SYMMARY

The present paper investigates the mode of action of earthquake on the structure of the auditorium of Nikopolis Roman Odeum, one of the most badly damaged Roman structures of this type in Europe. This investigation is a part of a wider study – architectural, structural, etc – of the monument, aiming to the rehabilitation of the Nicopolis Roman Odeum.

The first part of this investigation is qualitative, based on extensive observations on the field and also on the experience of similar projects. It has to be mentioned that there is a scarcity of papers or books on relevant matters.

The results of the first part of the investigation had to be verified by a proper research program, which was a combination of a geotechnical and an extended analytical investigation (using extensively finite element models of the structure under examination). The research was conclusive, verifying the results of the first part and revealing the causes of the partial collapse of the structure.

INTRODUCTION. ARCHITECTURAL CHARACTERISTICS OF THE MONUMENT

The archaeological site that today occupies the space that of the Roman city of Nikopolis lies few kilometers north of the modern city of Preveza on a vast plain situated between the Ambracic gulf and the Ionian sea. It is well known that Nikopolis (city of Victory) was founded by the Octavian to register his victory over Mark Anthony and Cleopatra at the naval battle of Aktion (31 BC). The Roman Odeum was placed near the centre of the city an indication of the importance the Romans attributed to this kind of buildings. The main bulk of its impressive substructure remains intact (although half hidden under ground) while most of its superstructure lies scattered around. Its outer skin and its decorative elements are missing due to systematic material theft throughout the ages.

The building can be inscribed in a rectangular measuring 44.63Χ59.61m. However the round auditorium is free-standing and not surrounded by rectangular outer walls to support it as is the case of other similar theatres. To its south side opposite-facing staircases are attached leading the upper tiers. Two more are found on each side of the stage building. As is the case with all the Roman theatres constructed from scratch, it is situated on mostly level ground without taking into account the natural inclinations.

It was built in one building phase. However as concerns its construction date scholars disagree. R. Meinel believes that it was constructed just before 128 AD for the reception of Emperor Hadrian in Nikopolis. Contrary to this view, Höpfner has dated the building taking after its marble
decoration in the period just after the founding of the city a view shared by Crema\[iv]. However *opus mixtum* its building method, is not registered before the first century AD so Meinel must have been right.

It is comprised of the stage (orchestra) and the auditorium. The latter is a full semicircle with a radius of 24.35m from the centre of the *frons pulpiti*, separated from the stage by the slightly inclined side entrances. There are 20 tiers (there were 22 originally) and the difference in height is 8.30m from the orchestra to the last tier. The latter are constructed by the inner cement core with a perpendicular brick face and covered with lime slabs.

The auditorium is based upon a very sturdy construction. Three concentric vaulted arcades form the substructure of the theatre. The two inner ones are quadrantal in section while the outer one is semicircular. Through 17 arched openings it connects to the exterior and also to the orchestra through the side entrances. The supporting piers are rectangular in section with embedded half columns on their exterior side. As with almost everywhere else at the theatre their elevations have lost their exterior marble facing; only their cement core is visible. Behind the auditorium the two staircases converge over a cross in plan small room, possibly a temple.

By a stroke of luck a big chunk of the superstructure of the monument was retained over the 12th pier, thus saving important architectural details. The springings of two arched openings can be traced. Exactly at their junction there is a Corinthian impost capital decorated with acanthus leaves still embedded in situ. Over the arches there is deep groove that a marble frieze used to decorate (not extant today). At the top there are traces of blind arcading.

Traces of sturdy rectangular construction remain over the temple at the junction of the south staircases. Only part of its north wall remains; it coincides with the external wall of the auditorium and the bases of two piers. This construction was sufficiently raised over the tiers so as not to allow immediate access from the auditorium. What use was given to this construction is not obvious. Isler\[iv] believes that it used to be a temple while Meinel\[iv] suggests that it was Emperor Hadrian’s box. Under this construction a gallery running along the whole of the auditorium semicircle was observed. It is faced internally with brick; however its dimensions (1.50m in height, 0.90m in width) allow only limited access. There is a perpendicular opening towards the last tier. There were also openings over the arcades from this gallery towards the external elevation of the theatre that can still be registered on the still standing, 12th pier. It seems therefore that this gallery was an air-duct, built to bring fresh air inside the closed space of the auditorium. This finding has not been observed in any other roman theatre.

Another important issue that has occupied scholars is the problem of the roof of the Odeion. According to Meinell\[vi] the following facts suggest that it was roofed:

a. The small hole for drainage at the centre of the orchestra is insufficient to drain the whole auditorium, if it was open air. It probably only served for cleaning purposes. If it was open air a circular open duct should be present.

b. The external walls are sturdy enough to bear a wooden roof with safety

c. In specific places there are recessions in the walls that could have housed drainage pipes for the draining of the roof. Similar pipes can be found in the theatres of Aphrodisias and Ephesus that are better preserved and used to bear roofs.

d. To the above reasoning we should add the existence of the air-duct that would have no meaning in an open air theater.

Although the existence of a roof can more or less be accepted, its form is very hard to be specified. The building was certainly not domed. The thickness of the walls is not sufficient to
bear a load of this magnitude (the span is 30m!). Moreover the collapse of a domed roof would produce a pile of ruins much higher inside the auditorium. Therefore a timber roof was an obvious choice. A successful theatre roof should have few or, even better, none at all intermediate supports, so as not obstruct the view to the stage. A circular roof is out of the question since all the weight would be born by a central support situated at the centre of the semicircle that is exactly in front of the stage, something totally irrelevant. That leaves us with the choice of timber roof with double inclination. In this case few powerful reticulated beams (χωροδικτυώματα) at specific places would bridge the span and bear the whole load of the roof. This is not unusual for a Roman building however the 30m span (in the middle) is too wide to be bridged with conventional methods. Following prof Korres’s research that the Herod Atticus’s Odeum in Athens with a 50m span was also roofed, it seems that the Romans were masters of an advanced building technique of bridging wide spans with timber roofs.

**DAMAGE ASSESSMENT**

*Present condition of the monument*

The monument is one of the most badly damaged roman structures in Europe. Most of the superstructure (i.e. standing walls) of the auditorium lies scattered around (Photo 1). Only a chunk of the superstructure is retained over the 12th pier (Photo 2), which is crucial to the purpose of structural and architectural research.
Although a great part of the substructure of the auditorium is half hidden under the ground, its main bulk appears as intact. Nevertheless its pathology has some grave characteristics: all the supporting piers are damaged in the same way, i.e. a part (the outer and higher) is “cut off” the remaining section (Photo 3). Moreover, the concentric vaulted arcades have severe structural problems (cracks, severe loss of section – especially where they meet the supporting piers, etc) (Photo 4).

**Causes of the structural problems**

During the first part of the study, all the efforts were directed to focus on the causes of the problems, in order to be able to propose the proper method of rehabilitation. Most of these efforts were qualitative, based on extensive observations on the field and the experience of similar projects.
(a) Vaulted arcades: As far as the vaulted arcades are concerned, the structural problems are mainly due to environmental factors, since their surface of roman concrete is constantly exposed to the weather. Though their endurance – two thousand years after the construction of the Odeum – is impressive, especially when it is compared to the endurance of modern concrete structures (among other factors, the first have superior performance to the latter due to the absence of the potentially corrosive steel reinforcement), their condition is currently highly problematic.

(b) In built strength of the piers: In contrast to the vaulted arcades, the environmental actions do not consist a serious threat to the piers of the substructure. The first reason is that their concrete is of better quality than that of the vaults since the brick and mortar skin provides better insulation for curing. Indeed, the Roman insistence on facing is due to the fact that this allowed the masons to built walls and piers without wooden framework. Moreover, this skin, which during the construction served as a mould into which the concrete or rumbled fill was introduced into layers provide to the inner concrete core a substantial protection towards the environmental actions.

The roman piers are quite robust structures due to the type of the materials which are used and the constructional procedure as well. The thick surface of bricks created a strong and rigid container during the pouring and setting process, when the liquid concrete generated outward thrust against it. Superior retaining capacity allowed the concrete to be introduced in larger and less frequent batches.

Technically, cured Roman concrete is a compound, not a mixture. In other words, it has uniform mechanical properties with no significant weakness of bonding between the components. On the other hand, bricks, i.e. fired clay mixed with various kind of aggregate, and mortar are a mixture. The weakness of their bond is evident in the traditional practice of laying bricks horizontally in staggered rows. Dead loads tend to pull walls apart horizontally, generating vertical cracks. If bricks were laid vertically on edge, they would be vulnerable to separating from their mortar courses. When laid in traditional overlapping fashion they resist vertical splitting by creating “stitched” vertical seams, which generate much more resistance to the horizontal tensile stress. Fully understanding this principle, Roman builders took its logic one step further: If the bricks were well bonded to the concrete core, perhaps their resistance to cracking could be transmitted to
the core as well. On conversely, the core’s nature as a highly coherent, monolithic compound could hold the bricks together. In roman bricks the maximum bond between facing and core was achieved with the shaping of the bricks like small cones or pyramids, the tapering end set inward to create a toothed bonding surface. The result was a quite robust structure.

(c) Factors that expose the piers to earthquake actions: In the way that the Nikopolis’ piers are constructed there are areas of weakness, i.e. the so called bonding courses. These are single horizontal courses of large bricks that run through the entire thickness of the wall (Fig. 1, Photo 5). The length of their sides, and sometimes their color, makes them immediately recognizable in an otherwise featureless wall. They are set in vertical intervals and during the construction of the piers “floated” free in the core, resting directly upon and under the concrete fill. The use of these bonding courses was that they represented the interval between a concrete pouring phase and the laying of the brick facing for the next pier stage. Moreover, these bonding courses help to prevent undue settling of a mass of wet cement by creating new “floors” for each stratum, and they also provide modular vertical measures so that the masons did not have to measure heights from the ground up.

However, these bonding courses – so useful for the management of work during the construction - have a negative effect (the opposite of “bonding”) in earthquake prone areas, since they create discontinuities in the concrete than can cause horizontal slipping and rotating, with potentially grave effects for the safety of the structures. It is remarkable, that the Roman historian Pliny mentions a professional disagreement on the use of bonding courses between engineers concerning the construction of a theatre in the city of Nicea, Asia Minor. It is interesting that the local dispute recorded by Pliny took place in Nicea, a town near the North Anatolian Fault.

Concluding, the bonding courses function as surface of discontinuity for the piers in earthquake prone areas, and this is the case for the piers of the Nikopolis Roman Odeum (Photo 5).

Photo 5

An, additional factor of weakness for the piers – especially in the area where the superstructure of the auditorium lies on the substructure - is an air-duct built to bring fresh air inside the closed
space. This air-duct—practically a gallery as it is shown in Fig. 1—weakens by its mere presence its neighboring area when an earthquake hits the structure.

Conclusion of the first part of the investigation
The qualitative approach concluded that earthquake has been the main cause of damage for the piers. It is worth noticing that their mode of fraction is the same for all of them (Fig. 1). In conclusion the earthquake action has been amplified by certain crucial factors which have to do with specific structural characteristics of the Nikopolis Odeum. In Figure 1 is represented the mode of fracture of the piers in combination with the collapse of the upper wall of the auditorium.

MODE OF FAILURE OF THE PIERS DUE TO EARTHQUAKE ACTION

![Figure 2](image-url)
FURTHER INVESTIGATION. RESEARCH PROGRAM
The conclusions of the first part of the study concerning the damage assessment had to be verified by a proper research program. This program was a combination, of a geotechnical and an extended analytical investigation.

(a) Geotechnical Investigation: Investigation of the underground conditions (bearing capacity of the soil, foundation settlements, effect of water table to bearing capacity, interaction between soil and structure) is prerequisite to the evaluation of the contribution of the ground to the damage of the monument, i.e. in addition to the earthquake and environmental action. It is also necessary to obtain sufficient information for the rehabilitation study.

The geotechnical investigation for the Nicopolis Odeum was based mainly on soil boring, sampling and the relevant tests. Actually, four boreholes (total depth of 80m) were materialized. The results of this exploration are in summary the following:

- The bearing capacity of the soil is completely satisfactory.
- The water table does not interfere with the monument and does not contribute to any problems of the structure.
- The Odeum as it was constructed (i.e. in its initial shape with all its weight, and not so much in its present condition) has some special characteristics as far as the interaction between soil and structure is concerned: due to the strongly uneven distribution of loading between the two lines of piers (i.e. the external line undertakes the greatest part of the loading, since it supports the superstructure as well), there is a strong tendency to differential settlements. Due to that, the structure is under permanent tension in the area of air-duct (Fig. 1) and the apex of the vaults. This characteristic exposes the monument to the earthquake actions.

(b) Analytical calculations: The use of analytical calculations (finite elements simulation of the structure under various loading) is prerequisite in the verification of the causes of damage which were based on a qualitative approach. It is also necessary to obtain useful data for the rehabilitation study.

The simulation of the monument consists of three models, each of them representing a different state of its existence:
(i) The initial structure – as it was constructed.
(ii) The present day structure – taking into account among others that it is half hidden under the ground.
(iii) The future structure - after its partial rehabilitation, i.e. after a complete excavation so that the whole height of the piers will be exposed, and the rehabilitation of the substructure but not the upper floor of the monument.

Samples of the in situ concrete were used in order to evaluate the technical characteristics of the material (i.e. roman concrete), as following:

- Specific weight γ=1.8KN/m³
- Modulus of elasticity E=400Mpa
- Compressive strength 4Mpa
- Tensile strength 0.6Mpa
Earthquake A = 0.24g

Main points of the results
- The calculations fully confirmed that the model of fracture presented in Fig. 1 is correct.
- For all of the three under examination models the max compressive strength was everywhere below the permissible stress.
- Apart from the first model (i.e. the initial structure as it was constructed), where the upper wall tends to move outwards starting the procedure of its collapse and the damage of the piers, in the two other cases the movements are practically negligible. That happens due to the great stiffness of the structure (calculated fundamental period 0.28 sec for the first model and 0.18 sec for the second). The negligible potential movements of the existing structure explain the fact that a chunk of the superstructure is still retained over the 12th pier.
- The continuous crack at the apex of the external vaults is due to exceeding tensile stress.

CONCLUSIONS
The mechanism of damage of the structure of the Nikopolis Roman Odeum due to earthquake action was examined in this paper. The contribution of some special features of the structure (i.e. plates of bonding course and an air-duct gallery) in its structural inadequacy were fully explored and their crucial role in the eventual failure and damage was confirmed.

REFERENCES