UrbanFootprint

TECHNICAL DOCUMENTATION

UrbanFootprint Earthquake Loss Methodology

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Overview

UrbanFootprint estimates structural losses due to earthquakes by leveraging trusted, publicly available damage functions provided by FEMA's Hazus program, as described in the Hazus Earthquake Model Technical Manual. These damage functions use a variety of structural characteristics to estimate the percentage of structure value lost due to increasing levels of peak ground acceleration (PGA). We calculate both conditional losses for specific peak ground acceleration, and annualized losses based on the annual probability distribution of PGA intensities. A comparison with FEMA's National Risk Index reveals strong overall agreement at the national level, with some regional variations, particularly along the West coast and in Nevada.

Calculating Annual PGA Probabilities

U.S. Geological Survey (USGS) provides national maps of PGA (%g) at specific probabilities, such as a 2% chance in 50 years, for site classes from the 2020 National Earthquake Hazards Reduction Program (NEHRP). These site classes reflect a range of soils from hard rock to soft soil and are described by the shear wave velocity in the top 30m of soil (Vs30). However, these maps don't directly provide the site-specific PGA. Calculating that requires knowing the local site class in order to obtain the corresponding PGA value.

UrbanFootprint leverages a novel machine learning-derived Vs30 dataset to significantly improve seismic risk assessment. First, this continuous Vs30 data allows us to interpolate PGA values, moving beyond the USGS's discrete Site Classes for more accurate, location-specific ground shaking probabilities. Second, the dataset's high spatial resolution enables us to downscale the USGS PGA maps, resulting in a unified, nationwide PGA map at approximately 270m resolution—both more detailed and accurate than the USGS's binned site class maps. In this process we convert from PGA values reported at standard probabilities to estimating the probability of standard PGA values. This transformation to estimate the probability distribution across PGA values for every location provides the basis for calculating structural damage, as described below.

Loss Methodology

UrbanFootprint estimates earthquake-induced structural losses using publicly available damage functions from FEMA's Hazus program. While Hazus utilizes detailed building and environmental characteristics to assess vulnerability, data limitations at a national scale necessitate a simplification of these archetypes. UrbanFootprint focuses on key structural attributes readily available in national datasets, such as building material, height, and occupancy type. By combining these simplified archetypes with UrbanFootprint's own earthquake risk assessments, we generate both conditional losses for specific ground shaking intensities and annualized losses based on the probability distribution of shaking levels. This approach enables a comprehensive evaluation of potential earthquake losses across the United States.

Hazus Archetypes

FEMA's Hazus program defines asset archetypes, a combination of structural and environmental characteristics that determine an asset's vulnerability to a hazard. In the case of earthquakes, described in the Hazus Earthquake Model Technical Manual, archetypes typically include information about: building material, building typology (including height) and seismic design level. The exact number of components that define an archetype varies, and only a few components are consistently required across all archetypes.

Structure Characteristics

While all archetype components are determinants of hazard impact, many are far too detailed to estimate at scale. In order to provide loss estimates across the US we identify a subset of component fields that we can estimate nationally using a variety of sources. In particular, we combine data from the National Structure Inventory (NSI) with UrbanFootprint's Base Canvas parcel data. The National Structure Inventory is a U.S. Army Corps of Engineers maintained database that catalogs structures across the United States, primarily to support risk assessments for natural hazards. Table 1 identifies the structural components we are able to estimate, the primary source of the data and how we handle null values.

Table 1. Sources and methodology for structural characteristics used in matching the HAZUS damage function with individual structures.

Structure Characteristic	**Source**	**Methodology**	**Required for every archetype**
Occupancy Type	NSI	The National Structure Inventory (NSI) point data was spatially joined to Base Canvas parcel polygons to assign parcel data to structures. Where parcels lacked corresponding NSI points, missing attribute values were imputed using mode or median calculations, based on the proximity and land use classification of neighboring UF parcels.	Y
Building material	NSI		Y
Square footage	NSI		N
Number of Stories	NSI		N
Year Built	UrbanFootprint Base Canvas	Pass-through from the parcel provider. Null parcel level values were filled using NSI year built data, which is a census block level average.	Y

Individual seismic damage functions also require structure information not present in the NSI or Base Canvas for steel, cement, and masonry structures. This includes attributes such as the type of reinforcement used in cement and masonry construction or the specific type of frame used for steel buildings. To account for this lack of data, we average damage functions for these structure types, as described below. Wooden and manufactured structures can be directly linked to specific damage functions based on NSI attributes, so no averaging is required for those structure types.
Wooden structures are differentiated by square footage, while manufactured structures do not have a size differentiation. Steel, cement, and masonry structures are all classified as high, medium, or low height based on the number of stories. The occupancy type of the structure, as provided by NSI, is used to link damage states to losses in terms of percentage of structure value lost.

Seismic Code Zones

In addition to the structure characteristics listed above, earthquake damage functions require the seismic building code for each structure. Hazus damage functions are differentiated into four different building code types, Pre-Code, Low Code, Medium Code, and High Code. Hazus provides guidance on how to derive the specific building code type based on the Uniform Building Code (UBC) seismic zone map (Figure 1) and the year the structure was built (Table 2). The UBC zone for each structure was determined by digitizing the map below and intersecting the structure locations with the resulting layer.

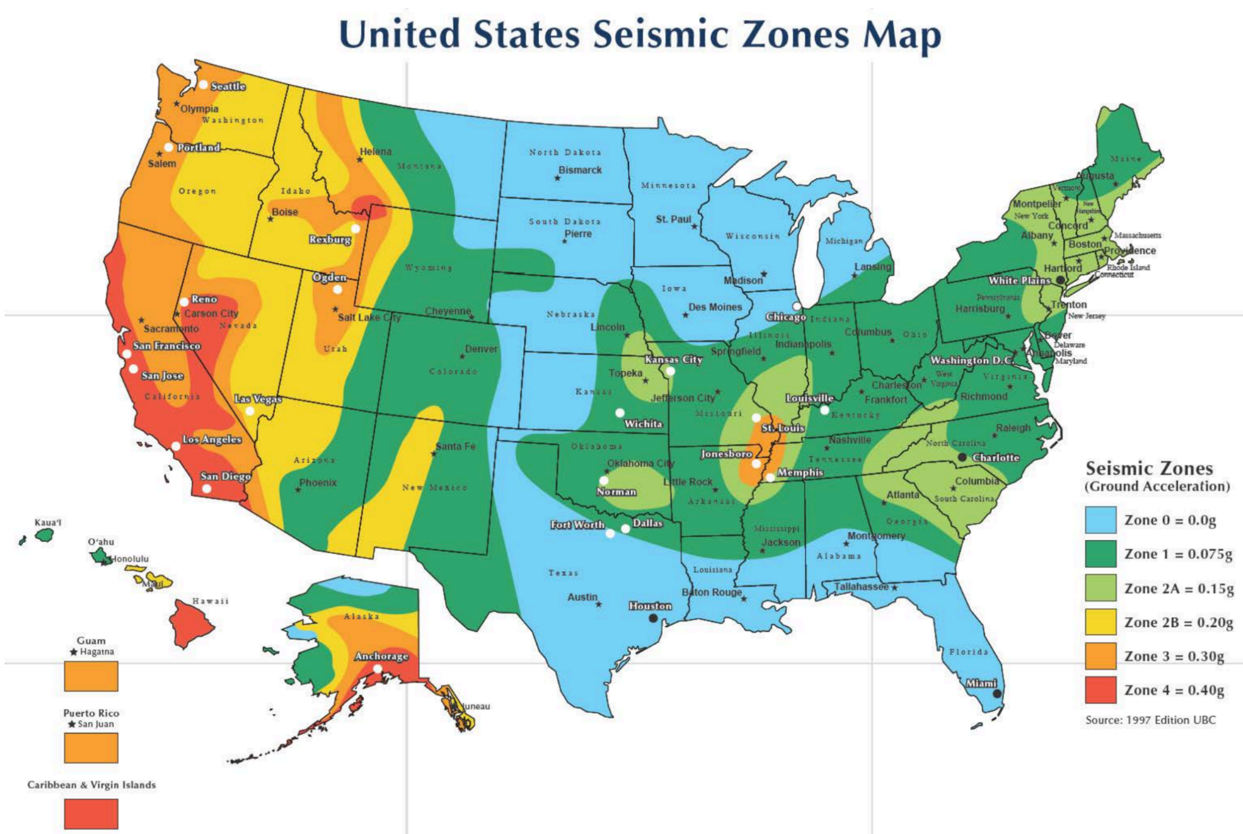

Figure 1. U.S. seismic zone map used to determine the Uniform Building Code (UBC).

Table 2. UBC zones and building year mapped to earthquake codes.

UBC Zone	Post-1975	1941-1975	Pre-1941
Zone 4	High-Code	Moderate-Code	Pre-Code (W1 = Moderate-Code)
Zone 3	Moderate-Code	Moderate-Code	Pre-Code (W1 = Moderate-Code)

UBC Zone	Post-1975	1941-1975	Pre-1941
Zone 2B	Moderate-Code	Low-Code	Pre-Code (W1 = Low-Code)
Zone 2A	Low-Code	Low-Code	Pre-Code (W1 = Low-Code)
Zone 1	Low-Code	Pre-Code (W1 = Low-Code)	Pre-Code (W1 = Low-Code)
Zone 0	Pre-Code (W1 = Low-Code)	Pre-Code (W1 = Low-Code)	Pre-Code (W1 = Low-Code)

Hazus Archetype Reduction

Each Hazus archetype has four associated damage curves, representing increasing levels of loss: Slight, Moderate, Extensive, and Complete (Figure 2). Each damage state has a corresponding damage curve, which shows the probability of reaching that damage state at different levels of ground shaking. However, due to data limitations, UrbanFootprint utilizes a reduced set of structure categories, each defined by a unique combination of building subtype, height (except for wood and manufactured structures), and building code. Figure 3 shows the Hazus damage curves for these consolidated UrbanFootprint structure categories.

In cases where an UrbanFootprint structure category maps directly to a single Hazus archetype, all necessary data is available, and a single set of four damage curves is used (as seen in some graphs in Figure 3). However, often, multiple Hazus archetypes correspond to a single UrbanFootprint structure category due to the lack of detailed national data. For example, steel, cement, and masonry structures in Hazus have subtypes based on frame construction or reinforcement (detailed in the Hazus Earthquake Model Technical Manual, Section 5.3). Since this level of detail is not available in the National Structure Inventory or Base Canvas parcel data, we consolidate these multiple Hazus subtypes into a single UrbanFootprint structure category. In these cases, we generate damage curves by leveraging Hazus's General Building Stock (GBS) data, which provides Census-tract level percentages for each subtype. Using GBS data, we create weighted average damage curves, effectively collapsing multiple Hazus curves into a single set for each UrbanFootprint steel, cement, and masonry structure category.

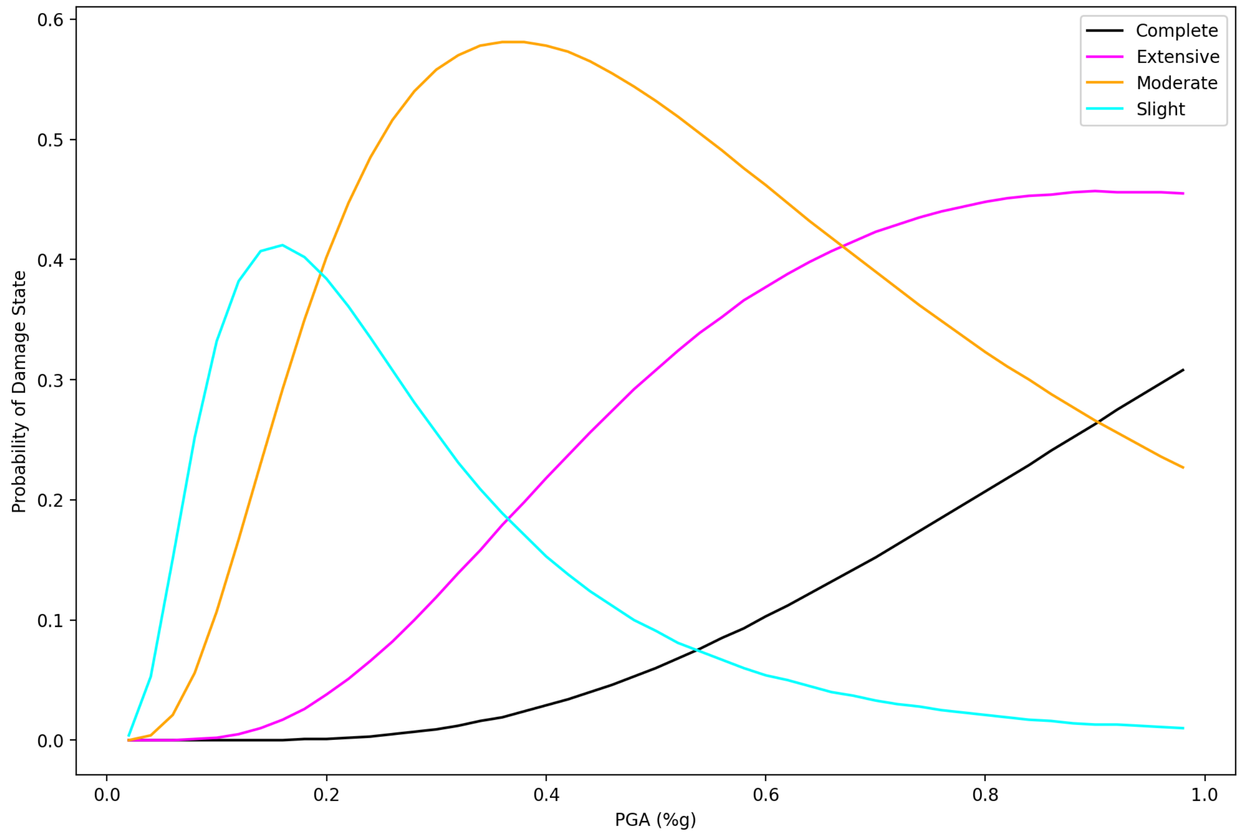

Figure 2. Example of damage curves for a single Hazus structure archetype.

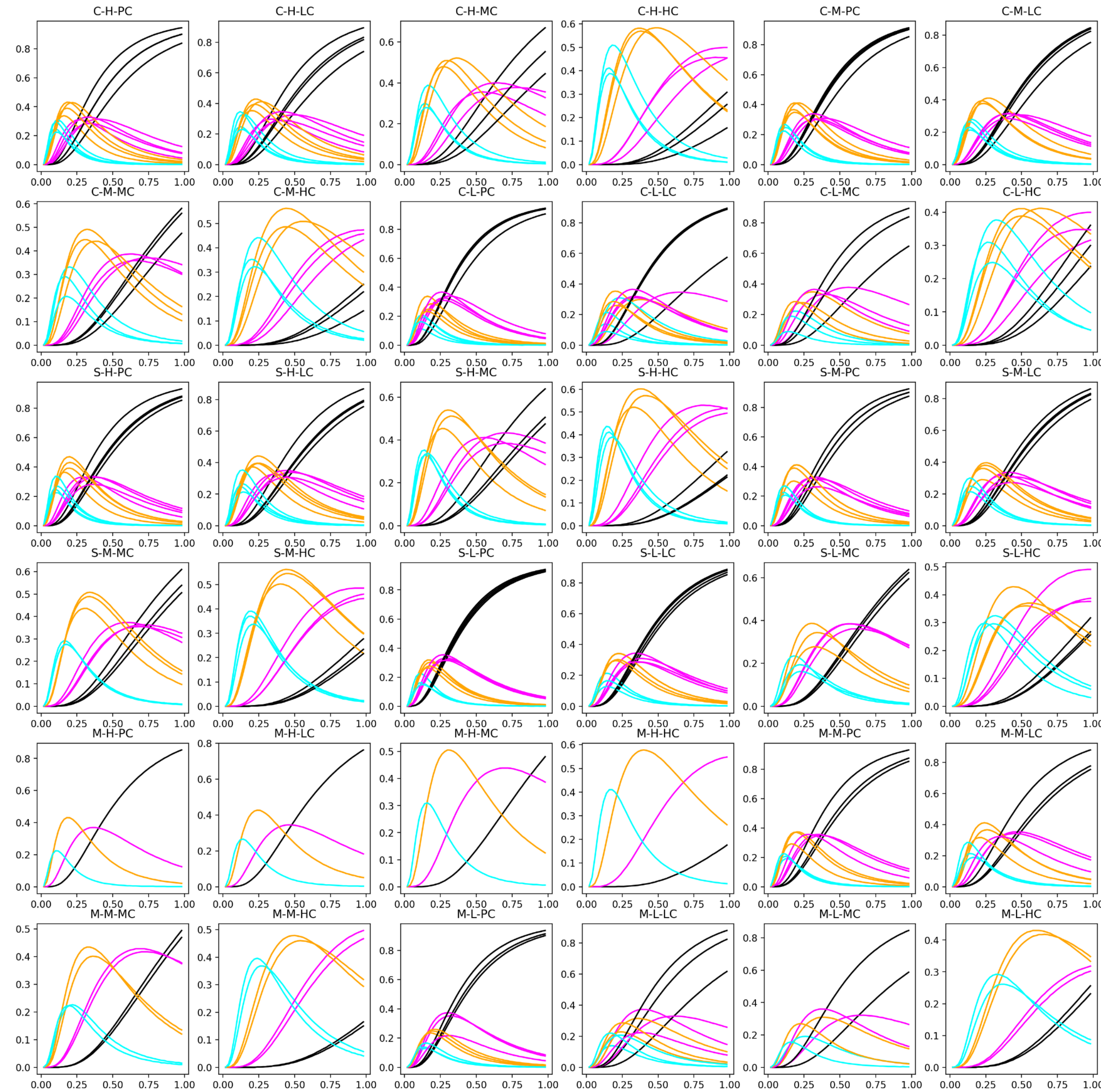

Figure 3. Damage curves to be collapsed for each UrbanFootprint structure category.

Converting Damage States to Losses

Using the UrbanFootprint structure categories and their associated damage curves, we adapt the Hazus methodology (see tables 11-2 - 11-4 in the FEMA Hazus Earthquake Technical Manual) to translate damage state probabilities into dollar losses.While Hazus focuses on building repair costs, we apply this relationship to a parcel's assessed improvement value, reflecting the potential impact of earthquake damage on property tax revenue.

For each structure i, the conditional loss given damage state ds is calculated by:

$$Loss_{ds,i} = AssdImpVal_i * DSProb_{ds,i} * RCS_{ds,k}$$

where:

- $AssdImpVal_i$ is the portion of the parcel's assessed improvement value attributed to structure i,
- $DSProb_{ds,i}$ is the structure's probability of being in a given damage state (Slight, Moderate, Extensive, Complete),
- $RCS_{ds,k}$ is the replacement cost ratio (% of total) for a given occupancy class k and damage state.

The probability of structure i being in damage state ds, $DSProb_{ds,i}$ is determined from the damage functions at the structure level according to the following equation:

$$P[ds|S_d] = \Phi\left[\frac{1}{\beta_{ds}} \ln\left(\frac{S_d}{\bar{S}_{d,ds}}\right)\right]$$

where:

- S_d is peak ground acceleration (PGA),
- $\bar{S}_{d,ds}$ is the median value of PGA at which the building reaches the threshold of the damage state ds,
- β_{ds} is the standard deviation of the natural logarithm of PGA for damage state ds,
- Φ is the standard normal cumulative distribution function.

Damage state specific losses are summed across the four damage states to yield conditional losses for structure i on PGA:

$$Loss_{i,pga} = \sum_{ds=1}^{4} Loss_{ds,i,pga}$$

Expected annual losses for structure i are then calculated by summing the product of conditional losses for each PGA value and the annual probability of that PGA value from UrbanFootprint's seismic hazard data (PGA values range from 2%g to 500%g):

$$EAL_i = \sum_{pga=0.02}^{5} Loss_{i,pga} * AnnualProb_{i,pga}$$

Model Validation

UrbanFootprint's building loss estimates can be aggregated to any spatial resolution, enabling comparisons with other public resources, such as FEMA's National Risk Index (NRI). The NRI provides data on natural hazard risk and losses at the county and Census tract levels. For earthquakes, the NRI's Expected Annual Loss to Buildings (EALB) metric represents the estimated average annualized economic loss to buildings in a specific area. This EALB value is derived by considering the total value of buildings, the likelihood and intensity of earthquake shaking (based on USGS data), and the historical loss ratio—the percentage of building value likely to be lost due to earthquake damage.

Comparison with FEMA National Risk Index (NRI)

Across the United States., the estimated annualized loss to buildings (EALB) from FEMA's NRI is $14.4B, while UrbanFootprint's estimate is $14.7B - a difference of only 2%. This close agreement is encouraging, especially given the different and complimentary methodologies employed. However, at the county level, greater variation emerges, with some notable spatial patterns. Specifically, NRI provides lower loss estimates than UrbanFootprint in the Northeast, along the California coast, and in the Seattle area, while NRI has higher damage estimates in inland California, Oregon, and Washington outside of Seattle (Figure 4).

To account for varying structure values across counties, we also compare the EALB ratios (Figure 5). Here we find similar patterns, with UrbanFootprint generally estimating slightly higher ratios in California, while NRI shows higher ratios in Nevada and Oregon. A comparison of select cities indicates that UrbanFootprint estimated damage ratios (Figure 6) and absolute losses (Figure 7) are slightly higher.

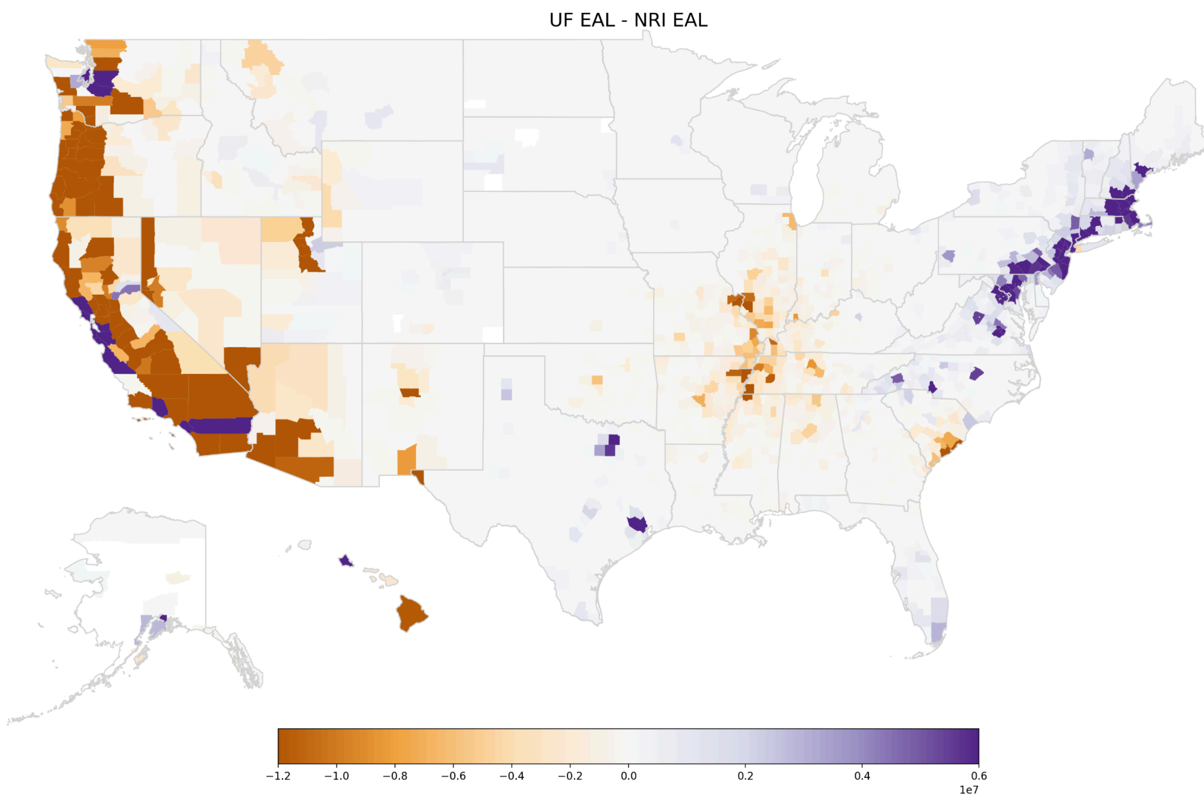

Figure 4. The difference between EALB between UrbanFootprint and FEMA NRI at the county scale.

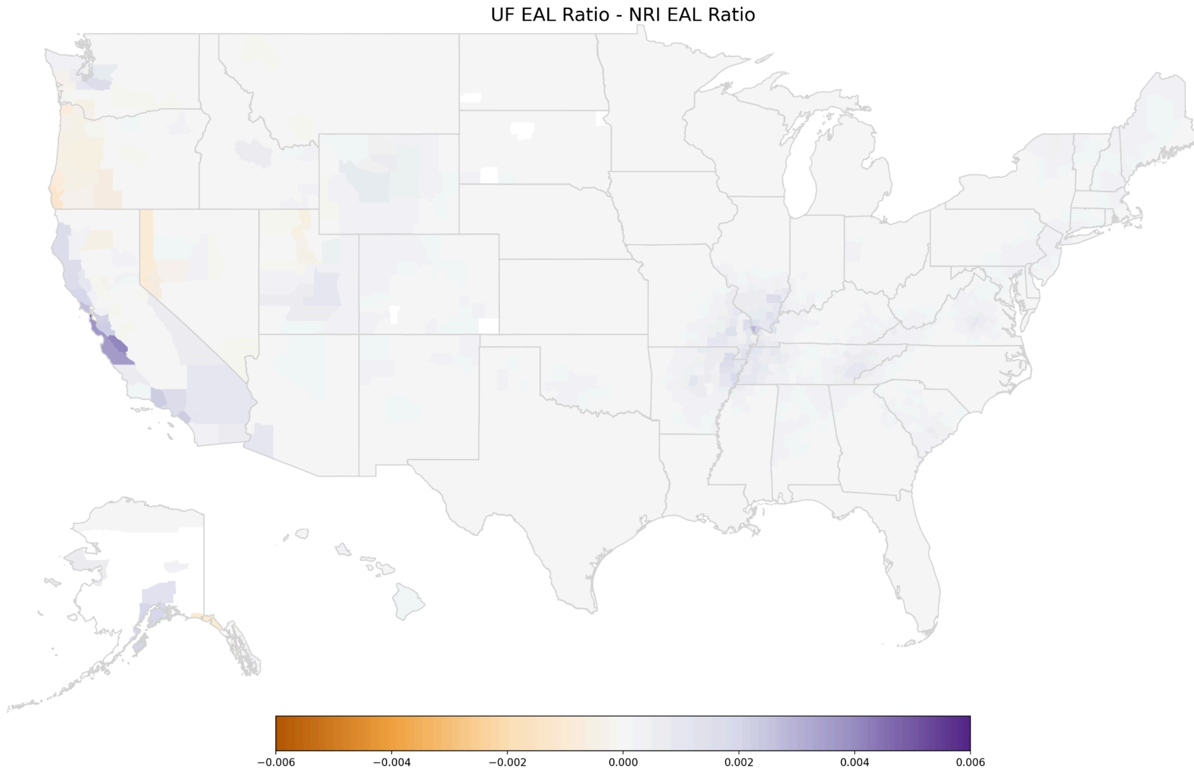

Figure 5. The difference in EALB loss ratios between UrbanFootprint and NRI.

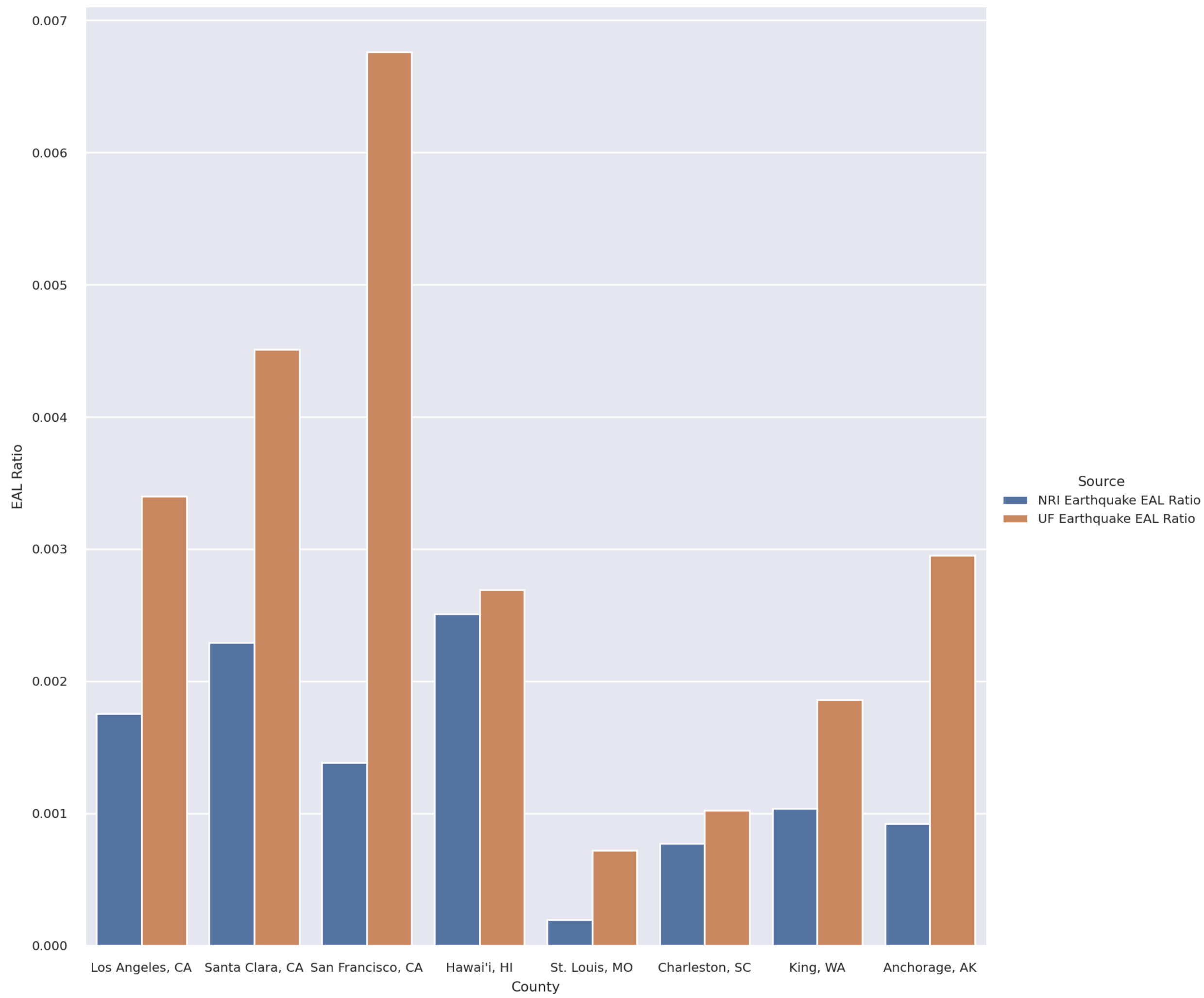

Figure 6. A comparison of EALB ratio between UrbanFootprint and FEMA's NRI for select cities in the US.

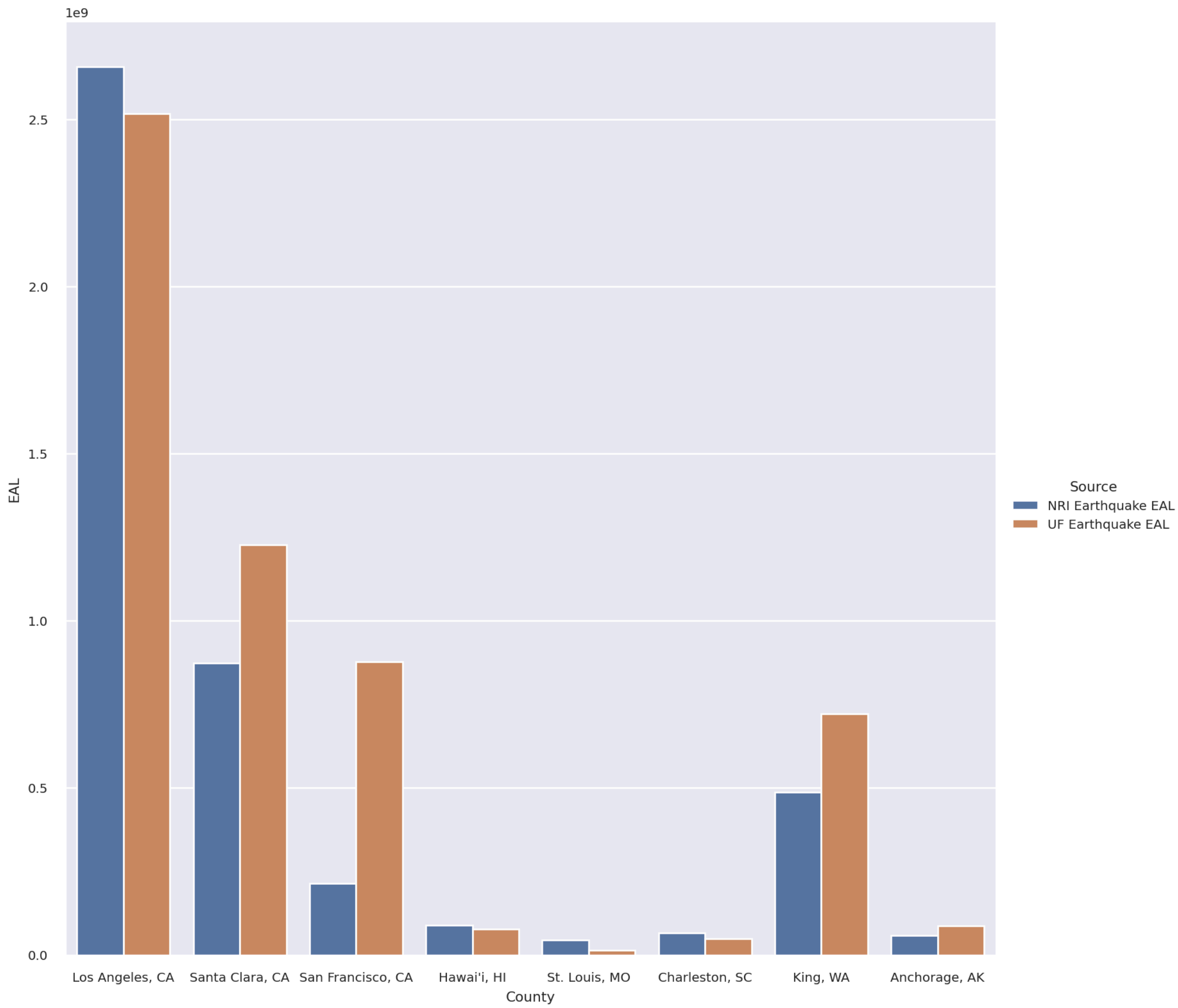

Figure 7. A comparison of EALB between UrbanFootprint and FEMA's NRI for select cities in the US.