Case Study

Collapse rates of reinforced concrete structures during large magnitude earthquakes: case study for Romania

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Abstract

This case study focuses on the evaluation of the collapse rates of various types of reinforced concrete structures (residential and industrial) as observed from the data collected in Romania after the M_w 7.4 Vrancea earthquake of March 4, 1977. The results of the analyses show that the largest collapse rates were attributed to elevated reinforced concrete silos and water tanks. Moreover, the majority of the collapsed elevated reinforced concrete water tanks were full at the moment of the seismic event. Very small collapse rates were observed for high-rise residential RC structures and for the multi-storey industrial RC structures.

Highlights

- The Vrancea earthquake of March 1977 was the most damaging event in Romania in the XXth century;
- The largest collapse ratio (0.0067) among the analysed structures was observed for RC silos;
- No collapses were observed for multi-storey industrial buildings and large panels structures;
- Very small collapse ratios were noticed for residential RC high-rise structures built in the '60s and '70s

Keywords Vrancea earthquakes · RC structures · Collapse rate · Seismic code · Base shear coefficient

1 Introduction

This short communication aims at evaluating the collapse rates of various reinforced concrete (RC) structures as observed from the data collected in the aftermath of the destructive Vrancea (Romania) intermediate-depth earthquake of March 4, 1977 (moment magnitude $M_w = 7.4$ and focal depth $h = 94$ km). The study focuses on both residential, as well as industrial buildings and structures designed and built after 1963 (the year in which the first seismic design code in Romania was enforced).

The damage data collected after the Vrancea 1977 earthquake for residential buildings in Bucharest (8

structural typologies) and Iasi (6 structural typologies) is presented in a concise manner by Balan et al. [1] and Sandi [11]. Recently, some additional damage data referring to other types of structures, namely multistorey RC industrial structures [3], elevated RC water tanks [6] and RC silos [4] has been retrieved and is used in this study for evaluating the collapse rate during the Vrancea 1977 earthquake.

A description of the existing fragility functions, as well as a review of the existing methods for constructing fragility functions are given by Rosetto et al. [10]. Among the main disadvantages of empirical damage data is that the surveys performed after the earthquakes are generally focused on safety and not on damage and moreover, only

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the collapse data can be reliable [10]. As such, in this study, only the collapse limit state is analysed. It has to be highlighted the fact that the damage data used in this study is rather biased because the surveys were focused mainly on structures situated in the most affected areas.

This case study consists of three sections. In the first part, the collapse rates of various RC buildings and structures using data from the damage surveys performed in the aftermath of the Vrancea 1977 seismic event are evaluated. Secondly, a short discussion related to the design of the analysed structures is shown subsequently. Finally, based on the presented data, a discussion related to the building strengthening strategy of the Romanian government in the aftermath of the 1977 earthquake is also presented.

2 Evaluation of collapse rates

The following structures are considered for the evaluation of the collapse rates observed during the Vrancea 1977 earthquake:

- Multi-storey industrial RC structures (having cast-in-place, precast or composite RC frame structures) [3],
- Elevated RC water tanks [6],
- RC silos [4];
- High-rise RC shear-wall structures [1, 11],
- Large panels structures (precast shear walls structure) [1, 11].

The geographical distribution of the samples is as follows:

- The high-rise RC shear-wall structures and the large panels structures are situated either in Bucharest or in Iasi. The epicentral distance of the two cities is of about 100 km for Bucharest and about 180 km for Iasi;
- The multi-storey industrial RC structures, elevated RC water tanks, RC silos are all situated in the southern part of Romania (an area of about 80,000 km²) which was the most affected region of Romania during the Vrancea 1977 seismic event.

The sample size and the collapse rate computed according to the corresponding sample size are given in Table 1. It can be observed that the largest collapse rate is observed for elevated RC water tanks, which are the structures with the longest fundamental eigenperiods. The positions of the collapsed structures (elevated RC water tanks, RC silo and high-rise RC residential structures), as well as the epicentre of the Vrancea 1977 seismic event are illustrated in Fig. 1.

However, if one considers the total number of structures at the date of the seismic event, the collapse rates are much smaller. Thus, in the case of the elevated water tanks, the collapse rate is less than 0.0025, in the case of the RC silos the rate of collapse is less than 0.0067, and in the case of the high-rise RC shear-wall structures, the collapse rate is less than 0.0003. Considering only the building stock of Bucharest, the collapse rate of high-rise RC shear-wall structures is about 0.005.

In the case of the elevated RC water tanks, an additional point which has to be discussed is the fact that three out of the five collapsed elevated RC water tanks were full at the moment of the earthquake. For the other two collapses, the information is missing. In addition, it has to be highlighted the fact that the design of water tanks (on-ground or elevated) at the moment of the earthquake was performed considering only hydrostatic pressure (no hydrodynamic pressure was taken into account). All the collapsed elevated RC water tanks were situated in or near Bucharest, an area in which long-period spectral amplifications were observed during several large magnitude Vrancea intermediate-depth earthquakes [9]. These amplifications are a result of the deep sedimentary layers present in the southern and eastern part of Romania.

In the case of the RC silos, the damage was mainly concentrated to the upper gallery (including the local collapse mentioned in Table 1. In this case, too, it has to be highlighted the fact that no overpressure due to the seismic action was considered in the design of the silos.

The seismic design of RC shear-wall structure (either cast-in-place or precast) was performed in an elastic manner using classic strength of materials relations.

Table 1 Evaluation of the collapse rates for various RC structures

Structure type	Sample size	No. of collapses	Collapse rate (considering only the sample)	Total number of structures	Collapse rate (considering the total number of structures)
Multi-storey industrial RC structures	81	0	0	> 500	0
Elevated RC water tanks	40	5	0.125	> 2000	< 0.0025
RC silos	37	1—partial collapse	0.027	> 150	< 0.0067
High-rise RC shear-wall structures	711	1	0.0014	> 3000	< 0.0003
Large panels structures	273	0	0	> 2000	0

Fig. 1 Locations of collapses structures (RC elevated water tanks, RC silo and high-rise RC residential structures) and epicentre of the Vrancea March 4, 1977 earthquake

Some additional observations regarding the seismic behaviour of other structures during the Vrancea 1977 earthquake are:

- No RC frame structure built after 1963 (the year in which the first mandatory seismic design code was enforced in Romania) collapsed during the Vrancea 1977 seismic event;
- One high-rise RC soft-storey structure collapsed in Bucharest (the second square shown in Fig. 1, the other one being a high-rise RC shear-wall structure). The number of such structures situated in Bucharest is not clear, but a rough estimation is that there are more than 200 soft-storey RC structures. Unfortunately, the seismic behaviour of this type of structure was not analysed in a more detailed manner in the aftermath of the earthquake,
- No residential masonry structure (unreinforced or confined) collapsed during the 1977 seismic event;
- No collapses of large panel structures occurred during the 1977 earthquake;
- No on-ground RC tank (either cast-in-place or precast) collapse or sustained significant damage during the earthquake.

3 Design of analysed structures

In order to better understand the seismic behaviour of the analysed structures, the design base shear coefficients (given in % of the building weight) for Bucharest and Iasi

according to the two Romanian seismic design codes (P13-63 [7] and P13-70 [8]) enforced before the Vrancea 1977 earthquake are given in Table 2. The code P13-63 was enforced in the period 1963–1970, while P13-70 was applied from 1971 until 1977.

It can be observed from Table 2 that the design base shear coefficients are small as compared to the ones given by modern seismic design codes such as Eurocode 8 [2], for instance (which can range between 7 and 20% depending on the structural system, ductility class and importance factor). Thus, it can be concluded that safety against collapse in the event of large magnitude Vrancea earthquakes, even in the case of small base shear coefficients as shown in Table 2 is rather significant. In addition, due to the small number of collapses observed for the analysed structures, either faulty execution or significant local ground motion amplifications can be the main causes of collapse. It is clear that the structural design even though it lacked many of the current rules employed for seismic design managed to ensure a sufficient safety level against structural collapse.

4 Discussion of building strengthening strategy after the 1977 earthquake

Finally, another point which has to be discussed refers to the decision of Romanian authorities in the aftermath of the earthquake to strengthen/repair the new buildings built in the '60 s and '70 s to the same level they had before the earthquake [5]. Today, this decision seems totally

Table 2 Design base shear coefficients for the analysed structures

Structure type	Design base shear coefficient for Bucharest and Iasi	
	P13-63 [7] (%)	P13-70 [8] (%)
Multi-storey industrial RC structures	4.3	3.8
Elevated RC water tanks	3.1	4.3
RC silos	3.2	3.4
High-rise RC shear-wall structures	3.7	4.9
Large panels structures	6.0	5.8

wrong as it is expected that the building stock built prior to 1977 will experience significant damage during a future large magnitude Vrancea earthquake, due to aging, due to the lack of adequate strengthening works and due to damage accumulation during the subsequent Vrancea earthquake of August 1986 and May 1990. However, based on: (1) the magnitude of the earthquake, (2) the damage data collected at that time (3) the performance of structures built after 1963 as compared to those which had no seismic design (unreinforced masonry or RC frames), (4) the level of knowledge regarding performance based seismic design at that time and (5) the economic situation of Romania at that time, this decision may seem as justified.

5 Conclusions

This case study aims at evaluating the collapse rates of various structures (residential and industrial) as observed from the damage data collected after the Vrancea earthquake of March 4, 1977. This study highlights for the first time the difference in terms of collapse rates for structures built in the same period and subjected to the seismic action generated by a large magnitude Vrancea intermediate-depth earthquake. Nevertheless, more studies are necessary in order to evaluate the geographical distribution of the damage, as the data samples from this study are not sufficient for such an analysis.

The study has shown that, among the analysed structures, the largest collapse rate was observed for elevated RC water tanks. In addition, it appears that there is a correlation between the filling level and the collapse as three out of the five collapsed elevated RC water tanks were full at the moment of the earthquake. The collected data shows that no collapse was observed for large panels structures or multi-storey industrial RC structures. Very small collapse rates were observed for the high-rise residential RC structures and RC silos built during the 1960's and 1970's even though their design can be considered as very simplistic if compared to the design performed

nowadays. Moreover, their design base shear coefficients are very small as compared to the coefficients given by today's seismic design codes. The cause of the observed collapses can be mainly attributed to either faulty execution or significant local ground motion amplifications. It can be concluded that the structural design performed at that time even though it lacked many of the current rules employed for seismic design managed to ensure a sufficient safety level against structural collapse. Finally, based on the data shown in this study, it appears as necessary to calibrate or at least compare the collapse rates obtained with those from existing fragility functions, especially for the high-rise RC residential structures (which house a significant number of people especially in the large cities).

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Declarations

Conflict of interest The author declares that he has no conflict of interest.

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