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MONTANA STATE COLLEGE
School of Architecture

Earthquake-Resistant Construction

Architecture 447
December 1959

Ronald R. Goldberg

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PREFACE

Earthquakes and their effects are at first examination rather mysterious. It is hoped that the following information will provide at least a sketchy picture of the nature of earthquakes and how structures react to them.

Credit for arousing my interest in the subject and aiding in other ways is due Hugo Eck. Stephen W. Nile, Charles C. Bradley, Nicholas Hellburn, William J. McMannis, and Verne Dusenberry have also been helpful in various ways. My friend and classmate, John W. Simpson, was a most excellent partner through the Hebgen Lake investigations and contributed much to the beginning phase of the research. Regretfully, many other helpful people must remain unmentioned. This paper would have been impossible without their aid, however.

R. R. G.

INTRODUCTION

Civilized man has been relatively successful in understanding, predicting, and safeguarding himself from most of the dangerous phenomena of nature. For example, the average Montanan has an elementary understanding of why a winter storm occurs, is usually informed of its coming, and generally is prepared to meet the resulting dangerous conditions.

Man has not been as successful in understanding or predicting the natural phenomenon known as earthquake. His efforts to safeguard his structures - and thus himself - vary from poor or nonexistent to overdone and even wasteful.

A better common level of understanding would help the picture and it is toward this end that this paper is written.

I. ORIGIN AND CAUSES OF EARTHQUAKES

An earthquake may be defined as a vibration or oscillation caused by a transient disturbance of the elastic equilibrium of the rock masses at or beneath the surface of the earth.¹

Earthquake origin is related to chemistry, physics, and especially strength of materials under conditions of which there is no direct knowledge.²

In spite of all speculations from the time when man first experienced an earthquake to the present, there has not been great advance in positive knowledge of the origin of earthquakes. Much more is known about the immediate cause of the earthquake than about the true origin - otherwise called ultimate cause - that is, the forces which lead up to the event. Most of the speculations and untested theories relate to ultimate cause, since the forces which produce a condition within the earth's crust are not known.³

There are two accepted immediate causes:

a. The great majority of the world's earthquakes appear to have as immediate cause slipping between two rock surfaces; this assumes that there is a fault plane at considerable depths.

For most earthquakes of this type there is little or no slipping at the surface and the fault planes along which motion occurs may be far below the surface.⁴

Earthquakes of this kind are called tectonic. The term refers to things pertaining to the architecture of the earth, that is, the development of its structures.⁵

¹H. H. Heck, Earthquakes (Princeton, N.J. : Princeton University Press, 1936), p. 5

²J. B. Macelwane, Theoretical Seismology (New York: John Wiley and Sons, 1952), p.72

³Heck 114

⁴Heck 129

⁵L. Don Leet, Practical Seismology and Seismic Prospecting (New York: McGraw Hill Book Co. Inc. 1948), p. 58

b. The elastic rebound theory which gives a reasonably satisfactory explanation of the release of stress which produces earthquake vibration; it is as follows: Rock will rupture when it is submitted to elastic strains greater than it can endure. Such strains may be the result of sudden explosions but ordinarily they are due to slow displacement of the earth's crust. This displacement sets up stresses between adjacent portions of the crust that grow slowly until the point of rupture is reached. The strained rock rebounds under its own elastic stresses until the strain is wholly or partially relieved.⁶

The ultimate cause lies in the production of stress differences in adjacent regions. There are five theories:

a. The volcanic theory which pictures the earth with a liquid molten interior and a thin crust so that the interior high temperatures could readily account for volcanoes and such disturbances as earthquakes.

b. Shrinkage of earth's crust which attributes the existence of mountain chains and ocean depths to shrinkage of the earth's interior with loss of heat and consequent wrinkling of the surface, the changes being sufficient to account for earthquakes.

c. Erosion and deposition

d. Mountain building and ocean trough formation, which seems to be the most probable ultimate cause.

e. The hypothesis of radioactivity of certain rocks due to the presence of radium-bearing minerals; the heat continuously given off by the radium cannot readily escape from within the crust.⁷

Efforts have been made to predict earthquakes by studying possible "trigger forces". Among such forces are the tidal pull of the sun and moon, heavy rains, changes in air pressure, melting of polar ice, and sun spots.⁸

⁶Heck 130

⁷Heck 137

⁸C. R. Anderson and M. P. Martinson, Helena Earthquakes (Publisher unlisted: 1936), p. 61

The research of Japanese seismologist Ishimoto and others indicate that certain earthquakes have been preceded by a definite pattern of ground tilts.⁹ Tiltmeters have been in use in California since 1935 but knowledge of the subject is still very imperfect.¹⁰

In brief, man cannot with certainty explain or predict earthquakes.

⁹D. L. Floras, Fundamentals of Aseismic Construction (New York: By the author, 1954), p. 24

¹⁰U. S. Department of Commerce- Coast and Geodetic Survey, Earthquake Investigations in California, (Washington: 1936), p. 23

II. HISTORY OF EARTHQUAKES

Although the world is constantly shaken by tiny earthquakes called microtremors, which only sensitive instruments can detect, noticable earthquakes occur somewhere on the globe approximately once every six minutes.¹¹ Potentially dangerous earthquakes strike only at the rate of two each week.¹²

Throughout the world there have been many severe earthquakes in modern times. In 1755 Lisbon, Portugal, was shaken by a tremor that was felt as far away as North America and Scandinavia. In the quake and tidal wave that followed it, about 40,000 people were killed. In 1783, 1881, 1886, and 1897, similar disasters occurred in other areas. Four hundred fifty-two persons lost their lives in 1906 during the San Francisco disaster. In a 1907 quake, Kingston, Jamaica, was completely destroyed. In 1908 about 80,000 persons were killed at Messina and Reggio. Thirty thousand were killed by quakes in Italy in 1915. In 1917 San Salvador was nearly destroyed and Guatamala was laid in ruins. In 1920 several hundred thousand persons died as the result of a quake in China. In 1923, 99,331 were killed in Japan and the same year about 100,000 perished at Kannon, China. In 1930 the death list as a result of quakes at Naples was reported at 1,404 and in Persia 20,000 were reported dead.¹³

The great quake in Japan that occurred at noon September 1, 1923 is one of the worst of recent times. Tokyo, Gotohama, Nagoya, and several smaller cities were completely devastated. Shock, fire, and sea waves killed more than 99,000 people, left 45,000 missing and over 100,000 injured.

¹¹ Macelwane 14

¹² A. Zeevaert, "Mexico City's Earthquake-Proof Skyscraper," Architectural Record, (1957, Oct.), p. 40

¹³ Anderson 71

Another severe quake that caused far greater topographical changes than other earthquakes that have resulted in great loss of life, was in 1811 and struck below St. Louis, Missouri, at New Madrid.¹⁴

¹⁴Anderson 72

III. EARTHQUAKES IN MONTANA

Accounts of tremors in Montana begin with those by the Lewis and Clark Expedition and show that quakes have not been uncommon since that time.¹⁵ By studying the clearer accounts it was possible to construct the following table.

TABLE I
NOTEWORTHY MONTANA EARTHQUAKES, 1869-1925, INCLUSIVE

Year	Approximate Epicenter	Probable Intensity
1869	Helena.....	Mercalli IV
1872	Deer Lodge, Helena.....	" V
1879	Dillon.....	" V
1897	Sheridan, Twin Bridges.....	" IV
1903	Helena.....	" III
1904	Pony, Norris.....	" IV
1908	Virginia City.....	" IV-V
1925	Three Forks, Manhattan.....	" VIII-IX

Helena suffered a series of shocks in 1935. The greater ones were Mercalli¹⁶ XIII-IX and several Mercalli V. Although these tremors were not considered major quakes, the damage is still very evident today. It was estimated that 14.2% of all Helena buildings suffered damage between 50% and 100%. The new (at that time) high school building was, among others, a total loss.¹⁷

Three Forks was struck by an earthquake of intensity IX in 1947. The most recent tremor centered near Hebgen Lake with intensity VIII. This area has also suffered a number of smaller quakes, the largest in 1950 with intensity VI.¹⁸

¹⁵ Anderson 71

¹⁶ The Modified Mercalli Scale of 1931 will be found in Appendix I.

¹⁷ Anderson 88

quakes, the largest of intensity VI.¹⁸

¹⁸U. S. Department of Commerce- Coast and Geodetic Survey,
Preliminary Report, Hebgen Lake, Montana Earthquakes, (Washington:
August, 1959), p.2

IV. HEBGEN LAKE EARTHQUAKES OF NOVEMBER 1959

On August 17, 1959, the first major earthquake of the region since November 23, 1947, occurred near the Montana, Wyoming border at 44 degrees 50 minutes north, 111 degrees 05 minutes west. The shock had a magnitude of 7.1 on the Richter Scale and was felt over an area of 550,000 square miles which extended from Utah and Nevada to British Columbia and from the Pacific Coast to western North Dakota.¹⁹

First-hand investigations of structures in that area indicate at least the complex and confusing way in which earthquakes strike. Two reinforced concrete bridges, approximately four miles from the epicenter of the major shock and separated by perhaps 600 yards, illustrate this. The larger bridge did not appear to be damaged while the smaller displayed considerable damage as shown in Fig. 1-3. Although several massive chimneys in West Yellowstone - eight or more miles from the epicenter - were severely damaged, (see Fig. 4) many chimneys very close to the epicenter were left in place. While small window panes in West Yellowstone were shattered the large panes in Figs. 6-9 came through intact. Small, top-heavy structures in West Yellowstone seemed not to be damaged (Fig. 5) even though chimneys, plaster, and older brick walls yielded in Bozeman, 60 miles distant.

Figures 10-20 show a few more examples of damage caused by this earthquake. It is interesting to note that the earth fill in Hebgen Dam settled nearly four feet despite efforts during construction to insure compaction.

Had the quake struck a more populated area, some definite patterns might have been discerned.

¹⁹Geodetic Survey, Hebgen Lake..., 1

BRIDGE NEAR HEBGEN LAKE



FIGURE 1



FIGURE 2



FIGURE 3



FIGURE 4
CHIMNEY IN WEST YELLOWSTONE



FIGURE 5
UNDAMAGED STRUCTURE IN WEST YELLOWSTONE



FIGURE 6
CULLIGAN RANCH

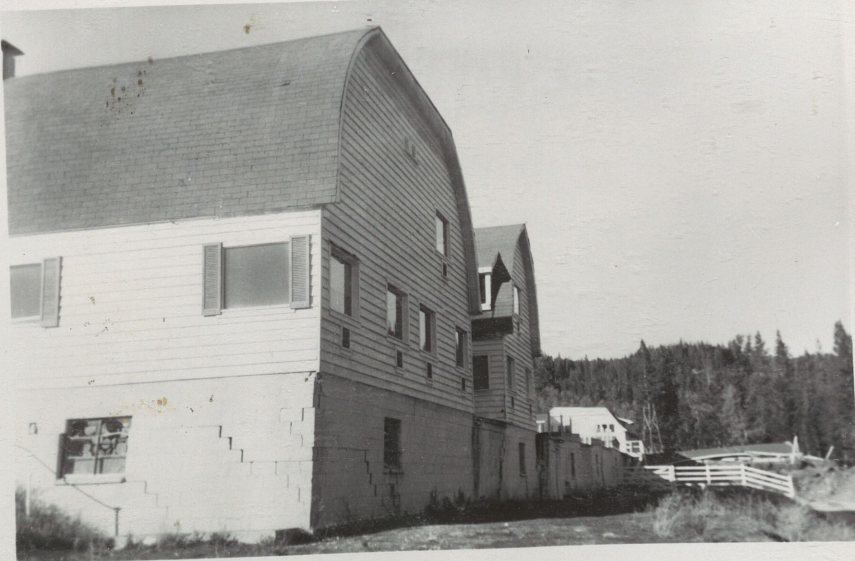


FIGURE 7



FIGURE 8



FIGURE 9



FIGURE 10



FIGURE 11

SLIDES ALONG HEBGEN LAKE





FIGURE 12



FIGURE 13



FIGURE 15



FIGURE 16

CABIN ON HEBGEN LAKE



FIGURE 17
SPILLWAY AT HEBGEN DAM



FIGURE 18



FIGURE 19
TYPICAL DAMAGE



FIGURE 20
FAULT

FIGURE 20
LONG FAULT

V. GROUND MOTION DURING EARTHQUAKES

Since a strong earthquake is a frightening experience at best, human observations seldom yield accurate information concerning ground motions. Modern scientific instruments have a number of frailties but fortunately the ability to panic is not one of these. With the aid of these instruments scientists have been able to "track" an earthquake from birth to death.

Scientists have discovered that the "birth" of an earthquake is a point release of energy somewhere below the surface of the earth. This point is called the focus; the area above it is called the epicenter.

Normal depth of focus is between zero and 10 Km.; intermediate between 10 and 50 Km.; deep 250 to 700 Km.²⁰ The energy released at the focus would be in the range of 1,000,000 Hiroshima-type A-bombs.²¹

This energy is transmitted through the earth by two types of depth waves and a surface or Rayleigh wave. The two depth waves are called P and S waves; the P waves being longitudinal and S waves transverse. These waves travel at the rate of several miles per second; P waves being slightly faster than S waves.

Although the waves are traveling at this tremendous rate, the particles on which they act are displaced in the order of a few inches per second. This idea would be illustrated by dropping a pebble into the water near a toy boat. The amplitude of a particle during a destructive earthquake is seldom greater than:²²

²⁰ Arthur Holmes, Principles of Physical Geology (New York: Thomas Nelson and Sons Ltd. 1947), p. 358

²¹ Zeevaert 249

²² Jacob J. Creskoff, Dynamics of Earthquake Resistant Structures (New York: McGraw Hill Book Co. 1934), p. 137

0.25" in bedrock
 1.00" in dry cohesive soil
 4.00" in soft marsh or fill

Although the intensity of vibration generally decreases inversely with the distance from the focus, intensity on one type of surface outcrop 100 miles distant may be the same as basement rock outcrop 5 miles distant.²³

A 22-fold increase in acceleration is indicated when earthquake vibrations passing through the granitic basement force the most responsive types of surface formations into vibration.²⁴

It is also interesting to note that earthquake waves are refracted and reflected as they pass from one type of material into another. This would account for the complicated movements of particles during an earthquake.

Intensity far below the surface of the earth is not as great as at the surface. Mine workers are often unaware of earthquakes. A foundation located 50' below the surface would only enjoy a 10% reduction, however.²⁵

Engineers and architects are primarily interested in the accelerations produced by the waves, since they can be used to calculate loads. Usually acceleration is measured in terms of MM/sec./sec. The Richter Scale uses the following values to measure earthquake intensity:²⁶

I	10-	MM/sec./sec.	VII	500 MM/sec./sec.
II	10+	"	VIII	1,000 "
III	25-	"	IX	2,500 "
IV	50	"	X	5,000 "
V	100	"	XI	7,500 "
VI	250	"	XII	9,800 "

Horizontal accelerations are sometimes converted to an equivalent static load in terms of the percentage of gravity.

²³Frank Neuman, Earthquake Intensity and Related Ground Motions (Seattle: University of Washington Press, 1954). p. 12

²⁴Neuman 33

²⁵Creskoff 51

²⁶Holmes 350

These figures are usually less than 20% although a maximum of 109% has been indicated.²⁷

²⁷ Kaiser Steel Corporation, "Behavior of Structures In Earthquakes," Modern Designing With Steel (1957, May) p.2

VI. REACTIONS OF STRUCTURES TO EARTHQUAKES

During an earthquake a structure is excited into vibrations and these vibrations produce stresses in the structure. During a shock a theoretically "clean" structure would be deflected into relatively simple shapes called the natural modes of vibration. (see Fig. 21)²⁸

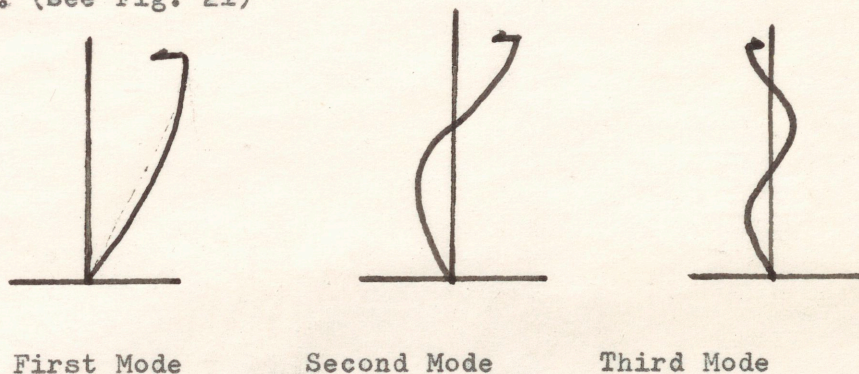


FIGURE 21

NATURAL MODES OF VIBRATION

Although all buildings have natural modes of vibration, the damping effect of the building and the discontinuity of structure complicate the picture somewhat. A more sophisticated analysis is represented by Figure 22.

The damping that structures may have during very strong vibrations is not known, though it is clear that cracking, rubbing, yielding may absorb appreciable energy and thus introduce relatively high damping. In particular, the plastic range deformations of steel members is very effective in absorbing vibrational energy.²⁹

An elastic structure with small damping can be excited

²⁸Kaiser Steel 3

²⁹G.W. Housner, "Limit Design of Structures to Resist Earthquakes," Proceedings of World Conference on Earthquake Engineering (San Francisco: Lithotype Process Co., 1956), Paper 5 p.1

into oscillations so violent as to produce stresses corresponding to lateral loads of 100% gravity or more.³⁰ The more usual figure would be around 10-20%.

³⁰ D. Hudson, J. Alford, "Measured Response of a Structure to Ground Shock," Bulletin of Seismic Society of America (July, 1954) p. 15

VII. NOTES ON EARTHQUAKE-RESISTANT CONSTRUCTION

The main problem in designing earthquake-resistant structures is one of dynamic lateral loads, since vertical elements are designed with a factor of safety usually sufficient to carry added vertical loads.

Many methods of analysis which treat the dynamic problem of structure subject to acceleration and displacement at the base have been developed both for mathematical and experimental solution. Unfortunately, these methods are very complicated and much design must be done on the "rule-of-thumb" static force basis.

The static force method ignores the elastic properties of the building. It assumes the building to be a completely rigid structure in which the acceleration of every point conforms to the acceleration of the ground. The theoretical lateral loads are then equal to the various masses of the building times the maximum ground acceleration.

In practice, the lateral design loads have been established on the basis of experience without any fixed relationship to the expected ground accelerations. It can be seen that such methods are useful for structures in the range of experience but are of doubtful validity for new types. It is fortunate that the static method is most reasonable for low rigid buildings of which many have been built. When tall and perhaps flexible buildings are being planned, the design criteria must be re-evaluated.

Dynamic analysis recognizes that buildings are elastic, not rigid, and that the ground motions are transient and of various durations and directions. It indicates that the stresses and distortions in structures will vary as a function of the natural periods of the structure and the applied motions.³¹

While the architect is most assuredly interested in safety, he is also concerned with the smaller headaches caused by earthquakes. A number of these are somewhat independent of structural design. For example, cracked plaster is so common following an earthquake that it is used as a rough indication of intensity. (see Appendix II) If it were possible to isolate the plaster-bearing partitions from the main structure and make the partition itself very rigid the problem would be solved. This does not seem practical, however.

A great deal of damage occurs when building masses of different size, shape, or direction hammer together due to their differing vibration patterns. The solution to this problem would be to isolate the masses or provide flexible connections such as are shown in Figure 23, and 24. An alternate solution would be to bind adjoining units so strongly that they would be forced to act as one unit. This would be costly but necessary in some cases.

Glass breakage during earthquakes is a problem especially in taller structures fronting on busy streets. Here again, the solution would be to isolate these units from the main structure and make them rigid in themselves.

Stairways must be designed so that they are either strong enough to carry the lateral loads, or again, be able to move as an independent unit.³²

The Japanese have attempted to isolate the structure from the ground by using crushed rock under their foundations. It would seem that this would aid one problem at the expense of another.

Many other problems arise and the designer must rely on judgement and experience to a large degree.

³²Portland Cement Association, Analysis of Small Reinforced Concrete Buildings For Earthquake Forces. (Chicago: by the Author, 1955), p. 28

VIII. EARTHQUAKE CODES

Although scientists and engineers have been able to gather a great amount of information concerning earthquakes, there has been a lag in incorporating it into rational codes. This is due in part to a "watch and see" attitude to see how the present relatively untested codes perform. San Francisco and Los Angeles are exceptions and have developed up-to-date, efficient, and rational codes which are strictly enforced. All parapet walls in Los Angeles have been either removed or reinforced to withstand a 100% Gravity load applied horizontally.³³

Although different areas have adopted their own codes aimed at earthquakes, the Uniform Building Code and the National Building Code are in wide use and contain earthquake provisions.

Helena became the first Montana city to adopt any form of earthquake code shortly after the disastrous quakes there in 1935.³⁴ This code was nearly identical to the Uniform Building Code which has since replaced it. Most of the larger Montana cities have also adopted the Uniform Building Code, although the enforcement of earthquake provisions is questionable.

Japan has been in the process of developing codes for this purpose since 1923. A somewhat different approach has been used there; buildings are limited in height and a greater safety factor is required on marshy ground.³⁵ In some cases structural adequacy has been determined by shaking the building with a machine and investigating the natural vibration characteristics.

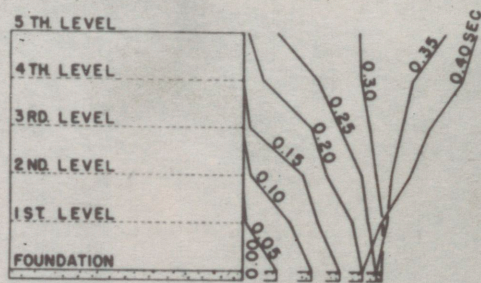
³³Merle A. Ewing, Charles M. Herd, "Criteria For Structural Design In California," Proceedings of the World Conference on Earthquake Engineering (Los Angeles: The Lithotype Process Co., 1956), Paper 5, p. 31.

³⁴Anderson 93

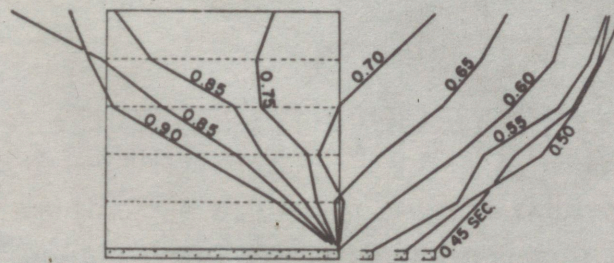
³⁵Yukio Otsuki, "Development of Earthquake Building Construction in Japan," Proceedings of Conference ... p. 16-1

This process has also been used in the United States as a method to determine the extent of damage due to earthquake, fire, or blast. It eliminates expensive removal and replacement of materials necessary to visually check the structure.

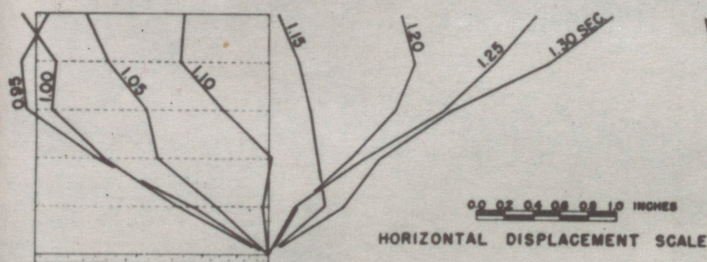
Earthquake codes are one of man's defenses against earthquakes. The seismic activity in a given area will determine whether or not he is spurred into employing that defense and how skillfully he is called upon to fashion it.



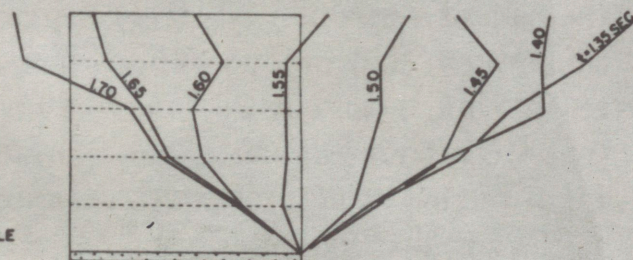
A. TIME, $t=0.00$ TO $t=0.40$ SECONDS



B. TIME, $t=0.45$ TO $t=0.90$ SECONDS



C. TIME, $t=0.95$ TO $t=1.30$ SECONDS



D. TIME, $t=1.35$ TO $t=1.70$ SECONDS

This figure, from a paper by Whitney, Anderson and Salvadori, shows how a building might move during an earthquake. The theoretical building is 60 ft wide and has a period of 0.83 sec. Earthquake pulse (half sine) is 0.6 sec, causing 1-in. foundation displacement

FIGURE 21



FIGURE 23
FLEXIBLE CONNECTION



FIGURE 24
FLEXIBLE CONNECTION

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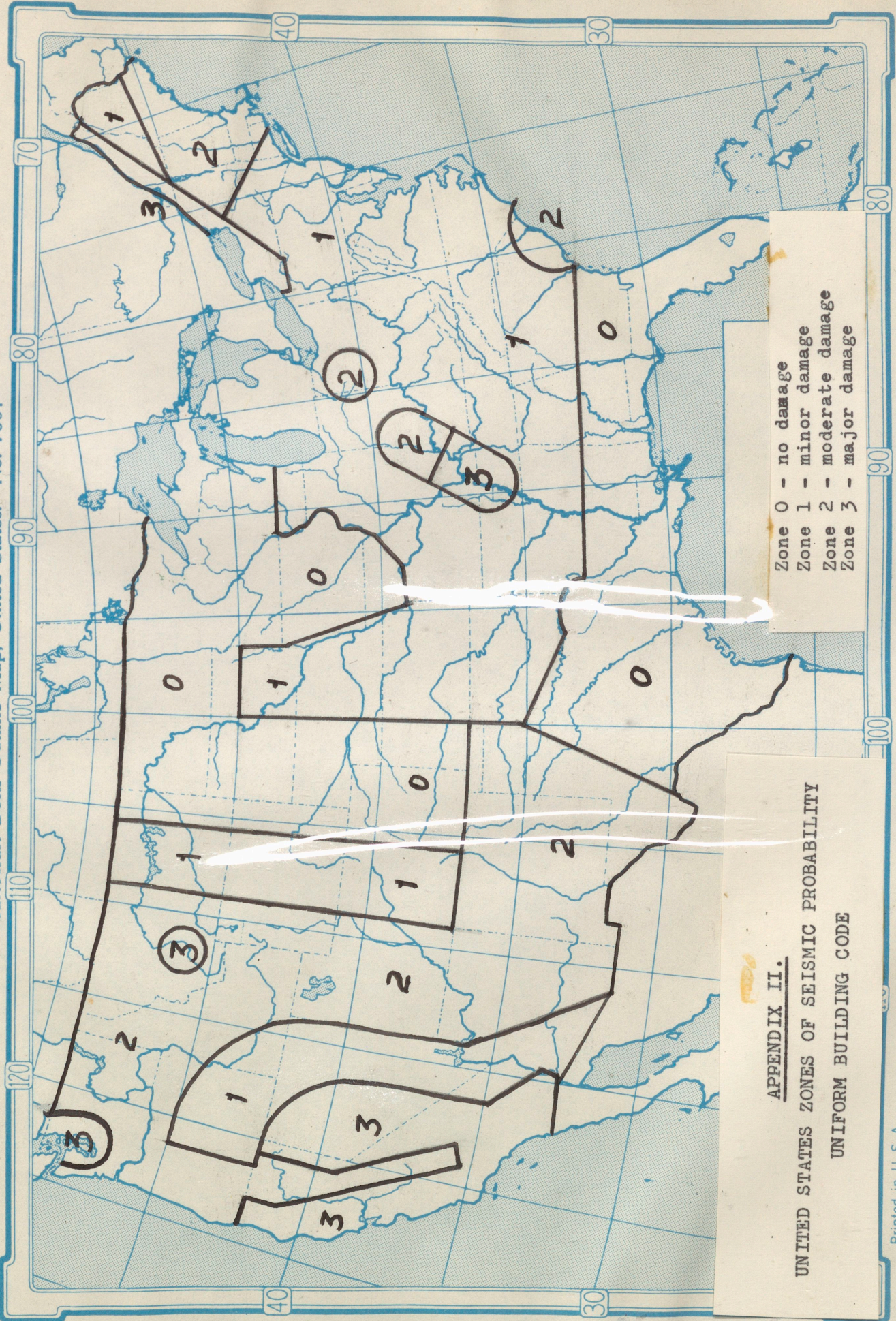
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APPENDIX



APPENDIX II
THE MODIFIED MERCALLI INTENSITY SCALE OF 1931
(Abridged)

- I. Not felt except by a very few under especially favorable conditions.
- II. ~~Felt~~ Felt only by a few persons at rest, especially in upper floors of buildings; delicately suspended objects may swing.
- III. Felt quite noticeably indoors, especially in upper floors of buildings, but many people do not recognize it as an earthquake; standing motorcars may rock slightly; vibration like passing of truck.
- IV. During the day felt indoors by many, outdoors by few; at night some awakened; dishes, windows, doors disturbed, walls make cracking sound; sensation like a heavy truck striking the building; standing motorcars rock noticeably.
- V. Felt by nearly everyone, many awakened; some, dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned; pendulum clocks may stop.
- VI. Felt by all, many frightened and run outdoors; some heavy furniture moved; a few instances of fallen plaster or damaged chimneys; damage slight.
- VII. Everyone runs outdoors; damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken; noticed by persons driving motorcars.
- VIII. Damage slight in especially designed structures; considerable in ordinary, substantial buildings, with partial collapse; great in poorly built structures; panel walls thrown out of frame structures; fall of chimneys, factory stacks, columns, monuments, and walls; heavy furniture overturned; sand and mud ejected in slight amounts; changes in well water; disturbs persons driving motor cars.
- IX. Damage considerable in specially designed structures; well designed frame structures thrown out of plumb; great in substantial buildings with partial collapse; buildings shift off foundations; ground cracked conspicuously; underground pipes broken..

- X. Some well-built wooden structures destroyed; most masonry structures destroyed, with foundations; ground badly cracked; rails bent; landslides considerable; from river banks and steep slopes; shifted sand and mud; water splashed over banks of streams.
- XI. Few, if any, masonry structures remain standing; bridges destroyed; broad fissures in ground, underground pipelines completely out of service; earth slumps and land slips in soft ground; rails bent greatly.
- XII. Damage total; waves seen on ground surfaces, lines of sight and level distorted, objects thrown upward into the air.

October 23, 1959

School of Architecture
Montana State College
Bozeman, Montana

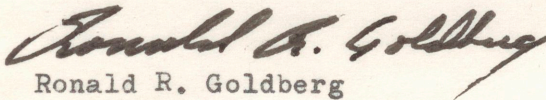
U. S. Department of Commerce
Coast and Geodetic Survey
Washington 25, D. C.

Gentlemen:

As part of my fifth year work in architecture I am doing some research on earthquakes and earthquake-resistant construction.

I would appreciate it if you could send me a copy of the preliminary report on the Hebgen Lake, Montana earthquakes. I would also appreciate any information concerning other sources of material related to this subject.

Yours,


Ronald R. Goldberg

U.S. DEPARTMENT OF COMMERCE
COAST AND GEODETIC SURVEY
WASHINGTON 25, D.C.

IN REPLY, PLEASE ADDRESS THE
DIRECTOR, COAST AND GEODETIC
SURVEY, AND NOT THE SIGNER
OF THIS LETTER, AND REFER TO

NO. 431:tf
807.1

October 29, 1959

AIR MAIL

Mr. Ronald R. Goldberg
School of Architecture
Montana State College
Bozeman, Montana

Dear Mr. Goldberg:

In compliance with your request of October 13, 1959 we are enclosing our Preliminary Report on the Hebgen Lake, Montana Earthquake.

We are also enclosing a list of the seismological publications of this Bureau with those which pertain to your problem indicated by asterisks. For further references on the earthquake effects on structures, we refer you to the Bibliography of Engineering Seismology by Edward P. Hollis, Second Edition, Earthquake Engineering Research Institute, 465 California Street, San Francisco 4, California.

Very truly yours,

Philip A. Earle
for Robert A. Earle
Captain, C&GS
Chief, Geophysics Division

Enclosures

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