).
- b) assess the level of safety during future seismic events (especially for the long circuit) through appropriate earthquake scenarios that account for a realistic representation of the overall seismotectonic and local site conditions.
- c) investigate the potential effect of ignoring spatially variability of earthquake ground motion in the analysis of long and monolithic structures.
- d) if possible, to compare through back numerical analysis, the level of the highest earthquake excita-

tion (that could have damaged the particular Wall section but apparently has not occurred yet) with the Maximum Credible Earthquake (MCE) defined through deterministic seismic hazard assessment for the same area. It is noted that the definition of upper limits on earthquake ground motions has been identified as the 'missing piece' for seismic hazard assessment for both deterministic and probabilistic approaches (Bommer, 2002).



Figure 1. Contemporary photograph of the 4th Century A.D. Byzantine Land Walls of Thessaloniki (North side view).



Figure 2. Contemporary photograph of the 4th Century A.D. Byzantine Land Walls of Thessaloniki (North side view).



Figure 3. Contemporary photograph of the 4th Century A.D. Byzantine Land Walls of Thessaloniki (South side view).



Figure 4. Axonometric view of rectangular wall between along the East-West axis (North side view). After Velenis, 1998.



Figure 5. Contemporary photograph of the 4th Century A.D. Byzantine Land Walls of Thessaloniki. East Gate, Trigonion Tower (South side view).

## 2 OVERVIEW OF THE ANALYSIS APPROACH ADOPTED

#### 2.1 Finite Element modelling of the Wall Section

Due to the complexity of the problem, it was deemed necessary to primarily establish the overall strategy that had to be followed for the study of the particular city Walls Section. At first, the 3-Dimentional Finite Element model was created based on the exact structural geometry as this was extracted by the satellite image (illustrated in Figure 1), scaled axonometric views (Velenis, 1998, Figure 4) and on-site measurements. The commercially used Finite Element program ANSYS (ver. 10.0) is used for the static, modal and transient response of the structure, which is modeled with 4000 (10-node) solid elements appropriately refined at the locations of the gate openings. The particular FE modelling was adopted in order to avoid unnecessary stress concentration at locations of ubrupt geometry change at a reasonable computational cost, especially towards dynamic analysis in the time domain. Although various approaches have been proposed for the modelling of masonry structures (Casolo, 1998, Galasco et al., 2004, Rota et al., 2005), with emphasis on the nonlinear response of the walls, the particular structure was studied herein as purely linear elastic, in order to permit primarily focus on the macroscopic dynamic response of the system under simultaneous excitation along the three principal axes. Subsequently both local material and geometric non-linearities (inclusive of cracking and sliding at critical locations) were not considered.

The structure was assumed as fully fixed at its base since geotechnical and geophysical studies have shown that the soil conditions at the particular city location are very stiff (Anastasiadis et al., 2001). Based on experimental results for monuments of the Byzantine Era (Manos et al., 2004, Stylianidis and Sextos, 2006) an average uniform compression strength of  $f_{mc}$ =2.0MPa was adopted for the construction materials of the whole system for simplicity, based on the weaker brick masonry. The corresponding tensile strength was set equal to  $f_{mt}$ =0.15MPa. The Young's modulus of the masonry was taken equal to E= $3.5 \times 10^6$  kPa (corresponding to the composite material as a whole) and the self weight equal to  $\gamma$ =22 KN/m<sup>3</sup> while 6% Rayleigh damping was assumed for the circular frequency range  $\omega$  = 40-200 rad/sec. It is noted that the two twin gates of the Trigonion Tower (i.e. Annis Palaiologinis Gate) as well as the Pyrros Gate (Velenis, 1998), have not been modeled due to their relatively smaller dimensions compared to the overall Wall Section length.

#### 2.2 Earthquake Scenario for Thessaloniki

Following the development of the Finite Element model of the structure, an effort was made to identify a 'reasonable' earthquake ground motion scenario for the earthquake under study. Along these lines, the three components of the seismic motion recorded at the city center (Ambraseys et al., 2000) during the earthquake that stroke Thessaloniki in 1978 (20/06/1978, Ms=6.4, PGA=0.15g) were taken as the reference motion and were appropriately deconvoluted (Figure 6) to the bedrock level at the location where the records were obtained based on geotechnical data from the Microzoning study of Thessaloniki (Anastasiadis et al., 2001). As mentioned previously, the local site conditions can bee assumed to correspond to rock thus classified as soil type A according to Eurocode 8. The outcrop motion along the axis of the Walls Section under study was then derived. As a result, three scenarios of earthquake excitation were developed involving the:

- a) earthquake ground motion of the 1978 seismic event corresponding to the local site conditions as illustrated in Figure 8 and described above. (Case A: 1978 excitation)
- b) the above seismic motion scaled to the level of PGA=0.22g, that is specified by the Microzoning study of the city of Thessaloniki, for the particular site. (Case B: Potential excitation corresponding to an average return period of 475 years)
- c) the predicted seismic motion of Case B, applied asynchronously, that is, considering the time lag that arises from the traveling of the seismic waves in finite velocity through the soil media. (Case C: Asynchronous excitation corresponding to an average return period of 475 years).

It is noted that for all the above three cases, the Wall complex is excited simultaneously along the three principal directions, X,Y,Z. Due to its particular feature involving the consideration of spatial variation of ground motion, Case C is further discussed in the following section.



Figure 6. Generation of earthquake ground motion scenario. 1978 earthquake record (top) and outcrop motion for the upper city Walls of Thessaloniki (bottom).

### 2.3 Spatially variable earthquake ground motion along the Land Walls under study

Development of spatially variable seismic ground motion scenarios for the study of the dynamic response of extended structures (primarily bridges but also dams and pipelines) is attracting increasing scientific attention after strong evidence that not only seismic motion may differ substantially in terms of amplitude and frequency content but also that this difference may have a detrimental effect on the displacements and stresses of the extended structure under certain circumstances (Sextos et al., 2003). The sources of this spatial and temporal variations of seismic motion have been well identified: (a) waves travel at a finite velocity, hence they arrive at consecutive support points with a time delay; (b) wave coherency loss in terms of gradual reduction of the waves' statistical dependence with distance and frequency, due to multiple reflections, refractions and superpositioning of the incident seismic waves during propagation and (c) variation in local site conditions that strongly affects wave amplification and frequency content.

For the particular Wall Section, and since the soil conditions are generally stiff, it can be assumed that from the above sources of spatial variability, the effect of local site conditions and the loss of wave coherency is rather small; as a result, the asynchronous excitation is estimated solely on the phase lag as is can be defined by the distance from the reference point and the apparent velocity of seismic waves (taken equal to  $V_{app}=2000$ m/sec). In order to account for the aforementioned time delay at all base points (nodes) of the 500m long Wall complex, the Finite Element model was internally programmed to permit the subsequent excitation of *each one of the 5830* supporting points *i* with a distinct 3-D ground displacement  $U_{i,x}$ ,  $U_{i,y}$ ,  $U_{i,z}$  which is a function of space and time *t* and is equal to:

$$U_{i,x}(x_i, y_i, z_i, t) = U_{ref,x}(x_{ref}, y_{ref}, z_{ref}, t - \frac{x_i}{V_{app}})$$
(1)

$$U_{i,y}(x_i, y_i, z_i, t) = U_{ref,y}(x_{ref}, y_{ref}, z_{ref}, t - \frac{x_i}{V_{app}})$$
(2)

$$U_{i,z}(x_i, y_i, z_i, t) = U_{ref,z}(x_{ref}, y_{ref}, z_{ref}, t - \frac{x_i}{V_{app}})$$
(3)

where  $x_i$ ,  $y_i$ ,  $z_i$  are the coordinates of a base point *i*,  $U_{ref,x}$ ,  $U_{ref,y}$ ,  $U_{ref,z}$  the three component seismic motion at the reference point,  $V_{app}$  is the apparent velocity of seismic waves and  $x_{ref}$ ,  $y_{ref}$ ,  $z_{ref}$  the coordinates of the reference point (which does not coincide with the zero coordinates due to the slight rotation along the z-z- axis of the left part of the Wall).

### 3 SEISMIC PERFORMANCE OF THE LAND WALLS UNDER STUDY

### 3.1 Dynamic characteristics of the long Wall circuit under study

The dynamic characteristics of the system were initially investigated, and as anticipated despite the height of the Walls, the overall complex is rather stiff (i.e. its fundamental period is equal to 0.12sec). It is also notable that due to the presence of the intermediate towers, there is no clear transverse mode; on the contrary the system vibrates on a large number of similar local modes having similar modal contribution to the overall response.



Figure 7. Characteristic eigenmodes of the system

Clearly, the fundamental mode is also local as it corresponds to the east main wall which is not only unsupported laterally (i.e. no intermediate defensive towers exist) but also is on average 2m higher than other parts of the Wall circuit. The most characteristic from these modes are illustrated in Figure 7 where it is seen that it is only after the 25<sup>th</sup> mode that the structure vibrates (asymmetrically) as a whole.

## 3.2 Seismic response of Land Walls under study in the time domain under synchronous excitation

Having assessed the dynamic characteristics of the system, the Walls were subjected to ground motions derived from the records obtained at the city center during the 1978 seismic event and were appropriately deconvoluted to account for the different soil conditions at the between the recordings and the Land Walls site. For the particular Case A earthquake scenario, the maximum tensile stress developed in time was approximately equal to 30% of the tensile strength (equal to 0.15MPa) assumed for the structure. Similarly, the compressive stresses developed where found also rather low (of the order of 25% of the overall compression strength that was taken equal to 2.0MPa). Apparently, the Walls remain primarily in compression and it is only few locations around the main gates that develop tensile forces along particular critical sections but just for a few peaks in time.

It can be claimed therefore, that the very good performance and lack of any damage of the Wall Section under study during the 1978 earthquake, is generally verified. This can be attributed not only to the massive dimensions of the walls, but also to the rocky (outcrop) foundation conditions which deamplify ground motions (compared to sites of softer soil formations as seen in Figure 6).

It is interesting to notice that this reduction of PGA (compared to the record site) appears to be more significant than the fact that outcrop motion that excites the Walls is of higher frequency content thus closer to the natural period of the structure (i.e. T=0.12sec).

Having assessed the structure for the equivalent level of the 1978 earthquake seismic forces, the linear elastic dynamic analysis in the time domain is repeated for the same ground motion, this time scaled to the level of PGA=0.22g, that is specified by the Microzoning study of the city of Thessaloniki, for the particular site (Case B). As seen in Figure 8, the variation of normal stresses with time for three characteristic locations of the Walls (i.e. West Gate, East Gate and East main Wall), neither the compression nor the tensile strength of the structure is exceeded at any point or time.

It is only few (two-three) peaks for each critical location that the stresses developed reach the available tensile strength of 0.15MPa (being 0.15, 0.12 and 0.13MPa respectively). On the contrary, the 'effective' tensile stress developed (as taken approximately equal to 2/3 of the maximum) does not exceed 0.1MPa on average for the most critical locations of the structure. It is noted however that strictly speaking, the critical checks should be performed at masonry sections instead of local points. Nevertheless, the overall assessment is that seismic demand developed is clearly inferior to the estimated capacity of the Walls.

In terms of shear stresses, the most critical location was identified to be the North side of the East Gate as depicted in Figure 9. Notably, both the shear stresses developed and the shear strength are a function of time as the latter depend on the compression stresses which also vary in time. For the assessment of the safety factor against shear, the following equation was used according to the provisions of Eurocode 6:

$$f_{vk}(t) = f_{vk0} + 0.40 \cdot \sigma_z(t)$$
(4)

where  $f_{vk}(t)$  is the shear strength of unreinforced masonry in time,  $f_{\nu k0}$  is the shear strength of mortar (taken equal to 0.1MPa) and  $\sigma_z(t)$  is the normal compression stress at the same location. As it is seen in Figure 9, the safety factor against shear varies between 1.5 and 2.5 in the extreme case, but it can be estimated to be clearly greater than 2.0 on average. As a result, as was observed for the normal (tensile and compression) stresses the performance of the Wall structure is very good also for the Case B earthquake scenario. This observation is interesting in the sense that, as the Microzoning-induced seismic intensity refers to a return period of 475 years, it can be claimed that the particular level of seismic forces predicted for T=475 years is not adequate to produce significant damage to the Wall structure a fact that is anticipated since the structure is not known to have suffered extensive damage over the entire period of 16 centuries. As a result, both the satisfactory future seismic performance of the Walls and the predictions of the seismic hazard assessment for the Thessaloniki area are (if not explicitly confirmed) at least not counteracted by the refined numerical analysis.



Figure 8. Variation of normal stresses with time for three characteristic locations



Figure 9. Variation of shear stresses with time. East city Walls gate (North view). Seismic response of Land Walls under study in the time domain under synchronous excitation

# 3.3 Seismic response of Land Walls under study in the time domain under $\alpha$ synchronous excitation

Following the dynamic analysis of the system for Case A and Case B earthquake scenarios, it was also deemed interesting to investigate the potential effect of ignoring (as it is commonly the case) the propagating nature of the travelling waves. As already discussed, the Walls where excited with 5830 spatially and temporary variable ground displacement vectors that were enforced to the corresponding base nodes according to equations (1)-(3). Figure 10 illustrates the variation of normal stresses with time under asynchronous excitation for the three characteristic and most critical locations identified (i.e. West Gate, East Gate and East main Wall). By comparing these stresses derived from the synchronous (Figure 8) and asynchronous excitation, it can be observed that although the response can be considered as rather similar, the extremes of the stresses are different. In particular, the extreme tensile stress at the East Gate has increased by 50% (from 0.12MPa to 0.19MPa) while the extreme tensile stress at the East Main Wall has decreased by 40% (from 0.13MPa to 0.08MPa). Especially for the middle point (on the East Gate) the maximum stresses occur at a slightly different time (7.15 sec instead of 7.02 sec). Such distinct response under asynchronous earthquake ground motion has also been observed in a large number of bridges (Sextos et al., 2003) and is pronounced in the case of long and stiff (monolithical) structures (Tubino et al., 2003) due to the excitation of higher (primarily antisymmetric) modes (Sextos et al., 2003) and the subsequent development of additional pseudo-static forces. However, it is also noted that the 'effective' tensile and compressive stresses are again lower than the estimated corresponding strength, hence the comments made regarding the satisfactory historical and future performance of the Land Walls under study remain valid.

In can be generally stated though, that the differences observed between the synchronous and the asynchronous excitation of the particular Wall Section, even if they do not impose a threat for the structural integrity of the system, are not negligible if one considers that due to the very stiff (rock) formations at the base of the Wall circuit, the variability of earthquake ground motion was attributed only to the time delay of the seismic waves and not to equally if not more important coherency loss and local site conditions variation. As a result, the spatially variable nature of the incoming seismic waves should not be a-priori neglected when assessing the seismic performance of long and high wall structures, as there is high probability that ignoring asynchronous excitation, certain aspects of their dynamic response that are related to their inherent stiffness as a structural system and the potential excitation of higher modes may be disregarded.



Figure 10. Variation of normal stresses with time under asynchronous excitation for three characteristic locations

### 3.4 Seismic response of simple stand-alone walls at different city locations

Following the numerical investigation of the seismic performance of the long upper city Wall circuit, case A scenario (1978 earthquake excitation) was applied for the free standing wall of the second location under study (Stylianidis and Sextos, 2006). Similarly to the long Wall complex, good performance was also verified as neither loss of stability due to rocking nor exceedance of its tensile strength was observed during the application of the 1978 ground excitation. Moreover, it was estimated that the particular system studied could resist at least twice the earthquake load imposed during the 1978 earthquake without significant damage.



Figure 11. Variation of normal stresses ( $\sigma_z$ ) with time for Case A scenario (excitation with 1978 earthquake record).

This paper is an attempt to propose a refined approach towards the assessment of the seismic performance of a part of the Land Byzantine Walls of the city of Thessaloniki. Utilizing advanced numerical tools and generating various earthquake ground motion scenarios, both a 500m long section of the Walls and a small free-standing part of the Walls at a second location were studied in the time domain under using synchronous and asynchronous excitation. The main conclusion drawn can be summarized as follows:

• It is feasible to study the dynamic and seismic response of extended systems such as high Walls through refined finite element models and reliable estimates of the overall geotechnical, seismological and structural conditions.

• For the first long Wall Section under study, its good performance during the severe 1978 Thessaloniki earthquake (20/06/1978, Ms=6.4, PGA=0.15g) was verified. A similarly good performance was numerically estimated for the second free-standing Wall where the results also indicated that the particular system studied, not only performed well during the 1978 earthquake but also it could resist at least twice the earthquake load imposed without significant damage.

• It was also numerically predicted that both the particular Wall Sections should not be expected to suffer significant damage for earthquakes with a return period of 475 years. As a result, the satisfactory future seismic performance of the Walls as well as the predictions of the seismic hazard assessment for the Thessaloniki area are (if not explicitly confirmed), at least not counteracted by the refined numerical analysis.

• The overall process adopted and proposed may be potentially implemented in a larger scale as a means to trace (through back analysis) the seismic history of monuments and possibly to assess an upper bound of the historical seismicity of a particular region or city.

• In the framework of the process proposed, the spatially variable nature of the incoming seismic waves should not be a-priori neglected, since it was shown for the long Wall circuit that (as for bridges and other stiff and long structures) the excitation of higher modes may impose significant pseudo-static forces that did not develop under synchronous excitation.

• Further investigation is certainly required with emphasis on the potential effect of material or geometrical nonlinearities (i.e. cracking and/or sliding/rocking at certain interfaces). Moreover, it is evident that the reliability of the methodology adopted is strongly dependent on the reliability in estimating the mechanical properties of the superstructure and foundation soil materials involved (which can be also spatially variable), as well as on the accuracy of the geometrical data that are used for finite element development.

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