ANNALI DI GEOFISICA, VOL. XXXVIII, N. 5-6, November-December 1995

Parameters and criteria for repair and strengthening of buildings in the old town core of Dubrovnik based on seismic risk analysis

Vladimir Mihailov
Institute of Earthquake Engineering and Engineering Seismology, IZIIS,
University «St. Cyril and Methodius», Skopje, Macedonia

Abstract
Definition of the seismicity conditions, the design seismic parameters and the seismic risk level are important and inevitable phases of the complex process of repair and strengthening of existing structures in certain towns located in seismically active areas. These should be studied in all necessary details in order to provide corresponding bases and define the necessary preventive measures against expected strong earthquakes. Such an approach becomes even more necessary after the experience regarding the last catastrophic earthquakes that occurred in Former Yugoslavia (Skopje, Banja Luka, Montenegro coast and Kopaonik) and inflicted heavy losses of human lives and material properties. The old town core of Dubrovnik is known for the large concentration of buildings of enormous cultural-historic importance. Considering the high seismic activity of this area, all these buildings are very likely to experience heavy damage and failure. The history of the town records many catastrophic earthquakes that inflicted heavy material losses and loss of human lives. Here, we can mention the great Dubrovnik earthquake of 1667 and the last Montenegro earthquake of April 15, 1979 with an epicenter in the Ulcinj-Bar area. The consequences of the latter are well known. The purpose of this paper is to present some results and experience gained from the investigations performed for the area of Dubrovnik illustrated by several examples of buildings existing in the old town core of Dubrovnik.

Key words *Dubrovnik – seismic hazard – seismic risk analysis – seismic microzoning – seismic design parameter – design and maximum earthquake – strengthening*

1. Introduction

Dubrovnik and particularly the old town core of Dubrovnik are known for the large concentration of buildings of enormous cultural-historic importance. On the other hand, the area of Dubrovnik is characterized by a considerably high seismic activity. In the seismological map, this area is defined as a zone of X MCS scale which has also been proved by the seismic microzoning of the old town core of Dubrovnik.

Throughout its history, Dubrovnik has been hit by a number of catastrophic earthquakes that induced enormous material losses and loss of human lives. Here, we can mention the great Dubrovnik earthquake of 1667 (I = X MCS) and the last catastrophic earthquake of April 15, 1979 (I = IX MCS) with an epicentre in the Montenegro coastal area the consequences of which are already well known.

Considering the high seismicity of this area, all the buildings and particularly the old ones in the old town core are permanently exposed to the risk of being damaged or experiencing total failure. The high level of vulnerability of these buildings that has been proved with the afore mentioned earthquakes 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 Dubrovnik were performed immediately after the catastrophic Montenegro earthquake of 1979. The objective of these investigations was to define the seismic hazard level, the vulnerability of the buildings, the existing seismic risk and the seismic parameters for design, repair and strengthening of the buildings. Special attention was paid to the old town core and the cultural-historic monuments.

2. Seismicity of the Dubrovnik area

2.1. *Main seismic characteristics*

Today, it is an undoubtedly accepted fact that a belt of intensive seismic activity runs through the whole Adriatic coastal area. The seismic activity is more intense towards the South, especially between the Dubrovnik area and the Montenegro coast.

The Dubrovnik area is situated within a zone of high seismic activity. This assertion has been proved by numerous earthquakes that have occurred in this area like the great Dubrovnik earthquake of 1667 and the catastrophic Montenegro earthquake of 1979 that inflicted enormous material losses in this area.

This is one of the reasons for the great interest of scientists in investigation of the seismicity of Dubrovnik and its wider region. There is a large number of studies in which the results of these investigations are presented (Cvijanovic, 1971; Makjanic, 1978; Cvijanovic and Prelogovic, 1978).

Being unable to show all aspects related to the seismicity of Dubrovnik due to the scope of these investigations, the results from the most recent seismological investigations performed for seismic microzoning of the old town core of Dubrovnik and for the needs of seismic hazard analysis and definition of seismic parameters and criteria for repair and strengthening of buildings in the old town core will be presented further in the text.

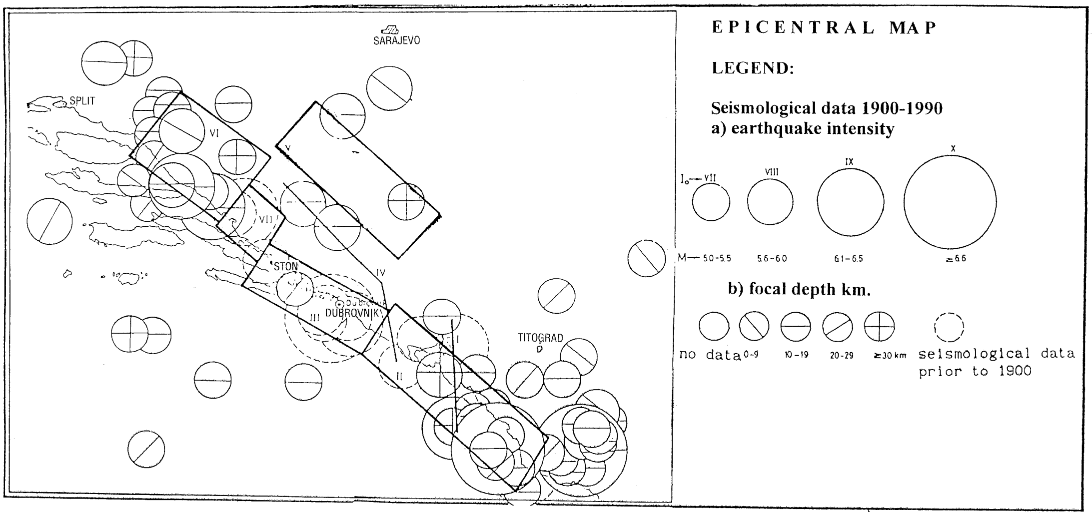


Fig. 1. Epicentral map of the investigated area and model of seismicity.

2.2. *Earthquake epicentres*

The investigation of the seismicity of the Dubrovnik area was performed by consideration of macroseismic data from the time period of 367 to 1900, as well as the microseismic and macroseismic data from the period between 1901 and 1990. A more detailed analysis of the seismic activity was made for the investigated area within coordinates 41.6-47.3° and 17.0-19.6°.

The greatest concentration of earthquake epicenters and the strongest earthquakes are related to the Adriatic submarine area (from Dubrovnik to the mouth of Bojana river). The strongest earthquakes in this region occurred in 1563 (Boka Kotorska, I = IX MCS); 1608 (Boka Kotorska, I = IX MCS); 1667 (Dubrovnik, I = X MCS) and 1979 (in the Adriatic submarine area, near Ulcinj, I = IX MCS).

Figure 1 shows the epicentral map of the investigated area in which several localities are distinguished according to the clustering of earthquake epicenters. The most important of these are the Dubrovnik and the Montenegro coastal areas.

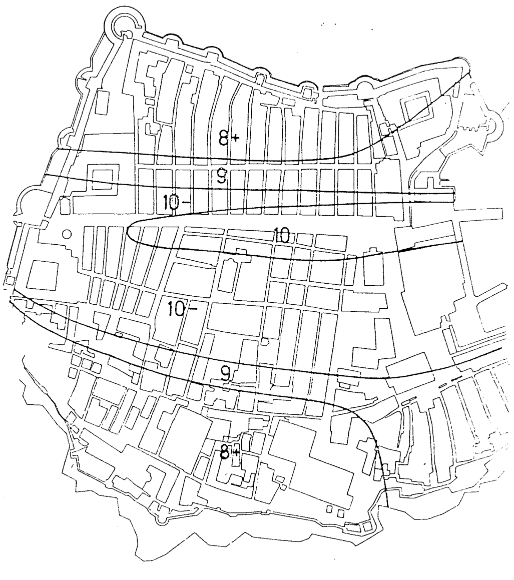
2.3. *Seismotectonic zoning*

The seismotectonic model is based on collected data. The initial tectonic movements take place at the depth of the Mohorovicic discontinuity or even at a greater depth. These motions are oriented northwest and north from the area of the so called Adriatic mass towards the Dinarides. The movement of the Adriatic mass towards land leads, first of all, to its thrusting under the Dinarides followed by compression of rocks over the Mohorovicic discontinuity, folding, reverse faulting and overthrusting of geotectonic units. The initial motions and their consequences are the main causes of earthquakes. Weakened zones of intensified seismotectonic activity are the boundaries of geotectonic units and the vertical tectonic units coinciding with the regional reverse faults.

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 Dubrovnik area from the seismotectonic aspect and the effect of initial tectonic movements within the framework of the assumed model.

The already mentioned maps (figs. 1 and 2) show that Dubrovnik is situated within a seismically active zone. Earthquakes with maximum magnitude of 6.0 to 6.5, with epicenters in the town itself are expected. In the south, southeast part of the tectonic block which includes Dubrovnik, earthquakes of maximum magnitude of 6.5 to 7.0 are expected.

This maximum value is assumed on the ba-



ZONE° MCS	$a = \frac{a_{max}}{g}$
10	0.60
10^-	0.48
9	0.32
8^+	0.20

Fig. 2. Microzoning map of the old town core of Dubrovnik (after Jakovljevic *et al.*, 1981).

sis of the occurrence of the earthquake of April 15, 1979 with magnitude $M = 7$ in the same zone of intensified seismic activity, *i.e.*, the Montenegro coast.

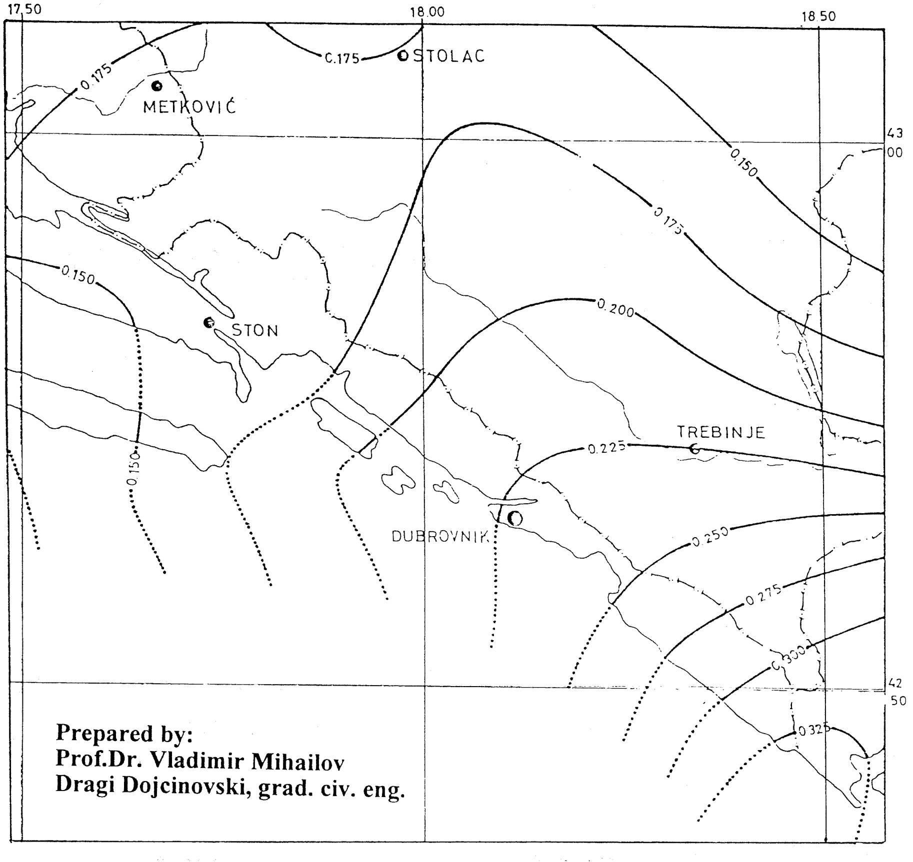
3. Seismic hazard map

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

Since the methodology of seismic hazard analysis is generally well known (Shah and Dong, 1984), only the results obtained will be presented in this paper.

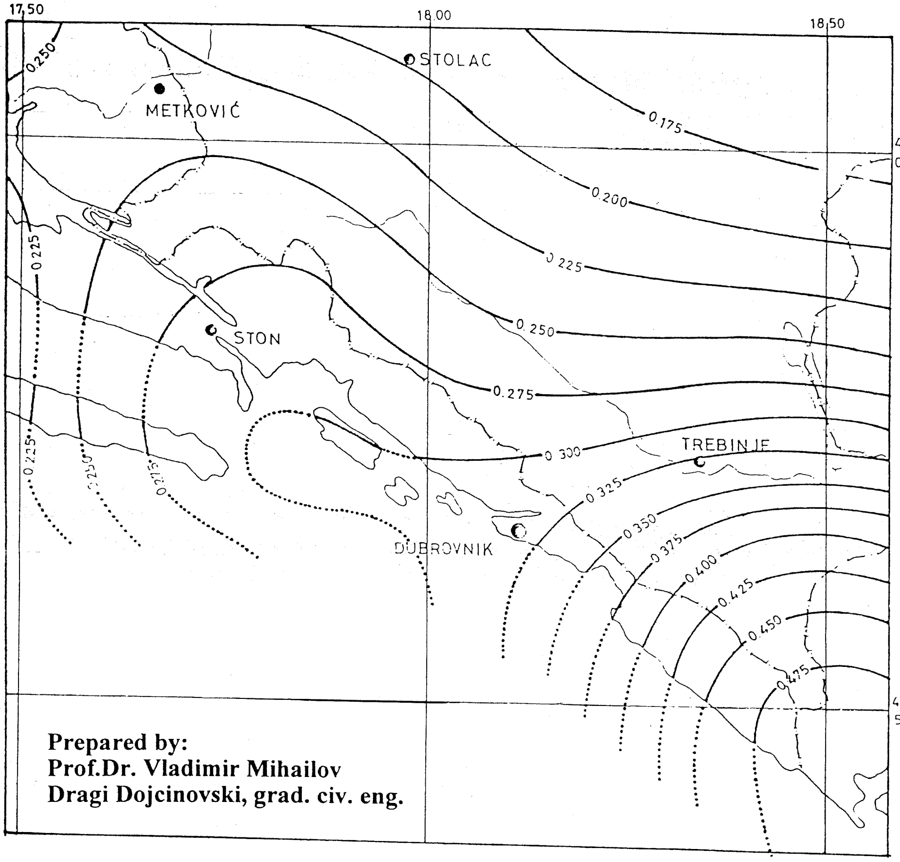
Special computer programmes (Shah and Dong, 1984; Mihailov *et al.*, 1986) were applied for computation of the main parameters for definition and elaboration of seismic hazard maps for the wider Dubrovnik area (figs. 3 and 4) and the return period diagrams for the occurrence of the maximum ground accelerations at the old town core of Dubrovnik (fig. 5).

The seismic hazard of the wider Dubrovnik area was defined by the maximum amplitudes of horizontal ground accelerations for characteristic time periods (return periods) of 25 to



Prepared by:
Prof.Dr. Vladimir Mihailov
Dragi Dojcinovski, grad. civ. eng.

Fig. 3. Seismic hazard map of the wider Dubrovnik area. Distribution of maximum ground acceleration for a return period of 200 years.



Prepared by:
Prof.Dr. Vladimir Mihailov
Dragi Dojcinovski, grad. civ. eng.

Fig. 4. Seismic hazard map of the wider Dubrovnik area. Distribution of maximum ground acceleration for a return period of 1000 years.

Table I. Maximum acceleration on bedrock.

Old town core of Dubrovnik	Maximum acceleration *a* for different time periods (g)						
	25	50	100	200	500	1000	∝
Bedrock level	0.096	0.132	0.170	0.230	0.291	0.318	0.350

1000 years with a probability of occurrence of 63% (table I and fig. 5) and the seismic hazard maps for return periods of 200 to 1000 years.

The seismic hazard maps, *i.e.*, the maps of the so called distribution of maximum accelerations for return periods of 200 and 1000 years are presented in figs. 3 and 4. The practical importance of these maps is that they can be used for determination and comparison of the relative seismic hazard for certain locations of the investigated areas (Mihailov, 1988). This is of a particular importance in all phases of social,

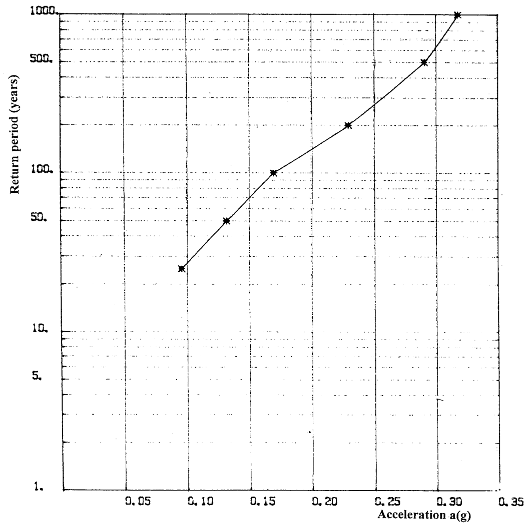


Fig. 5. Diagram of the ground acceleration-return period relationship for the old town core of Dubrovnik.

spatial and urban planning considering the fact that it is only on the basis of the results of the seismic hazard analysis that economically justified preventive measures against earthquakes can be taken.

4. Seismic microzoning of the old town core of Dubrovnik

The complex seismological, geological, geophysical and geotechnical investigations performed for the needs of seismic microzoning of the old town core of Dubrovnik proved the high level of seismicity of this area. The results from these investigations are presented in several studies (Cvijanovic, 1971; Makjanic, 1978; Cvijanovic and Prelogovic, 1978). They involve all professional aspects related to seismic construction that could have an influence on decision making regarding the seismic hazard level of the Dubrovnik area. A microzoning map of the old town core of Dubrovnik (fig. 2) that is used as a basis for designing repair of structures was elaborated (Jakovljevic, *et al.*, 1981).

Apart from dividing the old town core into areas of uniform seismicity according to the improved MCS scale, the seismic microzoning map (fig. 2) also presents the average ratios between the maximum ground acceleration and the gravity forces.

5. Seismic risk level

The main seismic hazard parameters for the old town core of Dubrovnik defined via the analytical (table I) and graphical relationships (figs. 2 and 3) 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 serviceablity life of the structures, classification according to purpose and importance of the structures, acceptable seismic risk, etc. are here omitted.

The next step in defining the seismic risk is to include these parameters in the seismic risk model. This is done by using the binomial distributions – probability of occurrence of «*k*» successful events in «*n*» independent trials with a probability of success «*p*» in each trial – which is generally given by:

$$P_n(K) = \binom{n}{k} p^k (1-p)^{n-k}$$

$$P_n(0) = \binom{k}{0} p^0 (1-p)^{n-0} = (1-p)^n =$$

= probability of zero successful events in «*n*» trials.

For instance, for an acceptable probability of 90% that a certain value will not be exceeded (10% that it will be exceeded) in 50 trials (50 years), this means that:

$$(1-p)^{50} = 0.90$$

i.e.,

$$p = 0.00210$$

or,

$$T = \frac{1}{p} = \frac{1}{0.00210} = 475 \text{ years.}$$

The obtained result can be interpreted as follows: if the serviceability period of a certain structure is 50 years and the seismic risk level is 10% (probability of 90% that a given value will not be exceeded), the structure should be designed by consideration of maximum acceleration corresponding to a return period of 475 years.

For different values of serviceability period of the structures and acceptable risk levels, corresponding return periods are obtained. Presented in fig. 6 are diagrams showing the relationship among the risk level, the serviceability life of the structure and the return period. These diagrams are spatially independent and are applicable for each location in any area under the terms that diagrams of return periods of maximum ground accelerations are available for the considered location (fig. 5 refers to the old town core of Dubrovnik).

On the basis of these diagrams, design seismic parameters – maximum ground accelerations corresponding to the serviceability life of the structure and the seismic risk level can be obtained. In other words, it is possible to de-

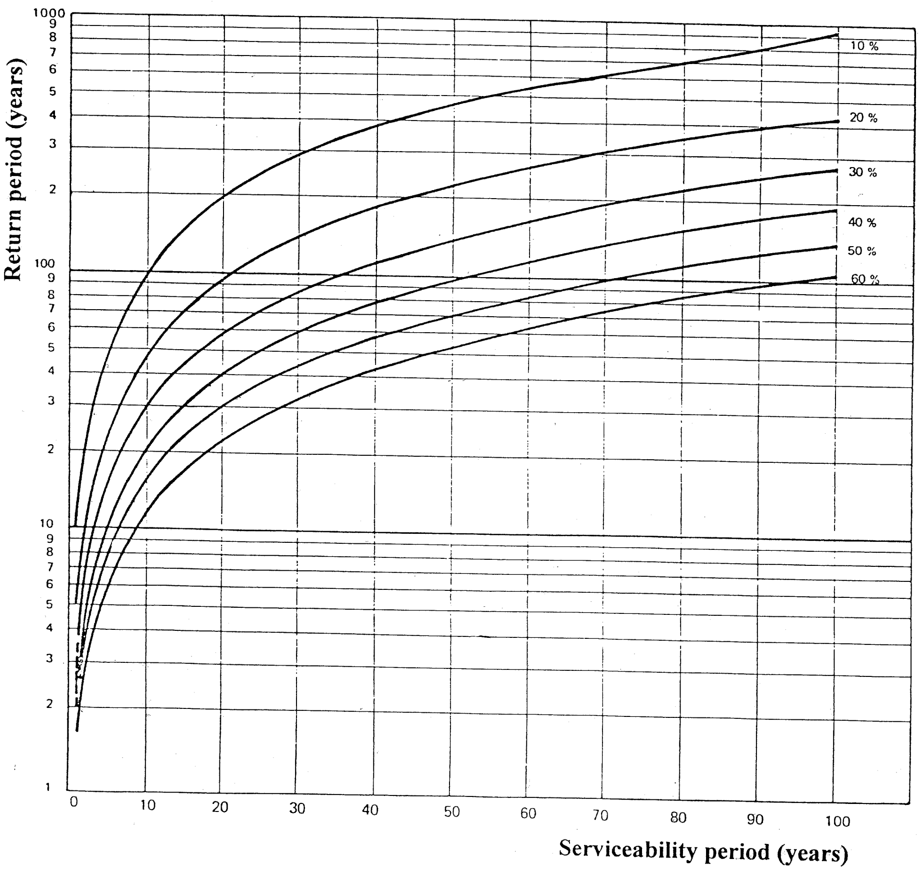


Fig. 6. Relationship between return period and serviceability period of the structure and the acceptable risk level.

fine the seismic loads as a function of the return period and the probability of non-exceeding the design parameters during the serviceability period. The seismic risk level or the probability of exceeding the design parameters is also defined in this way (Boissonade *et al.*, 1986).

5.1. *Acceptable seismic risk level*

Considering that it is practically impossible and economically unjustified to provide uniform protection against damage to all buildings in the process of design and construction, it is necessary to classify the buildings according to some criteria, their purpose and importance, and define the corresponding acceptable risk for each of these categories.

In principle, the risk must be very low for all important buildings and might be relatively high for auxiliary buildings, buildings of lower importance or accompanying buildings. The risk regarding total failure of the buildings must be eliminated by introducing special requirements for design and construction as well as quality of the materials used.

In a concrete case, the design of repair and strengthening of buildings in the old town core of Dubrovnik requires the following:

1) For computation of buildings using the method of equivalent static forces, an acceptable seismic risk of 10 to 30% has to be adopted depending on the building category:
- an acceleration level corresponding to seismic risk of 10% for the corresponding serviceability period of the buildings should be adopted for the first category buildings (buildings of extraordinary cultural and historic value);
- an acceleration level corresponding to seismic risk of 20% for the corresponding serviceability period of the buildings should be adopted for the second category buildings (buildings of high ambient value);
- an acceleration level corresponding to seismic risk of 30% for the corresponding serviceability period of the buildings should be adopted for the third category structures (structures of ambient and low ambient value).

2) For computation of buildings by using the dynamic analysis method, an acceptable seismic risk of 30%, *i.e.*, 10% has to be adopted as follows:
- for the design earthquake – an acceleration level corresponding to seismic risk of 30% for the corresponding serviceability period of the building;
- for the maximum earthquake – an acceleration level corresponding to seismic risk of 10% for the corresponding serviceability period of the building.

6. Categorization of structures

The old town core of Dubrovnik consists of many structures of high cultural-historic importance. These differently constructed structures of manifold purposes are mainly over 200 year old stone structures. Considering the high seismicity of this area, they are under permanent threat of being extensively damaged or ruined. Taking into account that almost all these structures are not seismically constructed, it is necessary to define their vulnerability and seismic risk level in order to define the criteria for their repair and strengthening. Since it is practically impossible and economically not justified to provide equal protection to all structures against earthquakes, it is necessary to classify them in a certain way.

As categorization of the structures in the old town core of Dubrovnik has already been performed for other purposes by the Institute of History of Art at the University of Zagreb, only verification of this categorization, *i.e.*, its adaptation to the requirements of the repair and strengthening criteria was performed within the framework of this study (Mihailov *et al.*, 1986). Classification of the buildings in the old town core of Dubrovnik was performed in cooperation with the Investor, *i.e.*, the Institute for Renovation of Dubrovnik. For the purpose of defining the design parameters and criteria for repair and strengthening of the structures in the old town core of Dubrovnik, modification of the building classification was performed on the basis of the cultural-historic values of the buildings.

A global description of the building categories in the old town core of Dubrovnik is given below:

– I-st category – buildings of extraordinary cultural-historic value;

– II-nd category – buildings of high ambient value;

– III-rd category – buildings of ambient and lower ambient value.

7. 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 Dubrovnik, it is necessary to explain, first of all, the term «serviceability period», *i.e.*, to define the meaning of this term in this study.

Taking into account the monumental character and the invaluable cultural-historic value of certain structures in the old town core, their serviceability life should be «infinite», in principle, which means that with certain interventions, these structures have to last for 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.* earthquakes in the considered case.

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 involving the structural system and the 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 are of a temporary nature and 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 damage to these 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. This damage is correlated 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 first category buildings (see the building categorization) 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 design seismic parameters (as presented in section 8) on the basis of the serviceability period of the structures, structural category (according to purpose and importance) and the seismic risk level.

8. Design seismic parameters

The seismic design parameters, as the ultimate goal of these investigations, were defined on the basis of the obtained: 1) expected values of maximum ground accelerations at the surface of the location for different return periods, 2) acceptable seismic risk level, and 3) building category. The design parameters are represented by the maximum accelerations, characteristic acceleration, time histories, and seismic intensity coefficients.

Such defined design seismic parameters (Mihailov *et al.*, 1986; Mihailov, 1990a,b) taken as a seismic excitation of the building structures, enable a corresponding analysis of their seismic stability not only by simplified methods of analysis like the method of equivalent static loads, but also more sophisticated modern methods involving dynamic analysis of seismic stability that are currently applied elsewhere.

The old town core of Dubrovnik consists of a large number of buildings of different purpose and importance that have to be repaired and strengthened. According to the mentioned regulations and their importance, the buildings can be classified into two or even three categories. Hence, a necessity arises as to defining parameters for all types of buildings in compliance with the regulations. The parameters defined in this way could be used depending on the category of the buildings and their characteristics. It is therefore necessary to define the probability of earthquake occurrence, and hence the risk of exceeding the expected – computed ground accelerations for all the building categories. In this way, the risk for occurrence of moderate damage and the risk for occurrence of heavy damage for different categories of buildings are defined. In principle, these values have to be very low for all important buildings and relatively high for the auxiliary and less important buildings. The risks related to total failure of the buildings have to be eliminated by introducing special requirements as to the way and the quality of design and construction of the buildings, the quality of the used materials, etc. (Mihailov, 1992).

Characteristic serviceability periods, *i.e.*, design time intervals of earthquake occurrence have been previously assumed for the purpose of introducing seismic risk elements in the definition of design seismic parameters. Depending on the category of buildings in the old town core of Dubrovnik, a wider range of 100 (for the building belonging to the first group) to 30 years (for the third category buildings) has been assumed.

The acceptable risk for the buildings in the old town core of Dubrovnik is:
- 30% for the design earthquake;
- 10% for the maximum earthquake.

9. Design and maximum earthquakes

The following criteria are proposed on the basis of our and world practice for the definition of the design seismic parameters based on the acceptable seismic risk level:

1) Adoption of an acceptable seismic risk level of 30%, *i.e.*, 10% for the design seismic parameters as follows:
– *for the design earthquake* – an acceleration level that corresponds to seismic risk of 30% considering the corresponding serviceability period of the structure;
– *for the maximum earthquake* – an acceleration level corresponding to seismic risk of 10% considering the corresponding serviceability period of the structure.

2) Serviceability period of the buildings of 30, 50 and 100 years.

These facts were highly influential when proposing the acceptable seismic risk level and defining the design seismic parameters. They are in favour of a low seismic risk level, *i.e.*, high level of seismic safety of the structures.

The maximum acceleration values for the design and the maximum earthquake were obtained by means of the functional relationships between the maximum accelerations and return time periods presented in fig. 6, the functional relationships among the serviceability period of the building, the risk level and the return period presented in fig. 4 and the application of the afore-stated assumptions. These values are systematized in table II and fig. 7.

The values of the maximum ground acceleration presented in table II represent the accel-

Table II. Design seismic parameters.

Building category	Serviceability period (year)	Seismic risk level (%)	Criterion Type of earthquake	Maximum acceleration $a_{\max}$ (g) for seismic analysis	Notes
Buildings of high cultural historic value	100	30% 10%	Design Maximal	0.250 0.320	Dynamic analysis is compulsory
Buildings of high ambient value	50	30% 10%	Design Maximal	0.200 0.290	Dynamic analysis is desirable
Buildings of ambient and lower ambient value	30	30% 10%	Design Maximal	0.160 0.250	

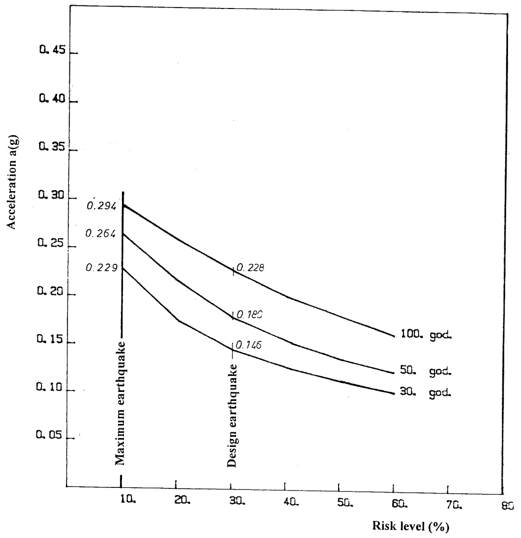


Fig. 7. Design seismic parameters depending on acceleration and seismic risk level.

eration level for a certain serviceability period (30, 50 and 100 years) of the building and a defined level of acceptable seismic risk of 10% and 30%. A risk level of 10% for instance, represents a probability of 10% that the expected accelerations will be exceeded during the serviceability period of the building.

The design seismic parameters (design and maximum earthquake) comply with the existing Regulations for Construction of High-Rise Buildings in Seismic Areas and mean the following:

– the term *«design earthquake»* is used to define seismic forces that have to provide seismic stability to the main structural system, taking into account the nonlinear behaviour and allowing negligible structural and nonstructural damage to buildings;

– the term *«maximum earthquake»* defines the seismic forces necessary for the verification of the seismic stability of the main structural system, taking into account the nonlinear behaviour and allowing major damage to structural and nonstructural elements that still do not affect the general stability of the buildings, *i.e.*, cannot result in failure.

The risk of total failure has to be eliminated in the design process by introducing special criteria for analysis, combination of loads and allowable stresses and deformations.

Based on our experience and considering the cultural-historic value of the buildings in the old town core of Dubrovnik, it is desirable that computation for repair and strengthening of buildings belonging to all categories be performed by using the method of dynamic analysis.

10. Seismic safety criteria

The seismic safety of structures that is necessary to be accepted as a criterion in designing the strengthening and repair of structures is closely related to seismic hazard that can be expected at the building site, depending on the serviceability period and the level of acceptable seismic risk, *i.e.*, damage to the building.

The basic concept of designing strengthening and repair of structures involves proper definition of the necessary strength of the structural elements and the necessary capacity for linear and nonlinear deformations of the structural elements, the structure as a whole and the foundation structure. On the basis of analysis of experimental and analytical investigations and the experience as to the behaviour of these structures during past earthquakes, the safety of buildings and their vulnerability can be closely related to:

- strength;
- ductility capacity;
- distribution and location of nonlinear deformations and cracks;
- damage due to shear forces;
- damage due to anchorage of reinforcement and steel rods;
- damage due to adhesion of reinforcement and concrete.

For the needs of this study (Mihailov *et al.*, 1986) the design parameters (the design and the maximum earthquake and the total seismic

Table III. Dynamic analysis method.

Building category	Type of structure	Maximal acceleration (g)		Maximal allowable ductility factors		Notes
		Design earthquake	Maximal earthquake	Design earthquake	Maximal earthquake	
Buildings of high cultural historic value	Nonductile Ductile	0.25 0.25	0.32 0.32	1.0 1.3	1.3 1.8	Dynamic analysis is compulsory
Buildings of high ambient value	Nonductile Ductile	0.20 0.20	0.29 0.29	1.0 1.5	1.5 2.0	Dynamic analysis is desirable
Buildings of ambient and lower ambient value	Nonductile Ductile	0.16 0.16	0.25 0.25	1.0 1.7	1.7 2.2	

Table IV. Equivalent static load method.

Building category	Type of structure	Seismic coefficient K	Safety factors γ	Notes
Buildings of high cultural historic value	Nonductile Ductile	0.30 0.22	1.30-1.50 1.30	Dynamic analysis is compulsory
Buildings of high ambient value	Nonductile Ductile	0.30 0.20	1.20-1.30 1.30	Dynamic analysis is desirable
Buildings of ambient and lower ambient value	Nonductile Ductile	0.20 0.13	1.20-1.30 1.30	

coefficient K) were defined on the basis of the performed categorization of buildings. Tables III and IV show the seismic safety criteria for design of repair and strengthening of structures in the old town core of Dubrovnik.

It is necessary to point out that the safety values in the tables are defined via two main criteria: the amount of stresses in the structure and the amount of deformations occurring under seismic effects.

The safety based on controlling the stress state of the structure is defined by consideration of ultimate states and applying the safety factors γ given in the tables. Deformation control is made possible by dynamic analysis of the mathematical model of the structure as well as definition of maximum deformations and ductility factors under seismic effect. The ductilities of structures induced by earthquakes should not be greater than those presented in Table III.

11. Conclusions

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 Dubrovnik. 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:

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

– the old town core of Dubrovnik 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. To that effect, it is worth mentioning the earthquake of 1667 and the last one of April 15, 1979, with an epicenter in the Ulcinj-Bar area, the catastrophic consequences of which are well known;

– 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, Dubrovnik 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 unacceptable level, which, during the Montenegro catastrophic earthquake of April 15, 1979, was 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 Dubrovnik, such an approach creates 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.

REFERENCES

BOISSONNADE, A.C., H.W. DONG, M.H. THURSTON and C.H. SHAH (1986): Risk based methodology for identification, evaluation and strengthening of hazardous building in *Proceedings of the VIII ECEE, September 1986*, Lisbon, Portugal, vol. 1, 2.4/55-2.4/61.

CVIJANOVIC, D. (1971): Seismicity of the Dubrovnik area (in Serbo-Croatian), *Acta Seismol. Yugoslavia*, **1**, Belgrade, 31-56.

CVIJANOVIC, D. and E. PRELOGOVIC (1978): The great Dubrovnik earthquake 1667, in *Sixth European Conference on Earthquake Engineering, September 18-22*, Dubrovnik, vol. 6, 9-16.

JAKOVLJEVIC, S. *et al.* (1981): *Seismic and Geotechnical Microzoning of the Old Town Core of Dubrovnik*, Report Institute for Construction, Zagreb.

MAKJANIC, B. (1978): On the maximum annual earthquake at Dubrovnik, in *Sixth European Conference on Earthquake Engineering*, Dubrovnik, vol. 1, 25-31.

MIHAILOV, V. *et al.* (1986): *Old Town Core of Dubrovnik, Seismic Parameters and Criteria for Repair and Strengthening of Structure (in Serbo-Croatian)*, IZIIS, Report IZIIS 86-71, Skopje.

MIHAILOV, V. (1988): Seismic risk reduction through urban planning, in *Second Japanese Workshop on Urban Earthquake Hazards Reduction*, UNCRD, Shimizu, Japan, 27-29 July 1988 and *IX WCEE*, Tokyo-Kyoto, Japan, 2 August 1988, 21-29.

MIHAILOV, V. (1990a): «Some aspects of the seismic risk analysis in aseismic design code, in *ESC School Symposium Earthquake Prediction and Earthquake Engineering*, 24-26 April 1990, Plovdiv, Bulgaria, 1-18.

MIHAILOV, V. (1990b): Seismic zonation based on the seismic hazard analysis – Study case, in *Proceedings IX ECEE*, Moscow, U.S.S.R., vol. 1, 93-101.

MIHAILOV, V. (1992): Seismic design parameters based on risk studies, in *Workshop on Application of Artifical Intelligence Techniques in Seismology and Engineering Seismology*, Walferdange, Luxemburg, 81-92.

SHAH, H.C. and W.A. DONG (1984): A reevaluation of the current seismic hazard assessment methodologies, in *8th WCEE*, vol. 1, 249-254.