Earthquakes

Description

An earthquake occurs when a fault suddenly ruptures and releases elastic energy in the form of seismic waves (Fig. 1-1). Rupture begins at the hypocenter (referred to as the epicenter at the surface). Seismic waves can also be generated by volcanic activity, mine blasts, and other natural and manmade sources, but are generally not strong enough to cause damage to the built environment. Magnitude is a measure of the size of an earthquake. As shown in Figure 1-2, it is also a measure of equivalent energy (for example, in comparison to a large lightning bolt or a nuclear test); because magnitude is not linear, a difference of one unit in magnitude is equal to 32 times the difference in equivalent energy.

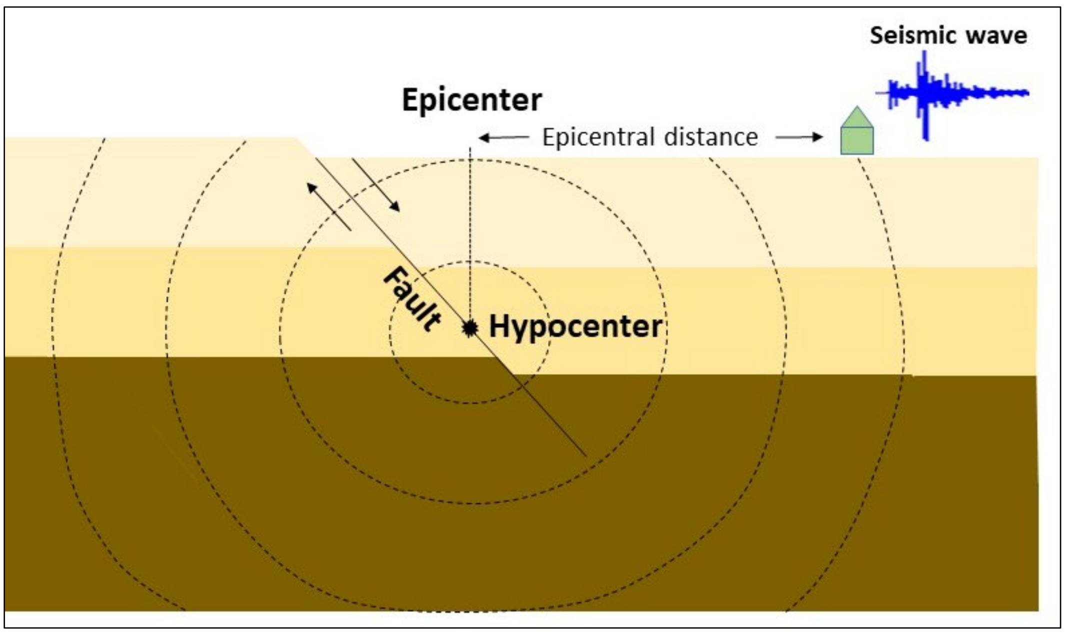


Figure 1-1. Earthquakes occur when two blocks of the earth suddenly slip past one another. The surface upon which they slip is called the fault or fault plane. The location below the earth's surface where the slip starts is called the hypocenter, and the location directly above the hypocenter on the surface is called the epicenter.

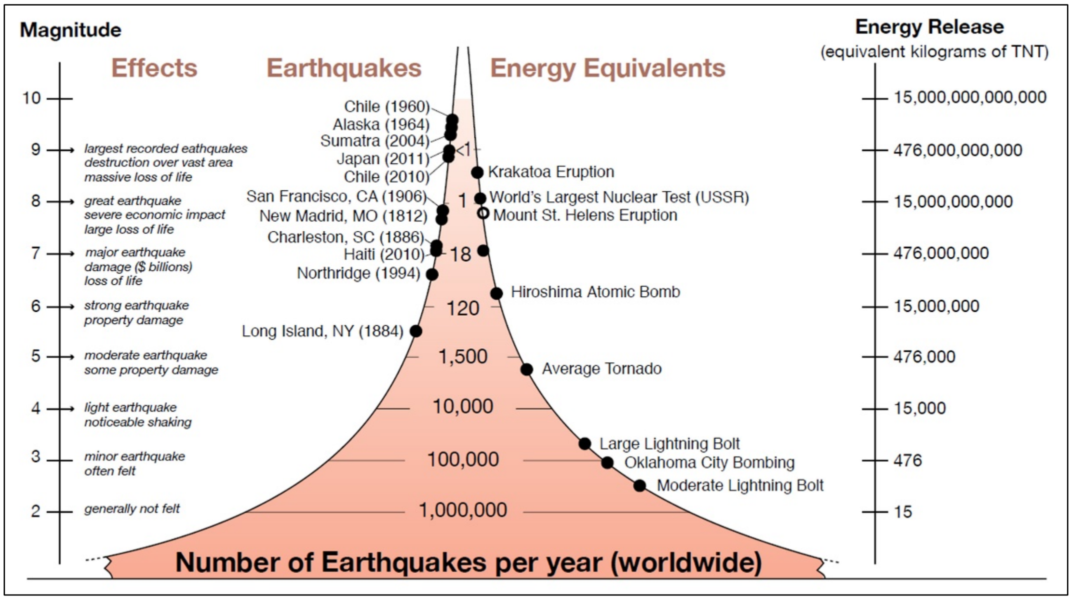


Figure 1-2. Numbers of earthquakes per year throughout the world, and the relationship between earthquake magnitude and energy equivalence. Illustration courtesy Incorporated Research Institutions for Seismology

Earthquakes are caused by the slow movements of tectonic plates. Figure 1-3 shows that earthquakes concentrate around the Pacific Ocean—the so-called Pacific Ring of Fire—where one tectonic plate subducts under the other (such as the Nazca plate subducting under the South American plate and the Pacific plate subducting under the Eurasian plate; where this occurs is referred to as a subduction zone); earthquakes also are caused by one plate sliding past the other (such as what happens at the San Andreas Fault along coastal California; where this occurs is referred to as a transform boundary). Earthquakes also concentrate along the mid-oceanic ridges, where two plates move away from each other (a divergent boundary) and in the Himalaya Mountain, where the Indo-Australian plate collides with the Eurasian plate and forms the highest mountain in the world (Fig. 1-3). The largest earthquakes (magnitude equal to or greater than 9.0) have all occurred along subduction zones (Fig. 1-3).

Although most earthquakes, especially large ones (magnitude equal to or greater than 8.0), have occurred along plate boundaries, a few strong earthquakes have occurred in plate interiors. Figure 1-4 shows locations of earthquakes with magnitude 3.0 or greater that have occurred in and around Kentucky since 1800. Kentucky is affected by several seismic zones: the New Madrid and Wabash Valley Seismic Zones to the west and the Eastern Tennessee Seismic Zone to the east (Fig. 1-4). The largest recorded earthquake inside Kentucky's borders was the Sharpsburg earthquake of July 27, 1980, in Bath County. Its magnitude was 5.2, and it caused an estimated $3 million in damage in Maysville. The 2003 Bardwell earthquake in western Kentucky (magnitude 4.0) caused some minor damage in Carlisle County, and the 2012 Perry County earthquake (magnitude 4.2) caused some minor damage in Letcher and Perry Counties in southeastern Kentucky, including at the Letcher County Courthouse. The most significant earthquakes affecting Kentucky, as well as the entire central United States, occurred from December 1811 to February 1812 in the New Madrid Seismic Zone. At least three large earthquakes, each estimated to have had a magnitude greater than 7.0, occurred during that short timeframe. Paleoliquefaction studies (studies of ancient sand blows) indicate that a similar sequence of large earthquakes occurred in the New Madrid area in 1450 A.D. and 900 A.D. Table 1-1 lists earthquakes with magnitude 4.0 or greater that have occurred in Kentucky since 1800.

Table 1-1. Earthquakes with magnitude 4.0 or greater occurring in Kentucky since 1980.

Date	Location	Magnitude	Notes
1980	Sharpsburg	5.2	Significant damage in Maysville
1988	Bath County	4.6	Shaking was felt in the area
2003	Bardwell	4.0	Some minor damage in Bardwell
2012	Perry County	4.2	Some minor damage in Letcher and Perry Counties

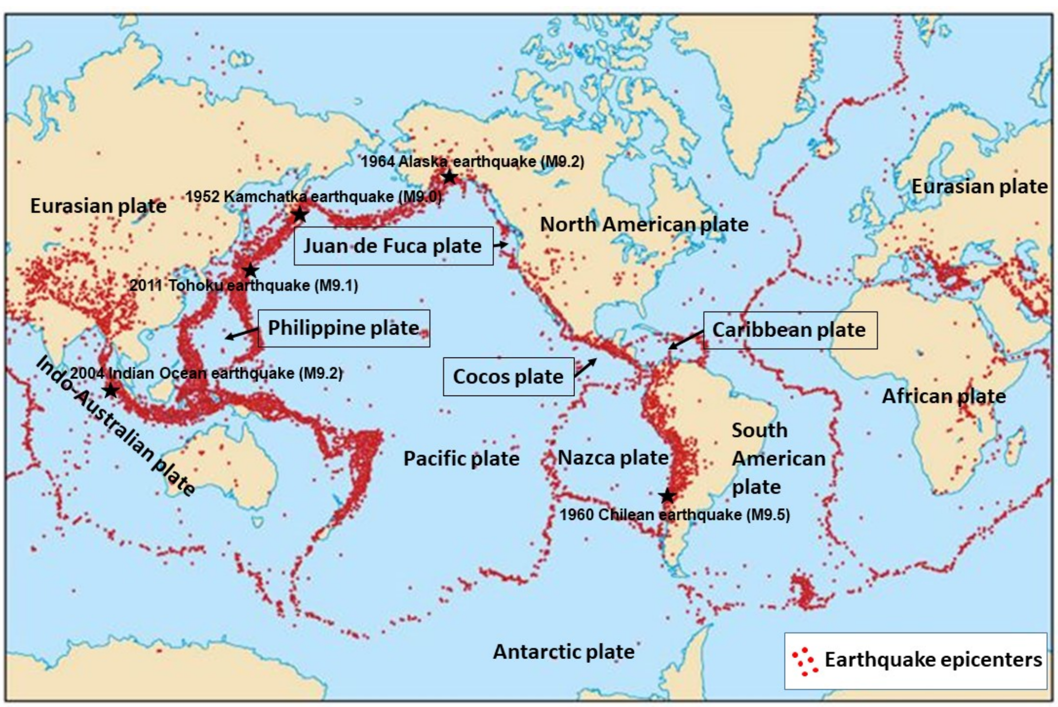


Figure 1-3. Plate boundaries and locations of earthquake epicenters. Black stars are the epicenters of the five largest earthquakes (magnitude greater than or equal to 9.0) in the world.

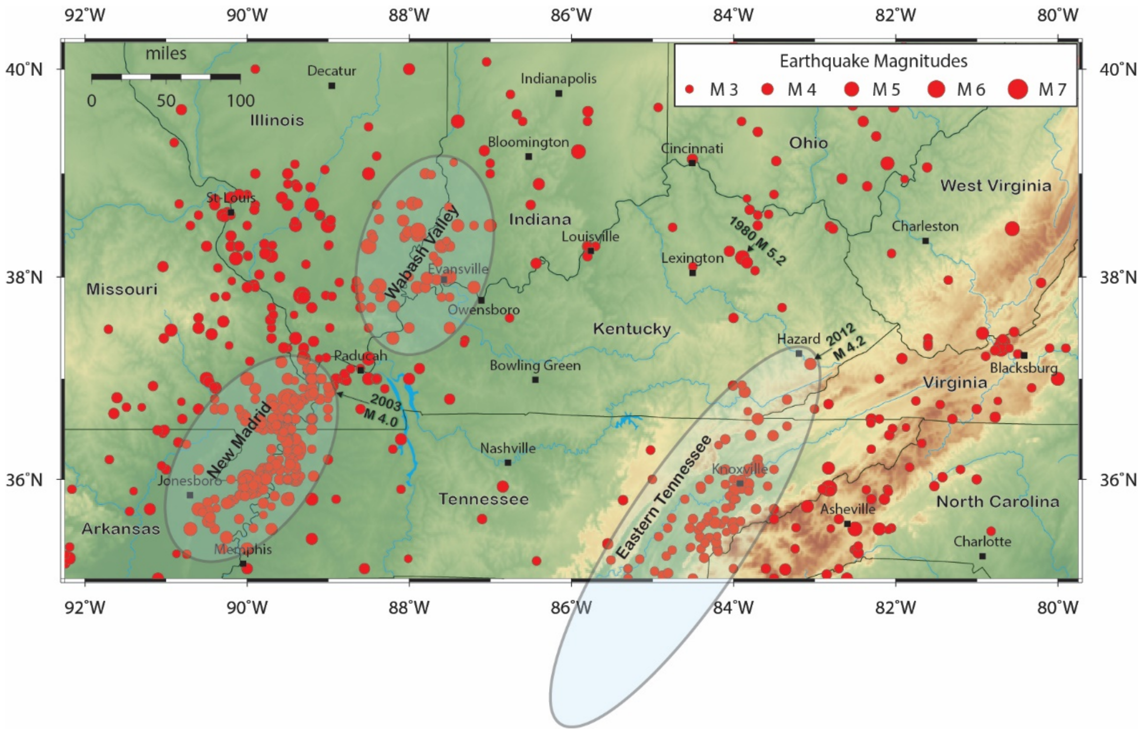


Figure 1-4. Locations of earthquakes of magnitude 3 or greater that have occurred in and around Kentucky. From Carpenter and others (2014).

Seismic Hazards

Seismic hazard is the physical phenomenon of an earthquake that can cause damage to the built environment (Fig. 1-5) (Carpenter and others, 2014). When an earthquake (fault rupture) occurs, the rupture may continue to the surface and create a *surface rupture hazard*, which can damage any building or structure built on it. The fault rupture also generates strong seismic waves that propagate along the ground surface and create a *ground-motion hazard* that can damage or even collapse buildings and other structures. Figure 1-6 shows damage to a home in Bath County caused by ground motion (shaking) from the 1980 Sharpsburg earthquake.

Surface rupture and ground motion are the primary hazards generated directly by an earthquake. Not all earthquakes generate surface rupture, however; in particular, quakes smaller than magnitude 6 do not. For example, the 1980 Sharpsburg earthquake (magnitude 5.2) did not generate surface rupture. Ground-motion hazard can affect a large area (Fig. 1-5), and is responsible for the majority of the damage from an earthquake. Thus, ground-motion hazard from earthquakes is of major concern.

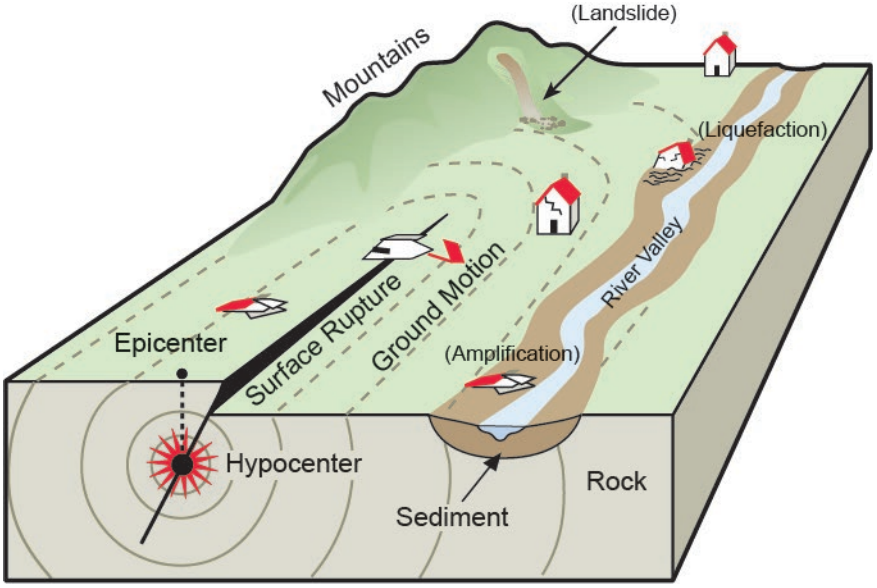
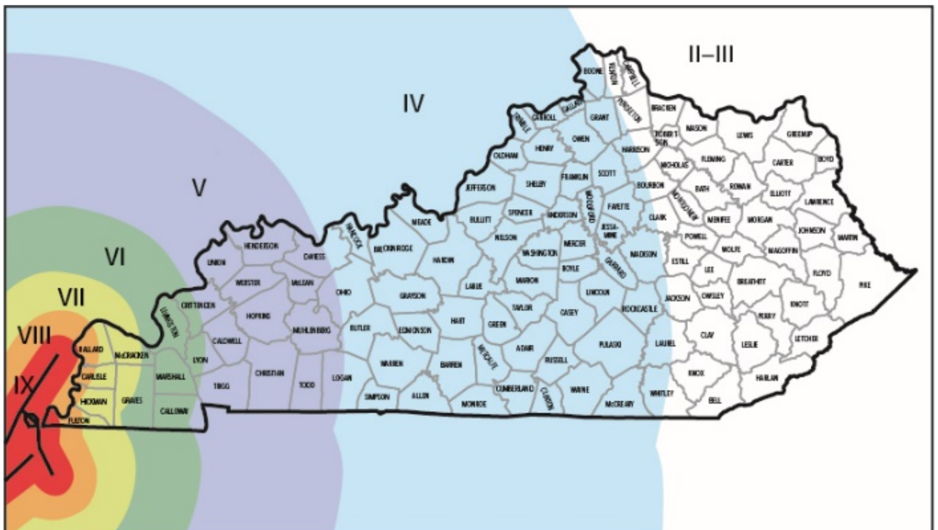


Figure 1-5. Seismic hazards produced from an earthquake (fault rupture). Strong ground shaking occurs throughout the region, and amplification, liquefaction, and landslides are induced at certain locations by the strong shaking. From Carpenter and others (2014).

Figure 1-6. Chimney damage in Bath County caused by the ground motion (shaking) from the 1980 Sharpsburg earthquake.

Ground motion is quantitatively measured as peak ground acceleration in terms of the percentage of the acceleration of gravity or peak ground velocity in terms of centimeters of shaking, potential damage level, or instrument intensity (i.e., modified Mercalli intensity). The table in the bottom part of Figure 1-7 lists the quantitative and qualitative measurements of ground motion. The level of ground motion at a site primarily depends on its distance from the fault that ruptured and the magnitude of the earthquake. Ground motion can be estimated from scientific information about earthquakes. The top part of Figure 1-7 shows the median peak ground acceleration on rock from a magnitude 7.5 scenario earthquake in the New Madrid Seismic Zone (Carpenter and others, 2014), which demonstrates that such an earthquake could have a significant impact on Kentucky, western Kentucky in particular.



Perceived Shaking	Not Felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent
Potential Damage	None	None	None	Very Light	Light	Moderate	Moderately Heavy	Heavy
PGA (%g)	< 0.17	0.17–1.4	1.4–3.9	3.9–9.2	9.2–18	18–34	34–65	65–124
Instrumental Intensity	II	III	IV	V	VI	VII	VIII	IX

Figure 1-7. Median peak ground acceleration on rock from a magnitude 7.5 scenario earthquake in the New Madrid Seismic Zone (top). Quantitative and qualitative ground-motion measurements (bottom). From Carpenter and others (2014).

Strong ground motion can also result in secondary hazards at sites under certain conditions (Fig. 1-5). Soft sediments overlying hard bedrock along river valleys tend to amplify ground motion, which is known as *amplification hazard*. For example, amplified ground motion caused by loose lake deposits contributed to the heavy damage in Mexico City during the earthquake of Sept. 19, 1985. Study (Woolery and others, 2008) has also shown that amplified ground motion by Ohio River alluvial deposits contributed to damage in Maysville during the Sharpsburg earthquake of July 27, 1980. Soft and saturated sandy soils can be liquefied by strong ground motion, a process called *liquefaction*. Liquefaction can cause damage by destabilizing foundations of buildings, bridges, and other facilities.

The 1811-12 New Madrid earthquakes caused widespread liquefaction along the Mississippi River. Strong ground motion can also trigger landslides, known as *earthquake-induced landslides,* in areas with steep slopes (Fig. 1-5). These secondary hazards can be assessed based on the primary ground-motion hazards, local geology, and site conditions. For example, the potential ground-motion amplification hazard can be assessed from geologic mapping, in-situ shear-wave velocity measurements, and geotechnical data (Wang, 2008). Figure 1-8 shows the potential hazard from amplification in Kentucky, developed from available shear-wave velocity and geotechnical data and geologic maps. KGS can produce more accurate amplification, liquefaction, and triggered-landslide hazard maps for the state or any county.

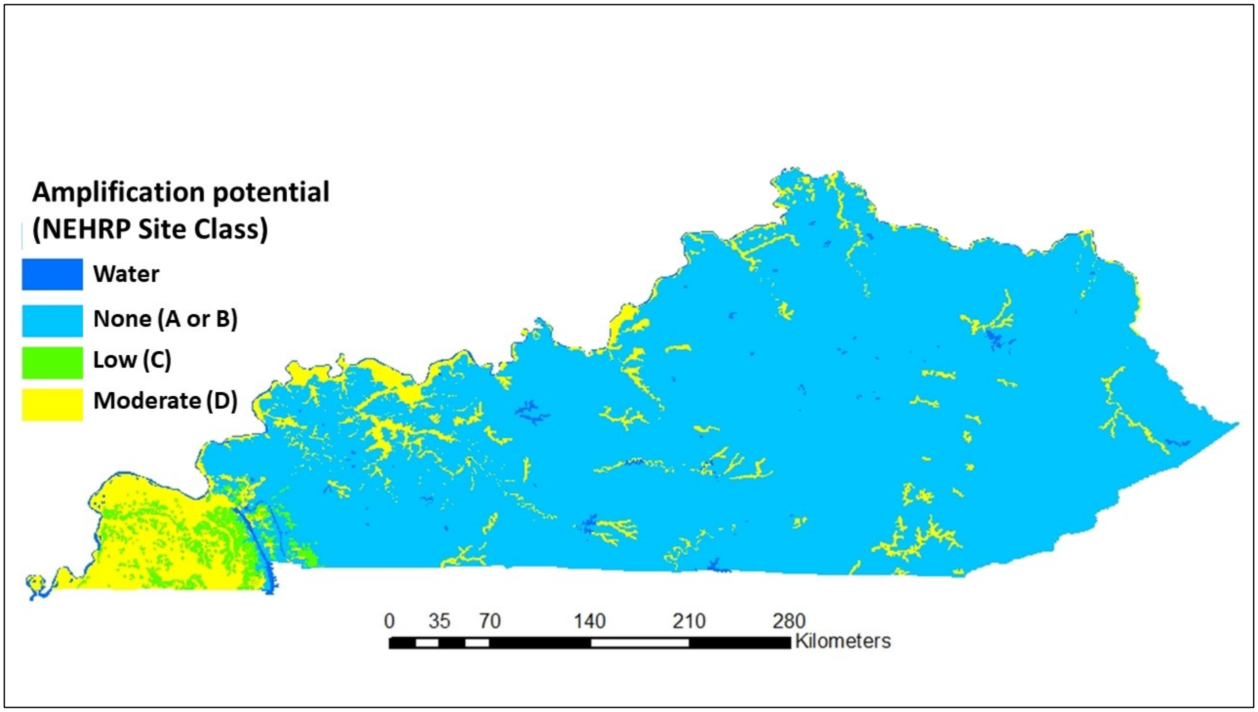


Figure 1-8. Potential ground-motion amplification hazard in Kentucky. The National Earthquake Hazards Reduction Program has classified this hazard for the United States. The moderate amplification potential shown on this figure is equivalent to NEHRP site class D; low amplification potential is equivalent to NEHRP site class C; nil amplification potential is equivalent to NEHRP site classes A or B.

Impacts

<u>Exposure</u>

The Federal Emergency Management Agency has developed the HAZUS methodology and software for federal, state, regional, and local governments to use to estimate losses in planning for earthquake hazard mitigation, emergency preparedness, response, and recovery. Extensive databases, containing information such as demographic aspects of the population in a study region, square footage for different occupancies of buildings, and numbers and locations of bridges and highways, is embedded in HAZUS. Figures 1-9 through 1-11 show population distribution, total building exposure in terms of dollar value, and locations of highways and bridges in Kentucky, respectively.

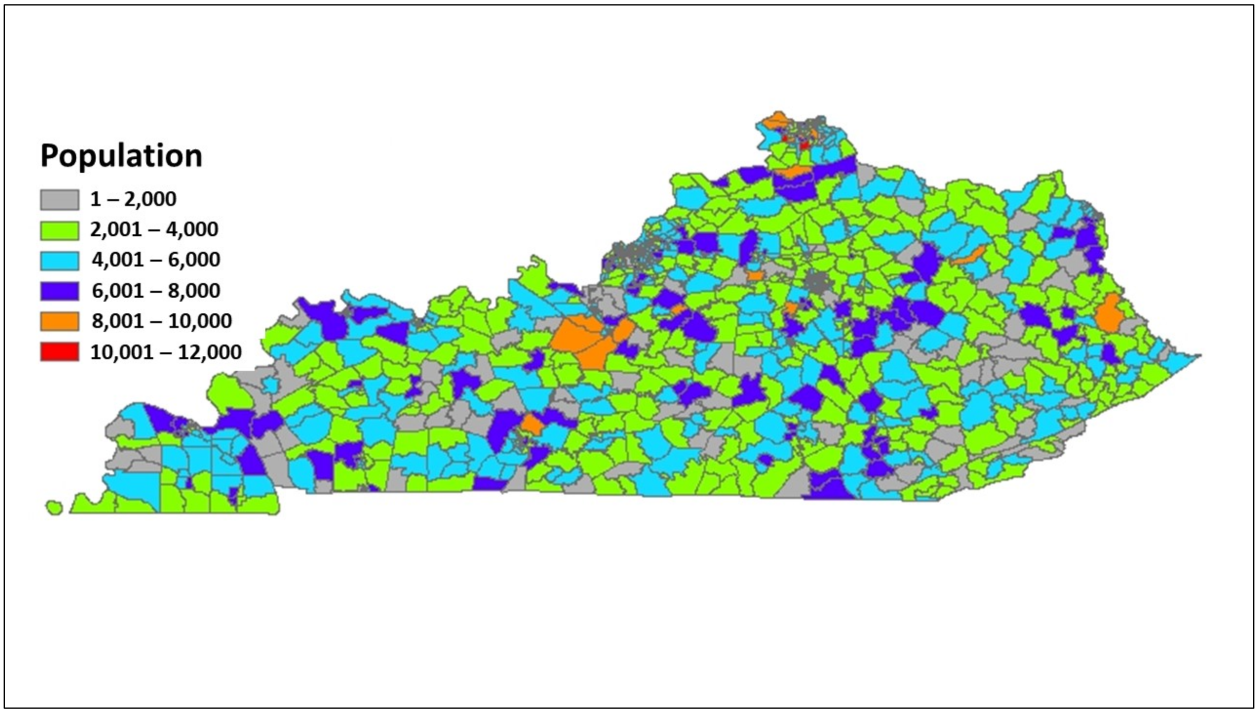


Figure 1-9. Population distribution in Kentucky.

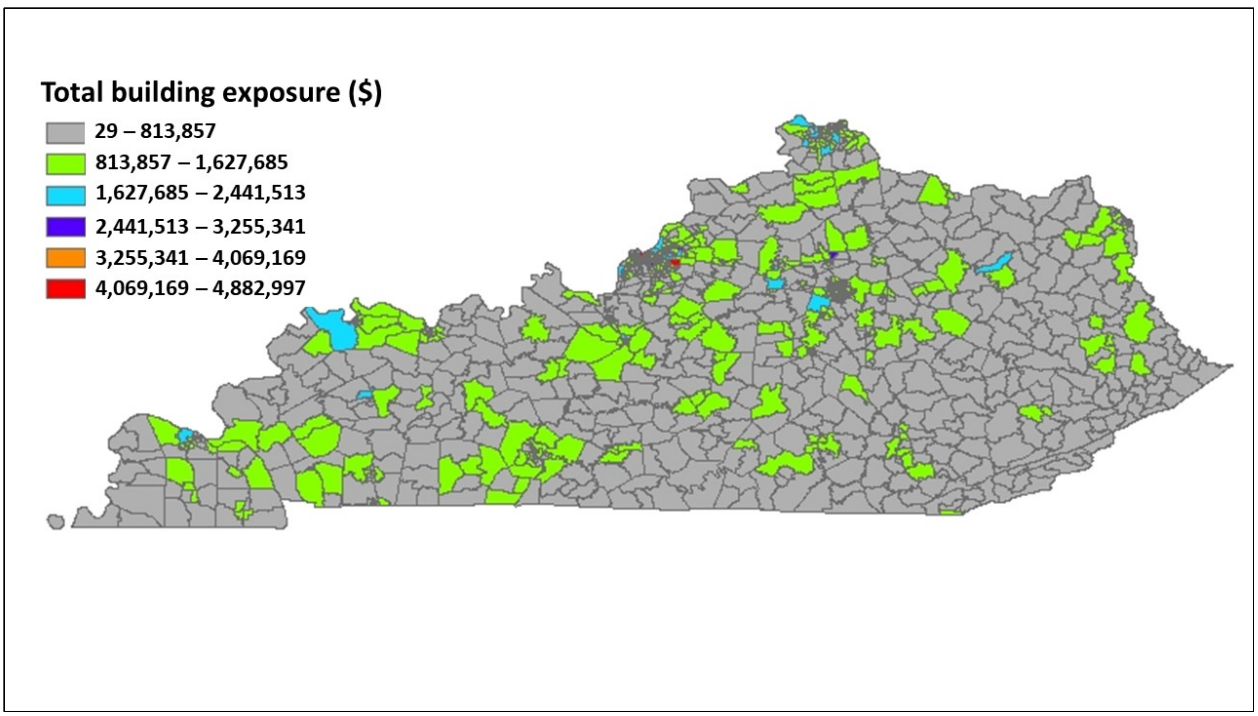


Figure 1-10. Total building exposure (dollar value) in Kentucky.

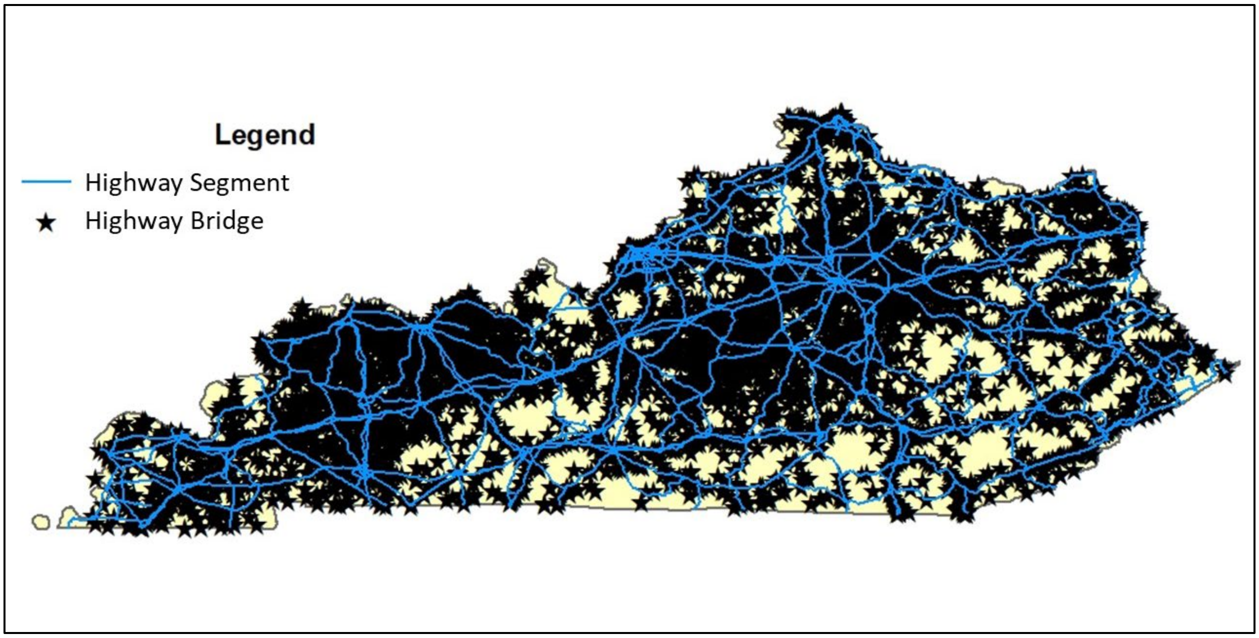


Figure 1-11. Locations of highways and bridges in Kentucky.

Potential Impacts

Potential impacts, including economic loss and life safety, can be assessed using the HAZUS software and databases. These potential impact assessments can be used for mitigation planning and emergency preparedness. Five scenario earthquakes (Table 1-2) were selected to assess potential impacts using the HAZUS databases and default amplification, liquefaction, and triggered-landslide hazards. Figure 1-12 shows peak ground acceleration on rock from the scenario earthquake of magnitude 7.5 along the central New Madrid Fault, and indicates that ground-motion hazard is very high in the epicentral area, with peak ground acceleration greater than 0.65g. Tables 1-3 and 1-4 list casualty and loss estimates for the five scenario earthquakes, respectively
(Table 1-2).

Table 1-2. Source parameters for scenario earthquakes.

Seismic Zone	Epicenter Location	Magnitude	Focal Depth
New Madrid I	36.52°N/-89.53°W	7.0	15 km
New Madrid II	36.52°N/-89.53°W	7.5	15 km
New Madrid III	35.50°N/-89.99°W	7.0	10 km
Wabash Valley	38.17°N/-87.71°W	6.5	15 km
Sharpsburg	38.17°N/-83.91°W	5.0	12 km

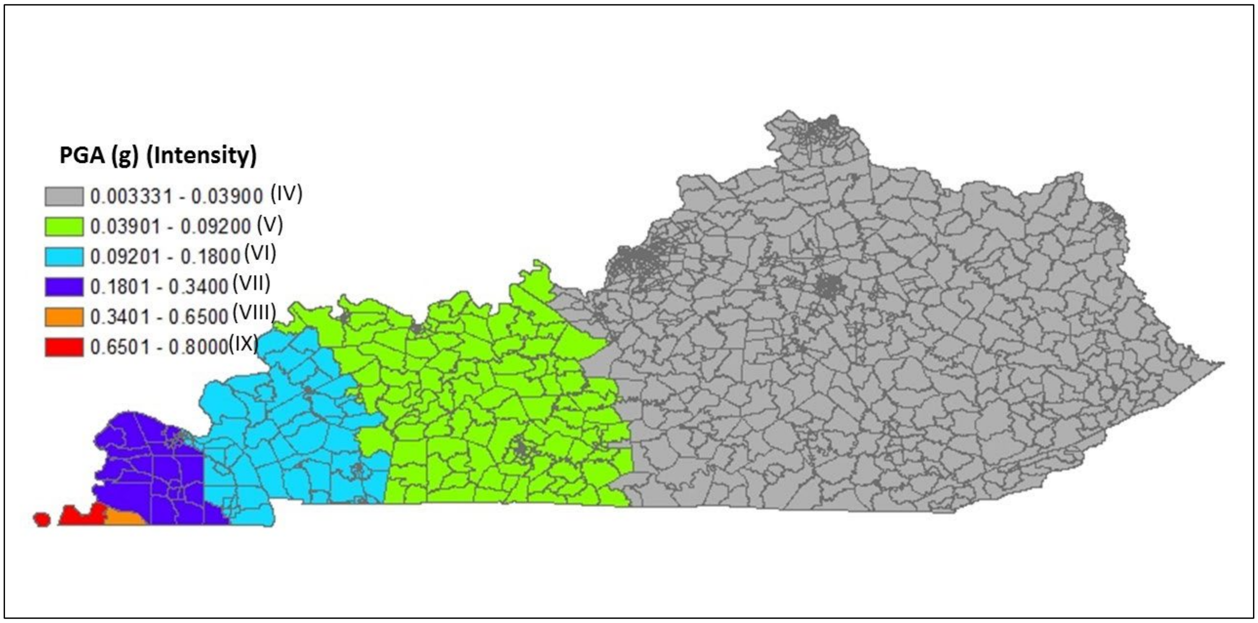


Figure 1-12. Peak ground acceleration on rock from a scenario earthquake of magnitude 7.5 in the central New Madrid Seismic Zone (New Madrid scenario II).

Table 1-3. Casualty estimates for Kentucky from scenario earthquakes.

Scenario	Time	Level 1	Level 2	Level 3	Level 4
New Madrid I	2 a.m.	354	61	6	11
	2 p.m.	700	131	16	28
	5 p.m.	652	124	31	26
New Madrid II	2 a.m.	1,969	465	48	88
	2 p.m.	6,992	1,917	273	517
	5 p.m.	7,016	1,910	313	488
New Madrid III	2 a.m.	76	10	1	2
	2 p.m.	157	23	2	4
	5 p.m.	153	23	5	4
Wabash Valley	2 a.m.	492	74	7	13
	2 p.m.	903	154	17	31
	5 p.m.	681	119	28	24
Sharpsburg	2 a.m.	1	0	0	0
	2 p.m.	1	0	0	0
	5 p.m.	1	0	0	0

Severity Level 1: Injuries will require medical attention, but hospitalization is not needed.
Severity Level 2: Injuries will require hospitalization but are not considered life-threatening.
Severity Level 3: Injuries will require hospitalization and can become life-threatening if not promptly treated.
Severity Level 4: Victims are killed by the earthquake.

Table 1-4. Building-related loss estimates for Kentucky from scenario earthquakes.

Scenario	Capital Stock Losses (million dollars)	Income Losses (million dollars)	Total Losses (million dollars)
New Madrid I	1,097.54	396.37	1,493.90
New Madrid II	6,304.28	1,884.46	8,188.74
New Madrid III	233.74	100.76	334.50
Wabash Valley	1,749.20	654.73	2,403.93
Sharpsburg	2.88	1.0	3.88

The HAZUS methodology and software are flexible enough so that locally developed inventories and other data that more accurately reflect the local environment can be substituted for the built-in tables, resulting in increased accuracy. Estimation of potential impacts can also be more accurately estimated with more accurate amplification, liquefaction, and triggered-landslide hazard maps.

Annual Frequency of Occurrence[1]

Though there are issues with expressing and conceptualizing the probability of an earthquake in terms of an annual frequency of occurrence, for illustrative purposes, to meet interpretations of risk assessment content for 44 CFR Section 201.4, and using count data presented in this section, consider the following:

There have been four (4) Magnitude 4.0 or greater earthquake events in Kentucky since 1980. (See Table 1-1.) Expressed as a frequency, that is four (4) events in 38 years or one (1) event every nine and one-half (9.5) years.

There have been 29 Magnitude 3.0 or greater earthquake events in Kentucky since January 1, 1970. There have been 24 Magnitude 3.0 or greater earthquake events in Kentucky since January 1, 1980. (See Figure 1-4[2].) Expressed as frequencies and with 1970 and 1980 being inclusive as year one, that is 29 Magnitude 3.0 or greater earthquake events in Kentucky in 49 years and 24 Magnitude 3.0 or greater earthquake events in Kentucky in 39 years. Respectively, that translates to a frequency of one (1) Magnitude 3.0 or greater earthquake event every 1.7 or 1.6 years.

[1] The following section on Annual Frequency has been added by the University of Kentucky Hazard Mitigation Grants Program Office (UK-HMGP) and by Kentucky Emergency Management (KYEM) and does not necessarily reflect the views of the Kentucky Geological Survey (KGS).

[2] The count of events was verified by Kentucky Geological Survey in reference to Figure 1-4.

A Note on Future Conditions[3]

The Commonwealth of Kentucky Enhanced Hazard Mitigation Plan for 2018 (CK-EHMP 2018) has relied on a recent study on climate conditions from modeling specific to Kentucky that was conducted by the United States Army Corps of Engineers (USACE) and the Ohio River Basin Alliance (ORB Alliance). This study is called *Ohio River Basin: Formulating Climate Change Mitigation/Adaptation Strategies through Regional Collaboration with the ORB Alliance*.

From this study, the Commonwealth of Kentucky assumes the following:

- There has been a gradual warming trend throughout the Ohio River Basin since the late 1970s.
- Precipitation has increased during the latter summer and early fall months since the late 1970s.
- Summer highs and winter lows between 2011 and 2040 will remain generally within what has been observed over that historic period. (But, record temperatures, rainfall, or drought cannot be ruled out.)
- The influence of the jet stream across the Ohio River Basin latitudes increases the *variability* of the weather (and further complicates forecasting future climatic conditions).
- Significant changes in river flow discharges and mean annual air temperatures will not be occurring before 2040. The climate will not vary substantially from what has been experienced between 1952 and 2001.

In other words, there has been gradual warming since the late 1970s. This gradual warming will continue without much significant change until 2040. (After 2040, the modeling in the study predicts temperatures may rise one (1) degree every decade through 2099.) Further, part of this gradual warming since the late 1970s involves precipitation increases. Precipitation increases affects nearly every hazard identified in this hazard mitigation plan: Landslides are triggered by precipitation; sinkholes flood with increased precipitation; flash flooding increases from severe storms; and winter storms either increase or become more severe.

The variability interpretation also is interesting and applicable to expected future conditions for Kentucky's identified hazards:

With gradual warming and its effects on summer highs and winter lows, with increased precipitation, and with increased variability of the weather, it is expected that the effect on probability (or, rather, the frequency and/or severity) of earthquake events will be indeterminate.

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[3] The below statement is made by the University of Kentucky Hazard Mitigation Grants Program Office (UK-HMGP) and by Kentucky Emergency Management (KYEM) and does not necessarily reflect the views of the Kentucky Geological Survey (KGS).

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Carpenter, N.S., Wang, Z., and Lynch, M., 2014, Earthquakes in Kentucky: Hazards, mitigation, and emergency preparedness: Kentucky Geological Survey, ser. 12, Special Publication 17, 11 p.

Wang, Z., 2008, A technical note on seismic microzonation in the central United States: Journal of Earth System Science, v. 117, no. S2, p. 749–756.

Woolery, E.W., T. Lin, Z. Wang, and B. Shi, 2008, The Role of Local Soil-induced Amplification in the 27 July 1980 Northeastern Kentucky Earthquake, Environmental & Engineering Geoscience, 14: 267–280.