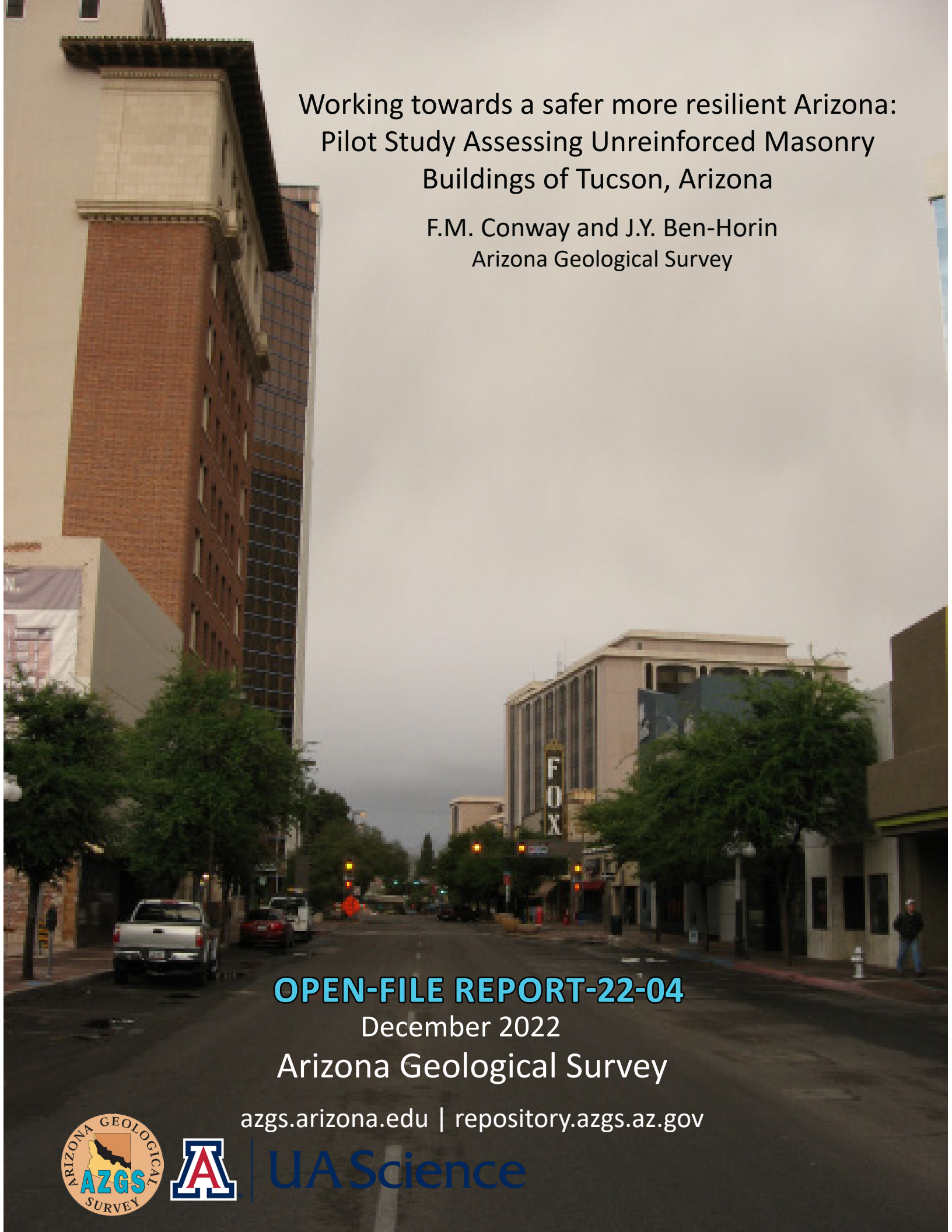

Working towards a safer more resilient Arizona: Pilot Study Assessing Unreinforced Masonry Buildings of Tucson, Arizona

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Arizona Geological Survey

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Arizona Geological Survey

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Executive Summary

Tucson resides in Arizona's tectonically active Basin and Range Province, where infrequent moderate- to large-magnitude earthquakes are capable of damaging homes, buildings, and infrastructure, injuring thousands and killing hundreds. The City of Tucson building stock includes more than 83,000 unreinforced or lightly reinforced masonry buildings that lack the ability to withstand moderate to strong ground-shaking that would accompany moderate to large-magnitude earthquakes on faults in the region. Preparing for the next damaging earthquake requires assessing and prioritizing which buildings should be retrofitted, such as schools, churches, and theaters, among other sites. Because most of Tucson's masonry buildings are single- or multi-family homes, civil authorities should pursue a campaign to inform citizens how to prepare their families and their homes in the event of a damaging earthquake. Recommendations for addressing Tucson's unreinforced masonry buildings are enumerated in the conclusion of this report, and are based in part, on mitigation activities pioneered in Utah, California, Oregon, Washington.

Introduction

Ground-shaking from the 2020 M5.7 Magna earthquake, immediately west of Salt Lake City, Utah, demonstrated that a moderate-magnitude temblor located within or close to an urban area can disrupt communities comprising older, unreinforced masonry buildings (URM). Rigid, non-ductile structures that place the public at high risk to fatalities or injuries include collapsing parapets, toppling chimneys, and failure of walls and roofs (Utah Seismic Safety Commission, 2021). Earthquake damage to rigid masonry building stock can cripple communities and hamper social and economic recovery. The number of people in Arizona living, learning, working and worshiping in URMs is unknown, and thus the risk is uncertain.

Established in 1775, Tucson is one of the oldest communities in the southwestern U.S. The current population numbers about 540,000 people with the metropolitan area hosting more than 1 million. In the summer of 2022, we approached the Pima County Assessor's Office for pre-1979 masonry building stock data for the City of Tucson. The Assessor's Office provided a database comprising 117,331 properties build prior to 1979 in Tucson. After purging buildings outside Tucson's city boundary and filtering out non-masonry buildings, the residual database comprises ~83,000, pre-1979 masonry buildings.

This report focuses on the number, distribution, age, condition, and physical parameters (Appendix I, size and number of stories) of pre-1979 masonry building stock of Tucson, i.e., URMs. A fuller understanding of the distribution and condition of older masonry buildings will inform city and county efforts, should they seek federal and state assistance to design and implement a systemic earthquake retrofit program (e.g., FEMA's Building Resilient Infrastructure and Communities Grant Program).

Earthquake Hazard and Risk of Tucson and Environs

Earthquakes occur where the Earth's crust is under tectonic stress. The accumulation of stress over thousands to tens-of-thousands of years can succeed in breaking and displacing adjacent rock units along planes of weakness that geologists refer to as faults. Energy is released when rocks along the fault zone slip relative to one another, resulting in earthquakes capable of producing light to severe ground-shaking. Large earthquakes are commonly associated with known fault systems, but earthquakes can also occur on cryptic faults – unreported faults generally lacking a surface expression. Figure 1 portrays faults and historical earthquake epicenters that have occurred within close proximity to Tucson (Table 1) (source: Natural Hazards in Arizona Viewer, 2022).

Known mapped faults that pose the greatest risk to Tucson and Pima County are the Santa Rita Fault system in Pima and Santa Cruz Counties, and several less well studied faults in the San Pedro Valley east of Tucson.

Table 1. Timing and magnitudes of moderate to large magnitude earthquakes near Tucson, Arizona.

Date	Magnitude	Distance from Tucson
Feb. 20, 1979	M3.0	Epicenter in Tucson
Nov. 24, 1888	M4.0	Epicenter in Tucson
Mar. 12, 1965	M4.4	25 Miles
May 4, 1887	M7.5	~ 190 miles to SE
Nov. 10, 1887	M6.0	30 Miles

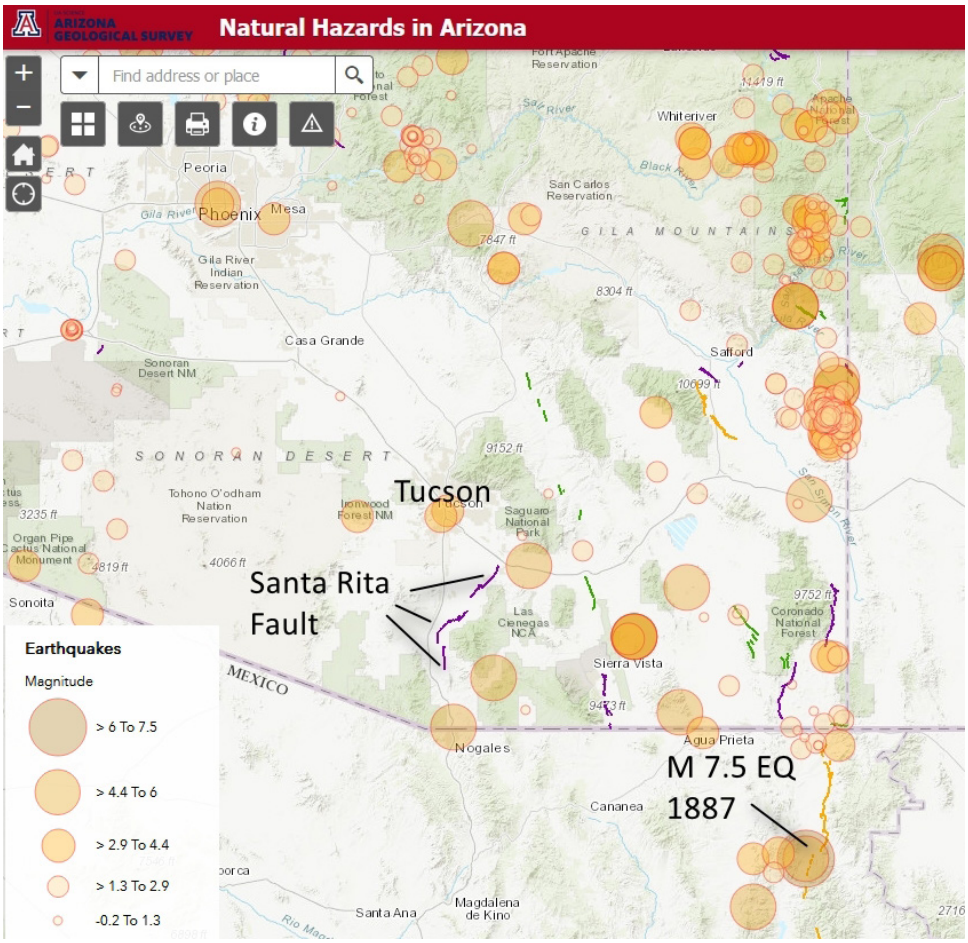


Figure 1. Historical earthquake epicenters and Quaternary faults of southeastern Arizona and northern Sonora, Mexico. Fault legend: purple lineaments represent faults active sometime in the past 2.6 million years; green lineaments represent faults active in the past 75,000 years; gold lineaments represent faults active in the past 10,000 years. Larger spheres represent larger magnitude earthquakes. The largest historical earthquake in the area is that of the 1887 M7.5 event on the Pitaycachi fault in northern-most Sonora, Mexico.

Pitaycachi Fault & Great Sonoran Earthquake of 1887

The Pitaycachi Fault of Northern Sonora, Mexico, south of the Arizona - Mexico border, produced the strongest historic earthquake felt in the region. On May 3, 1887, a magnitude 7.5 earthquake was felt over nearly 775,000 square miles (nearly two million square kilometers) of the southwestern United States and northern Mexico (Figure 2, Dubois and Smith, 1980). The epicenter of the 1887 temblor occurred along the western front of the Sierra Madre Mountains in Sonora, Mexico, 190 miles southeast of Tucson. The average vertical offset on the fault was nine feet with a maximum displacement of 16 feet. Rock falls occurred in 31 mountain ranges in Arizona, Sonora, Mexico, and New Mexico, including Tucson's Santa Catalina Mountains. Dubois and Smith (1980) recount that observers noted that in the Santa Catalina Mountains, "The quake broke large boulders from their moorings. Rocks crashed down the mountainsides, and large clouds of dust rose several thousand ft above the peaks."

The earthquake caused 51 deaths in northern Sonora, injured hundreds, and caused major destruction of property in northern Sonora and southeastern Arizona (Dubois and Smith, 1980). Moderate damage occurred in New Mexico. The intensity of the earthquake in the Tucson area was estimated at VII to VIII on the Modified Mercalli Intensity Scale (Table 2). Future earthquakes similar to the 1887 event could impact southeastern Arizona, including Tucson. A large magnitude event would likely cause substantial damage to older buildings and infrastructure. Damage to transportation corridors, e.g., Interstates 10 and 19 and surface roads, would hamper community response and could disrupt inter- and intra-state economies.

Table 2. Details of intensity VII and VIII from the US Geological Survey's Modified Mercalli Intensity Scale.

VII Frightens most; some lose balance. Heavy furniture overturned. Damage negligible in building of good design and construction, but considerable in some poorly built or badly designed structures; weak chimneys broken at roof line; fall of unbraced parapets. Tree damage, rockfalls, landslides and liquefaction are more and widespread with increasing intensity.

VIII Many find it difficult to stand. Very heavy furniture moves conspicuously. Tree damage, rockfalls, landslides and liquefaction are more and widespread with increasing intensity.

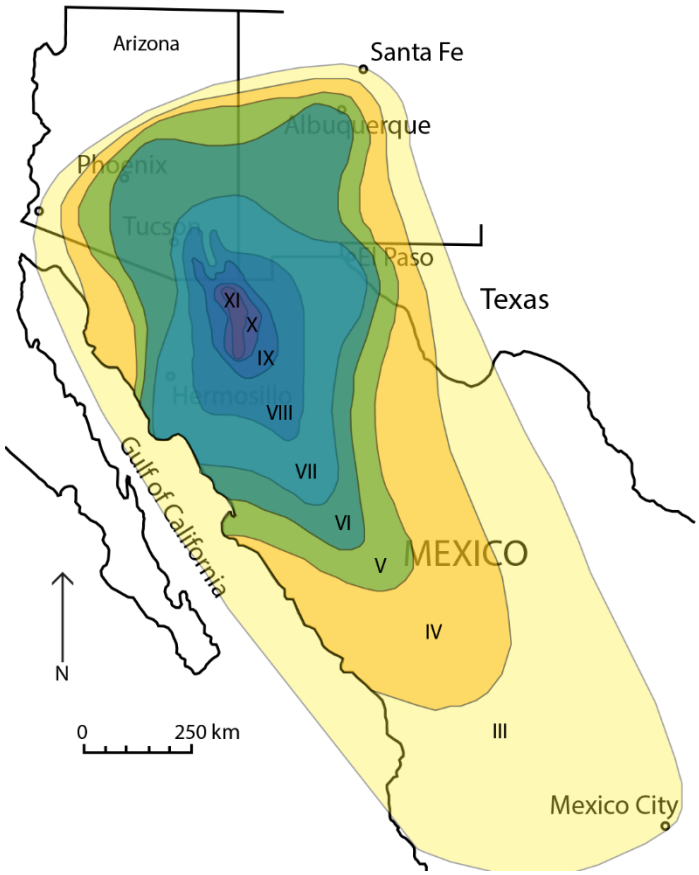


Figure 2. Isoseismic (intensity) map of the 1887 M7.5 earthquake with contours of Modified Mercalli Intensity Scale from XI to III (Dubois and Smith, 1980). Tucson is situated in zone VII and would have experienced damage to poorly built or badly designed structures.

Santa Rita Fault

The 35-mile long Santa Rita Fault trends north-northeastward along the western foothills of the Santa Rita Mountains, southeast of Tucson (Figure 1). Prominent fault scarps range from 3 to 22 feet high, commensurate with an earthquake ranging from magnitude 6.4 to 7.3 (Pearthree and Calvo, 1987). Based on their investigations, the most recent rupture event occurred 60,000 to 100,000 years before the present. With a potential maximum magnitude earthquake of about M7.2, rupture on the Santa Rita Fault would dramatically impact the communities of Tucson, South Tucson, Nogales, Sahuarita, and Green Valley, Arizona.

Santa Rita Fault HAZUS Report – Injuries, Fatalities, Economic Losses. A full HAZUS (Hazards United States) report evaluating the impact of a large magnitude earthquake on the Santa Rita Fault is provided in Appendix II (Young, 2012). The Santa Rita fault earthquake scenario is predicated on a M7.2 earthquake, with a rupture length of 37.8 miles oriented N26°E, and originating at a depth of 1.2 miles. In Young's model (2012), Tucson would experience peak ground acceleration ranging from a minimum of 0.0872 to a maximum of 0.2328, ~25% that of gravitational acceleration at Earth's surface. From page 8 of the HAZUS report (Appendix II), "… estimates that about 62,798 buildings will be at least moderately damaged. This is over 19.00 % of the buildings in the region. There are an estimated 4,502 buildings that will be damaged beyond repair." Estimates of fatalities, and where those fatalities are likely to occur, are a function of the timing of the main shock. A M7.2 earthquake at 2:00 a.m. (all times reported as MST) is likely to cause 85 fatalities,

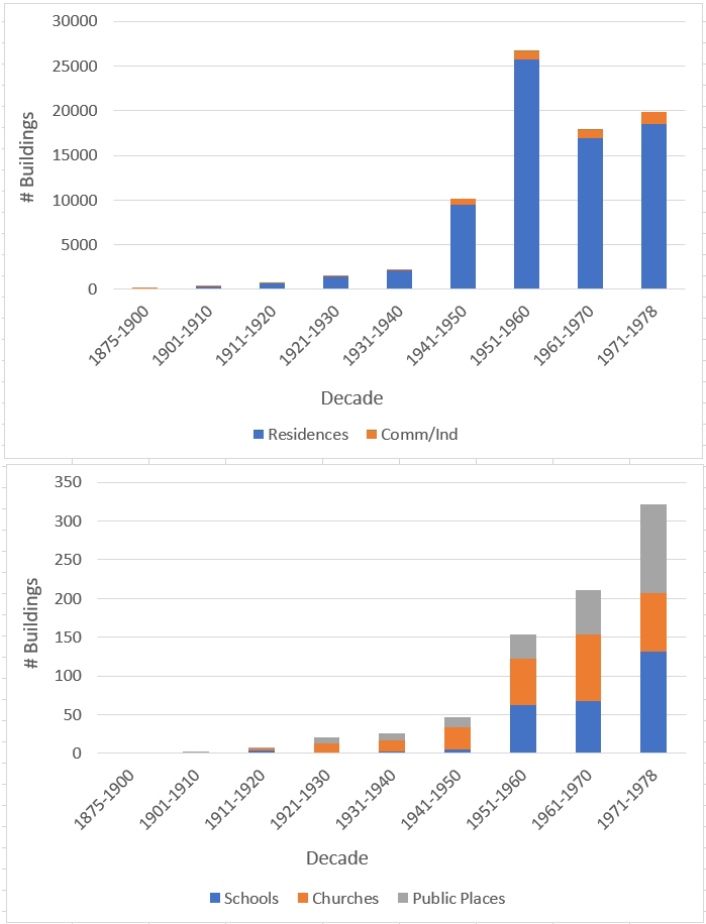


Figure 3. Number of pre-1979 masonry buildings constructed by decade for, A) Residences and Commercial buildings; and B) Schools, Churches, and Public Places on the basis of their estimated age. From 1875 to 1950, a total of 15,428 buildings were constructed; between 1951 and 1978, 67,982 buildings were constructed. We identified 303 buildings with an estimated age greater than 1978.

44 life-threatening injuries, 347 injuries requiring hospitalization, and 1,565 lightly injured. At that time of day, almost all of the injured and dead would occur in single family or other residential facilities. A M7.2 event at 2:00 p.m. would result in more injuries and fatalities in commercial and school settings; with fatalities estimated at 105; with 56 and 21 fatalities estimated for commercial and school settings, respectively. An event occurring at 5:00 p.m. would result in about 97 fatalities, 1,393, lightly injured, and nearly 450 more seriously injured.

Building-related economic losses are estimated at $1.3B ($1.68B in 2022 dollars) and for capitol stock losses at $4.6B ($6B in 2022 dollars), totaling nearly $6B ($7.8B in 2022 dollars). The HAZUS estimate of transportation system losses - highways, railways, bus and airport - totals $19.8M ($25.6M in 2022 dollars) (Young, 2012, p. 16). The economic loss to utility systems responsible for delivering potable water is estimated at $3.28 million ($4.24M in 2022 dollars). No estimates are provided for damage to energy production and delivery systems, but undoubtedly disruptions to utilities and services would occur.

Pre-1979 Masonry Buildings of Tucson, AZ

In the western U.S., masonry buildings constructed prior to the mid-1970s are likely to be unreinforced or lightly reinforced; thereby lacking the ductility to absorb seismic energy of a moderate- to large-magnitude earthquake (Utah Seismic Safety Commission, 2016). The City of Tucson has more than 83,000 buildings of masonry construction built prior to 1979 (Table 3); buildings that frequently lack rebar reinforcement, and thus may perform poorly in the face of lateral ground-shaking and retrograde ground motion that accompanies moderate to large earthquakes. Figure 3A and 4B portray pre-1979 masonry buildings constructed by decade.

Table 3. The Type and Number of Pre-1979 Buildings of Masonry Construction in Tucson[1].

Residential Buildings – 77,165
Commercial / Industrial Buildings – 4,560
Public Sites – 255
Churches – 282
Schools – 275

[1]Data provided by the Pima County Assessor's Office.

Residential Buildings

Single- or multi-family residences comprise 93% of the pre-1979 masonry buildings in Tucson (Table 3). Residential buildings as defined by the Pima County Assessor's Office include: Single Family Dwellings, SFR Grade 010-3 Urban Subdivid., SFR-Dominant, SFR-Non Conform, SFR Rural Non-Subdivid., Rural Subdivid., Status Unknown, SFR on > 5 acres Rural, SFR on > 5 acres Urban, SFR with affixed MFD Home, Mixed Residential any combo, Apartment buildings, Condo/Townhouse, Fourplexes, and Triplex. Masonry residential buildings constructed before 1979 are broadly distributed across Tucson (Figure 4)

Ninety-eight percent (75,485) of masonry residences are 1-story buildings; 1,610 residences are 1.5- to 2-story buildings, and 69 are 2.5-, 3-, or 4-story buildings. The living areas of 12,906 residences are equal to or less than 1000 square feet; living areas of ~ 54,500 residences are between 1001 square feet and 2,000 square feet; homes with 2001 to 3,000 square feet total nearly 8,000; approximately 1,800 residences have more than 3,000 square feet of living space.

Based on the type of masonry used in construction, residential buildings fall into one of seven categories (Figure 5a). The three leading masonry types are brick (~20,027), 8" painted masonry (17,864), and slump block masonry (14,271) (Figure 5b). Residences built with adobe brick number more than 8,100. The construction material types appear admixed, but slump block residences seem to concentrate on the east side of Tucson, probably a reflection of evolving building patters. Buildings comprising 8" painted block are concentrated in a north-south lense between Alvernon Way and Craycroft Rd.

According to the Pima County Assessor's Office, most residential masonry buildings (66,608 - 86% of all residences) are of average quality. Buildings rated as good (3,165), very good (205), or excellent (2) total 3,372 buildings. Residences characterized as salvage (4), low minimum quality (2), minimum quality (511), and below average (6,668) total 7,185 homes. Residences characterized as salvage to below average are generally confined to central Tucson, between Craycroft Rd. and I-10 and from Valencia Rd. north to the Rillito River (Figure 6). All other factors being equal, the nearly 7,200 below average residences are

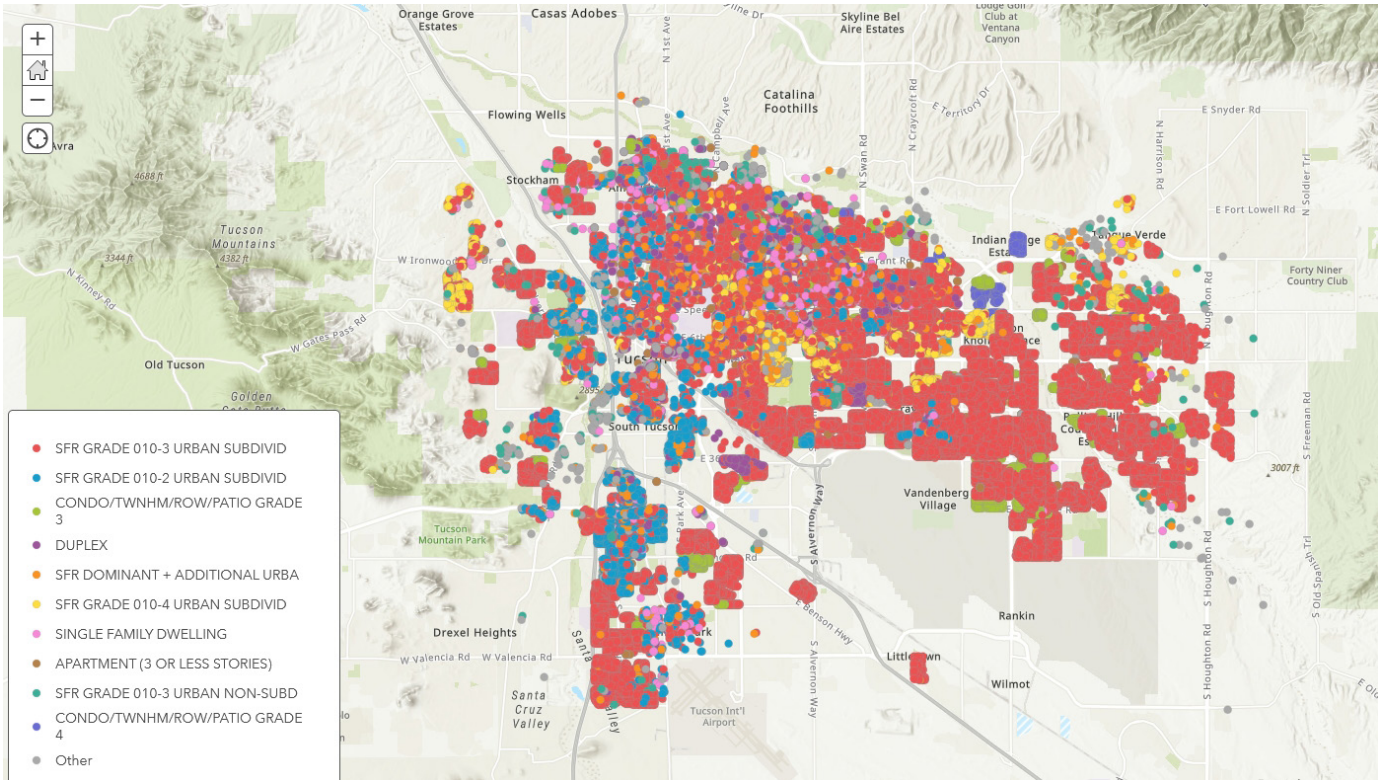


Figure 4. Distribution of the City of Tucson's pre-1979 masonry residences keyed out by the type of residential dwelling. For explanation of the legend, see the Property Use Code Manuel of the Arizona Dept of Revenue (2000). https://www.azdor.gov/sites/default/files/media/PROPERTY_useCodeManual.pdf

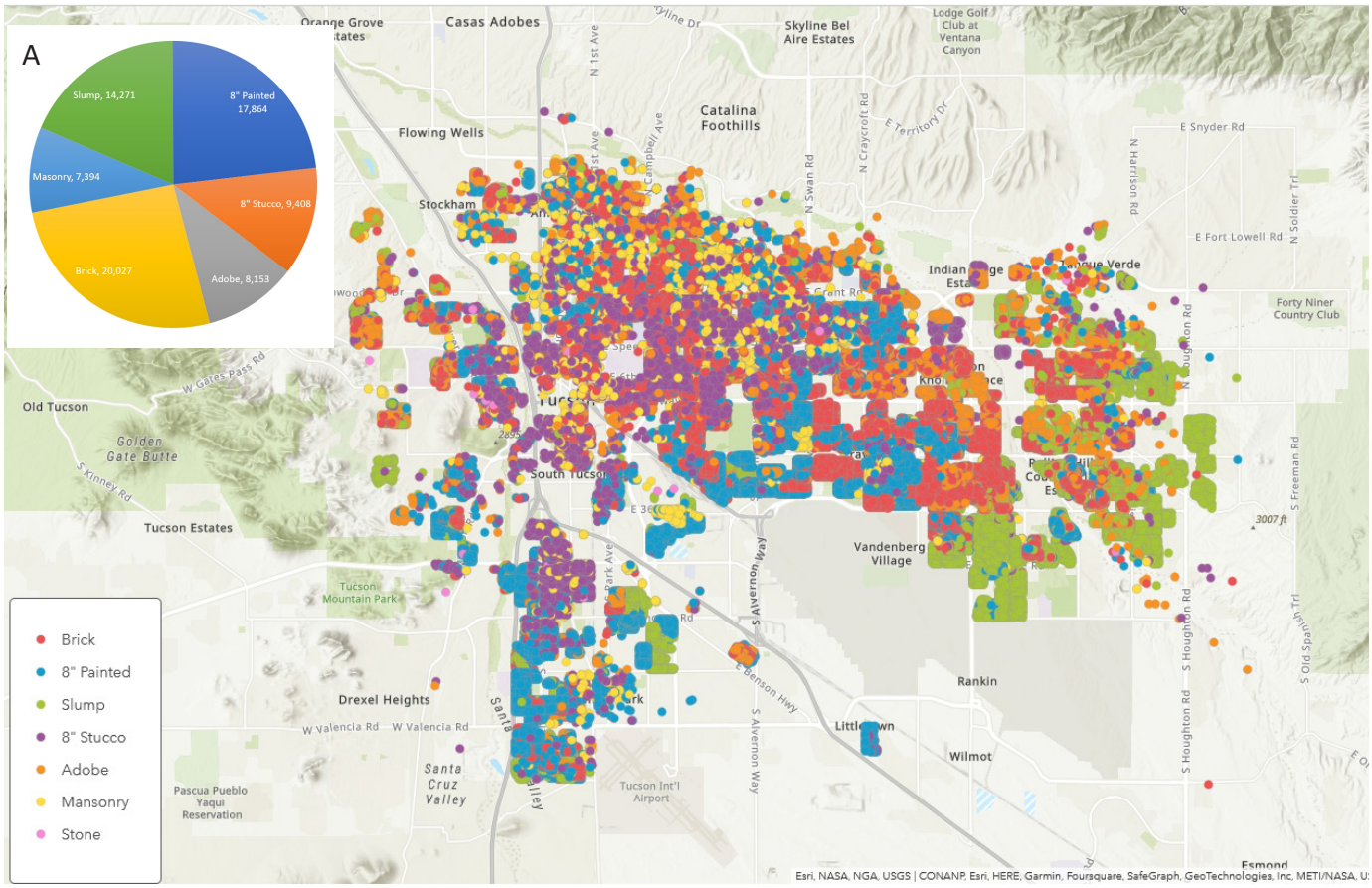


Figure 5A. Pie diagram illustrating the number of masonry residences on the basis of their construction material. Buildings made of local stone do not appear because there are only six incidences. **B)** Distribution map of residences on the basis of the type of masonry used in construction.

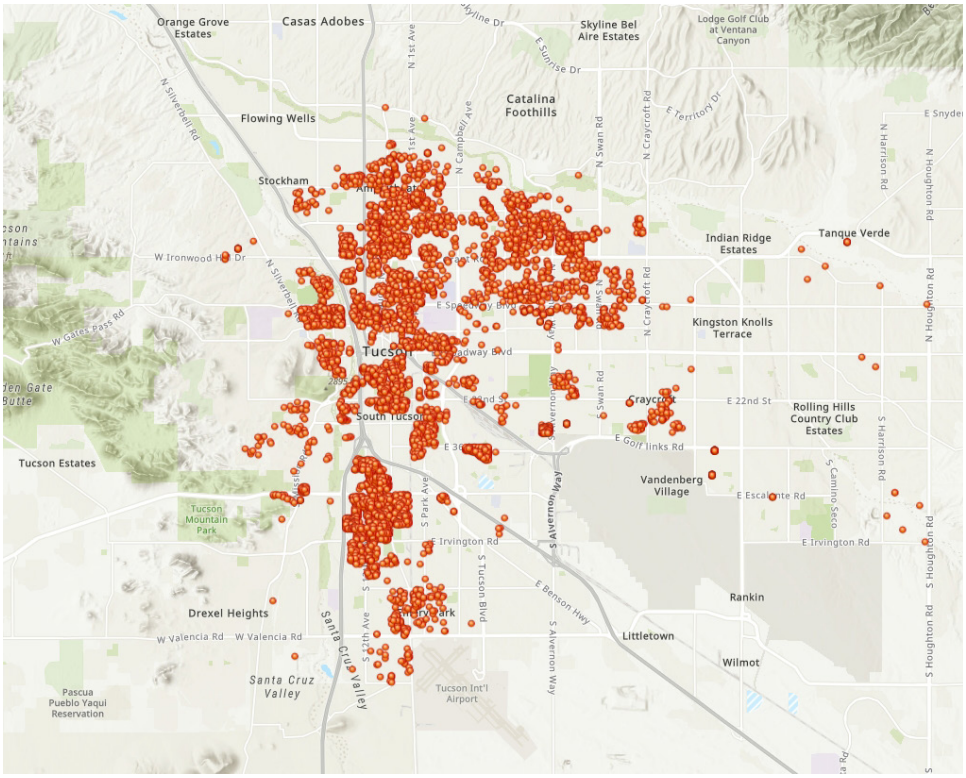


Figure 6. Distribution map of pre-1979 masonry residences of below average or minimum quality.

more likely to suffer serious damage or collapse in the event of a moderate to large magnitude earthquake.

Spatial Analysis of Residential Masonry Buildings.

We used ESRI's ArcGIS© spatial analysis tools to model the distribution of pre-1979 masonry residences. Density analysis identifies areas of high concentrations of pre-1979 masonry buildings, i.e., potential lightly-reinforced or URM buildings (Figure 7A). High density zones, with concentrations ranging from 2,141 to 2,677 per square mile, are represented in dark purple. Areas with lower density of masonry residential buildings are demarcated by lighter purple or purple-free zones.

Applying ArcGIS'© hot spot analysis, a measure of statistically significantly spatial clustering for point data, shows prominent hot spots at the 99- to 95-percent confidence level, trending NW-SE from near the intersection of S. Pantano Road and E. Irvington Street to 1st Avenue and Glenn Road (Figure 7B). Three smaller hot spots are situated in a triangular wedge south of the intersection of I-10 and I-19. Areas with low concentrations of masonry residences, 'cool spots', rim the perimeter of the hot spot zones.

Commercial/Industrial Buildings

Buildings characterized as commercial or as industrial comprise 5.5% of all pre-1979 masonry buildings in Tucson. Commercial/industrial building stock is concentrated immediately east of I-10, between Grant St. and the city of South Tucson, extending eastward along major transportation arteries, e.g., Grant Rd., Speedway Blvd., Broadway Blvd., and 22nd St, before thinning out at Kolb Rd (Figure 8A). This areal distribution pattern is particularly evident on a hot spot map of commercial/industry buildings (Figure 8B).

Most of the pre-1979 commercial-industrial masonry buildings were constructed from the 1940s to the 1970s (Figure 3A). Three-hundred and fifty-six buildings (8% of the total) were erected before 1941. Commercial-Industrial buildings characterized as average quality total 3,834; 598 buildings are characterized as below average; and 68 are minimum quality. Buildings characterized as below average and those of minimum quality should be examined by a structural engineer or building inspector to evaluate how they are likely to behave in the event of moderate to severe ground shaking. In terms of square footage, most of these building (3,284) range between less than 1,000 to 5,000 square feet. There are 711 buildings ranging from 5,000 to 10,000 square feet, and 561 buildings of more than 10,000 square feet - including 6 buildings of 100,000 square feet or more. Nearly 92% of these buildings are 1-story; 7.4% are 2-story, and the remaining 0.6% are 3- or 4-story buildings.

Schools, Churches, and Public Places

There are 812 schools, churches, and public places of pre-1979 masonry construction (Figure 9, Appendix III). Because they share a common trait, a site where people congregate to worship, learn, or recreate, and because their numbers are subequal (282 churches, 275 schools, and 255 public places)
(Figure 3B), we grouped them for analysis. Buildings characterized as public places, include: bowling alleys, clubs, clubhouses, country clubs, courthouse,

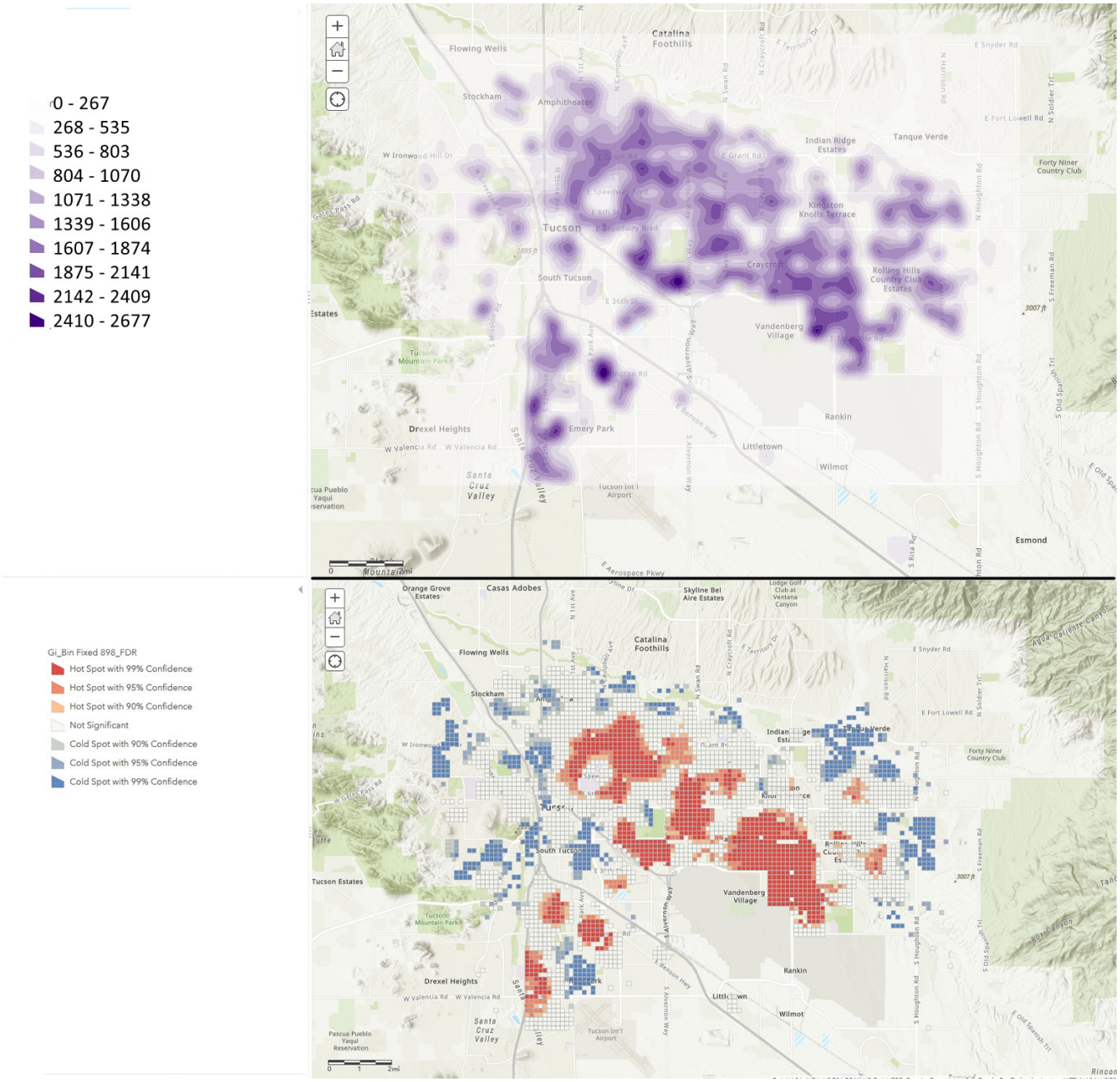


Figure 7. Spatial analysis of pre-1979 masonry residences. A) Density analysis illustrating clustering of residences northwest to southeast. Another area of high density is located south of Ajo Way in the wedge between I-10 and I-19. B) Hot spot analysis illustrates the same general pattern, but is more illustrative of low density areas and the presence of cold spots at the 99 and 95% confidence level outboard of the perimeter of notable hot spots.

handball-racquetball facility, hospitals, libraries, malls, neighborhood shopping center, US Post Office, recreational buildings, skating rinks, and supermarkets, and theaters.

Areas of highest concentration of schools, churches and public places straddle the I-10 corridor, north of W. 22nd Street (Figure 9). Lower concentrations occur in central and eastern Tucson, and in the wedge of land between I-10 and I-19 in south Tucson. Density and hot spot maps showcase this distribution pattern (Figure 10 A and B). Most schools, churches and public places are 1-story buildings, with a small number of 3-, 4- and 5-story buildings (Figure 12A). Square footage of these buildings ranges broadly from less than 1,000 square feet to massive facilities of more than 150,000 square feet (Figure 12B). The largest facilities, those with more than 30,000 square feet, are either schools or public places. Nearly all of the 800+ schools, churches, and public places are characterized as average quality by the Assessor's office.

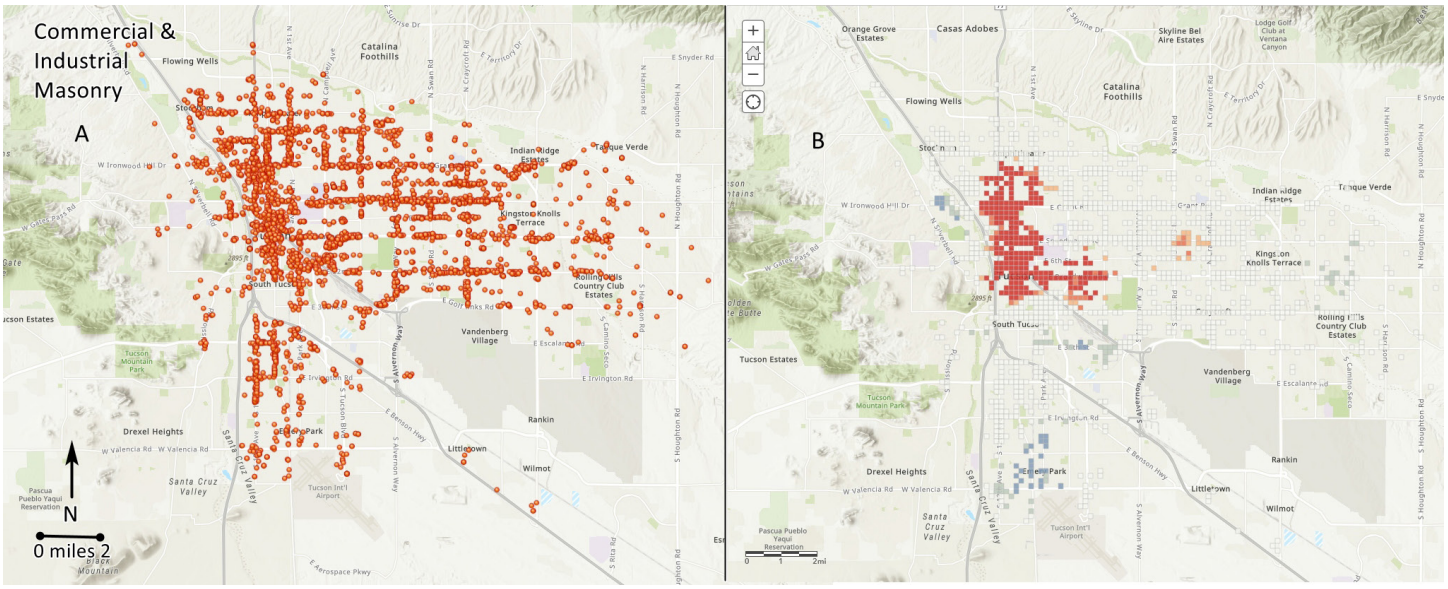


Figure 8. A) Distribution map of pre-1979 masonry commercial and industrial buildings. B) Hot Spot distribution map of pre-1979 masonry commercial and industrial buildings of Tucson. Individual commercial or industrial buildings appear as light orange circles.

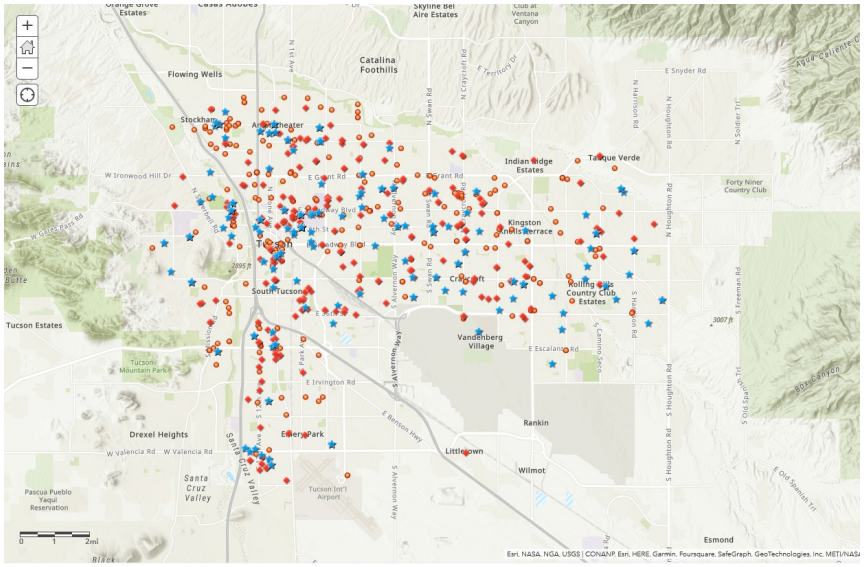
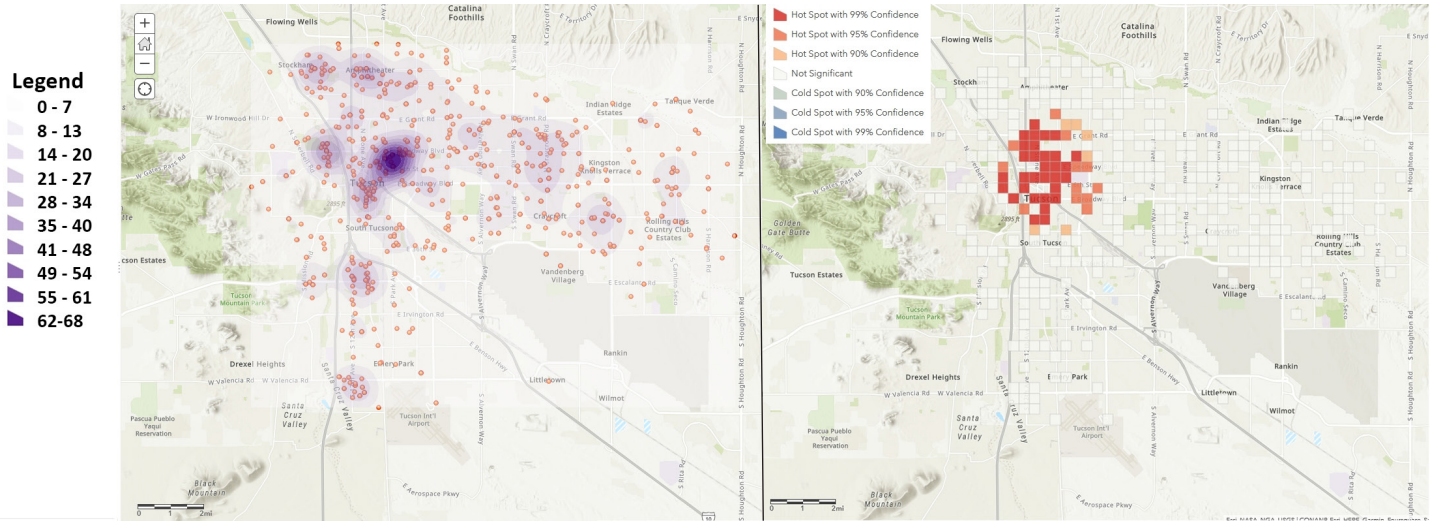


Figure 9 - left. Distribution of pre-1979 masonry schools (blue stars), churches (orange diamonds), places where the public congregates (orange circles)

Figure 10 - below. **A**) Density concentration map of masonry schools, churches, and public places reinforcing their presence along the I-10 corridor north of W. 22nd Street. The highest density areas are demarcated by deepening purple hue with values ranging from 54 to 68 buildings per square mile. **B**) Hot spot map illustrating the high concentration of masonry schools, churches, and public places at the 99% to 90% confidence level along the I-10 corridor between W. 22nd St and W. Grand Rd.



Conclusions

Moderate to large earthquakes on the Santa Rita Fault are infrequent, with the interval between large magnitude temblors on the order of tens-of-thousands of years. It is, however, an active fault with a high probability of future moderate- to large-magnitude earthquakes and aftershocks. Rupture along the 35-mile length of the Santa Rita Fault could produce a M 7.2 earthquake (Appendix II). Other faults in the region that are less well studied and somewhat farther away could also generate large earthquakes. Severe ground shaking would cause substantial damage in Tucson and environs, severely damaging or collapsing older URMs or lightly reinforced masonry buildings. Downtown Tucson would likely experience extensive damage, dozens of fatalities, with hundreds injured, dramatically hampering the city's physical and economic recovery.

This report spotlights the distribution, physical parameters, and condition of pre-1979 masonry buildings, i.e., those buildings most likely to perform poorly in the event of a moderate to large earthquake and aftershocks. Other western states, notably California, Utah, and Washington, and midwestern states proximal to the active New Madrid Fault (NAHB Research Center, 2003), have pioneered programs to retrofit older infrastructure to enhance survivability and minimize injuries (e.g., Applied Technology Council, 2022). Civil authorities of Tucson and Pima County can thus leverage best practices from lesson learned elsewhere to improve the performance of older buildings and mitigate fatalities and disruption of community liveliness as described by FEMA (https://www.fema.gov/emergency-managers/practitioners/lifelines).

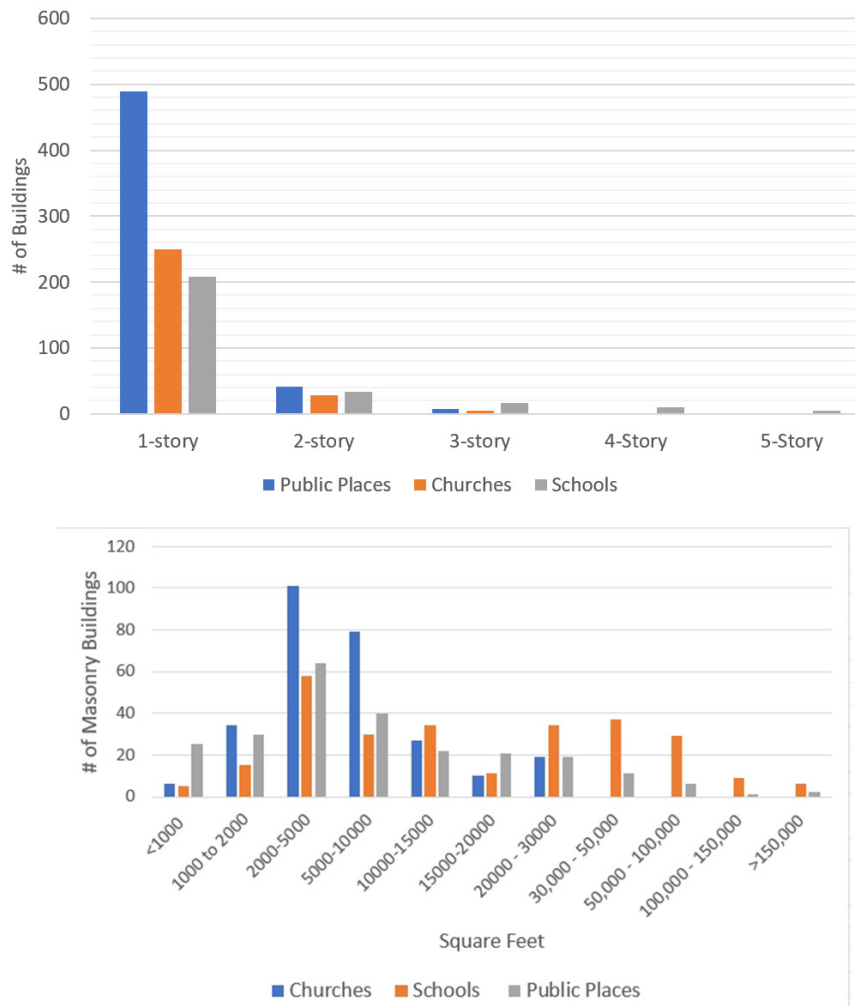


Figure 11. Physical parameters of pre-1979 masonry schools, churches, and public places. A) Bar graph illustrating the number of stories of schools, churches, and public places. B) Square footage of pre-1979 masonry schools, churches, and public places in Tucson, Arizona. Nearly 50% of these buildings fall in the range of 2,000 to 10,000 square feet.

Building a robust retrofit program to mitigate earthquake hazards and risk requires perseverance and sufficient funds to support a multi-year program (Utah Seismic Safety Commission, 2016). The first steps, however, are straight forward and require only those resources readily available to civil authorities of Tucson and Pima County. Chiefly, this involves prioritizing structures for retrofit that, should they be severely damaged, could cause disproportionally high fatalities and injuries. This includes schools, churches, and sites where people congregate – libraries, municipal and county buildings, museums, and theaters. Structural assessment by trained engineers would be instrumental in prioritizing URMs at highest risk to failure during ground shaking. The Utah Seismic Safety Commission (2016) provides a guide for seismic improvement of URMs.

Some simple actions that could minimize injuries and mitigate impact to the community, include:

- Encourage participation of schools,

businesses, and government offices in the annual *Great Arizona ShakeOut* earthquake preparedness drill: Drop, Cover, Hold On.

- Encourage Tucsonans to adopt the U.S. Dept of Homeland Security's Make A Plan (https://www.ready.gov/plan) to prepare for disaster.

Recommended Actions for the City of Tucson in mitigating risk from older masonry buildings

i. Engage Tucson civil authorities, Pima County Emergency Management, Arizona Dept. of Emergency Management, and FEMA in strategizing how to address Tucson's aging masonry (i.e., URM) building stock.

ii. Encourage county and city authorities to address aging, and unreinforced or lightly reinforced masonry (i.e., URM) building stock in their 5-year, multi-jurisdictional hazard mitigation plans.

iii. Collaborate/consult with civil engineers and GIS specialists on high-precision filtering of the existing database to better identify and prioritize retrofits of URM building stock.

iv. Prioritize physical assessment of pre-1979 masonry schools, churches, and public facilities by civil engineers or other qualified staff.

v. Consult with Utah Emergency Management about best practices in conducting and disseminating information on URM building inventory.

vi. Explore federal, state, and local funding agencies for external grants to facilitate URM assessment and remediation.

vii. Pursue opportunities for a 'Fix the Bricks' and 'Brace and Bolt' style retrofit programs for Prescott home owners. (sources: Salt Lake City (https://www.slc.gov/em/fix-the-bricks/ ; California Earthquake Authority (https://www.earthquakeauthority.com/Prepare-Your-House-Earthquake-Risk/Brace-and-Bolt-Grants)

Acknowledgments

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NOTE: As per AZGS agreement with the Pima County Assessor's Office, we are not attaching the City of Tucson database.