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A COMPARATIVE STUDY OF HISTORIC AQUEDUCTS AND VIADUCTS IN SEISMIC ZONES

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ABSTRACT

Increasing international sensitivity on the protection of architectural and techno-cultural heritage has opened new perspectives in the field of engineering preservation. Within this context, structural assessment studies on the historic masonry skeletons in seismic zones are on the way of gaining significant momentum. Starting from public assembly buildings , these studies have recently spread to investigations of historic infrastructural facilities, too. The present study aims a comparative analysis on masonry infrastructural works of major importance of Roman and Ottoman origin having similar engineering features to validate their prominence in seismic design.

KEYWORDS

Historic masonry skeletons, earthquake effects, seismic risk , restoration and repair, ,aqueducts and viaducts.

INTRODUCTION

The recent studies on conservation, preservation and restoration processes of historical buildings in seismic zones have shown that the assessment of their seismic vulnerability is of fundamental importance (Augusti et al., 1988; Karaesmen et al.,1989, 1992 ; Karaesmen and Karaesmen, 1994; Agostino and Frunzio, 1994 and Spence et al., 1994). The range of historical buildings is diverse. It covers a wide variety of structures of considerably different age, material, functionality and present state. In the last decade, monumental ancient public assembly buildings have been the focus of seismic assessment of the researchers. Recently, engineering structures of historic character with ancient masonry skeletons such as bridges,aqueducts , towers, etc., are of concern to the authorities in relation with their protection. Indeed, some of these structures are still functional and their maintenance is a practical necessity as well as a sign of respect for the safeguard of historic heritage.

The main scope of this work is the study of some almost intact structures of historic water supply systems. The two of them are the extensive water supply networks from the late Roman period (the second half of the fourth century). They have been constructed around Istanbul and in the vicinity of Nimes at southern

France. Since their erection, both of these structures were subject to several earthquakes of different magnitudes and they have resisted successfully. The comparative study is extended to still standing aqueducts of the sixteenth century Ottoman water supply systems around Istanbul, including the prestigious 'Maglova Kemeri'.

A summary of results of the computer aided assessment studies will be presented, herein. The conclusion will follow as that all of these structures possess well conceived and carefully constructed solid skeletons along elegant alliances with their environment. A regular maintenance work is needed, however, to ensure their perpetuation, to reduce action of fatigue effect throughout ages. On the other hand, soil and foundation aspects continue to form sources of some uncertainties and inaccuracies in the theoretical evaluation of these historic structures. Indeed , information on soil properties and also on shape and size of foundation blocks is of approximate character. All sophisticated computing facilities and efforts for obtaining the seismic response of ancient masonry skeletons would lead to erroneous numerical results under such cases. This disadvantage would likely be remedied by approaching the problem through the use of uncertainties involved as a guide for developing the decisive actions. Thus, the future structural repair and restoration works would highly benefit from such theoretical and quantitative results that will be integrated with opinions and recommendations and some of which are the goals of this study.

CONSIDERATIONS ON THE SEISMIC EVALUATION

General Concepts

Many of the great civilizations, since the antiquity, have settled either in or close to earthquake prone zones of the Mediterranean and Pacific regions. Consequently, vestiges, remainings or almost standing still old buildings, most of which are of masonry, exist in seismic areas. The concept of safeguard of architectural heritage covers first the perpetuation of still standing structures and also partial restructuring of some elements of the remainings in order to prevent their full disintegration throughout the future seismic events. Within this context old buildings of major size and public importance are given priority in seismic analysis. The case studies of historic engineering structures have also been subject of similar analysis recently (Fabres and Fiches,1989 ; Karaesmen, 1989; Karaesmen et al., 1992; D'Agostino et al., 1994).

The evaluation of the expected response of ancient masonry skeletons during an earthquake is rather difficult and complex to accomplish (due to basic uncertainties). Fortunately, collaborative groups in different European countries (Spence et al., 1994) and teams supported by National Science Foundation (NSF), Getty Conservation Institute of USA and many others (Karaesmen et al., 1993 ;Karaesmen and Karaesmen ,1993; Sykora et al., 1993) try to reduce uncertainties by increasing information on the relevant field. The aim of all those groups is to assess effective methods for strengthening historic structures . Computational techniques such as finite element and /or boundary element methods are of use in the preliminary state using elastic analysis. Indeed, the mortar cracks and aging effects of the overall masonry system should be considered for obtaining more realistic results. It is now a common belief and accepted fact that preliminary studies to gather information on historic buildings and structures on their past history and structural behaviour are a must for developing efficient design strategies and strengthening techniques. Thus motivated with regard, in particular, to protection against earthquake risks, the comparative studies on the Roman and Ottoman aqueducts and viaducts are initiated.

Structures of Roman Times

There are only a few aqueducts of significant size that are still standing as the remainings of historical hydraulic networks. A spectacular remaining of the Roman achievements is Bozdogan (Valence) aqueduct pre-byzantinean époque in this area. This aqueduct has served Istanbul, one of the eternal capital towns of the world till very recent years.

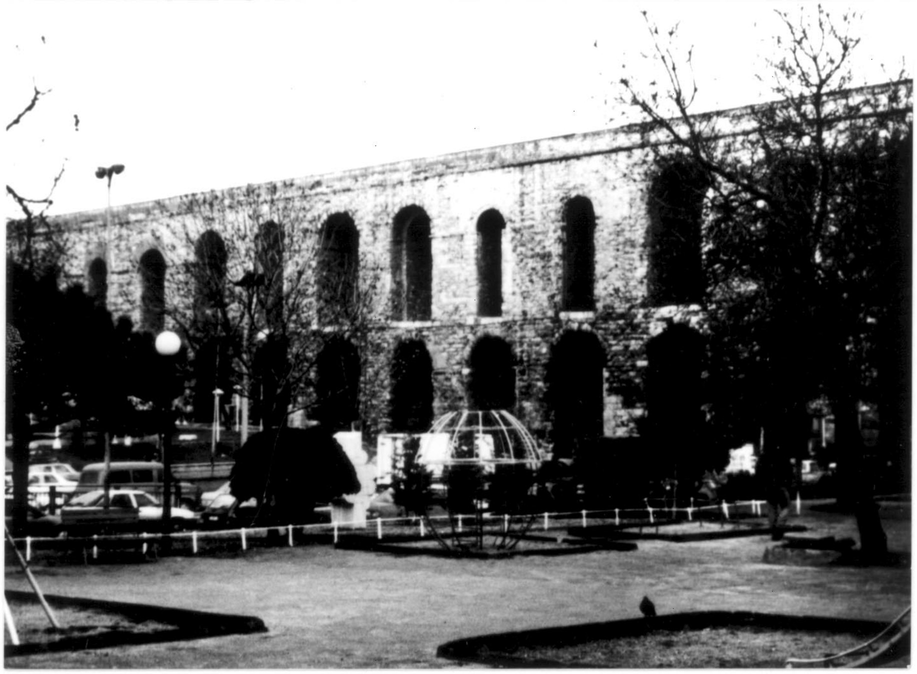

Fig. 1. A central view of Bozdogan (Valence) Aqueduct, Istanbul.

Around Nimes, a historic city of southern France, there is also a network of several tens of kilometers which was constructed in the 4th century (approximately at the same period as Bozdogan) . Although some of its parts do not exist , it can still be considered an engineering masterpiece of the late Roman period. The symbol of this network, is Le Pont du Gard, an impressive structure with three tiers (Fig. 2). The wonder of Le Pont Du Gard is that it is still mostly intact and functioning as a road bridge for the car traffic of our modern times at its lower tier level (Fig. 3). The upper tier formed from 35 arches on a length of 360 m. was used for water supply and the middle tier was designed for the discharge of sewage water.

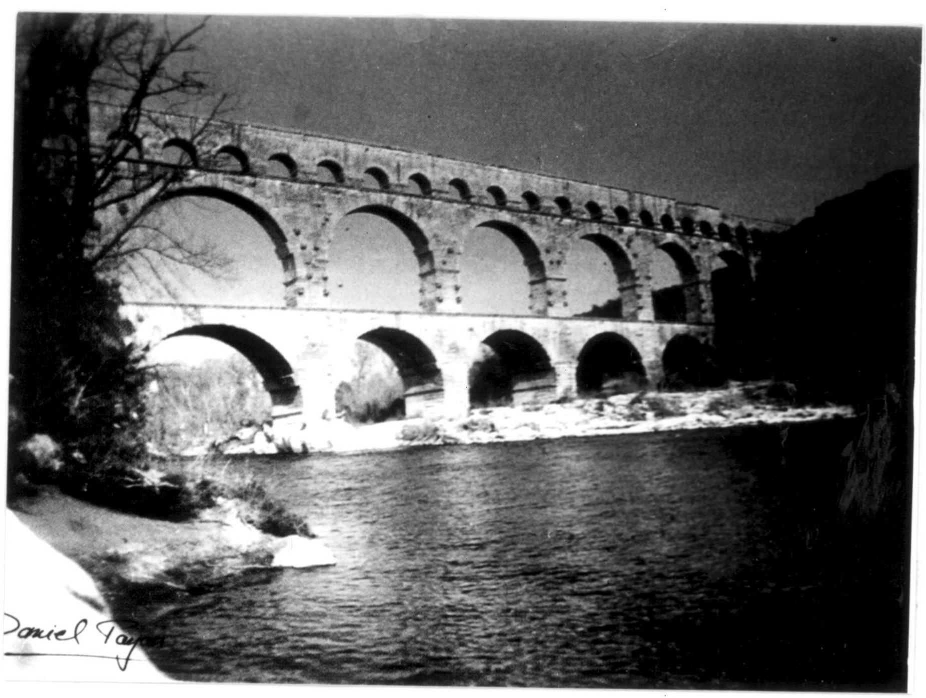

Fig. 2. General view of Pont du Gard.

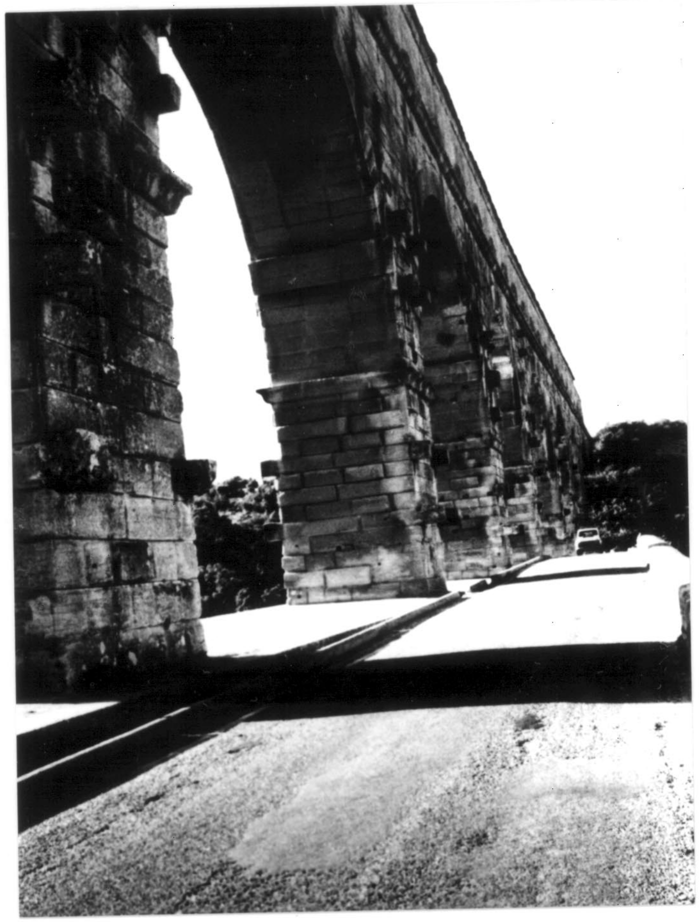

Fig. 3. A detail of Pont du Gard at its lower tier level.

Ottoman Structures

Nimes and its vicinities are at earthquake prone zones of medium risk level with large return period . As for the Istanbul area, the capital of Byzantine and Ottoman empires , the risk level for earthquake occurrence is much more higher and the return period for the earthquakes are significantly shorter. This is why the existing system has required a full repair and in the meantime it was extended with new lines, after the heavy hazards of the earthquakes of the late 15th and early 16th. centuries. Since then, t he reconstructed aqueducts were able to resist other violent earthquakes . Among them one aqueduct is also chosen as a reference for case study : Maglova Aqueduct. It is remarkable with its majestic size and its alliance with environment (Fig. 4).

At the introductory stage of a comparative study program two reference monuments , one from Roman and the other from Ottoman ages are given priority. Analytical findings of these cases (Roman Bozdogan and Ottoman Maglova) are going to be discussed in the following sections. For more details on the geometry and material properties of the Maglova aqueduct one may refer to the previous study of the authors (Karaesemen and Karaesmen , 1994).

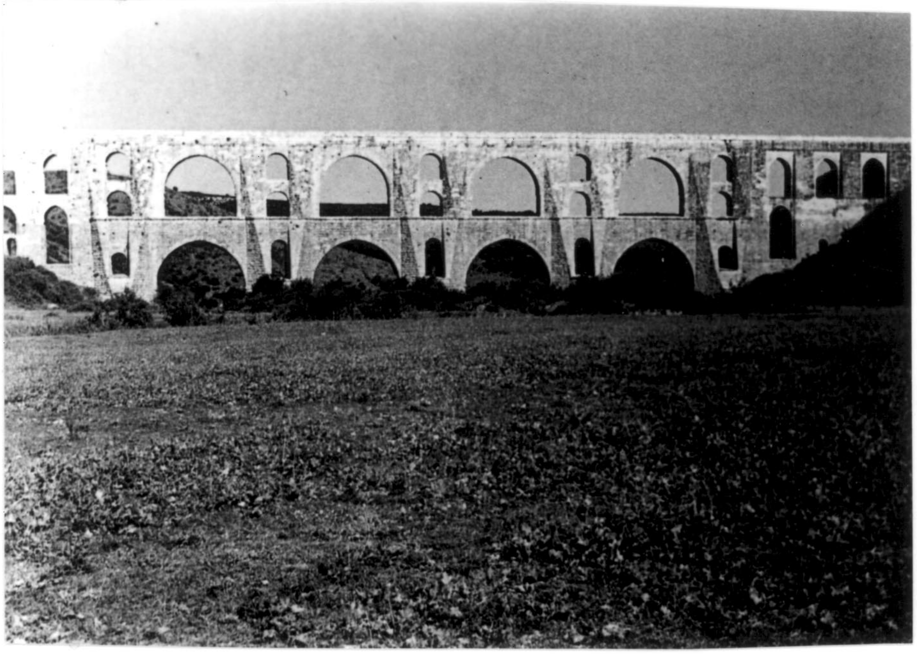

Fig. 4. General view of Maglova aqueduct.

Assessment of Bozdogan (Valence) Aqueduct

Istanbul has been always an intensely inhabited place, likely because of its exceptional location, beauty and mild climate. The city has immense water supply problems and in this hilly region the valleys had to be traversed by arched portions of aqueducts (Cecen, 1988). The Valence aqueduct was originally 900 m. long with a central part of two tiers of about 250 m. Series of regular double arches were established as seen in Fig. 1. The central part with a maximum height of 24.2 m. has been modeled as shown schematically in Fig. 5. The main idea in chosing such a model is to decrease defects that may not be removed by the refinement of the meshes in finite element analysis. The computations are done by the use of SAP 90 code, in the elastic range. A soil spectrum corresponding to rocky ground conditions has been adopted to simulate overall hilly character of the field.

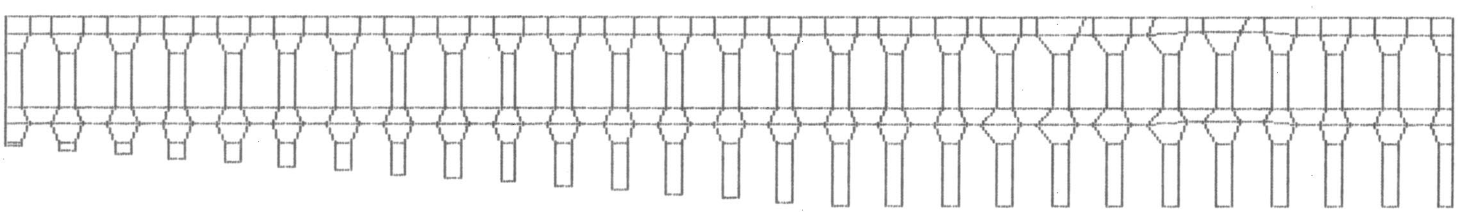

Fig. 5. The dynamic analysis model of Bozdogan aqueduct.

The first seven modes of the approximate structural response have been studied. The period of the first mode in the longitudinal direction is estimated as 0.42 sec. In Fig. 6 a descriptive computer output for the

vibrations of the structure in its third mode is presented. Tensile stresses were evaluated in the case of heavy seismic effect at the base of the pillars supporting lower arches. Knowing that structure has been partially
damaged at its central area during various earthquakes, the analytical findings should not be considered as surprising. Some exterior fortifications and inner restrengthening precautions as fine grouting of the mortar could be foreseen. More detailed investigations will be carried on with this reference.

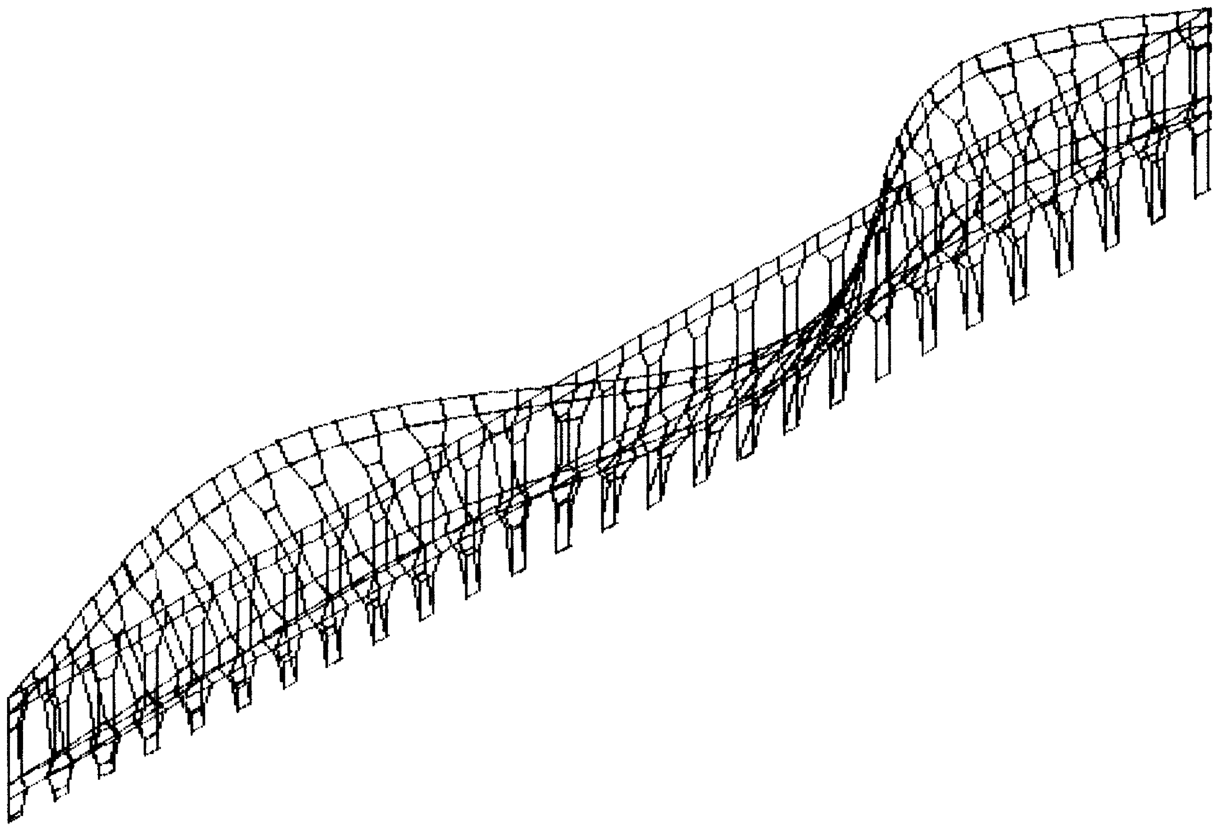

Fig. 6. Schematic view of seismic deformations in Bozdogan aqueduct.

Comparative Views

Basis of comparison among the three aforementioned structures is mainly their rather adequate behaviour under earthquake effect. Partial zonal hazards occurred on the Roman structures but they did not lose their functionality with the help of minor repair and restoration works. The Bozdogan aqueduct as remarked above would need some interventions to perpetuate its life span. When detailed studies on Pont du Gard will be accomplished , similar results will be likely obtained, despite its location in a seismic zone of smaller intensity.

In the analysis of the Maglova aqueduct (Karaesmen and Karaesmen 1994) the longitudinal period for the first mode was estimated as 1.07 sec. This aqueduct with an approximate height of 32.4 m and extending on larger daring arches at its central part has more flexible structural characteristics than Bozdogan. This fact is definitely assessed by the modal periods obtained via numerical simulations. Maglova has been devastated by a strong flood in its erection time and precautions had been taken to better its stability during this period.

Consequently, very small tensile stresses are observed in its dynamic response analysis and it is believed that no special restrengthening measures are needed except routine maintenance work that ancient structures may need.

Similarities between Pont du Gard and Maglova Aqueduct can be put into a general form. They are both located on river valleys where the soil is of deposit type. This characteristic is common to other aqueducts also, therefore information on soil properties seem to be of particular importance in the dynamic analysis of historic structures and thus, in their restrengthening phases.

CONCLUDING REMARKS

The aging effect is already known to be a source of deformations and mortar cracks in historic masonry structures. In earthquake free zones, these deformations and cracks could be monitored rather easily by regular observations. But, the old structures in seismic zones as considered in this study, are subject to sudden and unexpected changes, in addition to routine deformations due to the aging effect. Preventions should be planned and implemented before the recurrence of a hazardous earthquake or any other natural disaster. One of the three cases mentioned in this study has revealed a need for restrengthening intervention. Within this perspective all important historic structures should be assessed and investigated before any engineering work related with their conservation and reconstruction processes takes place.

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