*16th World Conference on Earthquake Engineering, 16WCEE 2017*

*Santiago Chile, January 9th to 13th 2017*

*Paper N° 4140*

*Registration Code: S-G1463124044*

# OLD TOWN CORE OF OHRID - SEISMIC PARAMETERS FOR REPAIR AND STRENGTHENING OF STRUCTURES

D. Dojcinovski(1), M. Stojmanovska(2), M. Garevski(3), W. Guoxin(4), B. Dimiskovska(5), I. Gjorgjeska(6), N. Kuljic(7)

*(1) Professor, UKIM-Institute of Earthquake Engineering and Engineering Seismology, IZIIS- Skopje, dragi@pluto.iziis.ukim.edu.mk*
*(2) Associate Professor, UKIM- Institute of Earthquake Engineering and Engineering Seismology, marta@pluto.iziis.ukim.edu.mk*
*3) Professor, Institute of Earthquake Engineering and Engineering Seismology, IZIIS- Skopje, garevski@pluto.iziis.ukim.edu.mk*
*4) Professor, Wang Guoxin, Earthquake Engineering Research Institute, Dalian University of Technology, gxwang@dlut.edu.cn*
*5) Scientific Advisor, Institute of Earthquake Engineering and Engineering Seismology, IZIIS- Skopje, biserka@pluto.iziis.ukim.edu.mk*
*6) Assistant, Institute of Earthquake Engineering and Engineering Seismology, IZIIS- Skopje, irena_gj@pluto.iziis.ukim.edu.mk*
*7) Civil Engineer,M.Sc., HE "Piva", EPCG A.D. Niksic, Crna Gora, nikola.kuljic@epcg.com*

## *Abstract*

Historic buildings and monuments are an important part of cultural heritage of one country and must be protected and preserved for future generations, especially against earthquakes as they cannot be predicted in time and intensity. Repair and strengthening of old buildings that are part of cultural and historical heritage is a very complex process consisting of various phases that require definition of the seismicity conditions, the design seismic parameters as well as the seismic risk level. All of these parameters should be studied thoroughly in order to provide corresponding bases and define the necessary preventive measures against expected strong earthquakes.

The old town core of Ohrid is known for the large concentration of buildings of enormous cultural-historic importance. On the other side, the Lake Ohrid region is earthquake prone where a number of strong earthquakes has caused great disasters. The strongest event ever recorded took place on February 18, 1911, located at the south end of Ohrid Lake. The magnitude 6.6 earthquake (MCS IX$^0$) occurred at depth of 15 km. The maximal expected magnitude for the Ohrid region is defined as 6.9. Considering the high seismicity of this area, all the buildings and particularly the old ones are permanently exposed to the risk of being damaged or experiencing total failure. Having in mind the age and importance of the church "Sveta Bogorodica-Perivlepta" in Ohrid, extensive, complex, engineering-seismological, geotechnical and other investigations were performed in order to define the seismic hazard level, the vulnerability of the building, the existing seismic risk and the seismic parameters for design, repair and strengthening of the building.

Main attention was focused towards the definition of the time period of the occurrence of earthquakes with certain intensity as a representative for determination of parameters needed for dynamic analysis and eventual aseismic strengthening of the structure. Making a decision about the acceptable level of seismic risk and corresponding maximal accelerations is an issue that, except the designer, also involves the investor and the beneficiaries, meaning that the decision should finely balance the level of acceptable risk, significance of the structure and the economic cost of the potential interventions.

*Keywords: earthquake; seismic hazard; seismic risk; damage; heritage; return period*

## 1. Introduction

Ohrid town and particularly the old town core of Ohrid are known for the large concentration of buildings of cultural-historic importance, a number of Byzantine Churches dating from X to XIV century. On the other hand, the area of Ohrid is characterized by a considerably high seismic activity. In the seismological map, this area is defined as IX MCS scale zone.

Throughout its history, Ohrid was exposed to a number of catastrophic earthquakes. The maximal expected magnitude for the Ohrid region is defined as 6.9. Considering the high seismicity of this area, all the buildings and particularly the old ones are permanently exposed to the risk of being damaged or experience total failure.

The high level of potential damage to the structures can also be expected in future, mainly due to the following reasons: the pronounced massiveness of the stone masonry buildings, the very low ductility capacity, the insufficient bearing capacity, the inadequate connection of the structural elements, etc.

For these reasons, extensive, complex, seismological, seismotectonic, geophysical, engineering-seismological, geotechnical and other investigations for the area of Ohrid were performed.

## 2. Seismicity of Ohrid Area

A significantly strong earthquake that has occurred in Ohrid Lake area is reported by the ancient historian Procopius (ca. 500–565 AD) who mentioned Lychnidus in his Secret History or History Arcana. Lychnidus commonly counts as the old name of Ohrid.

The text of the History Arcana describes the catastrophe during Justinian times, most probably 526AD. A local earthquake that destroyed the entire city and left the majority of the inhabitants dead, must have had a magnitude greater than 6, even taking into account poor building standards at the time and possible exaggerations of the author. Even if the fatalities were not caused by building collapse due to shaking but resulted of secondary seismic effects like rock falls, landslides, etc., a medium strong event must be assumed. Ambraseys (2009) lists a strong event in 527AD, which would fit the historical data of the reign of Justinian. Other significant events occurred in 548, 1673, 1871, 1889, 1896 and 1911 (Ambraseys and Jackson, 1990; Goldsworthy et al., 2002; Ambraseys, 2009).

Table 1 – Significant earthquakes in and around Ohrid basin (M≥6.0)

| **Year.** | **Month** | **Day** | **Time** | **$\phi$** | **$\lambda$** | **M** | **I** | **h (km)** |
|---|---|---|---|---|---|---|---|---|
| 1906 | III | 1 | 17h 45m | 41.10 | 20.01 | 6.5 | IX | 15 |
| 1906 | IX | 28 | 02h 30m | 40.90 | 20.71 | 6.0 | VIII | 20 |
| 1907 | VIII | 16 | 13h 00m | 41.10 | 20.12 | 6.2 | IX | 13 |
| 1911 | II | 18 | 21h 35m | 40.90 | 20.82 | 6.7 | IX | 15 |
| 1912 | II | 13 | 08h 03m | 40.90 | 20.62 | 6.0 | VIII-IX | 16 |
| 1942 | VIII | 27 | 06h 14m | 41.60 | 20.43 | 6.0 | VIII-IX | 12 |
| 1960 | U | 26 | 05h 10m | 40.60 | 20.73 | 6.4 | VIII-IX | 13 |
| 1967 | XI | 30 | 07h 23m | 41.40 | 20.43 | 6.6 | IX | 17 |

Instrumental seismicity records in the Ohrid area reach back to the early 20th century. The strongest event ever measured here took place on February 18, 1911 (Fig.1) located at the south end of Ohrid Lake. The magnitude 6.6 earthquake (MCS IX) occurred at depth of 15 km.

The location of the church St. Mary Peribleptos (Fig.2), is in the old town, where this earthquake has had intensity between VII and IX° according to MCS seismic scale. This means that on order to 'survive' earthquake exposure the structure should be in such condition that would enable to endure ground accelerations resulting from local earthquakes with magnitude M≥6..

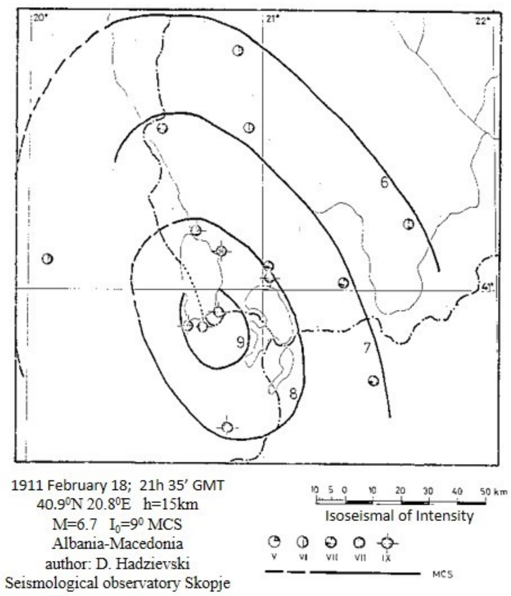


Fig.1 - Isosesmals of the 1911

Fig. 2 - St. Mary Peribleptos in Ohrid

According to the data from the Balkan catalogue of earthquakes, in the period 1900-2008, the studied area (20°00'E to 21°50'E and 40°50' to 41°75) is one of the most seismically active in R. Macedonia. Smaller recent events have shallow epicenters up to 25 km depth, deeper events are rare. Most of the earthquakes are associated to the fault zones that border the Ohrid Basin. Location of epicenters of earthquakes that have happened in the period up to 2008 are presented in Fig. 3.

## 2.1 Seismotectonic model

The seismotectonic model is based on collected data. Weakened zones of intensified seismotectonic activity are the boundaries of geotectonic units and the vertical tectonic units coinciding with the regional faults (Fig. 4).

Apart from the seismological parameters, geological parameters are also considered in defining the expected maximum magnitudes. The greatest importance is given to the position of the Ohrid area from the seismotectonic aspect and the effect of initial tectonic movements within the framework of the assumed model.

The already mentioned maps (Fig. 1) show that Ohrid is situated within a seismically active zone. Earthquakes with maximum magnitude of 6.0 to 6.5, with epicenters very near the town itself are expected. In the south, southeast part of the tectonic block which includes Ohrid, earthquakes of maximum magnitude of 6.5 to 6.9 are expected.

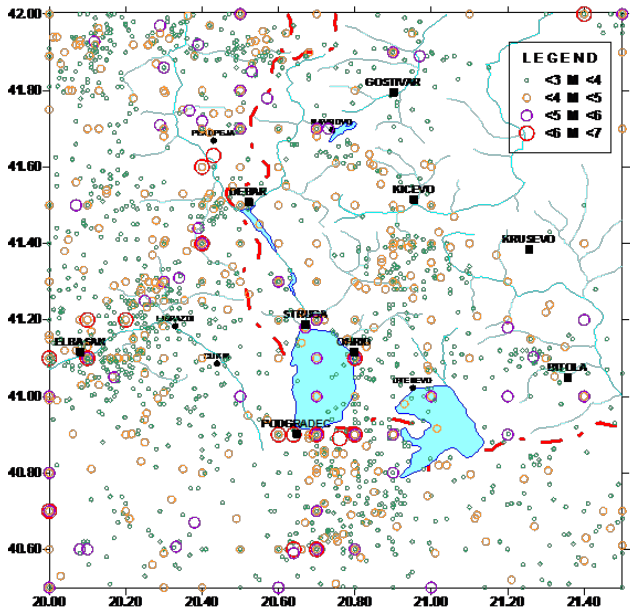


Fig.3 - Epicenters in Ohrid basin, M≥3.0, 1900-2008

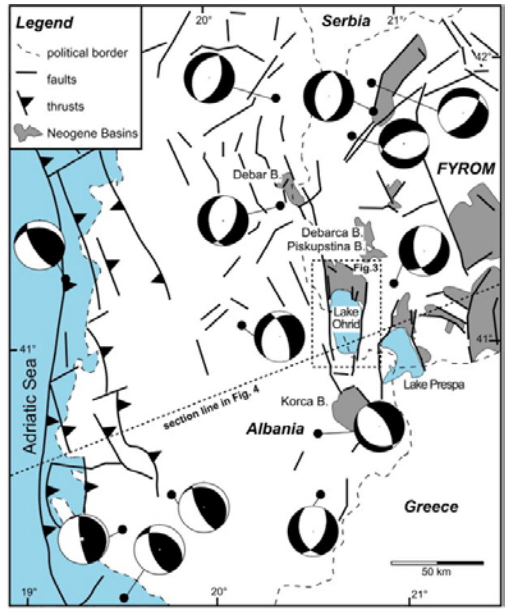


Fig.4 – Regional faults

## 3. Categorization of Structures

The church of St. Mary Peribleptos (13th century) is dedicated to Virgin Mary. "Peribleptos" is an attribute given to this church and means "the one, who can see everything, hear everything and knows everything". It is situated in the old city center of Ohrid and represents part of the world cultural and natural heritage of the Ohrid region. As such, it is on the UNESCO List of World Heritage. It is one of the most important medieval monuments in the Republic of Macedonia and also a referent monument of the Byzantine art from the beginning of the XIV in the world. The church was built in 1295 upon order of the Byzantine commander Prgon Zgur, son in law of the Byzantine emperor Andronicus II Palaiologus.

After the cathedral church of St. Sophia was turned into a mosque (XV century), the church of St. Mary Peribleptos became the centre of the Ohrid archiepiscopacy, a place where the relics of St. Clement of Ohrid were kept. Numerous church objects, icons and books were removed to this church. It is known that, within the church, there was a big prelate's library with parchment scripts dating back to the 11th and the 12th century as well as old music notations of Byzantine church songs.

Most of the building in the old town core of Ohrid are categorzied as I-st category - buildings of extraordinary cultural-historic value.

### 3.1 Serviceability Period of Buildings

The serviceability life of the buildings is one of the main elements in seismic risk analysis. Considering the specific nature of buildings in the old town core of Ohrid, it is necessary to explain, first of all, the term "serviceability period", i.e., to define what is the meaning of this term in this paper.

Taking into account the monumental character and the cultural-historic value of this church, its serviceability life should be "infinite", which in principle means that with certain interventions, this structure has to last a very long period of time. These interventions could include: (1) regular maintenance of the buildings, and (2) removal of the consequences of natural disasters, i.e. earthquake when it occurs.

If we adopt the criterion that the first category of structures should have a higher seismic stability and a lower possibility of being damaged due to earthquakes (provided through design and especially through repair and strengthening), then we can expect that there will be a rare need for interventions for removal of earthquake consequences regarding these structures, i.e., these interventions will be performed at longer periods of time.

This methodology enables definition of seismic design parameters on the basis of the serviceability period of the structures, structural category and the seismic risk level.

## 4. Seismic Hazard

Based on the seismic hazard analysis performed for the wider Ohrid area, seismic hazard maps and diagrams of return periods of earthquakes were elaborated.

Since the methodology of seismic hazard analysis is generally well known only the obtained results will be presented in this paper. Special computer programmes were applied for computation of the main parameters for definition and elaboration of seismic hazard maps for the wider Ohrid area and the return period diagrams for the occurrence of the maximum ground accelerations at the old town core of Ohrid (Fig. 5).

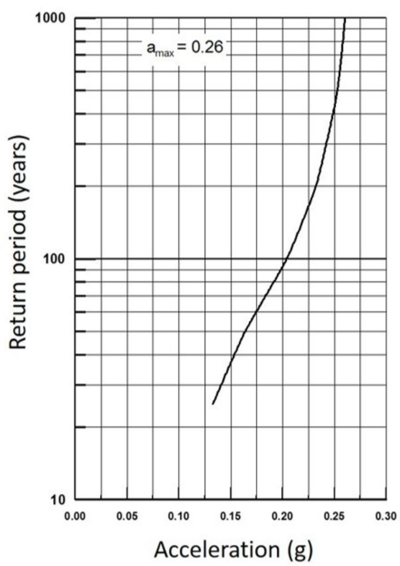


Fig.5 – Expected max a for different return periods

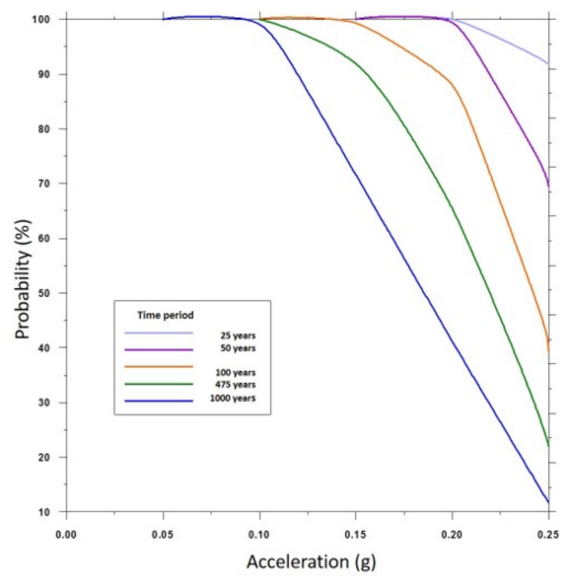


Fig.6 – Probability distribution function

The seismic hazard of the wider Ohrid area was defined by the maximum amplitudes of horizontal ground accelerations for characteristic time periods (return periods) of 25 to 1000 years with a probability of occurrence of 63% (Table 2 and Figure 5).

Table 2 – Maximum acceleration for different time periods

| **Old town core of Ohrid** | **Maximum acceleration a for different time periods (g)** | | | | | | |
|---|---|---|---|---|---|---|---|
| | 25 | 50 | 100 | 200 | 500 | 1000 | ∝ |
| **Bedrock level** | 0.130 | 0.160 | 0.200 | 0.230 | 0.250 | 0.255 | 0.260 |

## 4.1 Results from Seismic Hazard Analysis

The parameters that define the seismic hazard, i.e., the probability for occurrence of earthquakes generally include: cumulative probability for maximum ground acceleration, return period of earthquakes of a certain intensity (acceleration) and level of probability for maximum ground acceleration depending on the return period. These parameters are used for the following practical purposes: (1) elaboration of seismic hazard map and (2) elaboration of diagrams of return period of maximum ground accelerations for individual locations.

The seismic hazard for the wider Ohrid area has been defined through the cumulative distribution function of probability for occurrence of accelerations and values of maximum ground accelerations for different time periods (return periods) of 25 to 1000 years.

## 4.2 Acceptable Seismic Risk Level

The expected dynamic excitations to be caused by future earthquakes to which the structure of the St. Mary Peribleptos church will be exposed have been defined by seismic hazard parameters. These refer to a longer time period of more than 1000 years in respect to which the serviceability period of the structure is very small. Hence, there arises the question as to the selection of the time period of occurrence of earthquakes of a certain intensity that will be taken into account as representative for definition of the seismic strengthening parameters of the structure. During the serviceability period of the structure, earthquakes of different intensity may occur. The consequences that these will cause for the structure are different and depend on their intensity. Hence, a question is posed as to which level of resistance of the structure is to be achieved by its strengthening. The most recent approach in earthquake engineering is that a certain extent of damage that will not endanger the general stability of the structure should be allowed. Such an approach is based on economic criteria. The extent of damage to be allowed is in function of the type and the importance of the structure, the dangers that directly or indirectly arise from the damage, the possibilities for usage of the structure after damage, the repair possibilities and alike. The presented issues point out the necessity of applying the seismic risk methodology in defining the parameters for seismic design starting from the assumption that it is economically justified to allow a certain acceptable seismic risk for structures in seismically active areas.

The first step in defining the seismic risk is the seismic hazard. The next step is to include the seismic risk model and the parameters that are of crucial importance for rational design as are: the serviceability period of the structure, its purpose and importance, the acceptable seismic risk level and alike. For different values of serviceability period of the structure and level of acceptable risk, corresponding values of return period are obtained. The relationship between them is presented graphically in the diagrams shown in Fig.6. The presented diagrams are spatially independent and usable for each location in any area provided that the diagrams of return periods of maximum accelerations are previously defined for the observed location.

Based on the diagrams, one can define the seismic design parameters, i.e., the maximum accelerations corresponding to the serviceability period of the structure and the seismic risk level. In other words, it is possible to define the seismic excitation as a function of the return period and the level of probability of non-exceedance of the design parameters in the course of the serviceability period of the structure. In that way, we can arrive at definition of the seismic risk level or the probability for exceedance of the design parameters.

Considering that it is economically unjustified to provide equal protection against damage to all structures through design and construction, it is necessary to classify structures into categories depending on their purpose and importance and accordingly define the acceptable risk level.

## 4.3 Serviceability Period of the Structure

One of the main elements of seismic risk analysis used as a basis for making many decisions is the serviceability period of a structure.

Considering the specific character of the St. Mary Peribleptos church in Ohrid and its invaluable cultural-historic value, it is necessary, at this point, to explain the notion of serviceability period, i.e., what this definition means in this study. Considering the monumental character of this church, its serviceability period should be “infinite”, i.e., with some interventions, this structure is to last very long. The character of these interventions can be: (1) necessary regular maintenance and (2) removal of consequences of natural catastrophes – in this case, earthquakes.

Regular maintenance of the buildings is planned in advance and is performed at certain time intervals which means long-term planning and provision of necessary financial sources. The purpose of such a maintenance is to remove all visible and potential damage and defects of the buildings that are due to their utilization, quality of the used materials, fatigue of the materials, etc. by interventions that involve structural system and construction details. This improves the stability of the structure, creates conditions for its undisturbed utilization and prolongs its serviceability period whereby all the technical conditions for achievement of the mentioned "infinite" serviceability period are provided. Due to the monumental character and the cultural-historic values of the buildings, the economic aspects of such a maintenance are given secondary importance.

Unlike the regular maintenance, the interventions that have to be performed for removal of earthquake consequences could not be planned in advance. Their purpose is repair and strengthening of the buildings, i.e., retrofitting of buildings and improvement of their seismic resistance. They are performed after earthquakes of a certain intensity that may induce slight or severe damages to the structures. In other words, these interventions are closely related to the earthquake occurrence.

Since the methods for definition of return periods of earthquakes of certain intensities and maximum accelerations have already been discussed, they could be related to the periods of required interventions for these structures. The return periods at which interventions for removal of the earthquake consequences are expected, represent, in fact, the return periods of occurrence of earthquakes of a certain intensity that may induce slight or heavy damage. These damages are in correlation with certain characteristics of the buildings: the structural system and its seismic resistance, the foundation, the used materials, etc.

If we adopt the criterion that the structure is of a monumental character, i.e., a structure of a high cultural-historic value and that it should have a greater seismic stability and a lower possibility for damage due to an earthquake that should be provided through design, particularly its repair and strengthening, then we may expect that the interventions for removal of earthquake consequences in these structures will be rarer, i.e., such interventions will take place after longer time periods.

In this way, we arrive at the so called “design period” in which it is expected that an earthquake will occur with the possibility to cause certain damage for which engineering interventions on the structure will have to be done.

Based on all the above stated in this study, it is conditionally adopted that this “design period” of interventions on the structure is adopted, at the same time, as serviceability period and that the seismic risk level is to be defined based on its category.

## 5. Seismic Design Parameters

The parameters for analysis of the behavior of the St. Sophia church structure under the effect of seismic excitations that are expected at the site have been defined based on the results from the performed investigations described in details in the previous chapters.

Taking into account the needs of the dynamic analysis and design of repair and strengthening of the structure, the seismic parameters are given in the form of expected maximum accelerations and time histories of acceleration. The expected maximum accelerations are given for the design and maximum earthquake.

The seismic parameters have been defined by taking into consideration the seismic hazard at the site by which its seismicity is expressed in a probabilistic way and by application of the seismic risk methodology that includes not only technical but economic elements in design.

The basic parameters of seismic design, i.e., the maximum accelerations have been defined based on the results from the seismic hazard and risk analysis under the following assumptions:

- The serviceability life of the structure is 50 – 100 years,
- For the design earthquake, the acceptable seismic risk level is 30%;
- For the maximum earthquake, the acceptable seismic risk level is 10%.

For dynamic analysis of structures excited by earthquakes, the maximum accelerations reflecting the frequency characteristics of earthquakes and the time duration of intensive excitation are taken into account. Generally, they depend on the characteristics of the earthquake as are the geometry of the fault, the focal depth, the total released energy, the focal mechanism and alike as well as on the position of the location in respect to the source and the properties of its geotechnical media and the media through which the waves propagate. The distance of the location from the earthquake focus has a great effect consisting of predominant participation of high frequency components in the case of closer foci and predominant low frequency components in the case of far foci, due to filtration of the high frequency components proportional to distance.

Having no records of accelerations due to strong earthquakes in the region of the investigated site, the time histories have been defined by selection of characteristic records that exist in our country and in the world. The frequency characteristics of the structure have been taken into account to cover, with the selected records, the frequency range of interest for dynamic analysis.

### 5.1 Diagrams – Damage Curves for the Structure

The main bearing and deformability characteristics of the St. Mary Peribleptos church structure in Ohrid have been defined by detailed analytical and experimental investigations. The following has been defined:

- For accelerations in the range of a = 0.135-0.165 g, occurrence of minor damage to the structure may be expected.
- For accelerations in the range of a = 0.175-0.225 g, occurrence of moderate damage to the structure may be expected.
- For accelerations a ≥0.25 g, heavier damage and even partial failure of the structure may occur.

Taking into account the above statements, the diagrams shown in Fig. 7 and Fig. 8 have been elaborated. Fig. 7 shows the seismic risk level for a range of seismic excitations that may cause minor, i.e., moderate damage. This diagram shows that the seismic effects that may cause minor damage to the structure should be expected to occur at least once in a period of 30-60 years, with a probability of 70%.

Seismic effects that may cause moderate damage to the structure can be expected at each 80-160 year period with a probability of 70%. The mean values of accelerations that cause minor damage (a = 0.15 g) are with a return period of 50 years, while those causing moderate damage (a = 0.20 g) are with a return period of 120 years and probability for occurrence of 70%. These values are shown in Fig. 8.

The diagrams shown in Fig. 7 and Fig.8 represent curves of damage to the structure. Through variation of the acceptable seismic risk level, these can be used to define the time period of maintenance, i.e., necessary interventions on the structure for the purpose of removal of possible damage due to occurred earthquakes.

These diagrams should be used in making decisions about strengthening of the structure and definition of the acceptable seismic risk level.

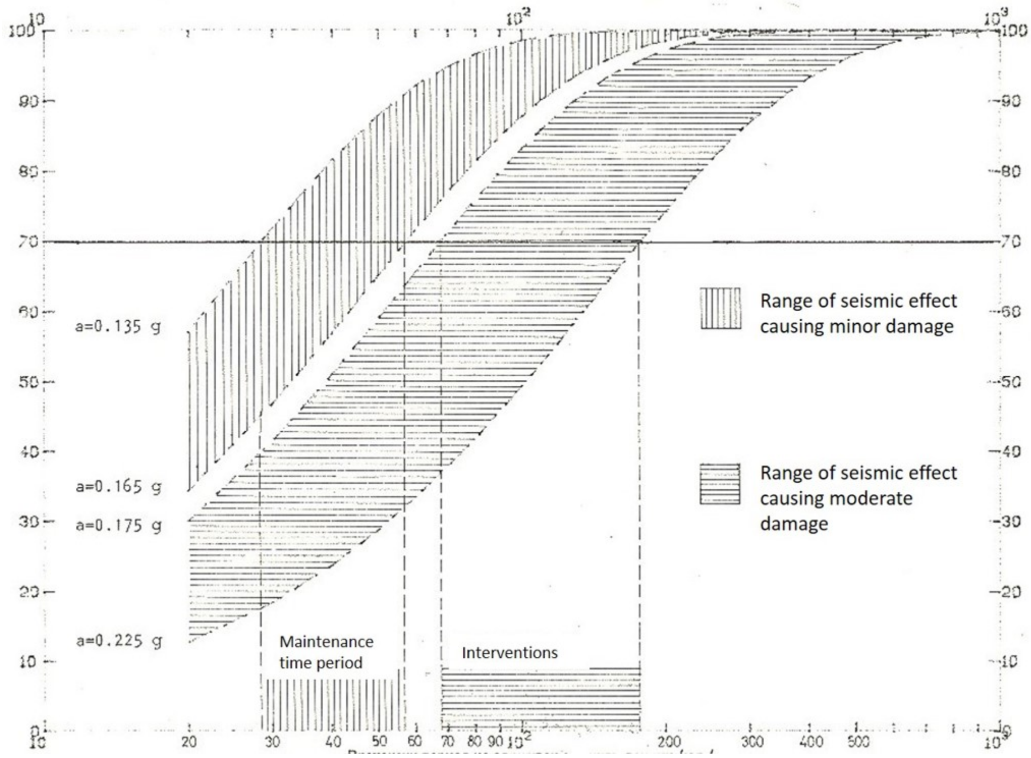


Fig. 7 - Damage range. St. Mary Peribleptos church structure - Ohrid

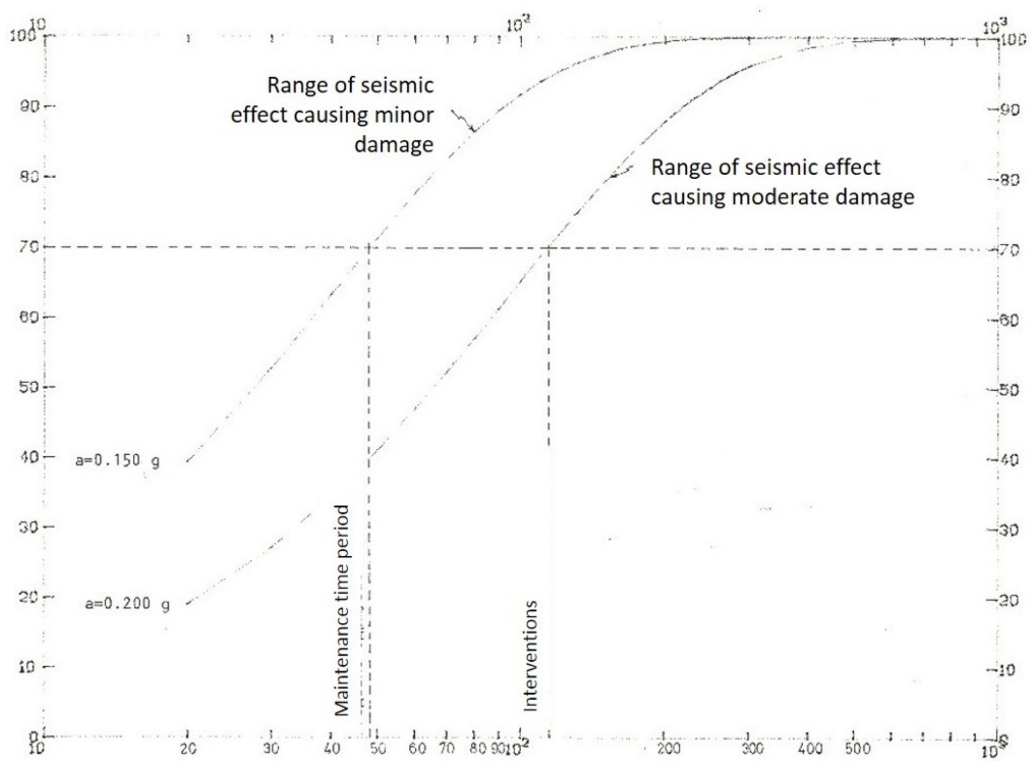


Fig. 8 - Damage curve for St. Mary Peribleptos church structure - Ohrid

## 6. Seismic Risk Level

The main seismic hazard parameters for the old town core of Ohrid defined via the analytical and graphical relationships give an insight into the seismicity of the site and enable comparison with the global seismicity of the area. However, these are not sufficient for seismic design based on seismic risk study. The crucial parameters for rational design as the serviceability life of the structures, classification according to purpose and importance of the structures, acceptable seismic risk, etc. are here omitted.

## 7. Conclusion

From the obtained results from all investigations following conclusions can be made:

- Small damage degree on the structure of the church "St. Mary Peribleptos" can be expected at earthquakes that yield ground acceleration of a= 0.135g - 0.165g (average a= 0.15 g). These levels of acceleration can be expected with probability of 60-70% in the period of 40-60 years, and with high probability (90-100%) in the period of 100 and more years.
- Moderate damage degree on the structure of the church "St. Sophia" can be expected at earthquakes that yield ground acceleration of a= 0.175g-0.225g (average a= 0.20 g). These levels of acceleration can be expected with probability of 60-70% in the period of 80-100 years, and with high probability (over 80%) in the period of 200 and more years.
- Heavier damages and possible partial collapse of the structure can be expected at earthquakes that would result with ground acceleration of a= 0.250g - 0.300g. The return period of such earthquakes in 500 and more years, and the probability of occurrence is 70%.

Mathematical modelling of regional seismicity and its application in seismic risk definition is of constant interest and takes a crucial place in seismology and earthquake engineering. This paper describes the method for analysis of seismic risk and its application in definition of parameters and criteria for repair of buildings in the old town core of

The results from the investigations for definition of the parameters and criteria for repair of buildings in the old town core point to the following conclusions:

- Ohrid area, including the old town core, belongs to a high seismicity zone with an intensity of IX degrees on the MCS scale as defined in the Preliminary Seismological Map of Former Yugoslavia;

- The old town core of Ohrid is characterised by a large concentration of buildings of high cultural and historical importance. Considering the high seismic activity of this region, these buildings are exposed to permanent risk of extensive damage and collapse. The history of the town keeps records of numerous catastrophic earthquakes which have caused enormous damage and loss of human lives

- The high vulnerability of the buildings that have already been proved during previous earthquakes, can be expected mainly due to the following reasons: pronounced massiveness of stone masonry buildings, very low ductility capacity, insufficient bearing capacity, inadequate connections of structural elements and floor structures constructed of materials of limited durability;

- For centuries, Ohrid area builders have tried to increase the seismic resistance of buildings, by increasing the bearing capacity above all, and to some extent, by increasing the deformability capacity through connection of structural elements. In spite of the efforts of the old builders, however, vulnerability of stone masonry buildings lies at an economically not acceptable level. During Montenegro catastrophic earthquake it turned out that the repair and strengthening costs were on the average higher than 70% of the building cost, and the global vulnerability ranges between 75 and 80% of the total number of stone masonry buildings constructed in the Montenegro coastal area.

- The extremely high seismicity significantly affects the concept and methodology for repair of buildings. The static approach to the problem of repair and strengthening, for such a seismicity, always results in very high seismic equivalent forces to be taken into account in the strengthening of the existing structure. For the soil conditions in certain zones of the old town core of Ohrid, such an approach makes great difficulties as to the existing foundation structures that require technically complicated and costly interventions. It is, therefore, necessary that the seismic parameters be used in the design in such a way that optimization of ultimate resistance and deformability of the structure is performed, which practically leads to the concept of acquiring sufficient resistance and high deformability of the structural elements.

## 8. References

[1] Aliaj, S., Adams, J., Halchuk, S., Sulstarova, E., Peci, V., and Muc¸o, B (2004).: Probabilistic seismic hazard maps for Albania, 13th World Conf. Earthquake Engineering, Vancouver, BC, Canada, paper no. 2469, 14 pp.

[2] Aliaj, S.: Neotectonics and seismicity in Albania, in: Geology of Albania, edited by: Meco, S.

[3] Ambraseys et al. (1996). Prediction of Horizontal Response Spectra in Europe, Earthquake Engineering and Structural Dynamics, Vol.25, 371-400

[4] Ambraseys, N. and Jackson, J (1990).: Seismicity and associated strain of Central Greece between 1890 and 1988, Geophys. J. Int., 101, 663–709,

[5] Ambraseys, N.(2009): Earthquakes in the Mediterranean and Middle East, Cambridge University 20 Press, New York,

[6] Anderson, H. and Jackson, J.: Active tectonics of the Adriatic Region, Geophys. J. Roy. Astr. S., 91, 937–983, 1987.

[7] Arsovsky, M. and Hadzievsky, D (1970).: Correlation between neotectonics and the seismicity of Macedonia, Tectonophysics, 9, 129–142

[8] Burchfiel, B. C., King, R. W., Nakov, R., Tzankov, T., Dumurdzanov, N., Serafimovski, T., Todosov, A., and Nurce, B (2008).: Patterns of Cenozoic extensional tectonism in the South Balkan extensional system, NATO SCI S SS IV EAR

[9] Burchfiel, B. C., King, R. W., Todosov, A., Kotzev, V., Dumurdzanov, N., Serafimovski, T., and Nurce, B.: GPS results for Macedonia and its importance for the tectonics of the Southern Balkan extensional regime, Tectonophysics, 413, 239–248, 2006.

[10] Dumurdzanov, N. and Ivanovski, T (1977).: Geological map of the Socialist Federal Republic of Yugoslavia, Sheet Ohrid, Geological Survey Belgrade.

[11] Dumurdzanov, N., Serafimovski, T., and Burchfiel, B. C.: Cenozoic tectonics of Macedonia and its relation to the South Balkan extensional regime, Geosphere, 1, 1–22, 2005.

[12] Dumurdzanov, N., Serafimovski, T., and Burchfiel, B. C (2004).: Evolution of the Neogene-Pleistocene basins of Macedonia, Geological Society of America Digital Map and Chart Series 1, Skopje

[13] Goldsworthy, M., Jackson, J., and Haines, J (2002).: The continuity of active fault systems in Greece, 20 Geophys. J. Int., 148, 596–618

[14] Jozja, N. and Neziraj, A (1998).: Geological heritage conservation of Ohrid Lake, Geol. Balcanica, 28, 91–95

[15] Lindhorst, K., Vogel, H., Krastel, S., S. Wagner, B., Hilgers, A., Zander, A., Schwenk, T., Wessels, M., and Daut, G. (2010): Stratigraphic analysis of lake level fluctuations in Lake Ohrid: an integration of high resolution hydro-acoustic data and sediment cores, Biogeosciences Discuss., 7, 3651–3689, doi:10.5194/bgd-7-3651-2010.

[16] NEIC – National Earthquake Information Center: neic.usgs.gov, last access: 28 March 2010.

[17] Velkov M., Mihailov V., Jankulovski E., & D. Dojcinovski (1998); Examination of stability of the cultural monument church "St. Sophia" in Ohrid. Book III, Report IZIIS 88-41, Skopje.