The Importance of Design Spectra and Site Class for the Design of High-Rise Buildings

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Abstract: On November 26, 2019 a strong earthquake of magnitude M6.4 occurred close to the City of Durrës, Albania (15.6 km WSW (west southwest) of Mamurras and 22 km SSW (south southwest) of Durrës), causing fatalities and considerable damages in many buildings. In this article we present and analyze, by means of observational data and numerical simulation, the behavior under this earthquake of an 8-floor RC (reinforcement concrete) building, by using design spectra referring to KTP-N.2-89 and Eurocode 8. The main purpose of the authors is to better understand and evaluate the seismic performance of high-rise buildings under the design spectra with a period of soil oscillation close to the fundamental period of the structure.

Key words: 2019 earthquake Durrës, design spectra, site class, structural damage.

1. Introduction

Durrës is one of the oldest cities in Albania (known as “Dyrrahum”), with a history of over 2,500 years. The region of Durrës is subjected to several strong earthquakes (I0 > VIII EMS-98). The most significant earthquakes of the latest 30 years occurred in September and November 2019, with the later one being the most devastating in Durres region. The earthquake of November 26, 2019 was a 6.4 magnitude earthquake, about 16 km off the coast of Mamurras at 3.54 CET (Central European Time) [1]. The most affected area was Durrës and Thumanë, while significant damages were reported in Shijak, Kruja, Tirana, Kamza, Kavaja, Kurbin and Lezha, as well. The earthquake caused 51 fatalities, 913 people injured at least, and the damages of hundreds of buildings [2].

2. Geotechnical Context

The geological, engineering-geological, geophysical and geomorphological settings that characterize the subsoil of a country are important factors to analyze the earthquake-induced phenomena manifested during the seismic events. Durrës City is situated close to Adriatic Sea. The plain of Durrës City is composed by very thick poor Quaternary sediments, which reach more than 130 m below [3]. The central area of the town comprises of organic layers of the former Durrës swamp (Qh-Holocene. Swamp deposits: clays, silts, sands and peats) or alluvial and proluvial deposits (Qp-h-Pleistocene-Holocene: sands, gravels and silts). The south, along the bay, consists of marine deposits, mainly sandy soils, and in the east (inland) to alluvial deposits. In all Periadriatic area of Albania, the liquefaction phenomena are observed during the earthquakes. In Durrës the phenomena of fountains with hot water and sand can be mentioned, during the earthquake in December 27, 1926, with 6.0 Magnitude [4]. According to different studies, Durrës City has a high potential liquefaction assessment.

3. The November 26, 2019 Earthquake

The earthquake of 26 November 2019, 3.54 CET, hit the north-central Albania. Parametric data of the earthquake are determined from different agencies. According to the data obtained from USGS (United
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States Geological Survey) Earthquake Hazards Program [1], the November 26, 2019 earthquake in Albania occurred as the result of thrust faulting near the convergent boundary of the Africa and Eurasia plates. This seismic activity had the following properties:

- Event time: 3.54 CET
- Event location: 15.6 km WSW of Mamurras, Albania
- Epicenter depth: 22 km
- Magnitude (ML/MW): 6.3/6.4

Fig. 1 shows the earthquake components on three axes and magnitude.

4. Structural Damages in 9-12-Storey Buildings with RC Frame System

After the year 2001, the number of high-rise buildings constructed in Durrës is increased rapidly. These buildings are designed mainly based on the Albanian Technical Codes KTP-N.2-89 (which includes the seismic design norms) [5], and on European norms (Eurocode), although until 2018, KTP-N.2-89 was the legal one. The main structure of these high-rise buildings is reinforcement concrete frame, with/without core wall and shear walls, and masonry infills, supported by raft foundation. The failure observed from Durrës Earthquake varied depending on the location, building type and the year of construction. The damages were evident in structural and non-structural elements. For this typology of buildings, most of the damages are evident in non-structural elements. From the empiric analyses of RC frame system, the fundamental period of these structures is greater than those referred in Eurocode. This leads to the reduction of seismic forces, but on the other hand produces large interstorey drift, which is reflected in the damages of non-structural elements (masonry infills), also in-plane and out-of-plane failures. Even for RC frame combined with core wall or shear walls, there are evident problems not related to damages of structural or non-structural elements, but due to the fundamental period of the structures, which approximates to the period of soil oscillation. The incorrect design of the foundation has led to the phenomena of inclination. The differential settlement of the foundation may be old in time, due to the irregularity in plan and height of the buildings, as well as the $P$-$Δ$ effect. However, the determining factor of the inclination of some buildings (up to 3%) has been the seismic actions, produced especially by the November 26, 2019 Earthquake. From the inspection carried out of these high-rise buildings, by taking in consideration the requirements of EC-2, [6], the key factors of their damages can be listed:

- The design of these buildings as very elastic structure, placed in foundation with period of oscillation ranging 0.3-2.0 s (referring to the Seismological Report of soil in the “D.Peza” street, Durrës, author Prof. Dr. Llambro Duni, 02.07.2010);
- Differential settlement of the foundation due to the irregularity in plan and height, and seismic actions;
- Inadequate structural system. In most cases they are designed as 3D reinforcement concrete frames, not combined with core or shear walls. In addition, there is evidence of hidden beams in slabs, causing the reduction of stiffness of the structure;
- The design of the stairs is done incorrectly, by using beams that reduce the height of the columns, causing the “short-columns” effect;
- Inadequate design of foundation, missing piles, even when they are necessary for transmission of vertical forces and seismic action;
- In many cases, which are composed of several sections on the same foundation slab, or buildings that are close to each other, seismic joints (seismic separation) are incorrectly designed or missing, causing the effect of the collision.
Fig. 1 November 26, 2019 earthquake, (a) E-W component, (b) N-S component, (c) Z-component [7].
5. Case Study

After the main shock of November 26, 2019 earthquake, many engineers from different countries (also from Italy, Republic of North Macedonia, Kosovo, Greece, etc.) and academic staff from the Faculty of Civil Engineering in Tirana organized a post-earthquake reconnaissance field mission. The scope was to observe structural and geotechnical damage patterns, evaluate the seismic performance of structures and explore the potential in code prevision for the design and retrofit of earthquake-resistant structures. During this mission, different areas in the Durrës region were inspected (as shown in Fig. 2). For the purpose of this study, the inspected buildings are 9-12-storey, located in the same geological conditions.

The studied 8-floor structure is a reinforcement concrete frame, composed by two rows of columns in a distance of 5.5 m in the transverse direction, and by five columns in a distance of 5.0 m in the longitudinal direction. The columns have a rectangular section of 120 × 40 cm along the verticality.

Beams along the perimeter are designed with rectangular section, and the other ones are concealed in reinforcement concrete slabs, so called “hidden beams” ($h = 30$ cm). The structure is designed with raft foundation ($h = 110$ cm), supported by R/C piles with a diameter of 50 cm and 650 cm long. The structure has no irregularity in plan and height.

The structure is modelled using advanced software such as ETABS Ultimate 19 (Fig. 3). This mathematical model can capture a satisfying degree of all actions on structure exerted by self-weight, imposed loads, seismic events and the effects of their combinations. For the purpose of this study, zero displacement is assumed for the vertical elements in the fixed support. The study is done according to KTP-N.2-89, Eurocode 8 [8] for $T_c = 0.8$ s (soil type D), and for $T_c = 1.0$ s that best suits seismic microzoning. The maximum displacements related to elasto-plastic stage is analyzed, that will be the elastic displacement amplified by the coefficient “$q$”. The studied structure lies on soil that has a fundamental period $T_p = 1.72$ s, according to seismic report. The same interstorey mass is accepted referring to the Eurocode and Albanian Technical Code in the calculation of vertical loads that affect the seismic action, regardless of the differences between them.

According to the seismic report, the most suitable design spectrum is the one with period $T_c = 1.0$ s.

Fig. 2  Inspected area in Durrës.

Fig. 3  Building with RC frame, 8-floor.
6. Results

In Fig. 4 are shown the design spectra according to KTP-N.2-89 and EC-8 for different periods. From the analysis of the structure, the results present the effect of design spectra on the maximum displacements of the structure and the base reactions.
As shown in Table 1, by using response spectra RS2, the base reactions increase by 22.1% (RS1) and 52% (RS3) for “Fx”, whereas for reaction in the other direction specifically 22.1% (RS1) and 69.2% (RS3).

According the results in Table 2, by using response spectra RS2, the maximum displacement increases by 24.8% (RS1) and 36.3% (RS3) for U1, and for displacement in the other direction specifically 24.9% (RS1) and 78.6% (RS3).

Table 3 shows the results from the model for the control of interstorey drifts in both directions (U1 and U2). Using response spectra RS2 (EC-08, for $T_c = 1.0$ s, soil type D) the minimum condition for interstorey drifts according to EC-8, for direction U2 is not satisfied.

Due to larger interstorey drifts, the building suffered damages of non-structural elements (masonry infill) and in-plane and out-of-plane failures, as shown in Fig. 5.

7. Conclusions and Recommendations

The analyses of this study conclude that it is important to choose the correct design spectra for structures built on land (soil) with periods close to that of the structure. Thus, the illusion can be avoided that by designing according to the spectra given by the technical codes we achieve the no-collapse requirement of the building. This condition relates to the fact that the structure does not suffer either local or global collapse. For structures with a height of 8-12 floors, which have the greatest damage mainly in the failure of the filling walls and inclinations in some cases, using a response spectrum according to EC-8, by accepting $T_c = 1.0$ s, leads to an increase of max displacements up to 24% and base shear force up to 22.1%. All these reflect in the incorrect reduction of the design parameters for the structure and its design (dimensioning and reinforcement) with lower values than required.

An important conclusion is the avoidance of high-rise buildings (especially in the range of 8-14 floors) in the areas where the period of soil oscillations is in resonance with the fundamental period of the structure.

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