Seismic Performance of Wine Caves

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INTRODUCTION

The South Napa Earthquake of 2014 caused ground motion at numerous reinforced concrete-lined (shotcrete-lined) winery tunnels in Napa County and Sonoma County, California. The occurrence of seismic ground motion at these tunnel complexes, known as wine caves, presented an opportunity to reevaluate seismic performance of reinforced concrete and reinforced shotcrete lined tunnels.

The authors of this paper updated the most recent comprehensive compilation and evaluation of case studies by Power and others (1998), which correlates peak ground acceleration (PGA) at tunnel sites to damage. For this update, the authors evaluated the seismic performance of 31 wine caves near the South Napa Earthquake epicenter; including some of the 90 wine caves they designed since 1991, some caves designed by others, and additional caves constructed by contractors that they frequently work with. Tunnel designers can use the new data presented in this paper to help evaluate the usefulness of detailed seismic design analyses.

THE SOUTH NAPA EARTHQUAKE

The South Napa Earthquake occurred at 3:20 AM Pacific Daylight Time on August 24, 2014. Figure 1 shows the approximate location of the epicenter, the measured/estimated PGA contours, and the location of wineries with wine caves added to the database where the PGA was at least 0.2 g.

The epicenter was along the West Napa fault, about 5 miles south-southwest of downtown Napa, California. The earthquake moment magnitude was 6.0, and measured/estimated PGAs were up to about 0.7 g. The duration of strong shaking was about 10 seconds. This earthquake was characterized by right lateral strike-slip fault movement, ground surface rupture, and afterslip at the ruptures. Increased surface water flows were observed at seven creeks after the earthquake. Groundwater level rises of up to 5 feet were observed in Sonoma County wells after the earthquake.

The earthquake was the largest seismic event in the San Francisco Bay Area, which includes Napa and Sonoma Counties, since the 1989 Loma Prieta Earthquake. The Napa event caused an estimated $400 million in damage. This damage included moderate to extensive structural damage to older commercial buildings and to some newer buildings in downtown Napa. This damage resulted from ground motions, subsequent fires, and failed underground utility systems.

The value of underground utility damage to 144 water mains was about $60 million, and damage to facilities at wineries was about $70 to $100 million (Silicon Valley Bank 2014). The most significant damage to winery facilities was toppling of barrel stacks at downtown Napa storage warehouses. There was notably no significant structural damage to underground wine caves or damage of wine cave contents.

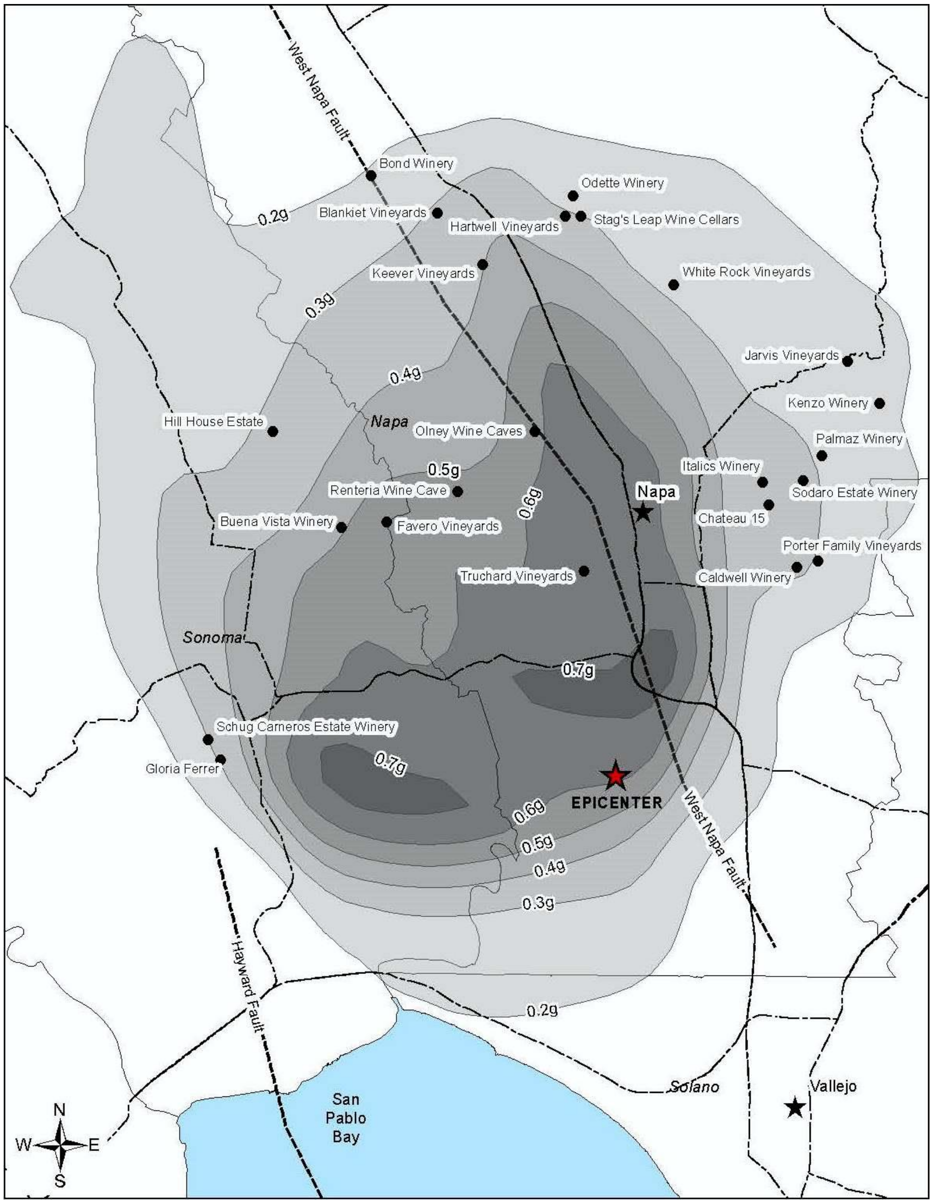

Figure 1 – PGA Contours – 2014 South Napa Earthquake (USGS 2014) and Winery/Wine Cave Locations

GEOLOGY AND SITE CONDITIONS AT WINE CAVES

Most of the Napa area wine caves are in hillsides containing Pliocene-aged rocks of the Sonoma Volcanics. Sonoma Volcanics includes rock such as rhyolite tuff, volcanic breccia, andesite, and interbedded basalt. This rock is typically massive to closely fractured, and tunneling ground in this rock is typically "very good" to "fair" (based on definitions by Bieniawski 1989). Some caves are in the Late Jurassic- through Cretaceous-aged Great Valley Sequence and Franciscan Assemblage. Rock in the Great Valley Sequence is mostly mudstone, shale, sandstone, and conglomerates. This rock is typically highly weathered, and closely fractured to sheared/crushed, and tunneling ground in this rock is typically "fair" to "poor." Rock in the Franciscan Assemblage is mostly greenstone, chert, greywacke, serpentinite, shale, and mélange. This rock is typically moderately fractured to sheared/crushed, and tunneling ground in this rock is typically "fair" to "poor."

Wine cave portals were typically excavated in colluvium over severely weathered rock, and most caves are above the saturated groundwater zone. Average annual precipitation in Napa and Sonoma Counties is about 20 inches. Most of the rain occurs seasonally from October through April.

WINE CAVE HISTORY AND CHARACTERISTICS

Approximately 160 to 180 wine caves exist in Napa and Sonoma Counties. The oldest caves include those at Buena Vista Winery, constructed around 1860, and those at Schramsberg Vineyards, constructed around 1870. About 15 to 20 caves were constructed between 1880 and 1900, including caves at Beringer Vineyards, Franciscan Estate Winery, Spring Mountain Vineyard, and Vine Cliff Winery. Following these early times, no new caves were developed until 1972, when Alf Burtleson Construction started rehabilitating the old Beringer wine caves. This was followed by a new era of wine cave development in the 1980s. Most of the existing caves have been constructed since that time.

Most of the wine caves in the region were excavated in rock formations using underground mining techniques. Some wine caves were excavated from the surface with cut-and-cover or have cut-and-cover portions where they abut aboveground buildings (such as caves at Buena Vista Winery, Seavey Vineyard, Hunnicutt Winery, Gloria Ferrer Vineyards, and Napa Valley Reserve).

Wine cave tunnels for barrel storage are typically 14-feet wide, and many caves have underground fermentation and entertainment rooms, which are 20- to 30-feet wide. The cave at Jarvis Estate has chambers that span 26, 30, and 85 feet. Some caves include tunnels for water storage behind dam bulkheads. Wine caves are typically characterized by thin ground cover at portals, crossing tunnels with frequent intersections, occasional relatively narrow pillars, and relatively high extraction ratios.

Floor areas of most wine caves range from a few thousand square feet to about 20,000 square feet, with a few caves up to 70,000 square feet. Floors at the deepest portions of caves are typically 50 to 100 feet below the ground surface. Ground cover at portals is typically less than 3 feet. Most tunnels have a constant radius arch over a level invert.

WINE CAVE DESIGN AND CONSTRUCTION

Prior to the early 1990s, design-build contractors designed most wine caves. From the early 1990s until recently, consulting engineers designed most caves and design-build contractors designed a fewer number. Currently, only three or four specialty tunnel contractors construct wine caves in the region. Owners facilitate most projects by negotiating contracts with tunnel contractors, and the contractors provide design consultation.

Current design practice for ground support of wine caves includes both numerical analyses and empirical evaluations. Prior design work consisted of semi-empirical analyses or empirical evaluations with no numerical analyses.

Design work now includes two dimensional and static finite element analyses for multiple (and representative) cross-sections through adjacent tunnels and pillars. Ground relaxation effects are sometimes modeled, and the contribution of initial support is included in the design of final support. No detailed seismic design analyses are currently performed.

Mined cave tunnels are typically lined with reinforced shotcrete and have concrete floor slabs. Shotcrete tunnel liners commonly range from 4 to 8 inches thick and are reinforced with one or two layers of welded wire fabric. Support sometimes includes rock dowels across the arch, footings along the base of the ribs or subinvert concrete. In very few caves, ground support includes steel sets with shotcrete, and occasionally, tunnels are unlined and unsupported, or unlined with rock-dowel support.

Prefabricated drain strips are typically placed along the exposed ground behind shotcrete liners to reduce potential hydrostatic loads. Moisture retarding membranes are usually placed over the structural liner followed by final architectural shotcrete or color coat. The architectural shotcrete and color coats are usually unreinforced, and therefore, shrinkage cracks at the exposed tunnel surface sometimes occur.

Wine caves are typically mined at one or multiple headings using mechanical methods (road headers and excavators equipped with milling heads or hydraulic hammers). Conventional drill-and-blast methods are sometimes used in harder and less fractured rock. The reinforced shotcrete liners are usually constructed in two phases: 1) initial support (with footings or subinverts, where needed), and 2) final support. The design and construction teams usually implement the sequential excavation method during wine cave construction. Deflection monitoring by tape extensometers is sometimes performed in poor ground or larger tunnels/rooms. Contractors take responsibility for initial ground support, and the designers assist with evaluating initial support. Designers perform engineering observations of exposed ground conditions. Construction special inspections are performed, and designers prepare construction record reports.

It is notable that some of the older caves are supported using relatively thin and lightly reinforced shotcrete liners. In addition, it is notable that three-dimensional effects of cave complexes (compared to single tunnels) may either strengthen or weaken seismic resistance depending on pillar widths, extraction ratios, thickness of ground cover and plan dimensions as compared to seismic wavelengths.

PREVIOUS CASE STUDIES

Duke and Leeds (1959) compiled data from 30 cases, did not correlate PGA to damage, and made some useful generalizations regarding tunnels at fault ruptures, tunnels near epicenters (damage correlated to liner types), and tunnels further from epicenter (damage correlated to liner types).

Dowding and Rozen (1978) looked at tunnels subjected to earthquakes. They concluded the following regarding tunnel damage from increasing levels of PGAs at tunnel sites:

- No damage occurred when PGAs were less than about 0.2 g
- Minor to moderate damage occurred when PGAs were up to 0.5 g
- Moderate to heavy damage occurred when PGAs were above 0.5 g

Owen and Scholl (1981) enlarged the database to 127 cases and concluded the following:

- Little damage occurred when PGAs were less than 0.4 g
- Severe damage and collapse occurred in only “extreme” conditions where tunnels had marginal ground support consisting of brick liners, unreinforced concrete liners, and liners with no ground contact

- Severe damage occurred where tunnels contacted faults, landslide surfaces, or liquefied soil
- Deep tunnels are subject to less damage than more shallow tunnels
- Observed damage to cut-and-cover tunnels is caused by increased lateral forces imposed by backfill
- More damage is observed with increasing duration of strong ground motion

Sharma and Judd (1991) extended the database to 192 cases and considered the additional factors of tunnel support type, tunnel depth, ground type, earthquake magnitude, and epicentral distance. They concluded the following:

- Damage level decreases with increasing tunnel depth
- More damage occurs at tunnels mined in colluvium compared to tunnels in harder rock
- Damage is not well-correlated with quality of ground support
- Higher PGA is correlated with more damage
- No damage reported for cases where PGAs are less than 0.15 g

Power and others (1998) concluded that the documentation for older cases was of lower quality and reliability and that the previous researchers used outdated and unreliable attenuation relationships to estimate PGAs. They noted that some of the cases in the preexisting database included tunnel damage from ground displacements instead of damage from earthquake ground motions, and that some of the reported damage was to cut-and-cover tunnels instead of mined tunnels. Power and others filtered the database by removing cases with unreliable documentation and cases with cut-and-cover tunnels. They adjusted PGAs in the case studies using an updated and more reliable attenuation relationship. They also added cases to the database: 97 cases from the 1995 Kobe (Great Hanshin) earthquake, 31 cases from the 1994 Northridge earthquake, and 22 cases from the 1989 Loma Prieta earthquake. Most of the added cases were railroad and water supply tunnels. The filtering and additions resulted in 204 cases with PGAs of up to 0.7 g at tunnel sites.

Power and others (1998) defined "damage state" as follows: heavy damage – partial to total tunnel collapse, moderate damage – significant liner cracking and spalling, and slight damage – minor liner cracking and spalling. They plotted the cases sorted by liner type (or for cases with no liner), with each case plotted at a corresponding PGA and with a plot symbol corresponding to the damage state. Liner type categories included "unlined" (exposed ground), "timber or masonry," "concrete" (unreinforced), and "reinforced concrete or steel pipe." They presented the following for all tunnels with varying support types:

- Very little damage for cases where PGAs were less than 0.2 g
- Slight to limited heavy damage where PGAs were from 0.2 to 0.6 g
- Slight to moderate damage where PGAs were over 0.6 g

RECENT WORK BY OTHERS

A team visited five wine caves in Napa County on September 5, 2014 to evaluate damage from the South Napa Earthquake (McMillen Jacobs Associates 2014). They reported that the caves were 7 to 19.2 miles from the epicenter, that Ragsdale Underground Associates constructed each over the last 25 years, and that McMillan Jacobs designed 2 of the 5 caves they visited (caves at Palmaz Vineyards and Sodaro Winery). These caves are reportedly mined in weathered rhyolite and tuff of the Sonoma Volcanics. This team reported the following:

- No observed tunnel liner cracks except for isolated circumferential cracks near portals
- Damage to bottles and wall hangings in buildings at the visited wineries
- Up to 5 inches of lateral movement of racks with full barrels and tanks in wine caves, but no damage to the equipment and contents

DATA COMPILED BY AUTHORS AND UPDATED DATABASE

The authors compiled additional cases and data by visiting 12 wine caves, holding discussions with cave contractors and winery personnel, reviewing press releases and reviewing the McMillan Jacobs report. We compiled data, including data from cases compiled by Power and others (1998). The authors added 31 cases to the database last updated by Power and others, which results in a total of 235 cases. Table 1 presents the data for the 31 cases compiled after the 2014 South Napa Earthquake. The full table of 235 cases is available upon request to the authors.

Tunnel Identification	PGA (% g)	As-Constructed Ground Support	Liner Type Category	Tunnel Width(s) (ft)	Floor Depth(s) (ft)	Year Finished	Geologic Conditions	Damage State	Description of Liner/Tunnel Damage and Notes
B Cellars	0.1	Shotcrete w/ WWF	Reinforced Concrete or Steel Pipe	12 to 30	15 to ~60	2014	fractured andesite	None	None
Blankiet Estate - Paradise Hills Vineyards	0.3	Shotcrete	Reinforced Concrete or Steel Pipe	13	14 to ~40	1990's	tuff breccia	None	None; some barrels moved
Bond	0.2	Shotcrete, steel ribs	Reinforced Concrete or Steel Pipe	13 to 20	14 to ~40	1990's	mudstone	Slight	None; seepage occurred after the event
Buena Vista	0.5	Exposed rock w/ rock dowels, limited shotcrete	Unlined	10 to 22	12 to ~50	1860's and 2014	ash tuff	None	None; Water storage tunnel under construction and unlined during event. Stacked bottles in historic tunnel fell over
Caldwell	0.3	Shotcrete w/ WWF	Reinforced Concrete or Steel Pipe	12 to 20	16 to ~100	2000's	tuff	None	None; a wine glass in the tasking room fell over
Chateau 15	0.35	Shotcrete in-progress	Unlined	14 to 30	15 to ~50	2015	tuff breccia	None	None; unlined portion under construction during event
Chateau 15	0.35	Shotcrete w/ WWF	Reinforced Concrete or Steel Pipe	14 to 30	15 to ~50	2015	tuff breccia	None	None; Lined portion - under construction during event
Favero Vineyards	0.5	Shotcrete w/ WWF	Reinforced Concrete or Steel Pipe	17	15 to ~100	1996	ash tuff	None	None; barrels stacked 3 high and were undamaged. Some bottles fell
Gloria Ferrer	0.3	Shotcrete w/ WWF	Reinforced Concrete or Steel Pipe	20	1 to ~30	2000's	alluvium	None	None; a portion of the tunnel is cut and cover
Hartwell Estate Vineyards	0.3	Shotcrete	Reinforced Concrete or Steel Pipe	13 to 20	20 to ~50	1990's	fractured diorite	None	None; seepage occurred after the event
Hill House	0.3	Shotcrete w/ WWF	Reinforced Concrete or Steel Pipe	14 to 20	18 to ~30	2012	fractured andesite	None	None; some bottles and wine glasses fell
Italics	0.35	Shotcrete w/ WWF and steel sets in progress	Unlined	14 to 20	14 to ~60	NC	tuff breccia	Slight	Minor widening of a pre-existing crack at steel set near Portal; support was not complete at time of event
Jarvis Vineyards	0.2	Reinforced Shotcrete and Rock Bolts	Reinforced Concrete or Steel Pipe	10 to 85	15 to ~100	1992	ash tuff	None	None
Keever	0.4	Shotcrete w/ WWF	Reinforced Concrete or Steel Pipe	13 to 20	15 to ~40	2000's	tuff breccia	None	Minor door frame shift, minor barrel stack shift, one bottle in wine rack came out but did not fall

Table 1. Data – Seismic Performance of Wine Caves – 2014 South Napa Earthquake

Tunnel Identification	PGA (% g)	As-Constructed Ground Support	Liner Type Category	Tunnel Width(s) (ft)	Floor Depth(s) (ft)	Year Finished	Geologic Conditions	Damage State	Description of Liner/Tunnel Damage and Notes
Kenzo	0.2	Shotcrete w/ WWF	Reinforced Concrete or Steel Pipe	14	15 to ~50	2000's	ash tuff	None	None
Odette	0.25	Shotcrete w/ WWF	Reinforced Concrete or Steel Pipe	13 to 20	12 to ~50	2011	mudstone	None	None
Olney	0.55	Shotcrete w/ WWF	Reinforced Concrete or Steel Pipe	13	15 to ~50	2000's	mudstone	None	None; surveillance video shows interior equipment and fixtures moving
Palmaz	0.3	Shotcrete w/ WWF, steel ribs	Reinforced Concrete or Steel Pipe	13 to ~60	15 to ~130	2000's	tuff	None	None
Porter Family	0.3	Shotcrete	Reinforced Concrete or Steel Pipe	n/a	n/a	2000's	n/a	None	None
Pride	0.1	Shotcrete w/ WWF	Reinforced Concrete or Steel Pipe	14	15 to ~35	2000	clay-like	None	None; a portion of the tunnel is cut and cover
Renteria	0.5	Shotcrete in-progress	Unlined	14 to 19	17 to ~50	NC	mudstone	Slight	1/8 to 1/2-inch cracks in arch at portals and at tunnel intersections; tunnel floor was not in-place during event
Schug Carneros Estate	0.3	Shotcrete w/ WWF	Reinforced Concrete or Steel Pipe	14	5 to 25	2002	n/a	None	None
Sinegal	0.1	Shotcrete in-progress	Unlined	14	13 to ~40	2015	alluvium	None	Unlined portion under construction during event
Sinegal	0.1	Shotcrete w/ WWF	Reinforced Concrete or Steel Pipe	14	13 to ~40	2015	alluvium	None	Lined portion under construction during event
Sodaro	0.3	Shotcrete	Reinforced Concrete or Steel Pipe	n/a	n/a	n/a	n/a	None	None
Spring Mountain Vineyards	0.1	Shotcrete w/ WWF	Reinforced Concrete or Steel Pipe	13 to 20	13 to ~60	2000's	serpentinite	None	None
Staglin	0.15	Shotcrete w/ WWF	Reinforced Concrete or Steel Pipe	13 to 30	15 to ~60	2000's	tuff and clay	None	None
Stags' Leap Wine Cellars	0.3	Shotcrete w/ WWF	Reinforced Concrete or Steel Pipe	13 to 30	13 to ~80	1990's	fractured diorite	None	None
Truchard	0.65	Shotcrete	Reinforced Concrete or Steel Pipe	n/a	n/a	1990's	soil and clay	None	None
Vineyard 29	0.1	Shotcrete w/ WWF	Reinforced Concrete or Steel Pipe	13 to 24	15 to ~60	2000's	alluvium	None	Bottles in tunnels fell over
White Rock	0.25	Shotcrete	Reinforced Concrete or Steel Pipe	n/a	n/a	1990's	Rock conditions	None	None

Table 1 Continued. Data – Seismic Performance of Wine Caves – 2014 South Napa Earthquake

Figure 2 plots the damage state and PGA of the cases compiled by Power and others (1998) and the new cases from the Napa event in each liner type category. We separated the plots for cases from the Napa event from the previous cases. Most of the new cases are for wine caves lined with welded wire fabric – reinforced shotcrete, and therefore, are in the “reinforced concrete/reinforced shotcrete or steel pipe” category. Some of the wine caves included have no liner or partially constructed liners, and therefore, are presented in the “unlined” category. We used the same definitions for damage state as did Power and others (1998), as summarized in the “Previous Case Studies” section of this paper.

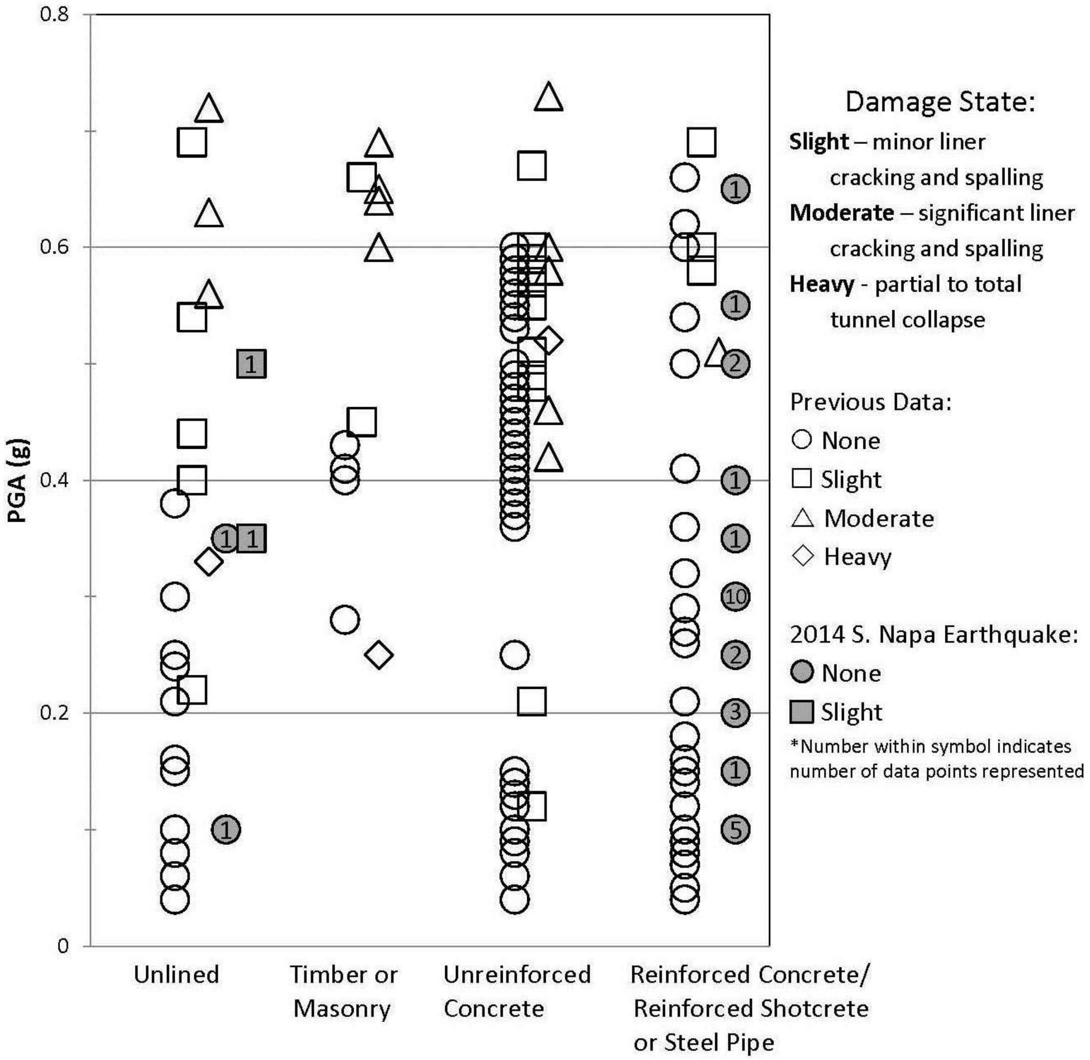

Figure 2 – Tunnel Damage State vs. PGA

For the additional cases from the Napa event, we interpolated the PGA to the nearest 0.05 g from the contours on Figure 1. The current database still excludes cases with damage of cut-and-cover tunnels or damage from ground displacements.

DISCUSSION

For the reinforced concrete/reinforced shotcrete or steel pipe category, including the added wine caves with reinforced shotcrete liners, there are only 4 of 50 cases with slight to moderate damage for PGAs up to 0.7 g and no cases of damage with PGAs less than 0.5 g. For this liner category, the authors added four cases from the Napa event with PGAs over 0.5 g (for a total of 13 cases) and 23 cases with PGAs less than 0.5 g (for a total of 41 cases).

For the unlined category, the authors added four cases from the Napa event showing similar trends in damage state as the former cases compiled by Power and others (1998), as shown on Figure 2. No cases were added to the timber or masonry category and the unreinforced concrete category.

The authors suggest that estimating PGAs to the nearest 0.05 g from shake maps or similar methods, as we did for the added cases, is adequate for the purpose of empirical evaluation of seismic tunnel performance. We also suggest that tunnel seismic design should consist of a stepwise increase in the complexity of evaluation, beginning with review and consideration of available case studies on seismic performance of tunnels, followed by more detailed analyses as warranted.

CONCLUSIONS

The authors conclude that for modern and proposed mined tunnels and wine caves, which are typically lined with reinforced concrete, reinforced shotcrete, or steel pipes and are properly designed for static conditions, there should be no significant seismic damage or hazard when the PGA is 0.5 g or lower. We conclude that for such tunnels and caves with similar characteristics as the cases in the database, there should be only a low potential for “slight” to “moderate” seismic damage requiring repair and a very low potential for “heavy damage” when the PGA is higher than 0.5 g and up to 0.7 g (based on damage state definitions described in the “Previous Case Studies” section of this paper). The authors added 27 cases with reliable data involving relatively shallow tunnels with ground support that is consistent with current design and construction practice and with PGAs up to 0.65 g, to support these conclusions.

Because there are few cases with PGAs above 0.65 g, designers should consider detailed seismic design analyses for tunnels with design PGAs of 0.65 g or higher. In addition, designers should consider consequences of damage, cost of repairs, and other important factors besides PGAs to evaluate whether detailed seismic design is warranted. Such additional important factors include geologic conditions, tunnel dimensions, floor depths and duration of strong shaking.

RESEARCH NEEDS

Future researchers should enlarge the database with reliable cases for mined tunnels and caves subjected to earthquakes occurring since the late 1990s through present and for future earthquakes. Damage to cut-and-cover structures and from permanent ground-displacement should be noted, but such cases should be excluded from the database used to correlate PGA and other factors to damage state. Researchers should use additional data to further support and/or revise conclusions presented in this study and by the previous researchers.

The authors suggest that data should include the following (in rough order of importance): tunnel liner category, damage state, PGA, geologic conditions, tunnel dimensions and floor depth, description of ground support, duration of strong ground motion, tunnel completion year, whether the tunnel was designed by an engineer, name of earthquake event, information required for estimating PGA using attenuation relationships (tunnel coordinates, epicenter coordinates, etc.), and description of the data source. Researchers should use these data for continued evaluation of correlations between PGA and damage state for tunnels with various liner types. In addition, the data should be evaluated for possible correlation of damage state to other factors for seismic performance of tunnels, such as geologic conditions, tunnel dimensions and depth, duration of shaking, and quality of ground support.

The authors have compiled available data from the cases electronically. The database will be made available to future researchers.

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