The Performance of the Natural Gas System - Magna M 5.7 2020 Earthquake

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The Council of Lifeline Earthquake Engineering

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1.0 Introduction and Key Findings

The Earthquake. The Magna M 5.7 earthquake occurred on March 18 2020. The epicenter of this earthquake was 11.9 km deep, located about 4 km north northwest of Magna, Utah, about 20 km west of downtown Salt Lake City.

Ground Motions. The level of shaking was about PGA = 0.15g to 0.55g in and around Magna, Utah, with about 2.5 seconds of strong shaking (PGA > 0.10g). There was no surface rupture. There were no landslides. Liquefaction was confined to zones very near the Great Salt Lake, where there was little infrastructure.

Instrumental Motions and ShakeMaps. The seismic instrument that recorded the strongest level of shaking is called instrument LKC. It is located about 2 miles from the epicenter and 1.5 miles from the Mobile Home Park that suffered the most structural damage. This instrument recorded peak horizontal ground acceleration of PGA = 0.54g and peak horizontal ground velocity of PGV = 33 cm/sec; the duration of strong shaking (PGA > 0.10g) was about 2.5 seconds.

The report provides a review of two versions of ShakeMaps that were developed by the USGS after the earthquake, so-called Version 1 and Version 2. The Version 1 ShakeMap was created the same day of the earthquake. The Version 2 ShakeMap was created several weeks after the earthquake. Neither ShakeMap version accurately captures the actually recorded motions at instrument LKC. For purposes of loss estimation, ShakeMaps are not true representation of actual ground motions, even at or near instrument recording stations. For this earthquake, the ShakeMap numerical values (PGA, PGV) (using the more refined Version 2) were 29% to 35% lower than the actual recorded values. In general, ShakeMaps should be considered no more accurate than about -40% to +60% at any given location. These variations can be quantified using uncertainty parameters, commonly using the lognormal standard deviation parameter ß (beta). If using a single ß to represent both uncertainty in the ground motion and structure response, a minimum value of 0.6 is recommended.

Regular Building Stock. In the oldest part of Magna, there were a few city blocks of unreinforced brick buildings, and these suffered various amounts of damage (falling parapets, cracked brick walls, etc.). This damage is well documented in other reports, and this damage is not addressed in this report.

Natural Gas System Performance. This report describes the specific performance of the natural gas system in the Magna earthquake with specific attention to gas meters at mobile homes. From a system-wide perspective, the natural gas system performed well: there were no gas leaks in gas transmission pipes, 1 leak in gas distribution mains, 5 gas leaks in gas lateral services and 468 leaks at gas meters. Even with these leaks, there were no fire ignitions. While many of these leaks may have pre-existed the earthquake, the correlation of the rate of leaks with the level of ground shaking shows that there is a strong correlation of increasing rate of gas leaks with increasing level of ground shaking.

Mobile Home Performance. This report elaborates on the performance of the natural gas meters adjacent to the mobile homes. The damage and leaks to the gas meters is a function of both the seismic performance of the mobile home structure itself, as well as the details of the gas meter, riser pipe and flex hose attachments.

At one mobile home park, the ground shaking was high, and there was widespread damage to mobile homes: about 23% (48 of 208) of the mobile homes suffered either extensive damage (dislodged and requiring re-installation), or collapse (falling completely off their supports and falling to the ground); many more mobile homes suffered lesser damage, such as buckling of skirts, various types of non-structural damage, and damaged carports. It appears that all (or nearly all) of these mobile homes included anchorage systems that met wind code. Back calculation of the capacity of these wind-required restraints show that their nominal capacity was high enough to meet or somewhat exceed the UBC Seismic Zone 4 code base shear provisions (V = 0.18W, implying a R_w coefficient of about 6, using the terminology of UBC 1988). Following the concepts of the UBC, the value of Rw could be set at 8 (wood panel structural panel walls for structures three stories or less) or 6 (all other light framed walls). Even with these wind-restraints that met $R_w = 6$, many mobile homes moved sideways on the order of a few to several inches. The relatively poor seismic performance of these mobile homes shows that the selection of $R_w = 6$ is not suitable for the actual style of construction. In the high seismic regions of the United States, there are likely more than 500,000 mobile homes; of these, those that are supported on steel stands with lateral restraint provided by steel straps, are seismically-fragile, and a significant percentage of them are expected to slide laterals or fall off the steel stands.

Another report (Maison and Eidinger, 2021) focuses on the seismic fragility of mobile homes having various styles of anchorage system (no lateral anchorage system, limited anchorage system, or anchored per code). That report shows that mobile homes on concrete masonry unit-type supports are seismically more robust than those on steel stands. For new mobile home installations, using steel stands with steel strap restraints similar to the type used at the Mobile Home Park described in this report, the authors would suggest setting the seismic base shear forces of at least V = 0.36W (Rw limited to no more than 3).

Natural Gas Meters at Mobile Homes. For some of the mobile homes that sustained either the collapse or extensive damage states, the structures moved sideways sufficiently to impact the adjacent natural gas meters sets. Many gas meter sets were sufficiently damaged that they had to be replaced in their entirety. Many gas meter sets were impacted and tilted, but with lesser repairs done. It is conceivable that some of the gas meter sets were tilted due to excessive inertial forces and the weak lateral resistance offered by the riser pipe and supplemental supports.

System-wide, there were about 468 gas leaks at natural meters. The bulk of these leaks reflect leakage through screwed fittings, and are easily repaired by adding pipe dope. At one mobile home park, some meter sets and riser pipes were replaced entirely, suggesting more severe damage and leaks. Post-earthquake, the gas system operator isolated the entire mobile home park from the gas system. Before the area was isolated, the rate of gas leakage at each meter set was not quantified. However, the gas system included excess flow valves at every service lateral, so any pipe breaks on the utility side of the gas meter would have had gas leakage minimized.

Even with the impacts of mobile homes on gas meter sets, there were no gas ignitions and no fires.

Considering the relatively low fragility levels established for mobile homes (Maison and Eidinger 2021), with median chance of collapse on the order of PGA = 0.5g (depending on style of mobile home anchorage system), it is apparent that there were many mobile home / gas meter interactions. With severely damaged gas meter sets, and no excess flow valves, high amounts of low pressure (40 psi or so) to very low pressure (0.25 psi or so) gas release can occur. If the gas / air mixture exceeds 5%, and if there is a spark, ignition can occur. The resultant fires can result in extensive property loss and possibly casualties. If it is windy at the time of the earthquake, the initial fire ignition can rapidly spread, resulting in larger property losses and increased chance of loss of life.

From the perspective of the natural gas system operator, it should be recognized that mobile homes that are anchored using strap systems, designed for wind speeds up to about 70 miles per hour, (as common through much of the high seismic regions of Western United States), that it should be assumed that some mobile homes will slide sideways off their supports. If the gas meter is located much less than about 3 feet from the mobile home, then allowance that the occasional mobile home (designed with wind restraints for 70 mph, or seismic loads of V = 0.18W, using strap systems of the type used in Magna) might fall onto the gas meter should be assumed in large earthquakes (PGA > 0.2g or so). These impacts can be mitigated by setting the natural gas meter (and adjacent riser pipes and appurtenances) about 3 feet from the mobile home; installation protective bollards between the mobile home and the gas meter; upgrading the mobile home seismic restraint system to prevent it from failing at the design level earthquake, with a minimum factor of safety of 1.5; or otherwise supporting the meter set and attached flex hose as to prevent leaks from broken pipes, even if the mobile home slides sideways.

The report shows that the number of gas leaks at meters was about 1 per 1,850 meters, when factored over the entire shaken area and all styles of construction. In the highest shaken areas, the ratio was about 1 per 600 meters. At one mobile home park within the highest shaken area, the ratio was about 1 per 20 meters. The gas meters at the highly-shaken mobile home park *always* included a flex hose between the mobile home and the meter; this required a supplemental support on the meter. From a structural stress perspective, it appears that this supplemental support is rather flexible, and this led to stresses (in this earthquake) in the various screwed pipe fittings on the order of 50% of yield, or higher. The combined high level of stress at screwed fittings, coupled with occasional impacts between the meter set and the mobile home, led to a high rate of leaks. While in this earthquake, none of the leaks led to an ignition, ignitions at damaged meter sets have sometimes occurred at mobile homes in other earthquakes in California and Japan. A more robust design of gas meter sets at mobile homes might be suitable, to prevent unintended impacts between the structure and meter set, and to lower the earthquake-induced stresses in the threaded joints.

Was Magna "lucky" in this earthquake? From the perspective of fire ignition and fire spread, the answer is "YES". From the perspective of the extent of damage to mobile homes, the answer is "NO". From the perspective of the natural gas system operator, Dominion Energy, the answer is "the amount of damage to the gas system was about as expected".

1.1 Acknowledgements

This report has been prepared by John Eidinger and Bruce Maison and Pete McDonough (collectively, "we").

In this report (TCLEE No. 6), we document the performance of the natural gas system in the Greater Salt Lake City area, as well as gas meters at a Mobile Home Park in Magna in the 2020 Magna earthquake. The natural gas system operator for the greater Salt Lake City area, including Magna, supported this investigation. Mr. Pete McDonough (Duhallow Consulting P.L.L.C, formerly Questar) reviewed damage reports and developed gas leak statistics. Mr. Bruce Maison (Consulting Structural Engineer) provided information about the performance of Mobile Homes in Magna area. Mr. Matt Bartol (Dominion Energy) provided valuable insight as to the performance of the gas system. Mr. John Eidinger (G&E Engineering Systems) inspected various facilities, developed statistics of performance of the gas system, and was the primary author of this report. This is a solid testament of this important task for the industry owning and providing lifelines services.

Throughout this report we use the term "Mobile Homes". In recent parlance, these are often called "Manufactured Housing". These terms can be used interchangeably.

We acknowledge the fact that all incur a cost in the effort to document the performance of lifelines in earthquakes, with the hope that all will recognize this as an investment for resilient lifelines and our intent to achieve a long term gain in increasing our understanding of the issues.

destroy any copies of this report you may have, whether in any hard copy format or any electronic format.

Respectfully submitted,

John M. Eidinger and Bruce F. Maison and Pete McDonough, April 7 2021

1.2 Limitations

As is not uncommon in post-earthquake reconnaissance, incomplete information in the weeks and months after the event can lead to omissions and misunderstandings. We apologize if the findings in this report are incomplete, and the reader is cautioned that it may take months to years of post-earthquake evaluations before a comprehensive understanding of lifeline impacts is available. Should readers uncover new information, which would improve the findings in this report, we request that they forward that information to the authors.

1.3 Endorsements

Nothing in this report should be considered as an endorsement of any particular product or company.

While we believe the information contained in this report reasonably reflects what occurred (or did not occur) in the March 18 2020 earthquake that affected Magna and the greater Salt Lake City area, there is no doubt that this report does not contain all possible information, and it may contain inaccuracies.

This report makes mention of major corporate and local government entities; some are listed on stock exchanges. While these entities shared information with us, the readers should know that none of these entities have endorsed the facts, conclusions or recommendations in this report.

1.4 TCLEE

This report has been prepared by researchers in lifeline earthquake engineering. Collectively, this group is called The Council of Lifeline Earthquake Engineering, *TCLEE*.

To date, *TCLEE* has published six reports. These reports are available for free at http://www.geEngineeringSystems.com.

- *TCLEE No. 1*. Napa, California earthquake, August 2014.
- *TCLEE No. 2*. Kumamoto, Japan earthquakes, April 2016.
- *TCLEE No. 3*. Mexico City and Chiapas, Mexico earthquakes, September 2017.
- *TCLEE No. 4*. Hokkaido, Japan earthquake, September 6 2018.
- *TCLEE No*. 5. Anchorage, Alaska, November 30 2018.
- *TCLEE No*. 6. Magna, Utah, March 18 2020.

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2.0 Earthquake Ground Motions

The M 5.7 earthquake occurred on Wednesday March 18, 2020, at 7:09:31 am local time. The causative fault was a normal fault feature, previously unmapped and not specifically factored into any local of nationwide seismic hazard maps. Figure 1 shows a map with the epicenter and the two MHPs discussed in this paper; other features are the Interstate Highways (pink lines), major roads (orange lines), and major rail alignments (dashed lines). The Snowbird ski area is highlighted, and is located about 10 km east of the surface expression of the Wasatch Fault Zone.

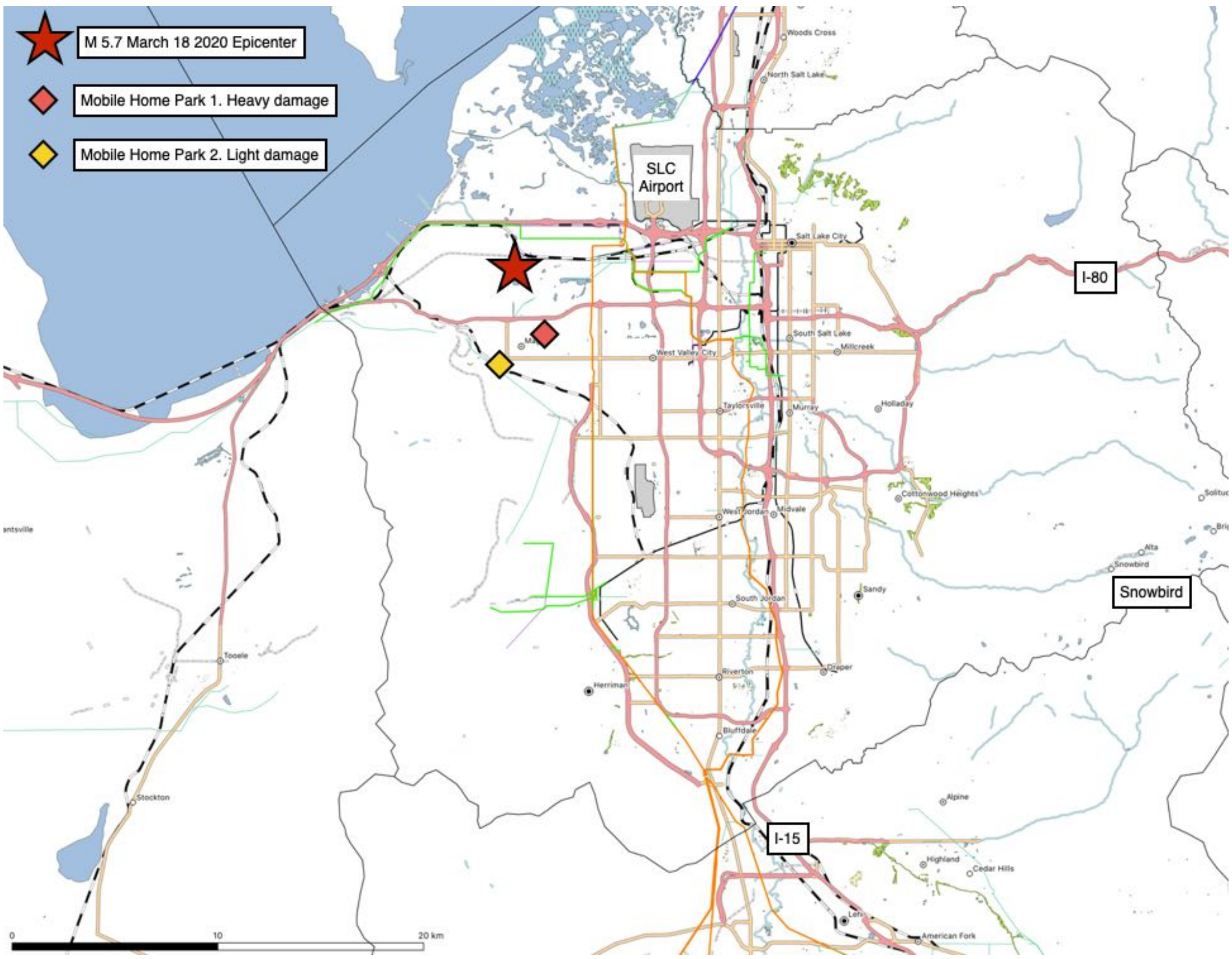


Figure 1. Map of Salt Lake City, Epicenter and Two Mobile Home Parks

Figure 2 shows a cross section of the region. The epicenter and main M 5.7 shock is indicated at about 11.5 km depth. The solid black line shows the assumed Wasatch Fault Zone, dipping steeply at the surface at about 60°, and then dipping more gently (about 45°) at depth. The general sense of fault movement is downward movement to the west (Normal faulting). An earthquake on the solid line Wasatch Fault Zone is the general planning-type earthquake for the Salt Lake City area, and would produce several feet of offset at the ground surface, and PGA ~ 0.5g for much of downtown Salt Lake City as well as the ski areas immediately east of the fault. The dashed lines in Figure 2 show back faults (locations speculative) consistent with the general dropping down of the greater Salt Lake City area relative to the up-thrusting Wasatch Mountain Range.

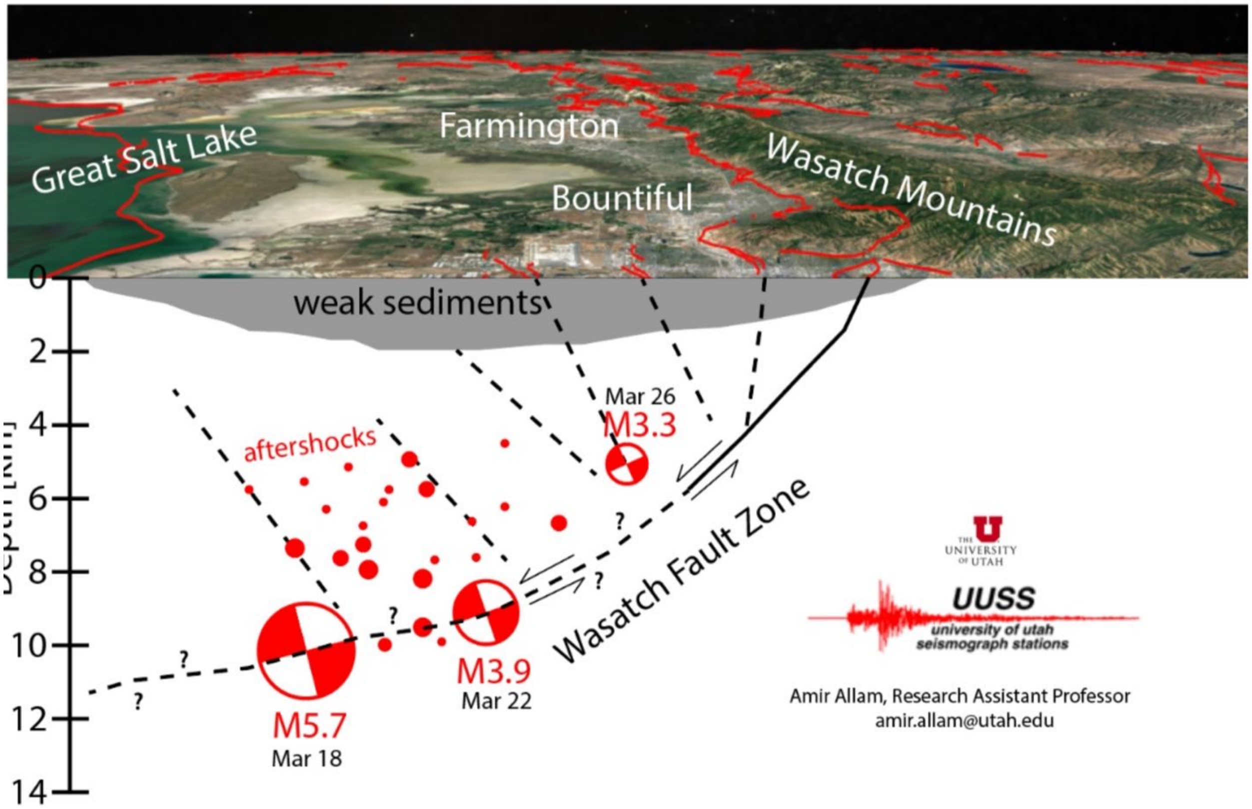


Figure 2. Cross Section showing Epicenter and Aftershocks (after UUSS)

East of the Wasatch Mountain fault zone are the Alta, Snowbird, Solitude and Brighton ski fields in Little and Big Cottonwood Canyons. A few km further to the east are the Park City, Canyons, and Deer Valley ski fields. North of Salt Lake City is the Snowbasin ski field. South of Salt Lake City is the Sundance ski field. All these ski fields are exposed to significant strong motions from a ~M 7 earthquake on the nearby WFZ.

For the Magna M 5.7 earthquake, the ground motions at the ski fields in Big and Little Cottonwood Canyons were modest (PGA on the order of 0.02g, PGV on the order of 1 cm/.sec), not likely high enough to trigger snow avalanches within ski area boundaries. However, for a future Wasatch Front ~M 7 event, ground shaking will commonly be PGA > 0.3g, and snow avalanches and triggered rock falls in the back country may pose significant life safety hazards to back-country skiers; these hazards may be somewhat mitigated within the ski area boundaries, with snow avalanches that can be mitigated through grooming of snow fields; and removal of rocks from source zones; but for days after significant snow falls, the avalanche and rock fall hazard within ski-area boundaries can still be significant. To the authors knowledge, the earthquake-induced avalanche and rock fall hazards along the Wasatch Front are largely unknown, and it is recommended that this hazard be further studied, and possible mitigation strategies developed. The membership of the former Technical Council on Lifeline Earthquake Engineering had considered extending its research area to cover ski lifts (essentially an uphill transportation system); but the former TCLEE was disbanded before action could be taken. Many ski fields in the USA are exposed to significant earthquake hazards (including those in the western Cascades due to a M 9 Cascadia Subduction Zone earthquake or local crustal earthquakes; ski fields near Lake Tahoe (exposed to faults near Reno or Lake Tahoe); ski areas near central California exposed to faults in the Owens Valley; the Alyeska Ski Area exposed to faulting along the Aleutian Trench subduction, and many back-country ski areas. To date (2021), there have been no known deaths in the USA due to earthquake-induced avalanche or rock fall. However, the 2015 M 7.8 event in Nepal triggered many avalanches / rock falls in the Himalaya, and many were killed due to avalanche. There were many earthquake-induced rock falls in Sichuan Province in the 2008 earthquake, with rolling and bounding rocks resulting in fatalities and much destruction. The authors hope that the earthquake hazards (avalanche and rock fall) will be addressed at ski areas, an area where further research is warranted, both to identify the level of risk, and suitable mitigation measures.

The USGS developed ShakeMaps using instrumental data, attenuation models and interpolation schemes. Table 1 shows the ShakeMap values at three locations, using two versions of ShakeMaps: Version 1 was processed on March 18 2020 (the day of the earthquake) and Version 2 was processed on April 8 2020 (about three weeks after the earthquake). We report both versions herein, reflecting that some users will do initial loss estimates based on the "soonest available" ShakeMap (such as for initial assessment, assignment of emergency crews, etc.); other users will use "most recent available" ShakeMaps that include the latest available instrument data, supplemented by operator review and manipulation of the ShakeMaps. If one is to try to obtain the "most accurate" loss estimates, it is evident that the user should rely directly on instrumental data for sites with instruments, and then proceed with due diligence for sites distance from actual instrumental recordings.

Table 1. ShakeMap Values (Version 1 = March 18 2020; Version 2 = April 8 2020)

Location	PGA (g) V1	PGV (cm/sec) V1	PGA (g) V2	PGV (cm/sec) V2
LKC (Actual recorded value)	0.5377	32.68	0.5377	32.68
LKC (ShakeMap value)	0.3016	15.85	0.3484	23.21
MHP-1 (ShakeMap value)	0.2568	15.70	0.3274	21.76
MHP-2 (ShakeMap value)	0.1772	34.18	0.2938	15.90
Maximum anywhere in ShakeMap	0.3470	40.80	0.3486	23.48

Note: while the ShakeMap values in Table 1 are shown to 4 significant digits, the reader is cautioned that the ShakeMap values are not accurate to even the most significant (left-most) digit; for example, the ShakeMap value 0.3484g in Table 1 means that the motion was most likely between about 0.21g and 0.56g.

Comparing the Version 1 and Version 2 ShakeMaps (see Figures 3 to 8), one sees that the Version 1 maps have concentrated high motions around then available instrument data; the LKC data would appear not to be reflected in Version 1. The Version 2 map has highest motion in the epicentral area, attenuating with distance from the epicenter. It is recognized that actual motions will sometimes be higher at a distance from the epicenter, so the Version 2 ShakeMap should be considered an estimate of median motions, and not to be interpreted as actual motions.

A further complication in using ShakeMaps is that the USGS may blend in "DYFI" data into the ShakeMap. DYFI is the acronym for "Did You Feel It", and relies on data submitted by people who felt the earthquake. DYFI data tends to reflect a "observed damage / observed intensity" sense. ShakeMap software includes DYFI to PGA and DYFI to PGV conversion algorithms. The merit of using DYFI data is that there might be over 30,000 such entries (as was the case for the Magna earthquake), which far outweighs the actual instrumental motions (several dozen instruments with strong shaking). However, the DYFI data "smooths out" the motions.

The reported values are for the grid cell values closest to location. For larger earthquakes, the USGS may issue multiple versions of ShakeMaps, reflecting the needs of the community. It is understood that in the first few minutes or hours after an earthquake, not all instruments "report in"; so the early ShakeMaps may not as accurate as later-processed ShakeMaps. Even so, the comparison of either version of ShakeMaps (either Version 1 or 2), to the actual recording at instrument LKC (the closest instrument to the epicenter, and the one with the highest recorded motions), shows that ShakeMap numerical data contains significant approximations, and the user should understand that any numerical ShakeMap data may be about -40% to +60% (sometimes less or more) from the true motions at any specific point.

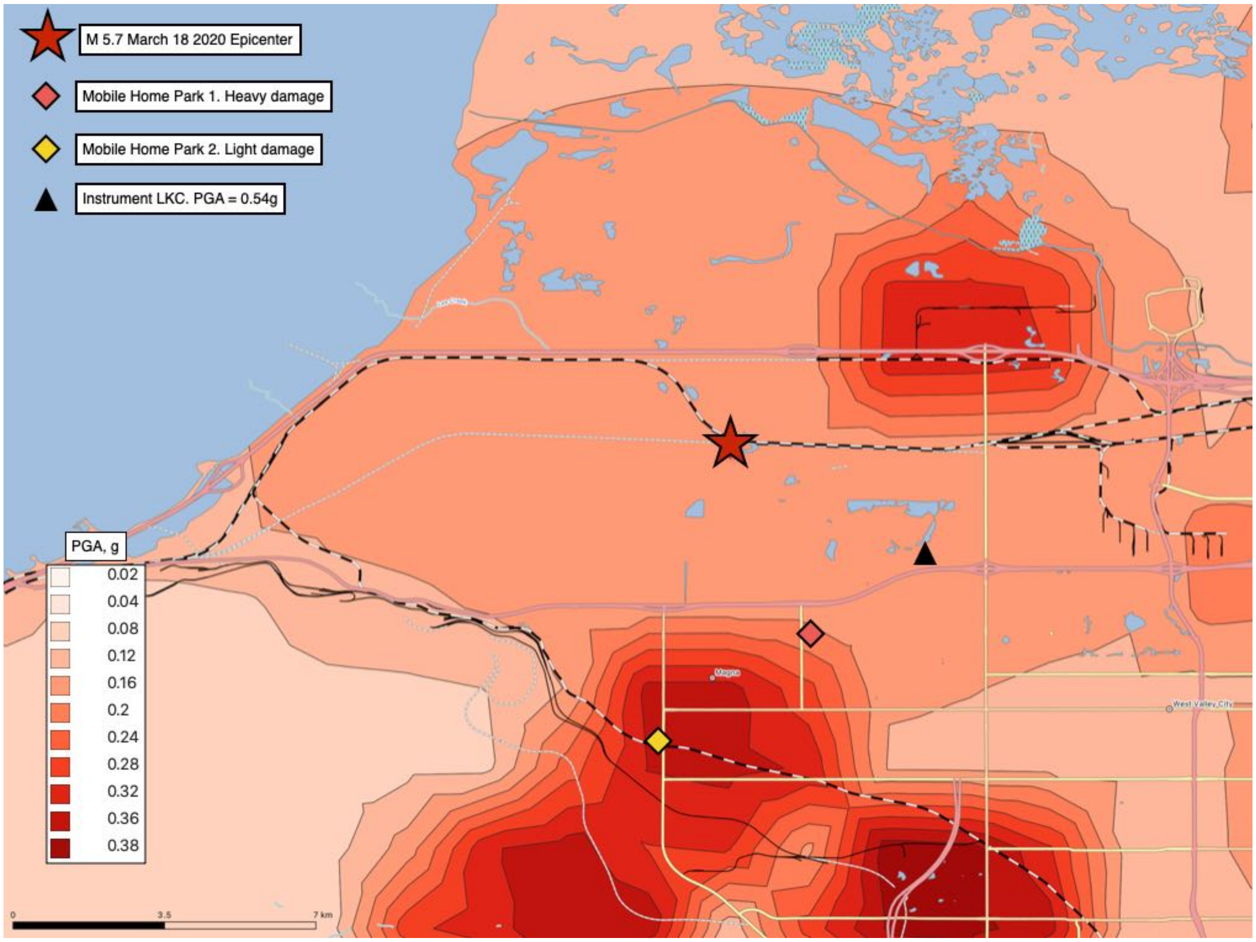


Figure 3. Horizontal PGA Shaking Map (g) (Version 1 March 18 2020)

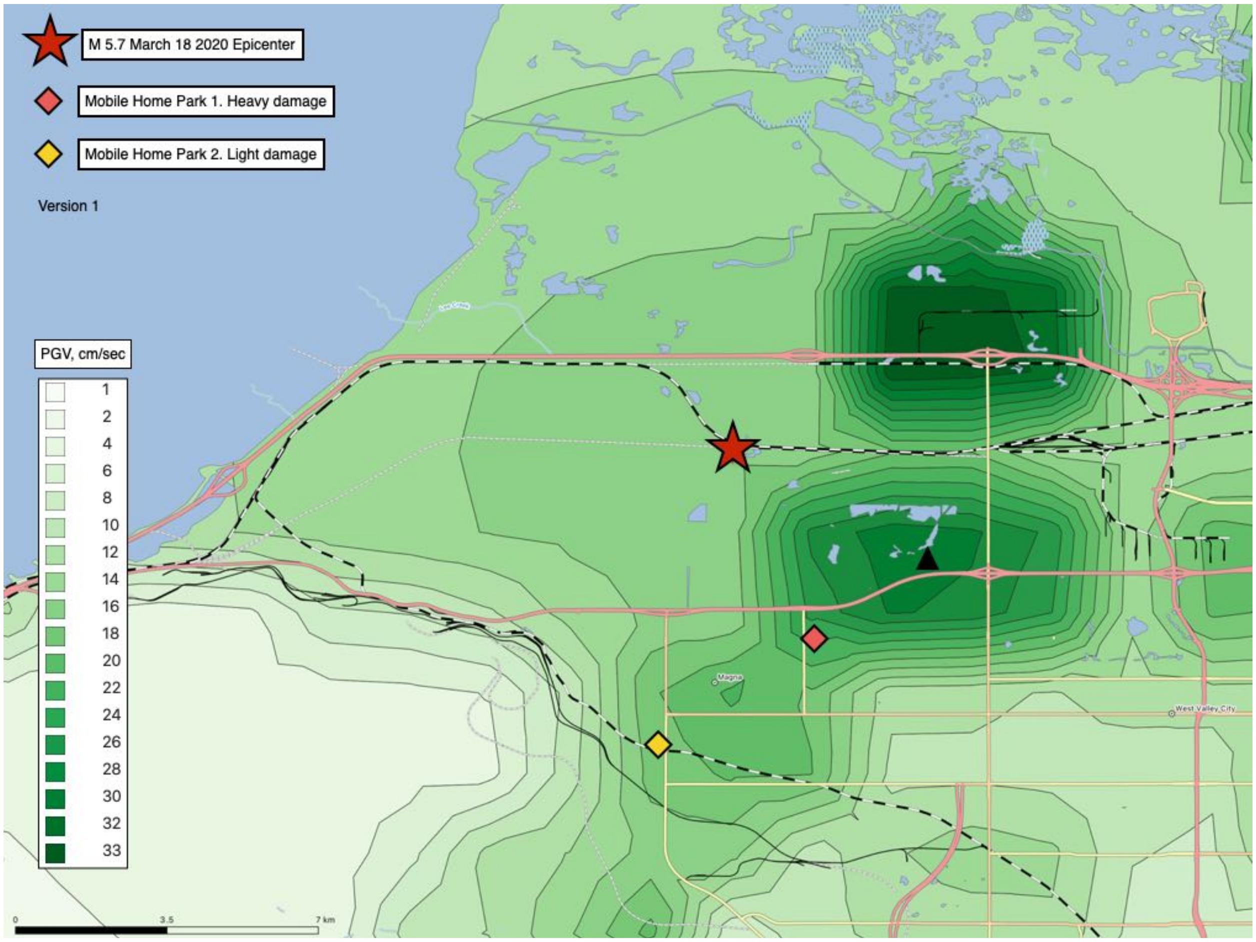


Figure 4. Horizontal PGV Shaking Map (cm / second) (Version 1 March 18 2020)

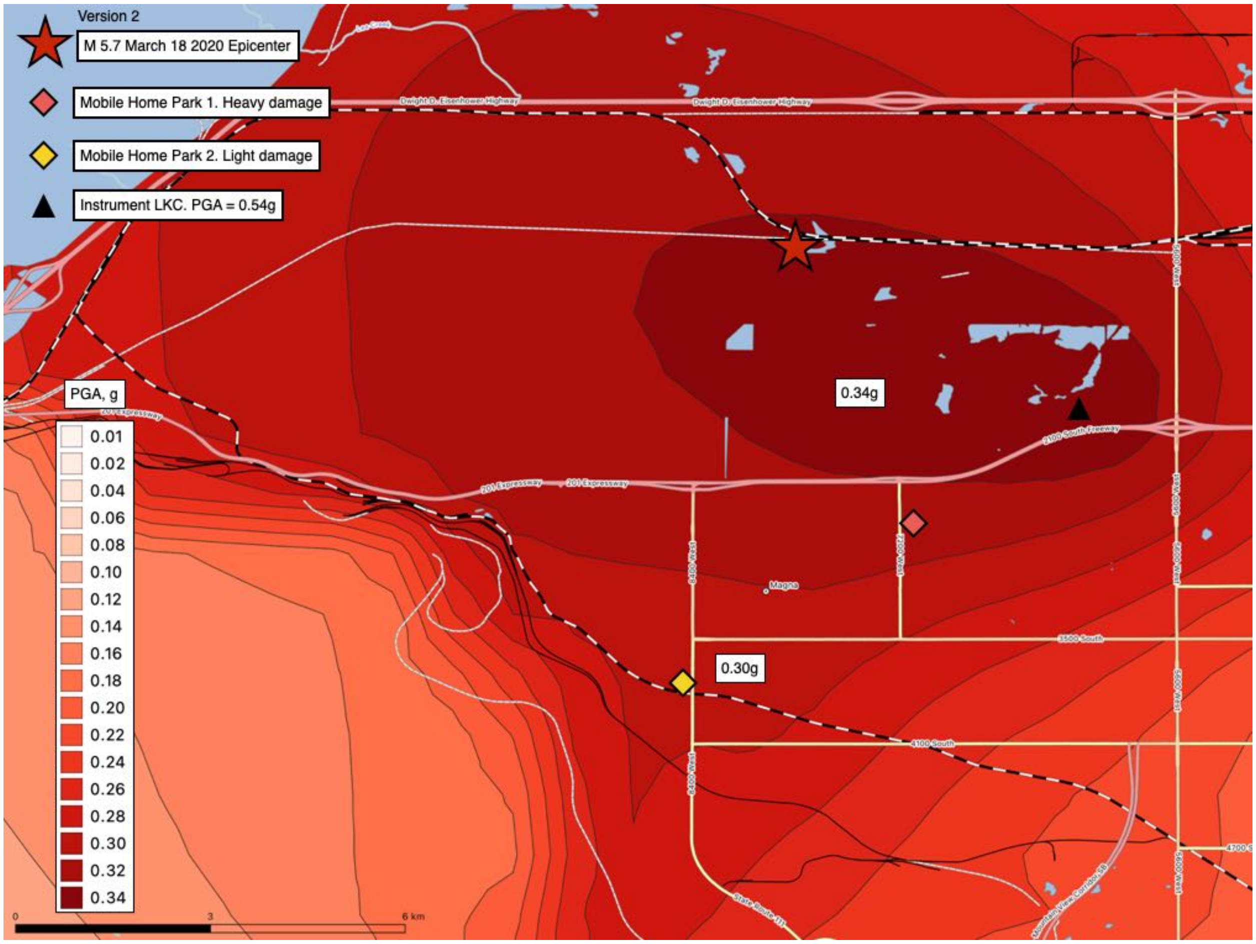


Figure 5. Magna Area Horizontal PGA Shaking Map (g) (Version 2 April 8 2020)

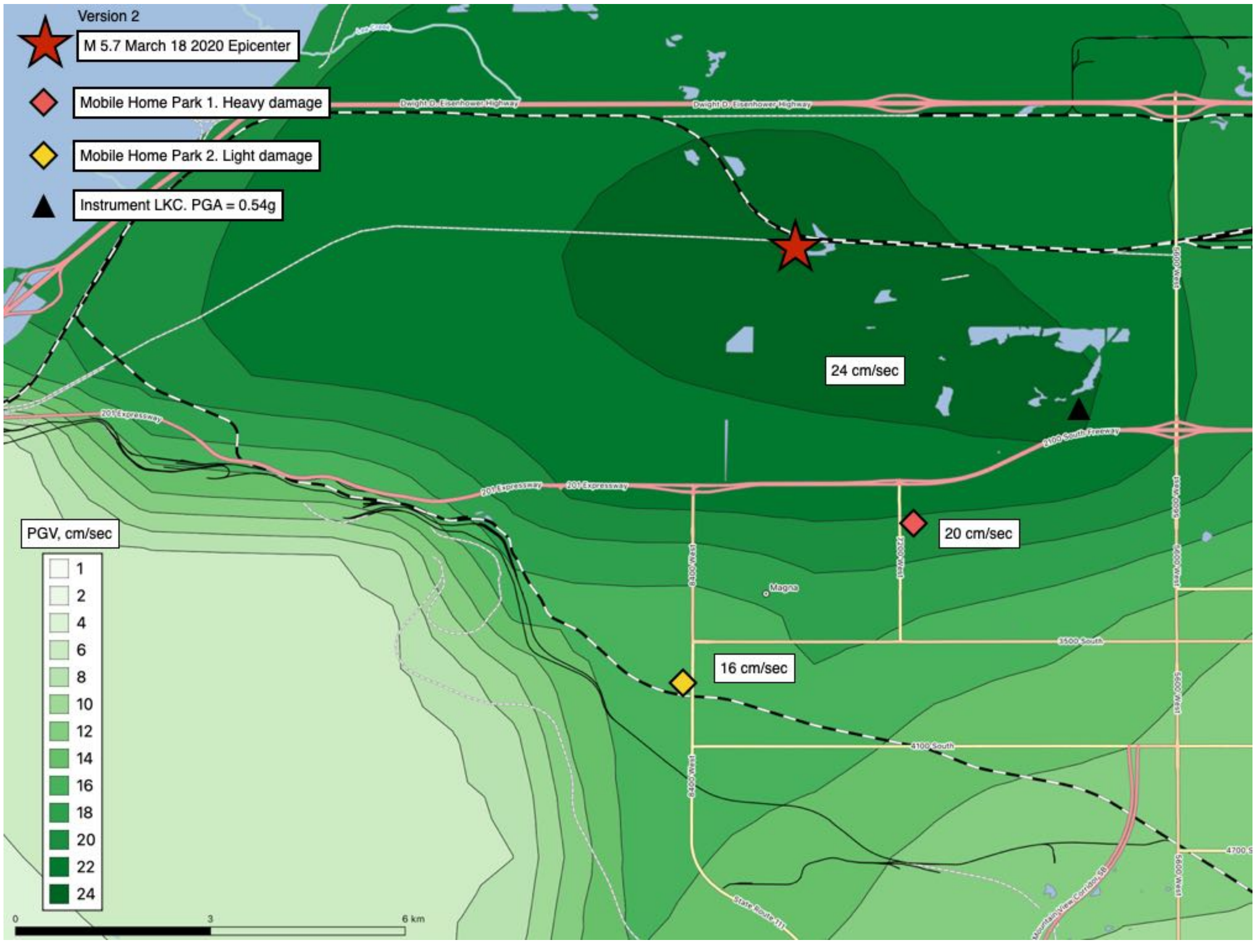


Figure 6. Magna Area Horizontal PGV Shaking Map (cm / second) (Version 2 April 8 2020)

Figures 7 and 8 show the regional ShakeMaps for PGA and PGV, respectively (Version 2). The ShakeMap-based motions in the region include:

- Downtown Salt Lake City (City Hall, State Capitol, etc.). PGA = 0.10g, PGV = 8 cm/sec.
- Downtown Magna. PGA = 0.32g, PGV = 22 cm/sec. Slight to moderate levels of damage to unreinforced brick buildings common.
- Layton (Home of Questar Earthquake Engineer). PGA = 0.06g, PGV = 4 cm/sec. "Shook me out of bed".
- Alta Ski Area. PGA = 0.02g, PGV = 1 cm/sec. No reported earthquake-induced avalanches within the ski area boundary.

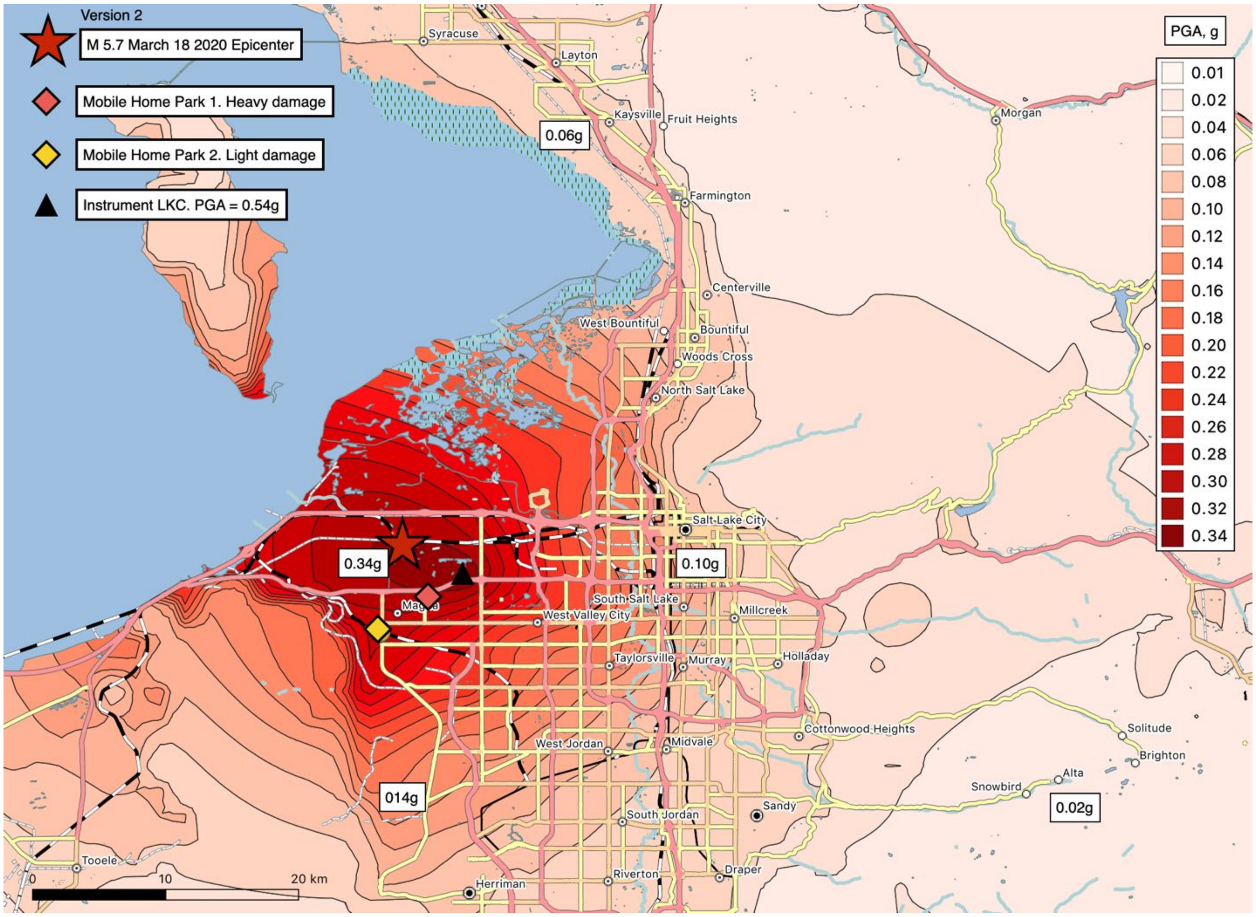


Figure 7. Regional Area Horizontal PGA Shaking Map (g) (Version 2 April 8 2020)

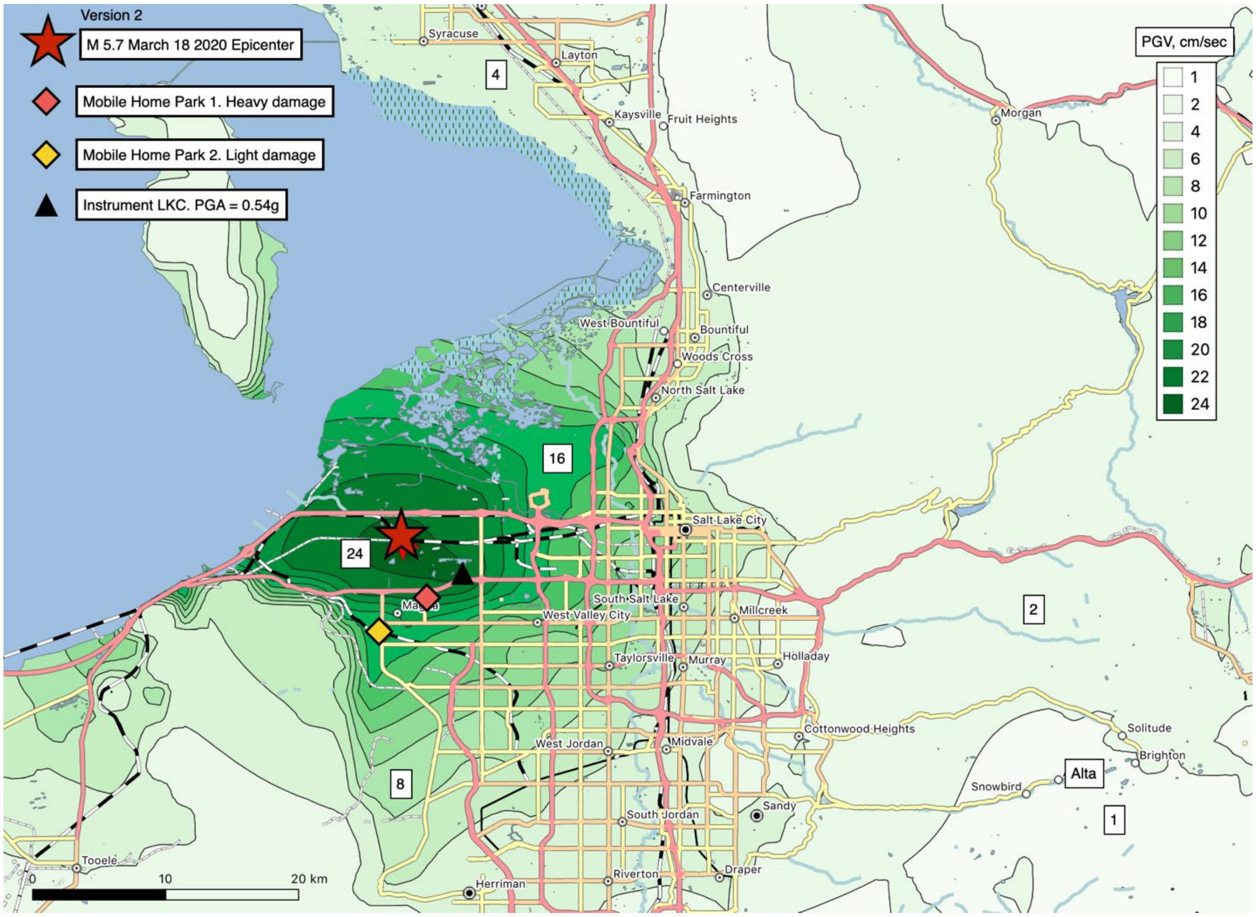


Figure 8. Regional Area Horizontal PGV Shaking Map (cm / second) (Version 2 April 8 2020)

Figure 9 shows the location of strong motion instrument LKC relative to MHP-1. Both LKC and MHP1 are considered to be deep soil sites, best characterized as Site Class D, with Vs30 in the range of 200 m/sec to 250 m/sec. Neither site was exposed to liquefaction.

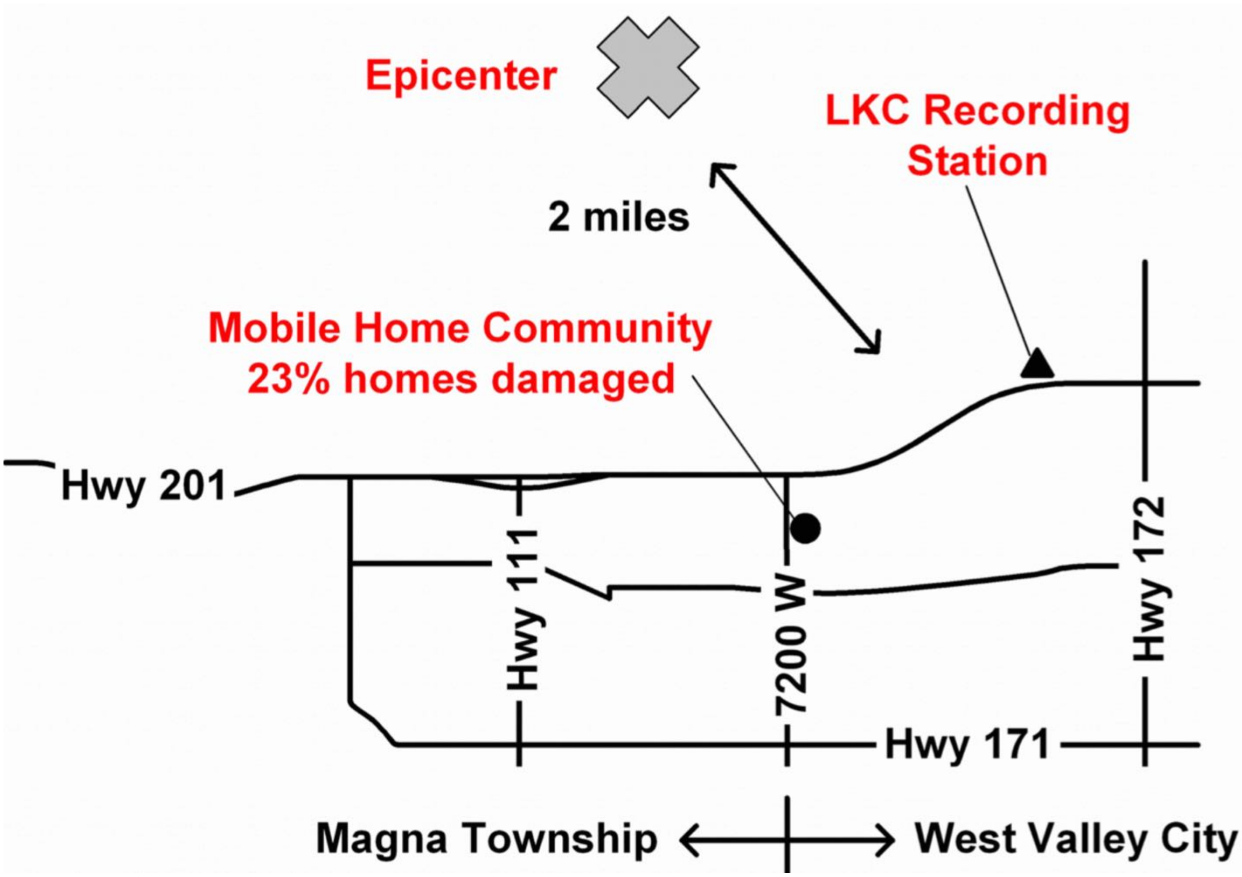


Figure 9. LKC Instrument.

Figure 10 shows Acceleration recorded motions and response spectra at LKC. The direction of strong shaking (PGA > 0.10g) was about 2.5 seconds. The horizontal spectra at LKC shows strong content of higher frequency energy (2 < F < 10 Hz), peaking at about 3 to 4 Hz. As discussed in Maison and Eidinger (2021), the dominant first mode period of mobile homes is in the 3 Hz range.

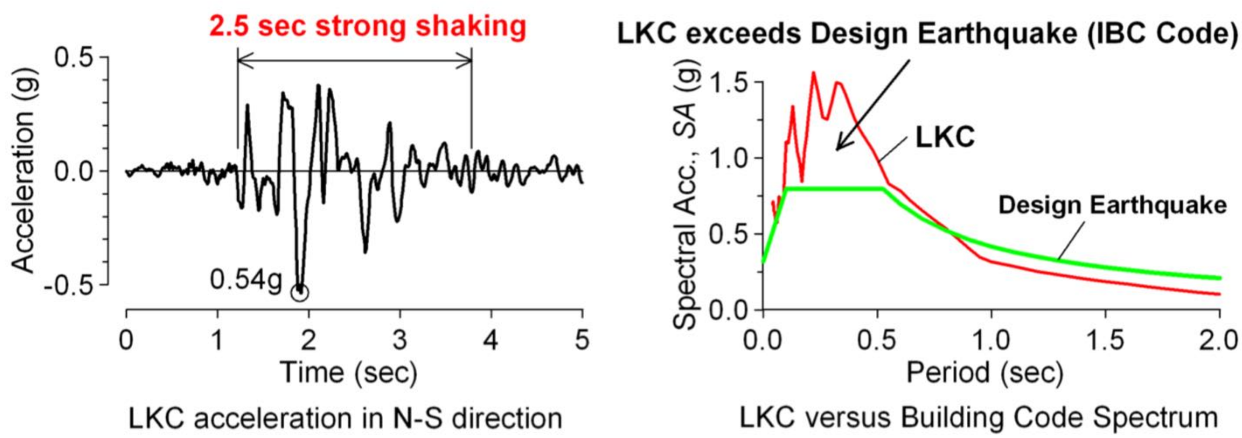
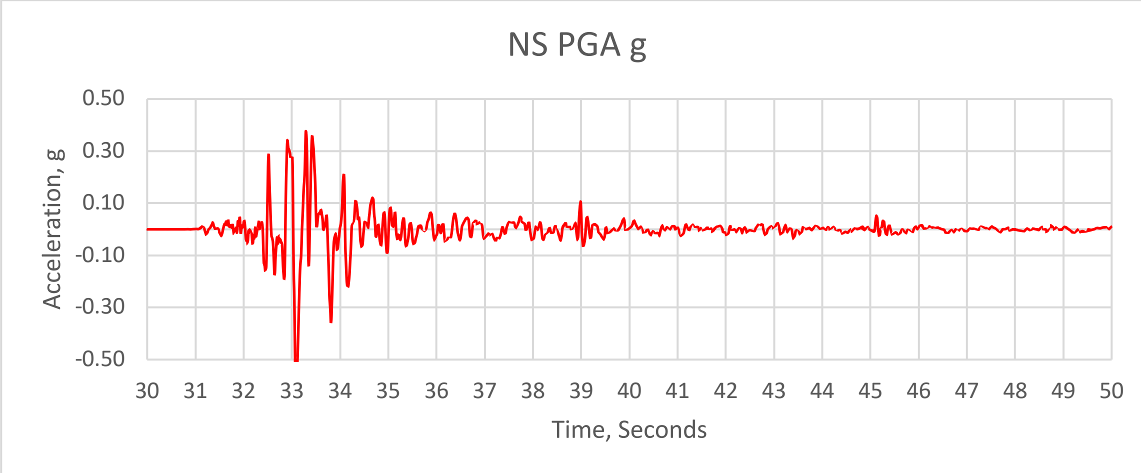


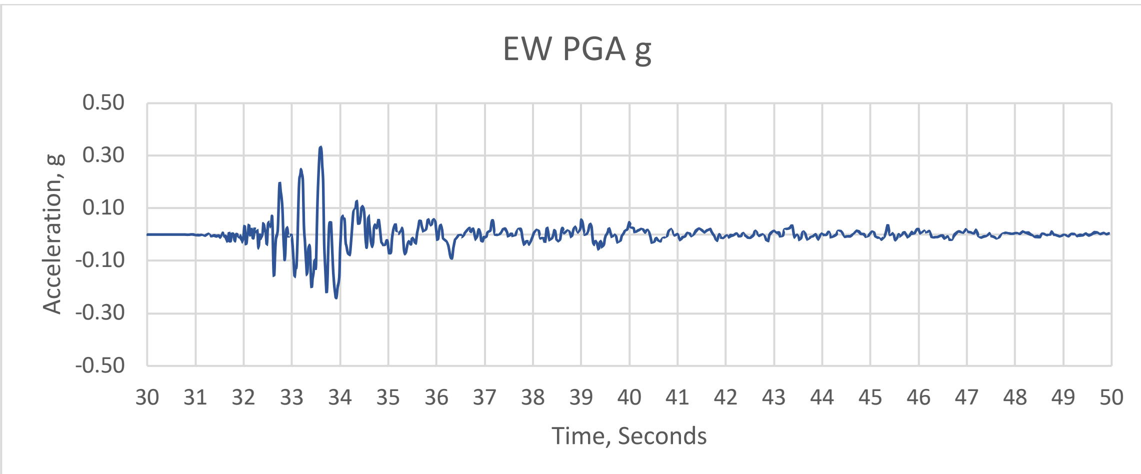
Figure 10. LKC Instrument Motions

Table 2 lists the minima and maxima motions from instrument LKC (data from file UULKC—n.60363602). The instrument is located at Latitude 40.7270 Longitude -112.0359. Recording length was 171 seconds. The data was processed March 24 2020. The data is derived from filtered motions, filtered below 0.10 Hz (for periods over 10 seconds) and above 40 Hz. The corresponding time histories are shown in Figures 11 (Acceleration) and Figure 12 (Velocity), showing the recording from time = 30 to 50 seconds. The instruments began recording motion at time = 30 seconds. The NS acceleration motions in Figure 10 are the same as those in Figure 11 (top graph).

Table 2. Ground Motions, Instrument LKC

Direction	Min	Max	Time at Min (sec)	Time at Max (sec)	Units
NS	-32.6809	26.8902	33.20	33.73	cm/sec
EW	-18.0451	24.471	34.23	33.66	cm/sec
Vertical	-8.4458	6.4133	32.76	33.28	cm/sec
NS	-0.5377	0.3767	33.10	33.28	g
EW	-0.2449	0.3369	33.91	33.58	g
Vertical	-0.2433	0.2167	32.69	31.87	g





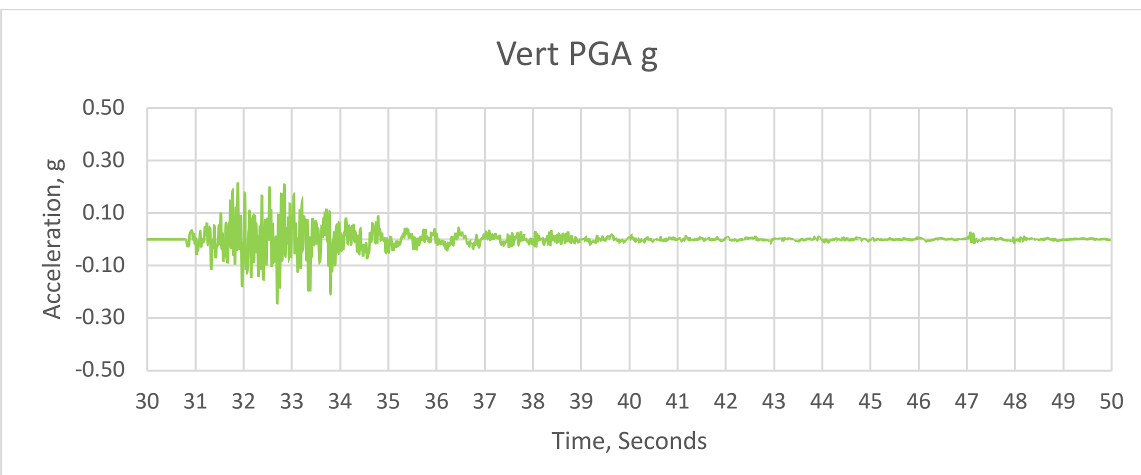


Figure 11. Ground Motions, Instrument LKC – Acceleration Time Histories

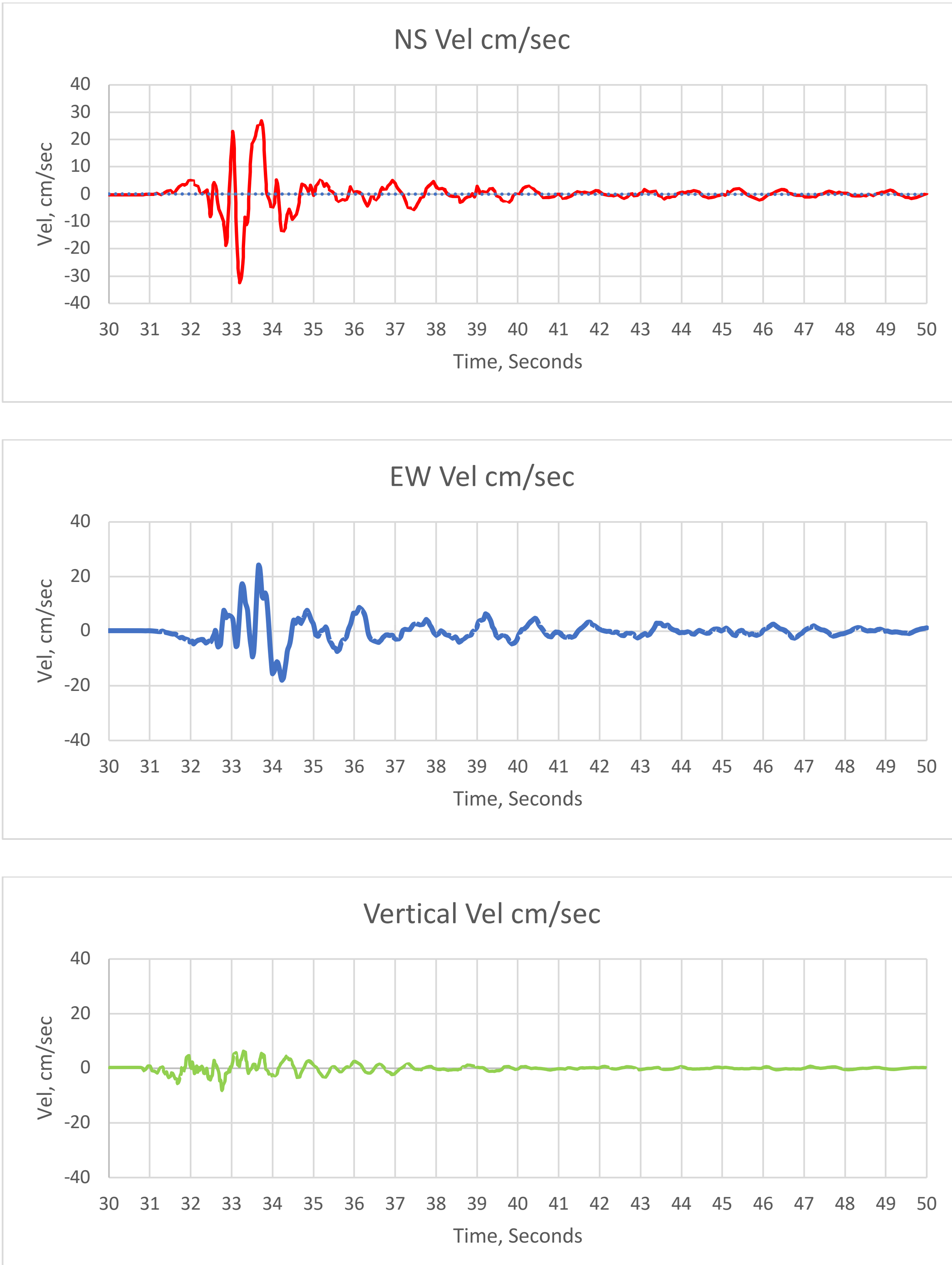


Figure 12. Ground Motions, Instrument LKC – Velocity Time Histories

3.0 Liquefaction

Figure 13 shows a map of the liquefaction susceptibility for the region. This map reflects the outwash from Little Cottonwood and Big Cottonwood Canyons, leading to the Great Salt Lake towards the northwest.

In the Magna M 5.7 earthquake, liquefaction effects were observed at the marinas along the Great Salt Lake, as indicated in Figure 13. There is little infrastructure in this area (no buried gas pipes). The general rule of thumb is that zones with high to very high susceptibility to liquefaction begin to have triggered liquefaction for M 7.5 earthquake at PGA = 0.10g (very high) or 0.20g (high).

Factoring in that liquefaction effects need time for pore pressure to build up, the general triggering models have a scaling factor to reflect duration of shaking. A commonly adopted scaling factor is PGA / (M / 7.5)**3. For example, for the M 5.7 earthquake, this ratio is 0.439. In other words, the liquefaction triggering levels are 0.10g / 0.438 (very high) or 0.20g / 0.438 (high), or PGA = 0.23g (very high) or 0.46g (high). Considering the PGA levels (Figure 7), and the liquefaction susceptibility (Figure 13), we would expect that liquefaction effects should be triggered along the shoreline of the Great Salt Lake (highest ground table, loosest granular materials), and perhaps sporadically for a few km southeast of the Great Salt Lake (in the red zones of Figure 13), but nowhere in Big or Little Cottonwood Canyons (PGA < 0.04g) or blue-mapped (moderate susceptibility) zones in the populated areas south of Salt Lake City (PGA < 0.15g or so). In contrast, for a M ~7 event along the Wasatch Front, one would expect widespread triggered liquefaction in the red zones in Figure 13.

There is nearly no natural gas system inventory located in the areas with PGA > 0.30g in Figure 7.

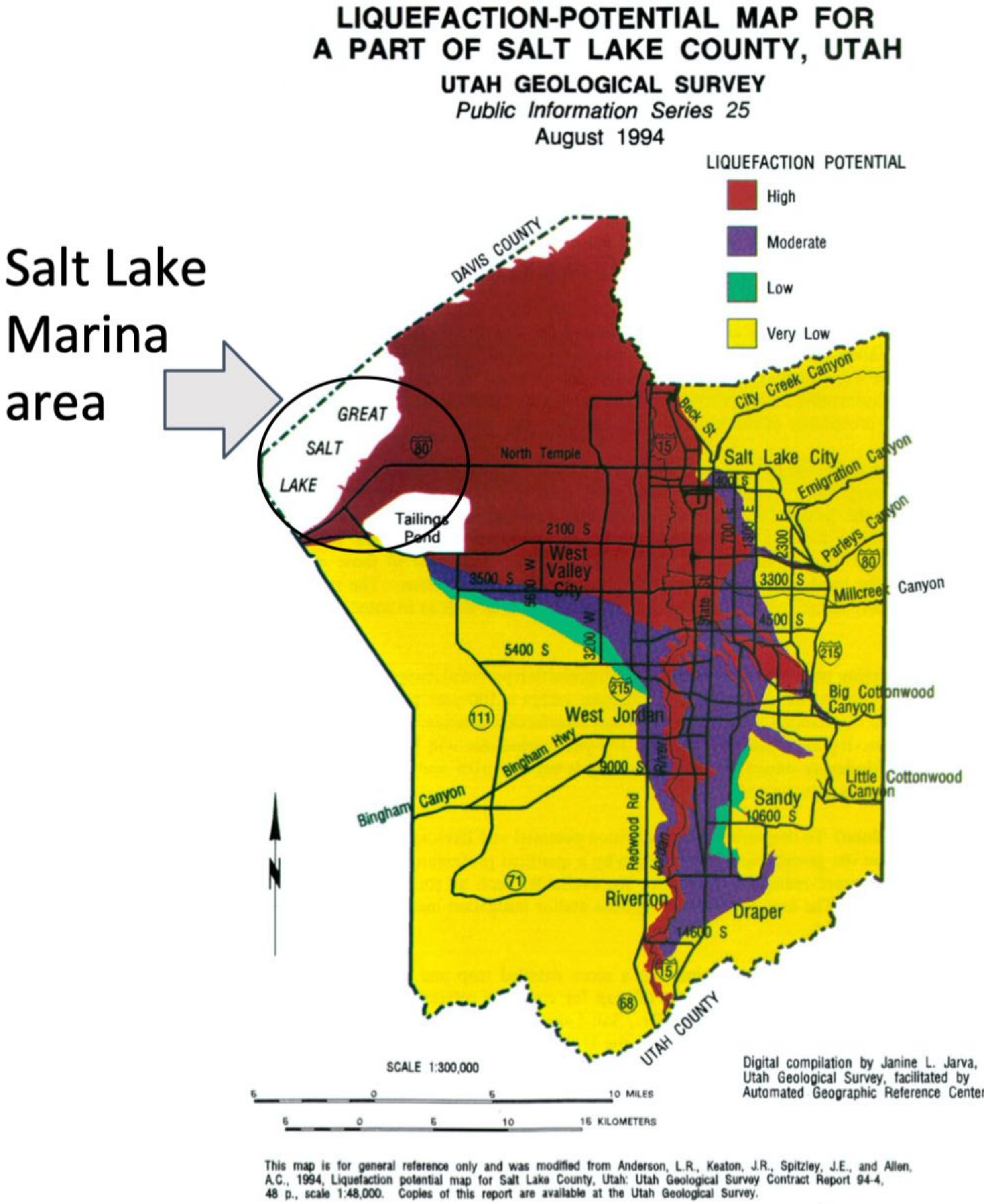


Figure 13. Regional Liquefaction Susceptibility (after Utah Geologic Survey)

4.0 The Natural Gas System

Dominion Energy (Dominion) operates the natural gas system serving the greater Salt Lake City area, including Magna.

Dominion is a producer and transporter of energy, listed on the New York Stock Exchange, with annual revenues on the order of $14 Billion and assets on the order of $96 Billion as of 2020. Most of Dominion's operations are in regulated electric generation, transmission and distribution infrastructure. Dominion's electric system portfolio includes about 30,700 MW of electric generating capacity, 10,400 miles of electric transmission lines, 85,000 miles of electric distribution lines. Dominion's natural gas portfolio includes about 94,200 miles of gas distribution mains and related service facilities. As of 2020, Dominion operates in 16 states and serves more than 7 million customers.

Dominion operates gas distribution systems in Ohio, West Virginia, North Carolina, Utah, southwest Wyoming and southeast Idaho. Combined, Dominion provides service to about 3.1 million gas residential, commercial and industrial customers.

In Utah, Dominion operates the natural gas distribution system serving the greater Salt Lake City area, including Magna. Dominion acquired these assets from Questar in 2016 for $4.4 Billion. In 2020, Dominion sold all of its transmission and gathering systems to Berkshire Hathaway Energy.

Today (2021), Dominion Energy Utah (formerly Questar Gas Company) is the only regulated public utility providing natural gas service in the state of Utah. Dominion has over 900,000 customers in Utah and serves about 90% of the households in Utah. There are about 3.206 million people in Utah (census data, 2019). The average natural gas customer (1 customer = 1 billing meter) represents, on average about 3.2 people. In Utah, Dominion operates about 30,000 miles of gas distribution mains and service lines.

The empirical evidence of the number of leaks in a modern natural gas system (G&E 2020) has been about: transmission (0 - 3%); distribution mains (3% - 30%); service laterals and meter sets (60% - 90%). In the 2020 Magna earthquake, the number of gas leaks was: transmission (0%); distribution mains (0.2%); service laterals (2.3%) and meter sets (97.5%).

4.1 Natural Gas Transmission System

Berkshire Hathaway Energy operates about 2,667 miles of interstate natural gas pipelines (as of 2015), that deliver gas from six major Rocky Mountain producing areas to various end users, including Dominion's gas distribution system in Utah. There are several other natural gas transmission system operators in the area, including Kern River Pipeline, Northwest Pipeline, Colorado Interstate Gas, Wyoming Interstate Company, Rockies Express Pipeline, and Ruby Pipeline.

- Of these transmission system pipelines, none are known to have suffered any gas leaks in the 2020 Magna earthquake. All the transmission pipes are believed to be welded steel pipelines.

- The Kern River Pipeline traverses the epicentral area (PGA > 0.3g). It was not known to have suffered any gas leaks.

- Many of Questar Pipeline transmission pipes are located near the epicentral area (PGA > 0.1g). None are known to have suffered any gas leaks.

4.2 Natural Gas Distribution System

Dominion distributes gas to customers along the Wasatch Front, including the following major populated areas (2020 Census data):

- Magna (population 27,000). Located adjacent to the epicentral area. This area was exposed to about PGA = 0.50g (northeast side) to 0.15g (south side).

- West Valley City (population 136,000). Located adjacent to the epicentral area. This area was exposed to about PGA = 0.10g (east side) to 0.30g (west side).

- Salt Lake City (population 200,000). Located east of the epicentral area. This area was exposed to about PGA = 0.05g (east side) to 0.30g (west side).

- West Jordan (population 114,000). Located south of the epicentral area. This area was exposed to about PGA = 0.10g (north side) to 0.05g (south side).

- Ogden. (population 87,000). Located 25 miles north of Salt Lake City. This area was exposed to about PGA = 0.05g (south side) to 0.01g (north side).

- Provo (population 117,000). Located 43 miles south of Salt Lake City. This area was exposed to about PGA ≤ 0.01g.

The Salt Lake City Metropolitan area is made up of 2 counties (Salt Lake and Tooele), and has a population of about 1.25 million people. The length of distribution pipes (including the length of distribution mains and service laterals) are estimated as follows:

Total length of natural gas pipe in Utah (distribution mains and laterals): 30,000 miles. Total population with natural gas service: 2,885,000 people; 900,000 meters.

Total people in the Salt Lake Metropolitan area (2 counties) served with natural gas, and exposed to PGA > 0.01g, PGV > 1 cm/sec = 1,200,000 people; 375,000 meters. Length of natural gas pipe (mains and service laterals): 13,000 miles.

The number of gas leaks in the distribution system was compiled after the earthquake. The underlying data was developed based on service calls and repair records. The data was aggregated in 71 communities around the greater Salt Lake City area, with a total population of about 2.6 million people.

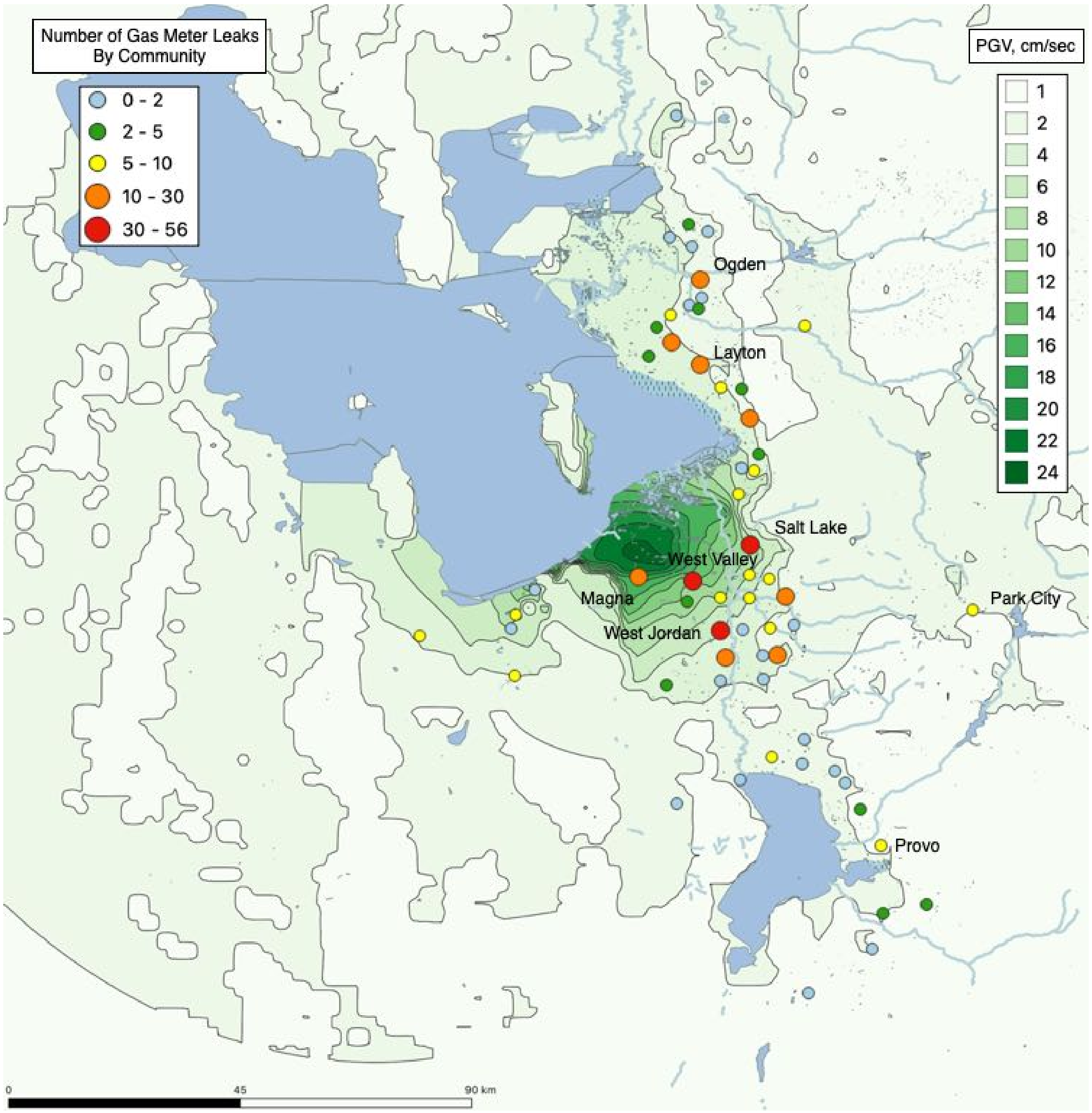


Figure 14. Number of Gas Meter Leaks, by Community

Figure 15 shows a plot of the number of meter leaks (468 total) versus the number of gas meters in each community. Figure 15 shows a generally increasing number of leaks in communities with a greater number of meters. Over the Greater Salt Lake City area, there was an average of one meter leak for every 1,730 meters.

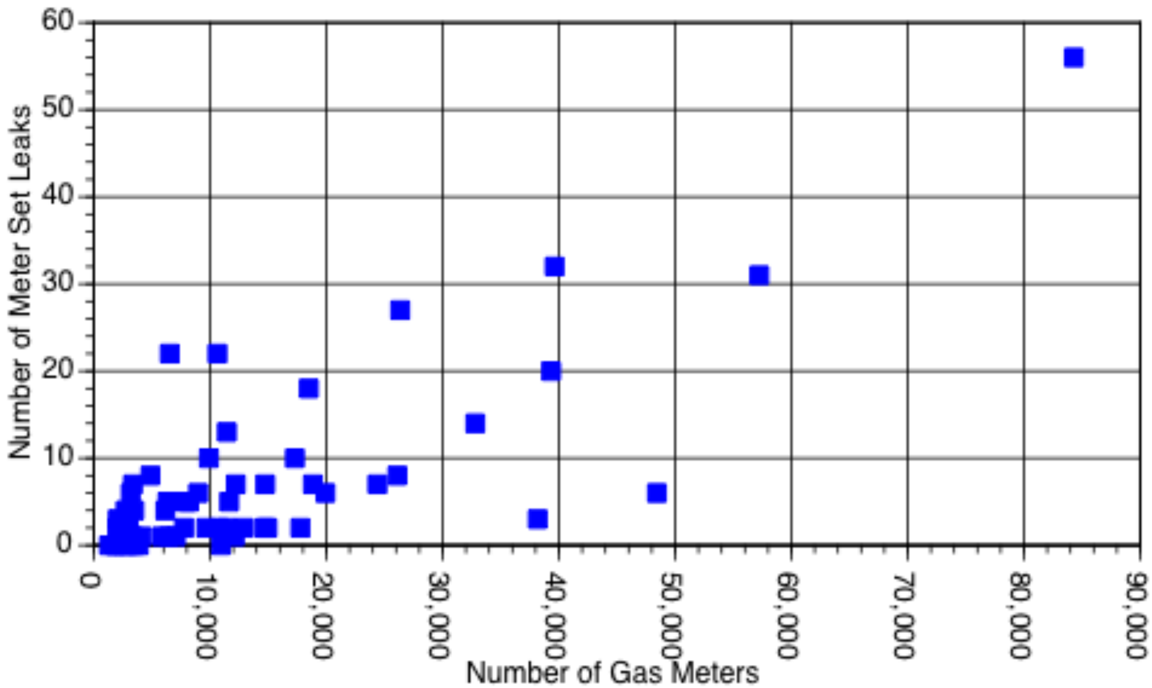


Figure 15. Number of Gas Meter Leaks vs Number of Gas Meters

Key points:

- The underlying leak data were originally geocoded by city / town / community. Geocoding to a more precise location (such as latitude / longitude) for each individual leak was not done.

- There was 1 reported leak to gas distribution pipe:

  - This leak was on a 2-inch PE distribution pipe. This PE pipe apparently impinged on rock. It is possible this leak pre-dated the earthquake.

- There were 468 meter leaks. These leaks are located at or near above ground gas meters where leaking gas was reported by customers or found by Dominion service crews. These leaks are classified as Class 1 or Class 2 leaks. These leaks include gas leaks found in the riser pipe, the meter set and its appurtenances, and generally the pipe (hose) between the meter and the building. Class 1 leaks are located generally within 5 feet of an occupied structure or otherwise considered hazardous. Class 2 leaks are located generally beyond 5 feet of a structure. Very minor leaks, (Class 3 leaks, generally at several parts per billion, non-hazardous, and not requiring immediate repair) were not tabulated.

  - Some of the meter leaks were likely leaking before the earthquake. It is common to find leaks after every leak survey, even without earthquakes.

    - The leaks reported after the earthquake include both leaks caused by the earthquake, as well as leaks caused by other factors, such as aging of materials. Practically speaking, all these leaks still need to be addressed post-earthquake.

- There were 11 service line leaks. Service line leaks are leaks found in buried pipe between the distribution main and the riser to the meter.

    - These include 4 leaks at the tap from the service line to the distribution main. Of these, 1 was for a PE service tee; 1 was at a steel cap; 1 was at a corroded steel service.

- There were 0 reported leaks in high-pressure subtransmission pipe. These are commonly 6-inch to 24-inch in diameter welded steel pipe.

- Almost all small diameter distribution pipe (pressures commonly < 60 psi) are PE.

- Almost all service laterals are buried. Service laterals include both PE (generally newer installations) and steel pipe (generally older installations). Most service lines are 1-inch diameter or smaller.

Figure 16, Risers and Meters. There were 468 leaks at gas meters. Figure 16 shows the correlation of gas meter leaks with PGV; the dots are the data and the plotted line is a linear best fit regression through the data. There is an increasing trend in the rate of leaks as PGV increases from 1 to 18 cm/sec. The data for the dots was computed by binning all the leaks by community (Figure 14), then assign the average PGV for that community, then assigning the number of gas meters in that community. Consistent with the findings in Maison and Eidinger (2021), we use PGV rather than PGA as the independent hazard variable. When using the data in Figure 16, it should only be used in a macro sense, meaning that it is an average leak rate for risers / meter sets, independent of the style of construction of the riser / meter set and the adjacent structure. Overall, at the highest PGV levels (18 cm/sec), about 1 in 600 risers / meters had a leak.

From a system-wide perspective, one could forecast the estimated number of leaks at about 1 in 1,800 riser / gas meter sets, for the Magna 5.7 earthquake in areas exposed to PGV $\geq$ 1 cm/sec. But, the user is cautioned that this earthquake had very short duration (~ 2.5 seconds of strong shaking); with higher magnitude earthquakes at similar PGV levels, one might expect a higher leak rate.

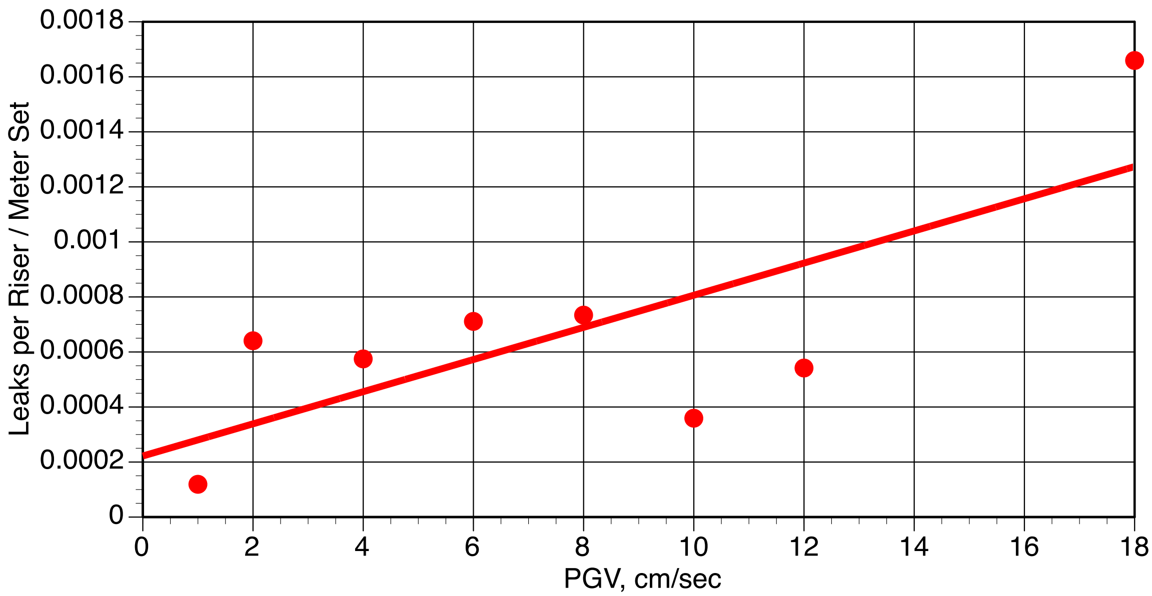


Figure 16. Leaks per Riser / Meter as a function of PGV

Figure 16 shows a trend in rising leak rate with rising PGV. In post-earthquake surveys of gas leaks, there is a question as to whether the recorded gas leak was pre-existing before the earthquake. For example, consider the gas leaks in the 2019 Ridgecrest earthquake; in that event, the field crews reported as to the proximate cause of the leak, and for about a tenth of all leaks, the reported cause with "earthquake / ground movement" or similar. This leads some to believe that the bulk of all reported leaks were pre-existing. However, when the leak data is plotted as a function of PGV (or PGA, etc.), there is an increasing leak rate as the level of hazard goes up, for both the Ridgecrest 2019 and Magna 2020 earthquakes. The engineering-based conclusion is that the extra forces (stresses) in the riser / meter sets caused by the earthquake do lead to increased rates of gas leak; quite possibly, had there been no earthquake, a smaller rate of gas leak might pre-exist the earthquake. The tentative conclusion is that the additional stresses imposed on the gas pipe riser / meter set does tend to open up more gas leaks at screwed joints, suggesting that if the riser / meter set was not leaking pre-earthquake, it might not leak; but if the riser / meter set was leaking pre-earthquake, the earthquake will tend to exacerbate the leak rate as the level of shaking increases.

Another interpretation of Figure 16 is that for PGVs between 1 and 12 cm/sec, there is possibly no (or little) increase in the rate of leaks per meter, averaging about 1 for every 1850 meters. It is only at the higher PGV levels (18 cm/sec) that there is a distinct increase in the rate of meter leaks (1 for every 600). But, the reader is cautioned that Figure 16 *does not differentiate* between meters that serve Mobile Homes versus meters that serve other types of structures. In Section 5, we examine the meters at one mobile home park (MHP). Statistically, the rate of riser / meter leaks was much higher at this MHP: on the order of 1 on 20 risers / meters at PGA = 22 cm/sec. This reflects that in the MHP, the sliding of structures impacted some meters; and the use of flex hose from the meter to the structure for all mobile homes, leads to a lower frequency of the riser / meter set (commonly around 1 Hz), leading to increased displacements, increased stresses in the riser / screwed joints, leading to increased chance of a gas leak. The much higher rate of leaks at meters in the MHP (see more discussion in Section 5), strongly indicates that the lower frequency of meters in MHP (due to use of flex hose and thus lower fundamental frequency) leaks to increased earthquake-induced stresses, leading to more leaks at threaded fittings, etc.

Figure 17, Service Laterals. There were 11 leaks. The leak locations were assigned in 12 PGV bins, from 1 to 22 cm/sec. Figure 17 shows a distinct increase in the rate of leaks as PGV increases from 4 to 14 cm/sec. The repair rate for PGV = 16, 18, 20, 22 bins is shown zero; the length of service laterals in these four PGV bins (about 220 km) is cumulatively about 4% of that in the PGV = 4, 6, 8, 10, 12, 14 bins (about 5,500 km). The lack of observed damage in these higher PGV bins (16 to 22) (primarily in Magna and West Valley City) likely reflects the relatively small inventory; and the relatively modern construction in these areas (meaning service laterals are all installed to modern standards, most installed post 1985, and most PE and relatively few steel. Another caveat: the length of service laterals is approximate; and based on an average of about 15 meters per meter (some are shorter, some are longer).

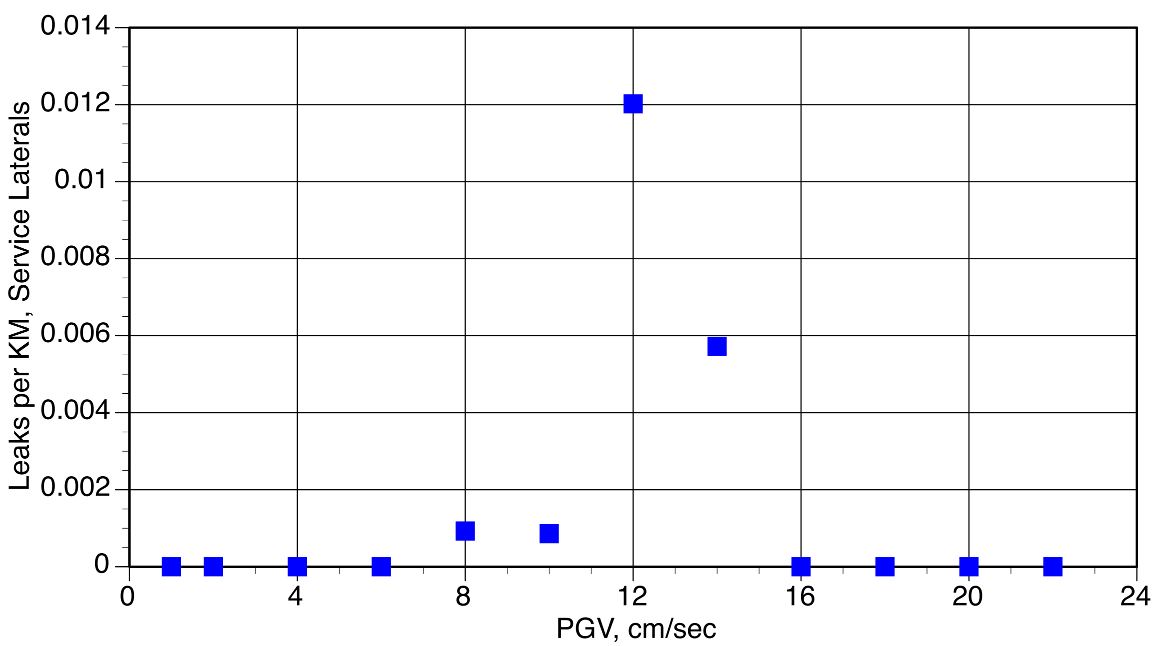


Figure 17. Leak Rate for Service Laterals per KM

For both Figures 16 and 17, the leaks are due to ground shaking hazard alone (in this case, quantified using PGV). In the Magna earthquake, only a very small length of gas pipe traversed zones with liquefaction-induced PGDs, and nearly no structures were exposed to PGDs. Additional damage would be expected if an earthquake triggers liquefaction, landslide or fault offset and there are gas infrastructure exposed to PGDs.

Further disaggregation of the data in Figures 16 and 17 would be useful, as for example:

- By pipe material (PE, steel)
- By type of meter (MH with flex hose, regular building with rigid pipe)
- By age of installation
- By corrosion protection system for steel pipe (uncoated, coated, sacrificial anode, impressed current)
- By soil resistivity (Rho, in ohm-cm). Soils with low Rho (under 1,000 ohm-cm) are very aggressive, and will rapidly corrode unprotected steel pipe. Soils with high Rho (over 10,000 ohm-cm) are relatively passive. Other measures, such as ground water table, clay, silt, granular, or other similar characteristics can also yield insight

Other facts related to the natural gas system for the Magna M 5.7 earthquake:

- About 48% of gas system customers who turned off their gas service, actually had gas leaks confirmed by Dominion. This compares to the 1994 Northridge earthquake (10%) and the 1987 Whitter earthquake (22%). Very small leaks of gas within structures may go unnoticed and post-earthquake testing for gas leaks will identify both pre-existing leaks and earthquake-caused leaks.
- In the 2018 Anchorage earthquake, the local gas company (Enstar) put out notices to people to stop manually turning of their gas services unless they smelled gas or otherwise observed gas leaks. The cost to inspect customer's facilities for gas leaks in small to moderate-sized earthquakes can reach about 90% of the gas companies restoration costs. In the interim, customers without gas supply, face issues due to loss of space heating, loss of cooking, etc.
- 9 earthquake valves are known to have been activated where ground shaking had PGA > 0.15g or so.
- 113 leaks were found on customer piping (inside the structure), of which 21.3% were on water heaters.
- The Dominion Energy Salt Lake Operations Center is located in Salt Lake City. It is a modern steel moment frame building. This building had been designed to remain function in the 2/3 x 2,475 year earthquake, following the concepts in IBC. The building was exposed to about PGA = 0.20g. It was reported that there was minor damage (things falling), but no structural damage.

5.0 Gas Meters at Mobile Homes

Section 4 of this report showed that the vast bulk of gas leaks (468) occurred at risers and meters sets; with relatively few leaks for service lateral pipes (11) and distribution mains (1).

In Section 5, we examine the situation of gas meters at the mobile home park, indicated at MHP-1 in Figures 1 and 3 through 8, or "Mobile Home Community" in Figure 9.

MHP-1 includes of about 206 mobile homes. There are similar numbers of double-wide and single-wide homes. The vintage of the mobile homes suggests common installations around 1990 or so. It is believed that all the mobile homes were anchored. The anchorage systems were installed to meet the requirements for wind loads. The equivalent seismic design of these anchorage systems were about V = 0.18W, which would reflect the common provisions for residential structures in seismic zone 4 (PGA = 0.40g), implying a response modification coefficient (R_w) of about 6, following the UBC code of 1988. Following the concepts of the UBC, the value of R_w could have been set as high as 8 (wood panel structural panel walls for structures three stories or less) or as low as 6 (all other light framed walls); no R_w values specific to mobile homes are listed in the UBC. Historically, this level of seismic design has been considered to meet the "life safety" provisions of various codes, like UBC 1997, and reflects that some amount of damage is expected if the design-level earthquake occurs.

What actually was observed at MHP-1 does not correspond well to UBC code-presumed performance. About 23% of all the trailers either collapsed (slid off their foundations) or had extensive damage (slid sideways on their foundations and required re-centering after the earthquake). For the estimated motions of about PGA = 0.33g at this site, and for a very short duration earthquake (2.5 seconds of strong shaking), the 23% failure rate is rather high, and undesired performance.

To be clear, the authors *do not* recommend that using a R_w value of 6 is suitable for mobile homes that are supported on steel stands and use steel straps for lateral restraint. Based on the observed performance at Magna, the authors would suggest adopting R_w in the range of 2 to 2.5; or no higher than 3 for this style of construction; further research in this area is suggested.

What was the level of shaking at MHP-1?

- If one relies on ShakeMap V2 (see Table 1), the median estimated horizontal motion at MHP-1 was PGA = 0.33g and PGV = 22 cm/sec.

- If one relies on instrument LKC (see Tables 1, 2), the actual recorded motion at LKC was PGA = 0.54g and PGV = 33 cm/sec.

- There was no instrument at MHP-1 to record actual motions. Therefore, we do not have certainty as to what the actual motions at MHP-1 were. One could assume that the hypocentral distance from the epicenter to LKC is nearly the same as to MHP-1, and then assume the LKC motions. Or, once could assume the ShakeMap V2 motions, and allow that the motions might have been -40% to +60% or so.

- Based on field observation, it is clear that MHP-1 experienced rather violent motions, lasting perhaps 3 seconds or so, with about 2 or 3 cycles of strong motion (see Figures 11 and 12).

- Many steel straps in the anchorage systems failed. By "failure", the straps broke entirely. Maison and Martinez (2020) shows the details, with the straps broken entirely.

- At MHP-2, the level of shaking was somewhat lower than at MHP-1. There were essentially no gross failures of MH at MHP-2; in part, this is attributed to the somewhat lower motions, but also attributed that many of the MH at MHP-2 were supported by concrete blocks. In the Anchorage 2018 earthquake, there were many MH, many supported on concrete blocks; with relatively few gross failures; Maison, Eidinger and Dai (2021) discuss this, suggesting that the superior lateral force resistance is attribute, in part, to the higher friction and wider sliding services afforded by concrete blocks; other factors include use of rigid skirts, which also provide some lateral resistance capability.

5.1 Gas Meters

Figure 18 shows a typical riser and gas meter configuration. For Mobile Homes, the "houseline" is a flex hose; for other structures (wood frame residential; concrete; masonry, steel), the "houseline" is commonly a rigid pipe.

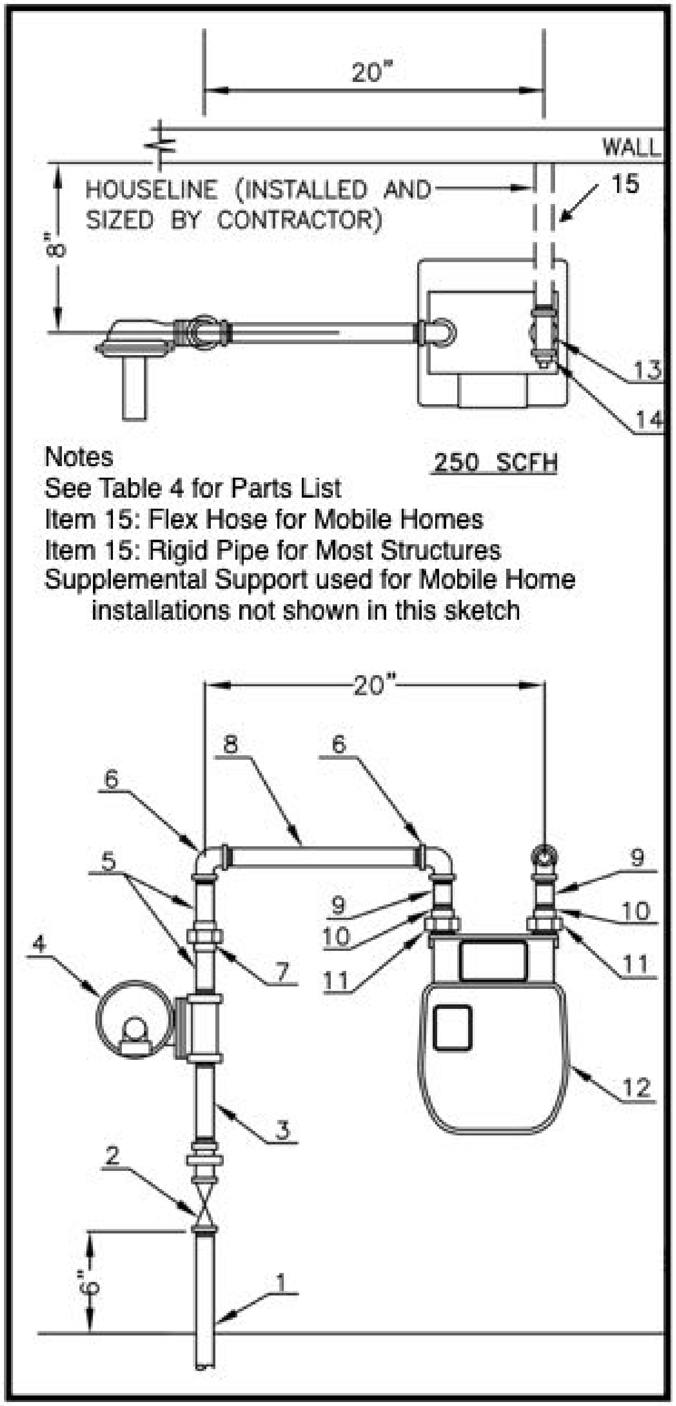


Figure 18. Common Riser and Gas Meter Typical Installation (see Table 4 for parts list)

Figure 19 shows a typical installation of the service lateral from the distribution main in the street, and towards the gas meter assembly. At the MHP, all the service lines are made from PE pipe, and there are Excess Flow Valves (EFV) for every service lateral. The function of the EFV is that should the PE pipe between the distribution main and the gas meter (operating up to 60 psi) be broken (say by accidental backhoe action), then the sudden change in pressure will activate the valve, and the flow of gas to the broken pipe will be reduced. It is recognized that the EFV does not provide as much function should the pipe break occur after the meter (after the gas pressure is much reduced to the 0.25 psi± level within the structure).

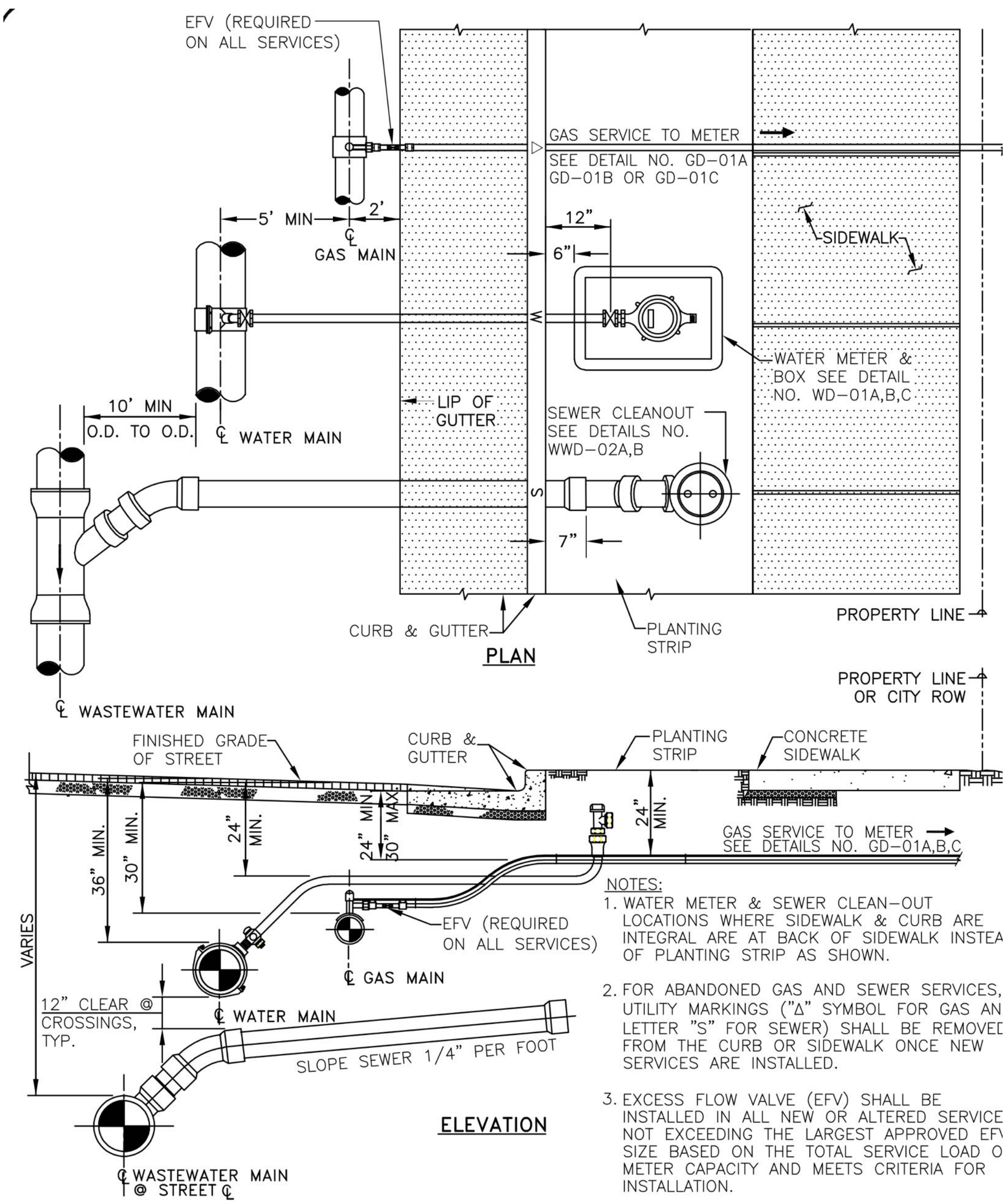


Figure 19. Typical Service Lateral Configurations

Figure 20 shows a typical detail of the gas service lateral pipe.

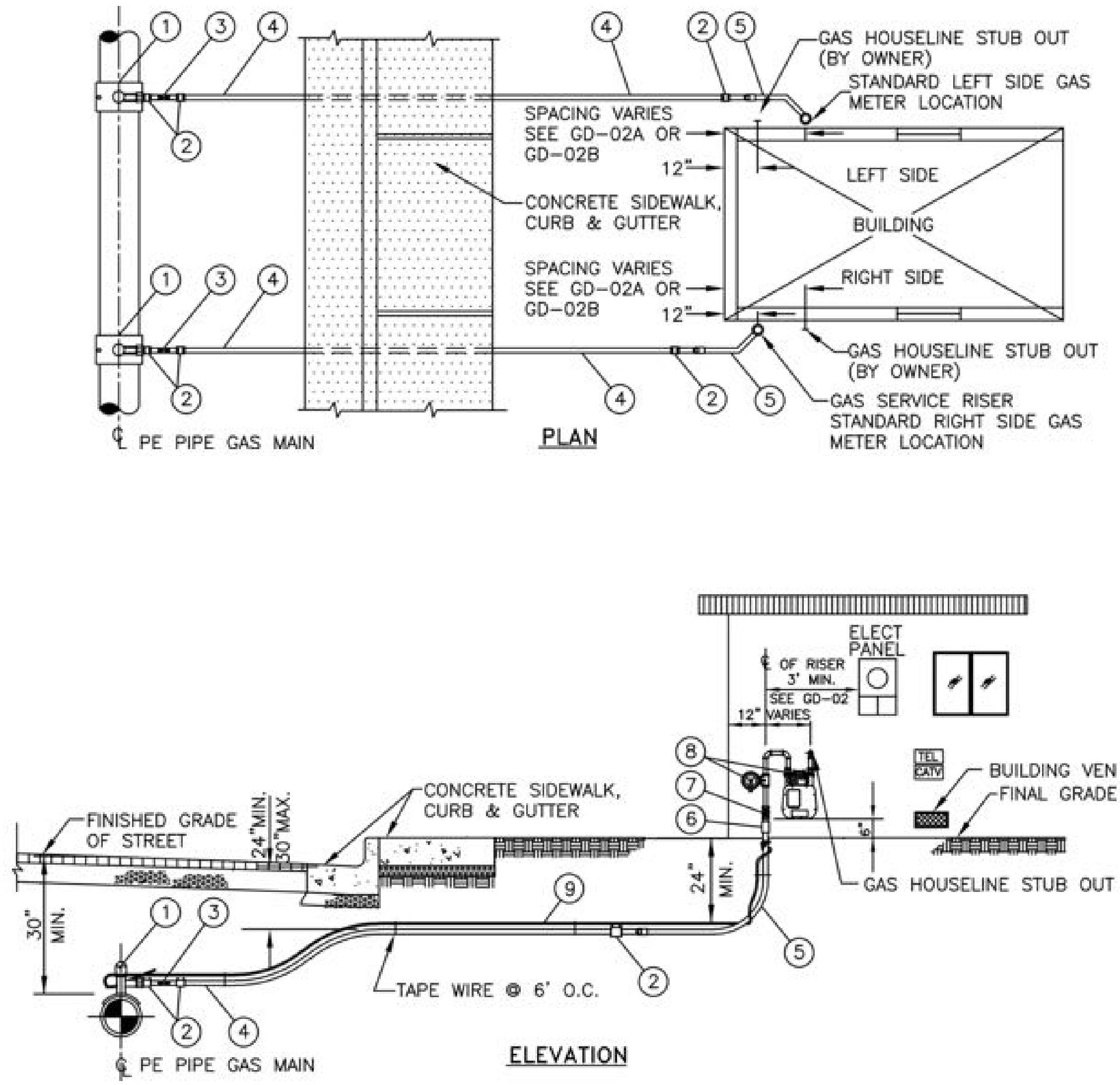


Figure 20. Typical Gas Service Line Details (see Table 5 for parts list)

Table 4 describes the various parts in the riser / gas meter assembly.

Table 4. Parts for Meter / Riser Assembly in Figure 16 for MH Application

Item	Comments
1	¾" x 1" riser (PE to steel)
2	¾" isolation valve
3	¾" pipe steel
4	Pressure Regulator
5	¾" pipe steel
6	¾" elbow
7	¾" union
8	¾" pipe steel
9	¾" pipe
10	¾" swivel
11	Nut
12	Gas meter, diaphragm
13	¾" tee
14	¾" plug
15	¾" flex hose (to MH)

From the riser to the connection to the mobile home, there are as many as 15 threaded connections.

For common installations not at mobile homes, part 15 (pipe from the meter into the house) is a rigid pipe, and is supported for gravity loads by the hole through the exterior wall of the house.

For common installations at mobile homes, part 15 (pipe from the meter into the house) is a flexible hose, which cannot sustain gravity loads. Therefore, an extra pipe support is provided at Mobile Homes; this extra pipe support is not shown in Figure 18. At MHP-1, two types of this extra pipe support are used (see next sections for more details and photos):

- Post Type 1. Vertical steel post, with welded horizontal steel to a steel attachment that is attached to the two pipes atop the gas meter. This type of support provides vertical load carrying capability, plus lateral restraint in either horizontal direction. See examples in Figures 22, 24, 26b, 30b, 32b.

- Tube Type 2. Vertical steel pipe, attached to a pipe "tee" that acts like a "tube". The rigid low pressure pipe from the customer-side of the meter goes through the "tee". This type of support provides vertical load carrying capability, plus some lateral restrain in one horizontal direction (transverse to the exit rigid pipe) and limited lateral restraint (other than afforded by friction) parallel to the exist rigid pipe. See examples in Figures 23, 25, 27, 28, 29, 31.

Table 5 describes the various parts in the service line. Item 5, the riser, consists of pre-bent 90° steel pipe, with an internal PE pipe and PE-to-steel connection. The PE pipe runs past the steel casing, below ground, so that it can be connected (commonly a fused joint) with the PE pipe to the service lateral. By "anodeless", it is meant that the steel riser is constructed with an epoxy coating. The riser can be connected to the underground PE pipe by means of a transition fitting, adapter or heat fusion.

Table 5. Service Lateral Parts

Item	Comments
1	Electrofusion tapping tee, 2" (main size) to 1"
2	1" electrofusion couplings
3	1" Excess Flow Valve
4	1" PE Pipe, SDR 11.5 gas service 2708
5	1" pre-bent anodeless riser, 1" PE to ¾" steel
6	Tag indicating size
7	¾" isolation valve, same as item 2 in Table 4
8	Regulator and Meter - see Table 4
9	Tracer wire, yellow

The operating pressure in the distribution pipe will commonly be in the range of 30 psi to 60 psi. Distribution pipe at the MHP are all PE. PE pipe is commonly type 2708 (medium density MDPE); Dominion does not use HDPE; this 4-digit number (XYZZ) refers as follows: X = resin type; Y = crack strength; ZZ = hydrostatic strength in 100s of psi (08 = 800 psi, etc.). Older installations (generally pre-1970) might use steel pipe. In very old installations (generally pre-1925), distribution pipe might be cast iron (such was the case in the 1906 earthquake in San Francisco; the last cast iron pipe in the Dominion Utah gas system was retired by the 1990s).

Service line lateral pipes are designed to operate safety at 125 psi. The service regulator on the riser at the meter location serves to reduce this pressure to about 7 to 11 inches of water column (1 inch water column (w.c.) = 0.036 psi at 39.2°F). The common pressure on the customer side is about 0.25 psi (= 7 inch w.c. = 4 oz)

An EFV is designed to reduce the flow of gas should a downstream break occur. An EFV is not designed to close if the downstream break is not large enough to allow enough flow to close the valve. This is potentially the case where a break occurs within the residence (say caused by toppling of a water heater), and the rate of gas flow lost through the damaged pipe is low enough so as not to activate the EFV at the main/service line connection. A second low pressure EFV could be installed on the customer side of the meter, but this was not observed at the MHP.

5.2 Frequencies, Stresses, Leaks in Above Ground Pipe

When consider the structural seismic performance of the service lateral / riser / meter / house connection, the following vulnerabilities need to be considered:

- Inertial shaking. The meter assembly with all attached above ground pipe and fittings may weigh about 25 pounds.

- Assuming the vertical steel pipe is ¾" with threaded connections, and a flex hose connection into the mobile home. If there is no other lateral support, and assuming the vertical pipe is "fixed" connection at the base (which is not the case), then the first mode frequency of the meter set is about 1 Hz (1.1 Hz if the vertical pipe is 1"). A factor that will reduce the frequency are the flexibility of the riser pipe, as it bends in the soil. A factor that will increase the frequency is the stiffness afforded by supplementary supports on the meter set. A meter that has a supplementary "Tube Type 2" support would have a lower frequency in one horizontal direction, once friction is overcome by differential lateral movement of the pipe-in-tube assembly. A meter that has a supplementary "Post Type 1" support would have similar frequencies in both horizontal directions.

- At the MHP, all the gas meter sets include a supplementary steel support. Two types are used:

    - Type 1. A "tee" configuration that is attached to the two vertical rigid pipes atop the meter. This provides vertical support and lateral support in both horizontal directions. See examples in Figures 22, 24, 26b, 30b, 32b.

    - Type 2. A "tube" configuration that has the discharge steel pipe go through another pipe, and that pipe attached to a vertical steel stand. This provides vertical support and lateral support in one horizontal direction; and more limited lateral support (depending on tightness of connection and friction) in the other horizontal direction. See examples in Figures 23, 25, 27, 28, 29, 31.

    - With either the Type 1 or Type 2 supports, the net increased in lateral stiffness is about double that afforded by the steel riser pipe.

    - Thus, the range of fundamental frequencies of the various riser / meter sets at the MHP will commonly be in the range of 1 Hz (near lower bound) to 2 Hz, to perhaps 3 Hz or so (near upper bound), with a common frequency of about 1.5 Hz. Comparing this to the response spectra for LKC (Figure 10), the 5% damped Spectral Acceleration will be commonly in the range of about 0.4g to 0.8g; but if at the peak of the spectra, on the order of 1.5g.

- Assuming that the riser pipe withstands most of the lateral motion of the meter, then a common seismic base bending moment is about 25 pounds x 1.5g x 30" = 1,125 pound-inch, and the bending stress in the riser pipe is 16 ksi.

- Threaded connections are not as strong as the pipe. If one allows that leakage begins at about 50% yield, and that the vertical steel pipes have Fy = 30 ksi, then leakage is expected at SA = 1.5g.

- Pipe joint compound (also called pipe dope) is typically applied on threaded joints, so as to lubricate threaded fittings and prevent leakage under normal operating conditions. There are various products that can be used. Over time, the effects of ultraviolet radiation from sun exposure may tend to embrittle the pipe dope, leading to leaks. Under earthquake loads, the extra stress applied to the threaded joints will tend to allow the threaded connections to start to leak; or if it is already leaking, to leak at a higher rate.

- As long as the seismic pipe stress is not excessive (say between 50% and 90% Fy) the pipe joints should retain their basic integrity, and gas leakage can be resolved by applying additional pipe dope.

- If the seismic pipe stress is excessive (much over Fy, as may be caused be extremely high shaking, not the case in this earthquake) or by impact by the sliding mobile home (which was the case at some locations in this earthquake), then failure of the threaded fittings in the above ground pipe, or imposed stresses at the first joint below ground at the riser-to-horizontal lateral pipe, are expected.

5.3 Gas Meter Damage

Figure 21 shows a map of a portion of MHP-1. This is the Western Estates mobile home park. One block to the south is the Kopper View mobile home park, which is not addressed in Section 5.3. Each structure was assigned a consecutive number from 1 to 145; carports were assigned the same number as the mobile home, appended with "A".

Figure 21. MHP-1 Map

Each of the MH was observed from the street. Each gas meter for each MH was also observed. The following statistics document what was observed in October 2020. The totals do not add up to 145, as some data was not collected for some structures. All photos (except four insets) were taken in October 2020, about 7 months after the earthquake.

Type of Mobile Home Structure.

- Single Wide. 62
- Double Wide. 68
- Empty Lot. 1 (MH removed)

Skirts. The damage to skirts at the base of the MH were classified into four categories:

- None. 85 (It is possible that more skirts were originally damaged, but the damage was not observable in October 2020, possible due to prior repairs)
- Minor. 29
- Major. 10

Gas Meter Supplement Supports.

- Post Type. 59
- Tube Type. 44

Gas Meter Condition

- Original. 67. These include repairs that consisted of adding pipe dope or other minor adjustment that could not be observed in October 2020.
- Tilted. 32. (Meter is tilted, suggested impact from the MH during the earthquake)
- Major. 8 (entire assembly replaced)

Gas Meter Setback from Mobile Home. This is the distance from the outside of the mobile home skirting to the nearest rigid pipe / meter on the above ground part of the meter. The distance D = "0.1" feet indicates that the pipe / meter set abuts the structure with very limited (perhaps an inch) setback. These distances were estimated from observation form the street, and are approximate.

- Minimum D. 0.1 feet
- Maximum D. 5.0 feet
- Average D. 1.3 feet
- Count, D < 0.2 feet = 2
- Count, ≤ 0.2 D < 0.5 feet = 10
- Count, ≤ 0.5 D < 1.0 feet = 18

Figures 22 to 33 show a range of gas meters, either original, or replaced.

Figure 22. Structure 5. Meter tilted (towards structure).

Figure 23. Structure 6. Original Meter. Tube-type supplementary support. No impacts.

Figure 24. Structure 7. Original Meter. Post-type supplementary support. No impacts.

Figure 25. Structure 16. Original Meter. Tube-type support. Limited clearance D.

Figure 26-a. Structure 18. Inset Photo shows structure immediately post-earthquake. Main photo shows structure after repair. Inset photo indicates impacted gas meter set. See Fig 24b for meter.

Figure 26-b. Structure 18. Restored gas meter set for Structure 18

Figure 27. Structure 19. Tilted Gas Meter Set (Tube Support). Indication is that the MH impacted the tube type support

Figure 28. Structure 33. Original Gas Meter Set (Tube Support). Limited clearance D.

Figure 29. Structure 44. Original Gas Meter Set (Tube Support). Tilted

Figure 30-a. Structure 49. Inset Photo shows structure immediately post-earthquake. Main photo shows structure after repair. Inset photo indicates impacted gas meter set. Figure 30-b shows gas meter set after repair.

Figure 30-b. Structure 49. Gas meter set after repair.

Figure 31. Structure 67. Tilted Gas Meter Set. Damage to MH suggests the meter was impacted during the earthquake.

Figure 32-a. Structure 75. Inset Photo shows structure immediately post-earthquake. Main photo shows structure after repair. Figure 32-b shows gas meter set after repair.

Figure 32-b. Structure 75. New flex hose (yellow). New Meter and Regulator. Original customer-side pipe (with rust).

Figure 33-a. Structure 141. Inset Photo shows structure immediately post-earthquake. Main photo shows structure after repair. 4 yellow bollards (foreground) intended to protect meter from impacts from vehicles. Replacement meter set back from low pressure customer pipe with new yellow flex hose (Figure 33-b).

Figure 33-b. New meter (foreground) new flex hose (yellow). Bollards are original.

6.0 Abbreviations

cm	centimeter
D	Distance between Riser assembly and mobile home (feet)
DYFI	Did You Feel It
EFV	Excess Flow Valve
F	frequency (Hz)
Fy	Yield stress of steel pipe
g	acceleration of gravity (= 32.2 feet / sec / sec = 981 cm / sec / sec)
HDPE	High Density Polyethylene
Hz	Hertz
km	kilometer
M	Magnitude (moment magnitude)
MH	Mobile Home (same as Manufactured Housing)
MDPE	Medium Density Polyethylene
MHP	Mobile Home Park
MMI	Modified Mercalli Intensity
mph	miles per hour
MW	Megawatt
PE	Polyethylene
PGA	Peak Ground Acceleration (measured in g)
PGD	Permanent Ground Displacement
PGV	Peak Ground Velocity (measured in inches/second or cm/second)
psi	pounds per square inch
R_w	Response Modification Coefficient
SCFH	Standard Cubic Feet per Hour. 1 SCF of methane ~ 1020 BTUs
Therm	1 Therm = 99.87 cubic feet of methane
USGS	United States Geological Survey
V	Seismic Base Shear (kips)
Vs30	Average shear wave speed in the highest 30 meters of a site
W	Dead weight of structure (kips)
WFZ	Wasatch Fault Zone

7.0 References

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