Basin and Range Province Seismic Hazards Summit III

Salt Lake City's Earthquake Threat and What is Being Done About It

Field Trip Guide

Salt Lake City, Utah
January 17, 2015

Photo courtesy Adam McKean (Utah Geological Survey)

Field Trip Coordinator:
Michael Hylland, Utah Geological Survey

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Jerod Johnson, Reaveley Engineers
Keith Koper, University of Utah Seismograph Stations
Kristine Pankow, University of Utah Seismograph Stations

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INTRODUCTION

Salt Lake City lies within the Intermountain Seismic Belt, along the trace of the middle part of the most continuous, active normal fault in the conterminous United States—the Wasatch fault zone (WFZ) (figure 1). On the west side of the city, the West Valley fault zone (WVFZ) forms an antithetic fault system to the west-dipping WFZ. Although no large earthquakes have ruptured the WFZ or WVFZ historically, both of these faults have a well-documented history of numerous surface-faulting earthquakes (M ≥6.5) in the recent geologic past. Salt Lake City and adjoining communities in Salt Lake Valley are home to over 1 million people, or 37% of Utah's population, so the risk associated with large earthquakes is clearly high.

On this field trip we will visit several sites related to Salt Lake City's earthquake threat and what is being done about it (figure 2). The trip will begin at the University of Utah Seismograph Stations, where we will discuss the regional seismograph network and historical earthquake catalog, the threat of both moderate and large earthquakes, and ongoing seismological research. From there we will travel south to the mouth of Little Cottonwood Canyon, where we will view prominent normal-slip fault scarps on the Salt Lake City segment (SLCS) of the WFZ. These scarps displace late Pleistocene glacial deposits and were first recognized and described by G.K. Gilbert in 1877, prompting him to issue Utah's first earthquake hazard warning in 1883. We will also discuss important topics of ongoing research, such as the potential for partial- and multiple-segment ruptures on the WFZ.

The last part of the field trip will take place at the Utah State Capitol building, which recently underwent a major seismic retrofit and houses the state's new Emergency Operations Center (EOC). We will tour the EOC and discuss the Utah Division of Emergency Management's role in preparing for

Figure 1. Five central segments of the Wasatch fault zone (WFZ). White lines indicate segment boundaries and white circles indicate paleoseismic sites. SLC – Salt Lake City, ULFF – Utah Lake faults and folds, WVFZ – West Valley fault zone.

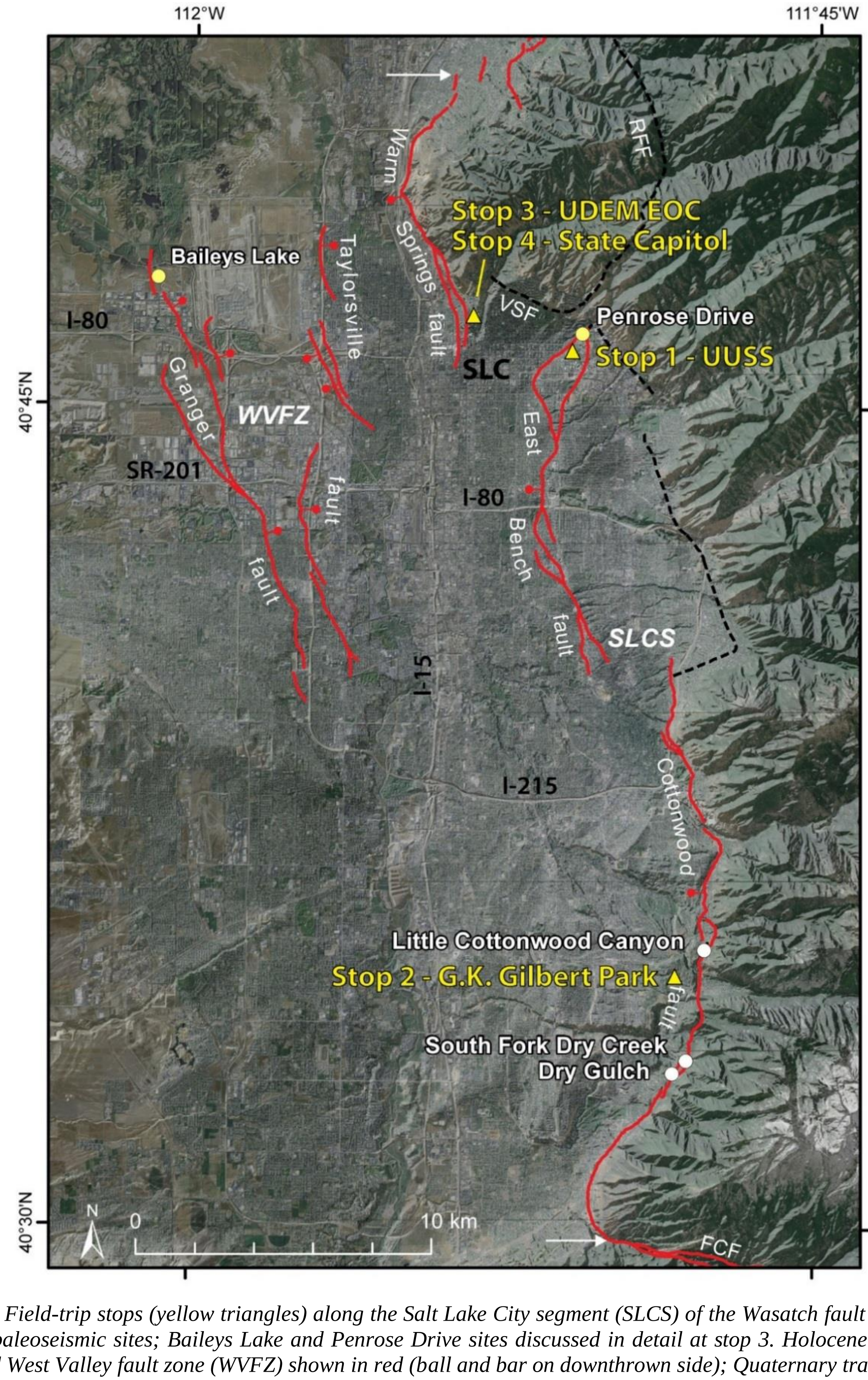

Figure 2. *Field-trip stops (yellow triangles) along the Salt Lake City segment (SLCS) of the Wasatch fault zone. Circles indicate paleoseismic sites; Baileys Lake and Penrose Drive sites discussed in detail at stop 3. Holocene traces of the SLCS and West Valley fault zone (WVFZ) shown in red (ball and bar on downthrown side); Quaternary traces in dashed black (traces from Black and others, 2003). White arrows indicate northern and southern ends of the SLCS. FCF – Fort Canyon fault, RFF – Rudys Flat fault, VSF – Viginia Street fault. Modified from DuRoss and others, 2014.*

and responding to an earthquake emergency. We will also use the EOC facility to present information from a recent paleoseismic investigation by the Utah Geological Survey of the seismogenic relation between the SLCS and WVFZ. Finally, we will tour the Capitol building and discuss details of the seismic retrofit and base-isolation design.

FIELD TRIP

Stop 1 – University of Utah Seismograph Stations

Keith Koper and Kristine Pankow, University of Utah Seismograph Stations

The University of Utah Seismograph Stations (UUSS) capitalizes on a state-federal partnership to conduct research, education, and outreach related to earthquakes, seismic monitoring, and seismic safety in the Utah region. As a founding member of the Advanced National Seismic System (ANSS), UUSS shares in the mission of providing prompt and accurate information related to seismic events, including their effect on the built environment. Notable UUSS partner agencies include the U.S. Geological Survey, Utah Geological Survey, Utah Department of Emergency Management, and Utah Seismic Safety Commission.

Seismic hazard in Utah is highest along the north-south trending Intermountain Seismic Belt, although significant seismicity occurs throughout the state (figures 3 and 4). Seismic risk in Utah is acute because 2.3 of Utah's 2.9 million residents (79%) live in the Salt Lake City–Provo–Ogden urban corridor, literally adjacent to the WFZ (table 1). Paleoseismic studies have found evidence for at least 22 M~7 earthquakes along the central segments of the WFZ in the past 6000 years.

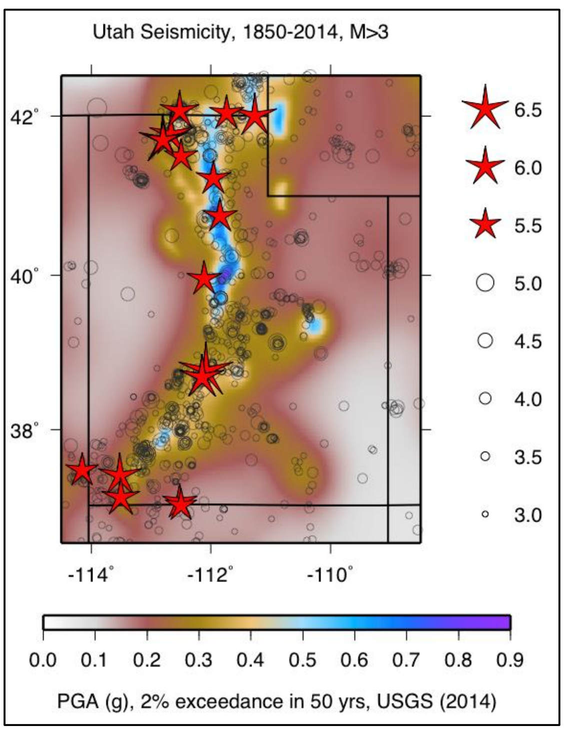

Figure 3. *Utah seismicity, showing a concentration of seismicity along the Intermountain Seismic Belt.*

UUSS operates and maintains a combined urban-regional network of 194 seismic stations (figure 5), which generate 632 distinct channels of data, to monitor Utah seismicity. The continuous 100 Hz data are archived locally at the UUSS Earthquake Information Center (EIC) as well as at the IRIS Data Management Center in Seattle, Washington, from which they are publicly available. The Utah network is designed to be robust with respect to power and telemetry failures. Redundancy is provided by 6 overlapping data collection nodes and 13 mountaintop relay sites. A hot-backup site for the UUSS EIC exists in Richfield, Utah, ~260 km south of Salt Lake City, and additional backup is provided by the U.S. Geological Survey (USGS) National Earthquake Information Center in Golden, Colorado.

Since October 2012, UUSS has used the state-of-the-art ANSS Quake Monitoring System (AQMS) to detect and locate seismicity in the Utah region.

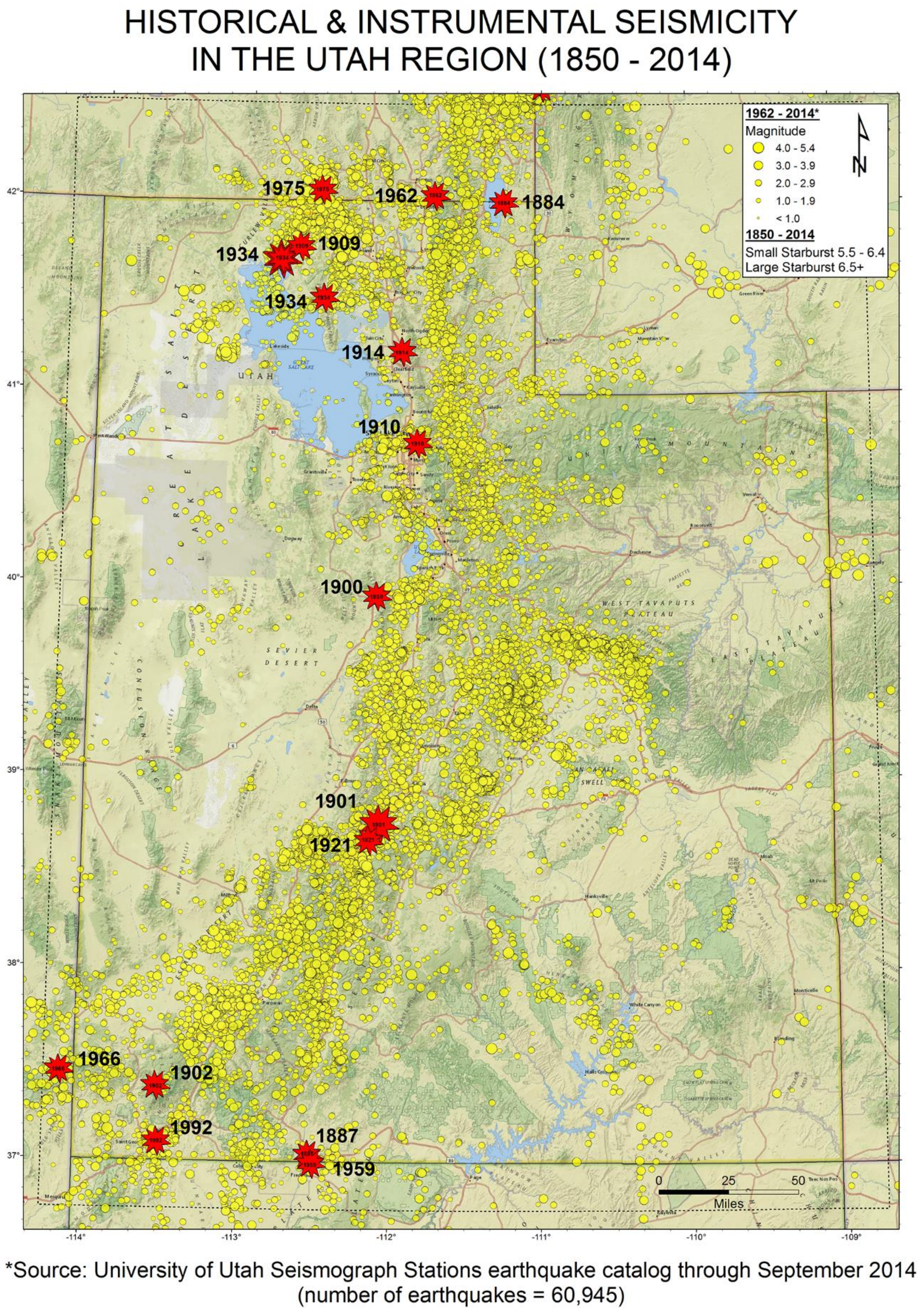

Figure 4. *Earthquakes in the Utah region, showing instrumental seismicity between 1850 and 2014 (circles) and large historical earthquakes (starbursts) that have occurred in the area following pioneer settlement around 1850.*

In a typical year, UUSS locates over 1500 earthquakes in the Utah region, including 1 in the M4 range, 12 in the M3 range, and 130 in the M2 range, with 20 earthquakes reported as felt. For earthquakes larger than M3.5, full moment tensors are estimated by inverting broadband, regional distance waveforms. UUSS also routinely computes ShakeMaps for events larger than M3 or M3.5, depending on location.

With additional support from the USGS Volcano Hazards Program, UUSS maintains a second seismic network in and around Yellowstone National Park (figure 5). Operations for the two networks are integrated, with, for example, both using the same instance of AQMS. The Yellowstone network is smaller than the Utah network (UUSS operates and maintains 27 stations with 93 data channels in Yellowstone); however, the seismicity rate is higher than in Utah. In a typical year, UUSS locates over 1700 earthquakes in the Yellowstone region.

Table 1. *Utah's earthquake risk.*

State Ranking of Utah in
Measures of Earthquake Risk[1]

	National Ranking	Regional[2] Ranking
Annualized Earthquake Loss	6	1
Annualized Earthquake Loss Ratios	5	1
Estimates of Debris	5	1
Displaced Households	6	1
Annualized Shelter Requirements	5	1
Casualties	4	1

[1] Data from *FEMA 366 HAZUS-MH Estimated Annualized Earthquake Losses for the United States* (2008).

[2] The Rocky Mountain Basin and Range seismic region in *FEMA 366* includes: MT, ID, WY, NV, UT, CO, AZ, and NM.

Stop 2 – G.K. Gilbert Geologic View Park at the mouth of Little Cottonwood Canyon

Christopher DuRoss (U.S. Geological Survey) and Michael Hylland (Utah Geological Survey)

G.K. Gilbert Geologic View Park is near the mouths of Little Cottonwood Canyon and Bells Canyon—prominent glacier-carved valleys in the Wasatch Range (figure 2). Here we will view evidence of Pleistocene glaciers and prehistoric normal faulting on the SLCS of the WFZ (figure 6), and discuss the rise and fall of late Pleistocene Lake Bonneville.

In his classic letter to the Salt Lake Daily Tribune in September 1883, G.K. Gilbert, then a senior geologist with the newly formed USGS, warned local residents about the implications of observable fault scarps along the western base of the Wasatch Range. Gilbert reasoned that large surface-rupturing earthquakes had occurred before Mormon settlement in 1847, and more would occur in the future. These scarps of course formed during surface-faulting earthquakes on the WFZ, which forms the structural boundary between the actively extending Basin and Range Province and the Middle Rocky Mountains in north-central Utah.

As one of the best studied intraplate faults in the world, the WFZ has played a prominent role in the development and advancement of earthquake geology and paleoseismology. G.K. Gilbert recognized that the fault scarps he observed at the base of the prominent Wasatch Range were evidence of incremental fault movement during earthquakes (Gilbert, 1890, 1928). Although Gilbert's pioneering ideas took decades to gain acceptance, they eventually led to focused paleoseismic investigations of prehistoric earthquakes on the WFZ. Early fault trench studies in

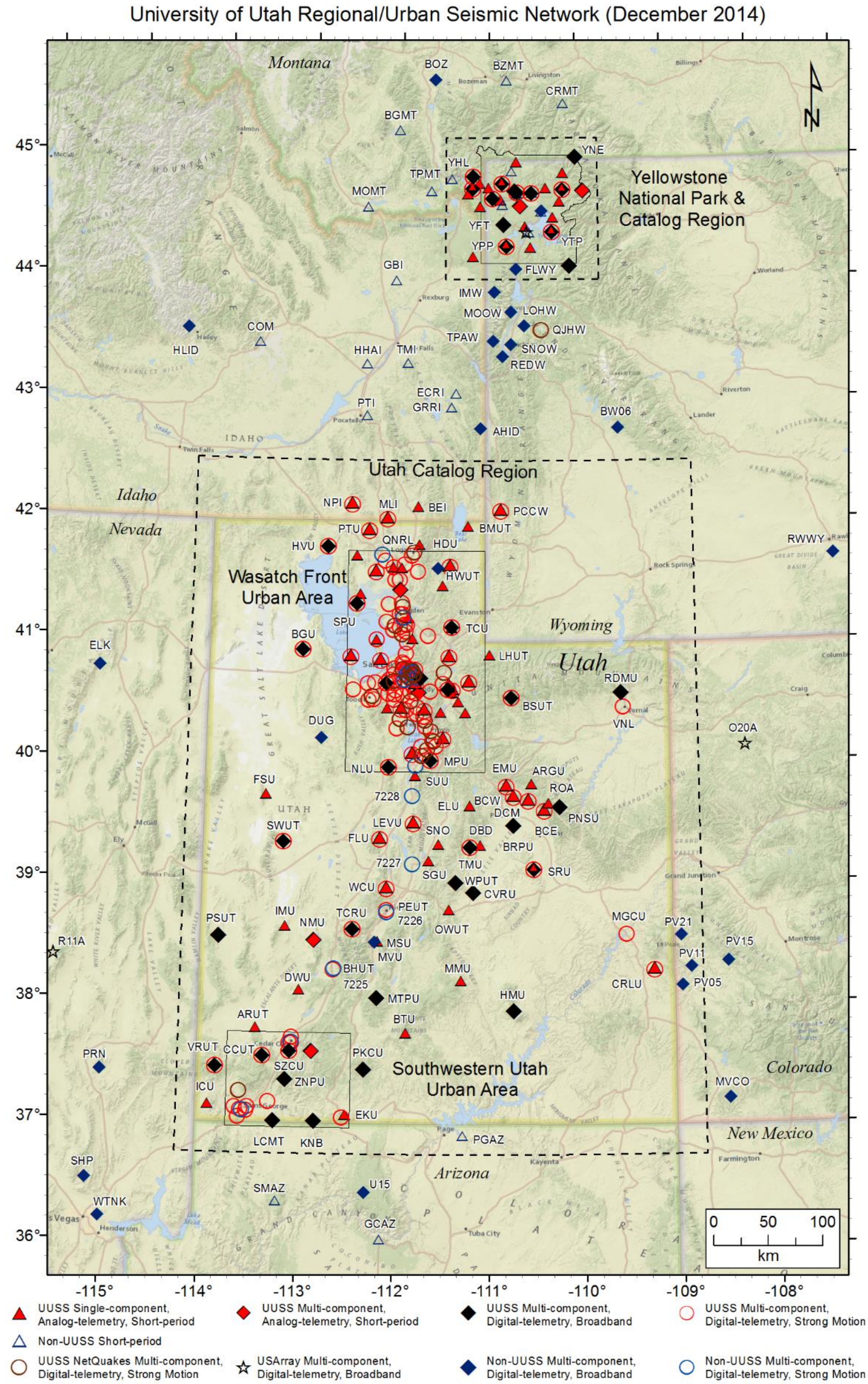

Figure 5. *University of Utah Seismograph Stations urban and regional seismic network.*

Figure 6. *Prominent fault scarps (white arrows) of the Salt Lake City segment near the mouth of Little Cottonwood Canyon as photographed by G.K. Gilbert in 1901 (view looking southeast). Uppermost two arrows show fault scarps on the Bells Canyon glacial moraine. Yellow arrow shows approximate location of stop 2.*

the late 1970s and 1980s focused on finding evidence of Holocene earthquakes (e.g., Swan and others, 1980), which formed the basis for models of fault segmentation and earthquake recurrence (Schwartz and Coppersmith, 1984). Ten WFZ segments are now recognized (Machette and others, 1992); however, recent paleoseismic investigations have focused on the five central segments that have evidence of multiple Holocene surface- faulting earthquakes and correspond with the most developed part of the Wasatch Front (figure 7). As a result of about three decades of research (and about 25 detailed paleoseismic investigations), we have substantially improved our understanding of the timing, recurrence, and displacement of latest Pleistocene and Holocene surface-faulting earthquakes on the five central segments and refined models of rupture extent and fault segmentation (for example, see reviews by Lund, 2005, and DuRoss, 2008).

At least 22 large earthquakes have ruptured the five central fault segments in the past about 6000 years (figure 7), yielding mean closed earthquake recurrence intervals of about 900–1300 years for individual segments or a composite recurrence interval of about 300 years for the central segments combined. The most recent large earthquake occurred about 300 years ago on the Nephi segment. Together, paleoseismic data for the WFZ provide important information for forecasting earthquake probabilities in the Wasatch Front region (Working Group on Utah Earthquake Probabilities; Wong and others, 2011, 2014; see also http://geology.utah.gov/ghp/workgroups/wguep.htm).

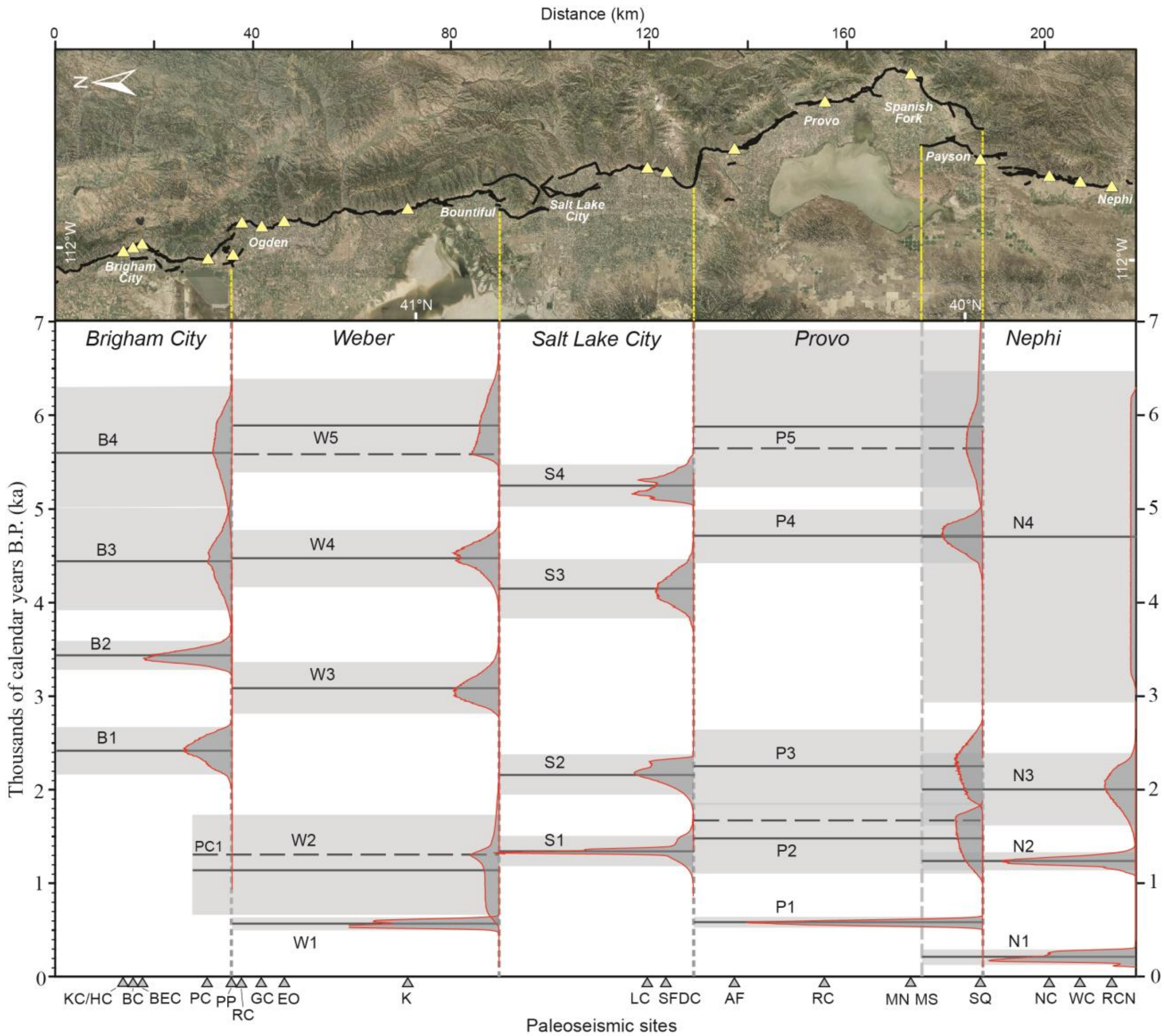

Figure 7. *Surface-faulting earthquakes on the central segments of the Wasatch fault zone. Boxes indicate two-sigma time ranges and horizontal lines show mean (solid) and modal (dashed) earthquake times based on an unpublished integration of paleoseismic data from Machette and others (1992, 2007), Lund (2005), DuRoss and others (2009, 2011, 2012), and Olig and others (2011) by the Working Group on Utah Earthquake Probabilities (Wong and others, 2011, 2014).*

Although our understanding of the WFZ has advanced significantly since the first trench was excavated in 1978, important questions remain regarding fault segmentation, dip, and the temporal and spatial variability of earthquake recurrence.

G.K. Gilbert Geologic View Park is also an excellent location to view and discuss evidence for glacial advances and the rise of Lake Bonneville, which overlapped in time. Evidence for Pleistocene glaciers in the area includes glacial outwash, lateral moraines and the terminal moraine of Bells Canyon, and the lateral moraines of Little Cottonwood Canyon. The crest of the Bells Canyon moraine has been vertically displaced 12–25 m by the SLCS (Swan and others, 1981) (figure 8). Lips (2005) determined a surface age for the moraine of 15.9 ± 0.7 ka based on two

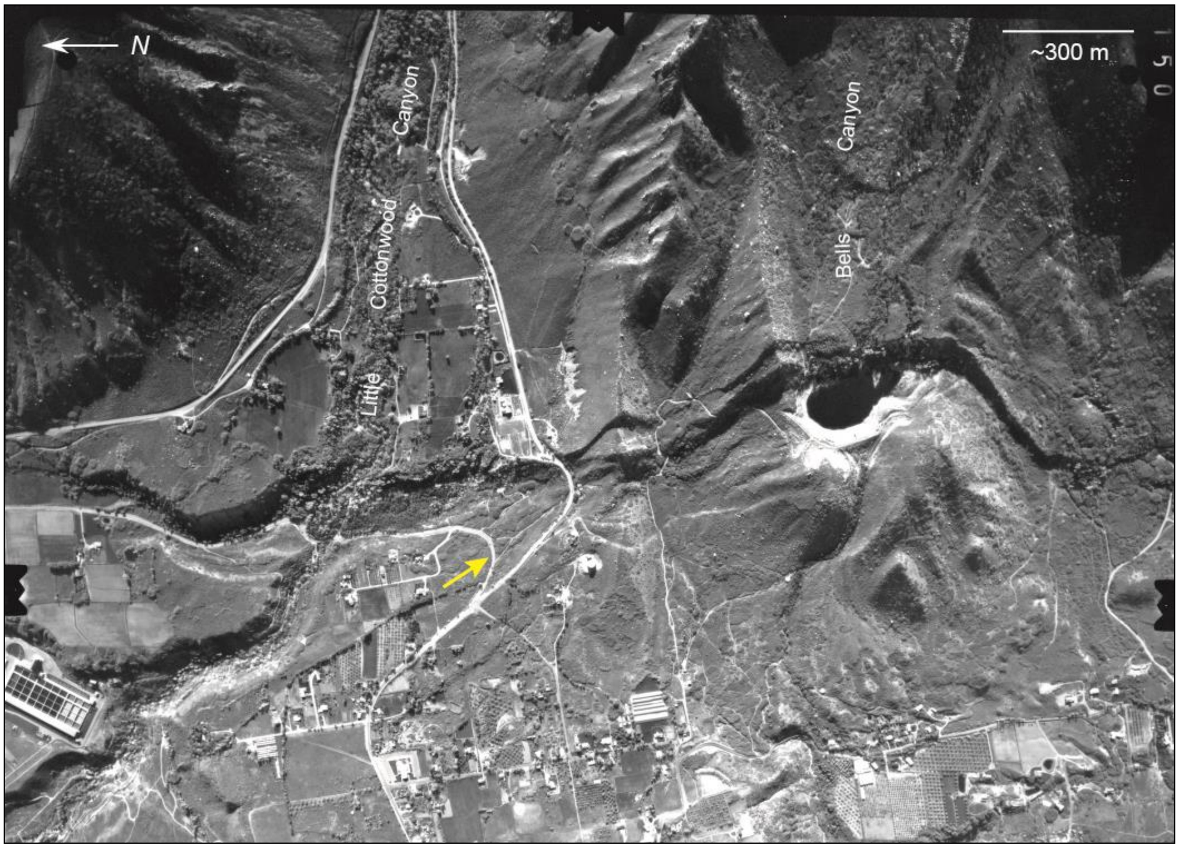

Figure 8. *Low-sun-angle aerial photograph (Cluff and others, 1970; Bowman and others, 2009) of Wasatch fault scarps at the mouths of Little Cottonwood and Bells Canyons. Yellow arrow indicates approximate location of stop 2 at the G.K. Gilbert Geologic View Park.*

^{10}Be exposure ages. Comparably, the highstand and Provo phases of Lake Bonneville occurred between about 18 and 14 ka (Godsey and others, 2005, 2011; Miller and others, 2013) (figure 9). Evidence of Lake Bonneville in the area includes shorelines having wave-cut terraces and beach berms, lacustrine sand and gravel deposited in deltas at the mouths of Big and Little Cottonwood Canyons, and shorelines weakly expressed in the Bells Canyon end moraine.

The following summary description of Lake Bonneville is taken from Hylland and others (2014):

> Climatic conditions during the Pleistocene were conducive to the episodic formation of pluvial lakes in the eastern Great Basin, and Lake Bonneville was the most recent and largest of these (Gilbert, 1890). As summarized by Currey (1990) and Oviatt and others (1992) and recently updated by Godsey and others (2005, 2011), Oviatt and others (2005), Benson and others (2011), and Miller and others (2013), the Bonneville lake cycle began around 30 ka. Over time, the lake rose and eventually reached its highest level at the Bonneville shoreline (~1550 m [5090 ft]) shortly before 18 ka. At the Bonneville highstand level, lake water overflowed the Bonneville basin threshold at Zenda in southeastern Idaho, spilling into the Snake–Columbia River drainage basin.
>
> The Zenda threshold failed catastrophically at about 18 ka, resulting in a rapid drop in lake level of approximately 110 m during the Bonneville Flood (O'Connor, 1993). The lake level stabilized

when erosional downcutting was impeded by a bedrock-controlled threshold at Red Rock Pass, about 2.5 km south of Zenda, or possibly about 9 km farther south near Swan Lake (Janecke and Oaks, 2011). Lake Bonneville remained at or near this level until about 15 or 16 ka (Godsey and others, 2005, 2011; Miller and others, 2013), forming the Provo shoreline (~1450 m [4760 ft]).

A climatic change to warmer and drier conditions caused the lake to regress rapidly from the Provo shoreline to near desiccation levels by the end of the Pleistocene (Eardley, 1962; Currey and others, 1988; Currey, 1990). A small rise in lake level to an elevation of 1295 m (4250 ft) marked the Gilbert episode, which culminated around 11.6 ka (Oviatt and others, 2005; Oviatt, 2014), after which the lake regressed to near modern Great Salt Lake levels (historical average elevation 1280 m [4200 ft]).

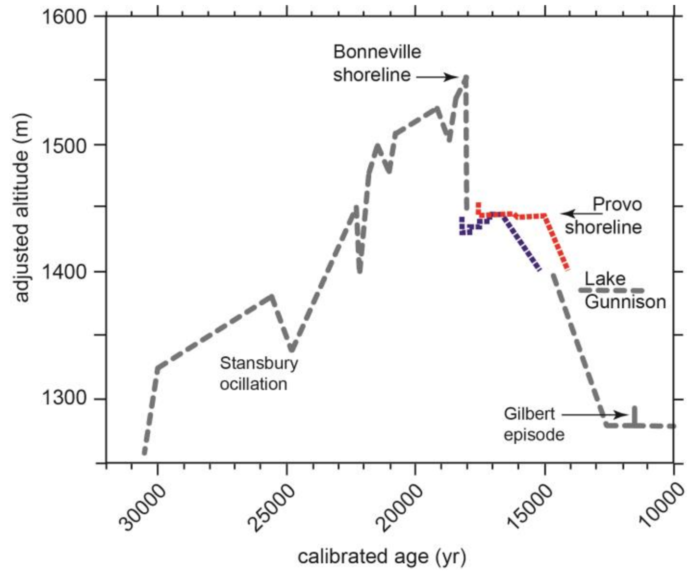

Figure 9. *Lake Bonneville hydrograph showing lake-level changes in the Bonneville basin since about 30 ka (modified from Reheis and others, 2014). Altitudes adjusted for differential isostatic rebound. Red and blue lines are from Miller and others (2013) and indicate two datasets related to the Provo shoreline.*

Stop 3a – Utah State Emergency Operations Center

Bob Carey, Utah Division of Emergency Management

The Utah Division of Emergency Management's (UDEM) Earthquake Preparedness Information Center (EPICenter) promotes seismic safety statewide and prepares Utahn's for earthquakes through community outreach programs, publications and presentations. The EPICenter works to implement broad-based yet specific proposals regarding preparedness and mitigation. It also acts as a resource to state and local agencies, schools, businesses, and others involved in earthquake preparedness.

State and local governments are responsible for protecting lives and property, and therefore play a primary role in earthquake hazard reduction. To reduce the effects of earthquakes on communities, an effective earthquake hazard reduction program must be developed. This is done by developing, implementing, and promoting earthquake hazard reduction measures including vulnerability assessments, preparedness and response planning, mitigation, public awareness, and education.

Injuries and loss of life from earthquakes are directly related to building damage and collapse, and the seismic performance of lifeline systems. The EPICenter monitors state and local programs that promote life safety activities and seismic structural enhancement.

Examples of the EPICenter's programs include:

- An outreach program is keeping the public informed of earthquake activities through public awareness (figure 10).
- Presentations to local church, community, and business groups continue to grow in demand.
- Communities and local businesses are incorporating earthquake preparedness as part of their daily life and a part of employee training. The EPICenter provides non-structural walk-throughs to businesses and local communities to reduce potential losses due to an earthquake.
- The EPICenter facilitates Applied Technology Council (ATC) workshops that address earthquake-related structural damage. The ATC-20 workshop is targeted specifically for volunteer engineers, architects, building inspectors, and others who will be required to make on-the-spot post-earthquake evaluations of buildings. The Utah Seismic Safety Commission has created an ATC-20 credentialing program for architects, engineers, and International Code Council (ICC) inspectors administered through the UDEM. Another workshop, ATC-21, gives local governments and building owners guidance for identifying seismically hazardous buildings through rapid visual screening.
- One of the main hazards during an earthquake is non-structural damage that occurs inside buildings. The EPICenter continues its non-structural mitigation education program that includes workshops, non-structural facility inspections, and distribution of non-structural mitigation materials.

Figure 10. *The Utah Division of Emergency Management's state Emergency Operations Center during Utah's first annual Great ShakeOut drill in April 2012. Participation in the 2012 drill included 945,000 citizens, or 33% of the state's population.*

The UDEM and EPICenter constitute only part of the Utah Earthquake Program. Other partner agencies help to promote a comprehensive, one-voice program with a united message for the citizens of Utah about the risks of earthquakes to the built environment. These partners include the Utah Geological Survey, the Utah Seismic Safety Commission, the University of Utah Seismograph Stations, and the Structural Engineers Association of Utah.

Stop 3b – Recent Paleoseismic Investigations of the Salt Lake City Segment (SLCS) and West Valley Fault Zone (WVFZ)

Christopher DuRoss (U.S. Geological Survey) and Michael Hylland (Utah Geological Survey)

The SLCS and WVFZ comprise Holocene-active normal faults that together form a 3–12-km-wide intrabasin graben in the northern part of Salt Lake Valley (figures 1 and 2). These faults have evidence of repeated, large-magnitude (M ~6–7) surface-faulting earthquakes, but because of extensive development along them, paleoseismic data are limited.

The SLCS consists of three subsections separated by left steps: the 7.5–10-km-long Warm Springs fault, 12-km-long East Bench fault, and 20-km-long Cottonwood fault (Van Horn, 1981; Scott and Shroba, 1985; Personius and Scott, 1992) (figure 2). The East Bench fault consists of large, prominent scarps bounding uplifted and incised alluvial-fan and Lake Bonneville lacustrine surfaces, and extends as far north as Dry Canyon, north of the University of Utah campus. To improve the quality and resolution of paleoseismic data for the East Bench fault, DuRoss and others (2014) completed a paleoseismic investigation at the Penrose Drive site, at the north end of the fault (figure 2). Prior to this study, questions remained regarding the timing of Holocene earthquakes on the northern SLCS as previous paleoseismic timing and displacement data were limited to the Cottonwood fault at the southern end of the SLCS.

At the Penrose Drive site, DuRoss and others (2014) excavated two trenches across an 11-m-high fault scarp near the northern end of the East Bench fault. They found colluvial-wedge evidence for six earthquakes (preferred model) postdating the Provo-phase shoreline of Lake Bonneville (~14–18 ka) at 4.0 ± 0.5 ka (all uncertainties are ±2σ), 5.9 ± 0.7 ka, 7.5 ± 0.8 ka, 9.7 ± 1.1 ka, 10.9 ± 0.2 ka, and 12.1 ± 1.6 ka. An additional earthquake occurred at 16.5 ± 1.9 ka based on an erosional unconformity that separates deformed Lake Bonneville silt and flat-lying Provo-phase shoreline gravel.

The timing of earthquakes on the East Bench fault (Penrose Drive site) corresponds well with that from two previous trench investigations on the Cottonwood fault (South Fork Dry Creek, Black and others, 1996; Little Cottonwood Canyon, McCalpin, 2002) (figure 11). Although questions remain regarding rupture extent, these paleoseismic data indicate that nine earthquakes have ruptured the SLCS since the Bonneville highstand (figure 12). These earthquakes yield mean closed-interval recurrence times of about 1300 yr (late Holocene), 1600 yr (Holocene), 1500 yr (post-Provo), and 2000 yr (post-Bonneville).

On the floor of northern Salt Lake Valley, the WVFZ consists of intrabasin normal faults that span an area 16 km long by 1–6 km wide (figure 2). The two subparallel, northwest-trending main traces of the fault zone and their associated subsidiary traces are known as the Granger fault (western traces) and Taylorsville fault (eastern traces). In conjunction with the study of DuRoss and others (2014), Hylland and others (2014) conducted a paleoseismic investigation of the WVFZ (Granger fault, Baileys Lake site)—which is antithetic to the SLCS (figure 13)—to address questions regarding the seismogenic relation between the two fault zones (e.g., can the WVFZ generate independent earthquakes?).

Hylland and others (2014) documented four surface-faulting earthquakes at the Baileys Lake site at 5.5 ± 0.8 ka, 12.3 ± 1.1 ka, 13.0 ± 1.1 ka, and 15.7 ± 3.4 ka. Combining these data with earthquake times from consultant trenches on both the Granger and Taylorsville faults results in an earthquake record of six earthquakes on the WVFZ since ~18 ka (Hylland and others, 2014) (figure 14). Mean earthquake recurrence intervals for the WVFZ range from 2.0 to 3.6 kyr, depending on the time period. These relatively long mean recurrence intervals for the WVFZ likely stem from an incomplete earthquake record on account of limited paleoseismic data and the complex, distributed pattern of faulting.

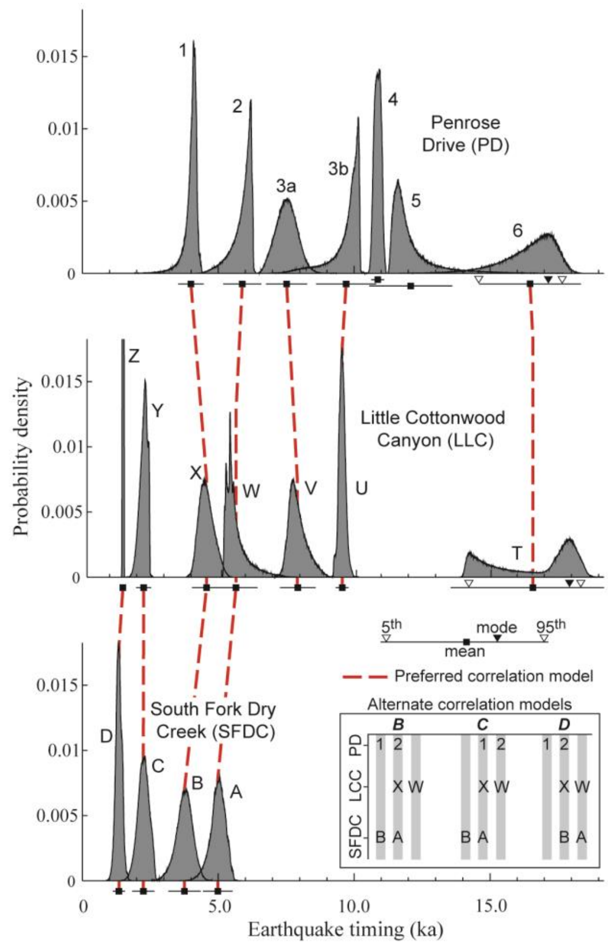

Figure 11. *Correlation of site earthquakes (earthquake-timing probability density functions [PDFs]) on the Salt Lake City segment (from DuRoss and Hylland, in press). Site PDFs are derived from OxCal models of the Penrose Drive, Little Cottonwood Canyon, and South Fork Dry Creek trench sites. Dashed lines indicate preferred correlation model; inset shows alternate correlation models. Preferred model is non-unique, but is supported by proximity of sites, continuity of scarps, and limiting numerical ages.*

Figures 14 and 15 show WVFZ earthquake timing compared to individual SLCS site chronologies and the revised chronology for the SLCS as a whole, respectively. Based on comparison of SLCS and WVFZ earthquake timing and displacement data, Hylland and others (2014) concluded that large earthquakes on the WVFZ that are coseismic with or triggered by fault movement on the SLCS have a higher likelihood than WVFZ earthquakes that occur independently of movement on the SLCS. When considered together with mechanical and geometric models of the fault system, the paleoseismic data support a high likelihood for synchronous rupture of the WVFZ with the SLCS.

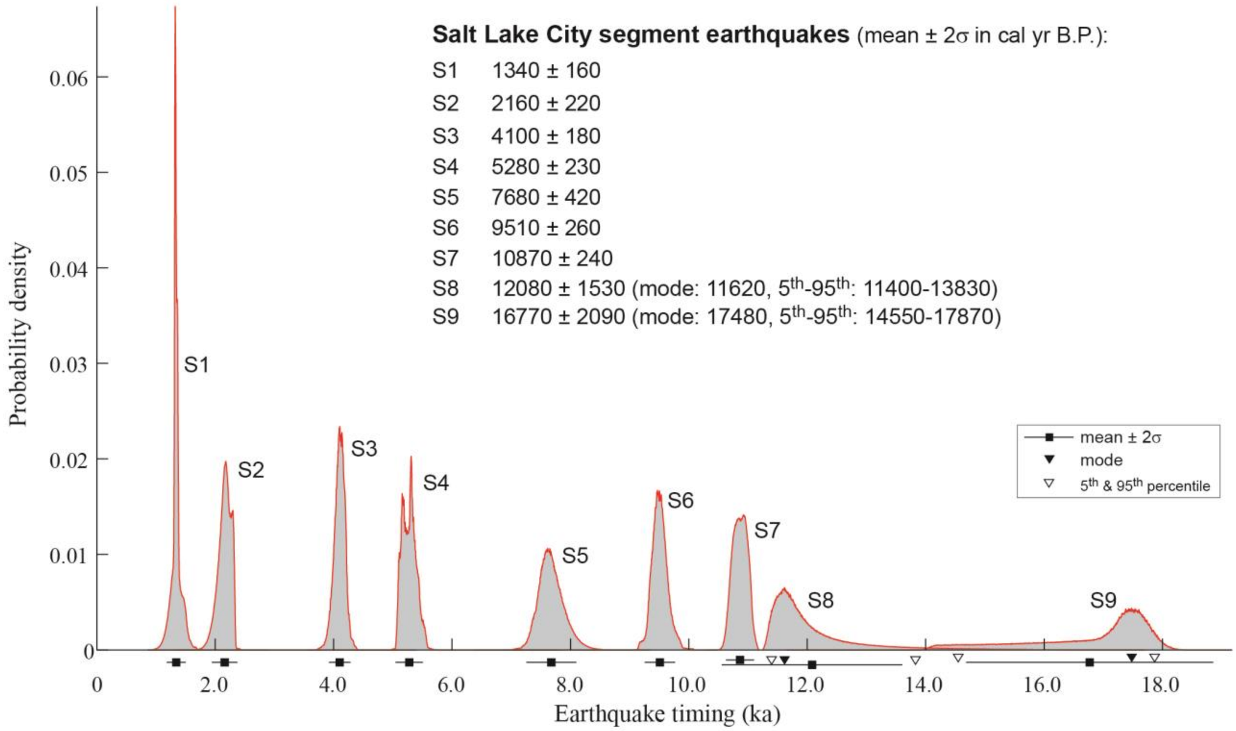

Figure 12. *Revised surface-faulting earthquake chronology for the Salt Lake City segment based on the correlation of site earthquakes shown on figure 11 (from DuRoss and Hylland, in press).*

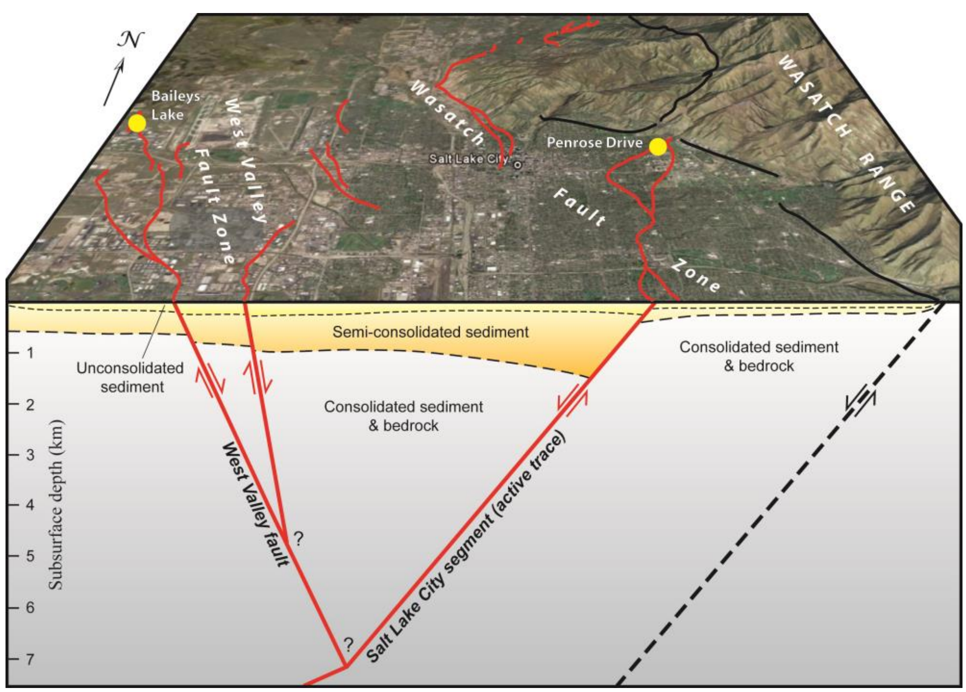

Figure 13. *Schematic cross section across northern Salt Lake Valley, showing possible subsurface geometries of the Salt Lake City segment (SLCS) and West Valley fault zone (from Hylland and others, 2014). Mapped fault traces from Black and others (2003), superimposed on a Google Earth image. Dashed black line indicates a likely inactive strand of the SLCS. Map scale varies; no vertical exaggeration implied. (GoogleEarth™ imagery ©Google Inc., Digital Globe, TerrraMetrics, and GeoEye. Used with permission.)*

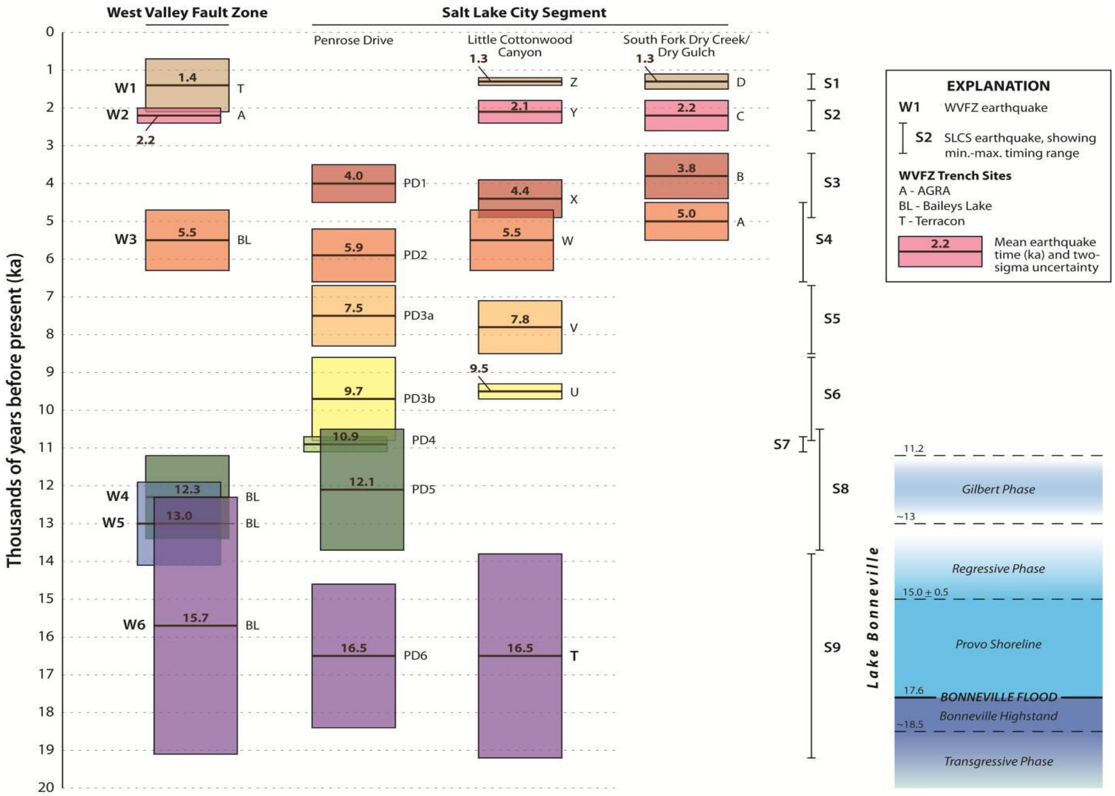

Figure 14. *Comparison of surface-faulting chronologies for the West Valley fault zone (WVFZ) and individual sites on the Salt Lake City segment (SLCS) (from Hylland and others, 2014). Note that the times of earthquakes W1 and W2 are based on* ^{14}*C ages of samples from consultant trenches, and W1 timing is constrained by a single limiting age. Schematic Lake Bonneville chronology shown at the same temporal scale for comparison with late Pleistocene earthquake times. Sources of earthquake timing information: WVFZ—Hylland and others (2014); Penrose Drive site—DuRoss and others (2014); Little Cottonwood Canyon site—McCalpin (2002), modified by OxCal modeling (DuRoss and others, 2014); South Fork Dry Creek/Dry Gulch site—Black and others (1996), modified by OxCal modeling (DuRoss and others, 2014).*

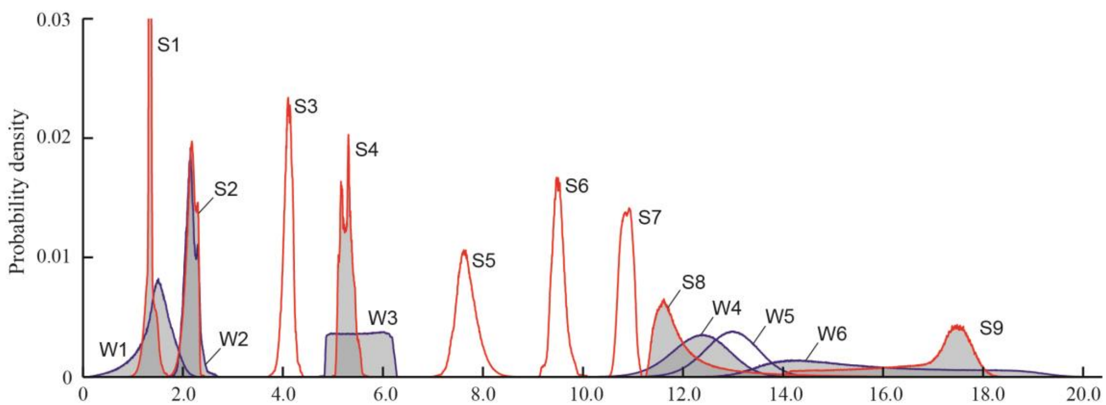

Figure 15. *Comparison of Salt Lake City segment (SLCS) and West Valley fault zone (WVFZ) earthquake chronologies, showing very similar timing PDFs for S1-W1, S2-W2, and S4-W3. S8-W4 and S9-W6 overlap, but have broadly constrained PDFs. The PDF for W5 lacks an apparent temporal correlation with a SLCS earthquake; however, W5 occurred during a period for which the SLCS chronology may be incomplete. Vertical scale truncated at 0.03; S1 peak probability is 0.07. Light shading indicates possible correlation of SLCS and WVFZ earthquake PDFs. From DuRoss and Hylland (in press).*

Stop 4 – Utah State Capitol

Jerod Johnson, Reaveley Engineers

The Utah State Capitol building (figure 16) ranks high among the inventory of historically significant structures in the western United States. It was originally constructed between 1912 and 1914 as a concrete frame structure, one of the first such structures west of the Mississippi River. The exterior of the building was made from large blocks of Oligocene quartz monzonite from Little Cottonwood Canyon. Because the stone blocks were stacked and not anchored to the frame, and the concrete frame had little reinforcing steel, the building was susceptible to damage and possible collapse from lateral loads that could be generated in a magnitude 7.0 earthquake (e.g., a surface-faulting earthquake on the SLCS) (see Solomon and others, 2005).

A seismic retrofit of the Capitol began in 2004, and included the addition of base isolators to decouple the building from horizontal ground motions, vertical shear walls to limit inter-story drift, and other seismic mitigation. The installation of 265 base isolators required a complete removal of the existing foundation, thus requiring a method for temporarily supporting the loads of individual building columns (figure 17). A collaborative effort with the construction manager led to an ingenious method of load transfer, saving months of construction time and millions of dollars.

Figure 16. *Construction to seismically retrofit the Utah State Capitol. Photograph taken September 2006 (UGS file photo).*

The base isolation system was designed using borehole data collected from the Capitol site. The data were used to develop site-specific response spectra from synthetic time histories (AMEC Earth and Environmental, 2003). Each of the base isolators is designed for a horizontal displacement of 24 inches in any direction, making a total swing from one extreme to the other of 48 inches. The base isolation also lengthens the periodic response of the Capitol building from <1 s to 3-4 s (figure 18), with a corresponding reduction in lateral accelerations from ~1.4 *g* to ~0.3 *g*. This reduction allowed the use of other seismic design elements in the retrofit that were less intrusive than would otherwise have been required (Solomon and others, 2005).

Figure 17. *The Capitol building required temporary support to allow removal of the existing foundation and installation of the base isolation system. Photo courtesy Bob Carey.*

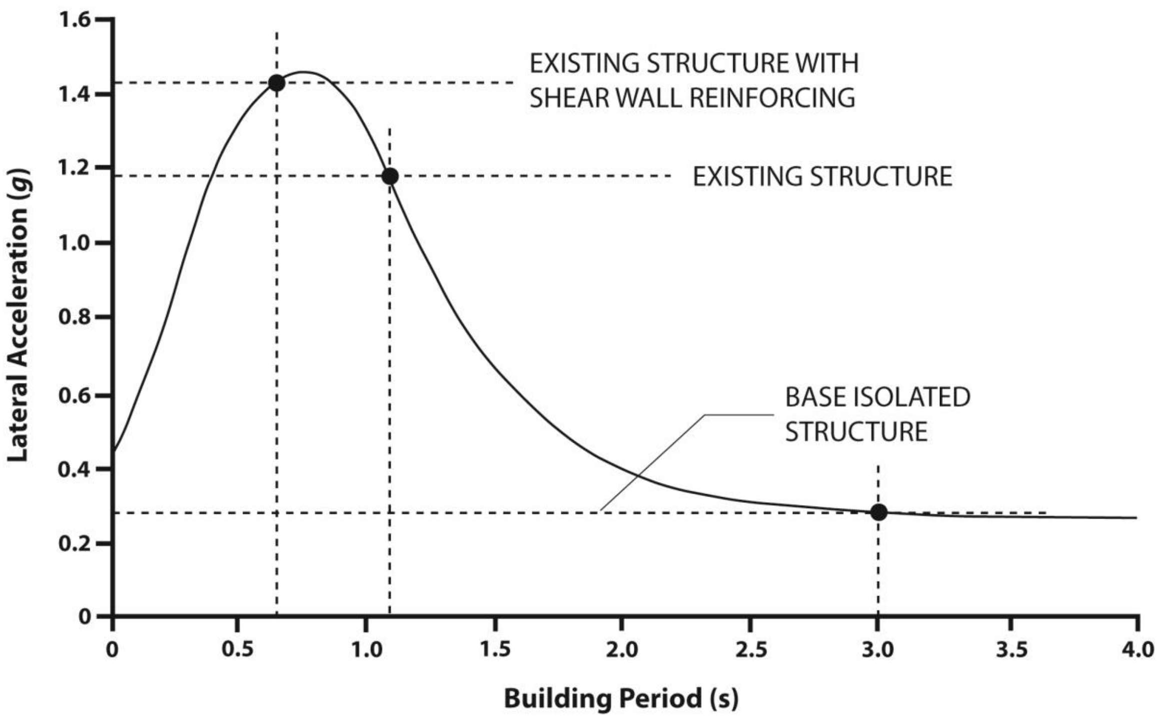

Figure 18. *Typical seismic response spectrum illustrating the effects of base isolation and shear-wall reinforcement (after Reaveley Engineers and Associates, 2003). Base isolation lengthens the periodic response of the Capitol building, decoupling the building from the lateral component of ground shaking. Shear walls resist and limit inter-story drift.*

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Basin and Range Province Seismic Hazards Summit III

Utah Geological Survey and Western States Seismic Policy Council

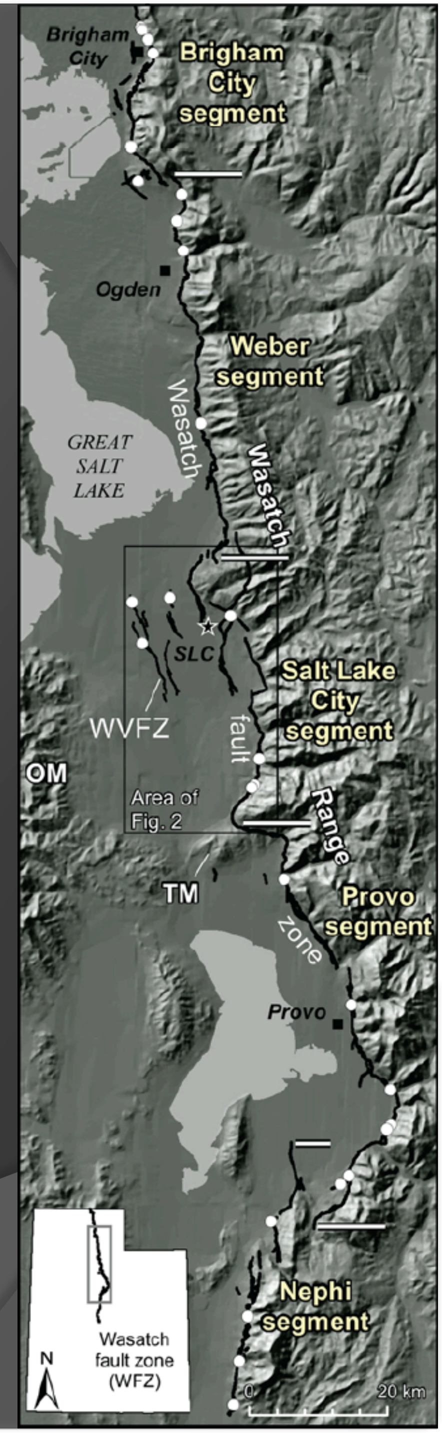
Field Trip Presentations

Synchronous Ruptures Along a Major Graben-Forming Fault System: Wasatch and West Valley Fault Zones, Utah: *Chris DuRoss, USGS; Michael Hylland, Utah Geological Survey*

Utah State Capitol Building Restoration and Seismic Base Isolation: *Jerod G. Johnson, Reaveley Engineers + Associates*

SYNCHRONOUS RUPTURES ALONG A MAJOR GRABEN-FORMING FAULT SYSTEM: WASATCH AND WEST VALLEY FAULT ZONES, UTAH

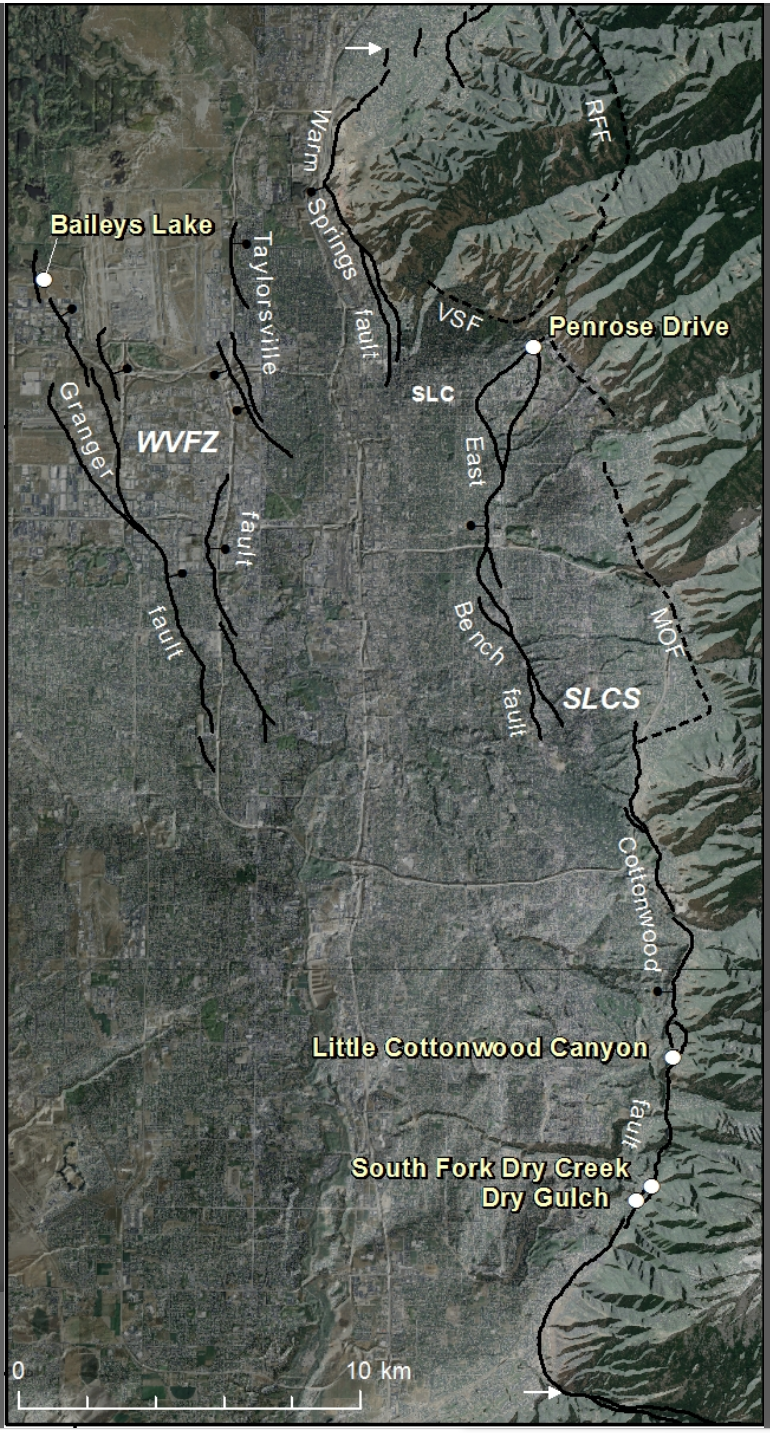
Chris DuRoss* and Mike Hylland
Utah Geological Survey
*Currently U.S. Geological Survey



Salt Lake City Segment

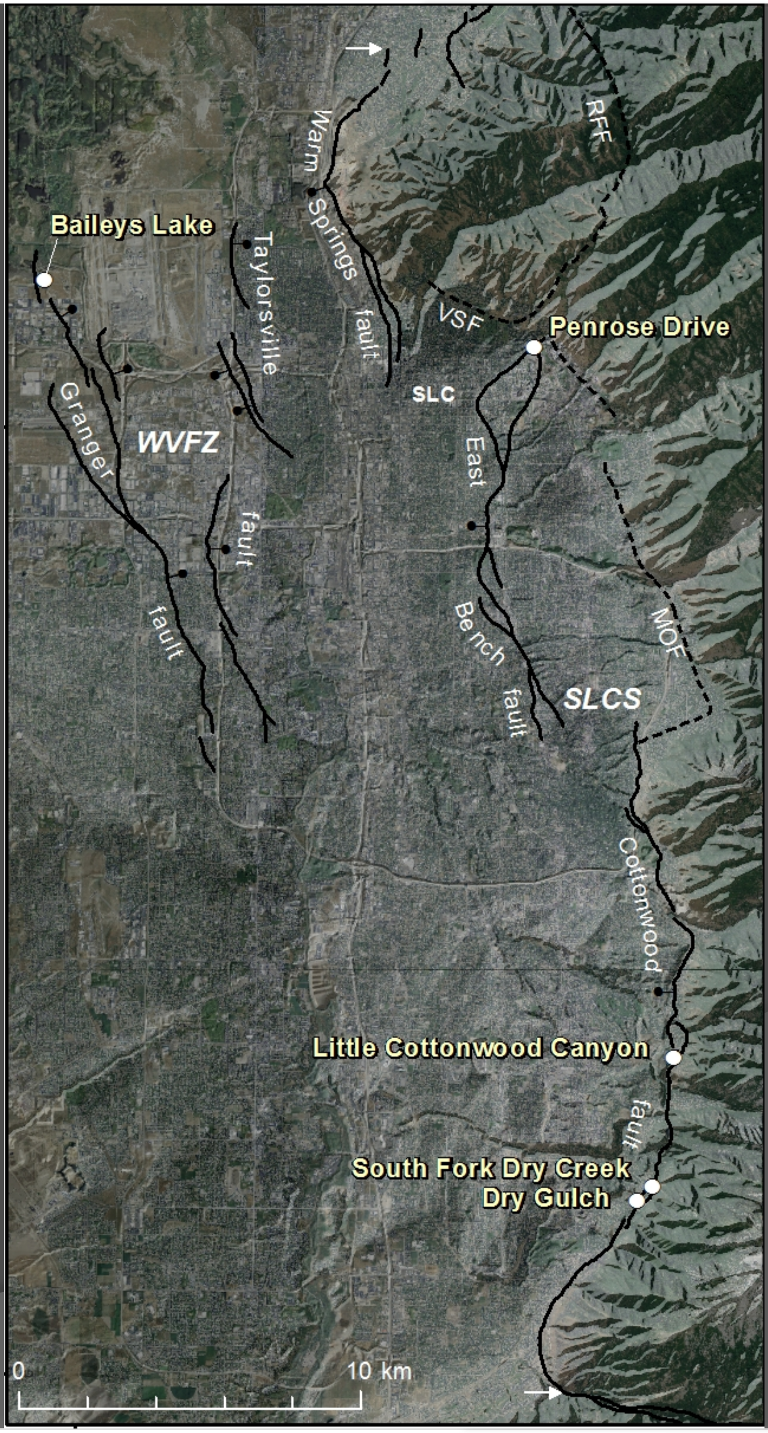
- *Holocene surface faulting in Salt Lake Valley*
  - West-dipping Salt Lake City segment (SLCS)
  - Mostly east-dipping West Valley fault zone (WVFZ)

- *Remaining questions:*
  1. Earthquake chronology for the East Bench and Warm Springs faults
  2. Overall Holocene and latest Pleistocene chronologies for the SLCS and WVFZ
  3. Seismogenic between the SLCS and WVFZ: *To what extent the WVFZ is seismogenically independent of, or moves synchronously with, the SLCS*



Salt Lake City Segment

- *2010-2014 Study:*
  1. Reviewed earthquake-timing and displacement data for the SLCS & WVFZ
  2. Developed data for the Penrose Drive and Baileys Lake sites
  3. Integrated SLCS and WVFZ data (separately) to determine their earthquake chronologies, mean recurrence, and slip rates
  4. Compared SLCS earthquake-timing data with that for the West Valley fault zone (WVFZ) to assess their seismogenic relation



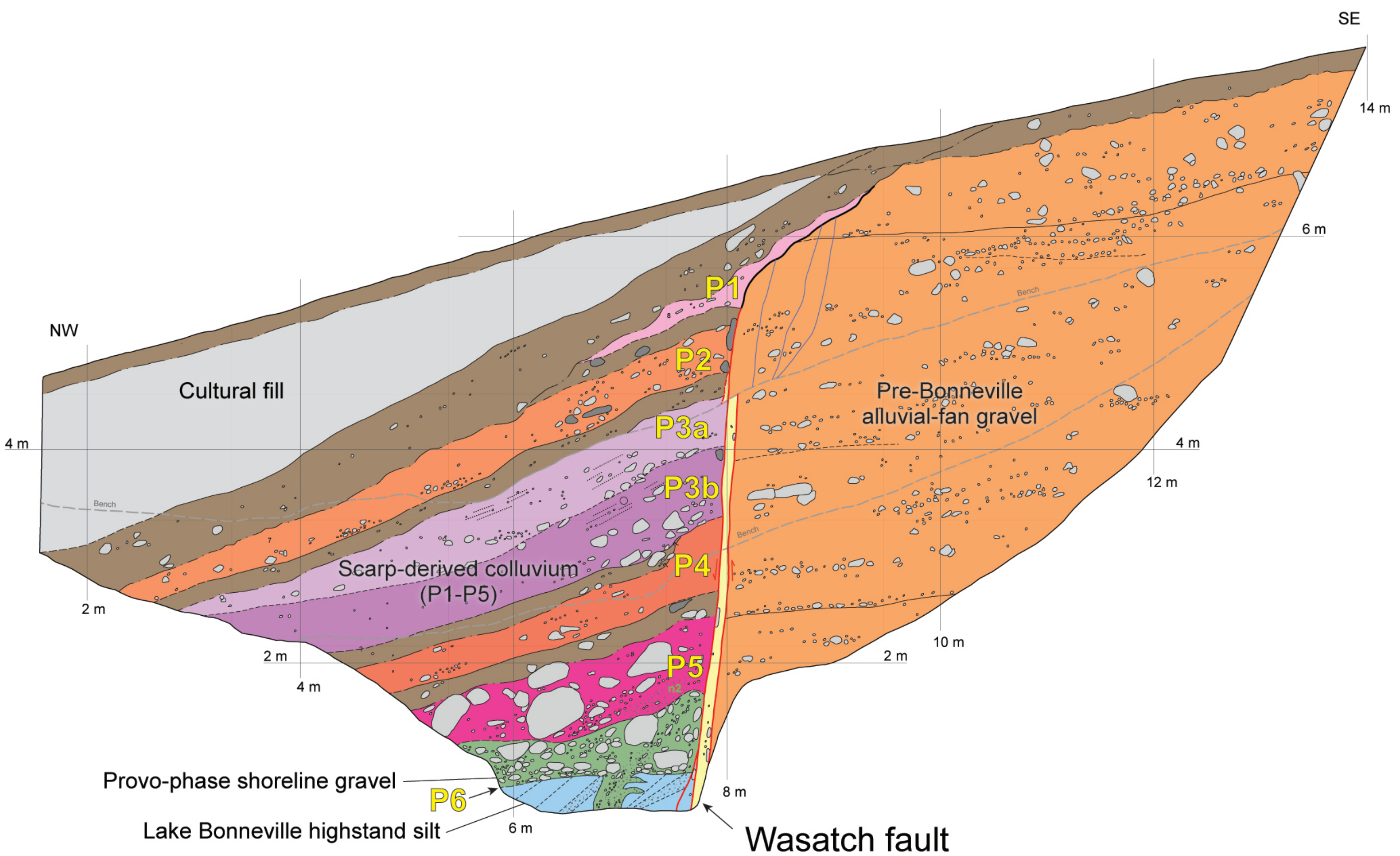
Previous Paleoseismic Data

Earthquake Timing per Site (ka)			
Little Cottonwood Canyon		**South Fork Dry Creek**	
Z	1.3 ± 0.04	D	1.3 ± 0.2
Y	2.1 ± 0.3	C	2.2 ± 0.4
X	4.4 ± 0.5	B	3.8 ± 0.6
W	5.5 ± 0.8	A	5.0 ± 0.5
V	7.8 ± 0.7		
U	9.5 ± 0.2		
No earthquakes between ~9.5 and 16.5 ka			
T	16.5 ± 2.7		

- *Mean recurrence*
  - Mid-Holocene: ~1.3 kyr
  - Holocene: ~1.6 kyr
  - Lt. Pleistocene (post-Bonn.): ~2.5 kyr
- *Displacement*
  - ~1.5–2.5 m per event
- *Vertical slip rate*
  - Bells Canyon glacial moraine ~0.7–1.7 mm/yr (<~16 ka)

Penrose Drive Trench Site

Penrose Drive Trench Site



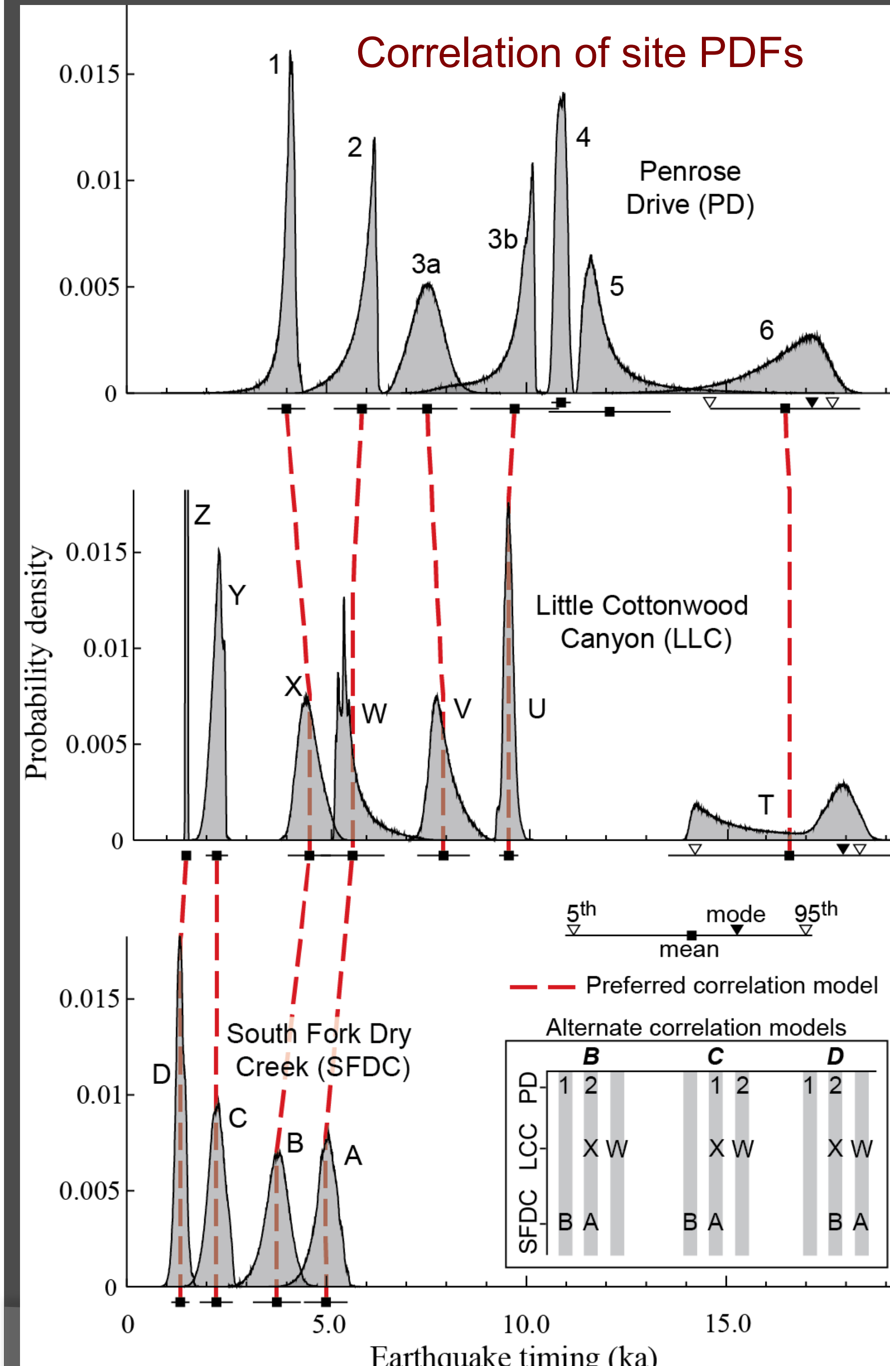
Penrose Drive Results

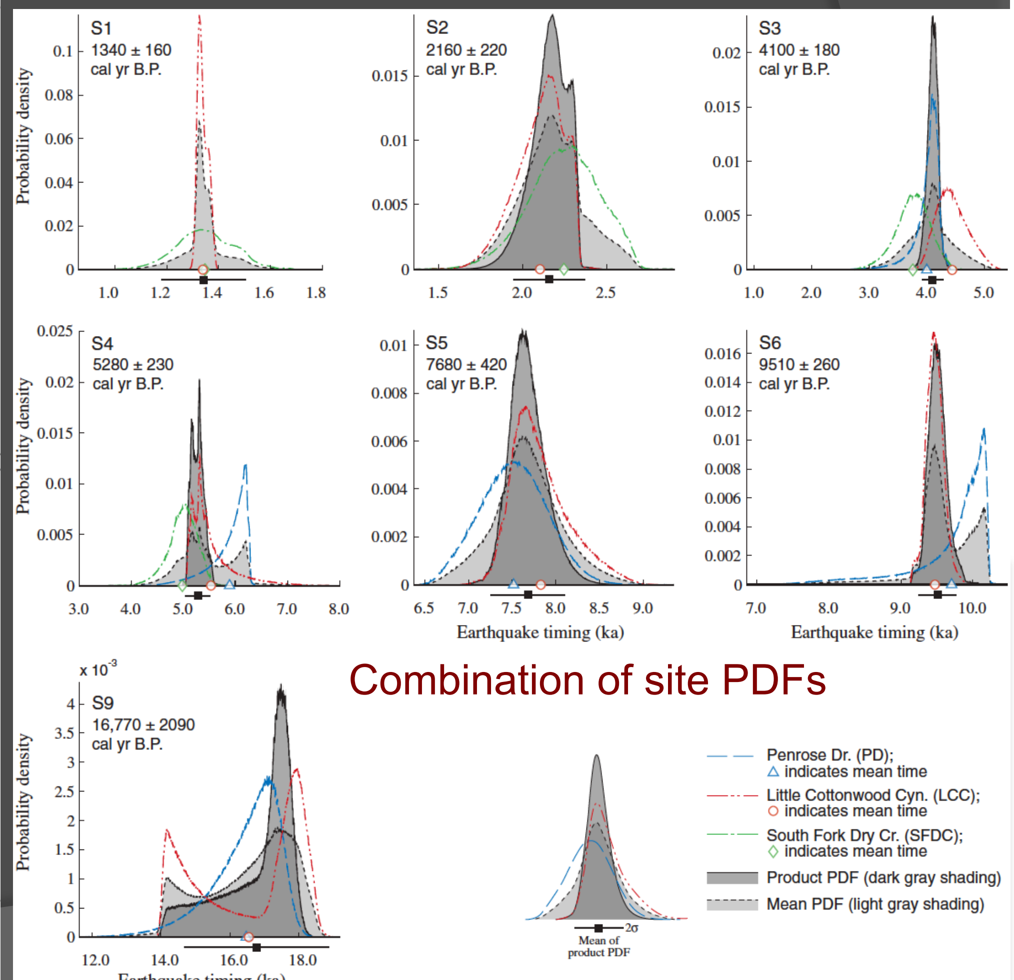
Earthquake Timing per Site (ka)					
Penrose Drive		**Little Cottonwood Canyon**		**South Fork Dry Creek**	
no evidence		Z	1.3 ± 0.04	D	1.3 ± 0.2
no evidence		Y	2.1 ± 0.3	C	2.2 ± 0.4
PD1	4.0 ± 0.5	X	4.4 ± 0.5	B	3.8 ± 0.6
PD2	5.9 ± 0.7	W	5.5 ± 0.8	A	5.0 ± 0.5
PD3a	7.5 ± 0.8	V	7.8 ± 0.7	*not exposed*	
PD3b	9.7 ± 1.1	U	9.5 ± 0.2	"	
PD4	10.9 ± 0.2	*no evidence*		"	
PD5	12.1 ± 1.6	*no evidence*		"	
PD6	16.5 ± 1.9	T	16.5 ± 2.7	"	

- *Mean recurrence*
  - Holocene: ~1.7–1.9 kyr
  - Lt. Pleistocene (post-Provo): ~1.6 kyr
  - Lt. Pleistocene (post-Bonn.): ~2.1 kyr (record likely incomplete prior to ~14 ka)
- *Displacement*
  - ~1.0–1.4 m per event
- *Vertical slip rate*
  - Holocene/Lt. Pleistocene (post Provo): 0.5–0.9 mm/yr

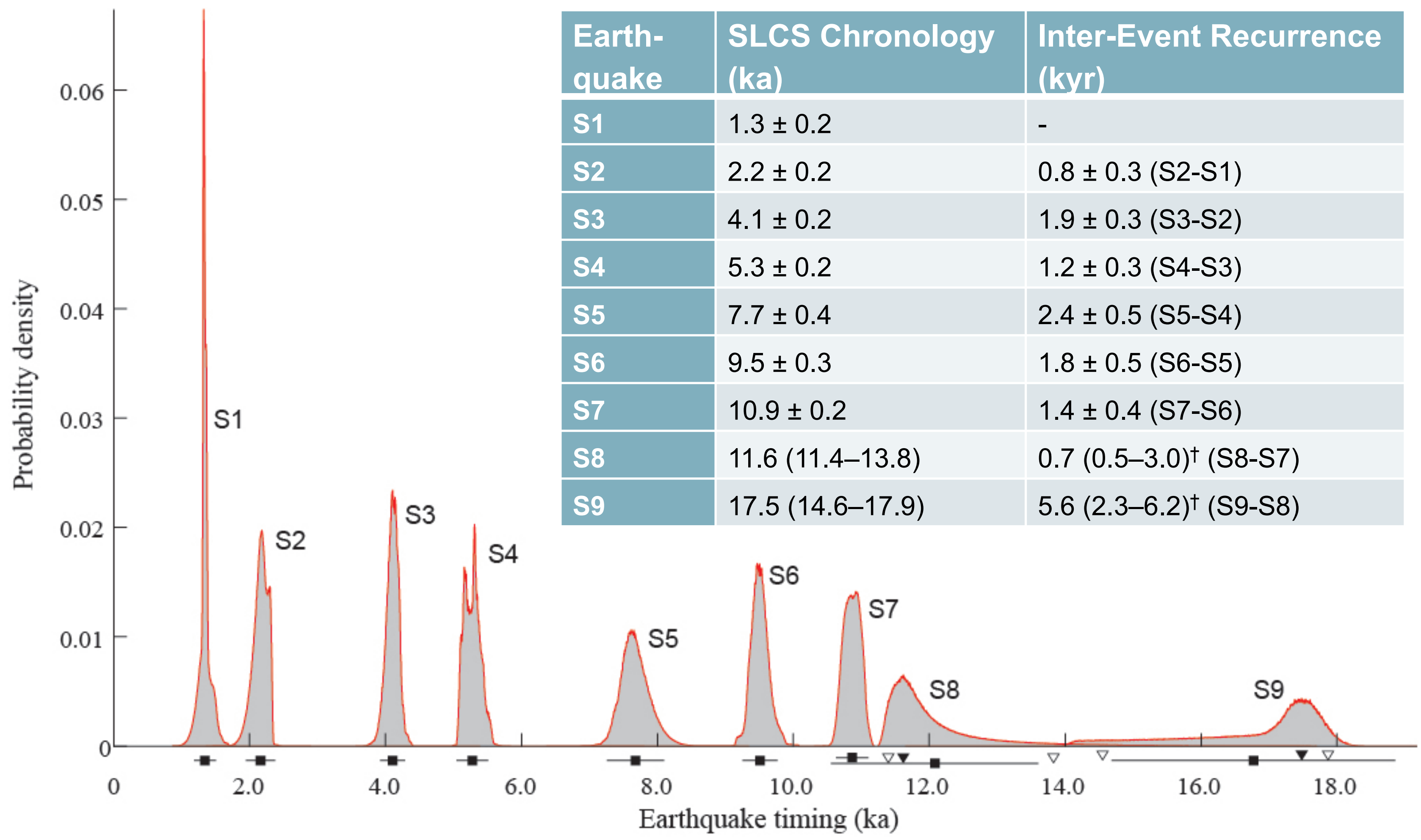
Correlation of Site Earthquakes

- *9 surface-faulting earthquakes since Bonneville highstand*





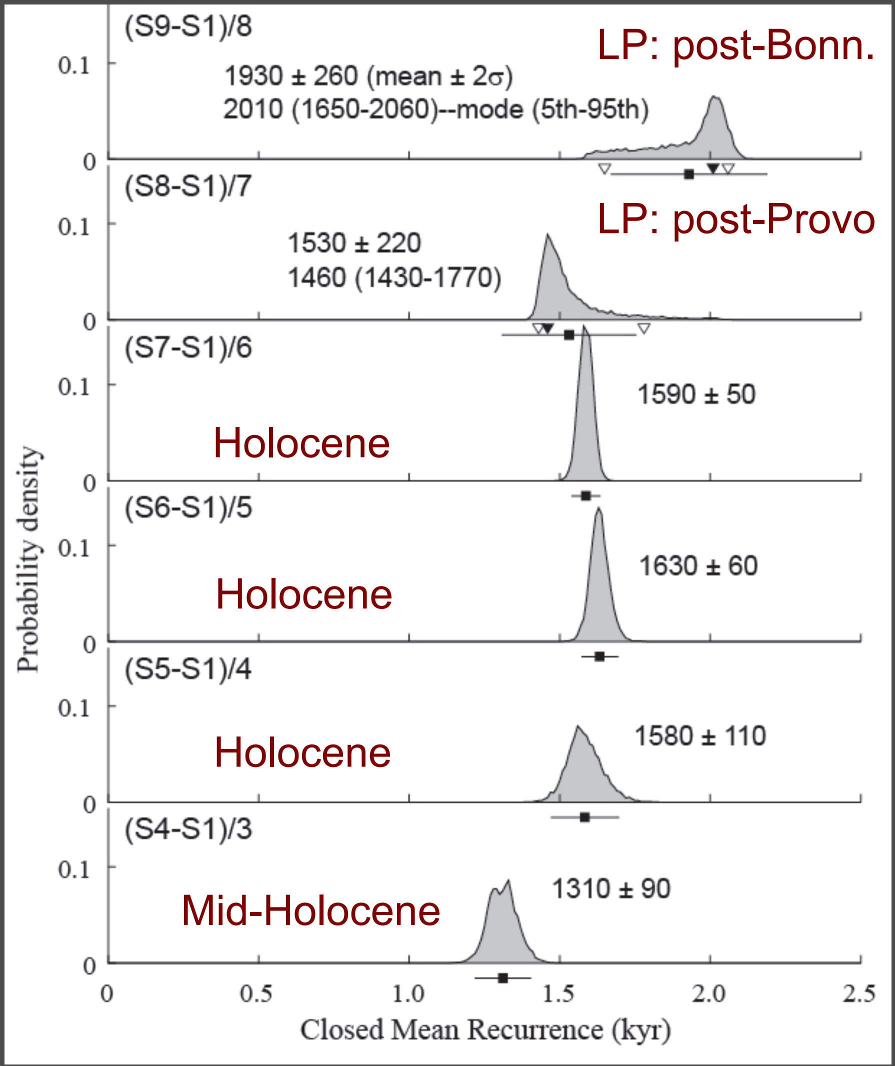
SLCS Earthquake Chronology



Earth-quake	SLCS Chronology (ka)	Inter-Event Recurrence (kyr)
S1	1.3 ± 0.2	-
S2	2.2 ± 0.2	0.8 ± 0.3 (S2-S1)
S3	4.1 ± 0.2	1.9 ± 0.3 (S3-S2)
S4	5.3 ± 0.2	1.2 ± 0.3 (S4-S3)
S5	7.7 ± 0.4	2.4 ± 0.5 (S5-S4)
S6	9.5 ± 0.3	1.8 ± 0.5 (S6-S5)
S7	10.9 ± 0.2	1.4 ± 0.4 (S7-S6)
S8	11.6 (11.4–13.8)	0.7 (0.5–3.0)† (S8-S7)
S9	17.5 (14.6–17.9)	5.6 (2.3–6.2)† (S9-S8)

SLCS earthquake-timing PDFs

Mean Recurrence and Slip Rate



Closed mean recurrence PDFs

Time Interval	Elapsed Time (kyr)	Closed Intervals	Mean Recurrence (kyr)
S9-S1	16.1 (<16.8)	8	2.0 (1.6–2.1)
S8-S1	10.3 (<12.1)	7	1.5 (1.4–1.8)
S7-S1	9.5 (<10.9)	6	1.6 ± 0.05
S6-S1	8.2 (<9.6)	5	1.6 ± 0.1
S5-S1	6.3 (<7.7)	4	1.6 ± 0.1
S4-S1	3.9 (<5.3)	3	1.3 ± 0.1

Disp. interval	Time Interval	Mean SR (mm/yr)
S8-S1	S9-S1	0.7 (0.6-1.1)
S7-S1	S8-S1	1.0 (0.7-1.2)
S6-S1	S7-S1	0.9 (0.8-1.2)
S5-S1	S6-S1	0.9 (0.8-1.2)
S4-S1	S5-S1	1.0 (0.9-1.3)
S3-S1	S4-S1	1.4 (1.1-1.7)

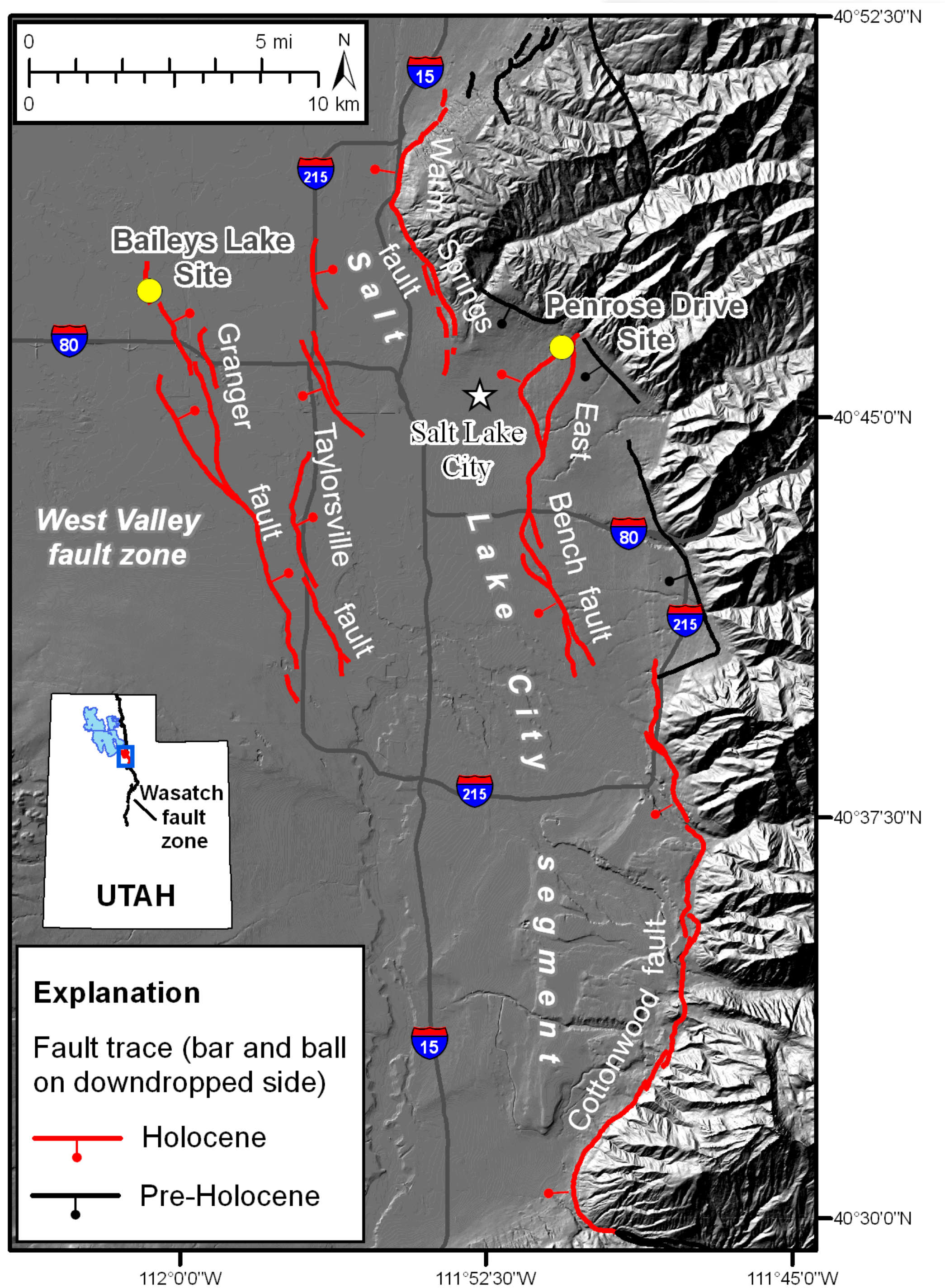
Conclusions

- *SLCS is more active than previously thought:*
  - Nine surface-faulting earthquakes (S1–S9) postdate the Bonneville highstand (previously 7)
  - S7 and S8 fill a previously interpreted ~8-kyr gap in the paleoseismic record
- *The earthquake record is most complete since ~14 ka,*
  - post-Provo mean recurrence is ~1.5 kyr, comparable to:
  - Holocene (~1.6 kyr) and late Holocene (~1.3 kyr) estimates
- *Important questions remain regarding rupture extent and the behavior of the Warm Springs, East Bench, and Cottonwood faults*

West Valley Fault Zone

- *Holocene surface faulting in Salt Lake Valley*
  - Mostly east-dipping West Valley fault zone (WVFZ)
  - WVFZ antithetic to west-dipping Salt Lake City segment (SLCS)
  - WVFZ forms intrabasin graben with SLCS

- *Remaining questions:*
  1. Overall Holocene and latest Pleistocene chronologies for the WVFZ and SLCS
  2. Seismogenic between the WVFZ and SLCS: *To what extent the WVFZ is seismogenically independent of, or moves synchronously with, the SLCS*



Previous Paleoseismic Data

Earthquake Timing per Site (ka)	
Granger Fault	**Taylorsville Fault**
1.4 ± 0.7 (Terracon)	?
?	2.2 ± 0.2 (AGRA)
?	?

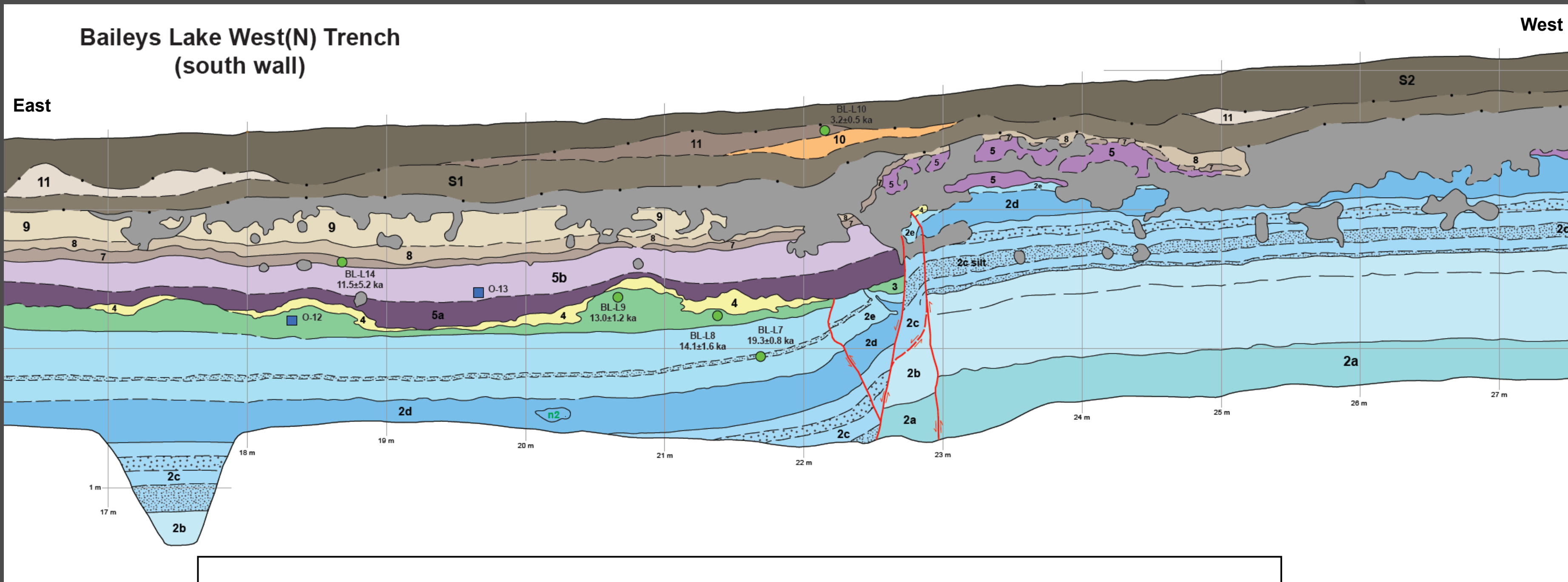
Earthquake times are poorly constrained; based on limited C-14 ages obtained by the UGS from consultant trenches

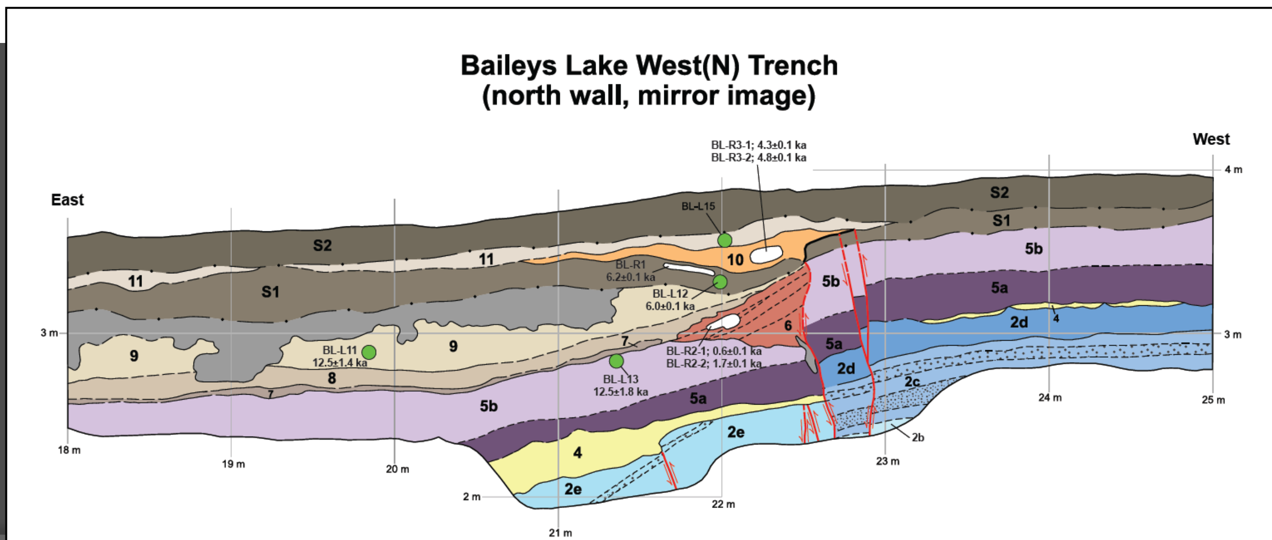
- *Mean recurrence*
  - Holocene:
    - ~2.6–6.5 kyr (Granger fault)
    - ~6.0 kyr (Taylorsville fault)
    - ~1.8–2.2 kyr (WVFZ)
  - Lt. Pleistocene (<~28 ka):
    - ~7.3–14.0 kyr (Granger fault)
- *Displacement*
  - ~1.2–1.5 m per event(?)
- *Vertical slip rate*
  - ~0.03–0.5 mm/yr (Granger fault)
  - ~0.1 mm/yr (Taylorsville fault)
  - ~0.5–0.6 mm/yr (WVFZ)

Data from Keaton and others (1987) and Keaton and Currey (1989), primarily from boreholes and geomorphic mapping, and limited trenching. Recurrence calculated using an assumed 1.2–1.5 m displacement per event.

Baileys Lake Trench Site

Baileys Lake Trench Site



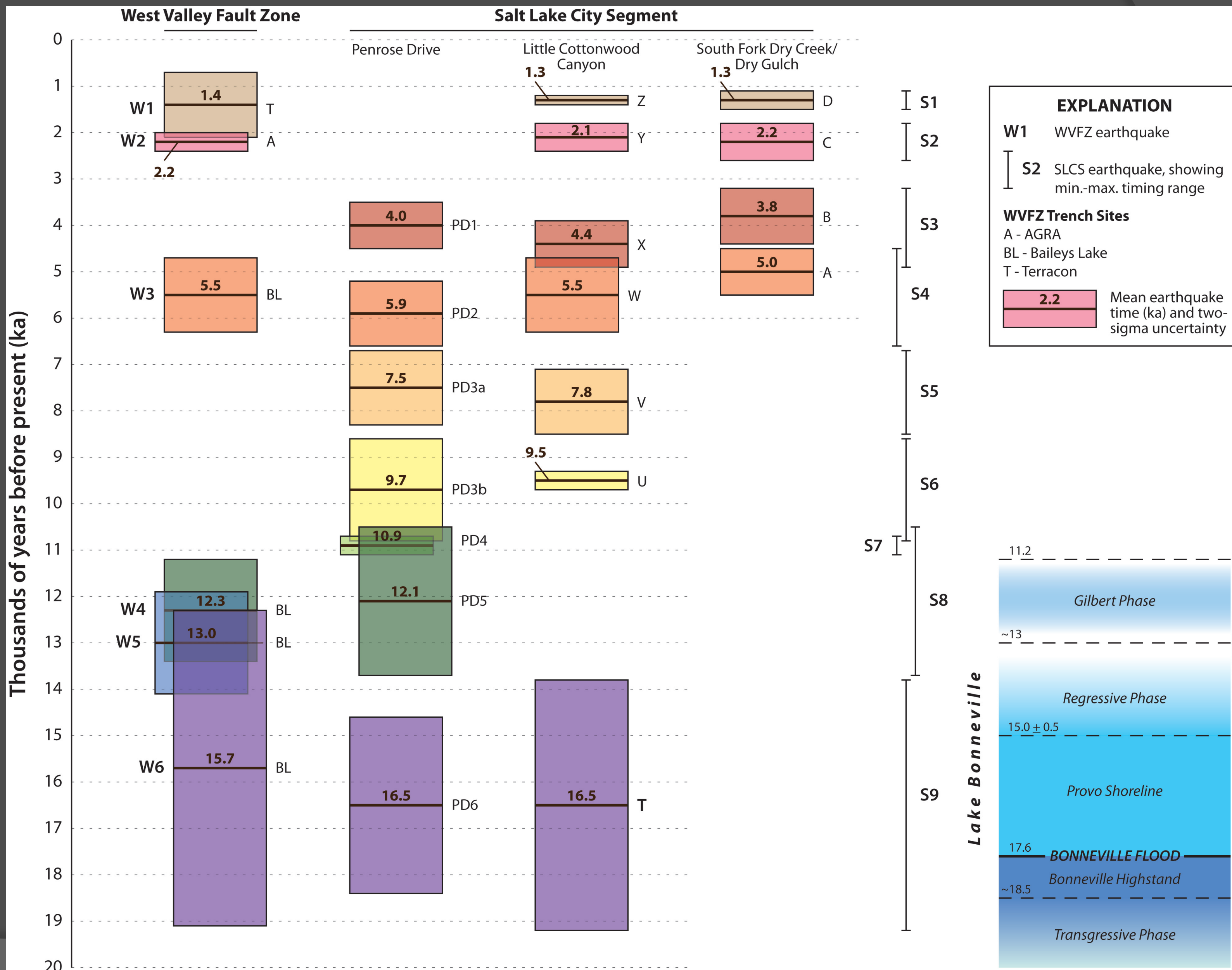


Baileys Lake Results

	Earthquake Timing per Site (ka)			
	Baileys Lake (Granger fault)		Terracon (Granger fault)	AGRA (Taylorsville fault)
	no evidence		1.4 ± 0.7	*no evidence*
	no evidence		*no evidence*	2.2 ± 0.2
	BL1	5.5 ± 0.8	*not exposed*	*not exposed*
	BL2	12.3 ± 1.1	"	"
	BL3	13.0 ± 1.1	"	"
	BL4	15.7 ± 3.4	"	"

- *Mean recurrence*
  - Lt. Pleistocene (post-Provo): ~3.8 kyr
  - Lt. Pleistocene (post-Bonn.): ~3.4 kyr
- *Displacement*
  - ~0.5 m per event
- *Vertical slip rate*
  - Holocene/Lt. Pleistocene (post-Provo): 0.06–0.1 mm/yr

WVFZ Earthquake Chronology



WVFZ Mean Recurrence and Slip Rate

Time Interval	Elapsed Time (kyr)	Closed Intervals	Mean Recurrence (kyr)
W6-W1	14.3	5	2.9
W5-W1	11.6	4	2.9
W4-W1	10.9	3	3.6
W3-W1	4.1	2	2.0

- *Vertical slip rate*
  - 0.06–0.1 mm/yr (Baileys Lake)
  - ~0.03–0.5 mm/yr (Granger fault)
  - ~0.1 mm/yr (Taylorsville fault)
  - ~0.5–0.6 mm/yr (WVFZ)

Given the small number of documented earthquakes and the likelihood of an incomplete paleoseismic record, we did not attempt to evaluate changes in slip rate over time based on inter-event times and per-event displacements.

Conclusions

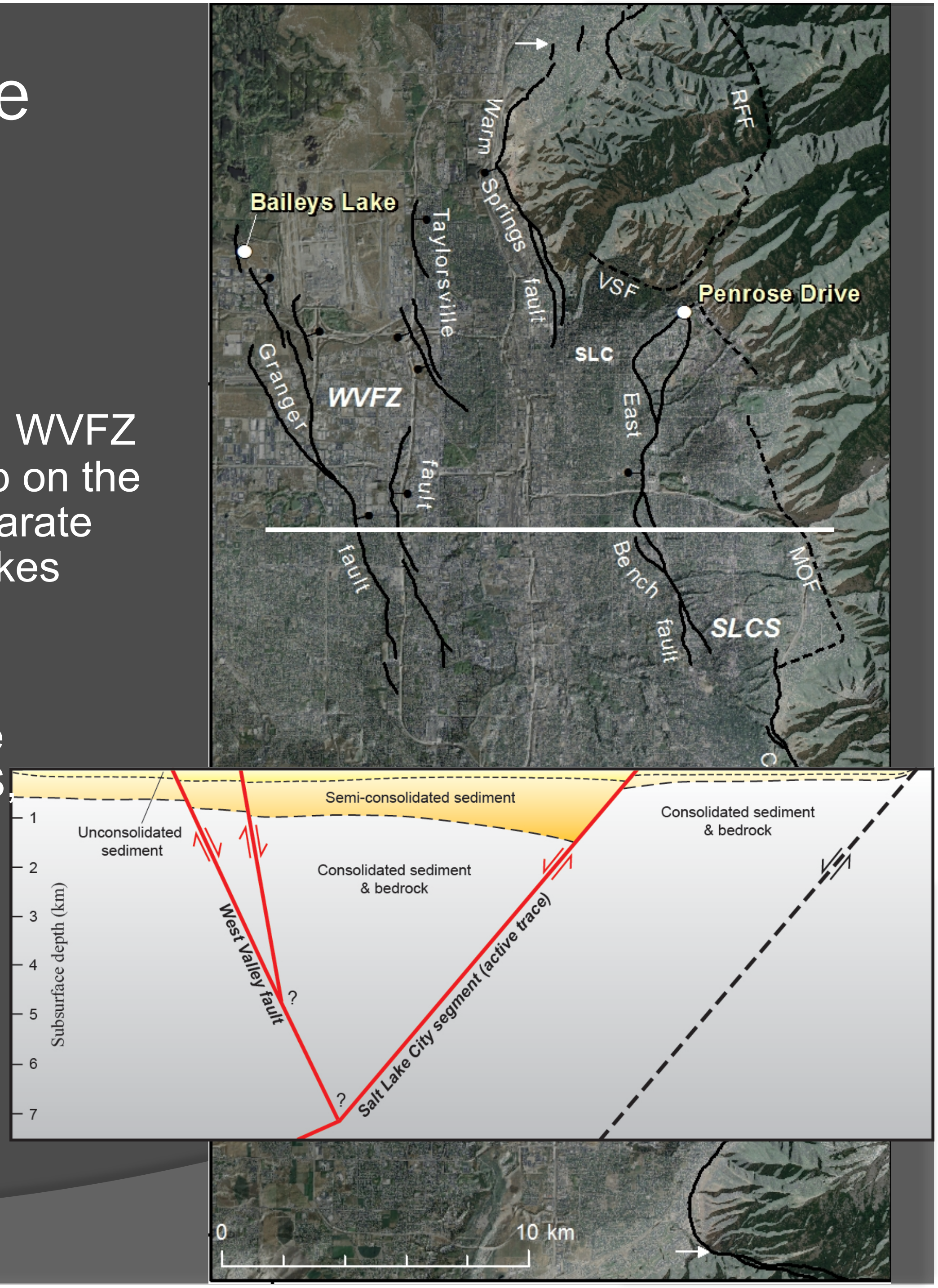
- *The WVFZ has ruptured at least 6 times since ~19 ka*
  - 5 earthquakes have been documented on the Granger fault; only 2(?) earthquakes have been documented on the Taylorsville fault
  - Given the distributed nature of the fault zone (numerous strands) and the small number of sites where earthquake timing has been determined, the paleoseismic record is likely incomplete
- *Five WVFZ earthquakes have mean times and 2σ uncertainty ranges that are very similar to those of SLCS earthquakes*
  - Another WVFZ earthquake occurred during a period in which the SLCS may be incomplete
- *Important questions remain regarding rupture pattern and extent, and the earthquake chronology (especially the Taylorsville fault)*

SLCS & WVFZ Rupture

- *WVFZ Rupture Options:*

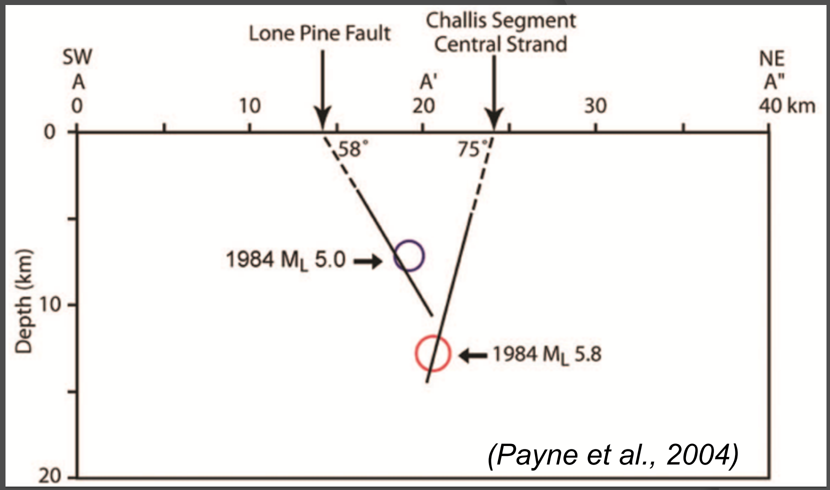
1. Independent Rupture
   - Completely independent. WVFZ slip has no relation to slip on the SLCS. The WVFZ is separate source of large earthquakes

2. Dependent Rupture
   - Triggered. WVFZ rupture initiated by slip the SLCS, but does not contribute seismic moment to a SLCS earthquake
   - Synchronous Simultaneous rupture of SLCS and WVFZ

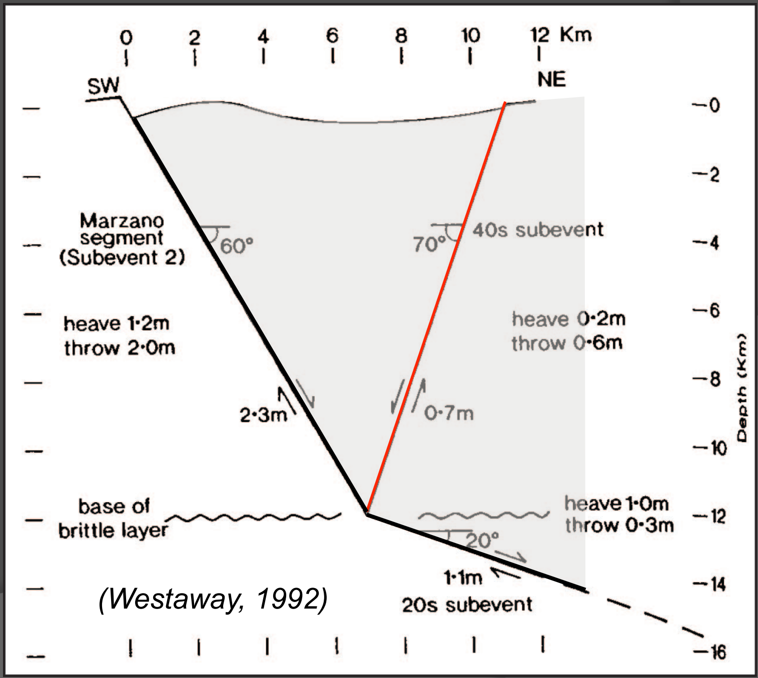


Antithetic-Fault Rupture Examples

- *Independent*
  - 1934 M 6.6 Hansel Valley earthquake?
- *Triggered*
  - M 5.0 aftershock to 1984 M 5.8 Devil Canyon, Idaho earthquake
  - Triggered rupture of Lone Pine fault
- *Synchronous*
  - M 6.9 1980 Irpinia, Italy earthquake
  - Antithetic fault rupture (at 40s) contributed moment (~12%) to earthquake as a whole
  - Vert. slip: main–2.0 m, 0.6 m–antithetic



1984 Devil Canyon earthquake

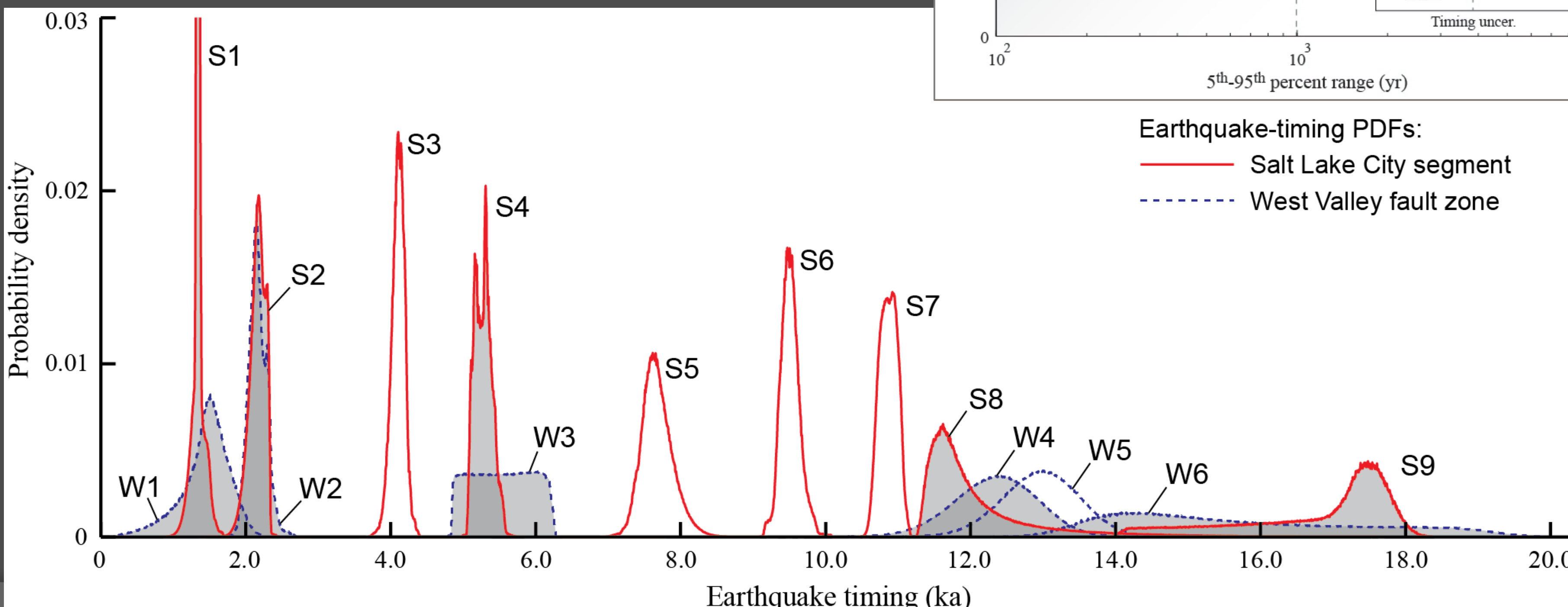


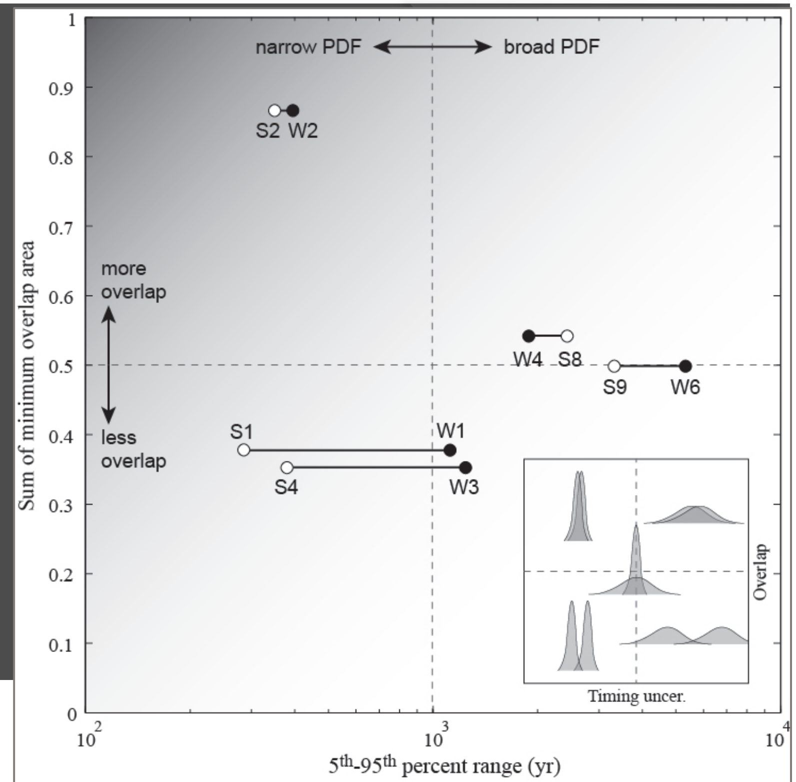
1980 Irpinia, Italy earthquake

SLCS & WVFZ Rupture

- *Earthquake timing data suggest independent rupture is unlikely*

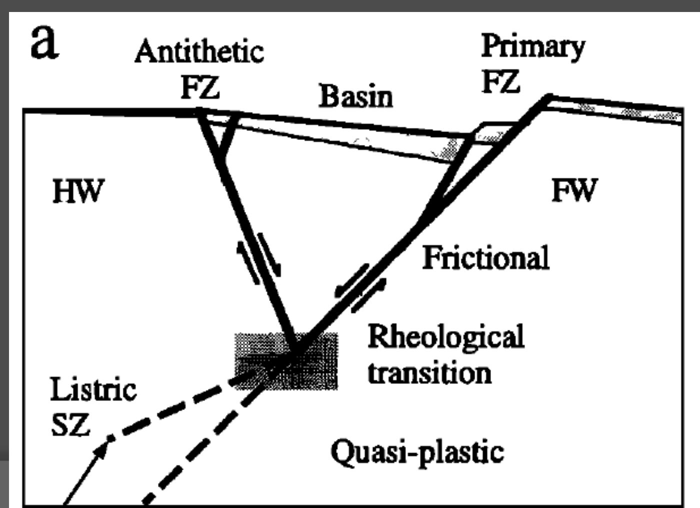
Comparison of SLCS and WVFZ earthquakes



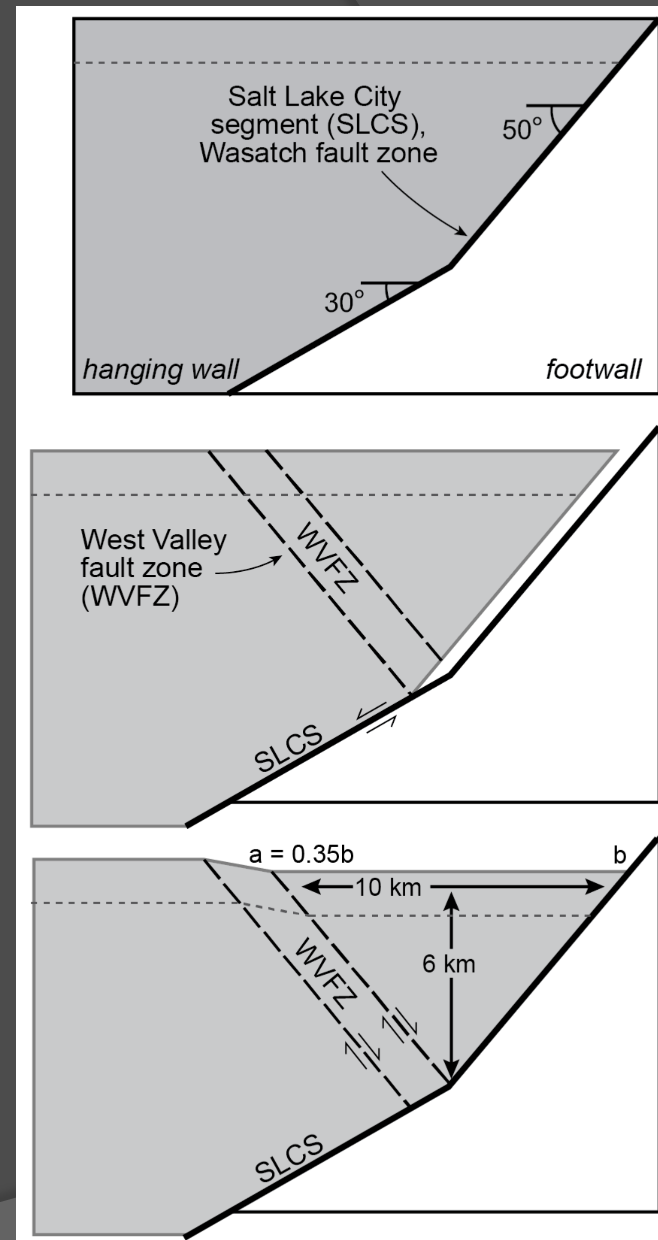


SLCS & WVFZ Rupture

- *Mechanical models support synchronous rupture*
  - Subsurface geometry is poorly understood, but surface-fault geometry, seismic data, and kinematic models support a change in dip at depth
  - During SLCS rupture, hanging wall deforms (instantaneously) to fill void created by change in master-fault dip
  - Antithetic fault slip is some fraction (~20–40%) of master-fault slip



Bruhn & Schultz (1996)



Possible SLCS & WVFZ geometries; after Xiao and Suppe (1992)

Conclusions

- *Improved paleoseismic data for the SLCS and WVFZ allow for the comparison of earthquake times on both the master and antithetic faults of a major graben-forming system*

- *We prefer a model of synchronous rupture on the SLCS and WVFZ based on:*
  1. Historical analogs. Based on the fault geometries and displacements, synchronous rupture in the Irpinia earthquake is good analog for SLCS-WVFZ rupture
  2. Paleoseismic data. Holocene earthquakes on the SLCS and WVFZ have similar earthquake times and uncertainties—supporting synchronous or triggered behavior
  3. Mechanical models. Significant (surface-faulting) deformation of the SLCS hanging wall (WVFZ rupture) likely occurs instantaneously with earthquake rupture—supporting synchronous behavior

- *However…*
  - Triggered slip is still possible. The Devil Canyon, Idaho earthquake may be a good analog for non surface-rupturing earthquakes restricted to hanging wall

Utah State Capitol Building Restoration and Seismic Base Isolation

Presented by

Jerod G. Johnson, PhD, SE, LEED(AP)

Principal, Reaveley Engineers + Associates

for the

Basin and Range Province Seismic Hazard Summit III

January 17, 2015

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Building Characteristics

- Designed in 1912 by R.K.A Kletting.
- 4 Stories with partial basement / crawl space and dome.
- Approximately 400’ x 215’ in plan.
- Basic structural system is reinforced concrete frame.
- Steel trusses for dome and skylights, otherwise sparse use of structural steel.

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Nonstructural Features

- Stacked Granite Columns on South, East and West Sides.
- Exterior carved/stacked granite cladding.
- Skylights and atrium.
- Pediments and parapets.
- Rotunda and dome.
- Interior tile, marble, other unusually heavy components.
- Unusually heavy overall structural massing. The building is roughly 2 times the weight of a modern office building of comparable space

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Primary Findings of Early Studies

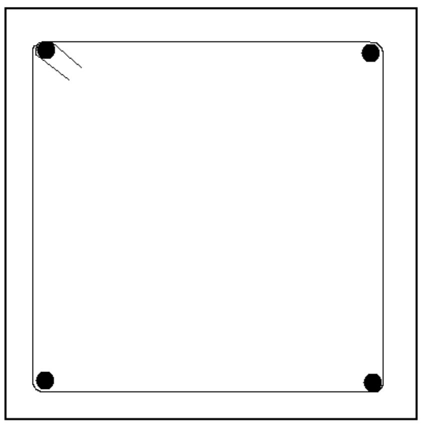
- Structural frame is inadquate with respect to the expected seismic motion.
- Inadequate reinforcement in walls, columns and beams to provide ductile performance.
- Large diaphragm openings in levels 3, 4, attic, roof.
- Non-continuous infills comprised of HCT and URM.
- Exterior cladding backed by URM.
- Lack of bracing for parapets, pediments, and balustrades.
- Window penetrations of dome create ‘soft’ story.
- Dome seismic forces are amplified due to its height.
- Lack of uniform lateral stiffness. Rotunda is stiff, wings are flexible.
- Inadequate anchorage of cladding.

Primary Retrofit Scheme

The only practical approach in terms of cost, performance, and preservation is to use a seismic base isolation system coupled with new interior and perimeter shearwalls.

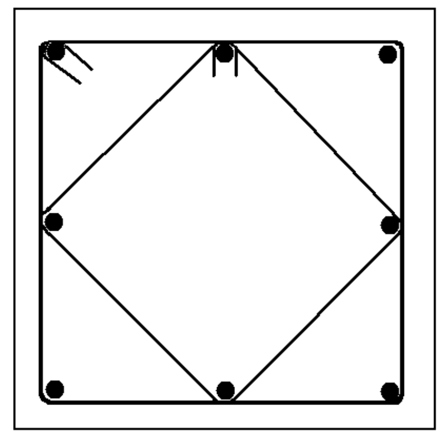
The Need for Seismic Retrofit:

- Primary structure is reinforced concrete beams and columns. Although innovative in its day, the concrete is lightly reinforced by today's standards. Concepts of seismic design did not exist 90 years ago.
- The building is within a very short distance of the active Wasatch Fault.
- Expected seismic performance (pre-retrofit) was extremely poor. Significant earthquake would likely have meant loss of life and loss of the building.



Typical Column - Utah State Capitol
As=0.4% of Gross Column Area (Ag)

Top of existing column in attic of Capitol



Typical Column - Modern Construction
As=1.0% of Gross Column Area (Ag) Minimum

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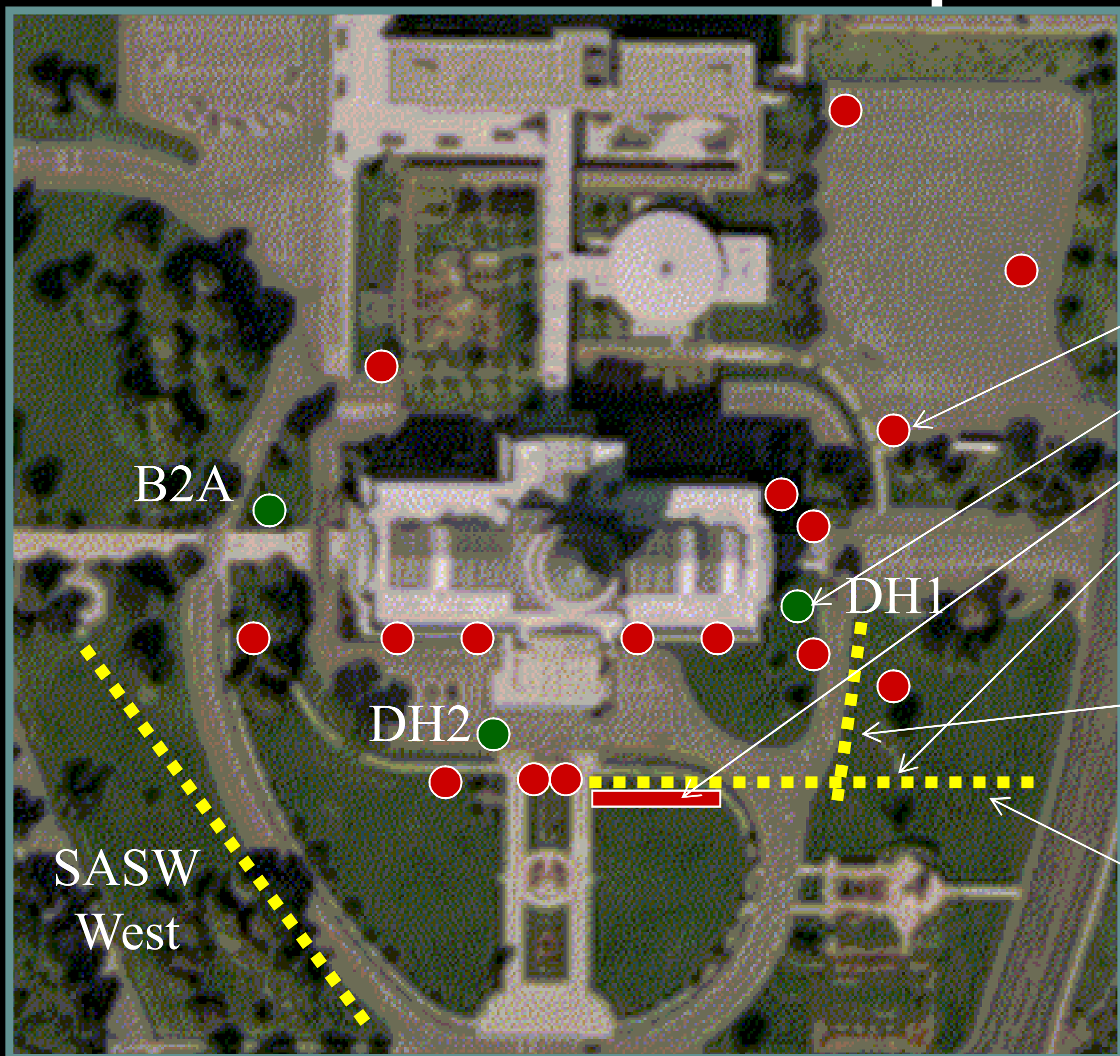
Site Response



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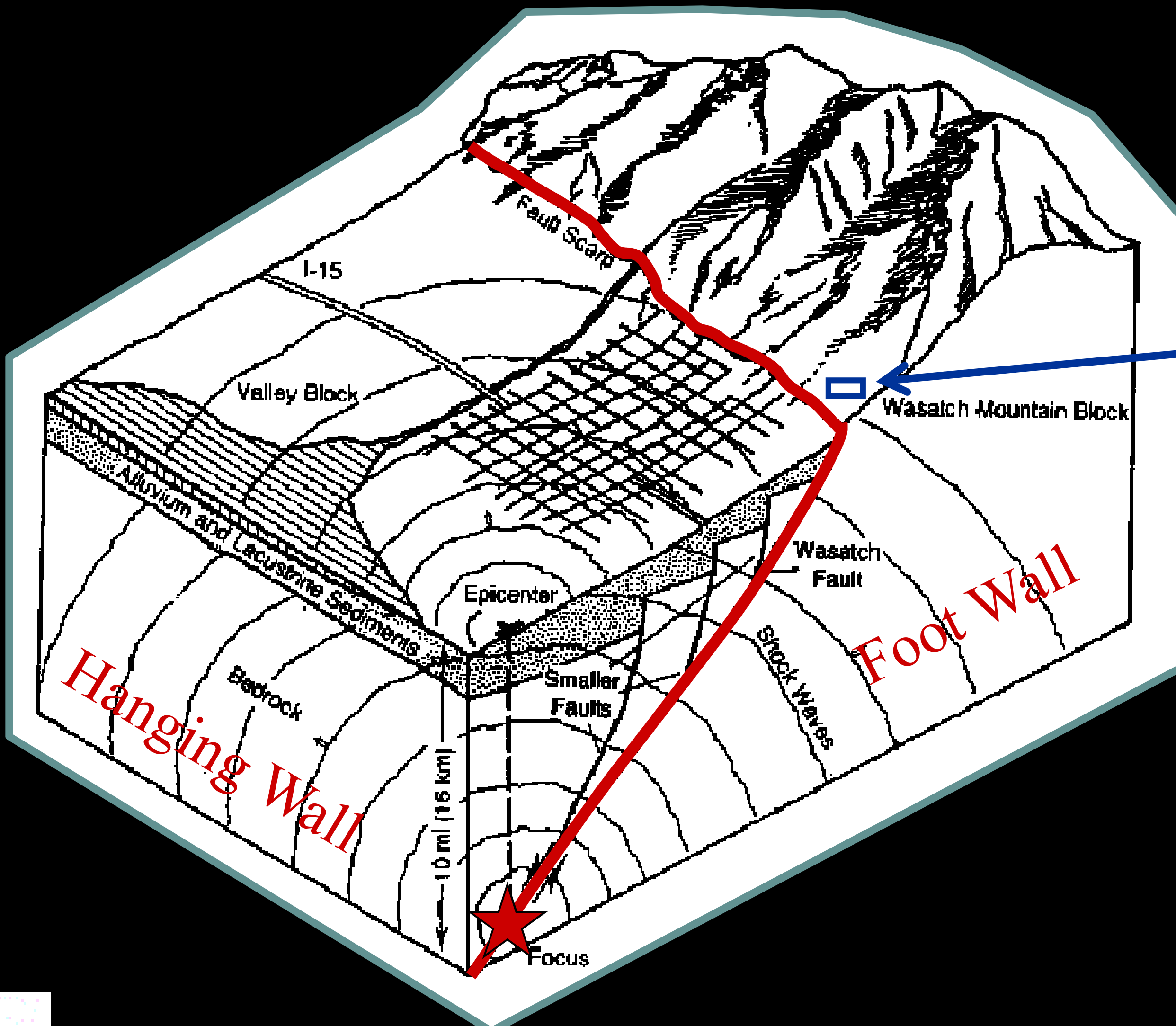
Source-to-Site Geometry



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Composite Source Methodology

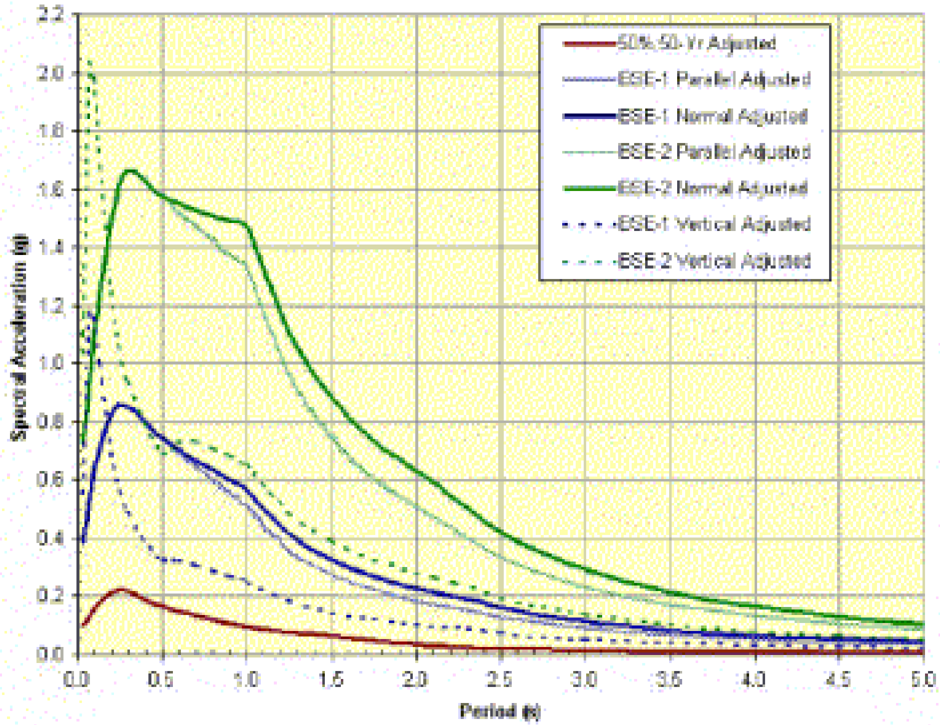

Figure 8. Adjusted spectral acceleration based on constant spectral displacements above periods of 2 to 2.5 s. Vertical spectra were adjusted based on ratios of vertical to horizontal spectral ordinates.

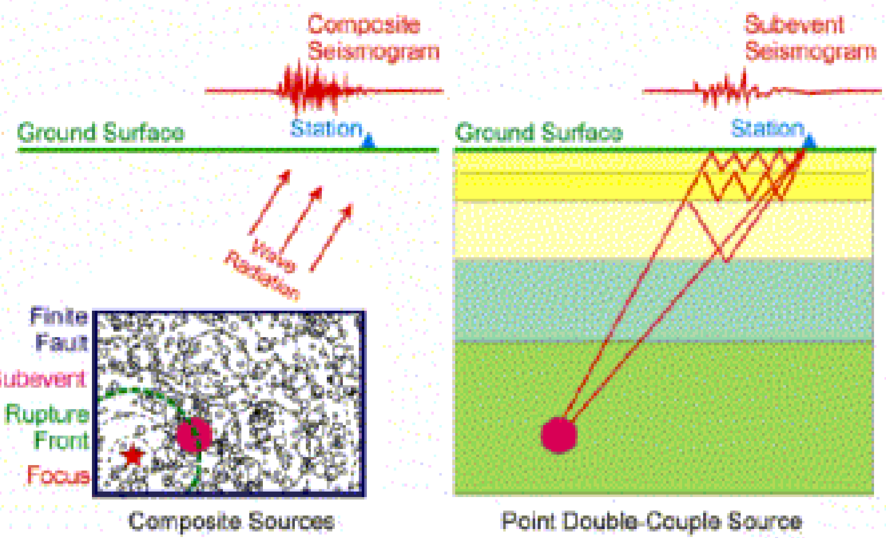

Figure 9. General features of the Composite Source Model.

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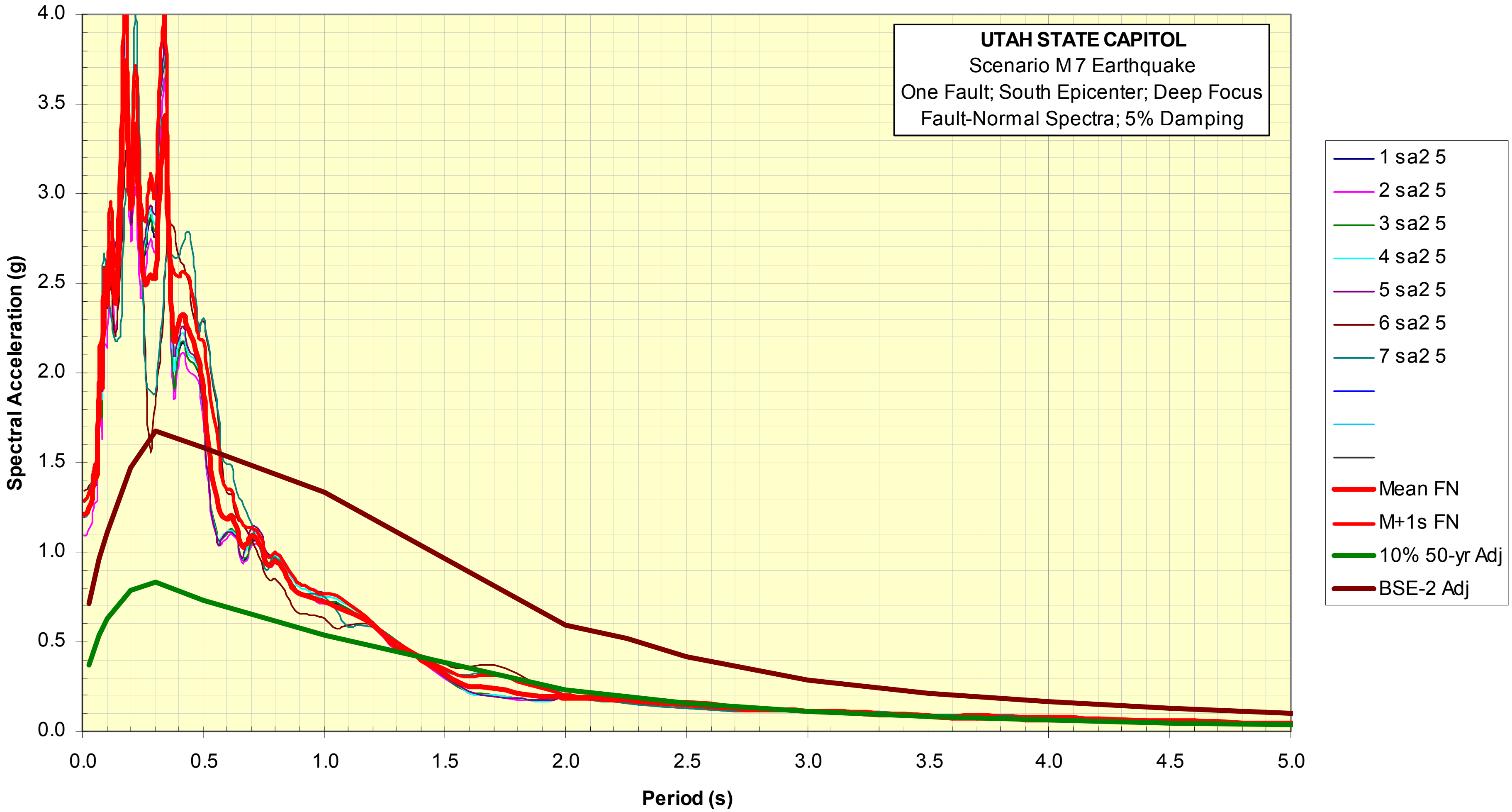
Utah State Capitol Fault-Normal Spectra



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Base Isolation Fundamental Concept

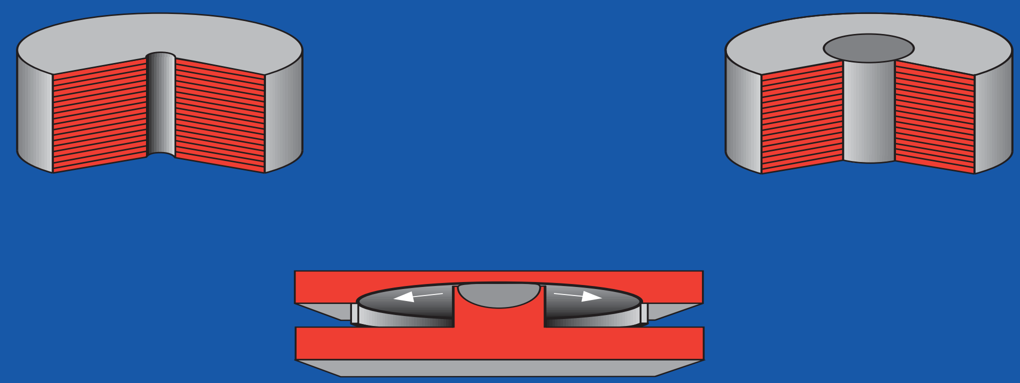
- A base isolator is a bearing mechanism upon which a building rests. It is very stiff vertically but very limber horizontally.
- A group of base isolators tied together beneath a building creates a seismic base isolation system.
- Because a base isolation system is very limber horizontally it can dramatically increase the fundamental period of the global system (base isolation system and building structure)
- An increase in period results in a decrease of earthquake forces but an increase in displacements.
- A base isolation system enables most of the displacement to occur at the base isolated level thus helping a building to maintain the advantages inherent in a stiff system

Types of Base Isolators

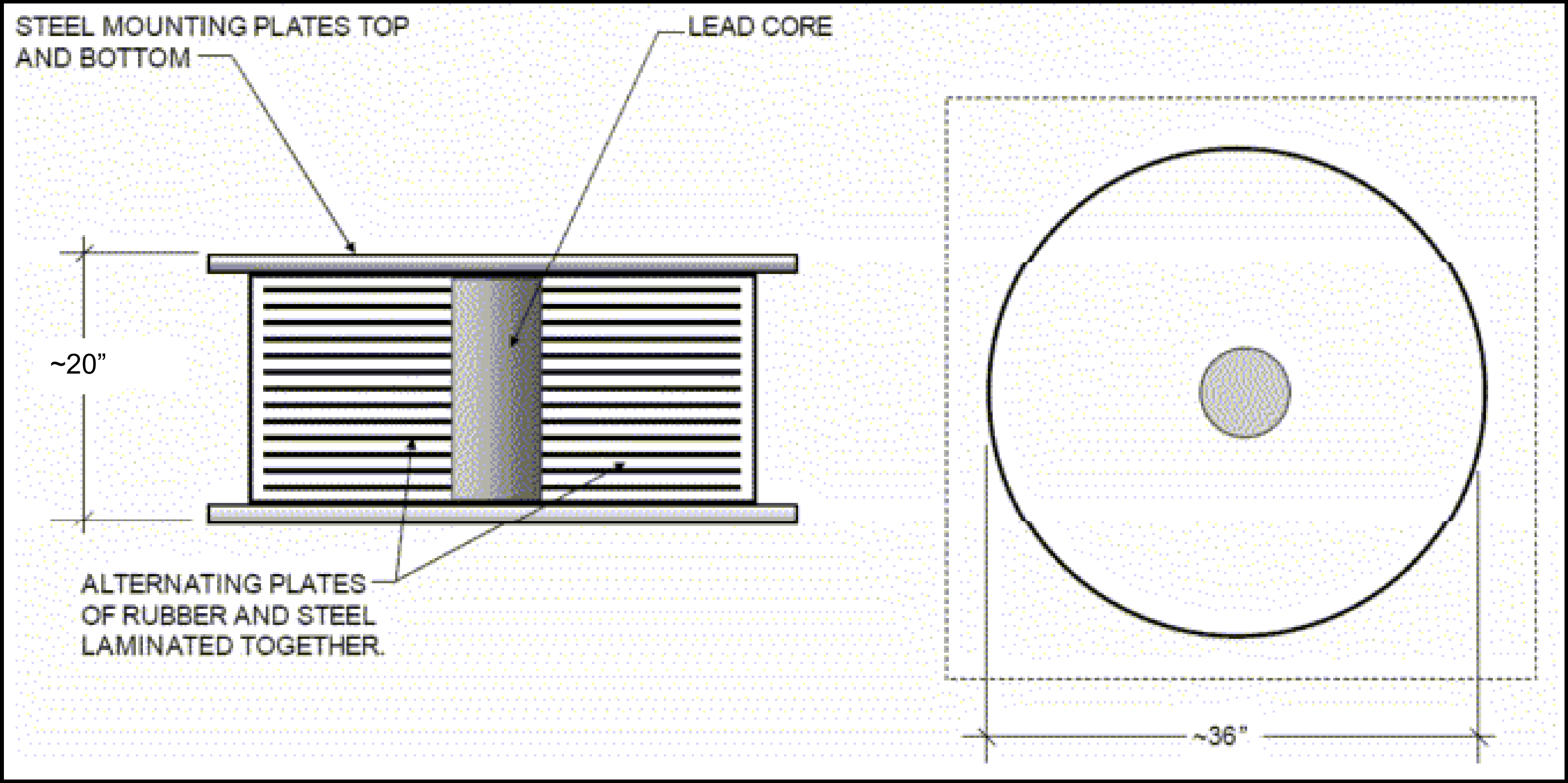
•Elastomeric with HDR (High Damping Rubber)

•Elastomeric with Lead Core

•Friction Pendulum



Isolator Anatomy



- Note– Each isolator weighs approximately 5000 pounds.

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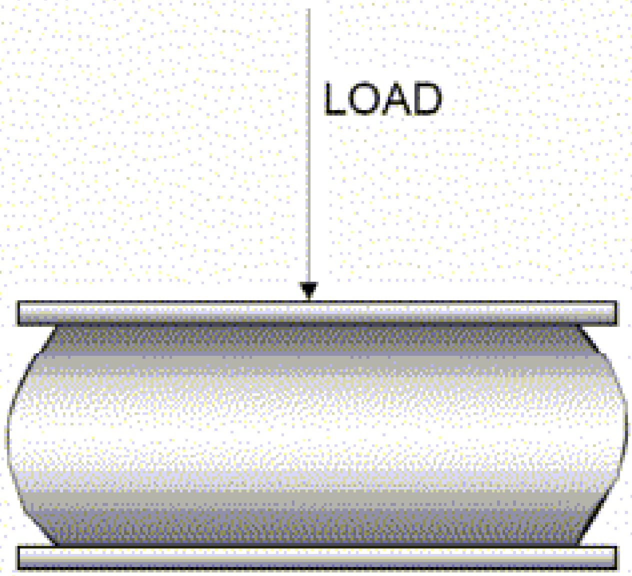
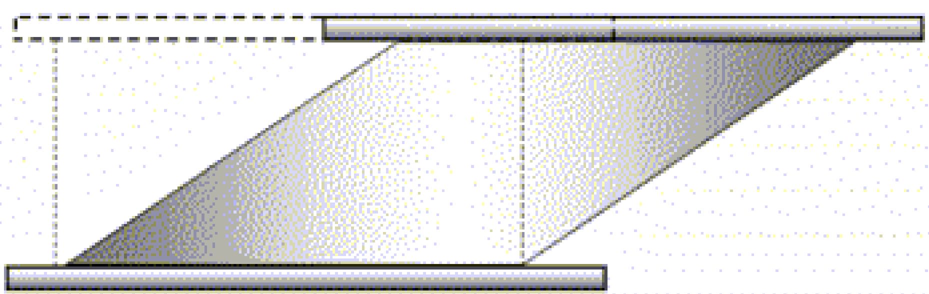
Isolator Anatomy – Why Steel Plates?



Without steel plates the isolator would suffer a “bellying” effect, and lose vertical stiffness



Steel plates prevent the isolator “bellying” effect, making it rigid vertically, while the rubber enables it to be limber horizontally.

Note: depicted deflection is true to scale

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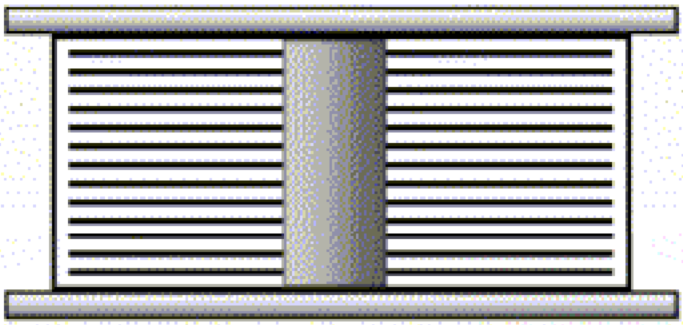
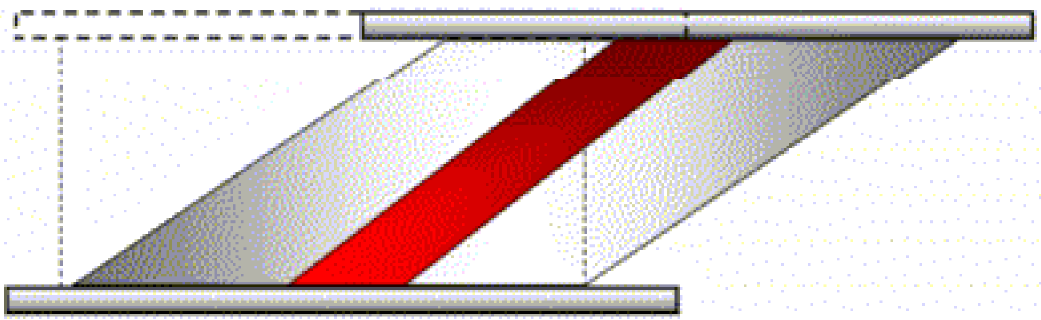
Isolator Anatomy – Why Lead Core?

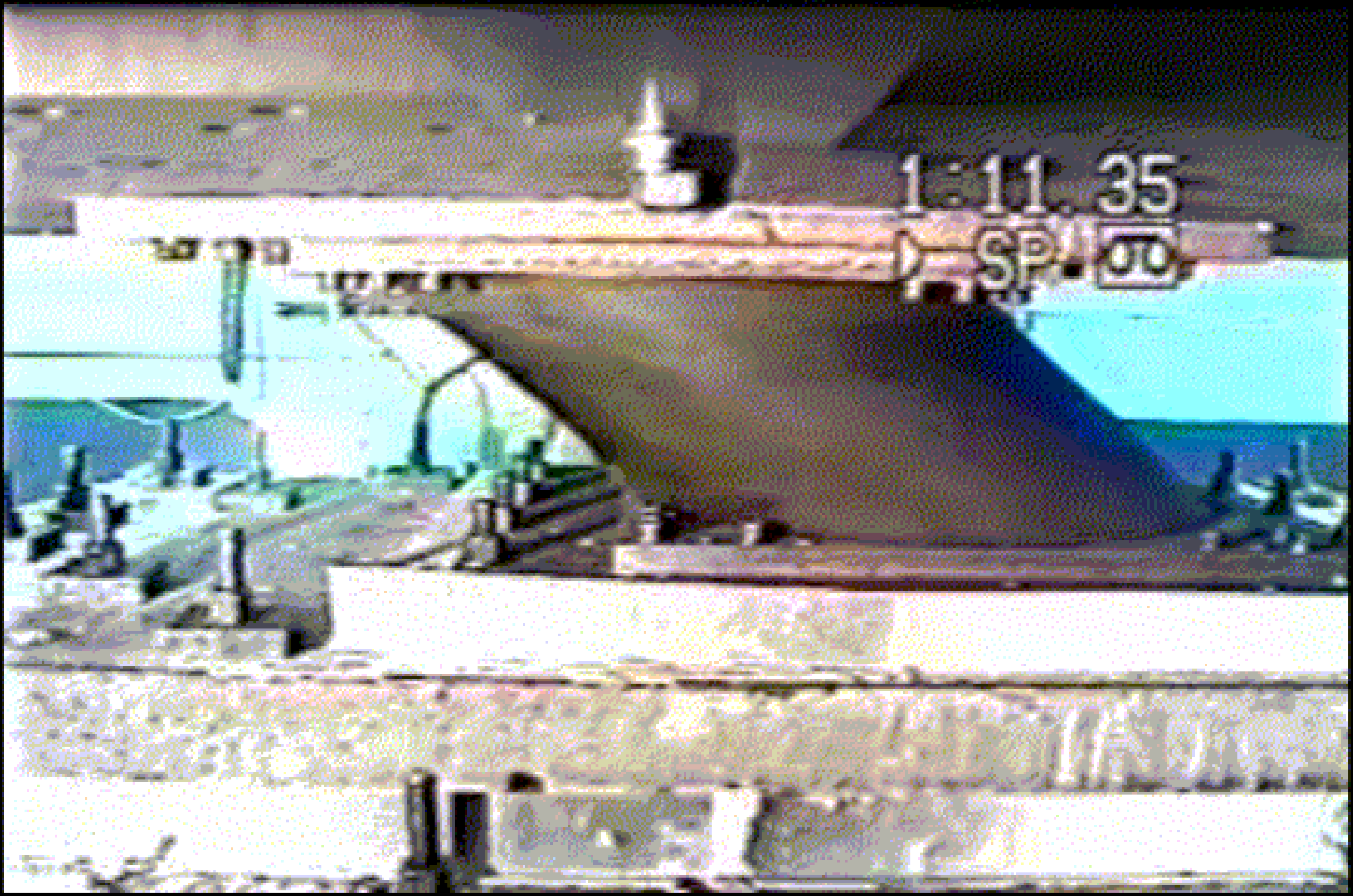


The lead core acts as an energy dissipating mechanism.



As it suffers a forced distortion, the lead core partially liquefies. This dissipates large amounts of energy in a safe, controlled manner. When motion stops, the lead will re-crystallize.

Real Time Isolator Testing



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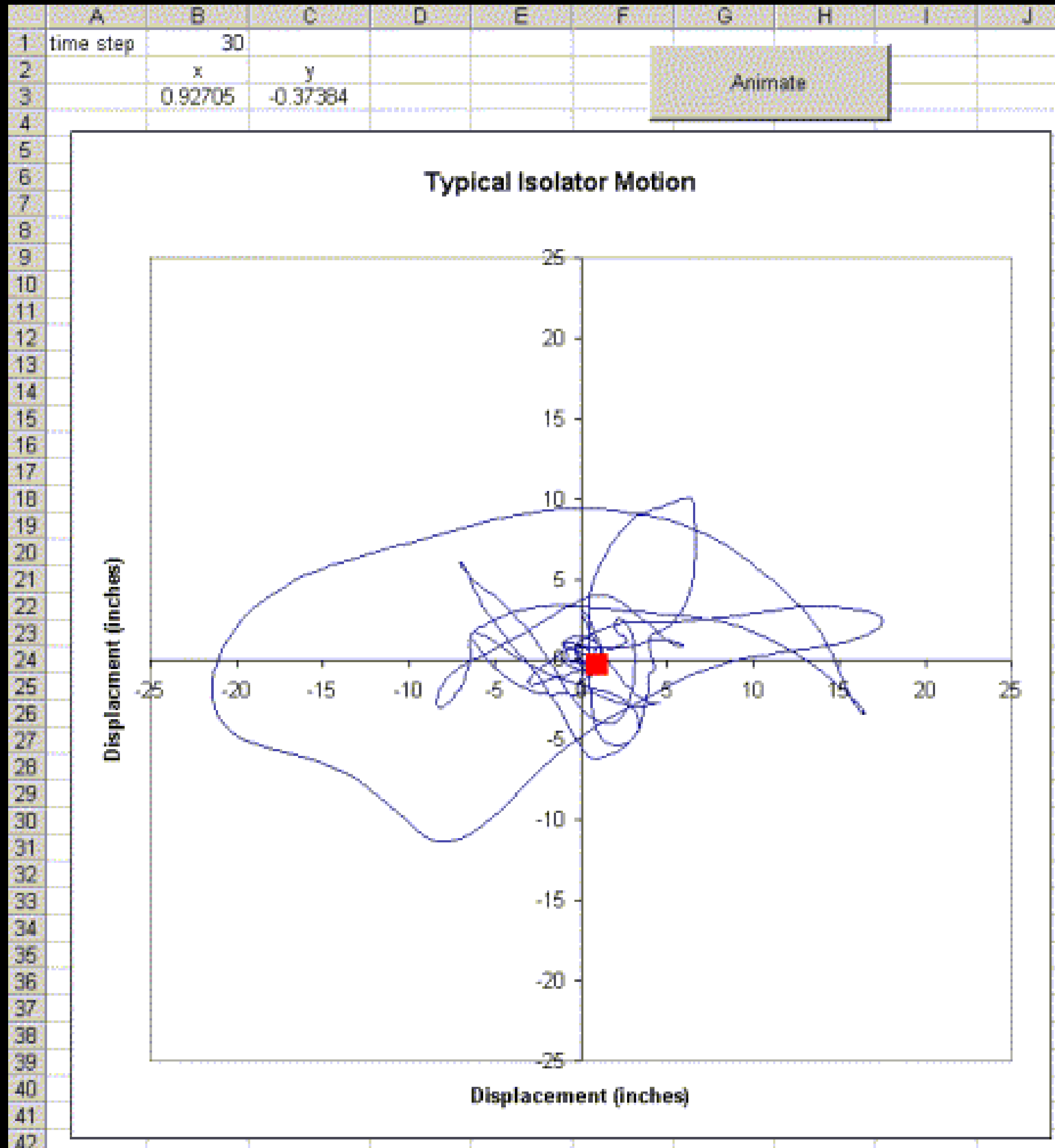
Typical Isolator Behavior

Elastomeric Isolator

(Excel Based Animation.)

(Click on image to start animation.)



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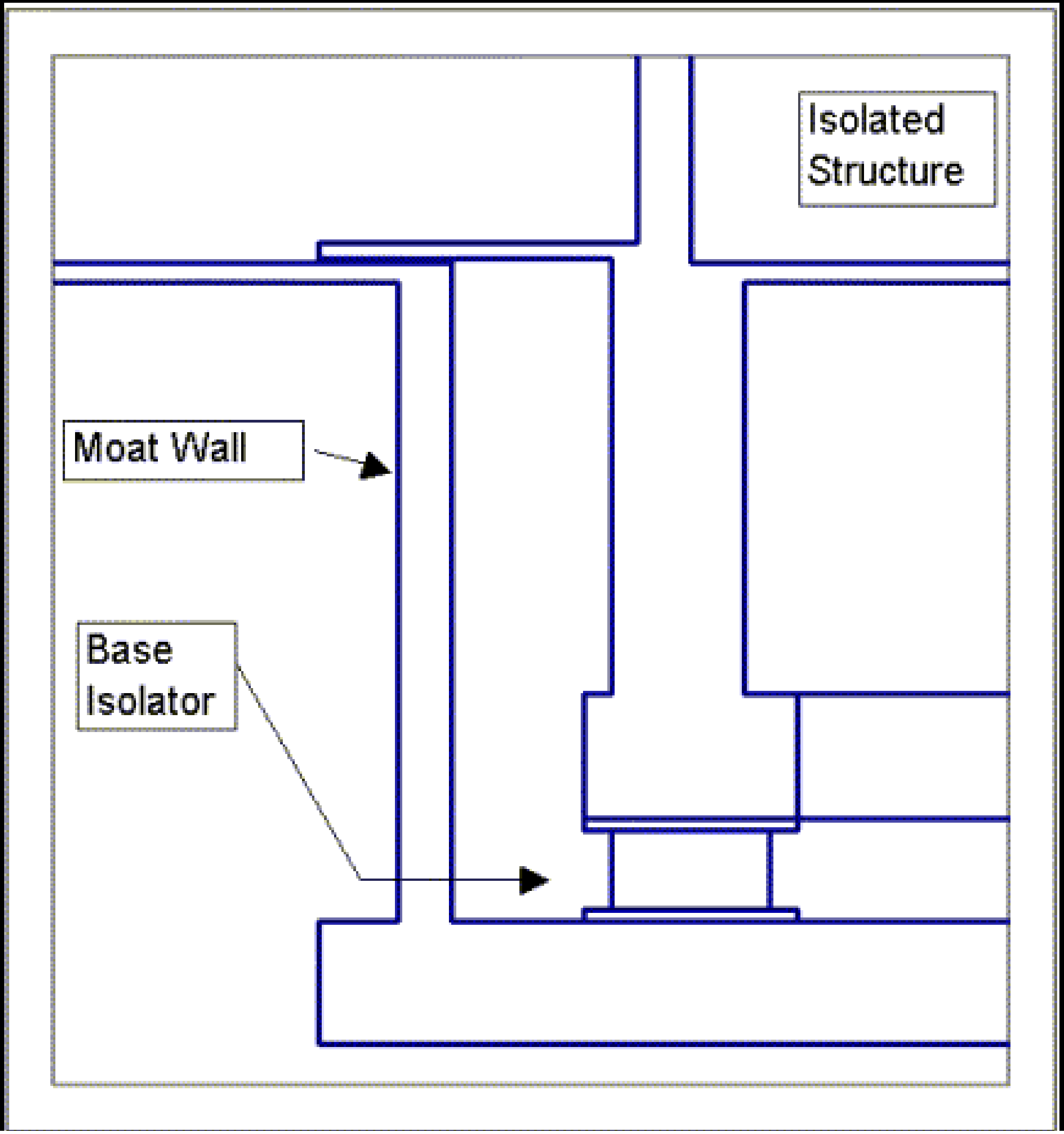
Behavior of Base Isolated Building at Moat

(Excel Based Animation.)



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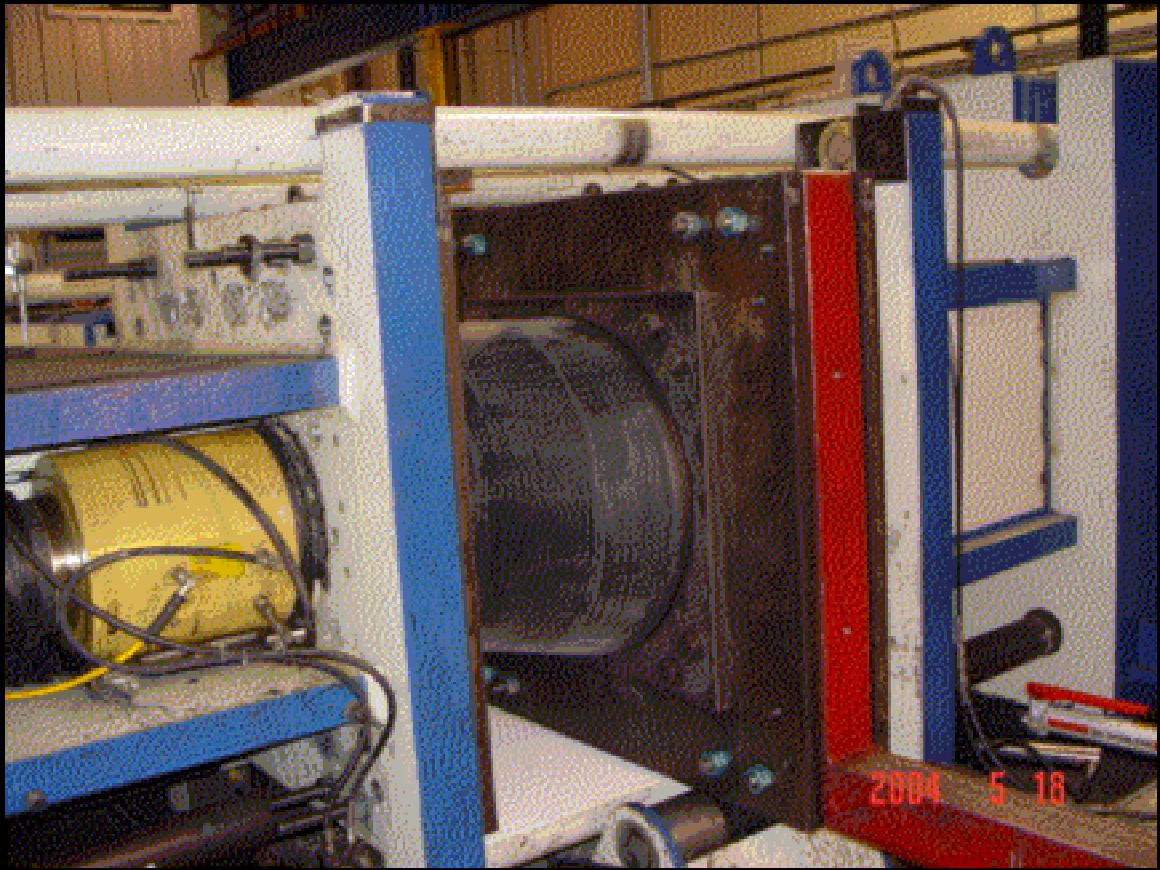
Isolator Prototype Testing



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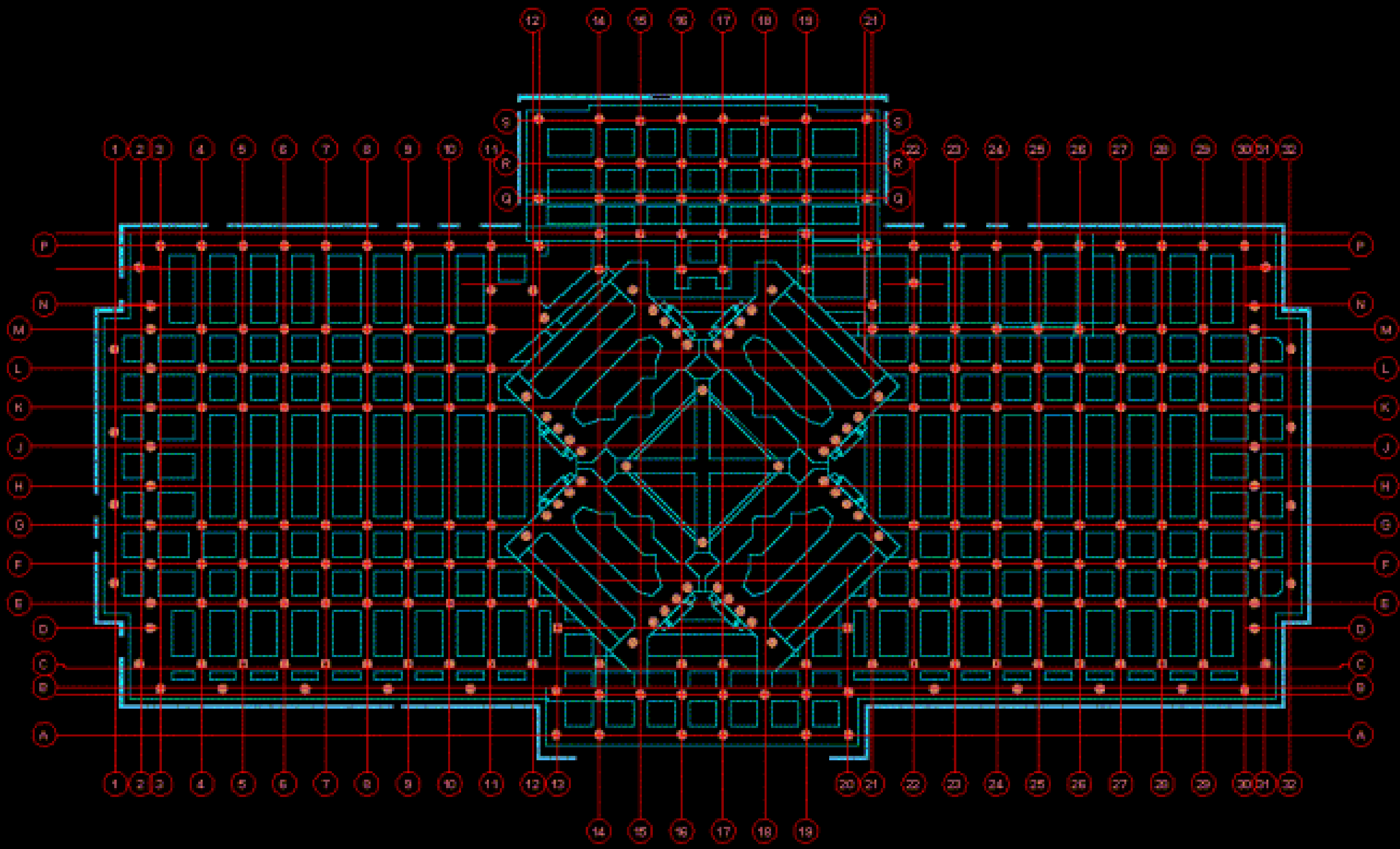
Isolator Plan



265 Isolators

15 Sliders

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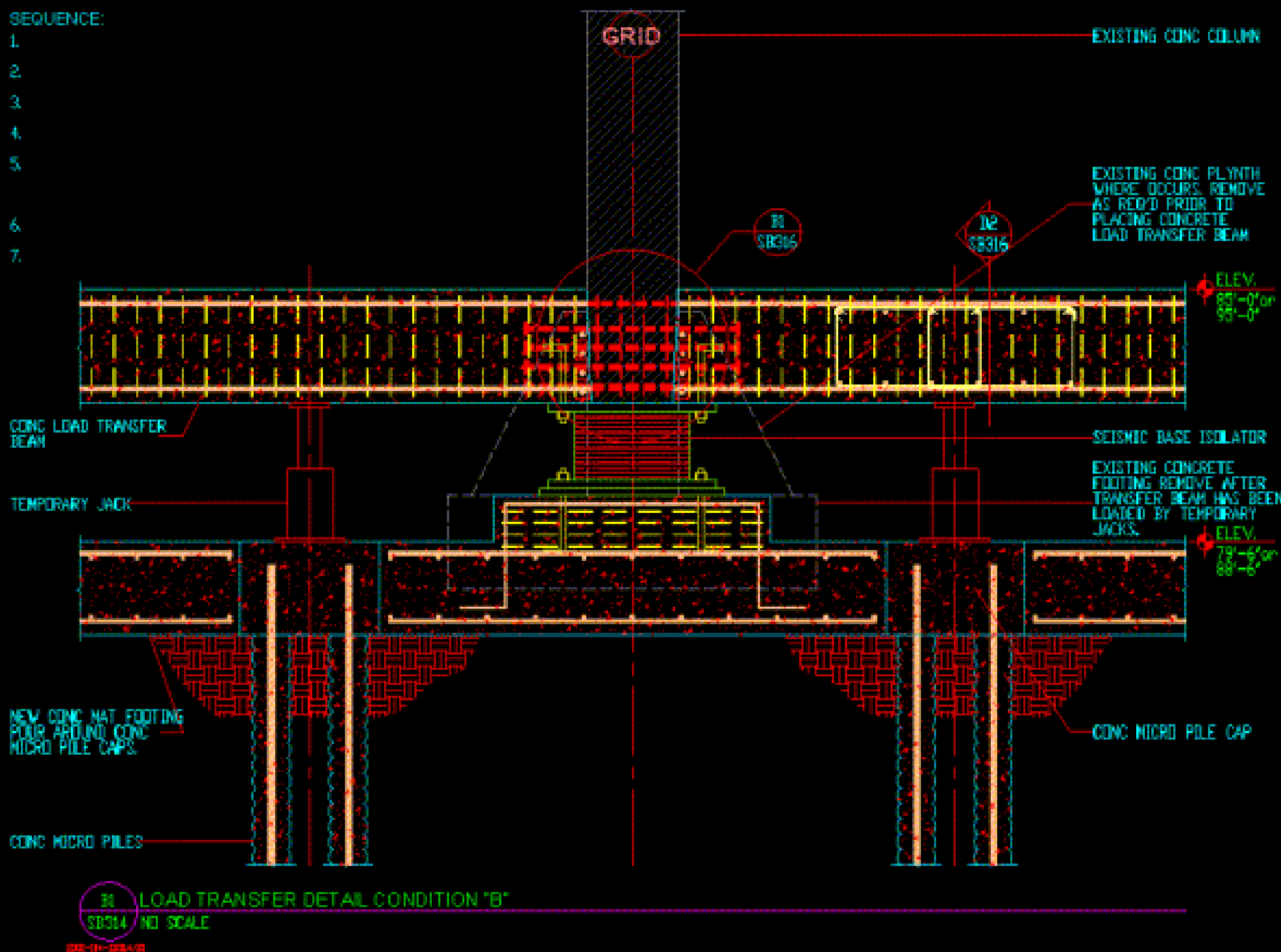
Load Transfer Scheme(s)



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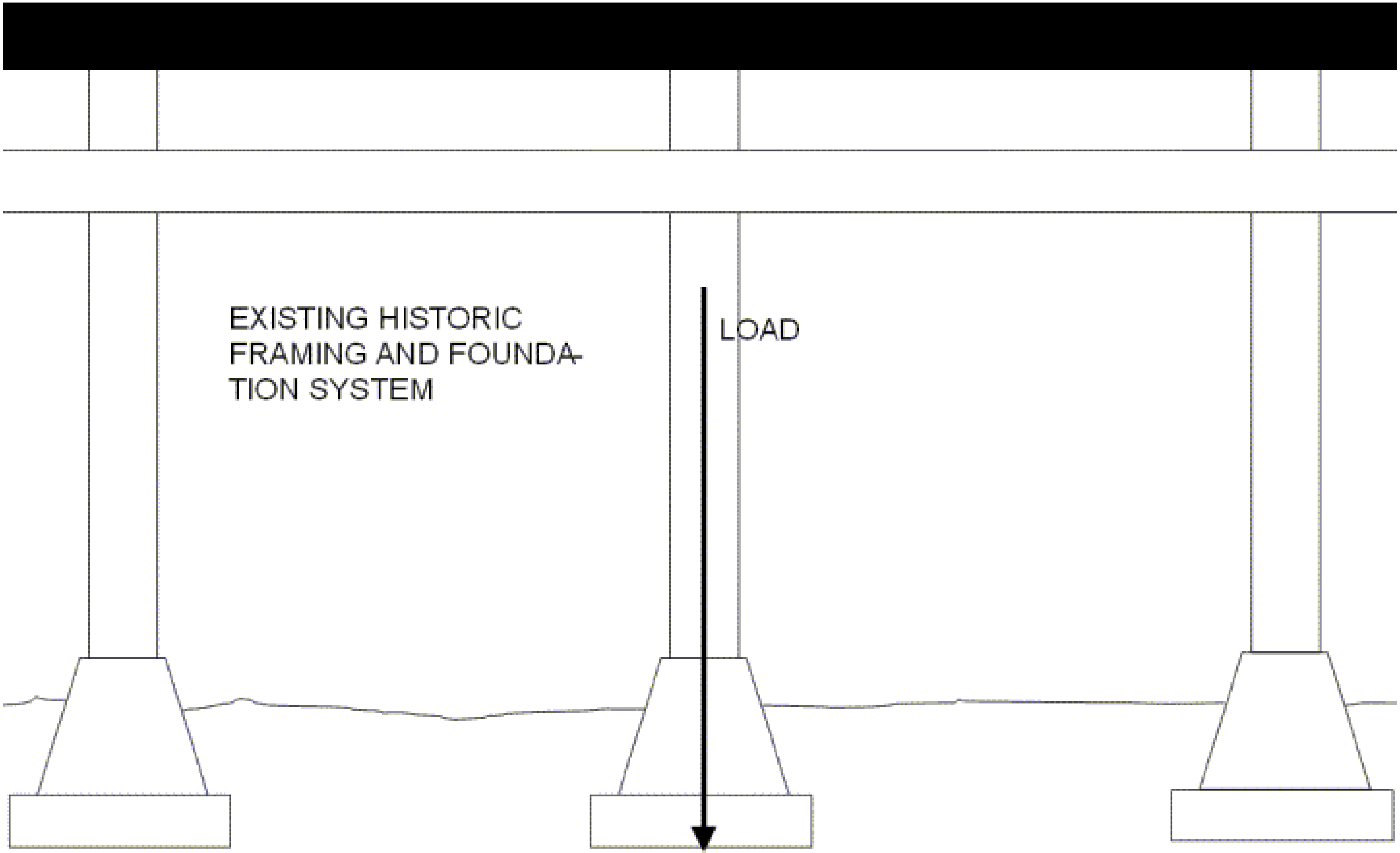
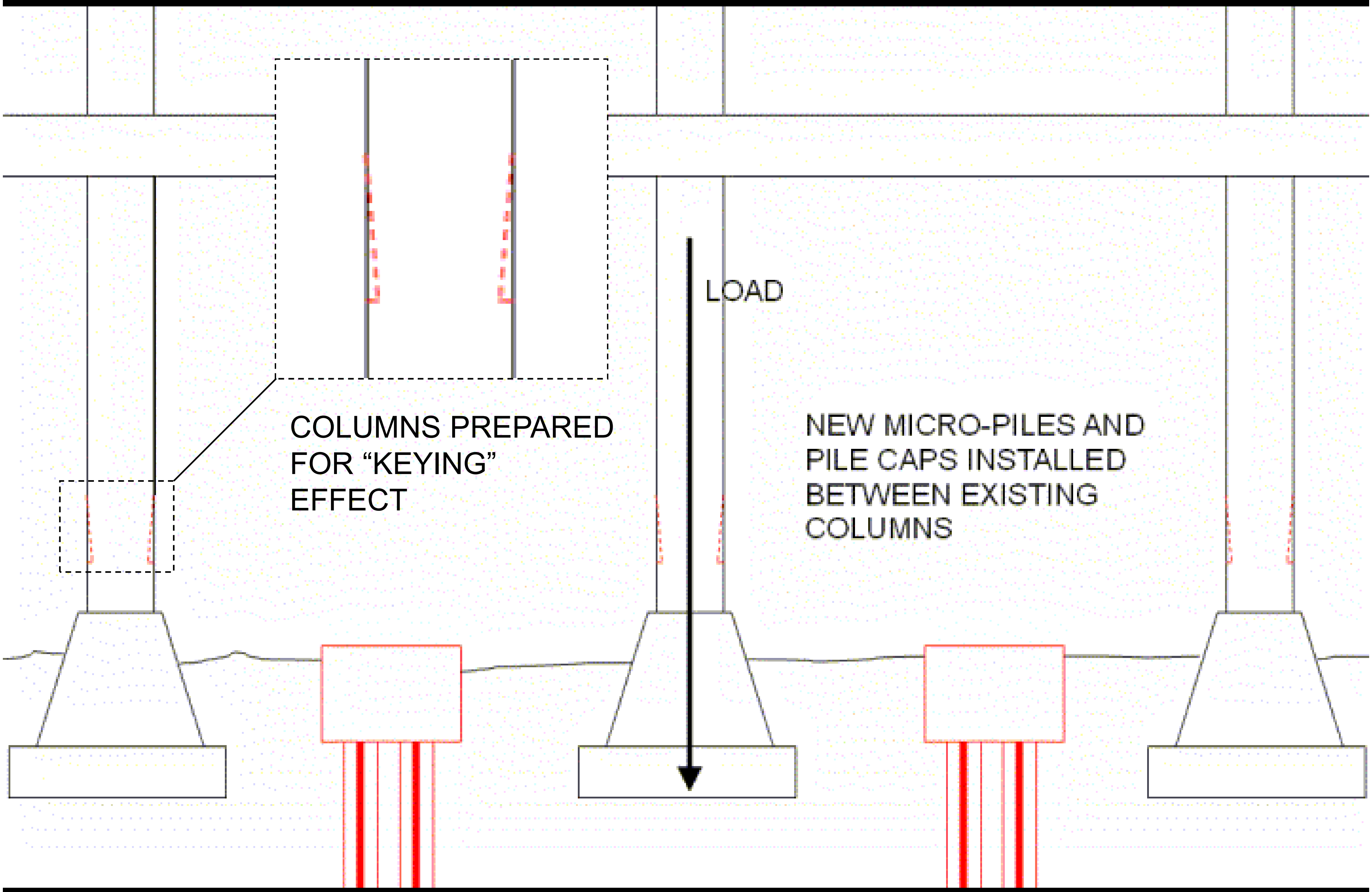
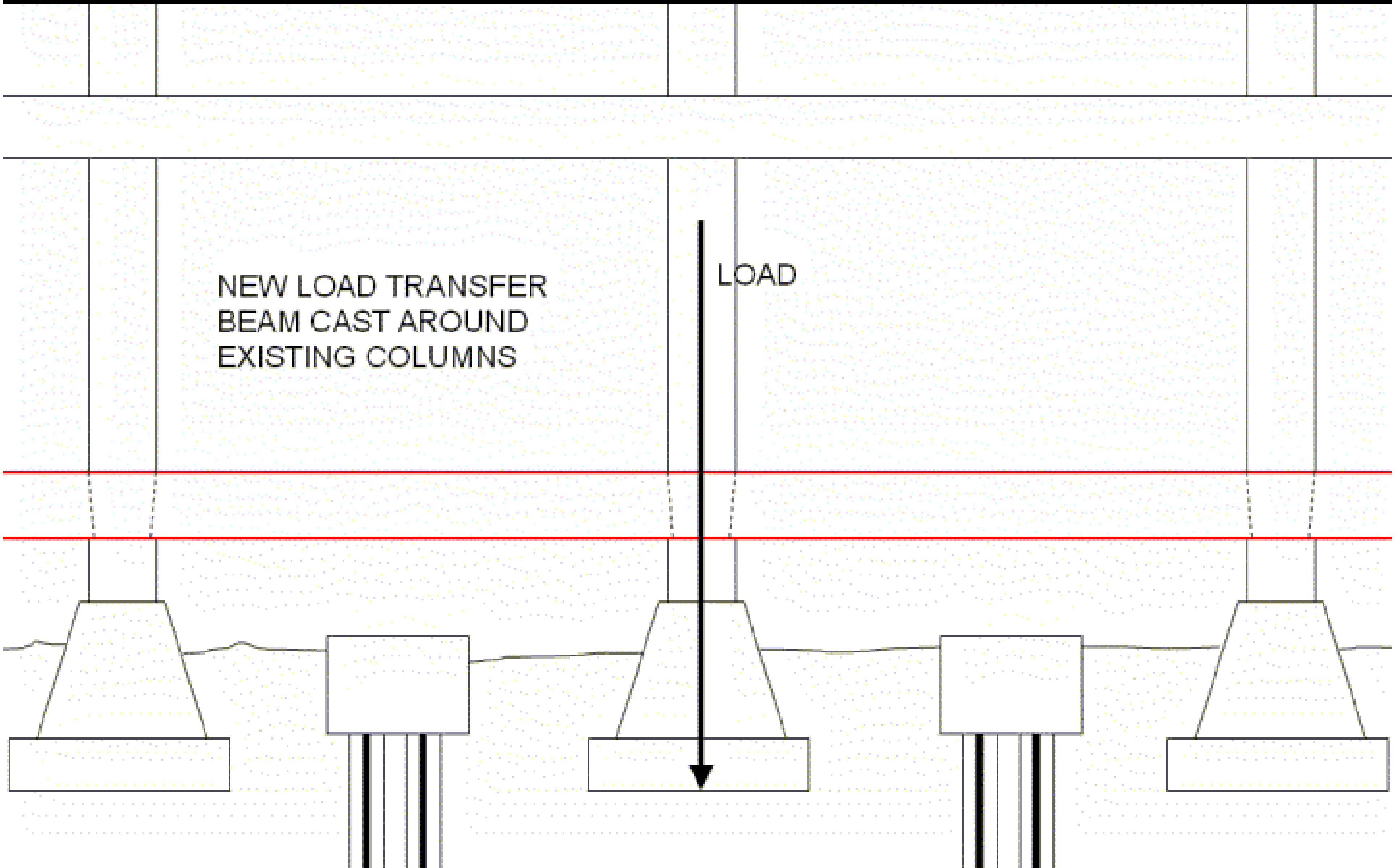
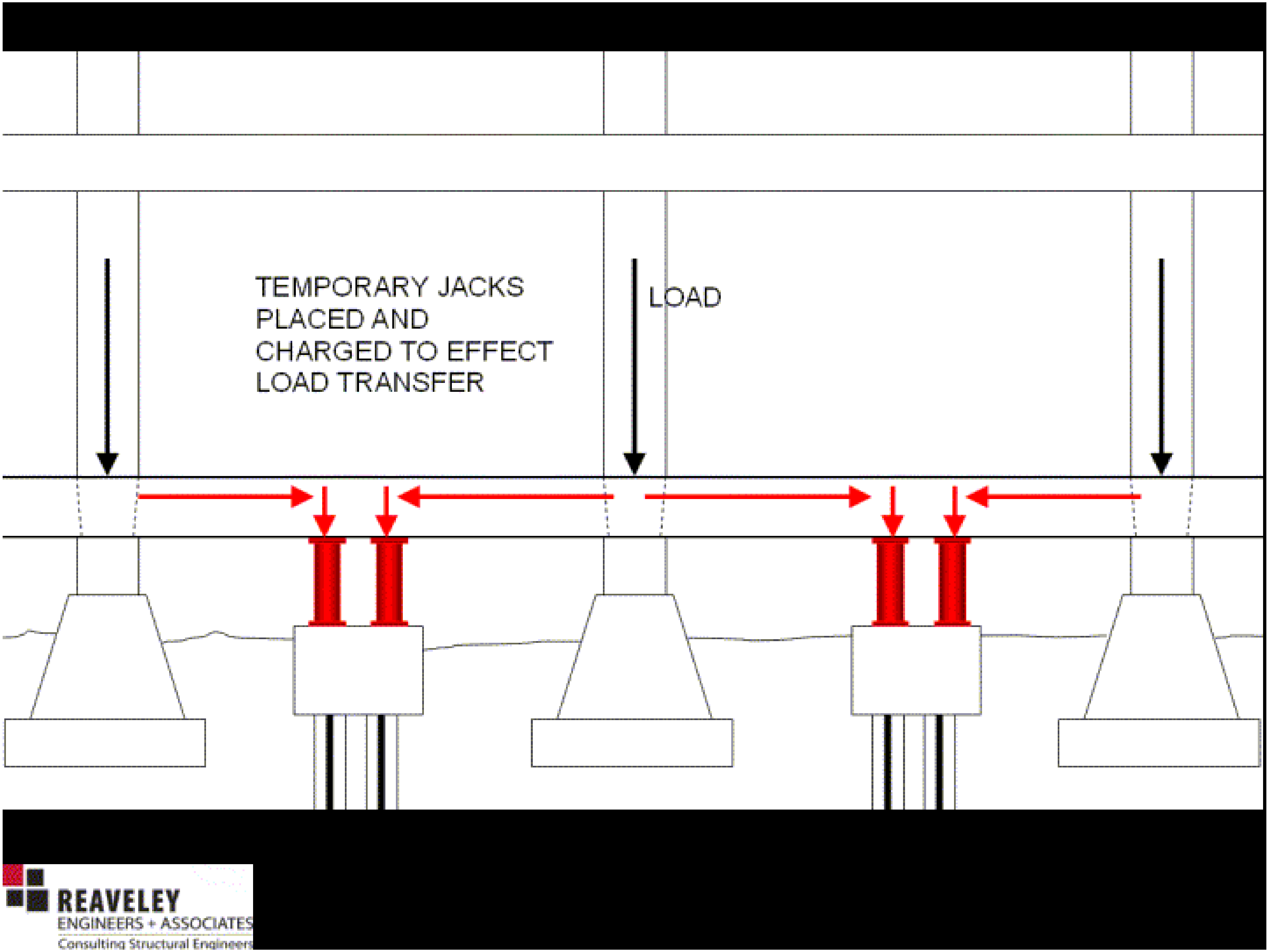

EXISTING HISTORIC
FRAMING AND FOUNDA-
TION SYSTEM
LOAD



LOAD
COLUMNS PREPARED FOR “KEYING” EFFECT
NEW MICRO-PILES AND PILE CAPS INSTALLED BETWEEN EXISTING COLUMNS


NEW LOAD TRANSFER
BEAM CAST AROUND
EXISTING COLUMNS
LOAD


TEMPORARY JACKS
PLACED AND
CHARGED TO EFFECT
LOAD TRANSFER
LOAD
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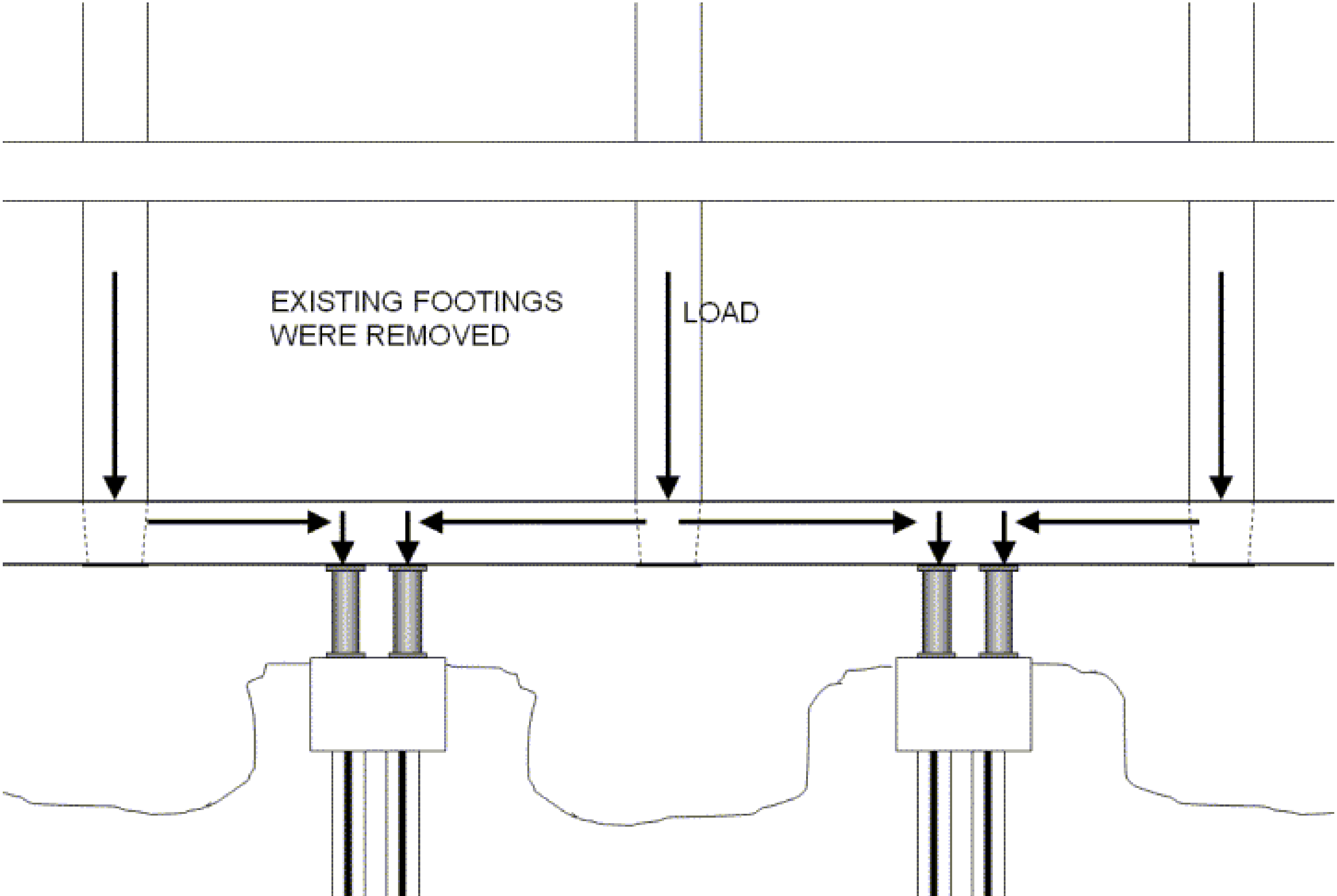

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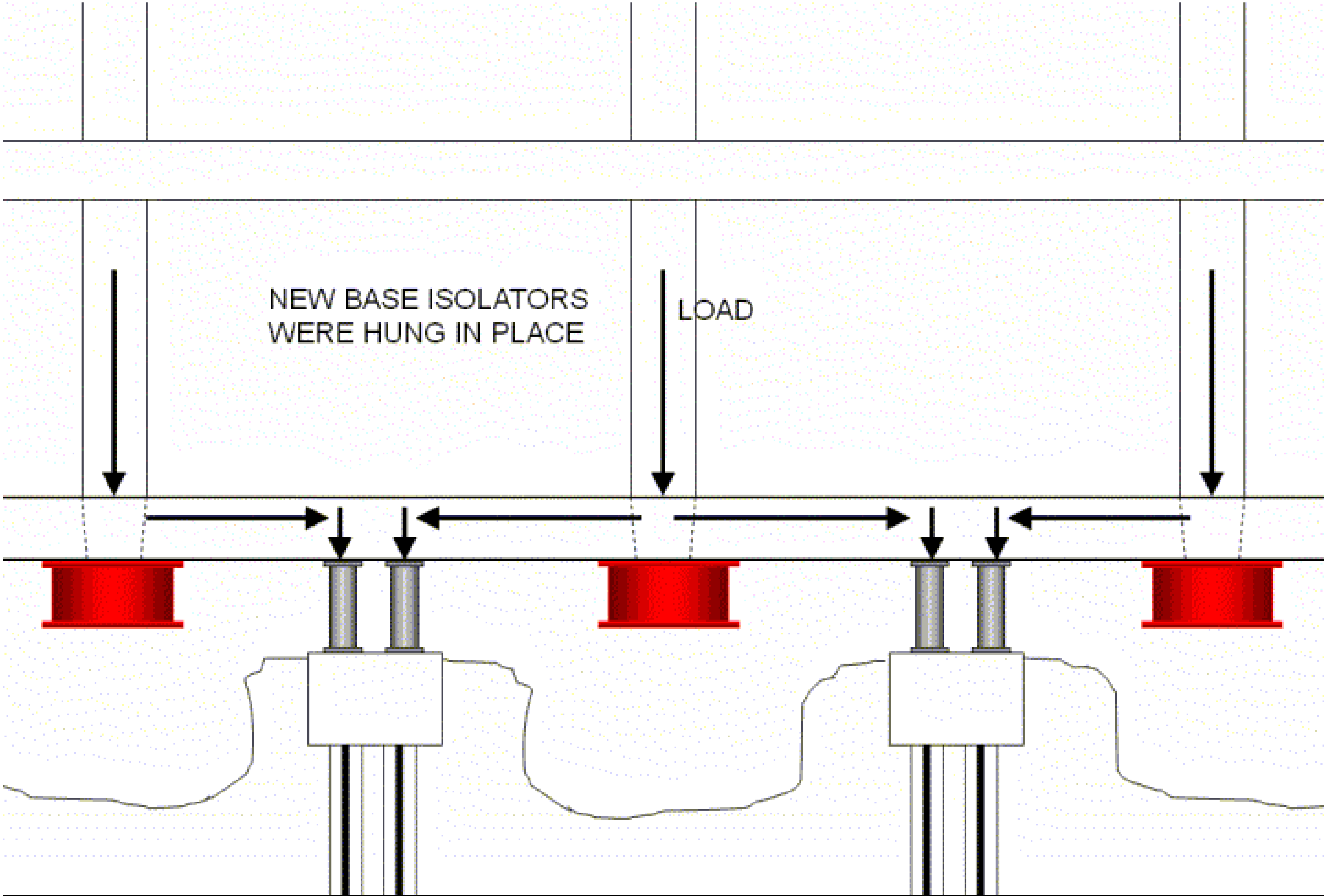

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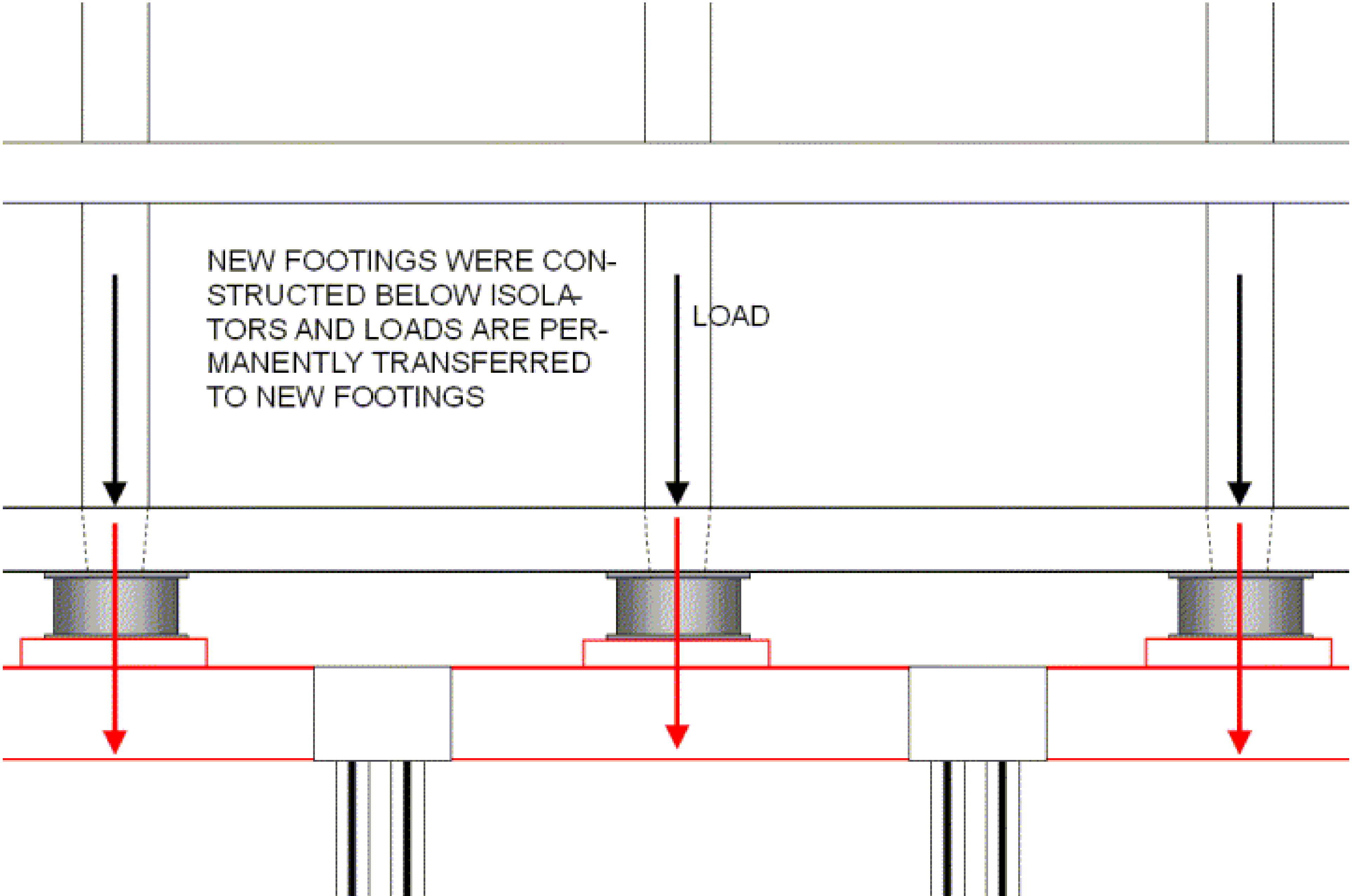

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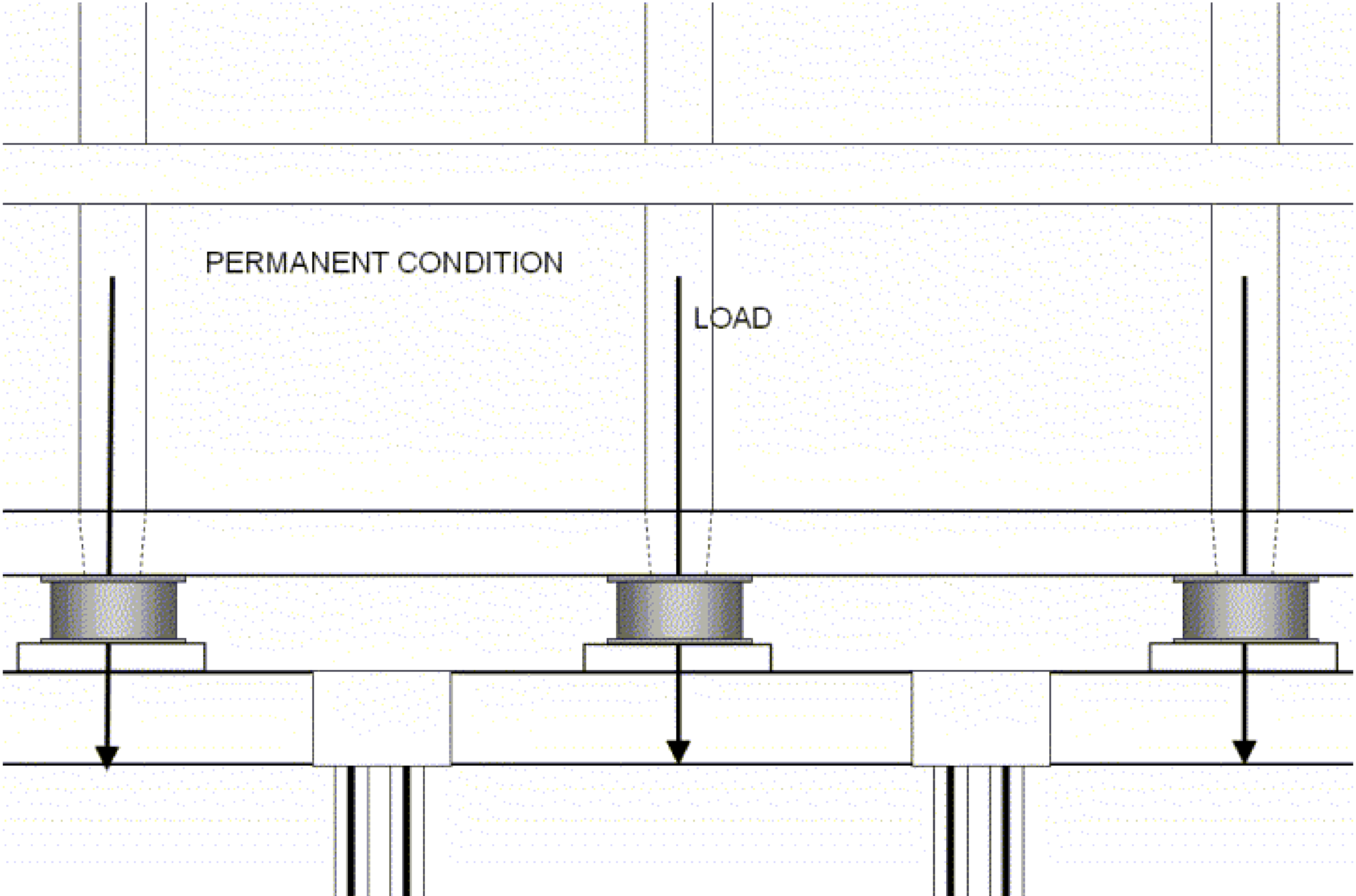

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Footing Removal

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Installation of First Isolator – May 16, 2005

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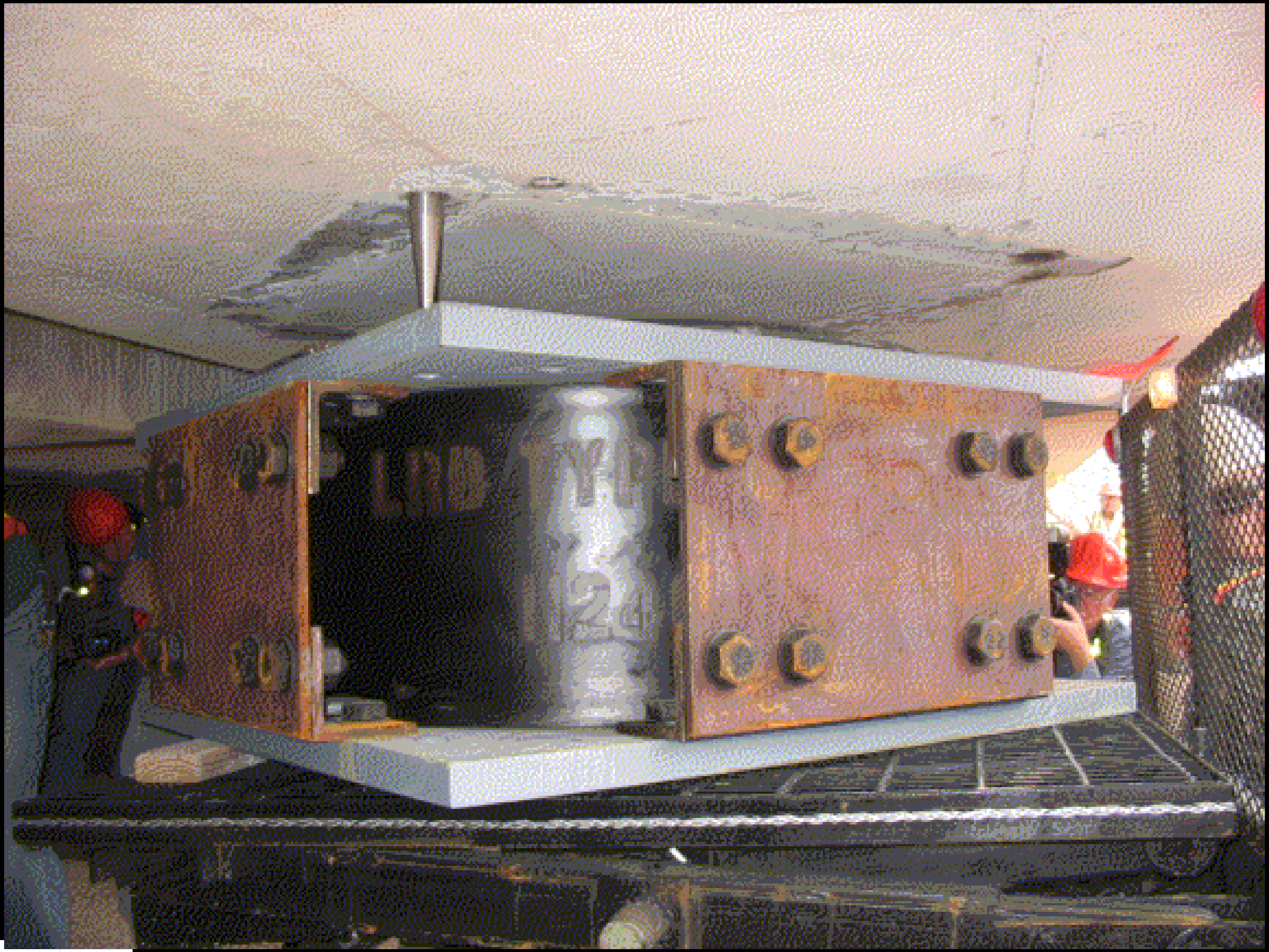
Isolator Placement



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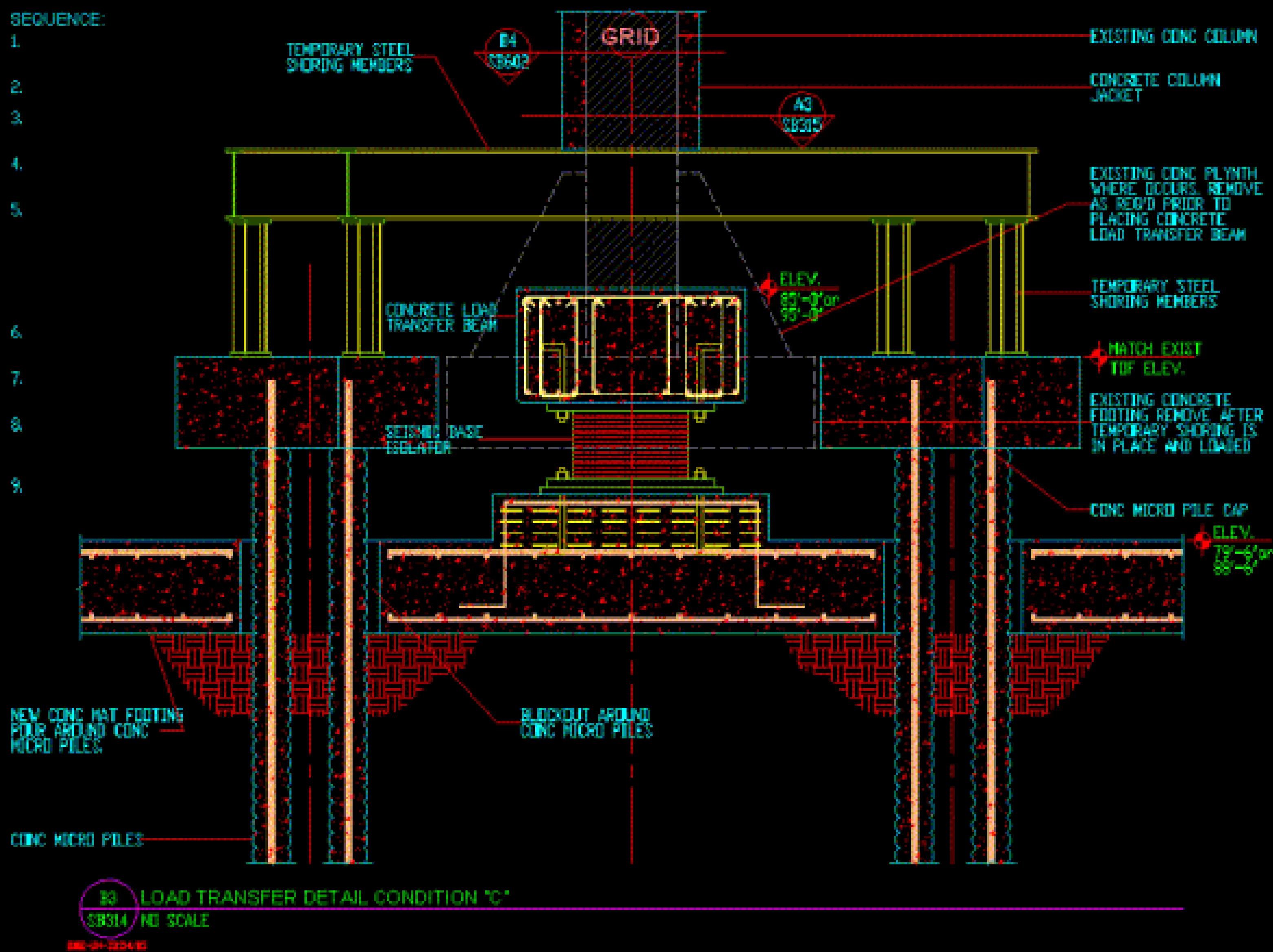
Load Transfer Scheme(s)



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Load Transfer Scheme(s)

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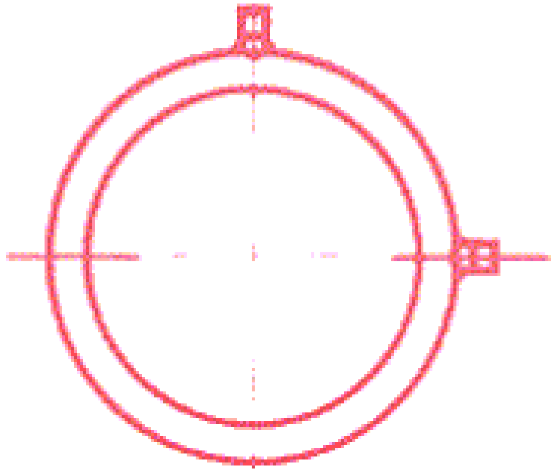
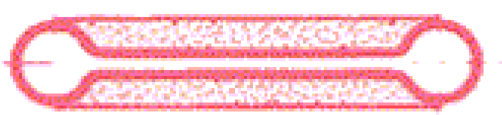
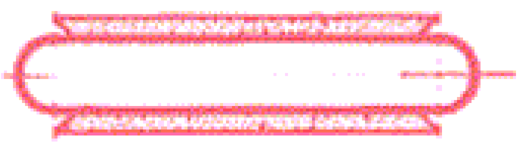
Load Transfer Mechanism

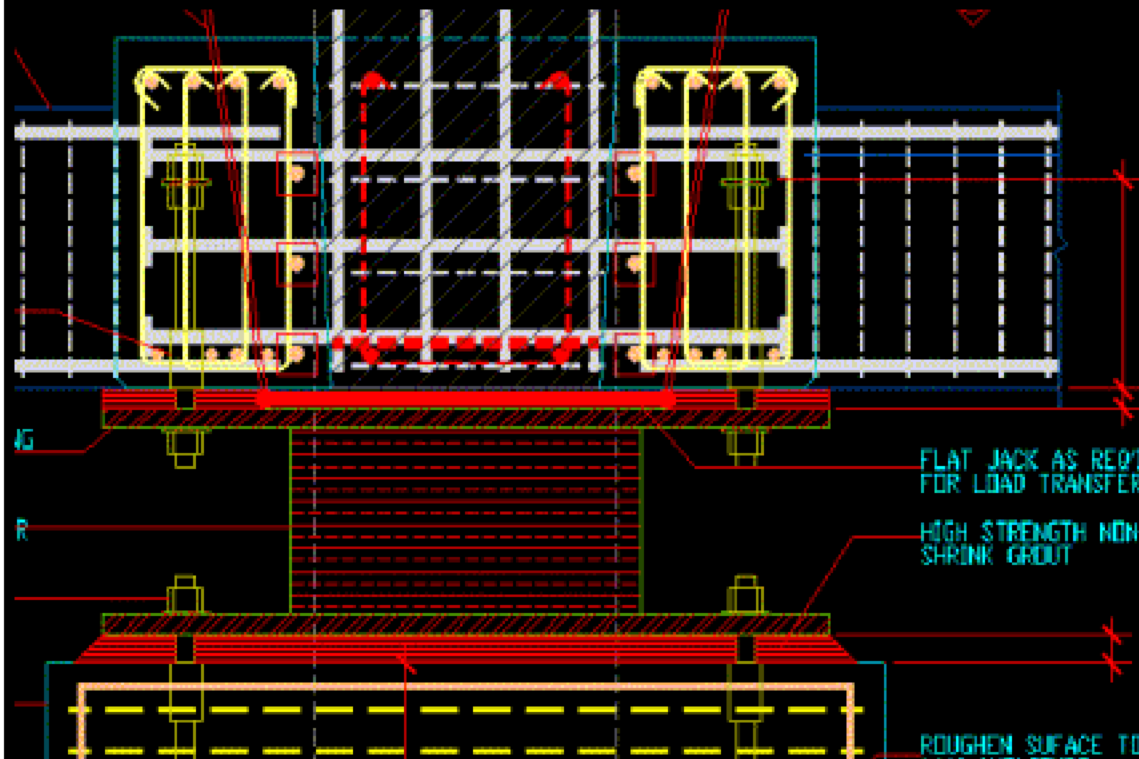




Before Pressurizing



After Pressurizing



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Load Transfer Scheme(s)

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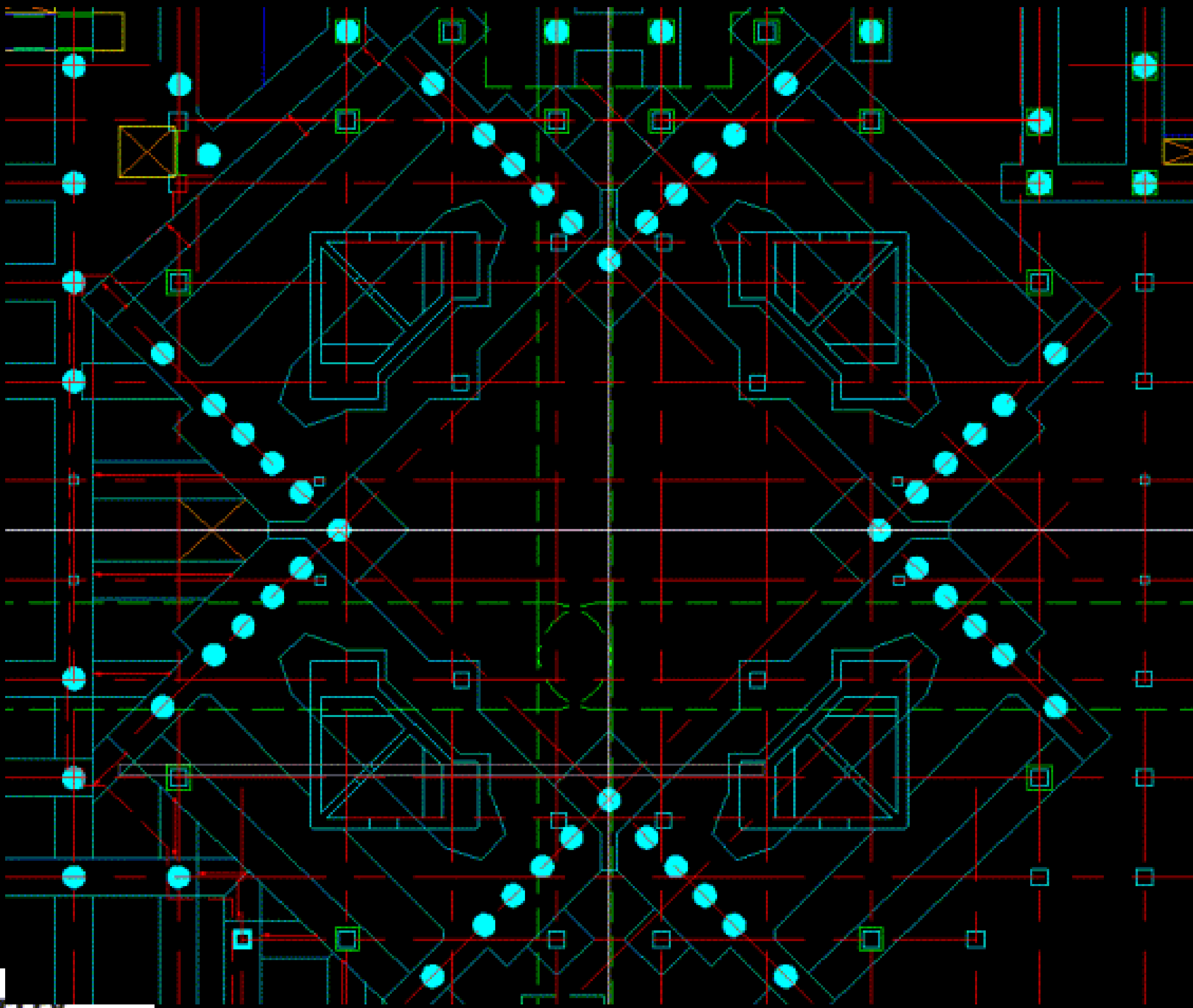

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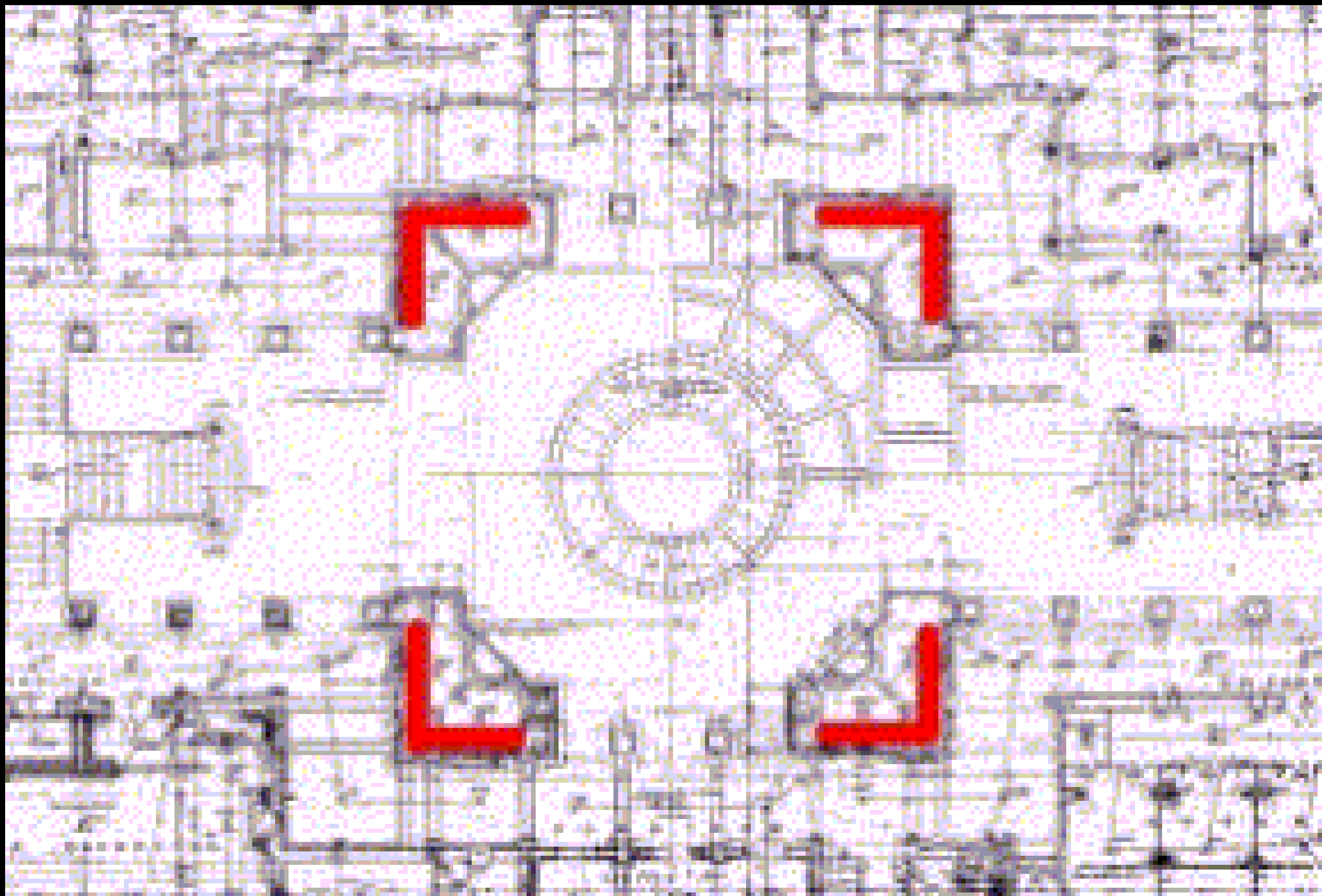
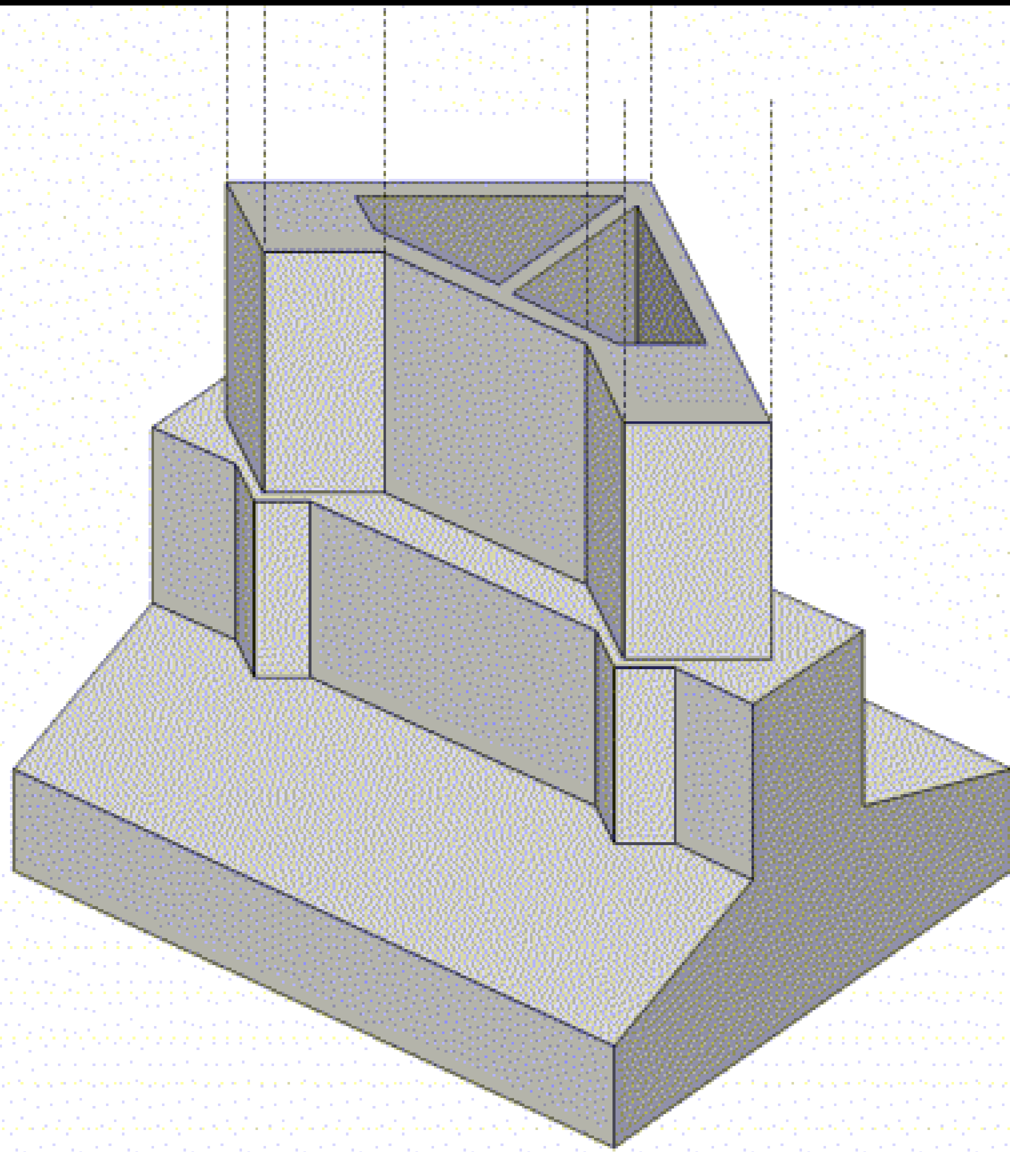
Isolator Installation at Rotunda



Isolator Installation at Rotunda



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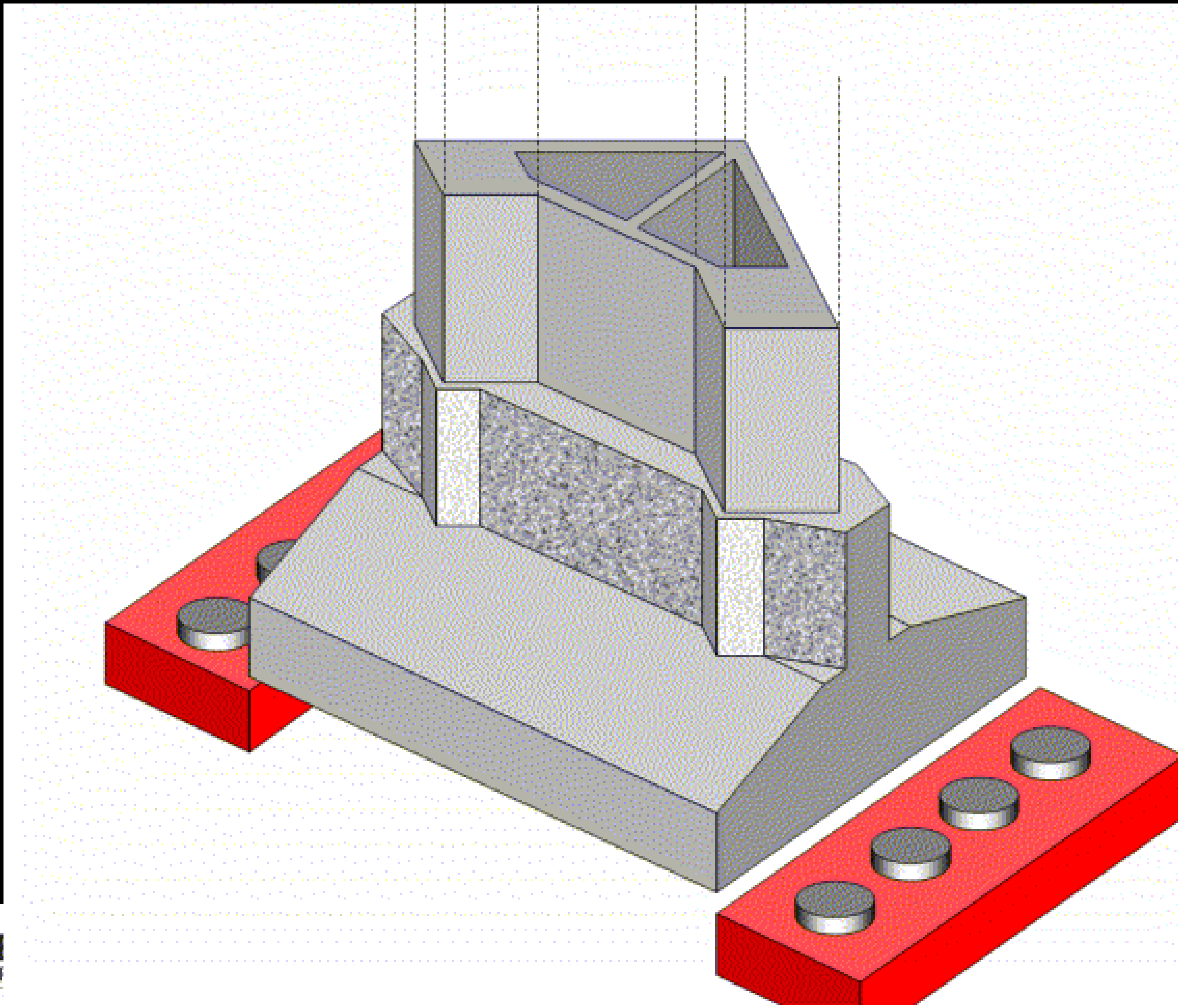
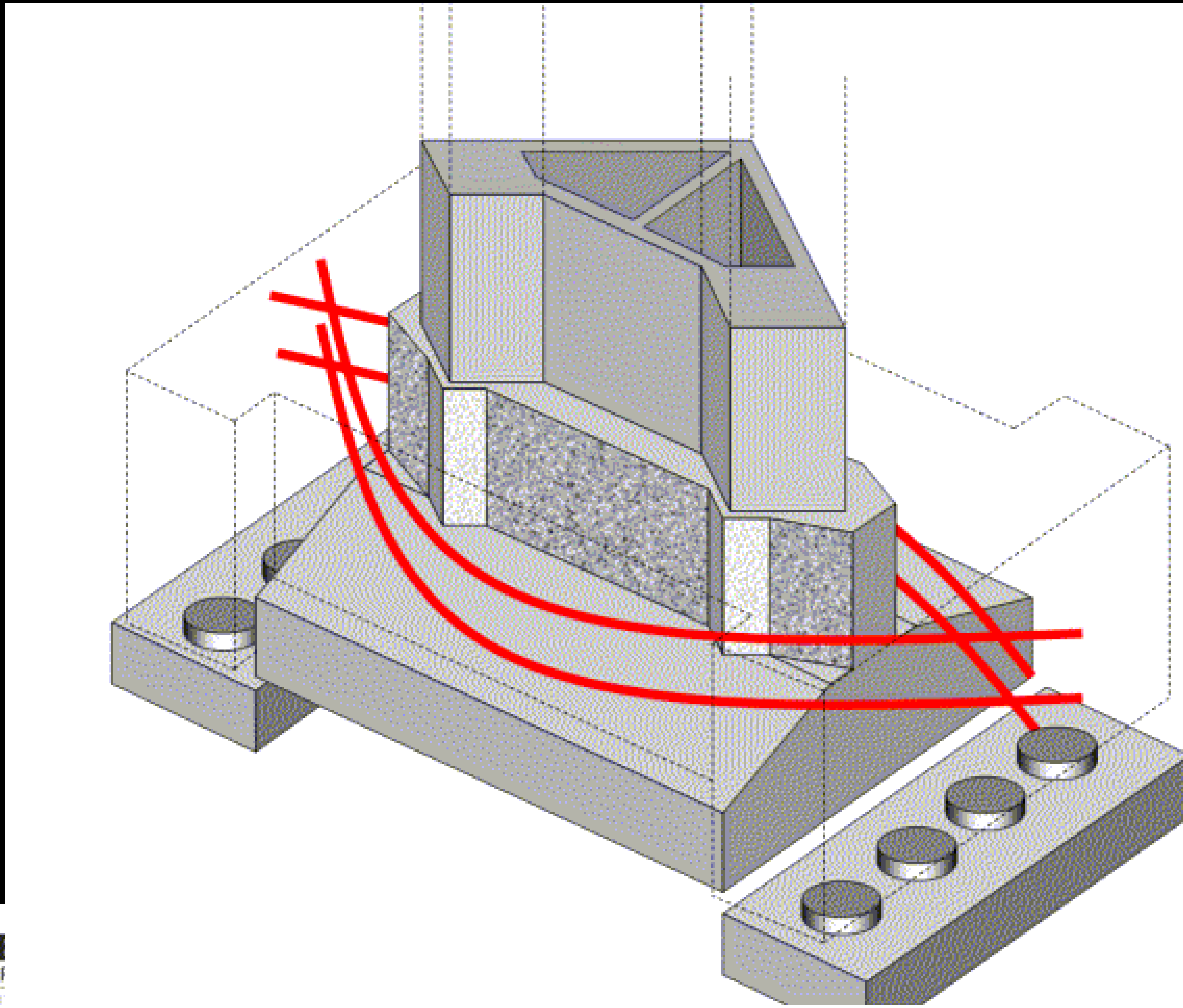
Isolator Installation at Rotunda



Isolator Installation at Rotunda



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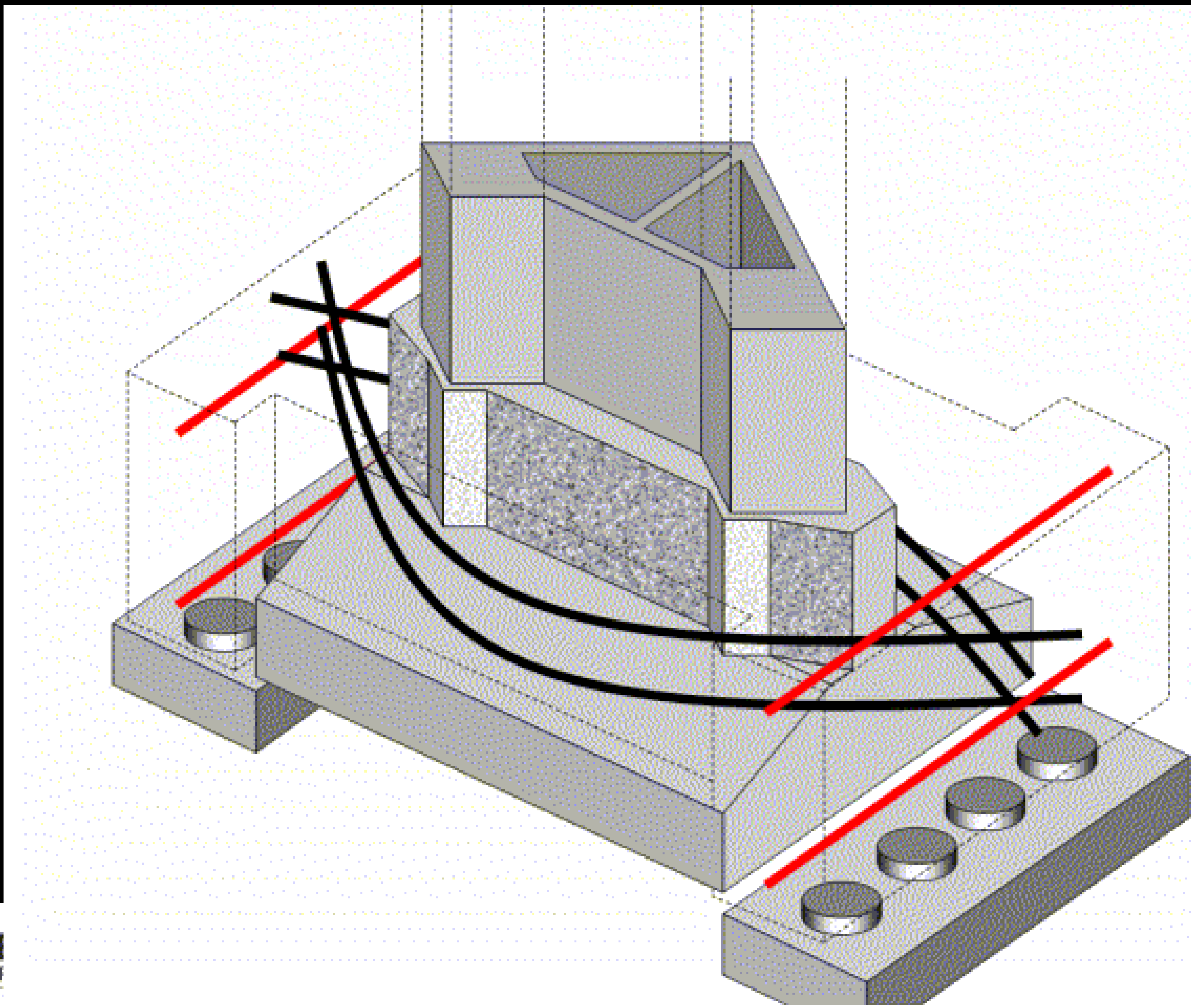
Isolator Installation at Rotunda



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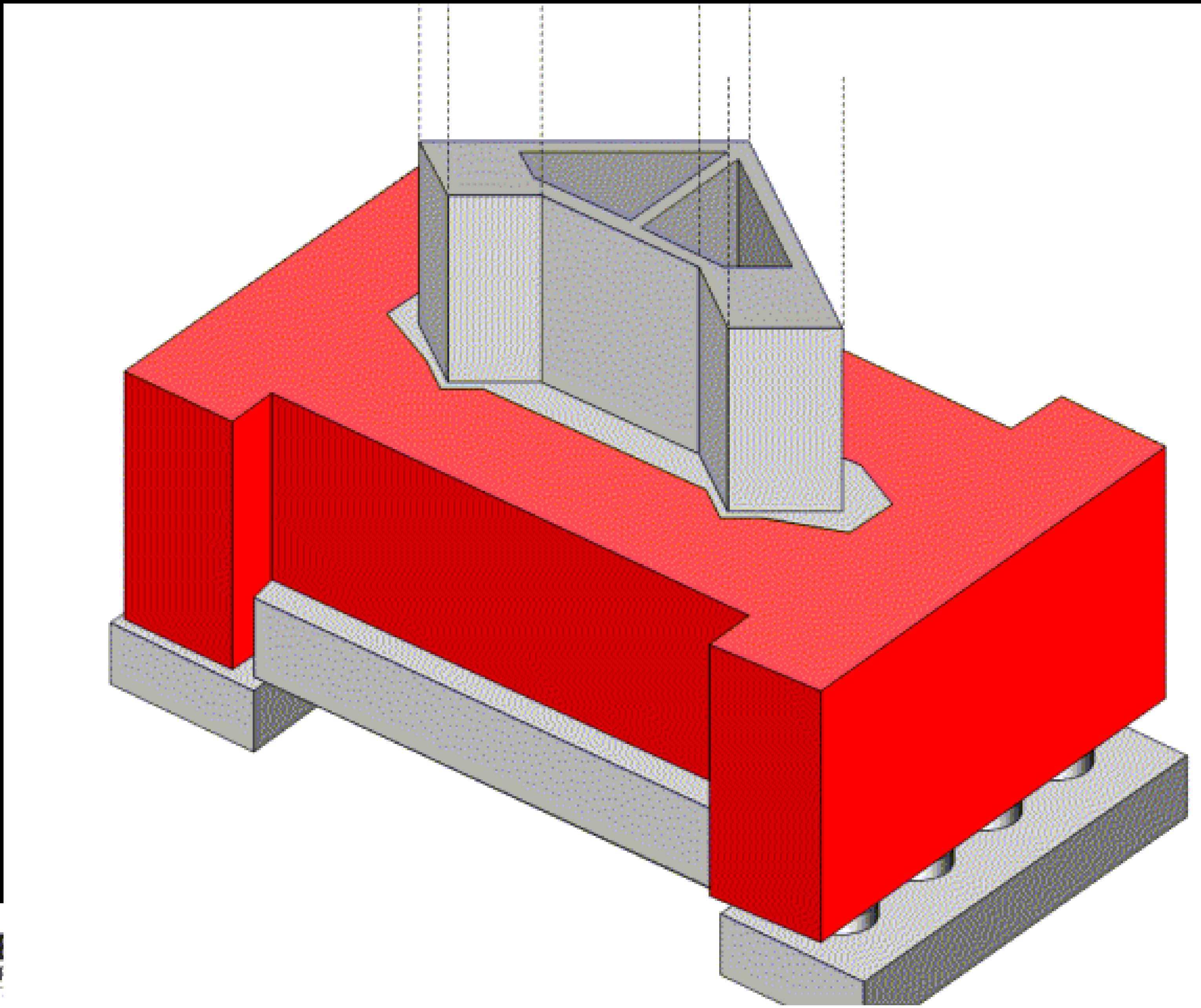
Isolator Installation at Rotunda



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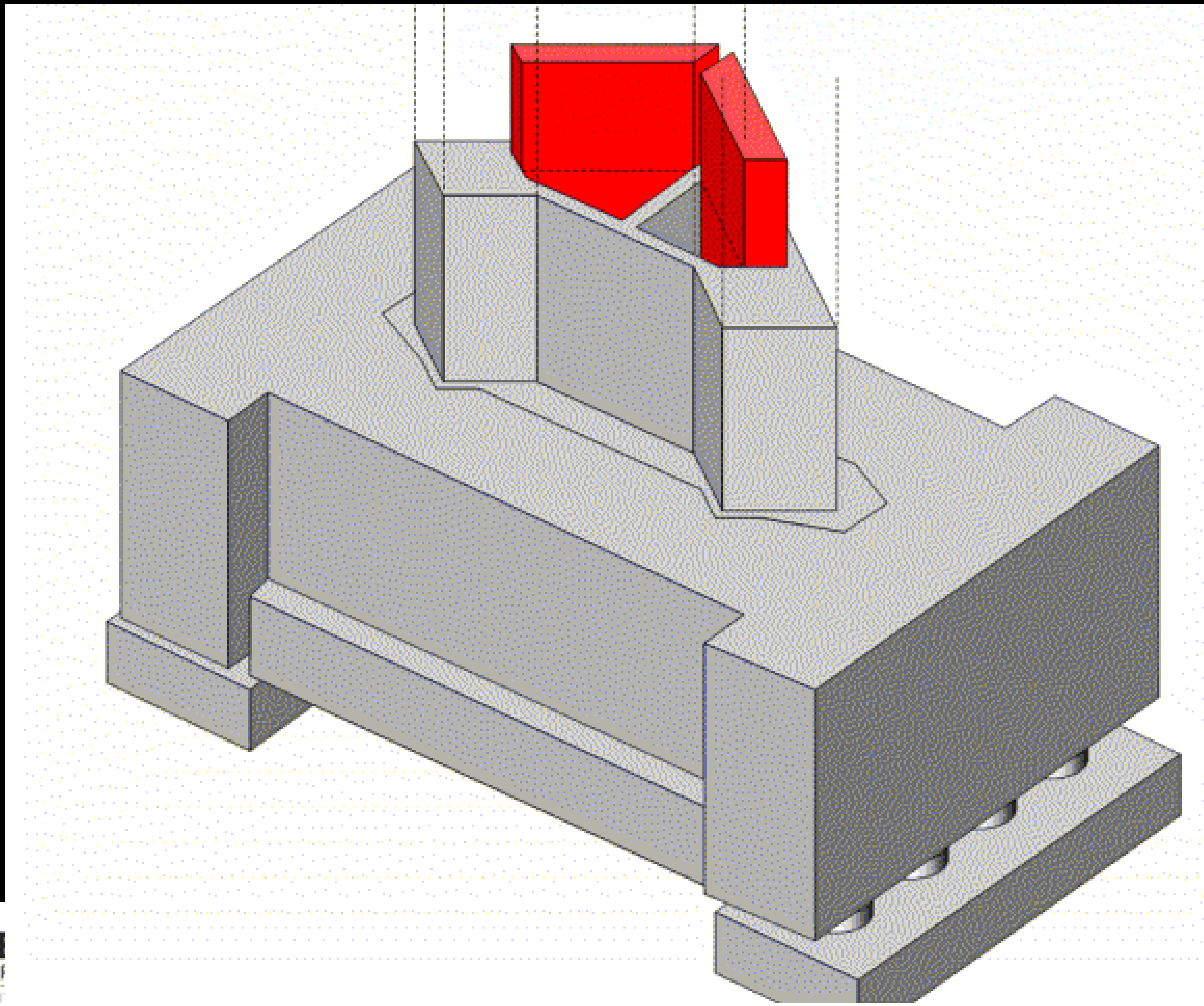
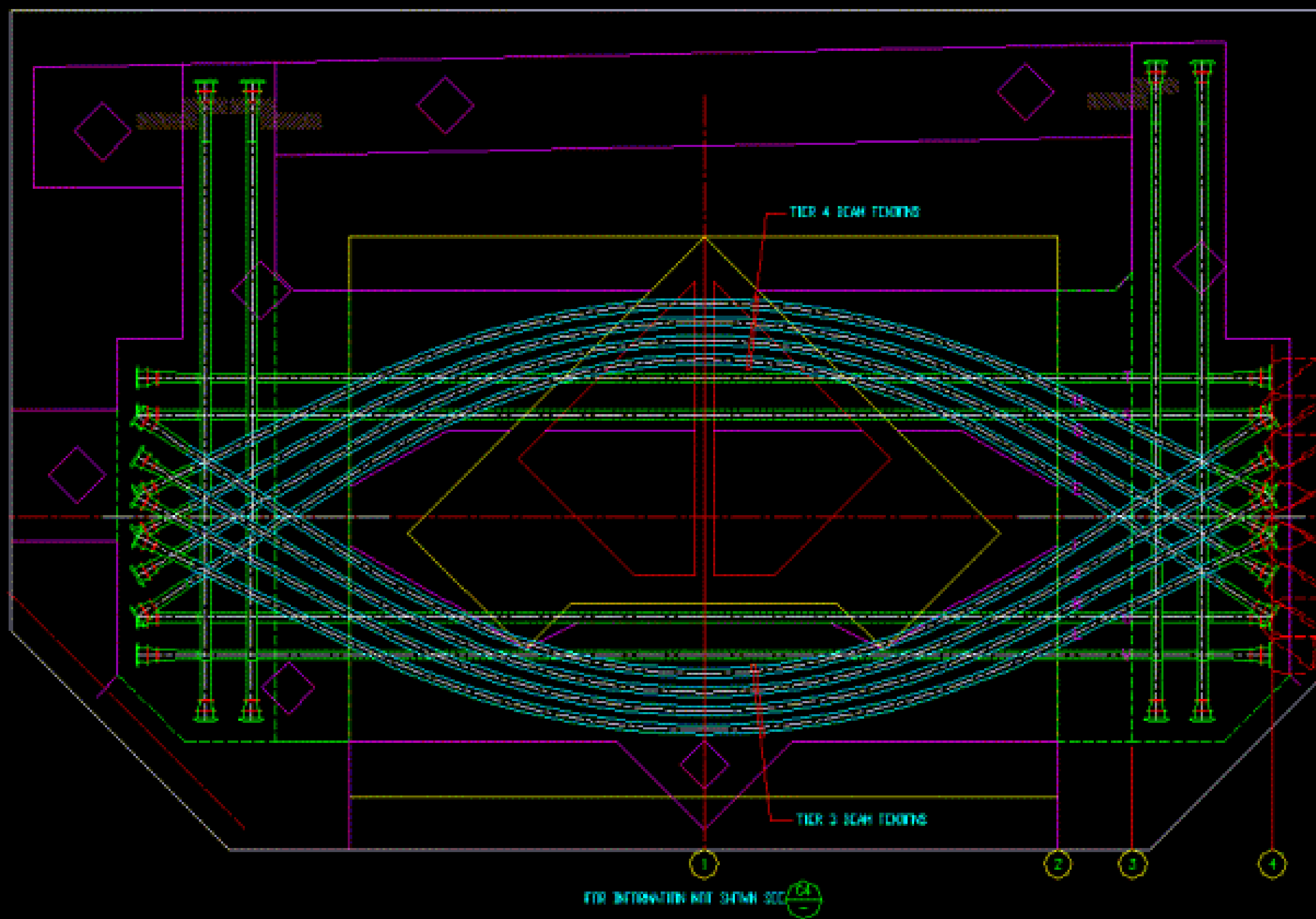
Isolator Installation at Rotunda





A4 TYPICAL BEAM TENDONS - TIERS 3 & 4
1/4" = 1'-0"

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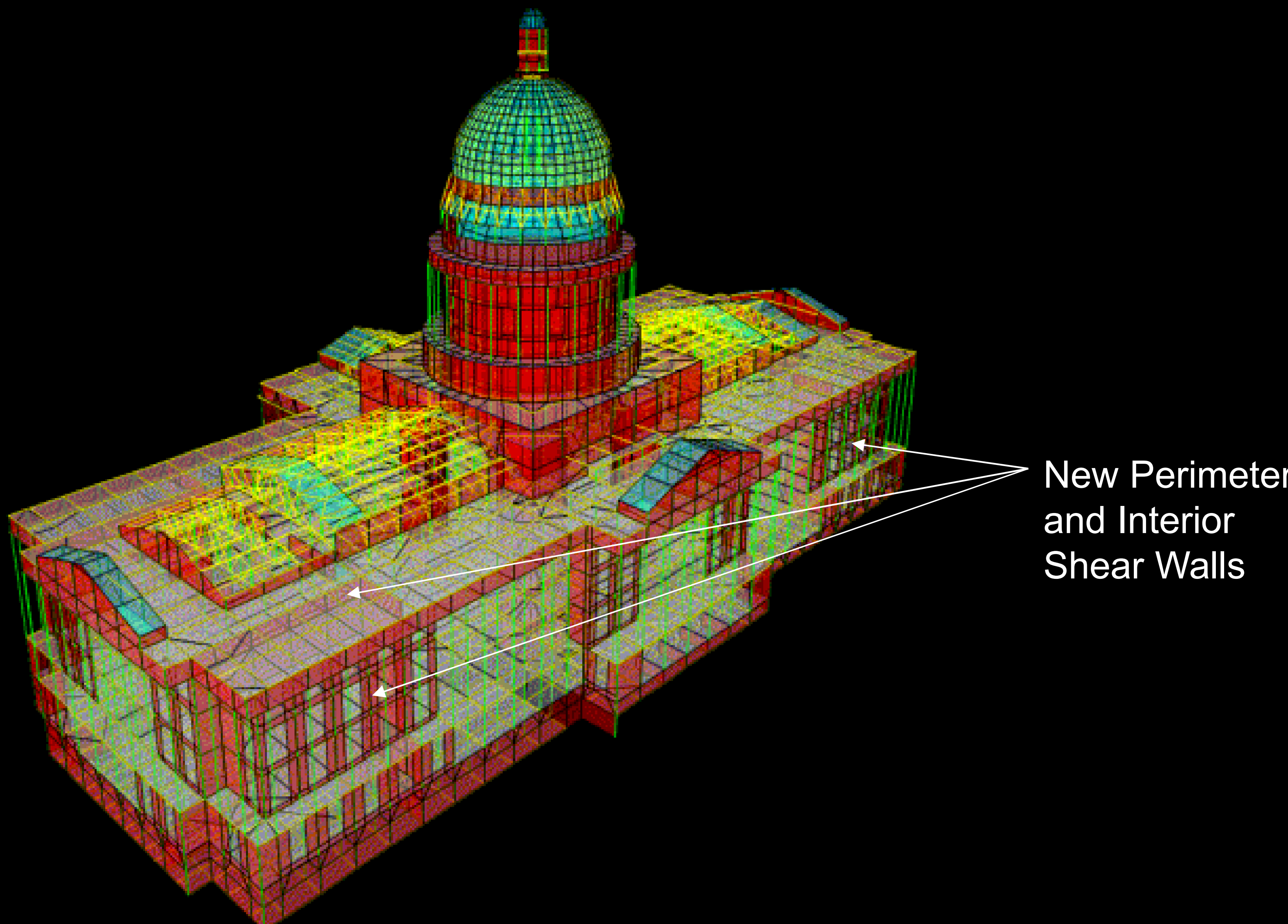

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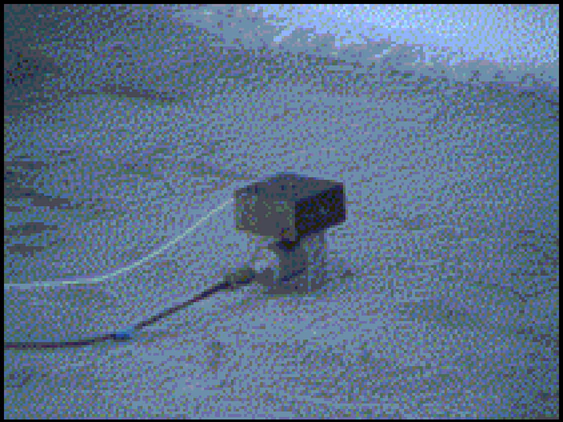
Forced Vibration Testing



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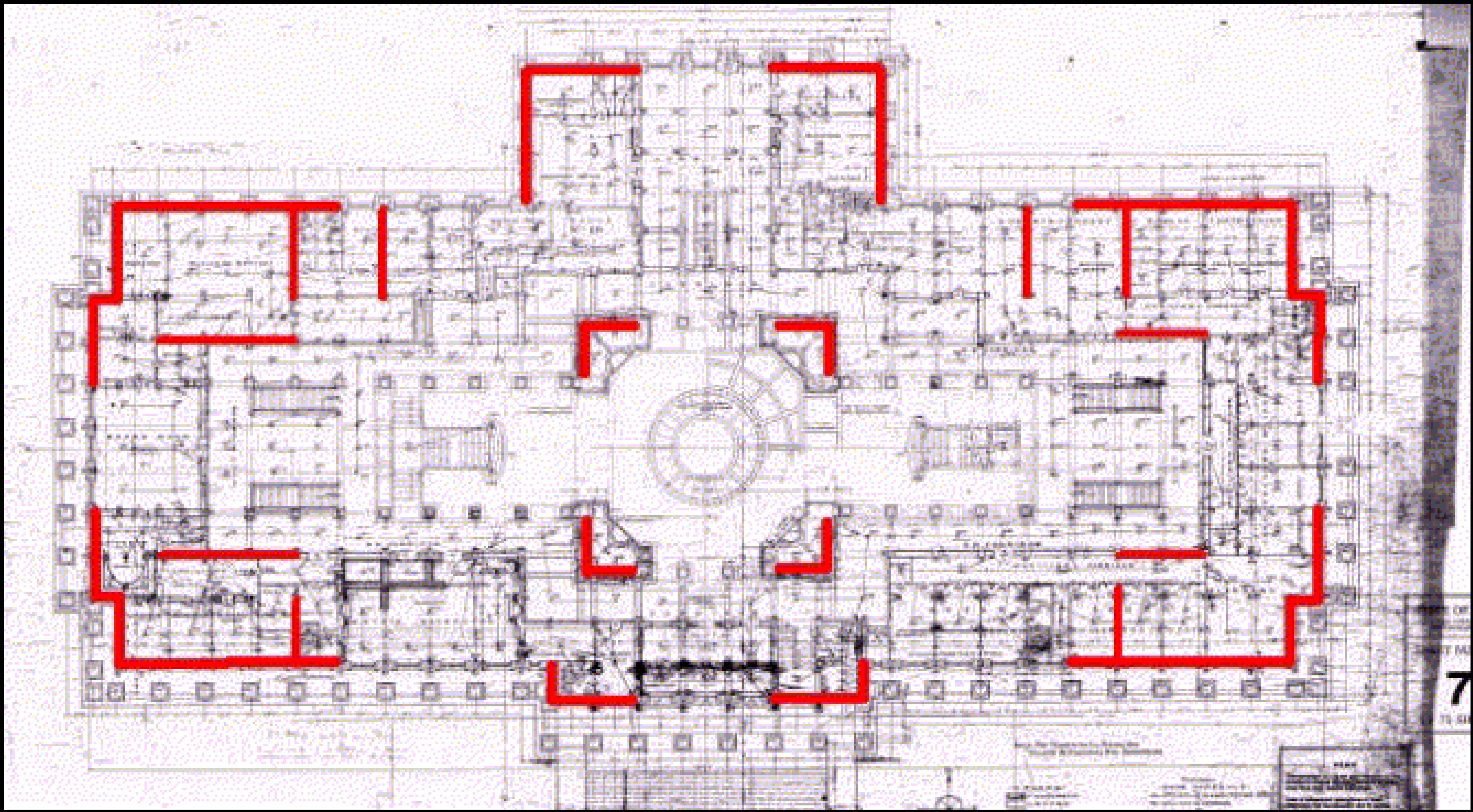
New Shearwall Configuration



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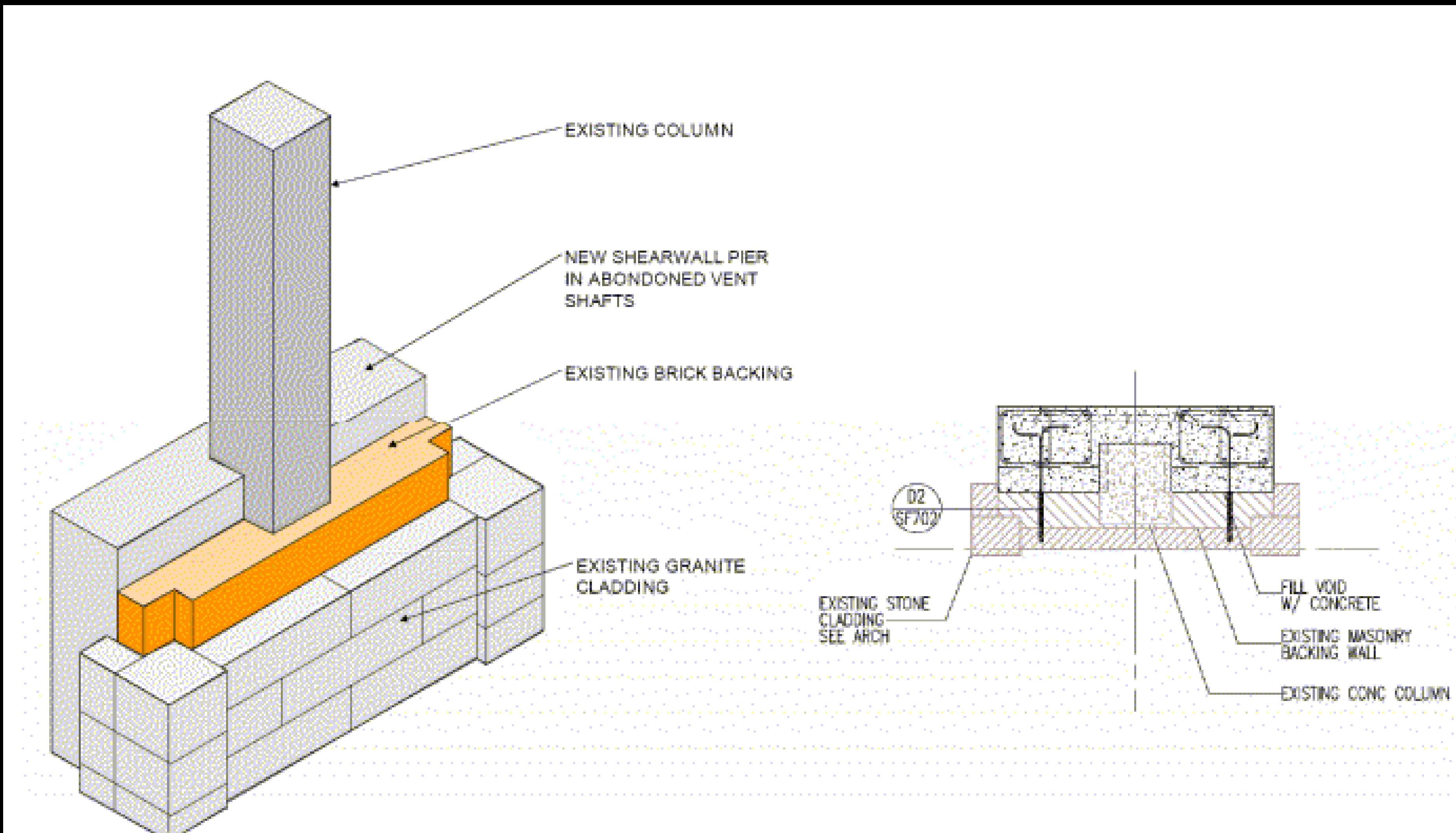
Shear Walls at Perimeter



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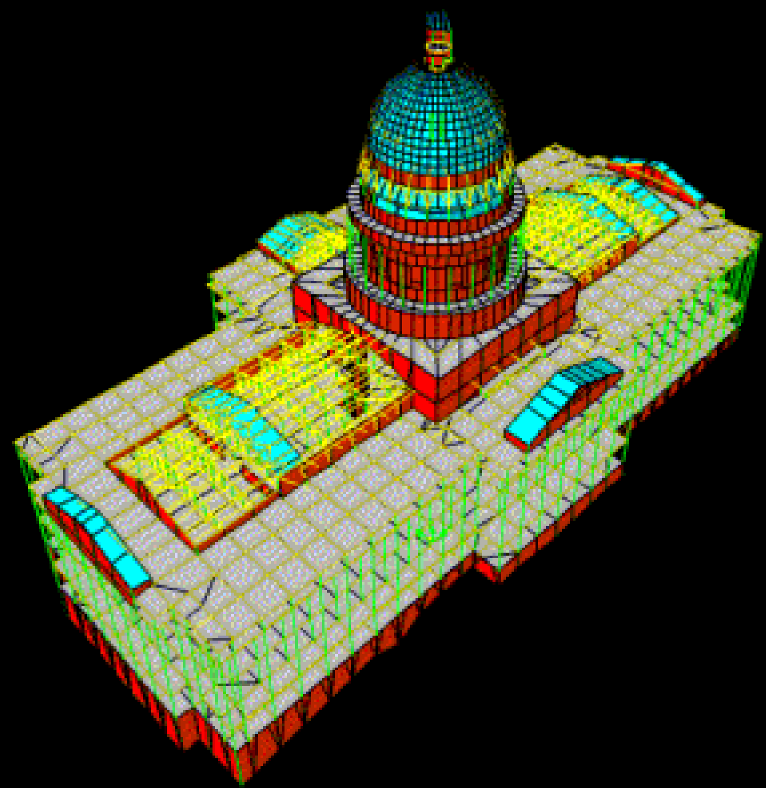
As Is Building Model - 30x Amplification

(Click on image to start animation)



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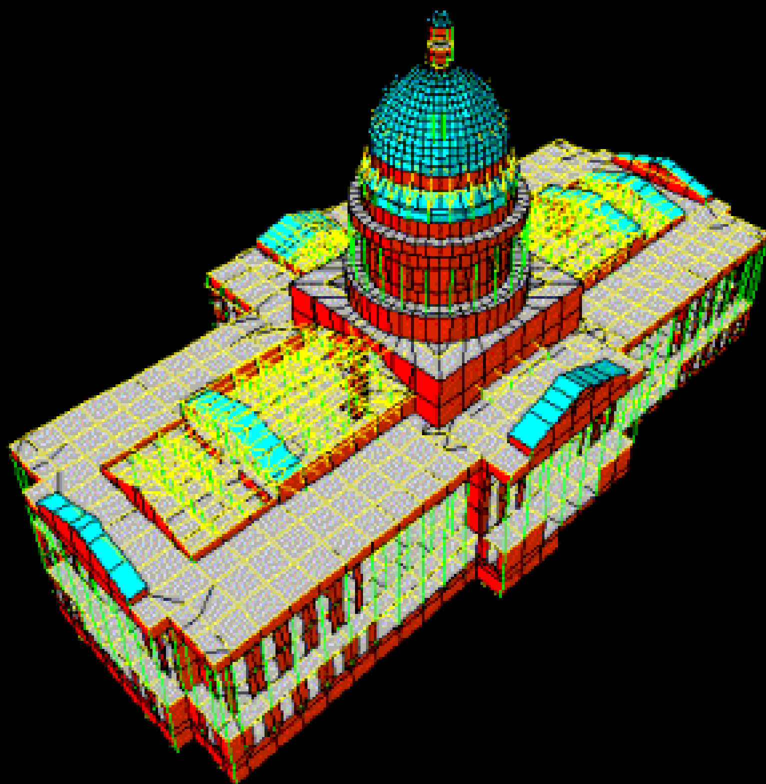
Fixed Base Model - 30x Amplification

(Click on image to start animation)



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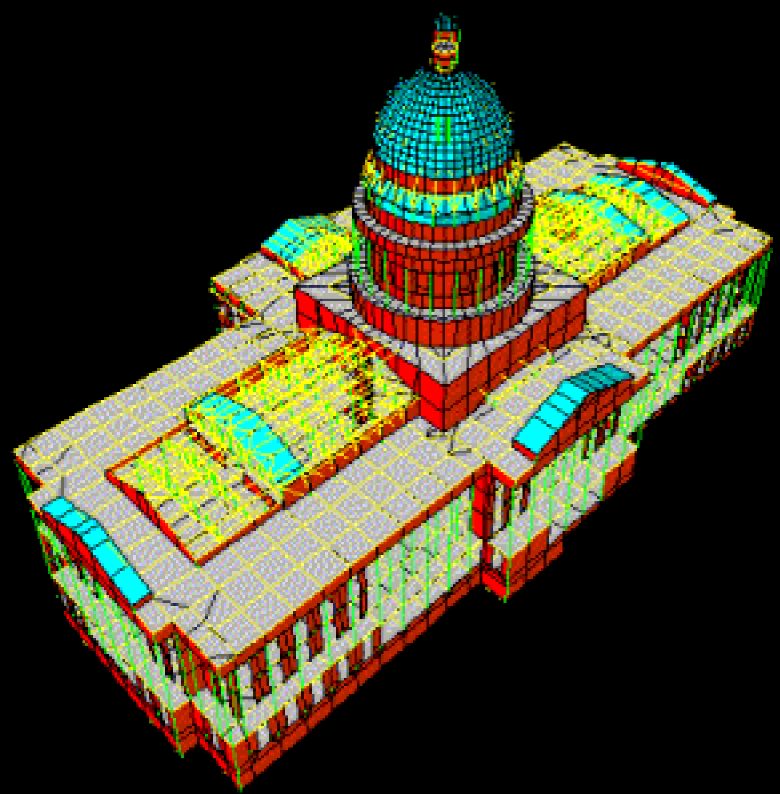
Base Isolated Model - 30x Amplification

(Click on image to start animation)



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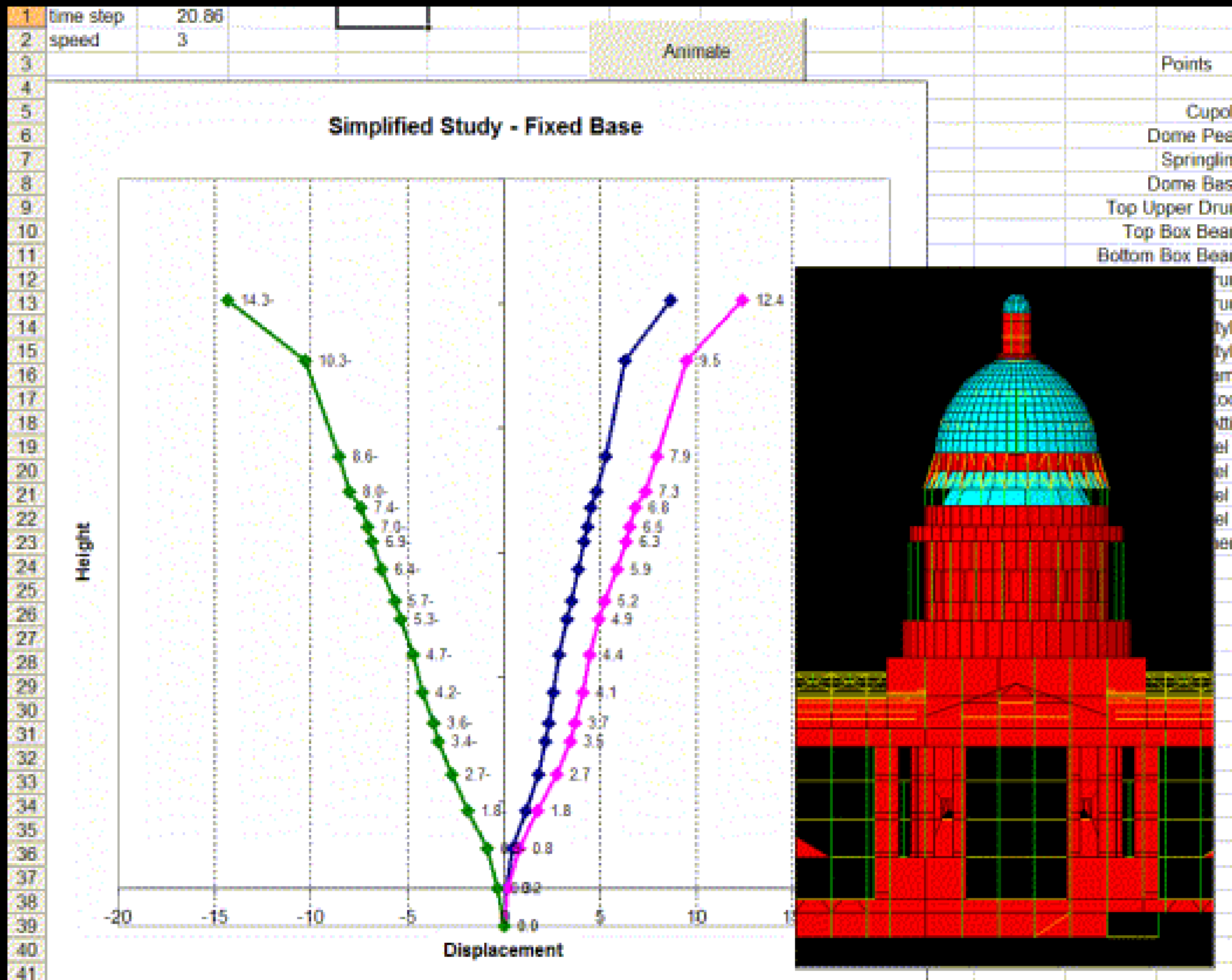
Reduction of Computer Output



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How does Base Isolation benefit the Utah State Capitol?

- Horizontal Seismic Accelerations are reduced by approximately 75% to 80% for a large earthquake.
- Preservation of Life.
- Preservation of Utah Heritage.

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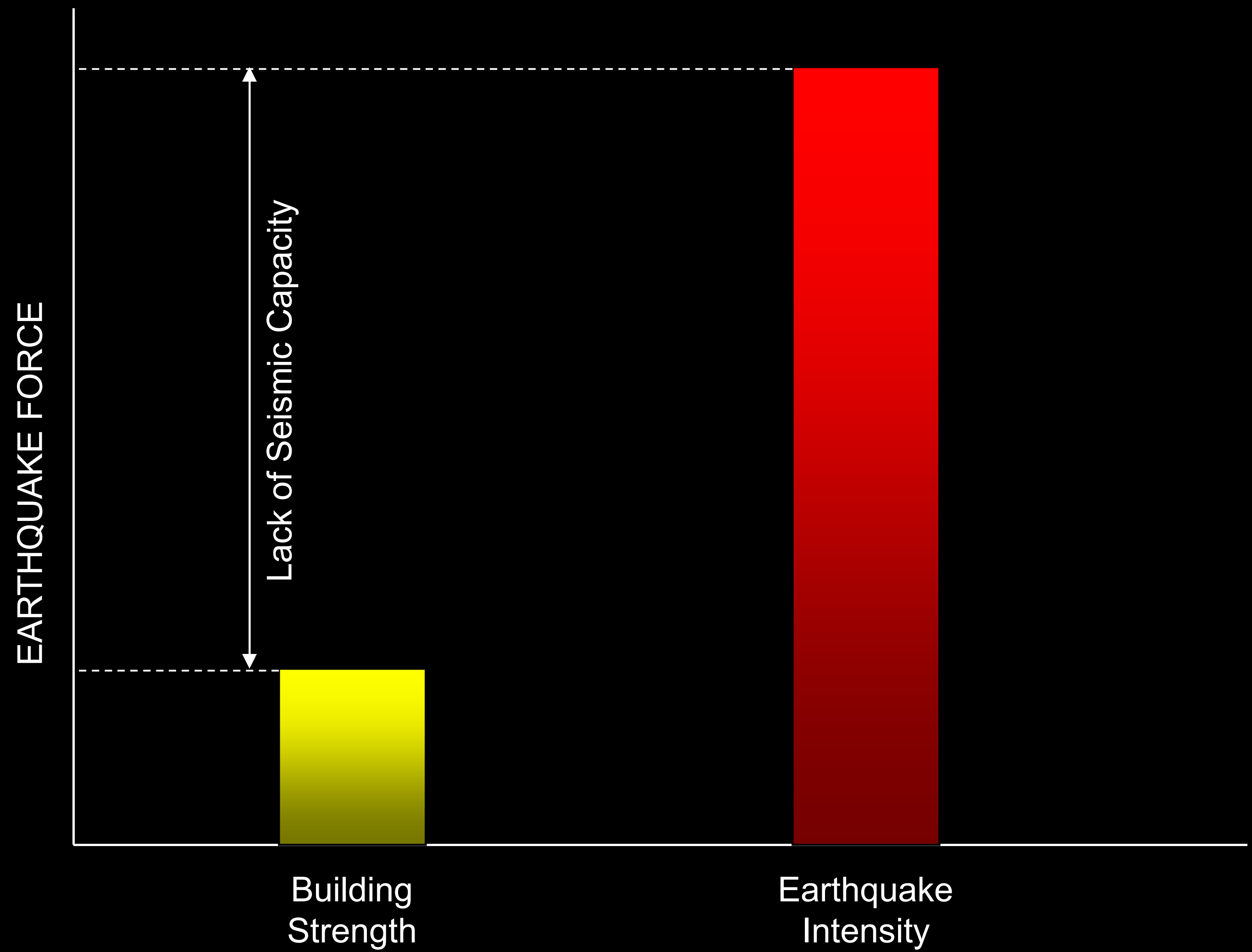
How does Base Isolation benefit the Utah State Capitol?



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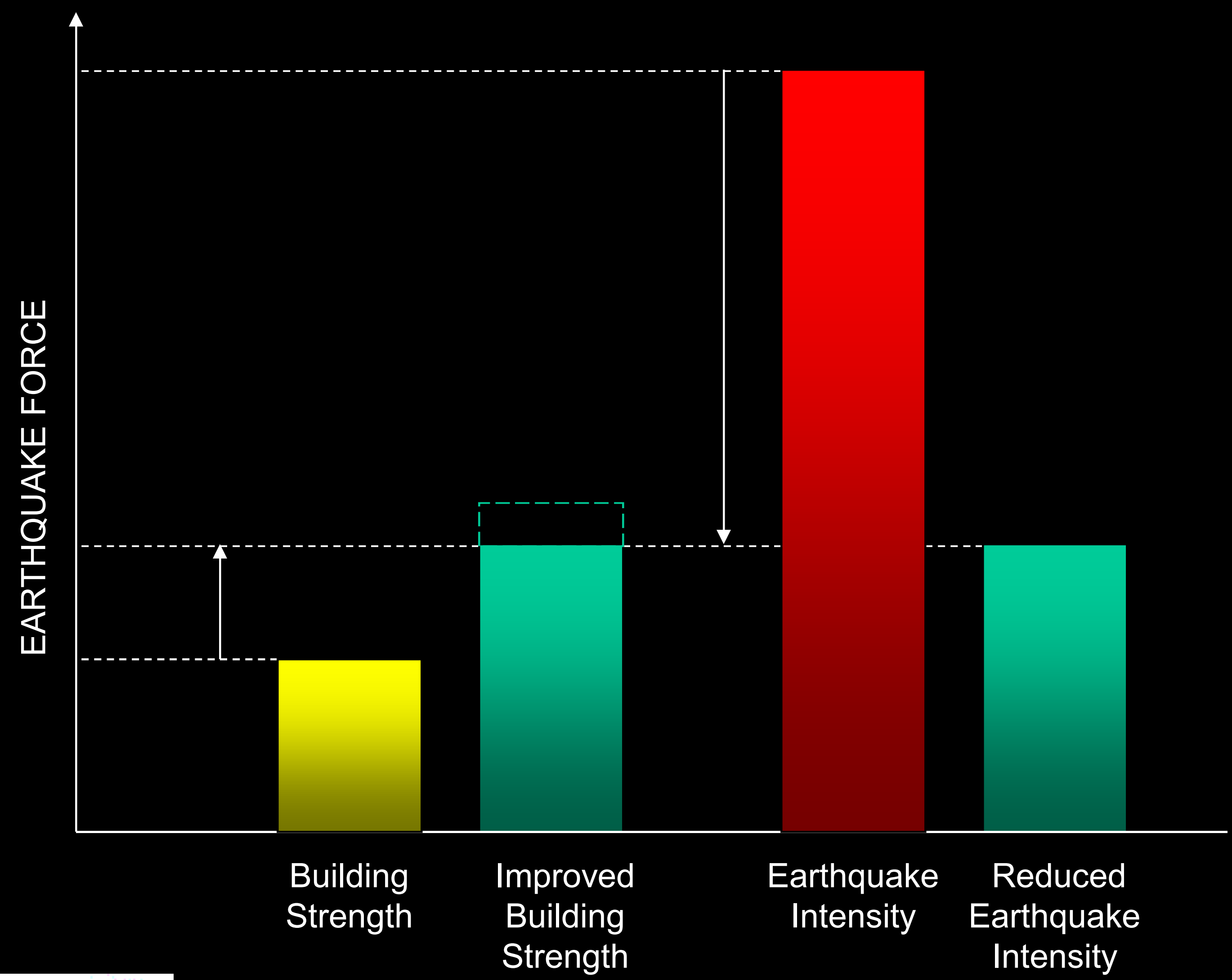
How does Base Isolation benefit the Utah State Capitol?



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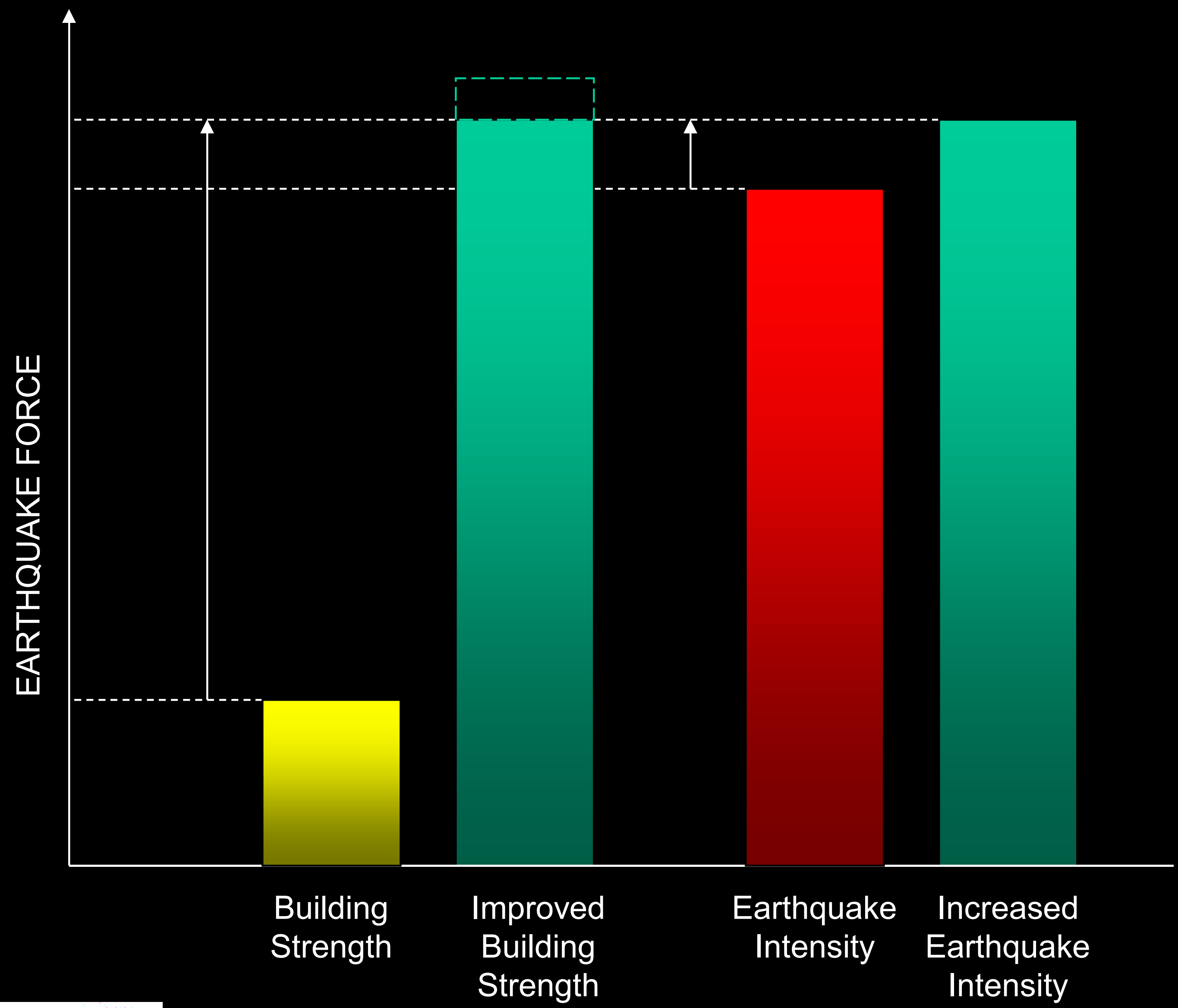
A more conventional retrofit approach?



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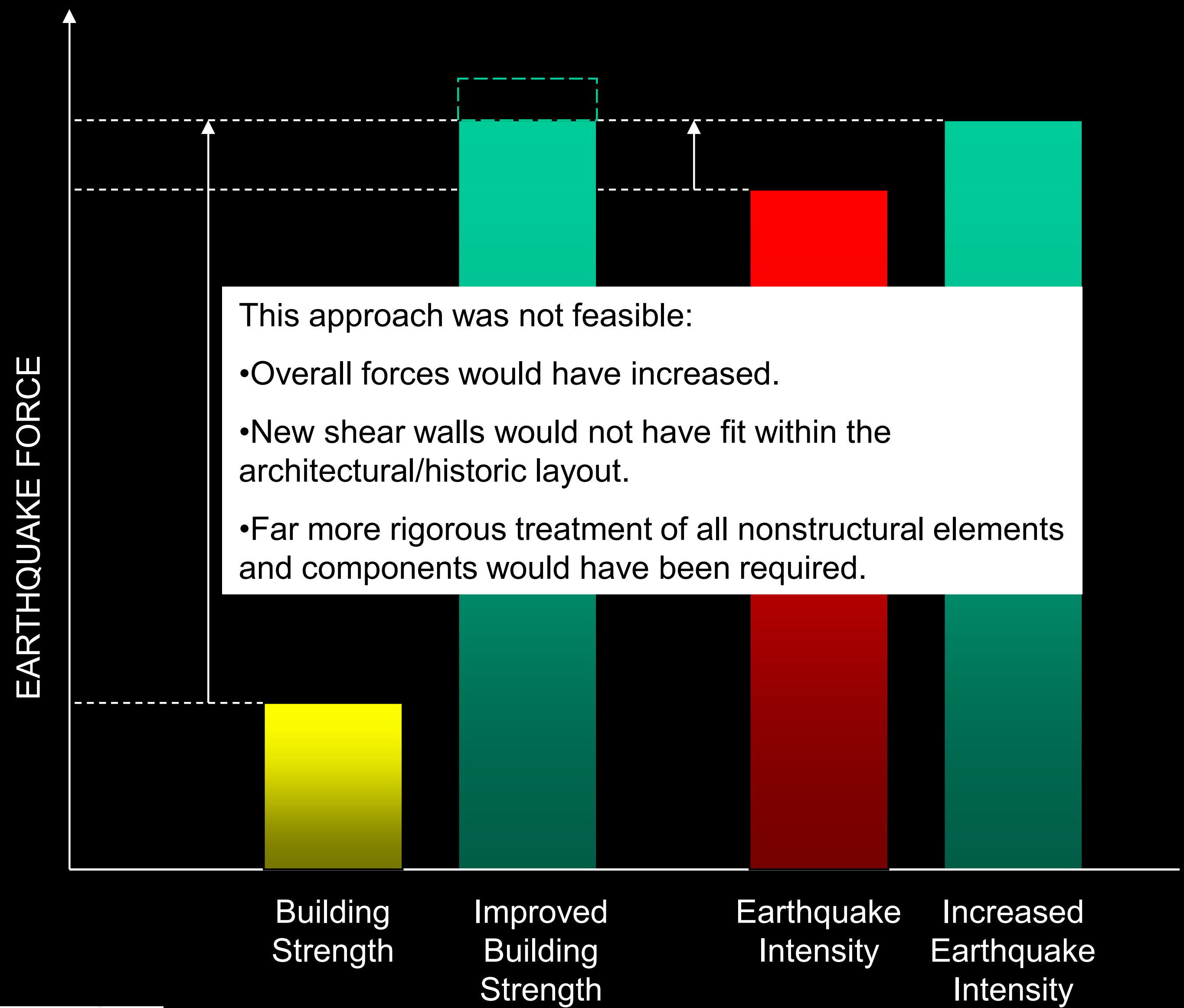
A more conventional retrofit approach?



This approach was not feasible:

- Overall forces would have increased.
- New shear walls would not have fit within the architectural/historic layout.
- Far more rigorous treatment of all nonstructural elements and components would have been required.

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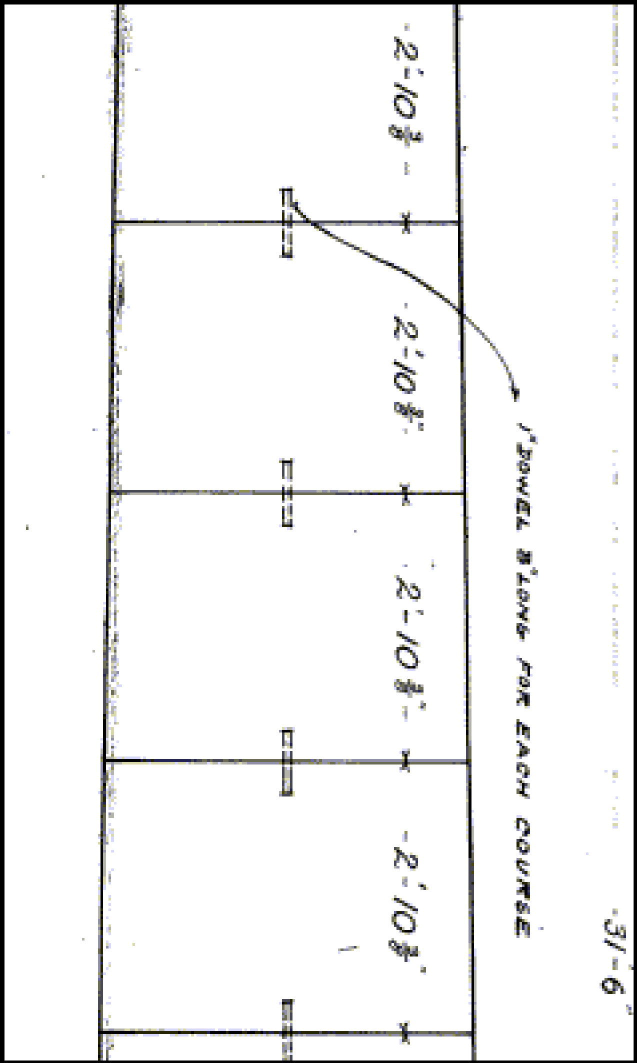
Creative Solutions

Exterior Granite Columns



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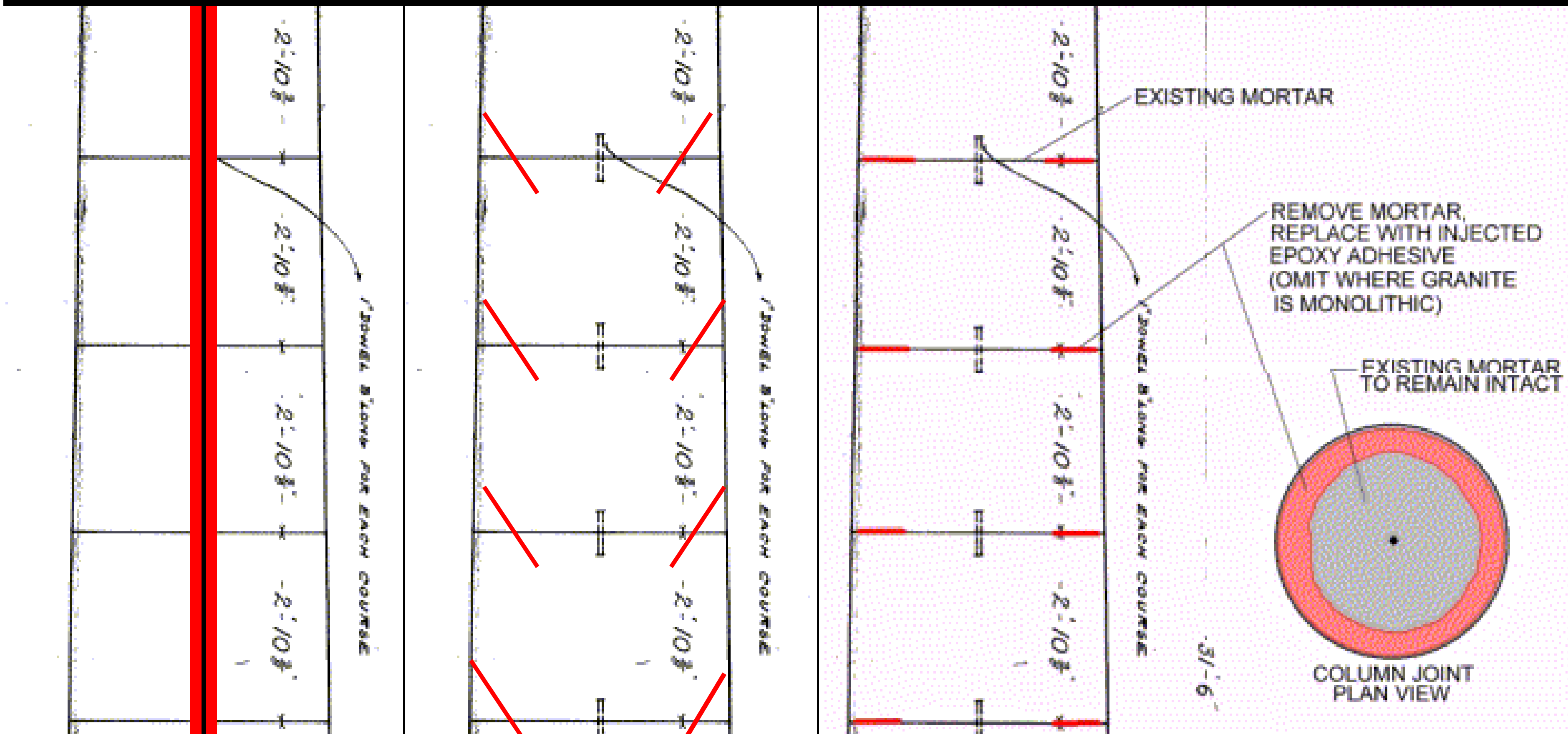
Creative Solutions

Exterior Granite Columns

Center Core | “Toenail” | Joint Adhesion with Epoxy



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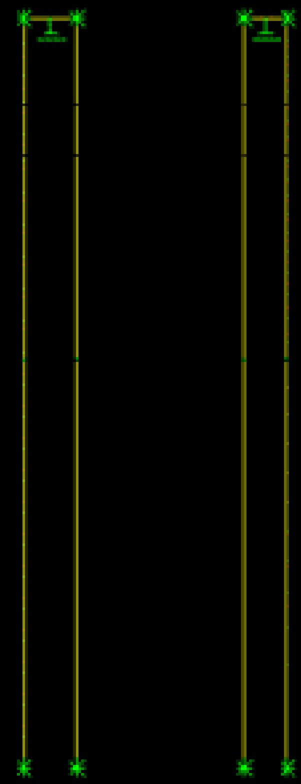
Stacked Granite Columns – Stability Analysis

2x motion



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Typical Rooftop Parapets

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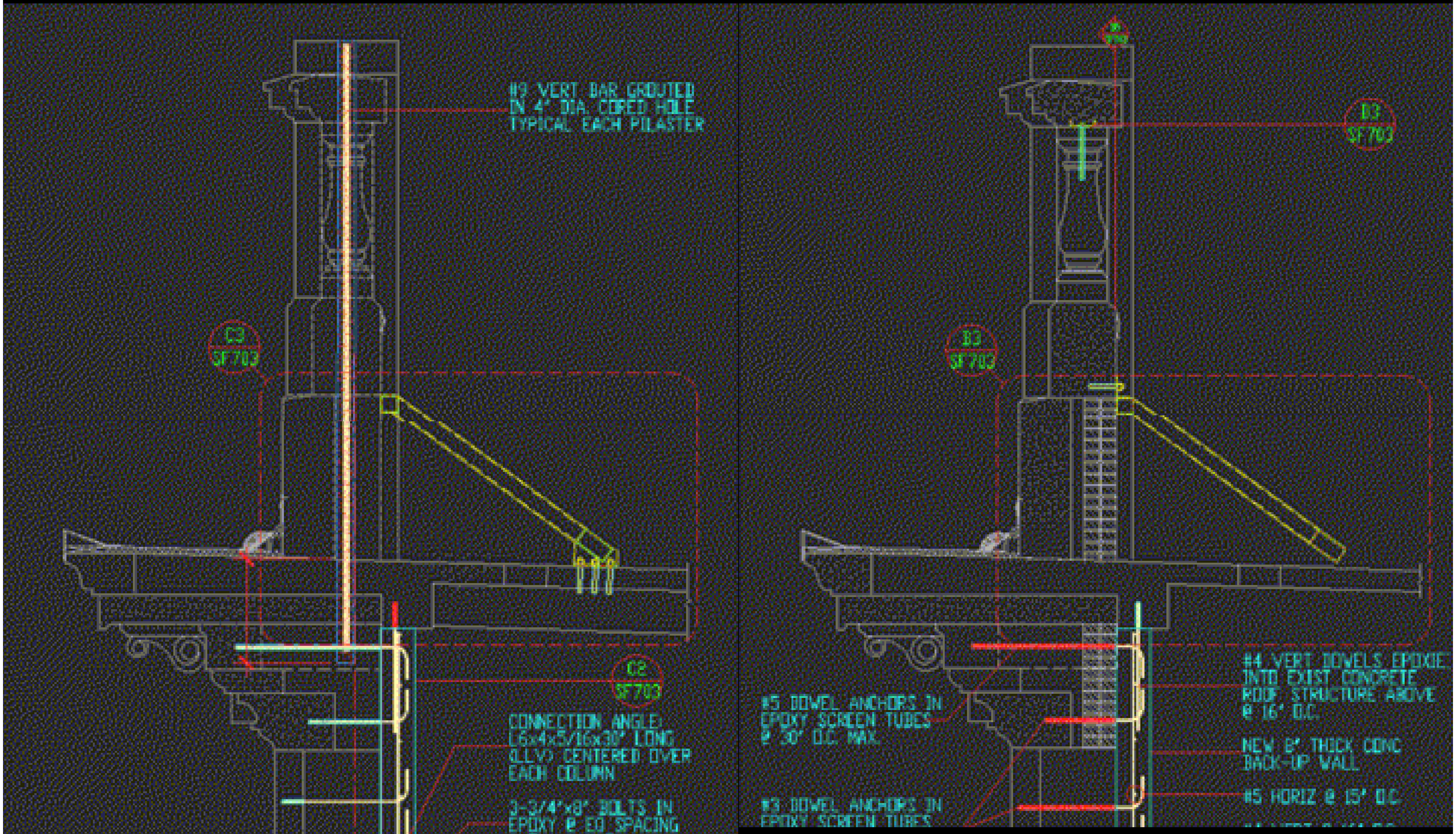
Details for Bracing Parapets



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Details for Bracing Parapets

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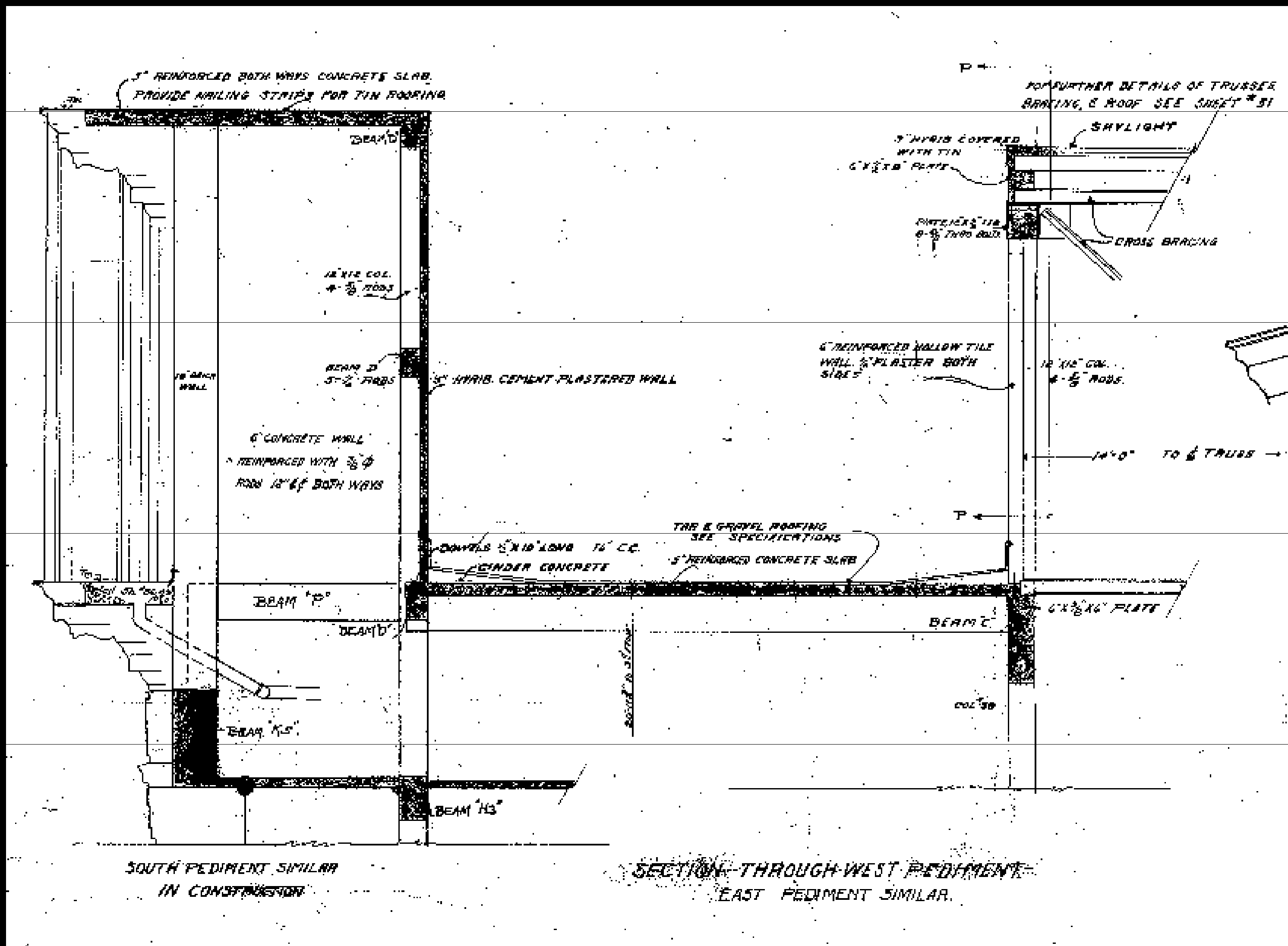
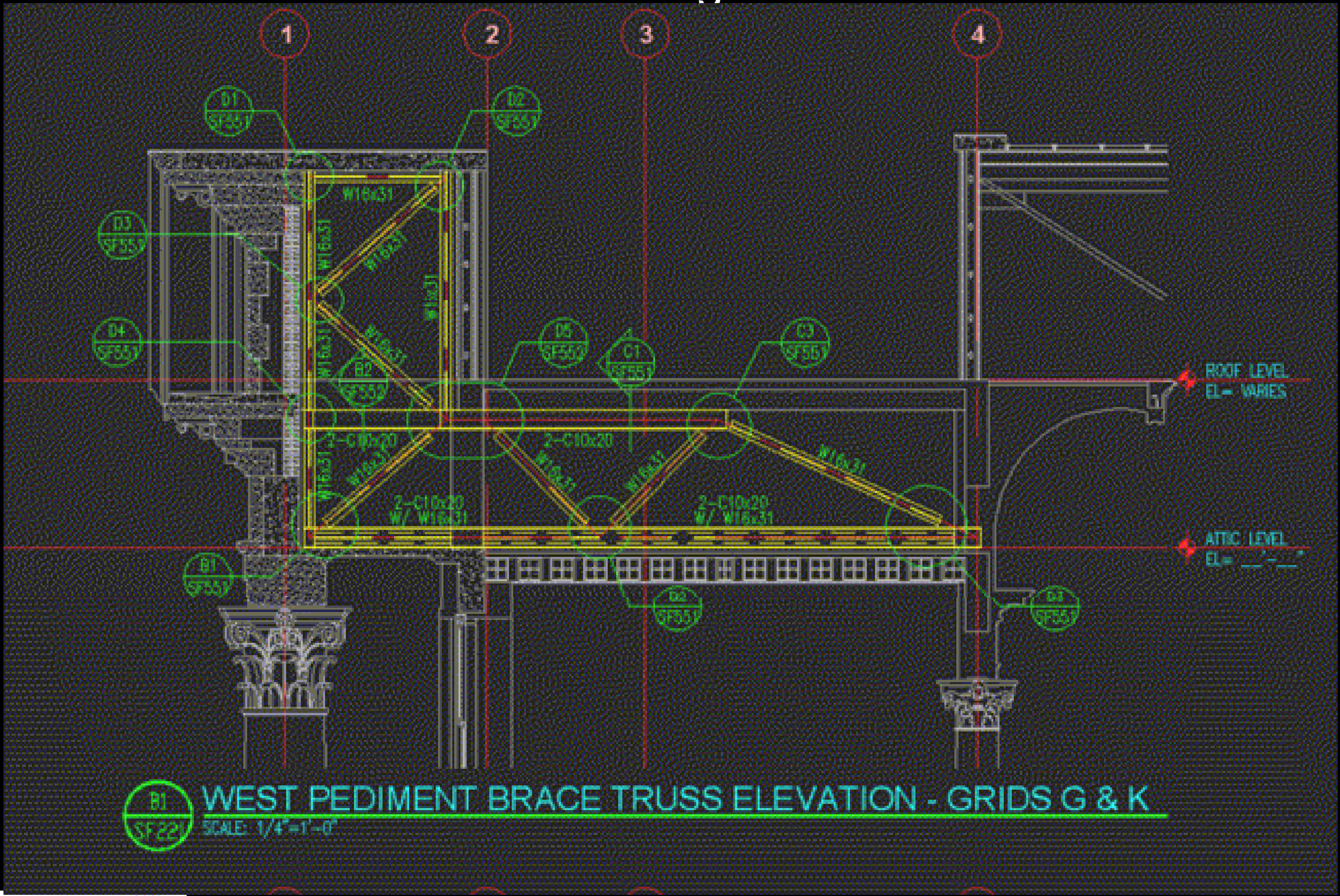
Pediments


SKYLIGHT
CROSS BRACING
6" CONCRETE WALL
TAR & GRAVEL ROOFING
SEE SPECIFICATIONS
CINDER CONCRETE
BEAM "P"
BEAM "K5"
BEAM "H3"
BEAM C
SOUTH PEDIMENT SIMILAR
IN CONSTRUCTION
SECTION THROUGH WEST PEDIMENT
EAST PEDIMENT SIMILAR.

Details for Bracing Pediments



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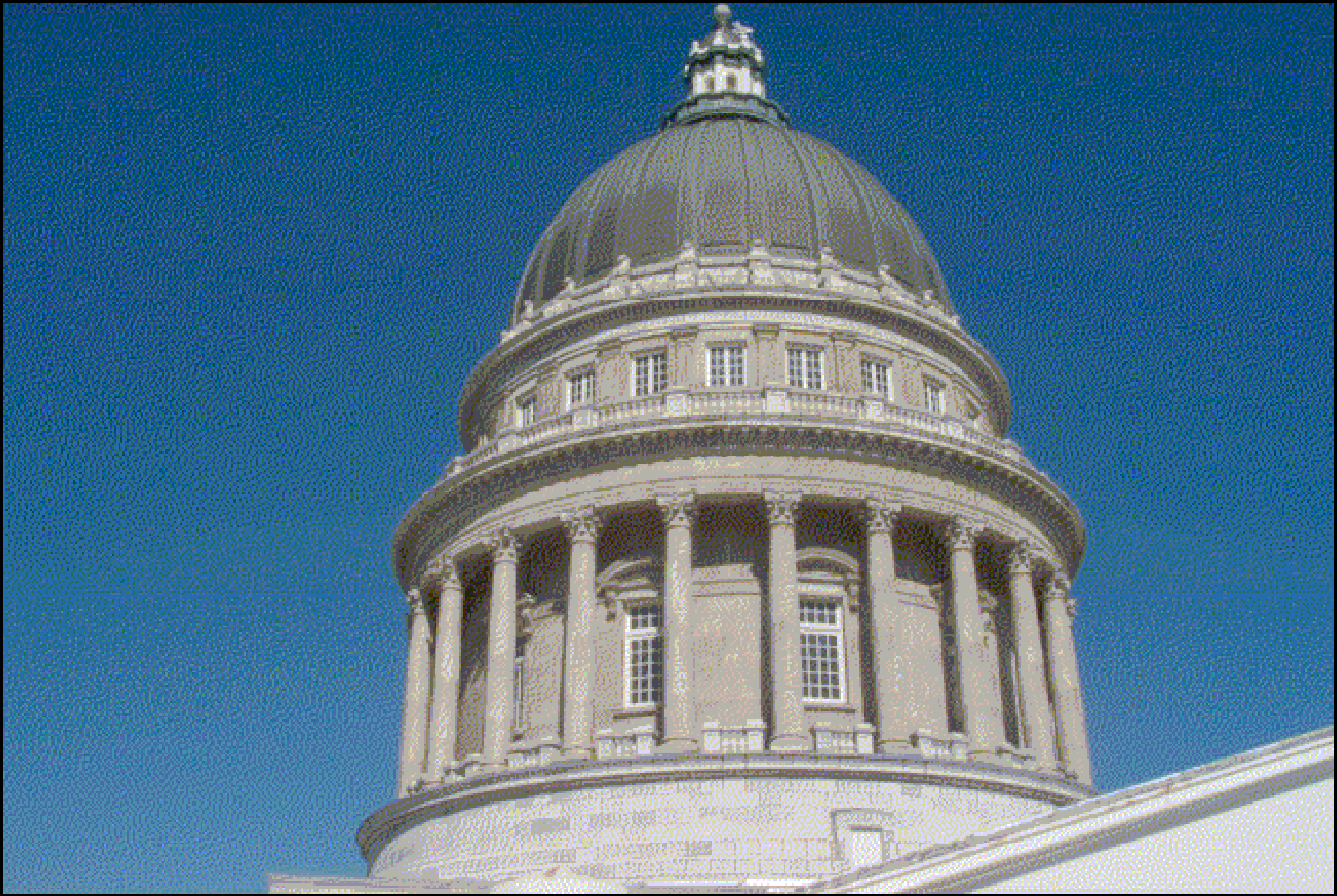
Dome / Drum



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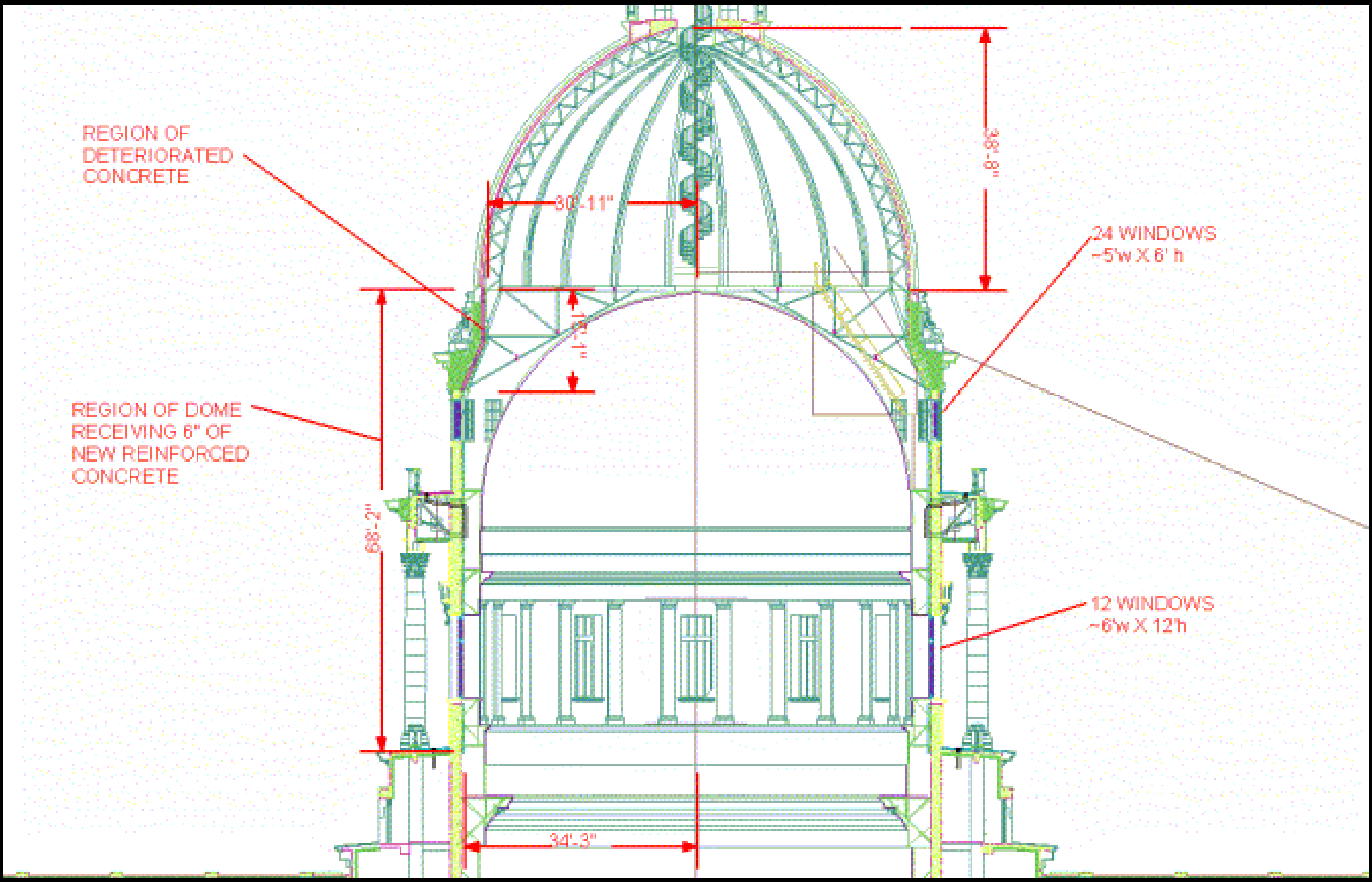
Dome / Drum



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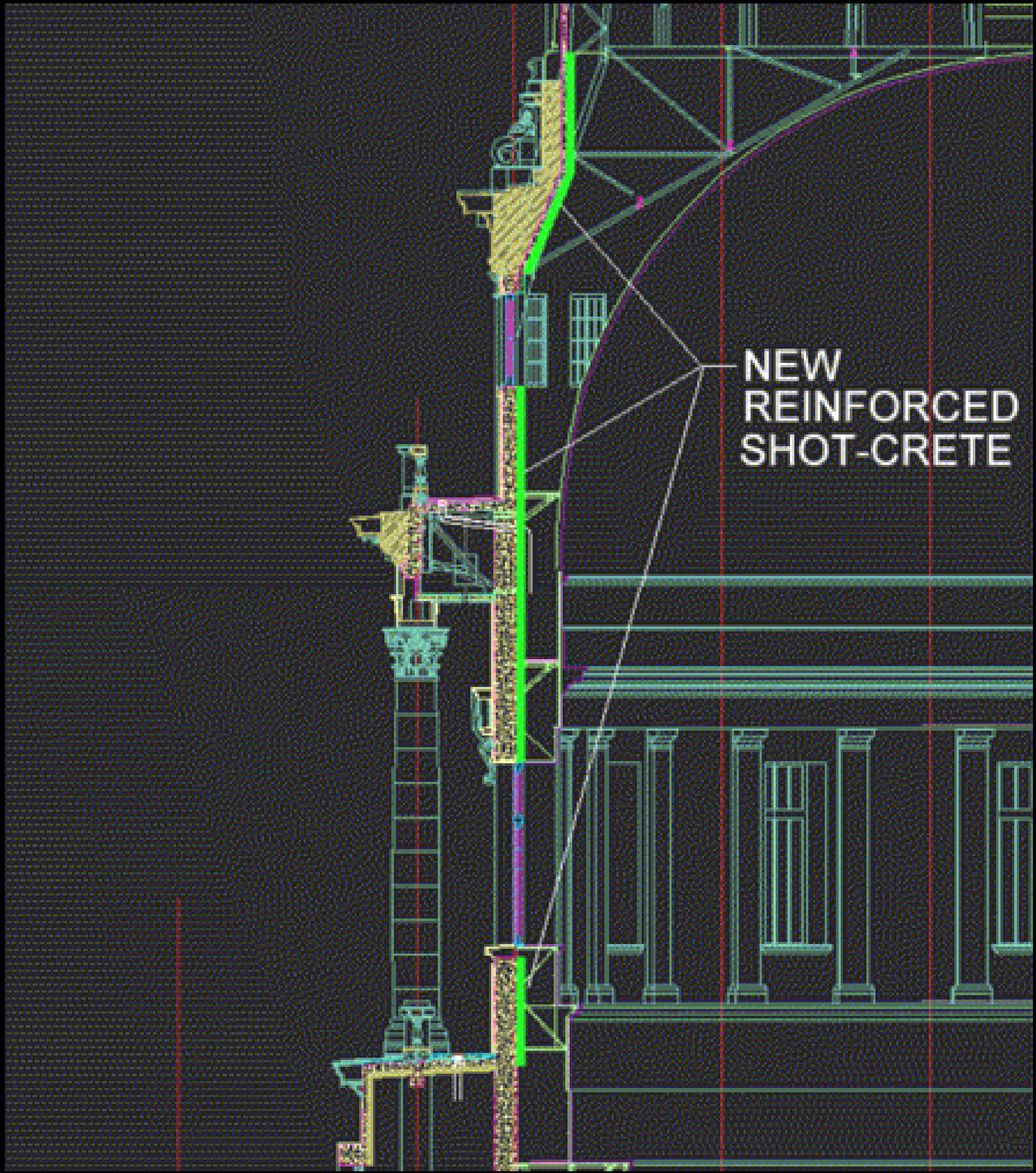
Detail for Reinforcing Drum



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Arresting and Preventing Corrosion – Dome

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Arresting and Preventing Corrosion – Dome

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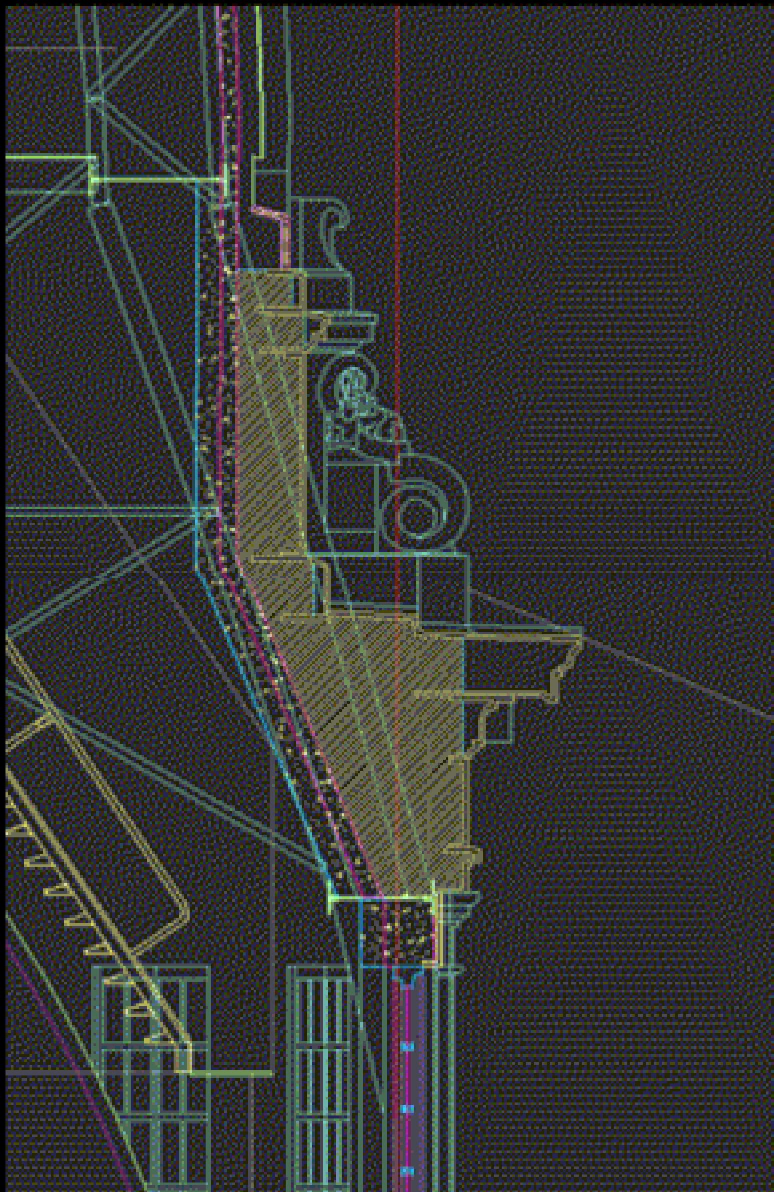

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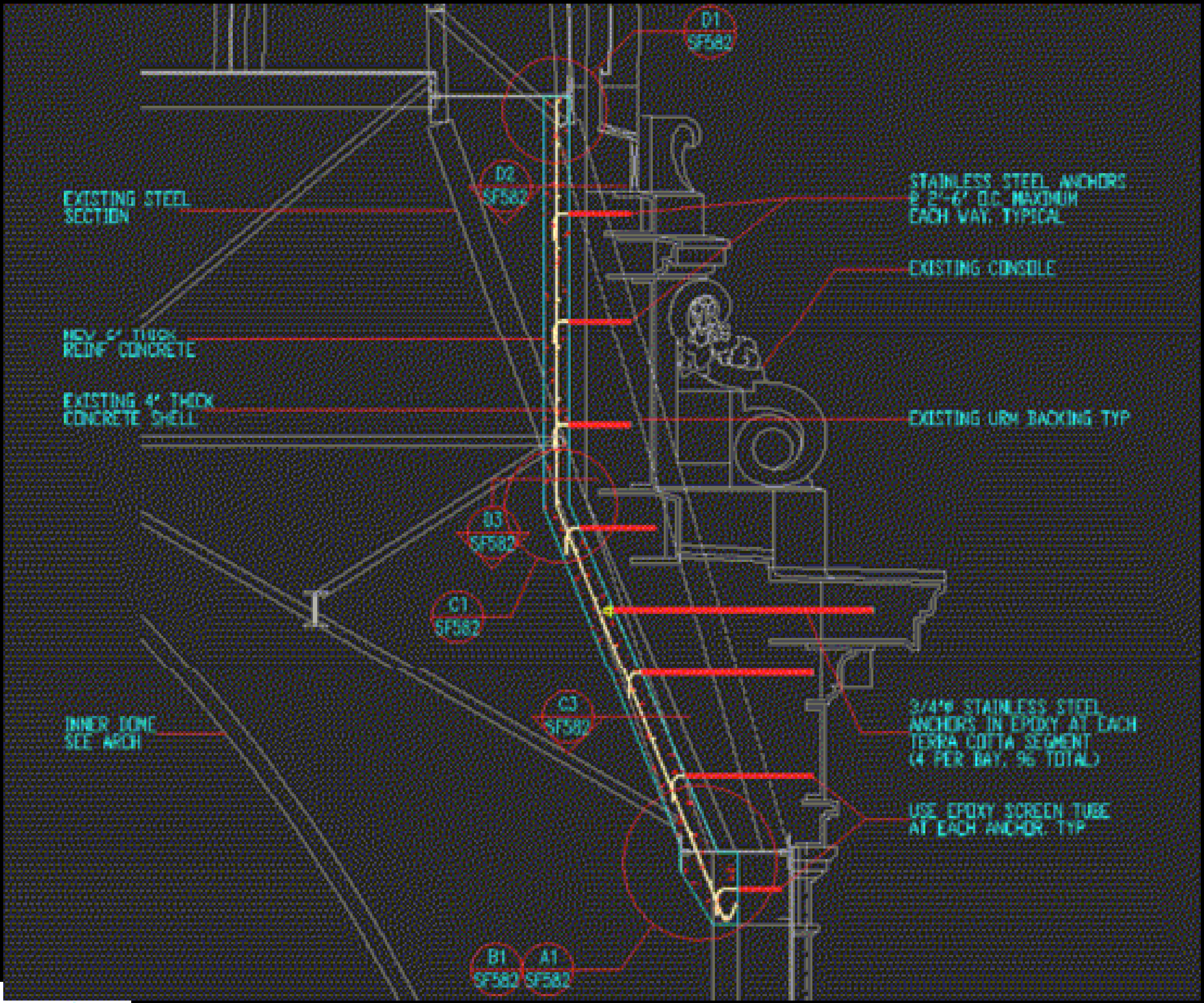
Anchoring of Existing Terra Cotta



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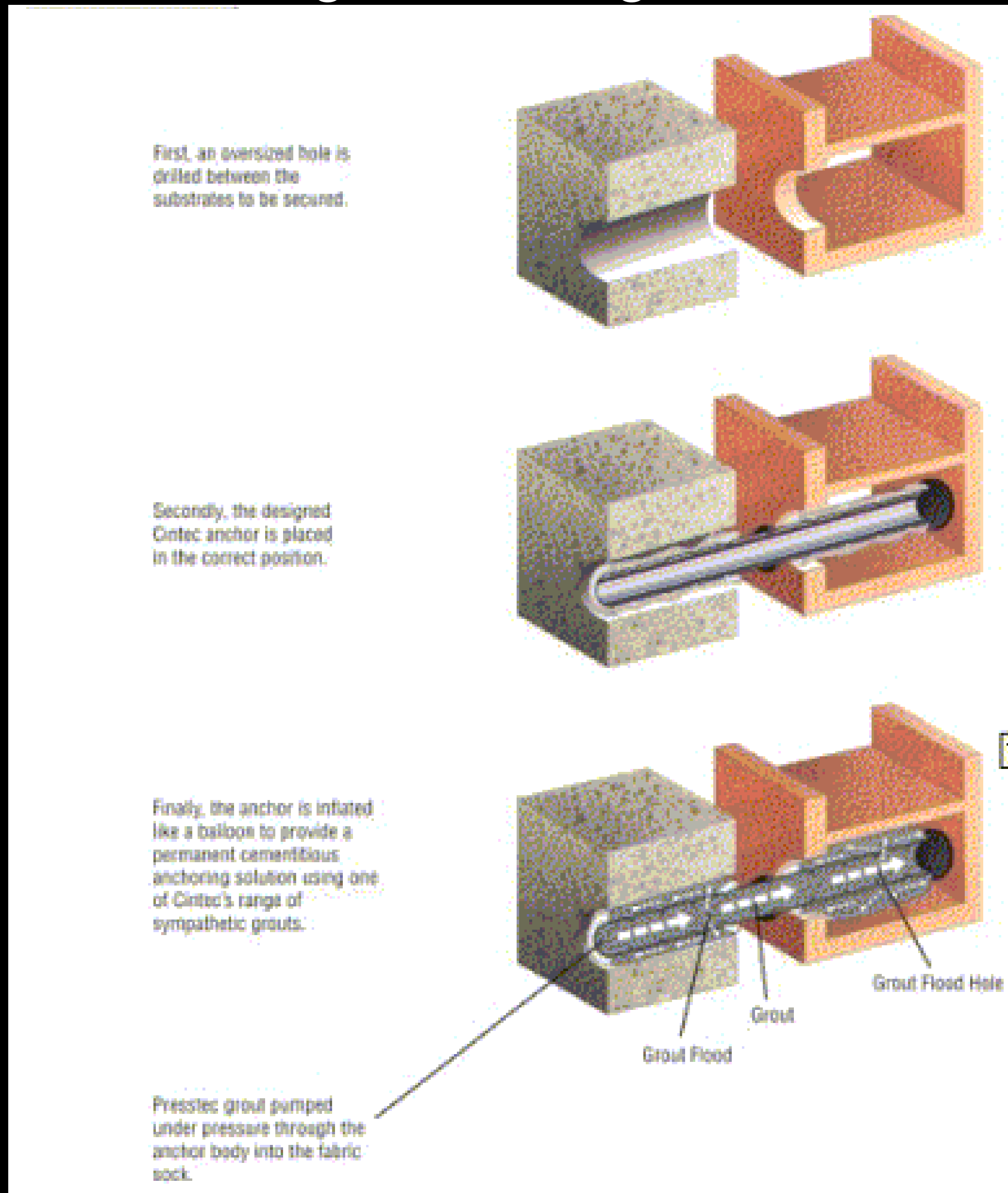
Anchoring of Existing Terra Cotta



Cathodic Protection System:

•Titanium mesh anode will be place at the interior surface of the new reinforced shotcrete.

•Anode current density is 1.23mA/ft^2 or approximately 3.78 A for the entire cathodically protected area.

•This is thought to be a ‘pioneering’ project for corrosion protection of historic structures.

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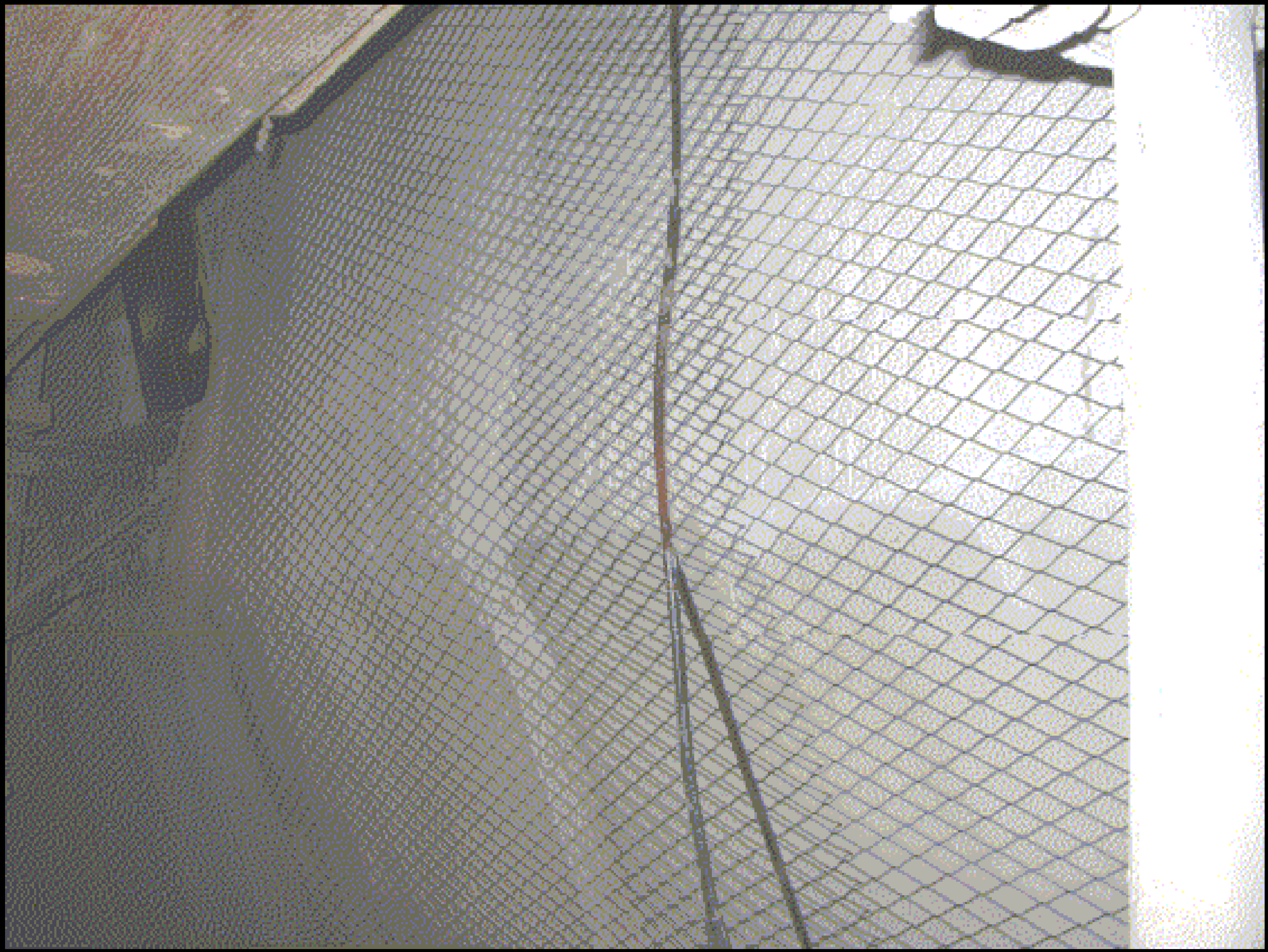
Arresting and Preventing Corrosion – Dome



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