A GUIDELINE FOR EARTHQUAKE RISK MANAGEMENT OF HISTORICAL STRUCTURES IN TURKEY

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ABSTRACT:

Turkey is one of the most earthquake-prone countries in Europe. In the past, many destructive earthquakes occurred in Turkey, in which numerous historical structures were damaged seriously or even collapsed. In spite of the high seismic hazard in Turkey, unfortunately there exists no technical document regarding the seismic assessment and rehabilitation of historical structures. Considering this issue, efforts to prepare an advisory guideline document for architects and engineers regarding seismic risk assessment and strengthening of historical structures in Turkey were initiated. The guideline document under preparation is intended to follow the principles of the Venice Charter and the ICOMOS Guidelines. The guideline will be composed of different sections including the ways to collect data about the building, the selection of appropriate non-destructive or semi-destructive techniques, assessment of the existing building damage, the structural modeling strategies and types of interventions for strengthening. The guideline will also cover the emergency response after earthquakes and the short-term remedies.

KEYWORDS: Historical structures; Earthquake; Guideline; Seismic risk.

1. INTRODUCTION

Turkey has a rich repertoire of historic buildings dating from the ancient, medieval and more recent times. The responsibility of protecting these buildings is divided among the Ministry of Culture and several other public institutions like the General Directorate of Foundations and municipalities. These authorities are also responsible for the development of a national policy for the protection of cultural heritage from earthquakes. In a country with recurrent earthquakes, it is necessary to develop and implement disaster risk reduction strategies for cultural heritage. It is also important to raise the awareness of the public and to integrate the cultural heritage protection into the broader disaster management field.

Many of the historic buildings in Turkey show signs of suffering from earthquakes in the past. Some have been strengthened using traditional techniques. Since it is important to take action to transmit cultural heritage to future generations without a lot of damage and losses, the responsible institutions want to assess the present condition of the historic buildings and consider ways of disaster mitigation. The Ministry of Culture and the General Directorate of Foundations have initiated the development of a guide which will help the cultural heritage professionals in their efforts to assess and improve the condition of historic buildings. In order to inspect and evaluate the safety of the structures properly, cultural heritage professionals, architects, archaeologists, structural engineers and other specialists need to be trained and guided. In order to prepare this guideline, a multidisciplinary team of experts from structural engineering, material science and conservation have worked together, discussing issues and exchanging opinions.

Cultural heritage professionals should familiarize with international charters about conservation of cultural property and examples of good practice. The civil engineering education in Turkey does not include courses on cultural heritage and ancient technology. Therefore, there is a need to provide information about the current rules and methodology for developing proper documentation and projects for the conservation of cultural heritage.
Interdisciplinary analysis of historic buildings includes research about materials and structure, documentation of the extant state of the building, assessment of the structure and proposals for intervention. The characteristics of traditional buildings with masonry or timber, as well as more recent structures from 19^{th} or 20^{th} century constructed with steel and reinforced concrete are presented with notes about the necessary researches to be conducted to assess the condition of the materials and the structure. Non-destructive tests and other modern tools necessary to understand historic structures are also included.

Restoration of historic buildings should be carried out with due respect to principles of integrity and authenticity. The use of traditional materials and technologies is preferred, if they are adequate. Reinforcements should be compatible with original materials and reversible. Emergency interventions should avoid further harm to cultural heritage.

This paper presents the headlines and general information related to the prepared guideline for earthquake risk management of historical structures in Turkey. It should be noted that such a comprehensive guideline only exits in Italy, which is another earthquake-prone Mediterranean country with numerous historical buildings and monuments [General Directorate for Architectural Heritage and Landscape, 2006]. The headlines of the guideline sections can be listed as follows:

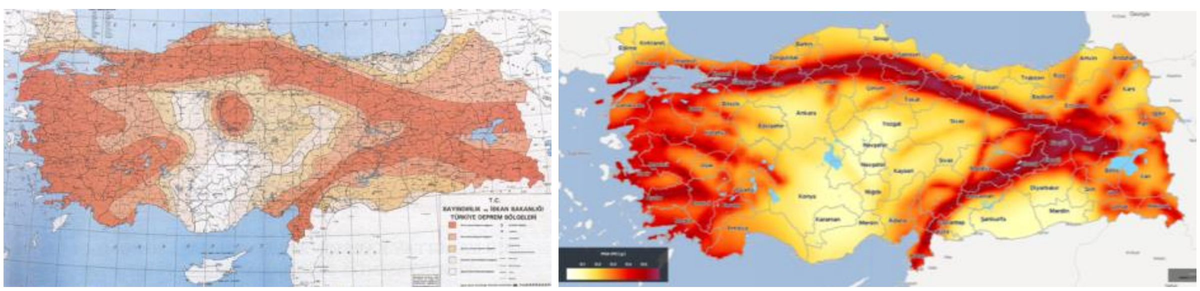
- Introduction (including purpose of developing the guideline and its scope),
- Basic definitions and concepts,
- Collection of data about the structure (archival and historical research, field work, field and laboratory tests, monitoring),
- Identification of material properties of historical structures,
- Structural systems and the related damage mechanisms,
- Structural modeling, analysis and performance evaluation of historical structures (including the loads on structures, load paths within the structural systems, choice of modeling and analysis strategies, interpretation of the results from a performance-based evaluation perspective),
- Intervention strategies (Minor repair, strengthening interventions for different components of the structure like walls, floors, arches, vaults, connections, foundations, etc., preparation of intervention projects),
- Earthquake risk and emergency management for historical structures (emergency response after an earthquake, countermeasures, etc.).

The aforementioned headlines are briefly covered in the following sections. In Section 2, the current status regarding seismic risk of historical structures in Turkey is discussed. Section 3 is about the performance evaluation of historical structures. Intervention strategies for historical structures are explained in Section 4. Section 5 includes emergency response management for historical structures.

2. CURRENT STATUS REGARDING SEISMIC RISK OF HISTORICAL STRUCTURES IN TURKEY

Turkey is located in one of the most seismically active regions of the world. The seismicity of Turkey has been studied for a long time resulting with national seismic risk maps. The current seismic risk map and a draft seismic risk map expected to be legally valid within the year 2017 are presented in Figure 1

[Ministry of Public Works and Settlement, 2007: Disaster and Emergency Management Presidency, 2017]. According to the current seismic risk map (Figure 1.a), the country is divided into five seismic risk regions, for which base ground accelerations vary from zero to 0.4g, where g is the gravitational acceleration. These base ground accelerations are for a design earthquake of 10% probability of exceedance in 50 years (475 years return period earthquake) for ordinary buildings. In the more recent draft seismic risk map expected to be implemented in near future, seismic risk is defined using different seismic design parameters such as peak ground accelerations and short or 1s spectral accelerations for different levels of seismic events. One example of these seismic risk maps, which gives peak ground accelerations for a 475 year return period earthquake, is presented in Figure 1.b. As seen in this figure, the peak ground accelerations on this map can reach to values greater than 0.5g and the concept of seismic zones is invalidated in this draft seismic risk map [Akkar et al. 2014]. It should also be mentioned that currently there is no official guideline for seismic safety assessment of historical structures. Therefore, structural engineers experience significant difficulty in deciding the seismic hazard level to take into account during seismic safety assessment and seismic strengthening of historical structures. Further details about historical development of documentation in terms of seismicity of Turkey and seismic design regulations can be found elsewhere [Erdik et al. 2004; Ilki and Celep, 2012].



(a) (b)

Figure 1. a) Current seismic risk map of Turkey [Ministry of Public Works and Settlement, 2007], b) Draft revised seismic risk map of Turkey [Disaster and Emergency Management Presidency, 2017]

There are many invaluable historical structures in seismically active regions of Turkey. These cover a wide range of different types of structures from ancient civilizations to Ottoman period. While most of the historical structures in Turkey are composed of masonry structural systems, there are also historical structures with structural systems composed of timber, steel or concrete structural members. The masonry structures of historical value are either constructed with brick and stone units or a combination of these different materials sometimes with wooden or metallic connectors, ties or reinforcement. Many of these structures were damaged or collapsed during past earthquakes. In Figure 2.a, a column of Apollon Temple in Dydma toppled due to effects of earthquakes is presented. The main dome of Hagia Sophia, with a span larger than 30 meters, is known to have collapsed in years 557/558 during devastating earthquakes. The reconstruction of the dome with its current form was completed in 562. Several sources reported that the dome with its new form also experienced different levels of damage during other major earthquakes in Istanbul. A photo of one of the main arches of Hagia Sophia with some irregularities, which may be attributed to seismic actions, is presented in Figure 2.b. Figure 2.c depicts the 1754 earthquake that affected Istanbul and its surroundings. The drawing is taken from [Ambraseys and Finkel, 2006], where it is reported that many villages around Izmit Bay had been totally destroyed and many structures in Istanbul were heavily damaged and monumental structures like Hagia Sophia, Topkapi Palace, Yedikule and Galata Tower were affected during this devastating earthquake. A more recent damage in the closed bazaar of Istanbul that was observed during the 1894 earthquake is presented in Figure 2.d [Genç and Mazak, 2001].

In addition to inherent weaknesses of masonry structures against seismic actions due to their excessive mass and rigidity, low tensile strength capacity, poor connections between various components, deterioration in masonry units due to environmental conditions and aging and the decay of wooden and metallic elements make historical masonry structures highly vulnerable against earthquakes.

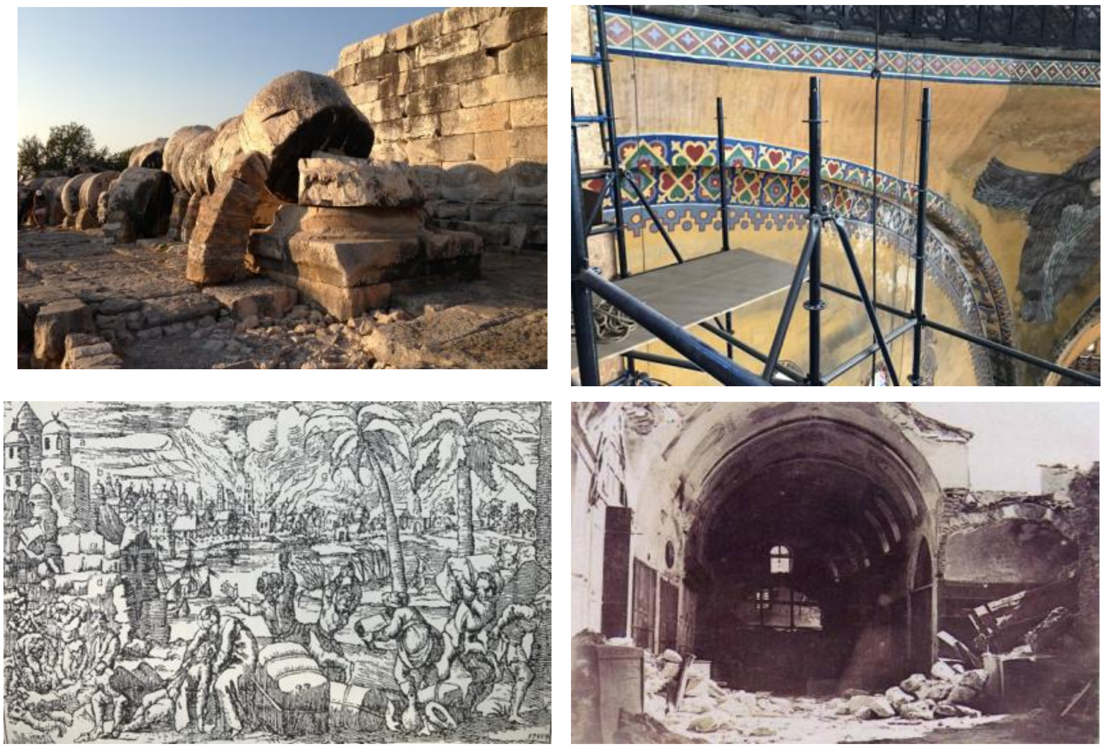


Figure 2. a) Apollon Temple in Dydma (top left), b) current status of one of the main arches of Hagia Sophia (top right), c) drawing depicting a scene from the 1754 Istanbul earthquake [Amsbraseys et al. 2006] (bottom left), d) covered Bazaar in Istanbul after the 1894 earthquake [Genç and Mazak, 2001] (bottom right).

Very often structural analyses have conducted for various types of historical structures in terms of seismic safety assessment. As it is common, 475 year return period earthquake has been considered during these assessment analyses. According to the results of these analyses, the historical structures under consideration were investigated whether a structural intervention is required. An example of these assessment analyses and structural interventions that were applied for Gazi Ahmet Pasha Madrasa in Istanbul is given in this paper [Celep and Güler, 2001; Celep, 2017]. The structural layout of the mosque and the observed damage are shown in Figure 3. Distribution of stresses obtained from finite analyses is shown in Figure 4. As expected, there exist concentrations of critical tensile stresses around the openings and connections of the structural walls.

Typical seismic damage modes frequently encountered in historical structures are separation of connecting walls, out-of-plane deformations/damages of walls, disintegration of multi-leaf walls, cracking in domes/arches and collapse of minarets or towers. The historical documentations, field observations and numerical analysis results show that seismic safety assessment of historical structures in high seismicity areas of Turkey is vitally important. Hence national guidance is required for the determination of seismic hazard levels to be considered as well as target seismic performance levels to be adapted for a rational and consistent seismic safety assessment strategy in order to conserve historical structures of various characteristics and importance in Turkey.

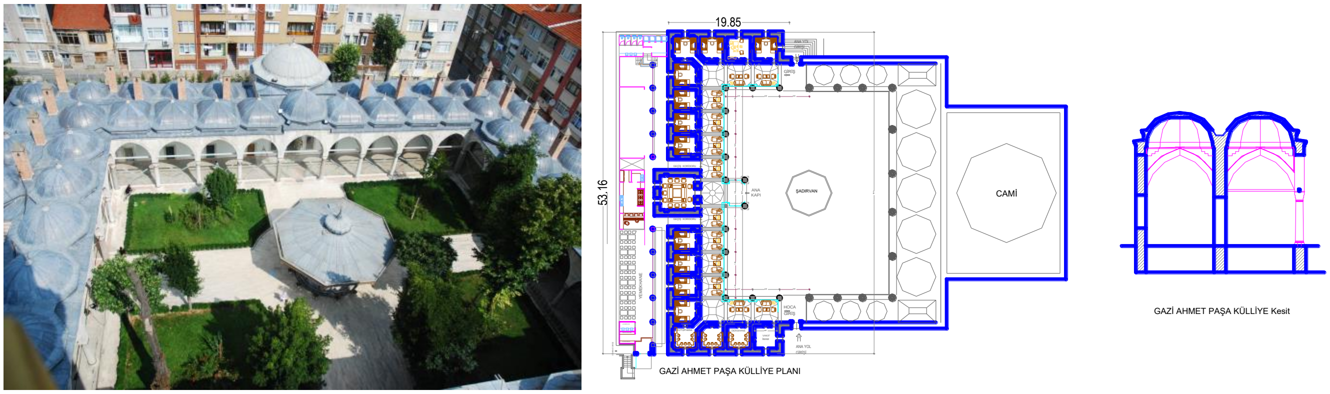


Figure 3. Structural layout of Gazi Ahmet Pasha Madrasa

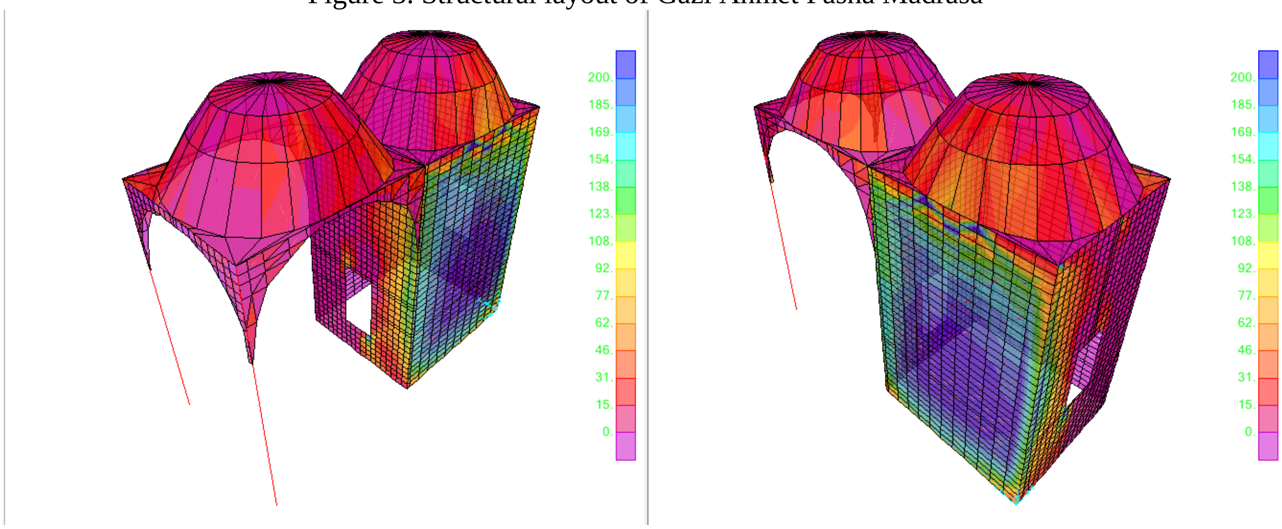


Figure 4. Variation of shear stresses under combined action of vertical gravity loads and seismic loads

3. PERFORMANCE EVALUATION OF HISTORICAL STRUCTURES

The new version of the Turkish Seismic Code, which is expected to be effective within this year, gives very detailed requirements related to both seismic design of new buildings and seismic safety of existing buildings. The code adopts the well-known force based design and evaluation approaches, as well as deformation based design and evaluation approaches at the same time, similar to other new generation seismic codes. Being aware of the diversity of the historical structures, the code specifically states that it does not cover the historical structures. Since there is not any official document prepared specifically for the historical structures, the requirements of the Turkish Seismic Code are employed with or without modification by the structural engineers dealing with the historical structures. Hence, the guideline is developed to fill the gap for seismic risk assessment of historical structures specifically with up-to-date information, knowledge and previous experiences of the experts. Assuming that the Turkish structural engineers are familiar with the requirements of the Turkish Seismic Code, similar concepts in terms of seismic risk and analysis were adopted during the preparation of the guideline. However, by considering the diversity in historical structures and the uncertainty in material parameters and geometry, the requirements adopted from the Seismic Code should be re-examined. Therefore within the guideline, some general statements are provided without giving specific rules and limits, except predefined limits for performance levels. This is in accordance with the main philosophy of the guideline, which is not a legal document, but only provides recommendations.

In the guideline, three seismic intensity levels are defined as it is usual in similar documents: (a) Extremely rare ground motion with a probability of exceedance of 2 % in 50 years with a return period of 2475 years (DD-1, Maximum Considered Earthquake), (b) rare ground motion with a probability of exceedance of 10 % in 50 years with a return period of 475 years (DD-2, Design Earthquake) and (c) occasional ground motion with a probability of exceedance of 50 % in 50 years with a return period of 72 years (DD-3, Service Earthquake). These ground motions are defined in terms of peak ground acceleration (PGA), spectral acceleration (S_a) at T = 0.2 s and 1.0 s. Definition of the seismic hazard in the guideline completely conforms to the one stated in the Turkish Seismic Code.

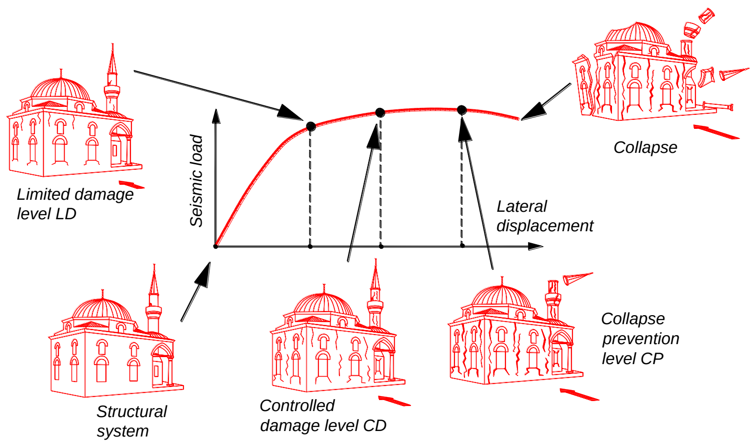


Figure 5: Typical performance curve for a historical structure

The guideline defines three performance levels related to the damage states in historical structures, similar to the Turkish Seismic Code, as follows (Figure 5): (a) Limited damage level (LD), (b) Controlled damage level (CD) and (c) Collapse prevention level (CP). In the limited damage level, the structure is assumed to be almost in the elastic region or just above it, by tolerating fine cracks in the structural elements. Collapse prevention level is the one just before the collapse and controlled damage level corresponds to the one in which the structure can be strengthened and used without extensive intervention. It is worth to remember that it is not an easy task to express these requirements in mathematical form, so that they can be checked by using the results of a structural analysis. Therefore it should not be expected that all analysis yields the same results, due to the uncertainty of the geometry of the historical structures. Furthermore, it is often not easy to differentiate structural and non-structural elements.

The guideline adopts all the analysis methods given in the Turkish Seismic Code, including linear and non-linear approaches together with their static and dynamic applications. However, in the guideline it is pointed out that linear methods require less material parameters to be known and they can be checked easily. On the other hand, nonlinear methods claim to yield more realistic results, since inelastic material properties can also be considered. Due to the uncertainties in the historical structures in terms of material parameters and geometry, the guideline recommends the use of linear methods, whereas nonlinear methods can be employed to ascertain and to increase the accuracy of the results of linear methods.

Recommended methods of analysis and limits of stresses, strains and drifts for each performance level are presented in Table 1. Linear analysis seems to be applicable for all performance levels whereas nonlinear analysis can be used only for controlled damage and collapse prevention levels, for which inelastic deformations are more pronounced.

Table 1: Recommended methods of analysis and limits of stresses, strains and drifts

Performance levels	Methods of analysis / limits
Limited damage Level (LD)	1. Linear analysis is employed, a) ultimate stresses of the material or ultimate strength of the structural element and joints are not exceeded, when the structure is subjected to vertical and unreduced earthquake loads. b) Drifts do not exceed 0.3%, when the structure is subjected to vertical and unreduced earthquake loads.
Controlled damage level (CD)	1. Linear analysis is employed. a) Ultimate stresses of the material or ultimate strength of the structural element and joints are not exceeded, when the structure is subjected to vertical and earthquake loads reduced with $R_a \leq 3$, b) Drifts do not exceed 0.7%, when the structure is subjected to vertical and unreduced earthquake loads. 2. Nonlinear analysis is employed. a) Ultimate strains of the material are not exceeded, b) Drifts do not exceed 0.7%, when the structure is subjected to vertical and earthquake loads.
Collapse prevention level (CP)	1. Linear analysis is employed. a) Ultimate stresses of the material or ultimate strength of the structural element and joints can be exceeded with a certain ratio (i.e. 50%), when the structure is subjected to vertical and earthquake loads reduced with $R_a \leq 3$, b) Drifts do not exceed 1.0%, when the structure is subjected to vertical and unreduced earthquake loads. 2. Nonlinear analysis is employed. a) Ultimate strains of the material can be exceeded with a certain ratio (i.e., 20%) , b) Drifts do not exceed 1.0%, when the structure is subjected to vertical and earthquake loads.

Table 2: Targeted performance levels

Targeted performance levels	Nationally important historical structure (relatively moderate importance)	Internationally important historical structure (relatively high importance)	
	DD-3/LD	DD-2/LD	DD-1/LD
Locally important historical structures (relatively less importance)	DD-3/CD	DD-2/CD	DD-1/CD
	DD-3/CP	DD-2/CP	DD-1/CP

Table 2 shows the recommended matches between the recommended seismic intensity and performance levels. As observed from the table, for the historical structures, which are of universal significance, very strict performance levels are recommended, whereas relaxed performance targets are defined for the locally important historical structures. Similar performance levels are also required for nationally important historical structures. For each case, i.e. for internationally, nationally and locally important historical structures, three different performance levels are defined. These performance levels do not differ significantly from the requirements point of view except DD-3/CP and DD-1/LD. Strict performance targets are demanded for all historical structures, particularly for important ones, however, strict performance levels cannot be satisfied and when extensive structural intervention are required, it is very difficult, often impossible, to apply them to these structures. Therefore, when selecting a target performance level for a specific historical structure, it is not wise to choose a single performance target; it is more appropriate to choose from at least two different performance targets. One of these targets can be more strict and compatible with the historical value and feature of the particular structure, whereas the other can be for a more relaxed performance target. The final decision can be made at the intervention stage by comparing the alternatives not only from the structural point of view, but also their applicability and compatibility with the architectural characteristics of the historical structures.

4. INTERVENTION

The main objective of the intervention strategies for historical structures is safeguarding the structure against adverse environmental effects, impacts and destructive earthquakes and at all times while observing the principles of conservation and preservation for the building. Within this general context of structural safety against seismic action, two major goals can be expressed as the provision of a required performance level in relation to its intended function and protection of its historical value with due respect to historic materials and the building's historical character. Besides, alternative strategies with their evaluations for required performance parameters and levels of reduced vulnerabilities are also an important part of the intervention attempts.

The guideline for historical structures intends to be an in-depth document with respect to intervention strategies, starting from the traditional and minor repair techniques to advanced technologies used for monumental structures. In the following paragraphs, a general outline and some aspects of different intervention techniques mentioned in the guideline are presented.

4.1 Minor Repair

For a historical structure the first requisite is to keep it standing by maintenance and small repairs. Unless a proper maintenance strategy is adopted for the structure, there is the risk of its falling into ruin; in the case costly upgrading works are required to restore the integrity and safety of the building.

Principle decisions as expressed by the Culture of Ministry regulations, repairs are categorized as "minor repair" and "major repair". Minor repair is a procedure of the replacement or renewal of damaged façade elements, wall coverings, plasters etc. of historical or monumental structures using as much as possible their original materials, respecting original forms and colors. Interventions within this context must follow the original design and not make any changes that may affect the plan and appearance of the building.

4.2 Major Repair

Major repair is an intervention based on the principles and concepts determined by the Monument Council with respect to the building survey, reconstitution and restoration projects and to the documents containing all important information. Major repair basically includes consolidation, strengthening, reconstruction, reintegration, renovation and moving. Under the heading of major repair the following interventions can be implemented:

Interventions to Soil and Foundations: Among the major problems in relation to foundations and soil are the low bearing capacity of the soil, changes in the soil type through the years, effect of vibrations due to traffic, construction works nearby or increase in loads due to new floor additions or functional change. Change in water table and liquefaction problems during earthquakes contribute to already existing vulnerabilities. As a result, damages such as foundation settlements and/or movements occur and the structure is subjected to increased stress levels in load carrying members due to foundation-structure interaction. Intervention strategies generally considered are, foundation enlargement, insertion of piles, the use of soil improvement techniques, water drainage and alike. In interventions to foundations and/or soil, it is important not to change the existing support conditions and to obtain a uniform stress distribution underneath the foundation. Instrumentation is a good approach in foundation interventions to record possible deformations. If slope stability problems exist not only the foundation level but also the surrounding area must be considered. The use of stone columns and geosynthetics are among the solutions to prevent it. Archaeological remains at the site must be preserved.

Interventions to Walls: The combined effects of vertical and lateral loads for in-plane and out-of-plane directions of load bearing masonry walls induce the most damaging effect. Different damage levels may be observed based on the resulting compressive and shear stresses as well as tension stresses. There are many repair techniques developed for masonry walls, among them mortar injection, reinforced plastering and addition of reinforcing bars are very common. Explanation of each technique is provided in detail within the guideline.

Intervention to Piers and Columns: Confinement of vertical compression members of masonry structures is a very effective technique for increasing strength and ductility of such members. Since the formation of cracks is also prevented, encircling the monolithic columns by using rings increases overall strength and stability. Before an attempt to apply any of these measures, it is essential to carry out researches to identify the inner material composition, damages and, if necessary, reintegration methods.

Intervention to Joints: In order to assure safe load paths for masonry structures, joints like wall-to-wall, wall-to-floor and wall-to-arches/vaults should not be subjected to any strength deterioration, damage and loss of stability. However, damages occur at these joint locations and cause out-of-plane failure of load carrying walls. Therefore, inspections of joints have primary importance before making any intervention decisions.

Intervention to Floors: Floors are horizontal load transferring members of structural systems. Among many problems like excessive deflections and deficiencies at wall-to-floor joints, diaphragm action is of a major concern under earthquake loads. Since the types of floor systems of historical structures generally are not capable of providing adequate in-plane rigidity for diaphragm action, interventions to achieve this become important.

Intervention to Arches, Vaults and Domes: To reduce the bending moment action to a minimum level and to obtain mainly compressive forces in members of historical structures, the use of arches, vaults and domes is a general approach. Developed tensile stresses in supports of arches and vaults are balanced through tension bars for integrated action, and similarly tensile stresses at supports of domes are balanced with ring beams. Damage types in these structural forms and intervention strategies are described in detail within the guideline.

Intervention to Timber Roofs: Roof structures of historical buildings are generally made up of timber truss systems. Environmental effects such as moisture and termite action may cause material degradation in those members. Joints can also become vulnerable under earthquake forces due to the insufficient roof connection designs.

Intervention to Minarets and Towers: The intervention strategies for minarets and towers are quite limited because of their geometry. In the related section of the guideline, main characteristics of these structures and damage types during earthquakes are described in detail. Several strengthening procedures as well as preventive measures to avoid heavy damage are suggested.

Intervention to Adobe Structures: Adobe units and binding mortar deteriorate, therefore similar techniques as wall interventions can be applied to these structures in general. Main differences with respect to materials used are emphasized in the related section of the guideline.

Dismembering and Moving: Historical structures belong to their original locations, and they should be preserved at those locations as a historic landmark and reference to the cultural landscape of that particular region. However, under certain adverse conditions, it might be necessary to move historical buildings in order to rescue them from being destroyed by road or dam constructions. Moving and reconstruction procedures are described in detail in the related section of the guideline.

5. EMERGENCY RESPONSE MANAGEMENT FOR HISTORICAL STRUCTURES

For the disaster risk management of cultural heritage, actions to be taken on strategic, tactical and operational basis can be listed as follows:

- Before disaster: Risk evaluation, mitigation, and preparedness,
- During disaster: Emergency response,
- After disaster: Damage assessment, immediate intervention, and rehabilitation.

Disaster related legislations in Turkey always consider the rehabilitation stage after disaster. However, there are no regulations related to the emergency response in the critical period, i.e. during the first two weeks after the earthquakes. In order to prevent the evolution of damage within the historical structure after an earthquake, the guideline includes the recommended legal actions for the emergency response that will be applied to the damaged historical structure in terms of approval processes and resource management. The guideline proposes the following recommendations if a vast number of historical structures are damaged after an earthquake:

- Actual damage distribution just after the earthquake should be determined by using satellite or aerial images, videos taken by unmanned aerial vehicles (UAVs) before reaching to the damaged area for emergency response.
- After arrival to the earthquake site, a requirement analysis should be carried out based on the damage classification of historical structures in order to develop priority decisions in emergency response.
- Immediate interventions should be applied to the historical structures in accordance with the priority levels determined during requirement analysis.

There are some important points to be noted about emergency response management section of the guideline. First, the guideline will be a novel technical document since it covers emergency response policies for historical structures, which do not exist even for modern buildings in Turkey. Second, emergency response section is an important part of the guideline also in the sense that it gives recommendations for immediate interventions to prevent collapses of damaged historical structures during aftershocks. Finally, it is strongly emphasized in the guideline that during damage assessment and intervention decision stages, experienced engineers and architects should be involved in the process for effective emergency response.

6. CONCLUSIONS

The main principles of the guideline document under preparation are summarized in the paper. The guideline is prepared to give general recommendations in investigation of the seismic safety of the historical structures and in deciding proper intervention extent, specially paying attention to the properties of historical structures. Although the guideline is prepared to consider all possible materials, structural types and method of analysis, it is not a complete document due to very diverse properties of the historical structures.

The guideline is novel in the sense that it does not only cover before-earthquake actions for historical structures to mitigate seismic risk, but also includes emergency response strategies for damaged historical structures on strategic, tactical and operational basis.

The authors believe that the application of the guideline needs to be followed so that it can be revised/updated to increase its coverage and extent. However, the guideline is not a regulatory document setting rules, but a document which can be used to develop more appropriate and applicable interventions for historical structures and disseminate the existing knowledge and experience.

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