THE SEISMICITY OF INDIANA AND ITS
RELATION TO CIVIL ENGINEERING
STRUCTURES

DECEMBER 1972 - NUMBER 44

BY

W. D. KOVACS

JHRP

JOINT HIGHWAY RESEARCH PROJECT

PURDUE UNIVERSITY AND
INDIANA STATE HIGHWAY COMMISSION

Digitized by the Internet Archive
in 2011 with funding from
LYRASIS members and Sloan Foundation; Indiana Department of Transportation

<http://www.archive.org/details/seismicityofindi7244kova>

ERRATA SHEET

"The Seismicity of Indiana and Its Relation to Civil Engineering Structures"

By William D. Kovacs JHRP:C-36-30E 12/28/72

- Page 12, 21. Reference name: "Gorden" should read "Gordon"
- Page 20 10th line from top: "Northwestern" should read "Southwestern"
- Page 22 13th line from top: "Gutenbery" should read "Gutenberg"
- Page 24 Lower right of graph: "Nuttly" should read "Nuttli"
- Page 29 2nd line from top: "North Carolina" should read "South Carolina"
- Page 29 8th line from bottom: "Earth" should read "Each"
- Page 41 13th line from bottom: "Ro ers" should read "Rogers"
- Page 42 18th line from top, reference under Nuttli:
"International Conference...etc." should read
"Bulletin of the Seismological Society of America for
Publication (April, 1973)"

Final Report

TO: J. F. McLaughlin, Director
Joint Highway Research Project

FROM: H. L. Michael, Associate Director
Joint Highway Research Project File: 9-4-2

The Final Report attached is submitted in fulfillment of the objectives of the approved Phase A of a research study of similar title to the Report, "The Seismicity of Indiana and Its Relation to Civil Engineering Structures". The Study has been directed and the Report written by Professor William D. Kovacs.

The Report reviews the past history of earthquakes in Indiana and locates the areas of principal concern, the southwestern part of the state. The Report recommends development and inclusion of seismic design provisions in an Indiana Building Code for buildings and highway structures. Procedures are also recommended for development which would permit the State to retrofit existing bridges with safeguards in the area of highest seismic risk. A continuation of the Study is therefore recommended to accomplish the development of the recommended procedures, designs and codes.

The Report is submitted for acceptance as fulfillment of Phase A of the Study.

Respectfully submitted,

Harold L. Mitchell

Harold L. Michael
Associate Director

HLM:ms

cc: W. L. Dolch M. L. Hayes C. F. Scholer
R. L. Eskew C. W. Lovell M. B. Scott
W. H. Goetz G. W. Marks J. A. Spooner
M. J. Gutzwiller R. D. Miles N. W. Steinkamp
G. K. Hallock J. W. Miller H. R. J. Walsh
R. H. Harrell G. T. Satterly E. J. Yoder

Final Report

THE SEISMICITY OF INDIANA AND ITS RELATION
TO CIVIL ENGINEERING STRUCTURES

by

William D. Kovacs
Assistant Professor of Civil Engineering

Joint Highway Research Project

Project No.: C-36-30B

File No.: 9-4-2

Conducted By

Joint Highway Research Project
Engineering Experiment Station
Purdue University

In Cooperation With

Indiana State Highway Commission

Purdue University
West Lafayette, Indiana
December 28, 1972

Table of Contents

	Page
Introduction	1
Seismic Geology of the Indiana Area	9
Structural Framework of Indiana	9
Fault Systems in Indiana	9
Relationship Between Earthquakes and Faults	17
Seismic History of the Indiana Region	19
Future Seismic Effects in the Indiana Area	26
Potential Damage to Highway Structures	29
Existing Seismic Design Standards for Indiana	34
Conclusions	38
Recommendations	39
Acknowledgements	40
References	41

THE SEISMICITY OF INDIANA AND ITS RELATION
TO CIVIL ENGINEERING STRUCTURES

by
William D. Kovacs
Joint Highway Research Project

Introduction

A new awareness of possible earthquake damage has been brought to the attention of the engineering profession. Two significant events leading to this new awareness are the publication of the revised Seismic Risk Map of the United States (Algermissen, 1969) and the occurrence of the San Fernando, California, Earthquake of February, 1971. The San Fernando earthquake caused approximately \$15 million dollars in Freeway damage and an estimated \$18 million dollars damage to local streets. This was a significant amount of damage for what is considered to be a minor earthquake.

Since that time many publications have been written on earthquakes and recently the Committee on Seismiology, National Academy of Science (1969), mentioned that the existing building codes do not provide adequate damage control features. This same report pointedly notes that existing standards for highway structures are "grossly inadequate" and it recommends revision of standard code requirements for earthquake design of highway bridges.

The 1949 Seismic Risk Map is shown in Figure 1. On this figure, approximately 20% of the state of Indiana is in Zone 2 corresponding to a maximum ground acceleration of 16% of gravity. Zone 3 is located adjacent to Zone 2, along the Mississippi River.

Fig. 1 Seismic probability map of the United States. This map is commonly used to establish seismic design criteria; the following maximum ground accelerations are associated with the zones: Zone 3, 33 % g; Zone 2, 16 % g; Zone 1, 8 % g; Zone 0, 4 % g. In Zone 3 close to a major active fault the maximum ground acceleration is estimated to be approximately 50 % g.

During 1967 and 1968, the U. S. Coast and Geodetic Survey studied approximately 28,000 earthquakes in the conterminous United States and presented various statistical summaries of their work. One such summary was the cumulative strain release from earthquakes in the time span 1900-1965. The strain release of an earthquake is taken proportional to the square root of the earthquake's energy release. The energy released by an earthquake is related to earthquake magnitude on the "Richter Scale". (Richter defined magnitude as the common logarithm of the trace amplitude, in microns, of a standard Wood-Anderson seismograph having a magnification of 2800, a natural period of 0.8 seconds, and a damping coefficient of 80 percent and is located on firm ground 100 km. (62 miles) from the epicenter of the earthquake. The epicenter is defined as the vertical projection on the earth's surface of the focus or underground origin of the earthquake).

The strain release for the United States was obtained by dividing the country's area into squares of 10,000 square kilometers and the strain release in each area was summed. The strain release was represented by the equivalent number of Magnitude 4 earthquakes occurring in each block. This data is presented in the form of a contour map in Figure 2. Locations of high strain release are indicated by the darker areas. The dark area of western Ohio has 64 to 256 equivalent Magnitude 4 earthquakes while southeast Illinois is rated from 16 to 64 equivalent Magnitude 4 earthquakes.

Based upon the above information (amount and pattern of strain release plus other factors), the 1949 Seismic Probability Map was replaced by the 1969 Seismic Risk Map of the United States. This map

Figure 2 Strain release in the United States, 1900 to 1965, expressed as the equivalent number of magnitude four earthquakes

After Algermissen, 1969

is presented in Figure 3 where it can be seen that over one half of the State of Indiana is within Seismic Risk Zone 2 while the extreme southwest corner of the state is in Zone 3. Zone 2 corresponds to a "moderate damage" zone, of earthquake Intensity VII while Zone 3 corresponds to "major damage" with Intensities of VIII and higher. Earthquake Intensity is an important term to understand. Intensity describes the damaging effect of an earthquake or earthquake motions on man made structures. Intensity is not a measured parameter by an instrument but it is evaluated by the reports of effects by trained observers. The Intensity scale predominately used in the United States is the Modified Mercalli scale of 1931 (abbreviated MM). Intensity ranges from I through XII, using Roman Numerals so as not to confuse Intensity with Magnitude. The Modified Mercalli scale is given in Table 1. There exists approximate correlations between Magnitude and horizontal ground acceleration and between Modified Mercalli Intensity and ground acceleration.

With the above background and information, it appears that potential damage to structures from earthquakes can occur in the State of Indiana. To study this potential damage from earthquakes it is necessary to study the earthquakes in the past. The historical seismicity is useful because the historic record, however sparse, can be extrapolated into the future as world seismicity has not really changed in thousands of years. This study was accomplished by examining records of previous earthquakes and noting their location and year of occurrence. The number and location of earthquakes in Indiana and adjacent states is discussed in relation to geologic faulting.

Figure 3 Seismic Risk Map of the United States

After Algermissen, 1969

TABLE 1

MODIFIED MERCALLI INTENSITY SCALE OF 1931

- I. Not felt. Marginal and long-period of large earthquakes.
- II. Felt by persons at rest, on upper floors, or favorably placed.
- III. Felt indoors, Hanging objects swing. Vibration like passing of light trucks. Duration estimated. May not be recognized as an earthquake.
- IV. Hanging objects swing. Vibration like passing of heavy trucks; or sensation of a jolt like a heavy ball striking the walls. Standing motor cars rock. Windows, dishes, doors rattle. Glasses clink. Crockery clashes. In the upper range of 4, wooden walls and frames crack.
- V. Felt outdoors; direction estimated. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters, pictures move. Pendulum clocks stop, start, change rate.
- VI. Felt by all. Many frightened and run outdoors. Persons walk unsteadily. Windows, dishes, glassware broken. Knickknacks, books, and so on, off shelves. Pictures off walls. Furniture moved or overturned. Weak plaster and masonry D cracked. Small bells ring (church, school). Trees, bushes shaken visibly, or heard to rustle.
- VII. Difficult to stand. Noticed by drivers of motor cars. Hanging objects quiver. Furniture broken. Damage to masonry D including cracks. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices, unbraced parapets, and architectural ornaments. Some cracks in masonry C. Waves on ponds; water turbid with mud. Small slides and caving in along sand or gravel banks. Large bells ring. Concrete irrigation ditches damaged.
- VIII. Steering of motor cars affected. Damage to masonry C; partial collapse. Some damage to masonry B; none to masonry A. Fall of stucco and some masonry walls. Twisting, fall of chimneys, factor stacks, monuments, towers, elevated tanks. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Decayed piling broken off. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes.

TABLE 1 (Cont'd)

- IX. General panic. Masonry D destroyed; masonry C heavily damaged, sometimes with complete collapse; masonry B seriously damaged. General damage to foundations. Frame structures, if not bolted, shifted off foundations. Frames racked. Conspicuous cracks in ground. In alluviated areas sand and mud ejected, earthquake fountains, sand craters.
- X. Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dikes, embankments. Large landslides. Water thrown on banks of canals, rivers, lakes, etc. Sand and mud shifted horizontally on beaches and flat land. Rails bent slightly.
- XI. Rails bent greatly. Underground pipelines completely out of service.
- XII. Damage nearly total. Large rock masses displaced. Lines of slight and level distorted. Objects thrown into the air.

Construction Type

Masonry A, B, C, D. To avoid ambiguity of language, the quality of masonry, brick or otherwise, is specified by the following lettering (which has no connection with the conventional Class A, B, C construction).

Masonry A. Good workmanship, mortar, and design; reinforced, especially laterally, and bound together by using steel, concrete, etc.; designed to resist lateral forces.

Masonry B. Good workmanship and mortar; reinforced, but not designed in detail to resist lateral forces.

Masonry C. Ordinary workmanship and mortar; no extreme weaknesses like failing to tie in at corners, but neither reinforced nor designed against horizontal forces.

Masonry D. Weak materials, such as adobe; poor mortar; low standards of workmanship; weak horizontally.

SEISMIC GEOLOGY OF THE INDIANA AREA

Structural Framework of Indiana

"The entire Central Stable Region of the United States, of which Indiana is a part, is underlain by Precambrian crystalline rock and varying thickness of Phanerozoic sedimentary rock. The crystalline basement forms an overall foundation and structural framework for the overlying sedimentary strata; thus, large depressions, highs, and scarps in the basement are expressed in Paleozoic strata by structures such as the Illinois basin, the Cincinnati arch, the Michigan basin, the LaSalle anticline, the Rough Creek fault system, Wabash Valley fault system and the Mt. Carmel fault." (Frey and Lane, 1966)

Much of the bedrock topography is covered by glacial drift. The thickness of drift ranges from 50 to 100 feet in the South to more than 500 feet in the North.

Fault Systems in Indiana

1. Mt. Carmel Fault.

The Mt. Carmel fault is a major structural feature of Indiana. It extends roughly 50 miles across Washington, Jackson, Lawrence and Monroe counties to disappear under glacial drift in northern Monroe county. The fault strikes north 10 to 15 degrees west and dips approximately 70 degrees west, displacement is essentially dip slip and ranges from 60 to 200 feet. There is no evidence of cross faulting or minor scissor faults. Numerous subsidiary fractures are found as far as 1 1/2 miles from both sides of the fault. (Frey & Lane, 1966)

2. Fault Systems in Southwestern Indiana and Southeastern Illinois.

In this severely faulted area, there are three main fault systems; The Wabash Valley Fault System, Shawneetown-Rough Creek Fault Zone and Cottage Grove System.

The Wabash Valley System is a series of northeast trending faults. Its inferred extension southwest into the Mississippi Valley follows the trace of Fuller's (1912) epicentral line of the 1811-1812 New Madrid earthquakes. The 1968 earthquake in southern Illinois is related to this system.

The Shawneetown-Rough Creek Fault Zone is composed of high angle faults. It has a maximum displacement of 3000 feet or more. The east branch of this fault extends across Kentucky into West Virginia. In the southeastern corner of Illinois south of this fault zone is an area of intense faulting where most of the major faults trend southwest-northeast.

The Cottage Grove System consists of high angle faults with less displacement than the Rough Creek Fault. The above mentioned fault systems are shown in Figure 4, after Heigold (1968). Also shown on this figure is the epicenter of the November 9, 1968 South Central Illinois Earthquake.

A more detailed discussion of the regional structure and seismicity of the southwest Indiana-southeast Illinois and the New Madrid, Missouri area is quoted directly from Gordon, et al (1970) and includes Table 2 and Figure 5.

Fig. 4 - Regional faulting map of southeastern Illinois.
(After Willman and others, 1967.)

After Heigold, 1968

SEISMICITY AND STRUCTURE MAP

FIG. 5 Seismicity and structure map showing locations of intensity V or stronger earthquakes in the interval 1869-1968. Structure generalized after King (1967) and also Bayley and Muehlberger (1968).

After Gorden et al, 1970

TABLE 2

STRONGER EARTHQUAKES IN THE NEW MADRID SEISMIC ZONE: 1869-1968

Year	Locality	Lat. [°] N	Long. [°] W	Felt Area (sq. mi.)	Intensity (MM)
1895	Charleston, Missouri	37.0	89.4	1,000,000	VIII
1909	Indiana-Illinois Border	39.0	87.7	30,000	VII
1923	Marked Tree, Arkansas	35.5	90.3	40,000	VII
1927	Western Tennessee and Arkansas	36.5	89.0	130,000	VII
1934	Rodney, Missouri	37.0	89.2	28,000	VII
1965	Southwestern Illinois	37.1	89.1		VII
1968	South-central Illinois	38.0	88.5	580,000	VII

(after Gordon et al 1970)

"The November 9, 1968 earthquake, the strongest shock in the central United States since 1895, occurred within the New Madrid seismic zone, defined by Stauder and Bollinger (1963). This is a zone of relatively high seismicity that extends from Memphis, Tennessee, northeasterly to the vicinity of the Illinois-Indiana border. The seismicity and structure of the region surrounding the epicenter are illustrated in Figure 5. Here, the plotted points refer to intensity V or stronger earthquakes which have occurred since 1869. Despite the scatter inherently involved in plots of noninstrumental epicenters, the figure shows obvious correlation between seismicity, known faulting, and the trend of principal rivers. The New Madrid zone, which is approximately 75 miles wide near its center at the mouth of the Ohio, has been mapped as a high seismic risk area by Algermissen (1969). Shocks of maximum intensity VII or more which have occurred in the area during the period 1869-1968 are listed in Table 2. The numbers of earthquakes of intensity V or greater during this interval are as follows.

Maximum Intensity	Frequency*
VIII	1
VII	7
VI	28
V	68

"Southern Illinois forms the southern flank of the Illinois Basin, a downwarped portion of the Pre-cambrian basement underlying the central United States. In the vicinity of the epicenter, the stratigraphic section is composed of 13,000 feet of Paleozoic rocks, including coal

* Cumulative number of shocks greater than or equal to specified intensity.

and oil-bearing formations, overlying crystalline basement rocks. The structural framework of southern Illinois also includes portions of three major fault systems: the Rough Creek, St. Genevieve, and a northeast-trending fault system (King, 1967; Bayley and Muehlberger, 1968). In Illinois, the northeast-trending structure belongs to a series of faults known collectively as the Wabash Valley system. Its inferred extension southwest into the Mississippi Valley follows the trace of Fuller's (1912) epicentral line of the 1811-1812 New Madrid earthquakes. Other investigators (McGinnis, 1963) have placed this fault or a second parallel fault along the trend of the Mississippi near the town of New Madrid. According to Heinrich (1949) the middle Mississippi Valley represents a structural trough between the Ozark Uplift and the Cincinnati Arch. This suggests the existence of a northeast-trending fault forming the southeast boundary of the subsidence block occupying the valley. As shown in Figure 5, there is a sharp limit to the occurrence of epicenters southeast of the Mississippi. In Illinois, the east-west trending Rough Creek fault is represented as a normal fault upthrown approximately 3,000 feet on the south. The trace of the Rough Creek and major northeast-striking faults intersect near Eldorado, Illinois, approximately 11 miles south of the instrumental epicenter. Little seismicity has been associated with the eastern branch of the Rough Creek fault which extends across Kentucky into West Virginia. The third major fault system, the St. Genevieve, strikes northwest and forms the boundary between the Illinois Basin and Ozark Uplift. Displacement of basement rocks along the fault indicates vertical movement exceeding 2,000 feet.

"The New Madrid earthquakes, three catastrophic shocks during 1811-1812, dominate the seismic history of the middle Mississippi Valley. These shocks were each felt in an area exceeding 2 million square miles; they virtually destroyed pioneer settlements at New Madrid and nearby Caruthersville, Missouri. Dramatic landscape changes which accompanied the earthquakes, including formation of Reelfoot Lake in Tennessee, forced abandonment of agriculture in a 30,000 to 50,000 square-mile area of fertile floodplains. According to Fuller (1912) over 2,000 aftershocks associated with the earthquakes followed within a 2-year period. Aftershock activity extended from New Madrid, northeastward to the Illinois-Indiana border, covering an area of strain recovery which closely approximates the zone of high seismicity noted earlier.

"Six of the seven earthquakes listed in Table 2 lie along the northeast-trending lineament which passes through New Madrid (Figure 5). The 1895 Charleston, Missouri earthquake was the severest shock in the central United States since the historic New Madrid series. This earthquake, which was felt in 23 states, reached maximum intensity VIII in the Mississippi Valley below Cairo. The same area experienced an intensity VII earthquake in 1934 which caused damage in a 230 square-mile area near Rodney, Missouri. The 1965 quake listed in Table 2 was the largest of a swarm of 7 small shocks which occurred in an area approximately 20 miles north of Cairo. Nuttli (1965) attributed the relatively small felt area of these shocks to shallow focal depth which he estimated as 5 kilometers or less. In addition to the 1909 shock, the seismic history of the Indiana-Illinois border includes an earthquake which struck Mt.

Carmel, Illinois (38.4°N , 87.9°W) in 1958. The earthquake had a maximum intensity of VI and was felt over a 33,000 square-mile area. Stauder and Bollinger (1963) have discussed a group of five earthquakes which occurred in the New Madrid seismic zone in 1962. One of these, an intensity V shock, was located in southern Illinois approximately 20 miles southwest of the November 9, 1968 epicenter. The largest shock of the series was centered near New Madrid. It was felt over a 35,000 square-mile area and reached maximum intensity VI or VII. Although the radius of perceptibility (about 125 miles) and wide separation between isoseismals (contour lines of equal Intensity) associated with the earthquake suggested deeper-than-normal focal depth, the presence of crustal phases and short-eriod surface waves on seismograms clearly implied a focus within the crust. Stauder and Bollinger (ibid) estimated the focal depth as 20 to 25 kilometers."

Relationship Between Earthquakes and Faults

Comparing a plot of worldwide earthquake distribution with a corresponding relief map will clearly show a general correlation between epicentral concentrations with areas of high relief and large scale tectonic activity.

Evidence of faulting may indicate a relative structural weakness in an area. Since adjustment will probably occur in a area of structural weakness, seismic activity might be expected to be more prevalent in a faulted area than in an undisturbed area. An active surface trace is not required inasmuch as earthquakes originate at great depth, a fault may tend to be active at depth without surface evidence. Such appears to be the case with the New Madrid, Missouri

The relationship between faulting and earthquakes is complex and not too well understood by seismologists. Most authorities believe that faulting causes the earthquake; the earthquake does not cause the faulting (Richter, 1958).

Heigold (1968) has postulated several possible triggering mechanisms for earthquakes in the southern Illinois-Indiana area; they include 1) sudden changes in barometric pressure, 2) changes in surface water loads, 3) earth tides, 4) crustal rebound from unloading of glacial ice and 5) crustal sinking due to recent deposition in the Miss. embayment region.

The suggestion is frequently advanced that a straight line may be drawn between the historically seismically violent area of St. Lawrence Valley and New Madrid, Missouri areas. This line would pass through clusters of epicenters in Buffalo, N. Y. and in western Ohio. Figure 1 shows these epicenters and the distinct lineation. If this seismic lineation were valid, it would be logical to assume that an earthquake equal in Intensity to either the New Madrid or St. Lawrence Valley shocks could occur in any place along this line. However, no real evidence exists to connect those two earthquake active areas. While there are similarities in geologic conditions between those two areas, there are no such similarities in the extensive area between these two locations (Fox, 1970).

It is interesting to note that the New Madrid area was regarded as anomalous because of the sudden and violent nature of the 1811-1812 earthquakes. However, an extensive inferred fault crossing the Mississippi River appears for the first time on the Basement Map of

North America in 1967. This extensive fault is shown as a dashed line, trending NE on Figure 5. This indicates that the New Madrid area could be potentially hazardous even without the historical records.

On a geological basis, the active earthquake New Madrid area may be logically extended northward along the St. Genevieve fault (see Figure 5) and Mississippi Valley and southward along the Mississippi Embayment. Earthquake epicenters appear to support these geological extensions. It may also be reasonable to extend the area eastward along the Kentucky River Graben (the eastward extension of the Rough Creek Fault System), which has been seismically quiet.

SEISMIC HISTORY OF THE INDIANA REGION

The study of historical earthquakes in the eastern United States shows that the greatest concentrations of epicenters are located in the area of densely populated regions. This is certainly true for those areas that have been settled for the longest period of time. (Records go back to the year 1638 in the United States.) It is possible that some areas will not have earthquake epicenters simply because there were no people to report these earthquakes that may have occurred in the past. Since the early settlements were located near water, earthquake epicenters appear to be more numerous near large bodies of water.

Historical epicenters for the Indiana Region have been plotted on Plate 1 (located inside back cover). Many of the epicenters are located on or adjacent to the principal rivers. This is true not only for the reason mentioned above but because the river valleys tend to amplify the earthquake motion. Thus a small or distant earthquake may have only been felt at locations with ideal ground conditions such as

soft soil (unconsolidated sediments) sites which tend to amplify the base rock acceleration. The ground acceleration may be several times the base rock acceleration.

The roman numeral beside the epicenter locations plotted on Plate 1 represents the highest or epicentral Intensity for the event while the remaining notation denotes the year of occurrence. In some of the older earthquakes, the location and perhaps the Intensity are approximate.

A glance at this plate shows that earthquakes have occurred in all directions with the predominance of events located in the northwestern part of the state of Indiana.

Each of the seismic events shown on Plate 1 varied in Magnitude and Intensity. Depending upon the local soil and geological conditions, each event affected the surrounding areas in different ways. The recent November 9, 1968 earthquake in south central Illinois was studied in considerable detail. Figure 6 illustrates the extent of the felt area by the outer isoseismal (contour line of equal Intensity). This earthquake was felt over approximately 580,000 square miles with maximum Intensity VII and a Richter Magnitude of 5.5. It can be seen that the Intensity decreases with increasing epicentral distance. Besides isolated pockets of higher or lower Intensity within a given contour interval, a given Intensity contour appears to follow up the major river valleys. This aspect is significant because the river valleys contain soft unconsolidated sediments which tend to amplify the underlying base rock acceleration, as compared to other locations at the same epicentral distance.

FIG. 6 Generalized isoseismal map of the south-central Illinois earthquake. Intensities refer to the 1931 Modified Mercalli Scale.

After Gorden et al, 1970

When isoseismal maps from other earthquakes are superimposed upon one another, a final map of maximum historical Intensity can be obtained for the Indiana area. Such a map is presented on Figure 7. In general the maximum past or historical Intensity increases downward to the south west part of the state from Intensity V to Intensity VIII at the junction of the Wabash and Ohio Rivers. This lower area is in Seismic Risk Zone 3, as previously mentioned.

Since World seismicity isn't changing, a knowledge of the historical Intensity can be used to estimate future Intensity and ground acceleration. Figure 8 shows two correlations of Modified Mercalli Intensity with (log) ground (particle) acceleration. As the Intensity increases, the ground acceleration increases at an increasing rate. Until recently, engineers have used Gutenberg and Richter's (1942) relationship (there are others) to estimate ground acceleration from Intensity observations in lieu of actual seismograph acceleration records. However, Nuttli (1972) mentions that we cannot use the California empirical data of acceleration vs Intensity (upper curve in Figure 8) in the eastern United States due to the difference in surficial and crustal geology. Nuttli studied the 1811-1812 New Madrid and the November 9, 1968 south central Illinois earthquakes. He concluded that the reason why these earthquakes were felt over such a large surface area was due to the low attenuation of short period (high frequency) surface waves. The surficial and crustal geology in this eastern United States area is such that the short period waves require a very long epicentral distance to die out.

Leeds (1968) also mentioned that eastern earthquakes have been felt over much larger areas for the same magnitude as eastern United States earthquakes.

Roman Numerals Refer to the Modified Mercalli Scale of 1931

FIGURE 7 MAXIMUM HISTORICAL INTENSITY MAP OF INDIANA -1811 TO DATE .

FIGURE 8 HORIZONTAL GROUND ACCELERATION VS. MODIFIED MERCALLI INTENSITY.

Thus, for studies of the November 1968 Illinois earthquake, Nuttli (1972) was able to ascertain a correlation between Modified Mercalli Intensity and particle acceleration. This relationship is shown as the lower line on Figure 8 and represents a considerable difference in partial acceleration for the same Intensity.

However, many engineers assume that maximum acceleration governs design and may have failures if they used the lower curve in Figure 8 to estimate particle or ground acceleration from known or predicted Intensity in the eastern United States. Although the particle accelerations are widely different, particle velocities are approximately the same for both curves on Figure 8. This can easily be explained in terms of the frequency characteristics of California and Eastern United States earthquakes. Assuming equivalent sinusoidal (harmonic) motion, a California earthquake of Intensity VII (the threshold of structural damage) at an earthquake wave frequency of 3 Hertz (cycles per second) would have a particle acceleration of approximately 10% of gravity or 0.1 g and a particle velocity of 2 inches per second. Frequency, displacement, velocity and acceleration are all interrelated for harmonic motion.

Engineers who study the effects of blasting vibrations on building damage conclude that a particle velocity of 2 inches per second is the upper limit or threshold of damage (Nicholls et al, 1971). In the eastern United States, long period waves of 3 seconds or more predominate, corresponding to wave frequencies of 0.33 cycles per second or less (Nuttli, 1972). The corresponding acceleration for a frequency of 0.33 Hertz and 2 inches per second velocity (approximately Intensity VII)

is approximately 1% g, a factor of 10 lower than high frequency California wave.

Another possible method exists to evaluate particle acceleration at a site. Figure 9, presents relationships between maximum bedrock acceleration and epicentral distance for several different Magnitude earthquakes. For a given Magnitude, the acceleration falls off rapidly with increasing epicentral distance.

Nuttli (1972) estimated attenuation of acceleration with epicentral distance for vertical acceleration and stated that the horizontal acceleration is approximately 2 or 3 times as great as the vertical acceleration. A value of approximately two times agrees very well with the curves in Figure 9.

With the above mentioned correlations, it is possible to predict damage potential in the Indiana area by extrapolating Seismicity into the future.

FUTURE SEISMIC EFFECTS IN THE INDIANA AREA

There is a large likelihood that earthquakes will occur in places where they have previously occurred but when one looks at the world-wide seismicity, the majority of strong motion earthquakes in the last 50 years have epicenters where no previous large earthquakes were recorded.

Although the New Madrid shocks are not well understood, their "aftershocks" continue. Renewed activity in this area would not come as a surprise. The greater danger spot in the United States may be the New Madrid-southern Illinois-Indiana area due to the potential size of the shock and the general lack of preparedness and concern for its occurrence, not to mention the great population build-up since the turn of the 19th century (Leeds, 1968).

(From Seed, Idriss and Kiefer, 1969)

Fig. 9 RELATIONSHIP BETWEEN PEAK BEDROCK ACCELERATION, EARTHQUAKE MAGNITUDE AND FAULT DISTANCE

The New Madrid, Missouri area has been regarded as anomalous with respect to its seismicity because of the sudden and violent nature of the 1811 and 1812 earthquakes. However, this violent activity may not be the only activity as some evidence indicates similar violent seismic activity existed prior to the great 1811-1812 earthquakes. Trees over 200 years old can be found growing straight and true from depressions remarkably similar to those formed from local subsidence observed in the 1811-1812 earthquakes. This gives evidence that those depressions are at least 200 years old. This physical evidence of past or historic seismic activity is recorded by an Indian legend of a great shock that occurred in the past that affected the same area (Fox, 1970).

Nuttli (1972) has studied reports of the New Madrid earthquakes of 1811-1812. By correlating the 1811-1812 Intensity map with those of recent eastern earthquakes for which ground motion data are available, he back figured the magnitudes for these three earthquakes. Since seismic history will repeat itself, it is possible to have a reoccurrence of the New Madrid earthquake(s). These earthquakes would have Magnitudes of $7 \frac{1}{4}$ and would also cause damage in Indiana.

Another earthquake problem for Indiana will occur in the next few years and be associated with the Wabash River fault system. This earthquake will have a magnitude of 6 to $6 \frac{1}{4}$ and could result in damage at epicentral distances as large as 50 miles on competent ground (Nuttli, 1972a) and perhaps at larger distances along major river valleys.

Nuttli points out that the absence of large magnitude earthquakes in the eastern North America since the Charleston, North Carolina earthquake of 1886 (see Figure 1) has resulted in complacency or perhaps unawareness on the part of the general population of the probable earthquake damage threat on them. The same can be said for the New Madrid area.

POTENTIAL DAMAGE TO HIGHWAY STRUCTURES

Part of the construction plans (soil boring information) of highway bridge structures were obtained from the State of Indiana and reviewed. Emphasis of review was placed on foundation provisions and location, soil type and relative strength and relative density (as measured by the Standard Penetration test), and location of the ground water table. It is possible to damage such structures by ground shaking as well as foundation support loss due to liquefaction of loose saturated sands.

Soil conditions at 12 bridge sites were studied from I-70 at Terre Haute, Indiana down along the Wabash and easterly along the Ohio River to Louisville, Kentucky. This area (the southwest portion of the state) has the largest potential for earthquake damage.

Ground accelerations were predicted for earth of the twelve sites using acceptable seismological techniques (U. S. AEC, 1971). Using the estimated earthquake magnitudes for the Wabash River and New Madrid Fault systems, the epicenter is moved any place along the fault system to the closest point from a given site. This approach is entirely satisfactory from a geologic point of view. Figure 9 was used along with the known predicted Magnitudes and epicentral distances (Figures 4 and 5). The results are tabulated in Table 3. M in column (5)

TABLE 3

POTENTIAL GROUND ACCELERATION FOR SELECTED BRIDGE SITES
IN SOUTHWEST INDIANA ALONG WABASH AND OHIO RIVERS

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
No.	Route	River	Epical Distance (miles)	M	Accel. %g	Fault Name	Remarks
1	I-70	Wabash	80	6.4	1	Wabash	
			200	7.2	2	New Madrid	
2	SR-154	Wabash	40	6.4	4	Wabash	
			180	7.2	2	New Madrid	
3	US-50	Wabash	10	6.4	13	Wabash	10 piers on the east bank of river. 10' or 25' feet of loose sand or silty sand. No information on pier elevation, probably founded on rock.
4	SR-64	Wabash	2	6.4	18	Wabash	
5	I-64	Wabash	2	6.4	18	Wabash	20' or 30' of loose sand in river. No information about piers.
6	US-460	Wabash	2	6.4	18	Wabash	
7	SR-62	Wabash	2	6.4	18	Wabash	
8	US-41	Ohio	20	6.4	7	Wabash	2 piers on the north bank of the river, remainder on soft soil above a loose saturated sand layer 15 ft thick (10 ft below ground surface) N(SPT) = 11 Blows/Foot.
			120	7.2	3	New Madrid	
9	US-231	Ohio	50	6.4	4	Wabash	15 ft of loose sand above present ground water table
			150	7.2	3	New Madrid	
			10	6.4	12	Rough Creek	
10	SR-37	Ohio	70	6.4	2	Wabash	
			170	7.2	3	New Madrid	
			30	6.4	5	Rough Creek	
11	SR-135	Ohio	100	6.4	2	Wabash	6 piers on the north bank of the river are founded on medium coarse sand with N(SPT) =
			180	7.2	3	New Madrid	
			20	6.4	7	Rough Creek	9 Blows/Foot.
12	I-65	Ohio	100	6.4	2	Wabash	
	I-64		220	7.2	2	New Madrid	
			40	6.4	3	Rough Creek	

represents the expected Magnitude. The acceleration (% of gravity) in column (6) is the bedrock acceleration and more than likely the actual ground accelerations will be higher.

On some of the plans, as stated in the remarks column of Table 3, it appears some pier foundations are located on questionable material from a liquefaction point of view. Without as built drawings definite conclusions cannot be drawn. Presumably, most of the bridge foundations are located on firm material or shallow rock. It is concluded, however, that some of the bridge approach embankments, although statically stable, may suffer distress from liquefaction of the underlying soils. When loose ($N \leq 10$ to 15 Blows/foot), saturated sands and silts are stressed dynamically, liquefaction is highly probable. Figure 10 shows test results on soils that are most liquefiable. Water deposited, uniformly graded fine sands and coarse silts fall into this category.

Further studies are warranted to evaluate damage by shaking as well as liquefaction at the bridge areas mentioned above.

Jackson (1971), in discussing the seismic design changes in Idaho brought about by the revised (1969) Seismic Risk Map, asked why there was so much damage in the San Fernando, California earthquake of Feb. 9, 1971 (magnitude 6.5). Actually the Los Angeles area had about 40 years growth under seismic building codes. Perhaps we can all benefit by this occurrence. It appears that the largest source of damage was the failure to apply the lessons learned and relearned in previous earthquakes. Codes are intended to prevent a structure from collapsing during an earthquake. The code does not guarantee that the structure after the earthquake will be useful any longer.

a. GRAIN-SIZE DISTRIBUTIONS

b. EFFECT OF GRADATION ON CYCLIC STRENGTH

(From Lee and Fitton, 1968)

Fig. 10 GRAIN-SIZE & STRENGTH CHARACTERISTICS OF MOST LIQUEFIABLE SOILS

The Building Codes take into account the strength and flexibility of a structure but do not take into account vital aspects that may increase or decrease earthquake loads. These aspects include epicentral distance, thickness of soil layer, dynamic soil properties (shear modulus and damping factor), Magnitude, Intensity, duration of the earthquake, foundation type and soil-structure interaction, site resonance (relation of the natural period of the ground to the natural period of the structure). Thus, the code should be considered as the lower limit of design requirements as local soil conditions may increase the local intensity from 1 to 3 steps between rock and alluvium conditions.

Elliott (1972) summarized the lessons learned in the San Fernando earthquake with respect to highway and bridge design. Six areas of design weakness were observed. They include:

- 1) Concrete columns did not take twisting and grinding.
Increased strength and closer spiral reinforcing will reduce damage.
- 2) Failure of expansion joints to hold bridge decks in place. Excessive movement can easily be prevented by installation of tension retaining rods.
- 3) Inadequate concrete bond where concrete was shattered.
Eliminating lap splices in main columns along with footing dowels and stub bars for columns, but adding additional bars at the top of block footings and bottom of column cap will reduce damage.
- 4) Weak connection between pile and footings. Redesign anchorage system to take tension.

- 5) Failure of shear keys to laterally restrain bridge abutments. Larger shear keys and longitudinal ties are required.
- 6) Recognition that an equivalent static force does not represent actual dynamic earthquake forces. Research on soil-structure interaction is required.

Elliott mentioned that only a few percent of all structures are ever severely shaken. If the additional cost of the strengthening is greater than the repair cost, the money is wasted. However, money spent to strengthen a structure so it will not collapse during an earthquake may save a life. This cost is very much less than the cost of construction to prevent all damage.

Few areas of the United States have escaped severe earthquakes. Many who have not thought of the Indiana area as earthquake prone should consider the small additional cost of safeguards against earthquake damage.

EXISTING SEISMIC DESIGN STANDARDS FOR INDIANA

The present Indiana Building Code (1969 Ed.) does not contain any reference, whatever, to earthquakes, seismic conditions or any such occurrence (Gatlin, 1972). Correspondence with the city engineers of ten major cities in the state indicates that seismic design standards are not incorporated in any of those cities codes including the cities of Evansville and Vincennes which are in zone III of the Seismic Risk Map (Figure 3) and several other cities in zone II.

The State of Illinois does not have a state seismic building code. Southern Illinois, extending from East St. Louis southward, is included in Zone II & III on the Seismic Risk Map. Many communities have taken the initiative to subscribe to various codes, the predominate one being the National Building Code. The seismic design criteria included in the National Building Code is compiled from the recommendations of the Structural Engineers Association of California. The most comprehensive seismic design standard in the United States is the "Recommended Lateral Force Requirement" of the Structural Engineers Association of California (SEAOC). It has been reviewed several times since it was first adopted in 1959. In 1967 the UBC adopted the SEAOC Code on Lateral Force Requirements and made some changes such as using the seismic zone concept to allow for differences in local seismicity throughout the country according to the Seismic Risk Map. Southern Illinois University at Carbondale has two 19-story structures on its campus. For design purposes, the buildings were assumed to fall within Zone II. Loads were calculated and distributed to the various floor levels in compliance with the provisions made by National Building Code. Various degrees of stiffness were provided by the use of shear walls (Paja, 1972).

Seismic Risk Zone I in the state of Illinois extends from East St. Louis northward. The most damaging quake in this zone was one having its epicenter at the LaSalle anticline near the city of LaSalle. LaSalle is in an area of loose alluvial fill, which tends to magnify damages. The State buildings in this region are generally dimensioned such that seismic criteria does not control the design of the structures.

(Paja, 1972).

Many Illinois cities in Seismic Risk Zones II & III have made no provisions for seismic loads in the local building codes (Kirkman, 1972).

Major bridge structures in southern Illinois are designed for earthquake forces in accordance with the Standard Specifications for Highway Bridges as adopted by AASHTO.

The 1969 edition of AASHTO Standard Specifications for Highway Bridges provides a lateral force of 2% to 6% of dead load for earthquake load. The State of California has provisions to increase the AASHTO specification to 13% g (NTSB, 1972). As a result of the recent San Fernando earthquake in February 1971, these specifications are currently in the process of being extensively revised!

The western part of the state of Kentucky is in Zone II & III on the Seismic Risk Map. The City of Owensboro, which is in Zone II, operates under the Southern Standard Building Code, and follows the requirements in accordance with that building code (Reynolds, 1972). Several other cities in this area, however, have made no provisions for earthquakes loads (Upshaw, 1972).

The bridges in western Kentucky are designed according to the AASHTO Bridge Specifications. Aware of the fact that the AASHTO bridge specifications are being studied for revision, several recommendations from the State of California, such as more rigid and closely spaced column ties, fewer column reinforcement splices, etc., are already included in the seismic design of the bridges in that area.

During the past few years, the Administrative Building Council of the State of Indiana has been considering adopting one of the model codes or the prospects of updating the present Indiana Building Code (1969 Ed.). It has been suggested that the SEAOC recommendations be adopted for the state of Indiana (Gatlin, 1972).

Conclusions

Based on the information and data presented herein, the following conclusions appear warranted:

- (1) The State of Indiana has experienced violent shaking and damage in the past and will experience similar earthquakes in the future. Intensities as large as IX (as shown in Figure 7) can be expected in the future.
- (2) The areas of principal concern are located in the southwestern part of the State, especially in river valleys and stream channels.
- (3) Within the next several years, the Wabash River Fault System is expected to release earthquakes of Magnitude 6 to 6-1/4 with accelerations similar to or greater than those reported in Table 3. Base rock accelerations up to 18% g may occur at those sites with short epicentral distances. The ground accelerations may be increased several times above the base rock accelerations due to soil amplification. Magnitudes of 6 to 6-1/4 have been associated with structural damage in other locations and should produce damage in Indiana when they occur.
- 4) A reoccurrence of the New Madrid earthquakes with anticipated Magnitude of 7-1/4 could be expected to cause considerable damage in southwest Indiana.

Recommendations

Based on the conclusions of this study and the lack of any seismic design code in the State of Indiana the following recommendations are made:

- 1) A study should be made that will enable seismic design provisions be incorporated into an Indiana Building Code for buildings and highway structures.
- 2) Procedures should be formulated within the State to retrofit existing bridges with safeguards as outlined by Elliott in the area of the highest seismic risk.
- 3) Consideration should be given to the use of probability theory in assessing the factor of safety of structures based on a study of the frequency of occurrence of earthquakes in the Indiana area.
- 4) That the above be accomplished by a continuation of the Phase A study of the Seismicity of Indiana and its Relation to Civil Engineering Structures to include:
 - (a) An assessment of the probable response of geological materials in southwest Indiana.
 - (b) Recommendations for seismic bridge design.
 - (c) Suggested methods of analysis for seismic design for various structural types including earth structures (embankments, etc.).
 - (d) Recommendations for an Indiana seismic design code.

Acknowledgements

The writer is indebted to the Joint Highway Research Project, Purdue University for financial support for two graduate research students, Mr. T. J. McArdle, Jr., and Mr. J. W. Hwang who diligently gathered the data for this study. The writer also appreciates the assistance and helpful suggestions made by Professor A. G. Altschaeffl and Professor Wm. R. Judd.

References

- American Association for State Highway Officials, Standard Specifications for Highway Bridges, 10th ed., Tacoma, Wash., 1969.
- Algermissen, S. T., "Seismic Risk Studies in the United States", Proceedings, 4th World Conf. on Earthquake Engineering, Santiago, Chile, 1969, Vol. I, pp. A-1: 14-27.
- Committee on Seismology, "Seismology, Responsibilities and Requirements of a Growing Science, Part I: Summary and Recommendations. Part II: Problems and Prospects", National Academy of Science, Wash., D.C. 1969.
- Elliott, A. L., "The San Fernando Earthquake: A Lesson in Highway and Bridge Design", Civil Eng. Magazine, ASCE, Vol. 42, No. 9, Sept. 1972, pp. 95-97.
- Eppley, R. A., "Earthquake History of the United States-Part I", United States Government Printing Office, Wash., D.C., 1965.
- Fox, F. L., "Seismic Geology of the Eastern United States", Bulletin of the Association of Engineering Geologists, VII, Nos. 1 & 2, 1970, pp. 21-43.
- Frey, R. W. and Lane, M. A., (Editors) "A Survey of Indiana Geology, with road logs for two field trips", Indiana University Department of Geology, Bloomington, 1966.
- Fuller, M. L., "The New Madrid Earthquake", United States Geological Survey Bulletin 494, Washington 1912, pp. 1-119.
- Gatlin, D. R., Private communication, Feb. 9, 1972.
- Gordon, D. W., Bennett, T. J., Herrmann, R. B., and Rogers, A. M., "The South-central Ill. earthquake of Nov. 9, 1968: Macro Seismic Studies", Bulletin of the Seismological Society of America, Vol. 60, No. 3, 1970, pp. 950.
- Gutenberg, B. and Richter, C. F., "Earthquake Magnitude, Intensity, Energy, and Acceleration", Bulletin Seismological Society of America, 32, 1942, pp. 163-191.
- Heigold, P. C., "Notes on Earthquake of Nov. 9, 1968, Southern Illinois", Ill. State Geological Survey, Environmental Geology Notes, No. 24, 1968.
- Jackson, M. W., "Seismic Design Changes Implied by Revised Seismic Risk Map", Proc. 9th Annual Engineering Geology and Soils Engineering Symposium, Boise, Idaho, April 1971, pp. 31-46.

Kirkman, G., Private communication, Sept. 5, 1972.

Lee, K. L. and Fitton, J. A., "Factors Affecting the Cyclic Loading Strength of Soils", Vibration Effects of Earthquakes on Soils and Foundations, ASTM STP 450, American Society for Testing & Materials, 1969.

Leeds, D. J., "Seismicity of the Eastern and Midwestern United States", Technical Notes, Dames & Moore, Los Angeles, California, 1968.

Melhorn, W. N. and Smith, N. M., "The Mount Carmel Fault and Related Structural Features in the South-central Indiana", Indiana Department Conservation, Geol. Survey, Report of Progress No. 16, 1959, pp. 29.

National Transportation Safety Board, "Protection of Transportation Facilities Against Earthquakes", Washington, February, 1972, pp. 41.

Nicholls, H. R., Johnson, C. F., and Duvall, W. I., "Blasting Vibrations and Their Effects on Structures", U.S. Department of the Interior, Bureau of Mines Bulletin 656, Washington, 1971.

Nuttli, O. W., "The Mississippi Valley Earthquakes of 1811 and 1812: Intensities, Ground Motion and Magnitudes", paper submitted to the International Conference on Microzonation, Nov. 1972, Seattle, Washington, 1972.

Nuttli, O. W., Private communication, Sept. 11, 1972 (1972a).

Paja, A. G., Private communication, Sept. 25, 1972.

Reynolds, W. C., Private communication, Sept. 1, 1972.

Richter, C. F., Elementary Seismology, W. H. Freeman & Co., San Francisco, 1958.

Seed, H. B., Idriss, I.M., Kiefer, F. W., "Characteristics of Rock Motions during Earthquakes", Journal of the Soil Mechanics and Foundations Div., ASCE, Vol. 95, No. SM5, Sept. 1969, pp. 1199-1218.

Upshaw, W. S., Private communication, Sept. 18, 1972.

United States Department of Commerce, Environmental Science Services Administration, Coast & Geodetic Survey, "U.S. Earthquakes, 1928-1968", U.S. Government Printing Office, Washington, D.C., 1970.

United States Atomic Energy Commission, (10 CFR-Part 100) "Nuclear Power Plant Seismic and Geologic Siting Criteria", Federal Register, Vol. 36, No. 228, Nov. 1971.

Legend

- VIII Roman Numerals Denote the Maximum Earthquake Intensity (Based on the Modified Mercalli Scale of 1931)
- Indicates Earthquake Epicenter (Epicenter is Defined as the Area on the Earth's Surface Directly above the Earthquake Subterranean Origin)
- 1967 Year in which Earthquake Occurred

NOTE: DATA OBTAINED FROM EPPLEY (1965)

10 0 50miles 100miles
1:2,500,000