Earthquake in Romania, March 4, 1977: An Engineering Report (1980)

Pages
52

Size
8.5 x 10

ISBN
0309331951

Berg, Glen V.; Bolt, Bruce A.; Sozen, Mete A.; Rojahn, Christopher; Committee on Natural Disasters; Commission on Sociotechnical Systems; National Research Council; Earthquake Engineering Research Institute, Berkeley, California

EARTHQUAKE IN ROMANIA MARCH 4, 1977

An Engineering Report

By

Glen V. Berg, University of Michigan, Ann Arbor
Bruce A. Bolt, University of California, Berkeley
Mete A. Sozen, University of Illinois, Urbana
Christopher Rojahn, U.S. Geological Survey, Menlo Park

Sponsored Jointly by the
Committee on Natural Disasters
Commission on Sociotechnical Systems
National Research Council
and the
Earthquake Engineering Research Institute
Berkeley, California

NATIONAL ACADEMY PRESS
Washington, D.C. 1980

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the Councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the Committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to the procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

This material is based on work supported by the National Science Foundation under Grant No. NSF C 310 Task Order No. 115 and Grant No. PFR-7810631. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the National Science Foundation.

Copies of this report may be obtained from the Committee on Natural Disasters, National Academy of Sciences, 2101 Constitution Avenue, N.W., Washington, D.C. 20418, and from the Earthquake Engineering Research Institute, 2620 Telegraph Avenue, Berkeley, California 94704.

The National Research Council was established by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and of advising the federal government. The Council operates in accordance with general policies determined by the Academy under the authority of its Congressional charter of 1863, which establishes the Academy as a private, non-profit, self-governing membership corporation. The Council has become the principal operating agency of both the Academy of Sciences and the National Academy of Engineering in the conduct of their services to the government, the public, and the scientific and engineering communities. It is administered jointly by both Academies and the Institute of Medicine. The Academy of Engineering and the Institute of Medicine were established in 1964 and 1970, respectively, under the charter of the Academy of Sciences.

COMMITTEE ON NATURAL DISASTERS
(1980)

Chairman

PAUL C. JENNINGS, Division of Engineering and Applied Science, California Institute of Technology

Members

JACK E. CERMAK, Fluid Dynamics and Diffusion Laboratory, Department of Civil Engineering, Colorado State University
ANIL K. CHOPRA, Department of Civil Engineering, University of California, Berkeley
JAMES O. JIRSA, Department of Civil Engineering, University of Texas at Austin
JOHN F. KENNEDY, Institute of Hydraulic Research, University of Iowa
EDWIN KESSLER, III, National Severe Storms Laboratory, National Oceanic and Atmospheric Administration, Norman, Oklahoma
RICHARD D. MARSHALL, Structural Engineering Group, Center for Building Technology, National Bureau of Standards
KISHOR C. MEHTA, Institute for Disaster Research, Texas Tech University
THOMAS SAARINEN, Department of Geography, University of Arizona
ROBERT V. WHITMAN, Department of Civil Engineering, Massachusetts Institute of Technology

Staff

O. ALLEN ISRAELSEN, Executive Secretary
JOANN CURRY, Secretary

Liaison Representative

MICHAEL P. GAUS, Program Manager, Division of Problem-Focused Research, National Science Foundation, Washington, D.C.

FOREWORD

The Committee on Natural Disasters of the National Research Council was formed to study the impact of natural disasters such as earthquakes, floods, tornadoes and hurricanes on engineered structures and systems. The objectives of the Committee's work are to improve the protection against disasters by providing factual reports of the consequences of these extreme events of nature and to stimulate research needed to understand the hazards posed by natural disasters.

The Earthquake Engineering Research Institute was founded in 1949 as an outgrowth of the Advisory Committee on Engineering Seismology of the U.S. Coast and Geodetic Survey. It is a national, multidisciplinary society of engineers, geoscientists, architects, planners, and social scientists whose objective is to advance the science and practice of earthquake engineering and the solution of national earthquake engineering problems. The Institute's activities include investigating and reporting on destructive earthquakes, holding conferences and symposia, and advising government agencies on earthquake engineering problems.

This report is a cooperative effort of the Committee on Natural Disasters and the Earthquake Engineering Research Institute. The report was prepared by a team of engineers and scientists who visited Romania shortly after the March 4, 1977, earthquake that caused extensive damage in the city of Bucharest. The unusual nature of the ground motion and the extent and distribution of the structural damage have important bearing on earthquake engineering efforts in the United States.

PAUL C. JENNINGS
Chairman, Committee on Natural Disasters

JOHN A. BLUME
President, Earthquake Engineering Research Institute

ACKNOWLEDGMENTS

The study team was aided immeasurably by professional colleagues in Romania, who generously provided facilities, technical assistance, advice, information, and transportation without which it would not have been possible to observe and report on the effects of this catastrophic aberration of nature. The person in charge of receiving and accommodating us was Dr. Valentin Ionescu, Director of Foreign Relations, State Committee for Nuclear Energy. Dr. Ion Cornea, Director of the Institute of Earth Physics and Seismology, shared with us his extensive knowledge of the seismology and seismicity of Romania, and Eng. George Serbanescu, Section Chief for Seismic Structures, Building Research Institute (INCERC), inspected buildings with us, showed us the most instructive failures and nonfailures, and provided countless valuable insights. Other Romanian engineers, scientists, and officials who were helpful were Dr. Romulus T. Constantinescu, Director of INCERC, Mr. Radu Negru, Deputy Director of the Central Research Institute for Design and Management in Constructions, and engineers Alexandru Cismigiu, George Filipas, Emil S. Georgescu, Gheorghe Ionescu, Nicholae C. Laszlo, Mihai M. Mihaita, Traian Popp, H. Sandi, and Tiberiu Zorapapel.

Professor Karl Fuchs, of the Geophysical Institute at Karlsruhe, West Germany, had set up seismographs near the source region within a few days after the earthquake and provided much of the seismological information. Dr. Jakim Petrovski of the Institute of Earthquake Engineering and Engineering Seismology, Skopje, Yugoslavia, provided the strong-motion data and analyses of the ground motion recorded in Nis, Yugoslavia. Dr. Sidney G. Smith, Science Liaison Attache for the American Embassy at Bucharest, performed the liaison function admirably.

James Lefter, Director, Civil Engineering Service of the U.S. Veterans Administration, and Lloyd S. Cluff, with Woodward-Clyde Consultants, assisted the team in the field investigation and contributed to the report.

To all of these persons and many others unnamed but equally generous in their assistance, we are grateful.

The Authors

CONTENTS

FIGURES

INTRODUCTION

In the early hours of darkness on the night of March 4, 1977, tremendous tectonic forces ruptured the earth along a fault deep beneath the Carpathian mountains in the Socialist Republic of Romania, emitting seismic waves that were felt over a million square kilometers across Europe, from Moscow to the Adriatic. The earthquake damaged buildings in an area of about 80,000 sq km in Romania and Bulgaria and killed some 1,570 persons, injured more than 11,300, and left 35,000 families homeless (Ref 1). The city of Bucharest suffered the greatest destruction.

Shortly after the event, the Earthquake Engineering Research Institute (EERI) and the National Research Council (NRC) formed an earthquake study team to conduct a field investigation. Members of the team included Bruce A. Bolt, of the University of California, and Mete A. Sozen, of the University of Illinois, for NRC, and Glen V. Berg, of the University of Michigan, and Christopher Rojahn, of the U.S. Geological Survey, for EERI. These members were joined by Lloyd S. Cluff, of Woodward-Clyde Consultants, and James Lefter, of the Veterans Administration. The team entered Romania on March 9, five days after the event, and spent the next five days in intensive study of the effects of the earthquake. They left on March 14, leaving behind Mr. Rojahn to work with an American team of experts sent by the Agency for International Development. Mr. Berg revisited Bucharest in July 1977 while teaching at the Institute of Earthquake Engineering and Engineering Seismology at the University of Kiril and Metodij, Skopje, Yugoslavia.

A preliminary report, Earthquake in Romania, combining the reports of the team members, was published by the Earthquake Engineering Research Institute in May 1977 (Ref 2). The current report combines the information contained in that report with other information gathered by the team members and augmented by ground-motion data, spectral analyses, and structural analyses that were not available when the EERI report was published.

LOCATION AND FAULT MOVEMENT

The dominant topographic feature of Romania is the Carpathian Arc, formed by the beautiful and rugged Carpathian mountains extending eastward across central Romania and then breaking sharply northward.

The epicenter of the destructive Romanian earthquake of March 4, 1977, was located in the Vrancea region of the Carpathian Mountains approximately 170 km NNE of the capital city of Bucharest (Fig. 1). On the basis of data from a local seismograph network, Karl Fuchs of the Geophysical Institute at Karlsruhe, West Germany, located the event at latitude 45.87°N, longitude 26.75°E, at a depth of 110 km. The National Earthquake Information Service of the U.S. Geological Survey assigned a magnitude of 7.1 (M_S) and a time of occurrence of 19:21:54.2 (9:22 PM local time).

A peculiar feature of the historical earthquake pattern in the Carpathians is a persistent pocket of intermediate focus sources under the Carpathian bend at depths of between 100 and 160 km.

A plausible rupture surface for the March 4, 1977, earthquake is sketched in Figure 2. The actual source mechanism appears to be somewhat complex. Analyses of seismograms indicate (Refs 3, 4, 5) a weak foreshock followed by three separate ruptures. An almost vertical slip first occurred at the focus under Vrancea. This thrust the mountains (an old island arc) and Transylvania upwards over the deep sediments (old trench) to the east. The pattern of aftershocks and analysis of seismograms indicate that the rupture then extended upwards and to the south toward Bucharest for a distance of about 50 km.

Bucharest is near a projection of the fault plane to the earth's surface, on the basis of a reading of first P motions at Romanian stations. For 20 sec or more, therefore, the city was shaken by P waves of small energy traveling about 200 km through the upper mantle and crust. After about 20 sec the S pulse from the main rupture arrived. The long S-P warning period allowed time for some persons to escape from buildings that finally collapsed.

GROUND-MOTION RECORDS

Nine strong-motion accelerographs and two seismoscopes were installed in Romania at the time of the earthquake (Fig. 1). Two other accelerographs, which had been supplied to Romania several years ago under the Balkan project, were not installed. Of the nine installed accelerographs (Table 1), six were located at ground-level sites in Bacau, Vrincioaia, Focsani, Galati, and Bucharest (where there were two), and three were located near or at the top of 11-, 12-, and 13-story buildings in Bucharest and Galati. The seismoscopes (Table 2) were located at ground-level sites in Bucharest and Galati. Records were recovered from the ground-level accelerographs in Focsani, Vrincioaia, and Bucharest, from the accelerograph at the top of one of the two instrumented buildings in Bucharest, and from both

Figure 1 Map of Romania, showing cities affected by the March 4, 1977, earthquake, major dams within 250 km of the epicenter, and strong-motion instruments installed at the time of the earthquake.

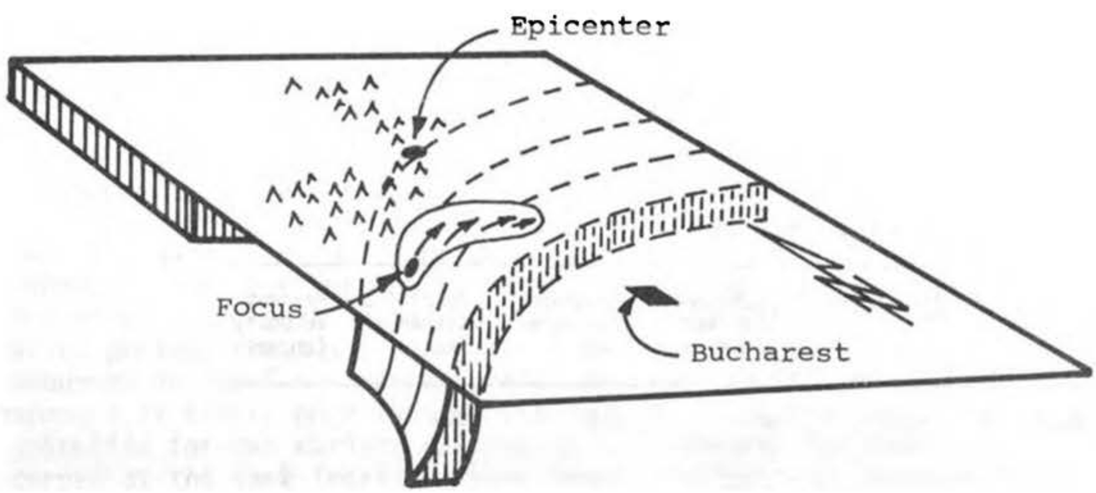

Figure 2 Inferred rupture surface, Romania earthquake of March 4, 1977.

Table 1 Accelerograph Data

Station	Structure	Instrument type and location	Epicentral distance (km)	Focal distance[1] (km)	Maximum acceleration (g)	Duration >.05g (sec)	Total record (sec)
Bacau	11-story reinforced concrete shear-wall building	MO-2 basement	78	135	--[2]	--[2]	--[2]
Bucharest	1-story reinforced concrete frame building	SMAC-B basement	166	199	0.20	14.7	75
Bucharest	11-story reinforced concrete shear-wall building	MO-2 basememt	166	199	--[3]	--[3]	--[3]
		MO-2 roof	166	199	0.3	--[4]	--[4]
Bucharest	13-story reinforced concrete frame building	RMT-280 12th floor	167	200	--[3]	--[3]	--[3]
Focsani	3-story brick building	MO-2 basement	39	117	--[5]	--[5]	--[5]
Galati	12-story reinforced concrete frame building	MO-2 basement	112	157	--[3]	--[3]	--[3]
		MO-2 12th floor	112	157	--[3]	--[3]	--[3]
Vrincioaia	1-story shed	MO-2 ground level	2	110	0.23	Unknown[6]	Unknown[6]

[1]Based on focal depth of 110 km
[2]Instrument not triggered
[3]Instrument malfunctioned
[4]Data available from Building Research Institute (INCERC)
[5]Record destroyed during development
[6]Record incomplete, film drive mechanism malfunctioned

Table 2 Seismoscope Data

Station	Structure	Instrument type and location	Epicentral distance (km)	Focal distance[1] (km)	Maximum velocity (cm/sec)
Bucharest	1-story rc frame bldg	Wilmot basement	166	199	42
Galati	13-story rc frame bldg	Wilmot basement	112	157	--[2]

[1]Based on focal depth of 110 km
[2]Data available from INCERC

seismoscopes. The accelerograph in Bacau, however, was not triggered, and the two accelerographs in Galati and two of those in Bucharest malfunctioned.

Of the six records recovered, only the two seismoscope records and two accelerograms from Bucharest are intact. The Vrincioaia accelerogram is incomplete because the instrument's film-drive mechanism did not operate continuously during the earthquake, and the Focsani accelerogram was destroyed while being developed. The complete Bucharest ground record is shown in Figure 3; the recording accelerograph was located in the basement of a one-story, reinforced-concrete frame building at the Building Research Institute (INCERC). The record was provided by G. Serbanescu of INCERC. The two seismoscope records are in Figure 4, and the partial Vrincioaia ground record is in Figure 5. The other existing analog accelerogram from Bucharest, recorded at the top of a 10-story building, is available from the Building Research Institute, Sos Pantelimon 266, Bucharest.

Both the Bucharest ground accelerograph record (Fig. 3) and the Bucharest seismoscope record (Fig. 4) were recorded in the basement of a one-story reinforced-concrete frame building located at INCERC in the eastern part of the city (Fig. 6). The accelerogram was recorded on a Japanese-built three-component SMAC-B accelerograph with 10 Hz natural frequency accelerometers that are critically damped. The seismoscope record was recorded on a Wilmot-type seismoscope with a natural period of 0.75 sec and damping inversely proportional to amplitude of recorded motion (nominally, from 7 to 15 percent of critical damping).

The most notable features of the Bucharest ground accelerograph record are the 1.1-sec and 1.6-sec large-amplitude (0.16 G and 0.20 G) pulses that occur in the E-W and N-S components about 20 sec after the instrument was triggered (trigger level is 0.01 G vertical acceleration). These pulses are unusual at this epicentral distance. After each pulse, the accelerations are lower in amplitude and higher in frequency. By contrast, there are no long-period pulses in the vertical component where accelerations are generally in the 8-10 Hz frequency range with the maximum acceleration being about 0.12 G.

Response spectra for the Bucharest accelerogram, computed from a digitized record prepared by the U.S. Geological Survey (Ref 6), are shown in Figures 7 to 9. A noteworthy feature is the pronounced peak in velocity response for the N-S component in the period range of 1.8-2.0 sec. The peak in acceleration response comes at a somewhat shorter period, about 1.5 sec. The corresponding peaks are less pronounced in the E-W component, and the spectrum for the vertical component is closer to a typical spectrum in its appearance.

Spectra for two earlier earthquakes of much smaller magnitude, recorded at the same location, have been computed by G. Serbanescu and are shown in Figures 10 and 11, replotted from his figures. Error has undoubtedly developed in the process of plotting, scaling, and replotting, but the trends are still evident. The N-S velocity

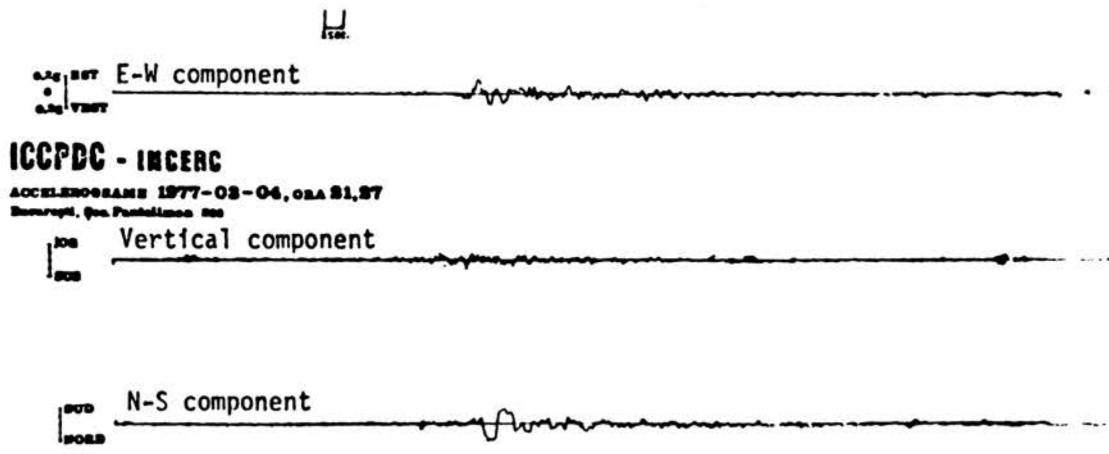

Figure 3 SMAC-B strong-motion accelerogram recorded in Bucharest.

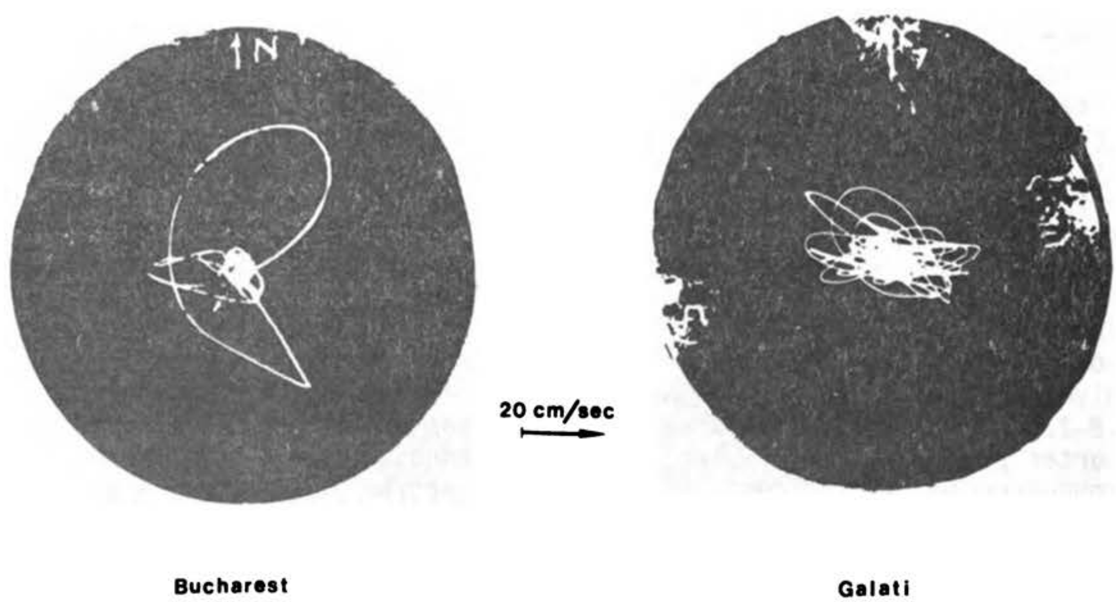

Figure 4 Seismoscope records obtained in Bucharest and Galati.

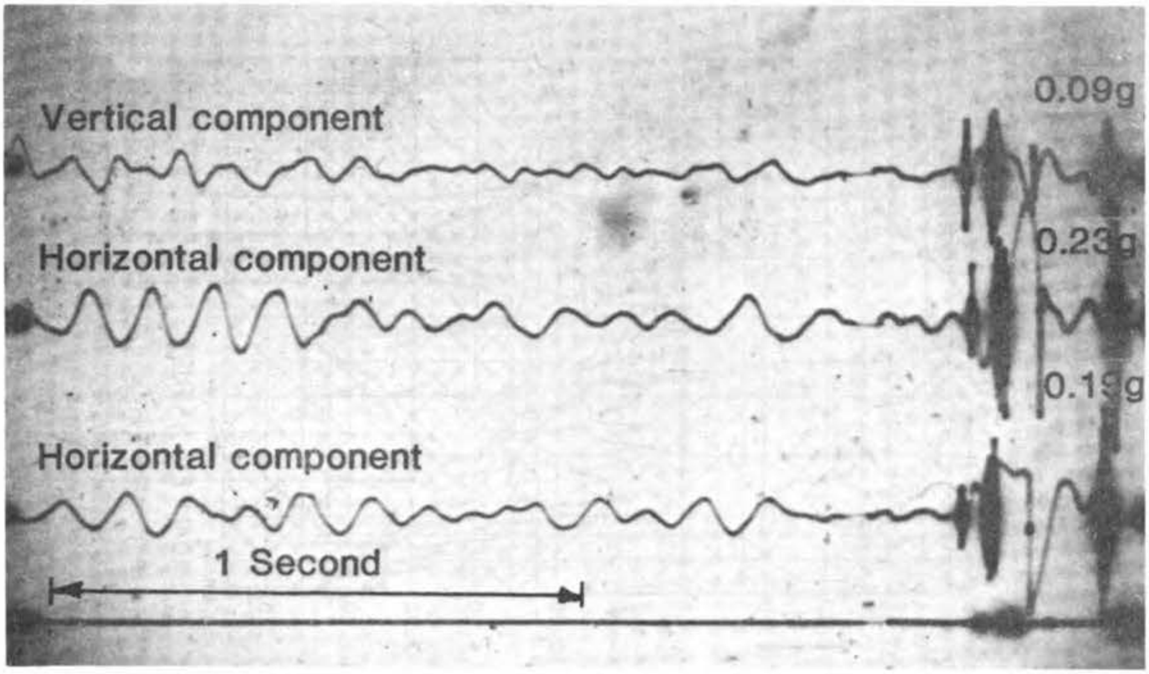

Figure 5 MO-2 strong-motion accelerogram recorded at Vrincioaia. Film drive malfunctioned.

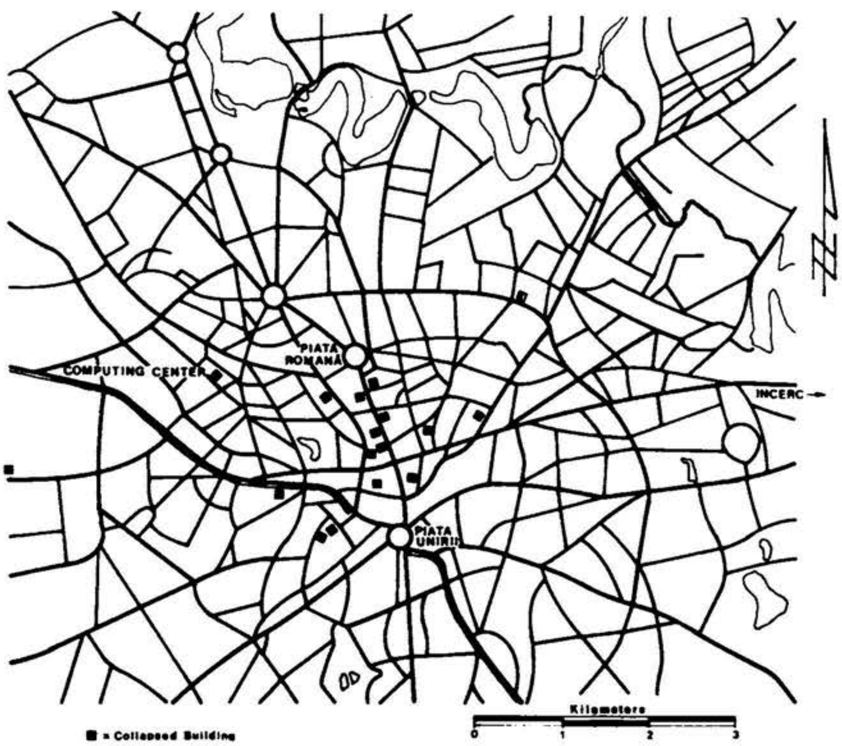

Figure 6 Street map of Bucharest showing collapse locations.

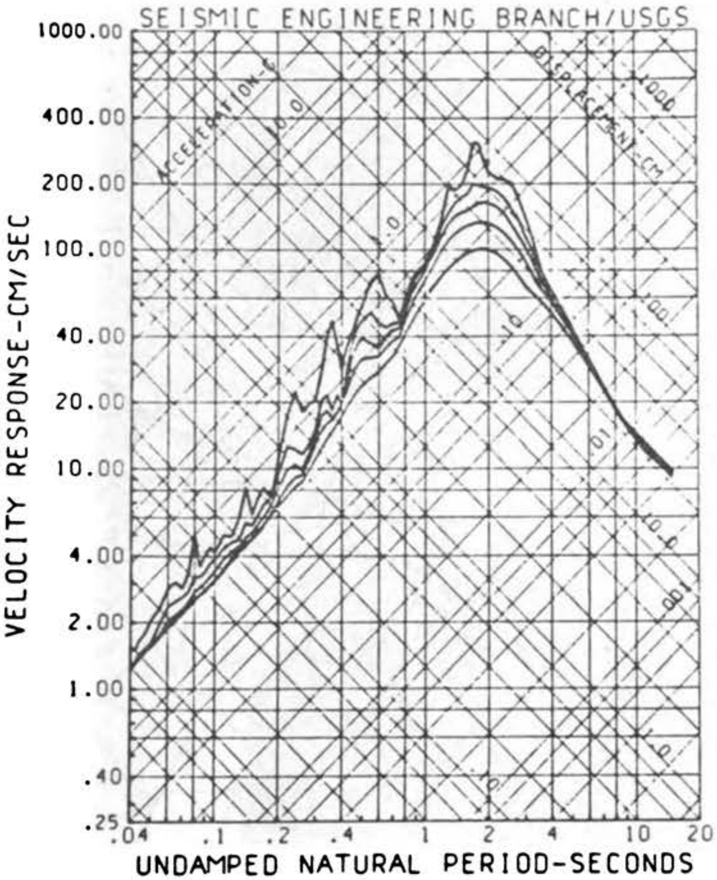

Figure 7 Response spectra, Bucharest (INCERC), March 4, 1977, 1922 GMT S-N 0, 2, 5, 10, 20 percent critical damping (Ref 6).

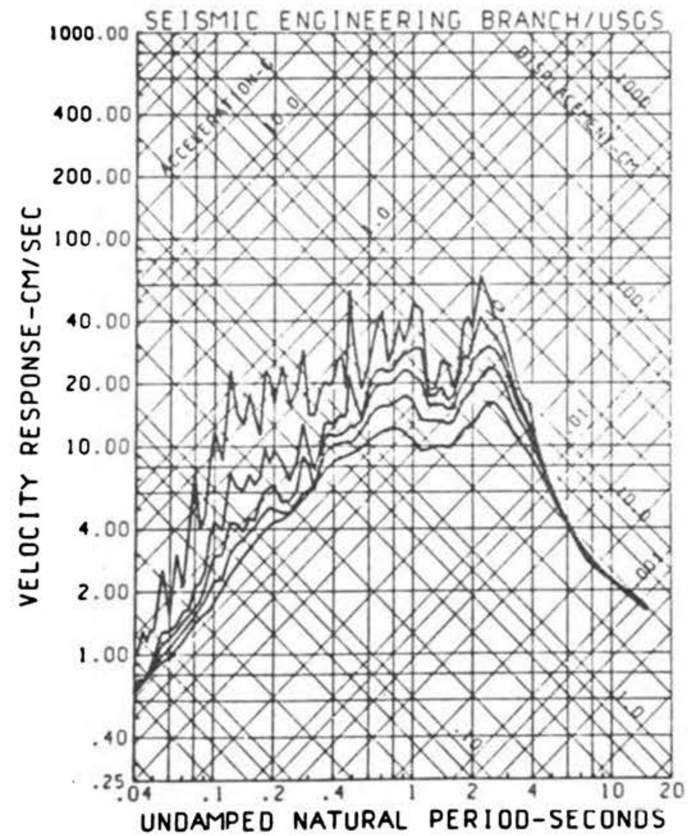

Figure 8 Response spectra, Bucharest (INCERC), March 4, 1977, down-up 0, 2, 5, 10, 20 percent critical damping (Ref 6).

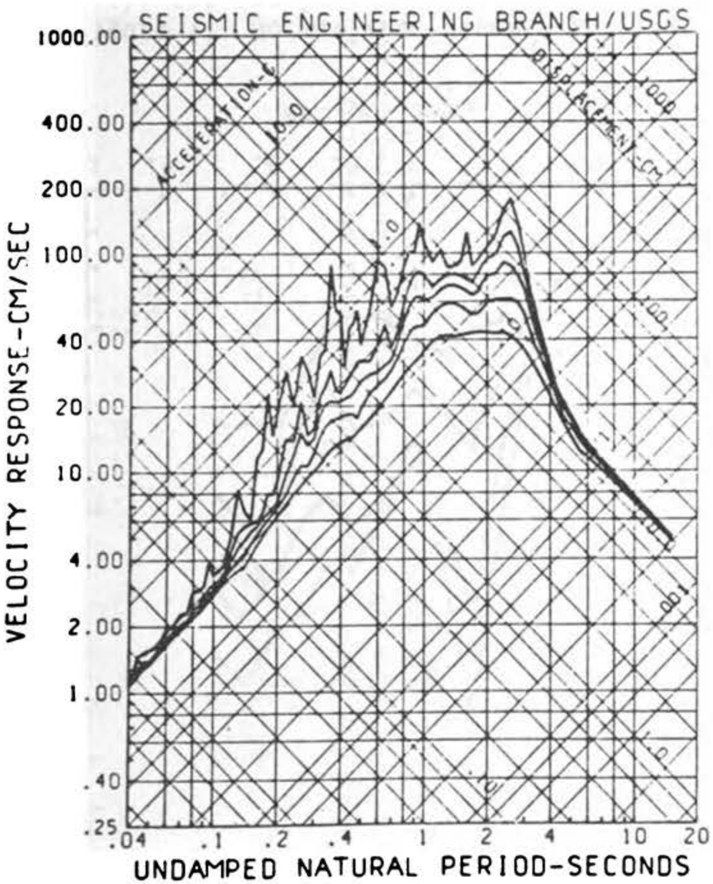

Figure 9 Response spectra, Bucharest (INCERC), March 4, 1977, E-W 0, 2, 5, 10, 20 percent critical damping (Ref 6).

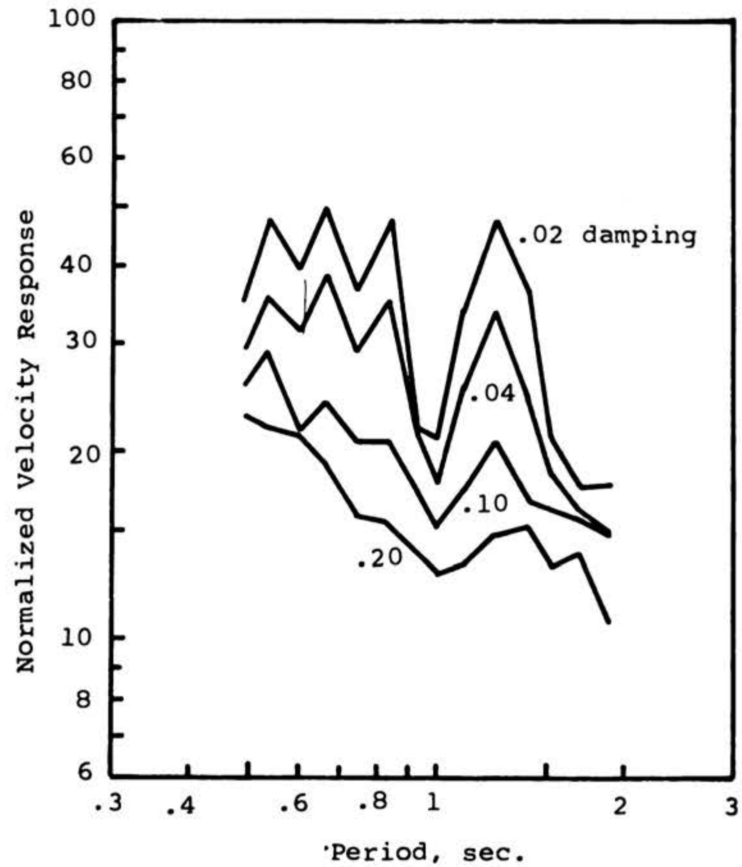

Figure 10 Normalized response spectra, Bucharest accelerogram of July 29, 1948, E-W component.

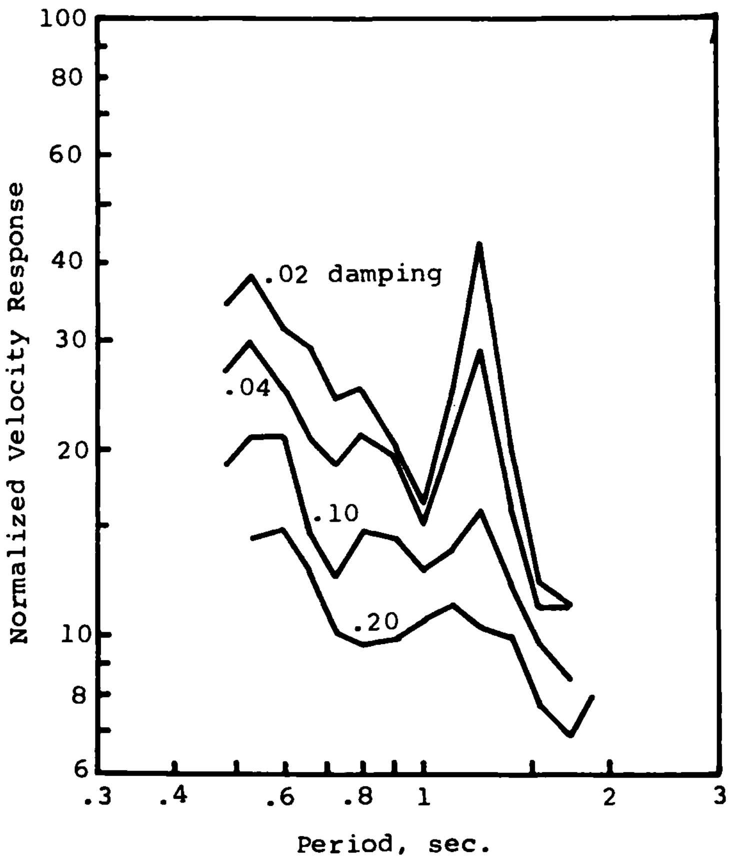

Figure 11 Normalized response spectra, Bucharest accelerogram of December 28, 1955, N-S component.

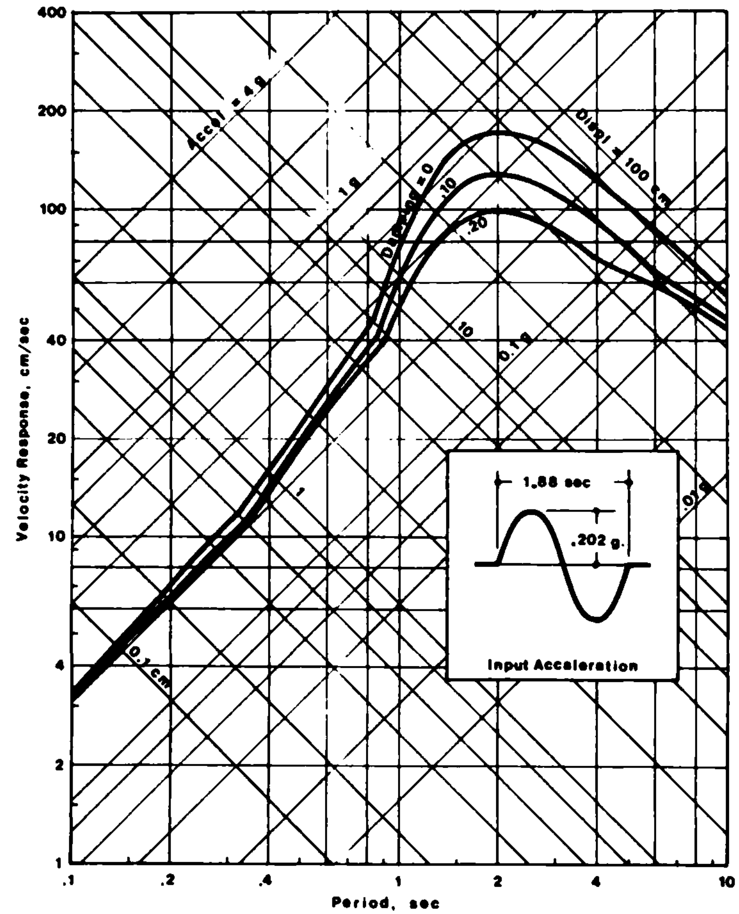

Figure 12 Response spectra for single sine wave input acceleration.

response peaks sharply at about the 1.25-sec period, and the E-W component shows a high in the same region but less pronounced.

The N-S component spectrum of Figure 7 is reminiscent of the spectrum for a single-sine pulse. To explore this further, a single-sine wave was fitted to the accelerogram in the region of the big pulse. It was found that the best fit in the sense of minimum mean square deviation was an acceleration wave with a half-amplitude of 0.202 G and a period of 1.68 sec. The spectrum for this single-sine wave acceleration is shown in Figure 12. The similarity to the N-S spectrum for the complete accelerogram is striking. The different character of the spectra at long periods arises because for the single-sine wave input the peak relative displacement for a long-period oscillator occurs after the input motion ceases, it never exceeds the extreme ground displacement, and it approaches the maximum ground displacement, 89 cm for this sine wave, as the period increases. For the complete accelerogram, however, the peak relative displacement may occur either during or after the end of the input motion, and it may exceed the maximum ground displacement, which is 20 cm for this accelerogram.

A strong-motion accelerogram was recorded at Nis, Yugoslavia, on an SMA-1 accelerograph installed and maintained by the Institute of Earthquake Engineering and Engineering Seismology (IZIIS) of the University of Kiril and Metodij, Skopje, as part of the Yugoslavia strong-motion network. The instrument is located at latitude 43.3°N, longitude 21.9°E, about 1200 km WSW of the epicenter. The response spectra for the horizontal components of the Nis record, computed by IZIIS (Ref 7), are shown in Figures 13 and 14. The undamped velocity response at Nis is about 30 percent of that at Bucharest, and for 20 percent damping it is about 15 percent of the Bucharest response. Nis is seven times as far from the epicenter as Bucharest.

The El Centro, California, earthquake of May 18, 1940, is a convenient benchmark for comparison. The spectrum for the N-S component recorded at El Centro is shown in Figure 15. Generally, the Bucharest N-S velocity response exceeds that of El Centro for periods longer than about 1.1 sec, and is smaller for periods less than about 0.8 sec. One might therefore expect the Bucharest ground motion to be more destructive than that of El Centro for long-period structures, and less destructive for short-period structures.

One objective index of the destructive potential of the ground motion is provided by the spectrum intensity (Ref 8), defined as

$$SI\ (\zeta) = \int_{0.1\ \text{sec}}^{2.5\ \text{sec}} PSV\ (\zeta,\ T)\ dT$$

where

SI = spectrum intensity
PSV = velocity response
ζ = damping, and
T = period

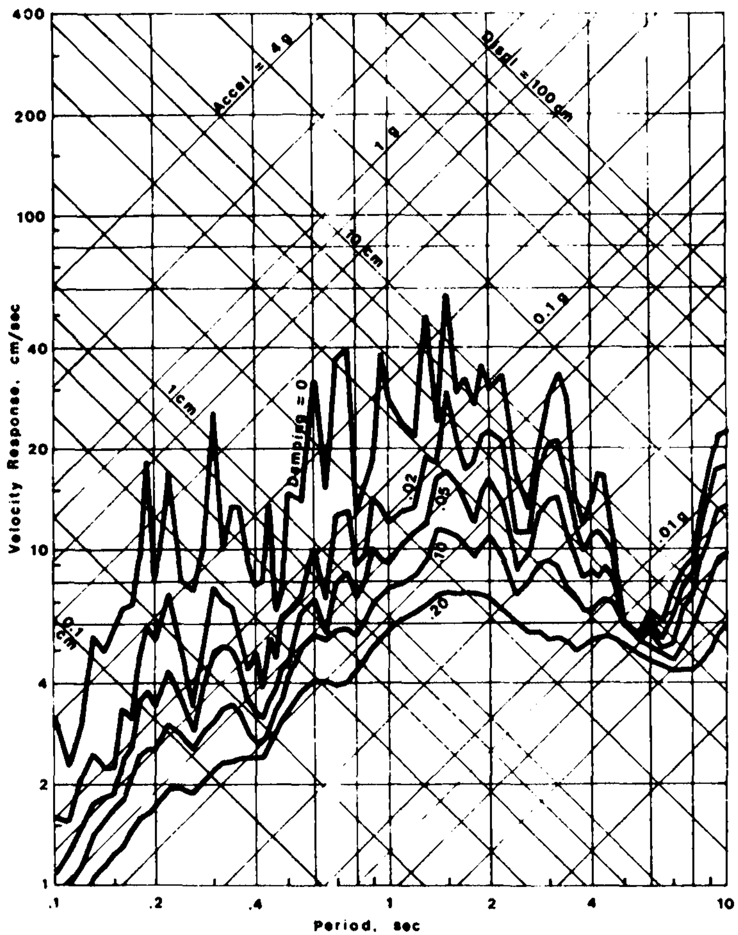

Figure 13 Response spectra, Nis, Yugoslavia, accelerogram of March 4, 1977, N-S component (epicentral distance = 1,200 km).

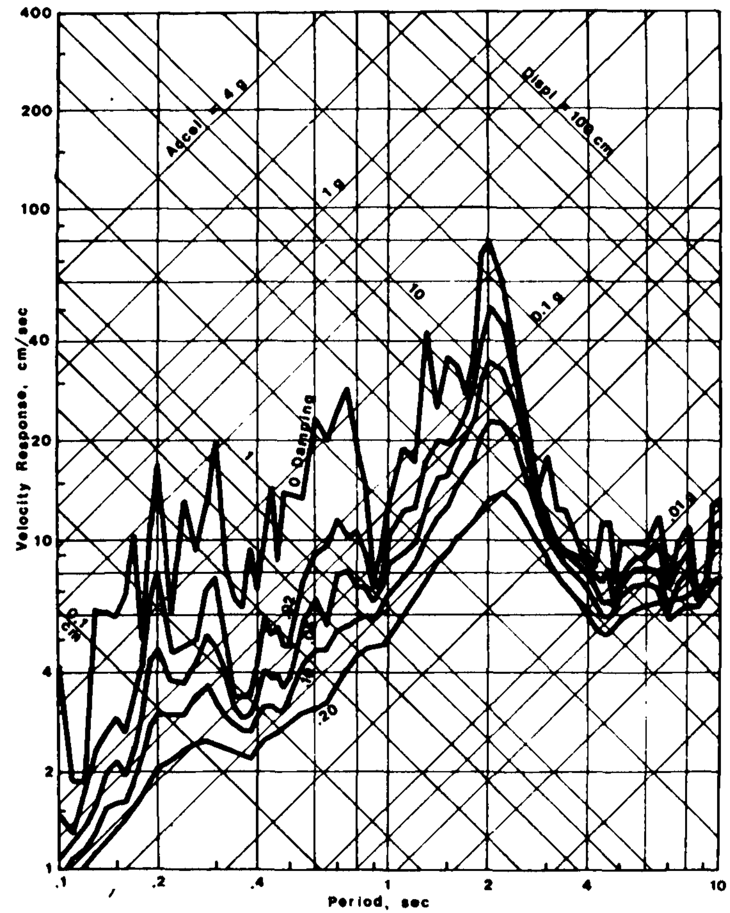

Figure 14 Response spectra, Nis, Yugloslavia, accelerogram of March 4, 1977, E-W component (epicentral distance = 1,200 km).

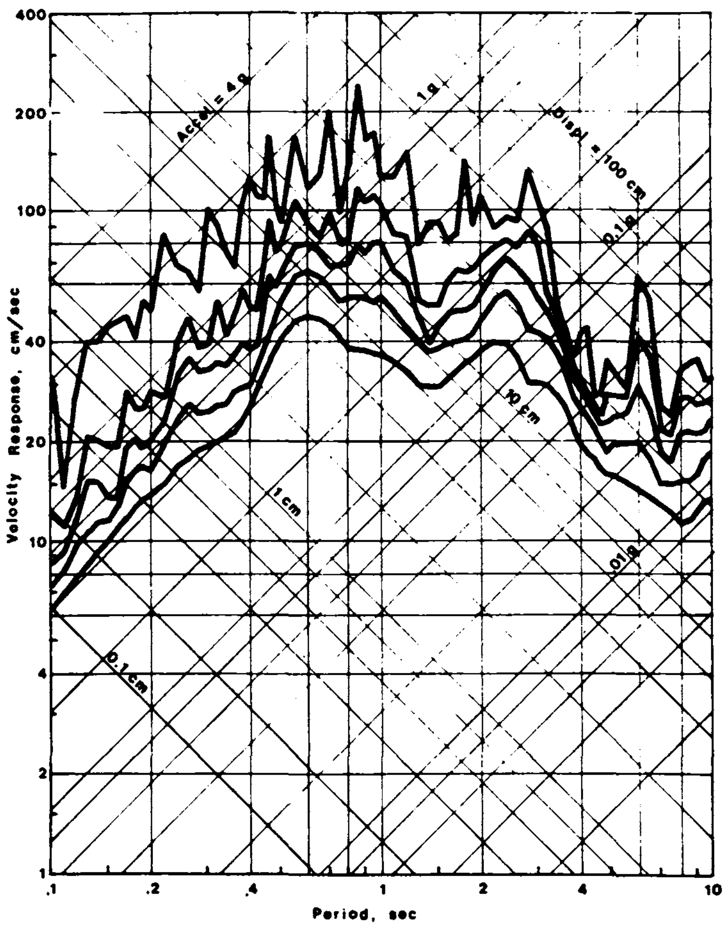

Figure 15 Response spectra, El Centro, California, accelerogram, May 18, 1940, N-S component.

Table 3 Spectrum Intensities

Location	Accelerogram component	Fraction of critical damping		
		0	0.05	0.20
Bucharest	N-S	357 cm	247 cm	159 cm
	E-W	226 cm	139 cm	80 cm
Nis	N-S	63 cm	25 cm	13 cm
	E-W	75 cm	38 cm	19 cm
El Centro 1940	N-S	265 cm	135 cm	81 cm
	E-W	264 cm	114 cm	68 cm

Table 3 shows the spectrum intensities of the Romanian earthquake of 1977 as recorded in Bucharest and in Nis. For comparison, it also shows the spectrum intensities for the 1940 El Centro earthquakes, which are, with one exception, less than those of the Bucharest record.

DAMAGE

Damage caused by strong ground shaking was most severe in Bucharest, 170 km from the epicenter, where 35 buildings collapsed, and numerous other buildings sustained structural and architectural damage and damage to contents. In the small town of Vrincioaia, only 2 km west of the epicenter, the effects of strong ground shaking were far less severe; superficial cracking of adobe- and wood-wall one-story dwellings was the typical extent of observed damage. In the cities of Focsani and Buzau, which are between the epicentral area and Bucharest, unreinforced masonry walls in low-rise construction collapsed partly or totally, and there were signs of movement between structural elements and adjacent masonry in-fill walls in recently constructed engineered buildings. In some small towns to the north of Ploiesti, at least one several-hundred-year-old building collapsed, and other unreinforced masonry-wall buildings were heavily damaged. In the cities of Craiova, Alexandria, and Zimnicea, which are located to the west and southwest of Bucharest, unreinforced masonry walls in low-rise construction reportedly collapsed, some partly and some totally. By contrast, the effects of strong ground shaking in Brasov, to the west of the epicenter, and in Bacau, to the north, were slight.

This asymmetric pattern has been noticed in earlier Romanian earthquakes from the Vrancea zone--for example, in the November 10, 1940, earthquake, $M_S = 7.4$, with focal depth of 150 km, previously considered the severest earthquake in Romania in modern times. In the March 4, 1977, earthquake, however, intensities were even more confined to the south than in 1940. Only moderate shaking occurred in 1977 in the Focsani region, for example, whereas in 1940 this region was given the maximum intensity of IX. To the east of the Carpathian Arc bend between Focsani and the 1977 epicenter a crustal depression 10-14 km deep filled with marine sediments exists. The maximum intensity in 1977 was VIII in Bucharest, 170 km SSW of the epicenter; VI to VII in Craiova, 290 km SW; V to VI in eastern Yugoslavia; and III to IV in western Yugoslavia. The maximum ground acceleration in Skopje, Yugoslavia, estimated from seismoscope records, was 0.01 G. Table 4 gives a more complete summary of the intensity data.

None of the large dams located within 250 km of the epicenter (Fig. 1) were damaged by the earthquake. The Poiana Uzului Dam, an 81-m-high concrete buttress dam 60 km northwest of the epicenter, was closest to the epicenter. The only reported effect there was that two men on and near the dam at the time of the earthquake had great trouble standing. This single observation would suggest an intensity of shaking of VII on the Modified Mercalli Scale. The other three dams were Bicaz Dam, a 128-m-high gravity dam, which was 129 km from the epicenter; Vidraru Dam, a 167-m-high reinforced concrete arch dam,

Table 4 Preliminary Estimates of the Intensity of Shaking in Various Parts of Romania

Intensity of shaking	Location	Epicentral distance	Focal distance[1]
V	Brasov	91	143
VI	Vrincioaia	2	110
VI-VII	Craiova	288	308
	Galati	112	157
VII-VIII	Alexandria	234	259
	Buzau	80	136
	Focsani	39	117
	Ploiesti, north of	115	159
	Zimnicea	268	290
VII-IX	Bucharest	166	199

[1]Based on focal depth of 110 km

which was 169 km from the epicenter; and Vidra Dam, a 121-m-high rockfill dam, 240 km from the epicenter.

There was no damage to railroads, highways, bridges, or utilities, except for power outages of short duration.

BUILDING DAMAGE IN BUCHAREST

Bucharest, the capital and largest city in Romania, has a population of 1-3/4 million. It is an old city and has many magnificent buildings constructed in the latter half of the nineteenth century, such as the House of Parliament, Palace of Justice, the buildings of the University of Bucharest, and many large churches. There are also many modern buildings in Bucharest. The skyline of the central business district includes many high-rise buildings up to 20 stories. The city also has great numbers of modern apartment buildings, most about 10 stories high. The government's present plan is to construct 35,000 new apartments annually, an effort that represents construction of about 350 10-story buildings of precast concrete construction.

Figure 16 Collapsed building constructed prior to the 1940 Romanian earthquake.

The city's history has been violent. It has been occupied by various invaders, including foreign troops in both world wars; it was heavily bombed during World War II, and suffered other disasters such as earthquakes, fires, and bubonic plague epidemics. Romania had serious floods several years ago. Yet Bucharest is attractive and picturesque, with extensive public gardens and main thoroughfares reminiscent of Paris. The Dimbovita River winds through the city, and a series of interconnected lakes lies on the northern outskirts.

Most of the earthquake damage was concentrated in the city of Bucharest. Thirty-five buildings collapsed, most of them near the heart of the city. Figure 16 shows one collapsed structure, and the street map of Figure 6 locates many of them. All but three of the buildings that collapsed were built before the adoption of seismic building regulations following the earthquake of 1940. They had survived the 1940 earthquake, an event of slightly greater magnitude than the 1977 event with about the same epicenter. The strong motion of the 1940 earthquake was, of course, not recorded. Some of the buildings that collapsed during this event had been damaged in 1940, and cumulative damage may have contributed to their demise. World War II damage also occurred in the city. Typically, these older buildings were reinforced-concrete frame structures, 7-14 stories high, with a soft first story; i.e., in comparison to the upper stories where numerous interior and exterior walls provided lateral stiffness, the first story was relatively open with many windows and a few walls and partitions. Figure 17 shows one example. Furthermore, the quality of concrete was poor (mortar could be chipped away with a pen) and little reinforcing steel and few ties were to be found in the columns and beams (Fig. 18). By contrast, modern buildings that were designed in accordance with lateral-force code requirements adopted after the 1940 earthquake performed far better than their older counterparts. With three exceptions, modern buildings incurred slight to moderate structural damage at worst. Nonstructural damage, however, was extensive, cracking of in-fill masonry walls being particularly prevalent.

The three exceptions to good behavior of modern buildings were the collapsed computing center, a three-story flat slab building discussed in more detail later, and two apartment buildings away from the center of the city. One of the apartment buildings collapsed completely and had been removed within a few days after the earthquake. Another new apartment building (Fig. 19) collapsed at one end, where trouble had been encountered with the foundation and some underpinning work had been done. The foundation problems and the partial collapse were probably related.

New apartment buildings abound in Bucharest. They come in many types and sizes, including cast-in-place reinforced-concrete frame structures, cast-in-place reinforced-concrete shear-wall structures, both conventionally formed and slip-formed, large-panel precast concrete structures, and mixed construction combining cast-in-place frames and cast-in-place shear walls with precast floor slabs and precast large-panel exterior walls. Apartment building heights range for the most part from 9 to 15 stories. In general, the behavior of apartment buildings was good. Except for the two collapses mentioned above, damage to new apartment buildings was confined mostly to occasional cracks in restrained beams, cracks in shear walls, and working of the joints between shear walls and floors and joints between perpendicular shear walls. At least one instance of column damage occurred in the open ground story of a new apartment building. Of the major types of modern construction in existence at the time of the earthquake, i.e., multistory reinforced-concrete frame buildings

Figure 17 Apartment building with soft ground story designed and constructed prior to the 1940 Romanian earthquake.

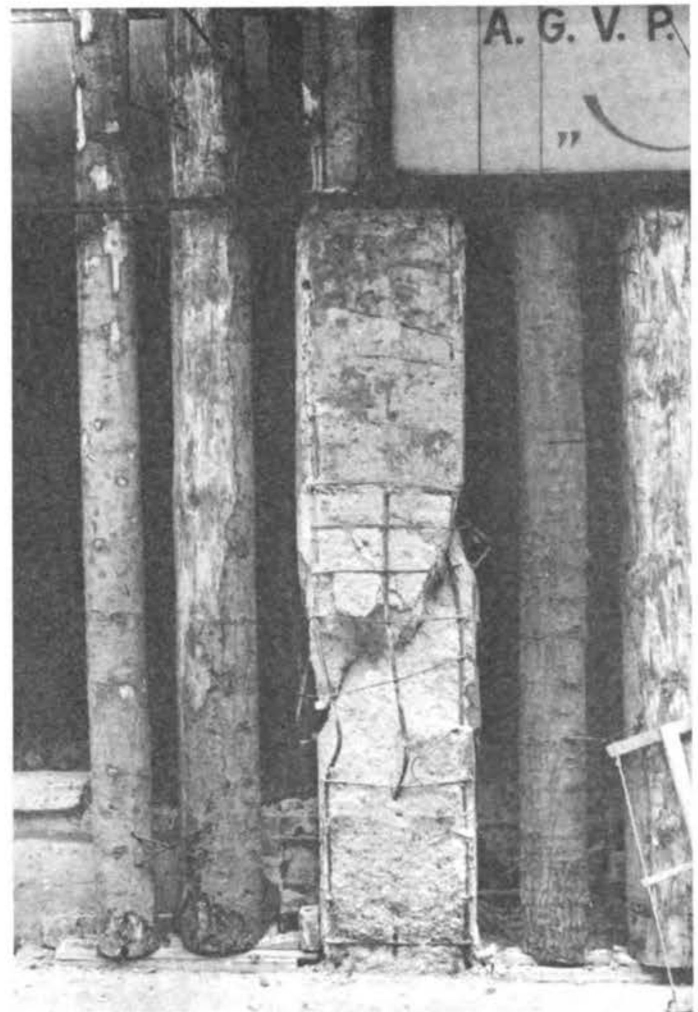

Figure 18 Column in open ground story of tall building designed and constructed before the 1940 Romanian earthquake.

Figure 19 Partial collapse of new apartment building.

with and without a soft first story, multistory reinforced-concrete shear-wall buildings, and large-panel buildings composed of large precast reinforced-concrete floor and wall elements, the stiffer structures sustained less structural and nonstructural damage than the more flexible structures. Large-panel buildings in particular performed very well. Their good performance may be related to the fact that their fundamental periods of vibration, 0.2 to 0.5 sec, are short in comparison with the predominant period of high-amplitude ground motion of this earthquake in Bucharest, which was 1 to 1.7 sec.

The Inter-Continental Hotel (Fig. 20) is probably the best known modern building in Bucharest, at least to Americans. It is a reinforced-concrete frame and shear-wall structure, shaped in plan like an equilateral triangle with blunt vertices and concave sides. It was apparently designed as a symmetric building, without regard to torsion coupling, whereas in fact that three vertical planes of symmetry are 120 degrees apart and torsional response is strongly coupled with translational response other than in a plane of symmetry. Damage to the building was insignificant, consisting mainly of partition cracks and plaster damage.

Figure 20 Inter-Continental Hotel.

Hospitals

Hospital damage created a considerable problem for medical authorities. No lives were lost in hospitals, but nine of the 35 hospitals in the city were damaged sufficiently to cause their evacuation; most of them were not seismically designed.

The Emergency Hospital had 635 occupied beds before the earthquake, and 600 additional patients were admitted immediately after the earthquake. At 4:00 a.m. on March 5, 1977, the hospital was ordered to be evacuated. Evacuation took over 3 hours. The building was constructed in 1970 with a relatively flexible reinforced-concrete frame. The tower (Fig. 21) is in the shape of a C. The end bents and columns of one end of the tower portion were severely damaged during the earthquake. A nonbearing masonry end wall fell out at the second and third stories (Fig. 22). Many medical supplies were lost, including water. The power was interrupted, but the hospital's emergency generator picked up the electrical load for the building. Elevators were not used after the earthquake struck. Moderate architectural damage occurred in the functional areas of the hospital.

Fundeni Hospital consists of two major units several hundred yards apart. One unit was constructed in 1958, with a 10-story wing added later. There was no seismic joint between the units. A second unit was completed in 1974 and was considered one of the most modern hospitals in Eastern Europe. The 1958 building suffered some

Figure 21 Emergency Hospital.

Figure 22 End wall of Emergency Hospital.

structural damage and a considerable amount of architectural damage that could be attributed largely to the two units battering each other during the strong shaking. This building was evacuated on the night of the earthquake. The new building also sustained structural damage (column bar buckling, flexural cracks in beams) as well as considerable architectural damage. The structural damage could be attributed to poor design and construction details. The first and second floors were evacuated. Although each of the hospital buildings originally had 800 beds, only about 250 beds were operating a week after the earthquake, all in the new building.

Colentina Hospital was a medical complex spread over several buildings. None of the buildings was designed to resist earthquakes. After the earthquake, one wing was occupied by patients despite several major cracks in exterior bearing walls and interior nonbearing walls. Few supplies were lost in this building. One part of an adjacent building, of similar construction, was evacuated because of several column failures and major cracks in a central stair tower. The most serious problems occurred in an adjacent orthopedic wing, which was originally constructed in the early part of this century. It had recently been completely remodeled and reopened to patients a few months before the earthquake. The hospital suffered extensive structural and nonstructural damage and was considered unsafe for reoccupation.

Computing Center

The most instructive building collapse in Bucharest was the new computing center, built in 1967, shown in the pre-earthquake photo, Figure 23. This was a three-story building comprising a central structure 30 m square with service towers at both ends structurally separated from the central building. It was designed according to the Romanian seismic code; the design base shear was 6 percent of the weight of the building. The central part of the building collapsed; the service towers did not. Figure 24 shows the collapse.

The central building was cast-in-place reinforced-concrete construction with precast concrete exterior walls above the ground story. No shear walls were in the central building. The upper stories had continuous bands of windows separating the precast wall units. The ground story was enclosed by walls set in from the exterior building lines and capped with a continuous band of sash. Figure 25 shows the ground-floor layout. The building above was supported entirely on nine columns spaced 12 m center to center in both directions, with the slabs cantilevered 3 m beyond the outside columns on all sides. Note in Figure 25 that the nonstructural exterior walls run around the columns; no column in the ground story had lateral restraint of any kind.

Figure 26 is a schematic diagram showing a typical column and floor and roof slabs. The roof slab was 45 cm thick and the floor slabs 55 cm. They were of cellular construction, with 6-cm cover

Figure 23 Computing center before the earthquake.

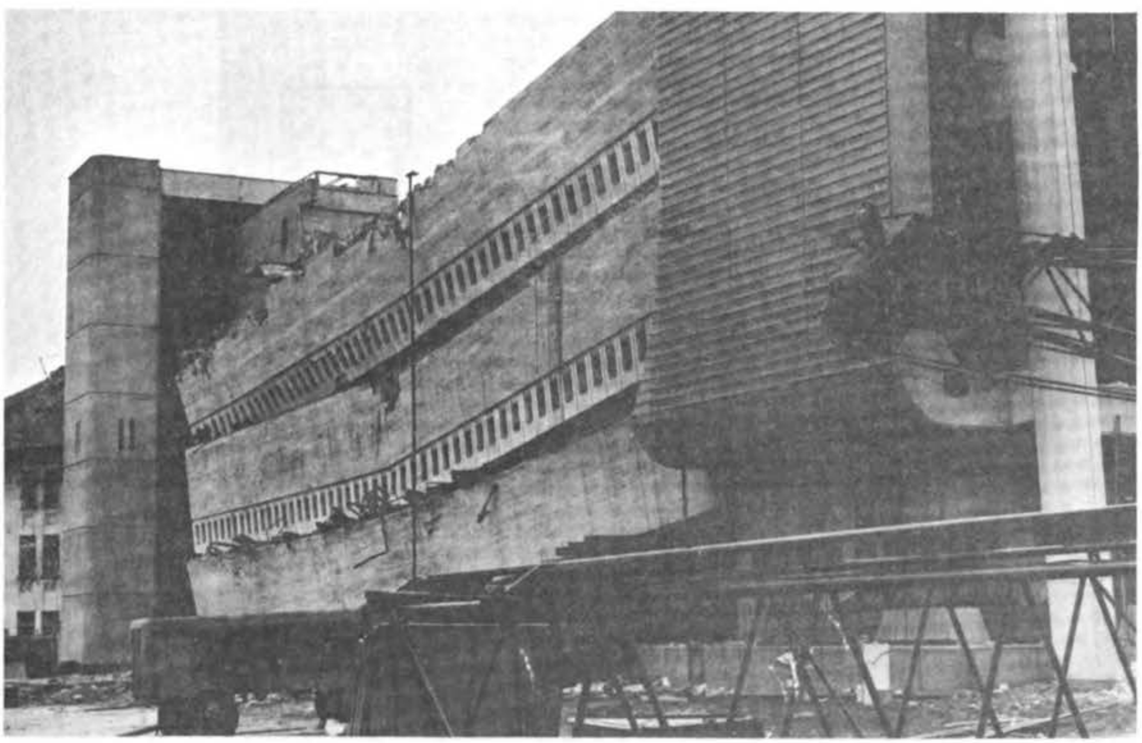

Figure 24 Collapsed computing center.

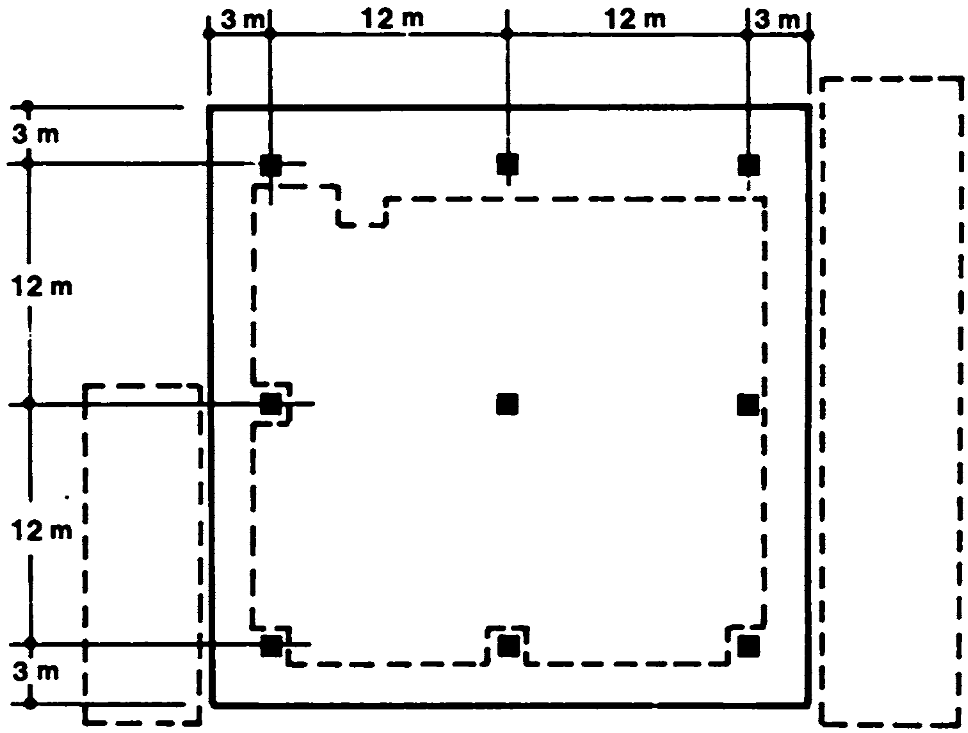

Figure 25 Computing center, ground-floor layout.

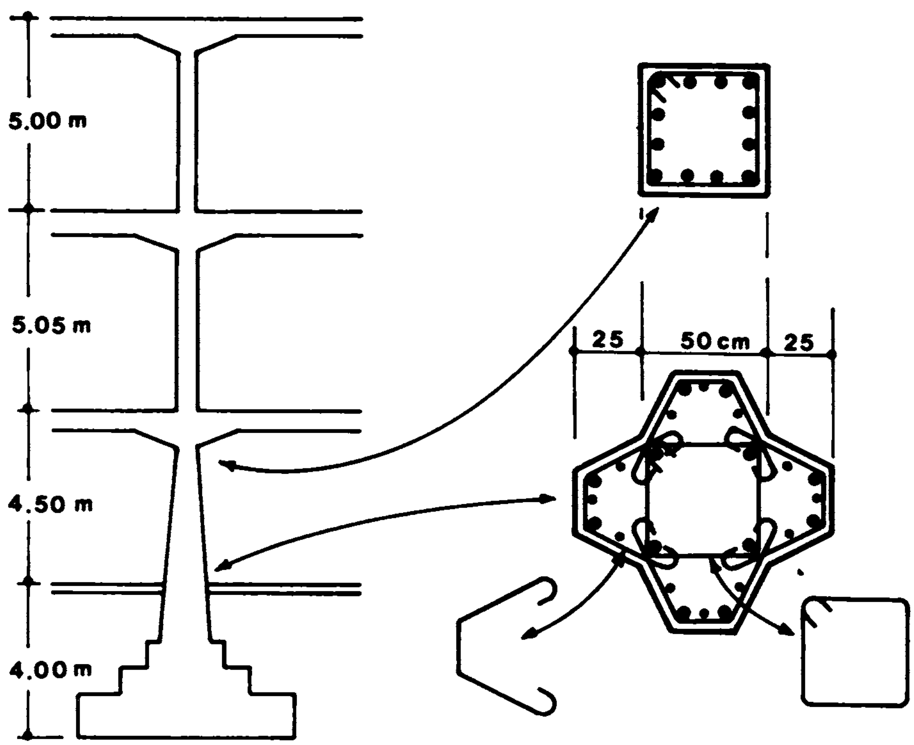

Figure 26 Computing center, typical column and slabs.

slabs top and bottom and 20-cm-wide ribs spaced 1.2 m center to center in both directions. The floor and roof slabs were designed as T-beams in both directions. Column capitals dropped 40 cm below the overhead floor or roof slab at each column.

Typical column cross-sections were 40 x 40 cm in the top story and 50 x 50 cm in the middle story. In the bottom story they tapered from 50-cm square at the top to a 1 m x 1 m fluted shape at floor level. The column in the center of the building was larger than the exterior columns. Each column was supported by a spread footing, typically 5.6-m square at the bottom.

The columns were reinforced in an unusual manner. A typical ground-story column had twelve 25-mm round bars extending the full height, in addition to twelve 20-mm round bars that extended from the base up to about two-thirds of the story height. Four of the twelve full-height bars were enclosed in square ties all the way; the remaining bars were outside the square ties except at the very top of the story, and were restrained by hairpin bars serving as auxiliary ties. Figure 26 shows the reinforcing scheme. All ties were 8-mm round bars. Four hairpin bars and one square tie were used in sets to restrain the vertical steel. Tie sets were spaced 15 cm apart up to the cutoff height of the twelve 20-mm bars, about two-thirds of the story height, and 20 cm apart above that height.

Figure 27 shows the failure of one of the ground-story columns. Some of the buckled vertical bars can be seen outside the visible

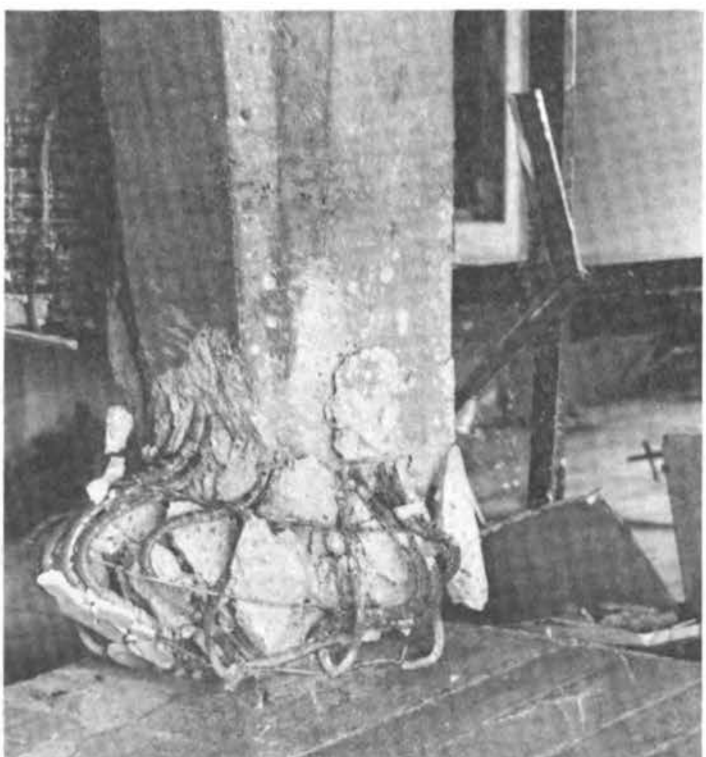

Figure 27 Computing center, column failure in ground story.

ties. Every one of the ground-story columns failed; the one shown in Figure 27 is the least damaged of the lot. All except the central column failed at the top in the manner of the column show in Figure 27, but worse. The central column may have failed elsewhere; it was squashed nearly flat and could not be examined.

Columns in the upper stories were square and prismatic. They too had failed, nearly all of them at the top. It seems likely that the ground-story columns failed first and the upper-level columns failed when the building fell.

The main building was structurally separated from the service towers, and nearly all of the lateral stiffness of the main building derived from the columns. If only column stiffness is considered, the column bases are treated as fixed, and the floors are taken to be rigid, then the three modes of vibration and their periods are as shown in Figure 28. Thus the fundamental mode period for this idealization is in the range of very strong spectral acceleration for both horizontal components of the ground motion recorded in Bucharest. Any flexibility of the floor system or column footings, or any structural damage, would lengthen the period and put it in the range of even greater spectral acceleration. The exterior walls were of virtually no benefit because they were isolated from the ground-story columns and contained a band of steel window sash in each story, which separated them structurally from the story above.

The building was constructed with B200 concrete with a cube strength of 200 kg/cm^2 (2800 psi) and PC52 steel with an ultimate strength of 5200 kg/cm^2 (74 ksi). The Romanian building code is

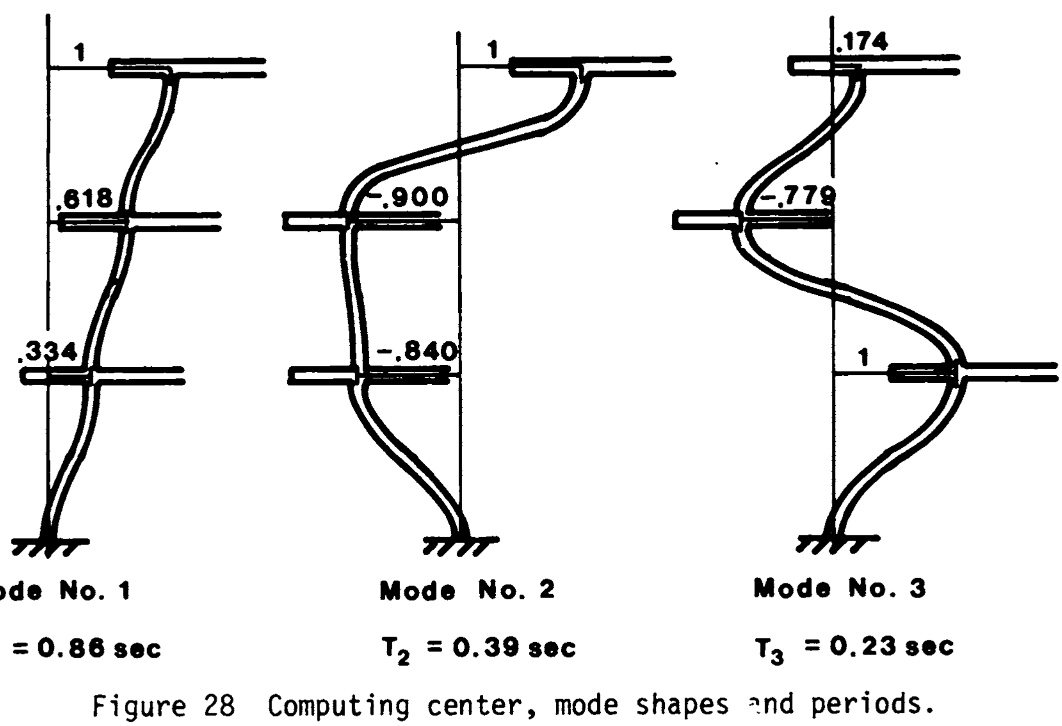

Figure 28 Computing center, mode shapes and periods.

subject to a different interpretation according to whether this was a monumental building or an ordinary building, and whether it should be classed as a reinforced-concrete frame structure or an inverted pendulum. The base shear coefficient could be as low as 0.025 or as great as 0.075, depending on the interpretation. We were told that the design was in fact for a base shear coefficient of 0.06. If the lateral force were resisted by the columns alone, the concrete and steel stresses for this base shear would be within code limits. Response to the ground motion recorded in Bucharest is quite another matter. The fundamental mode alone, calculated on the basis of elastic behavior from the response spectrum for 5 percent of critical damping, would produce theoretical stresses of nearly four times the cube strength of the concrete and three times the ultimate strength of the steel.

In retrospect it appears that catastrophic behavior might have been prevented if the column bars had been continued for the full height of the columns, if they had been enclosed within closed ties instead of hairpin bars, and if shear-wall strength had been mobilized to assist the columns in resisting lateral movement, thus providing a second line of defense. These observations are, of course, made with the advantage of hindsight.

EARTHQUAKE-RESISTANT DESIGN CRITERIA

Largely because of the 1940 earthquake, the professional engineering community of Bucharest has been acutely conscious of the earthquake risk. A section of the building code has been devoted to earthquake-resistant design since 1952. The 1970 code, which prevailed at the time of the 1977 earthquake, is quite sophisticated. It is given in Reference 9 in Romanian, in Reference 10 in English, and is summarized and compared with other European codes in Reference 11 in English.

For low buildings the code considers the fundamental mode only, whereas for tall buildings, tall chimneys, towers, etc., three modes are considered and their effects are combined in a root-sum-square process.

The lateral force at level k for mode number r is stipulated to be

$$S_{kr} = k_s \beta_r \psi \eta_{kr} Q_k$$

where Q_k is the total gravity load at level k, including dead load plus long-term live load plus 80 percent of the short-term live load.

The seismic coefficient k_s depends on the seismic zone and on the importance of the building and occupancy. A zone map, Figure 29, divides Romania into four seismic zones numbered VI, VII, VIII, and IX, corresponding to degrees of intensity in the MSK seismic intensity scale. Bucharest is in zone VII. The coefficient k_s is given in Table 5.

The factor β_r for mode number r depends on the period T_r and the soil conditions. For medium soil β_r is given by the formula

$$\beta_r = 0.8/T_r, \text{ with limits } 0.6 \leq \beta_r \leq 2.0$$

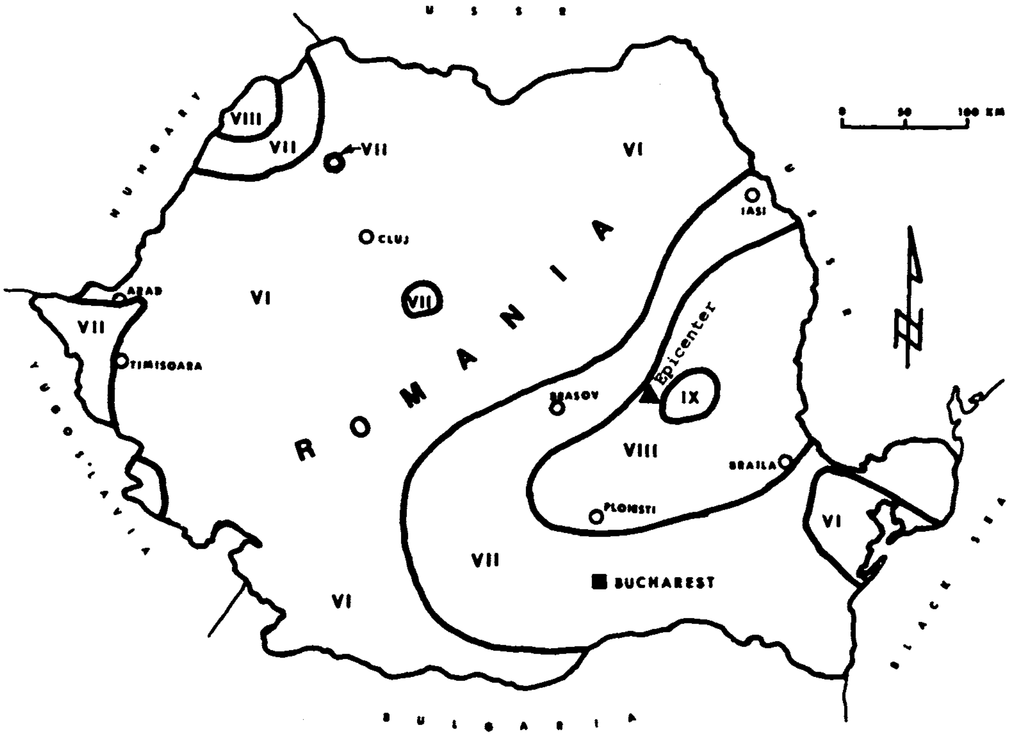

Figure 29 Seismic-zone map of Romania, 1970 code.

Table 5 Seismic Coefficient k_s, 1970 Romanian Building Code

Building Class	Description	Seismic zone VI	VII	VIII	IX
I	Monumental and important buildings	0.03	0.05	0.08	0.12
II	Buildings not in classes I, III, IV	--	0.03	0.05	0.08
III	One-story industrial, administrative, commercial, and communal office buildings, one-story utility buildings of local importance, buildings housing thoroughbred animals	--	0.03	0.05	0.08
IV	Buildings of low importance	--	--	--	0.03

For rock and stiff-soil sites, β_r is modified by a factor of 0.8, and for soft-soil sites by a factor of 1.5, subject to an upper limit $\beta_r \leq 2.5$ (Fig. 30).

The factor ψ is a function of the type of structure and the material of which it is built. The range of values is from $\psi = 1$ for reinforced-concrete frame structures at one extreme to $\psi = 2$ for elevated tanks at the other.

The distribution factor η_{kr} accounts for both the mode shape and the modal participation factor. It is computed from the modal properties

$$\eta_{kr} = \frac{u_{kr} \Sigma Q_k u_{kr}}{Q_k u_{kr}^2}$$

in which u_{kr} is the amplitude at level k of the r-th mode shape. The manner of normalizing the mode is immaterial.

A minimum first-mode base shear is provided, namely

$$\sum_k S_{k1} \geq 0.02 \sum_k Q_k$$

The design force S_{kr} is related to the yield capacity of the structure.

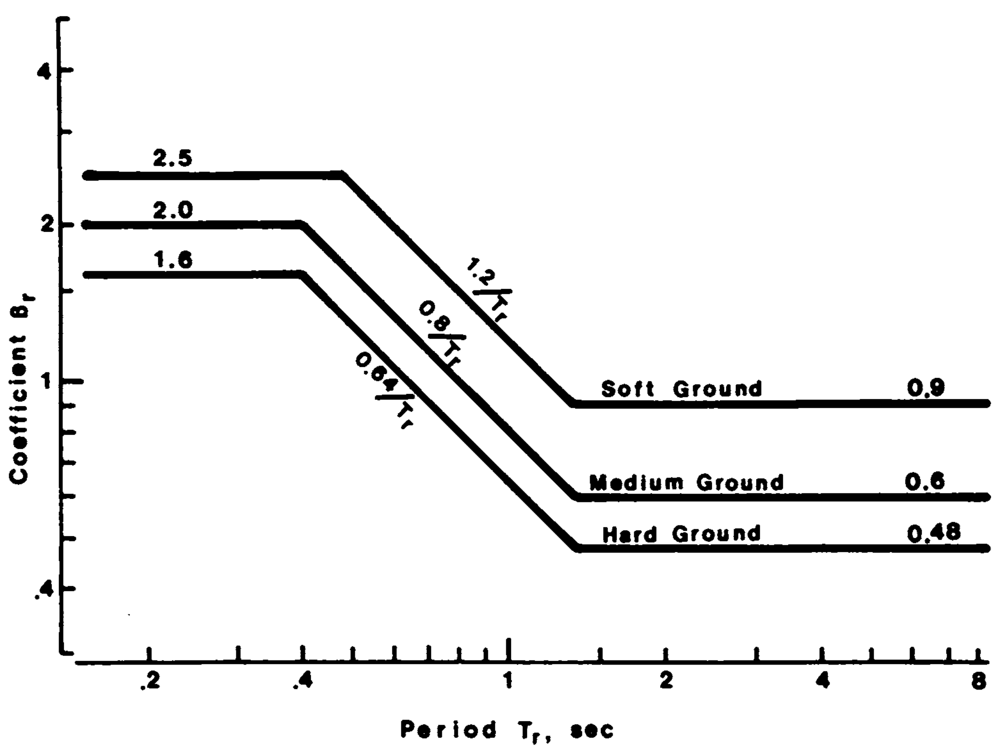

Figure 30 Coefficient β_r, 1970 Romanian code.

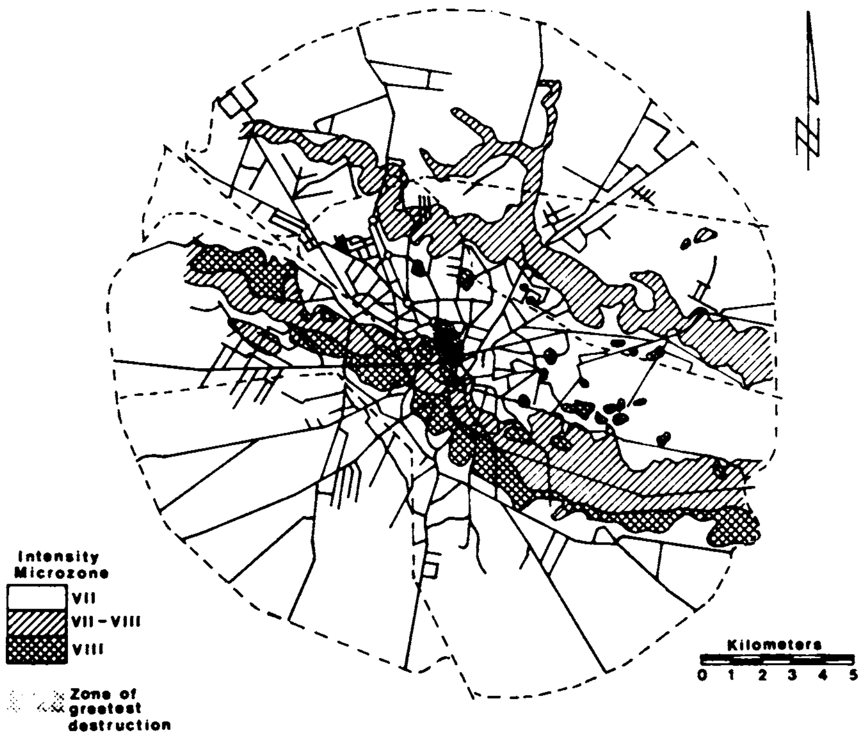

Figure 31 Microzone map of Bucharest.

The city of Bucharest was microzoned for seismic risk in 1973 as part of a UNESCO project, "Survey of Seismicity of the Balkan Region" (Ref 12), more commonly known as the Balkan Project. The microzone map is shown as Figure 31. Three levels of risk are identified for the city, corresponding to intensities VII, VII-VIII, and VIII. Generally the microzones indicating the greatest risk follow the course of the Dimbovita river southeastward through the city and are also found in isolated pockets away from the river. The intermediate risk zones form a broader band along the Dimbovita and also along a chain of lakes extending roughly parallel to the Dimbovita farther to the north. The region of greatest destruction, shown in Figure 31, lies mainly in the microzone designated as least vulnerable.

Typical bearing pressures permitted for foundations range from 2.0 to 3.5 kg/cm^2 (4100 to 7200 psf). Loess is encountered in about 10 percent of the sites in Bucharest, in which case the allowable bearing pressure is reduced as low as 1.0 kg/cm^2 (2000 psf).

The building code recognizes concretes from B100 to B600, whose cube compressive strengths are from 100 to 600 kg/cm^2(1400 to 8500 psi). Most buildings use B200 to B300 concrete, with a tendency for newer frame buildings to have higher design strengths. B400 is used for prestressed construction. Reinforcing steel ranges from 3800 to 6000 kg/cm^2 ultimate strength (54 to 85 ksi). Currently the maximum bar diameter in use is 32 mm. Plain bars still constitute about 40 percent of the steel used. Typical splices for deformed bars are 30 diameters for tension and 20 diameters for compression splices.

1977 BUILDING CODE CHANGES

Changes to the Romanian seismic building code were considered following the March 1977 disaster, as described in Reference 13. The nature of the code was preserved, but changes were made in the coefficients k_s, ψ, β_r, and the zoning. A new class of buildings was added at the top of the category list, buildings of extreme importance, for which the coefficient k_s must be established by special investigation. For other building categories the coefficient k_s is five times the 1970 value, and the coefficient ψ is 1/5 of the 1970 value. Although this may appear to be a cosmetic change, it makes the coefficient k_s correspond more closely to spectral acceleration expressed as a fraction of gravity, and it makes ψ correspond to a ductility factor or, more precisely, to the inverse of the ductility factor in United States parlance.

The substantive code change is in the coefficient β_r and the seismic zoning. The new zone map not only identifies zones of earthquake intensity but also separates the country into two macrozones. One of these, roughly the southeast half of the country, including Bucharest, is designated as subject to deep-focus earthquakes originating in the Vrancea region, and the other, roughly the northwest half of the country, as vulnerable to shallow-focus earthquakes. The coefficient β_r is a function of the building period, site conditions, and the macrozone, as follows:

Shallow-focus macrozone

Hard ground $\beta_r = 1/T_r$, with limits $0.8 \leq \beta_r \leq 3.0$
Soft ground $\beta_r = 1.5/T_r$, with limits $1.2 \leq \beta_r \leq 3.0$

Deep-focus macrozone

Hard ground $\beta_r = 3.6/T_r$, with limit $\beta_r \leq 2.0$
Soft ground $\beta_r = 4.5/T_r$, with limit $\beta_r \leq 2.0$

These values of β_r are plotted in Figure 32, which may be compared with the 1970 β_r plots in Figure 30.

A CODE COMPARISON

Comparison of Romanian and United States seismic building codes is difficult because of their many differences. Some notion of the comparison might be gained by considering a specific case. Let us take, for example, a five-story apartment building, reinforced-concrete frame, with uniform story heights and story

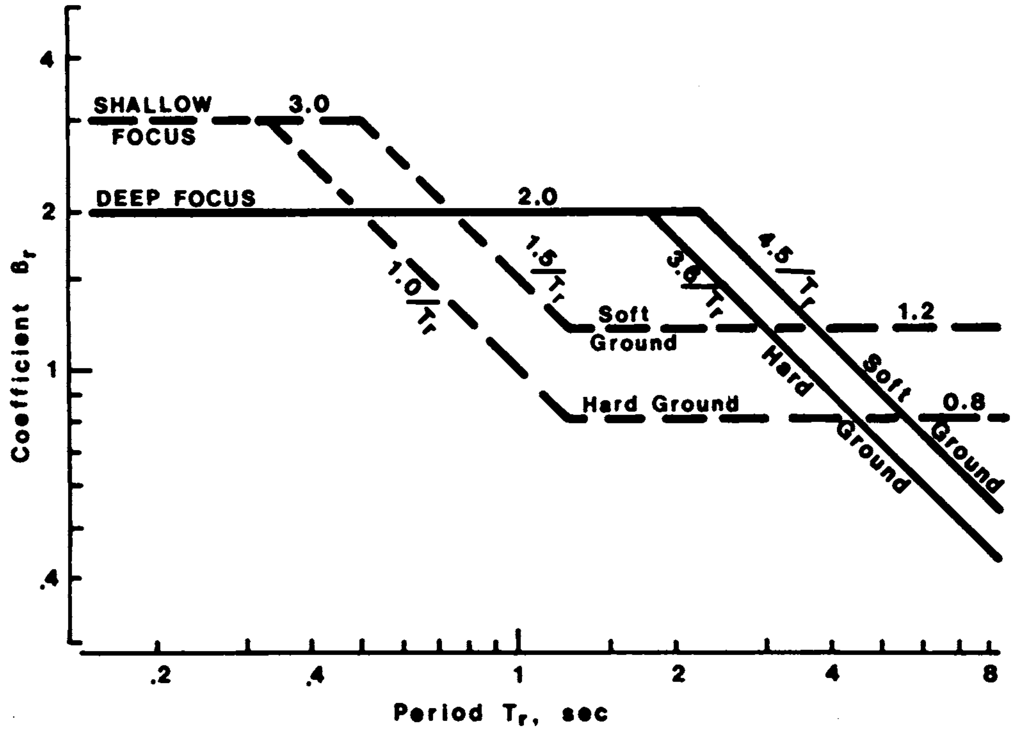

Figure 32 Coefficient β_r, 1977 Romanian code.

weights, on medium soil, and compare the 1970 Bucharest requirements with those of Zone 2 of the current Uniform Building Code. In each case, this is the second lowest of four seismic zones. Further, let us assume that the first mode shape is linear (an inverted triangle).

The Romanian code would require considering only the first mode for a five-story apartment building. In Bucharest the seismic forces for each level would be

$S_{k1} = k_s \beta_1 \psi \eta_{k1} Q_k$

k_s = 0.03 for a Class II building in Zone VII

β_1 = $0.08/T_1$ subject to the limits $0.6 \leq \beta_1 \leq 2.0$

ψ = 1 for a reinforced-concrete frame

$\eta_{k1} = u_{k1} \Sigma Q_k u_{k1} / \Sigma Q_k u_{k1}^2$

Q = dead load + 80% live load at level k

The base shear is

$$S = \Sigma S_{k1}, \text{ subject to the limit } s \geq 0.02 \, \Sigma Q_k$$

Combining all of these, we get a base shear

$$S = \frac{0.0196}{T_1}\Sigma Q_k, \text{ subject to the limits } 0.02\Sigma Q_k \le S \le 0.0393\Sigma Q_k$$

The Uniform Building Code prescribes a base shear

$$V = Z\ I\ K\ C\ S\ W$$

where

$Z = 3/8$ for Zone 2
$I = 1$ for apartment building occupancy
$K = 1$ for ordinary reinforced-concrete frame
$C = 1/(15\sqrt{T})$ subject to the limit $C \le 0.12$
$S = 1$ to 1.5, depending on building-to-site period ratio; assume $S = 1$
W = total dead load

Thus the base shear is

$$V = \frac{0.025}{\sqrt{T}} W \text{ subject to the limit } V \le 0.045W$$

Thus for this case the total lateral loads are not greatly different, 0.0196 x (DL + 80% LL)/T for the Romanian code and 0.025 x DL/$\sqrt{T}$ for the Uniform Building Code. Cutoff levels are 0.0393 x (DL + 80% LL) for the Romanian code and 0.045 x DL for the Uniform Building Code.

SUMMARY

The Romanian earthquake of March 4, 1977, had a focus of intermediate depth in a seismically active region in the Carpathian Mountains. The intensity pattern was strongly biased toward the south and southwest, with ground motion more destructive in Bucharest 170 km SSW of the epicenter than in villages just a few kilometers from the epicenter.

The strong motion was recorded in Bucharest and in Nis, Yugoslavia, with epicentral distances 170 km and 1200 km. The Bucharest response spectrum reaches its peaks at relatively long periods, around 2 sec. Its spectrum intensity exceeds that of the 1940 El Centro earthquake, which has long served as something of a benchmark for strong ground motion.

Destruction was greatest in Bucharest, where 35 buildings collapsed. All but three of the collapses and most other severe damage occurred to buildings that had been built before the adoption of seismic building regulations and that had survived a strong earthquake in 1940. Of recent buildings, constructed to comply with seismic regulations, two collapsed and one partly collapsed.

The building collapse of greatest significance was a Computing Center, a massive 3-story reinforced-concrete structure of relatively long period. The walls were constructed so that they contributed little to the lateral strength and stiffness of the building. Moreover, the long building period was near the period of peak spectral response. In retrospect, it appears that some unusual column reinforcement details and the reliance on columns to resist the entire lateral force, unaided by shear walls, were fundamental weaknesses of the building. These practices did not violate the Romanian building code, and the reliance on columns to provide the sole resistance to lateral forces would also be permitted by American building codes.

Utilities and railroad and highway systems were largely undisturbed by the earthquake.

Bucharest had been microzoned as part of a UNESCO Balkan Project, with microzones denoting three levels of risk. The worst destruction occurred in the lowest-risk microzone.

Further observations on the Romanian earthquake of May 4, 1977, may be found in References 14, 15, and 16.

REFERENCES

1. "Lessons from the Romania, March 4, 1977 Earthquake," by H. Sandi, G. Serbanescu, and T. Zorapapel, Proceedings, VI European Conference on Earthquake Engineering, Dubrovnik, Yugoslavia, September 1978.

2. "Earthquake in Romania, March 4, 1977," Earthquake Engineering Research Institute Newsletter, Vol. 11, No. 3B, Los Angeles, California, May 1977.

3. "The Vrancea Earthquake of March 4, 1977--A Multiple Event and Its Seismotectonic Implications," by T. Iosif and S. Iosif, EP-1-1977, Institutal Central de Fizica, 1977.

4. "The Romanian Earthquake of March 4, 1977: I. Rupture Process Inferred from Fault-Plane Solution and Multiple-Event Analysis," by G. Muller, K. P. Bonjer, H. Stockl, and D. Enescu, Journal of Geophysics, Vol. 44, pp. 203-218, 1978.

5. "Analysis of the Bucharest Strong Ground Motion Record for the March 4, 1977, Romanian Earthquake," by S. Hartzell, Bulletin of the Seismological Society of America, Vol. 69, pp. 513-530, 1979.

6. "Seismic Engineering Data Report, Romanian and Greek Records," by A. G. Brady, C. Rojahn, V. Perez, P. G. Carydis, and J. G. Sbokos, U. S. Geological Survey Open-File Report 78-1022, U. S. Geological Survey, Menlo Park, California, September 1978.

7. "Analysis of Strong Motion Records of the Vrancea-Romania Earthquake of March 4, 1977, Obtained in Nis-Yugoslavia," Publication No. 55, Institute of Earthquake Engineering and Engineering Seismology, University Kiril and Metodij, Skopje, Yugoslavia, May 1977.

8. "Spectrum Intensities of Strong-Motion Earthquakes," by G. W. Housner, in Proceedings of the Symposium on Earthquakes and Blast Effects on Structures, Earthquake Engineering Research Institute, June 1952, pp. 20-36.

9. "Normativ Pentru Proiectarea Constructilor Civile si Industriale din Regiuni Seismice," pp. 13-70, Bucharest, 1970.

10. "Earthquake Regulations, Rumanian People's Republic," in Earthquake Resistant Regulations, A World List, 1973, pp. 360-378, International Association for Earthquake Engineering, Tokyo, April 1973.

11. "Design, Construction and Control of Buildings to be Erected in Seismic Areas: Introductory Report on the Situation in Europe," by H. Sandi and G. Serbanescu, in Proceedings of the Seminar on Construction in Seismic Regions and in Regions with Difficult Ground Conditions, Economic Commission for Europe, Committee on Housing, Building and Planning, UNESCO, Bucharest, 14-18 October, 1974.

12. "Seismic Micro-Zoning of the Territory of S. R. of Romania, Bucuresti Town," Institutul Roman de Standardizare, STAS 8879/6-73, Bucharest, 1973.

13. "Normativ Pentru Proiectarea Constructilor Civile si Industriale din Regiuni Seismice," pp. 13-77, Institutal de Cercetari in Constructii, Bucharest, May 1977.

14. "Observations on the Behavior of Buildings in the Romanian Earthquake of March 4, 1977," by George Fattal, Emil Simiu, and Charles Culver, NBS Special Publication 490, National Bureau of Standards, Washington, September 1977.

15. "Long Period Effects in the Romanian Earthquake of March 1977," by N. N. Ambraseys, Nature, Vol. 268, pp. 324-325, 1977.

16. "The Vrancea Earthquake of March 4, 1977, and the Seismic Microzonation of Bucharest," by N. Mandrescu, EP-3-1978, Institutal Central de Fizica, 1978.

APPENDIX

National Research Council Reports of Post-Disaster Investigations 1964-1978

Copies Available From Sources Given in Footnotes a, b, and c

Earthquakes

[a]The Great Alaska Earthquake of 1964:

Biology, 0-309-01604-5/1971, 287 pp ($21.95)
Engineering, 0-309-01606-1/1973, 1198 pp ($37.50)
Geology, 0-309-01601-0/1971, 834 pp ($35.00)
Human Ecology, 0-309-01607-X/1970, 510 pp ($29.50)
Hydrology, 0-309-01603-7/1968, 446 pp ($25.00)
Oceanography and Coastal Engineering, 0-309-01605-3/1972, 556 pp ($32.50)
Seismology and Geodesy, 0-309-01602-9/1972, 598 pp ($25.00)
Summary and Recommendations, 0-309-01608-8/1973, 291 pp ($16.00)

[c]Engineering Report on the Caracas Earthquake of 29 July 1967, by M. A. Sozen, P. C. Jennings, N. M. Newmark, 233 pp, (1968)

[c]The Western Sicily Earthquake of 1968, by J. Eugene Haas and Robert S, Ayre, 70 pp, (1969)

[b]The Gediz, Turkey, Earthquake of 1970, by Joseph Penzien and Robert D, Hanson, 88 pp, (1970)

[c]The San Fernando Earthquake of February 9, 1971, by a Joint Panel on San Fernando Earthquake, Clarence Allen, Chairman, 31 pp, (March 22, 1971)

[b]Destructive Earthquakes in Burdur and Bingol, Turkey, May 1971, by W. O. Keightley, 89 pp, (1975)

[c]The Engineering Aspects of the QIR Earthquake of April 10, 1972 in Southern Iran, by R. Razani and K. L. Lee, 160 pp, (1973)

[c]Engineering Report on the Managua Earthquake of 23 December 1972, by M. A. Sozen and R. B. Mathiesen, 122 pp, (1975)

[c]The Honomu, Hawaii, Earthquake, by N. Nielson, A. Furumoto, W. Lum, and B. Morril, 95 pp, (1977)

[b]Engineering Report on the Muradiye-Caldiran, Turkey, Earthquake of 24 November 1976, by P. Gulkan, A. Gurpinar, M. Celebi, E. Arpat, and S. Gencoglu, 67 pp, (1978)

Flood

[b]Flood of July 1976 in Big Thompson Canyon, Colorado, by D. Simons, J. Nelson, E. Reiter and R. Barkau, 96 pp, (1978)

Dam Failures

[b]Failure of Dam No. 3 on the Middle Fork of Buffalo Creek Near Saunders, West Virginia, on February 26, 1972, by R. Seals, W. Marr, Jr., and T. W. Lambe, 33 pp, (1972)

[b]Reconnaissance Report on the Failure of Kelly Barnes Lake Dam, Toccoa Falls, Georgia, by G. Sowers, 22 pp, (1978)

Landslide

[b]Landslide of April 25, 1974, on the Mantaro River, Peru, by L. Lee and J. Duncan, 79 pp, (1975)

Windstorms

[c]Lubbock Storm of May 11, 1970, by J. Neils Thompson, Ernest W. Kiesling, Joseph L. Goldman, Kishor C. Mehta, John Wittman, Jr., and Franklin B. Johnson, 81 pp, (1970)

[c]Engineering Aspects of the Tornadoes of April 3-4, 1974, by K. Mehta, J. Minor, J. MacDonald, B. Manning, J. Abernathy, and U. Koehler, 124 pp, (1975)

---

[a]Available from Office of Publications, National Academy of Sciences, 2101 Constitution Avenue, N.W., Washington, D.C. 20418

[b]Available from Committee on Natural Disasters, National Academy of Sciences, 2101 Constitution Avenue, N.W., Washington, D.C. 20418

[c]Available from National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22161