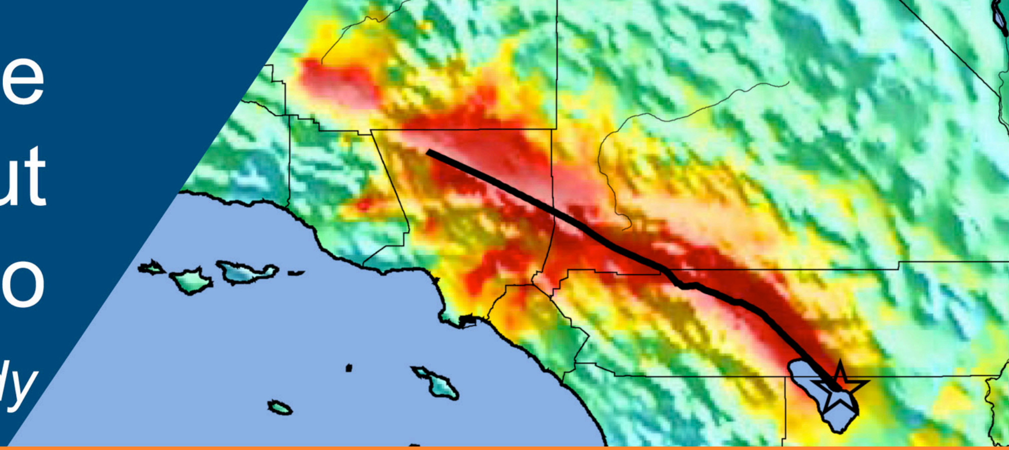
The ShakeOut Scenario
Supplemental Study



Oil and Gas Pipelines

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Note: over the course of the ShakeOut Scenario, the project name evolved. Where a study mentions *the SoSAFE Scenario* or *San Andreas Fault Scenario,* it refers to what is now named the ShakeOut Scenario.

M7.8 Southern San Andreas Fault Earthquake Scenario: Oil and Gas Pipelines

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Physical and Operational Impacts of Pipeline Failures

There is a long record of oil and gas transmission pipeline failures in California earthquakes due to ground shaking and liquefaction. The large majority of these have been joint failures where the joints were constructed using oxy-acetylene welds installed prior to approximately 1930. Pipelines constructed using electric arc welding (post-1930) have performed much better. There has been only limited mixed experience of modern pipeline performance at fault crossings.

In the 1994 Northridge earthquake, there were 209 repairs required to metallic distribution lines, and 27 to polyethylene lines. There were 35 non-corrosion –related transmission pipeline repairs of which 27 occurred on pipe joint with oxy-acetylene girth welds in pre-1930 pipelines. At one of those failures, gas leaked from a failed 56-cm line on Balboa Boulevard and was ignited by the ignition system on a nearby truck (T. O'Rourke, 1994). The fire resulted in burning nearby houses (Figure 1).

In the 1989 Loma Prieta Earthquake, PG&E had three failures of transmission lines, and extensive damage to the cast iron distribution system in the San Francisco Marina District resulting in an extensive pipe cast iron pipe replacement program using polyethylene. (EERI, 1990).

In the 1979 Imperial Valley Earthquake, three pipelines were impacted by fault movement; none failed. A 10-, 20-, and 25-cm pipe were subject from 40- to 60-cm of movement. The 10-cm line had oxy-acetylene welded joints, while the other two had electric arc welded joints. These lines were operating at pressures of up to 725 psi. (Dobry, 1992).

In the 1971 San Fernando earthquake, over 80 transmission line failures occurred in pipelines due to shaking that had oxy-acetylene welded joints while less than five occurred in pipelines with electric arc welded joints (including reconditioned joints). For transmission lines subjected to permanent ground deformation, approximately 10 failures each occurred in oxy-acetylene and electric arc welded pipe. Failures in electric arc welded pipe occurred in areas with offsets of two meters while no failures occurred in another are subjected to two to three meters of displacement (O'Rourke, 1994).

In Washington State, two high pressure gas transmission line failures occurred in 1997, both resulting from ground movement. Another failure occurred in 2003. One of the 1997 failures resulted in an explosion. In 1999, a pipeline carrying gasoline failed due to damage caused by a third party during construction on adjacent facilities. The pipeline failure resulted in discharging 277,000 gallons of product into a creek bed. In the ensuing fire, two boys burned to death, and one young man was killed after he was overcome by fumes.

In summary, modern steel pipelines with electric arc welded joints perform much better pipelines with oxy-acetylene welded joints (typically pre-1930 construction). Steel pipelines have performed well when subjected to ground displacements of 60 cm, but sometimes fail when displacements reach several meters. High pressure gas lines do fail when subjected to permanent ground deformation due to slides, and if an ignition source is available, can explode. Gasoline leaked from a damaged product line fueled a fireball when ignited.

Exposed Assets

Pipeline information was acquired using the HSIP Gold database, provided in both Google Earth and ArcGIS format. Six product pipelines were identified in areas of strong ground shaking, two of which cross the fault at Cajon Pass. Three run westerly from the node/distribution terminal in Colton towards Los Angeles, and one runs easterly from that same node as shown in Table 1.

Table 1. Product Pipelines Impacted by the Earthquake Scenario

Pipeline Name	Diameter	Location	Hazard
Colton-Barlow, CalNev Pipeline Company	35-cm	Cajon Pass; San Andreas Fault Crossing	Fault Crossing, Landslide, Liquefaction/Lateral Spread
Colton-Barlow, CalNev Pipeline Company	20-cm	Cajon Pass; San Andreas Fault Crossing	Fault Crossing, Landslide, Liquefaction/Lateral Spread
Colton-Yuma, Kinder Morgan SFPP LP	50-cm	Colton, east south-east along the west side (and crossing) of the San Andreas Fault to the Salton Sea	Fault Crossing, Landslide, Liquefaction/Lateral Spread, Shaking
Nogales-Colton	50-cm	Colton – Los Angeles	Landslide, Liquefaction/Lateral Spread, Shaking
Watson-Colton	40-cm	Colton – Los Angeles	Landslide, Liquefaction/Lateral Spread, Shaking
Colton-March	15-cm	Colton to March AFB	Landslide, Liquefaction/Lateral Spread, Shaking

Southern California Gas owns gas transmission and distribution pipelines throughout the region. Twenty-seven fault crossings were identified; eighteen transmission, and nine distribution pipelines (some lines are counted multiple times as they cross multiple splays of the fault). Two of these cross at Cajon Pass (transmission), one at San Bernardino (distribution), fourteen at Palm Springs (seven transmission and seven distribution), and ten at Palmdale (nine transmission and one distribution). The diameter of these lines is unknown. Southern California

Gas's entire pipeline inventory in areas with PGA's exceeding 10 to 15 percent gravity are subject to landslides and liquefaction/lateral spread through the region.

It is assumed that all of the product and gas transmission lines are constructed using welded steel joints. Some of these pipelines may have been constructed using oxy-acetylene welded joints (typically pre-1930), and some using electric arc welded joints (post-1930). Some of the distribution pipelines may be constructed of cast iron. In most cases, the cast iron would have been replaced with polyethylene.

Vulnerability of Assets

Buried pipelines are vulnerable to permanent ground deformation and wave propagation (shaking). Ground deformation can include fault rupture, landslide, and liquefaction and associated lateral spreading and settlement. Pipe damage mechanisms include: compression/wrinkling, joint weld cracking/separation (particularly for oxy-acetylene welds), bending/shear resulting from localized wrinkling, and tension.

This earthquake scenario is focusing on an event on the southern segment of the San Andreas Fault that is expected to offset as much as 13 meters near the Salton Sea. A 4.5 meter offset is expected at Cajon Pass. In addition to lateral movement, there may be an additional vertical offset. The fault offset places the buried pipe in shear, compression, or tension depending on the geometry of the pipe relative to the fault. The preferred alignment would be to place the pipe in pure tension; the worst alignment would place the pipe in pure compression. In tension, steel pipelines with welded joints can distribute tensile strain over hundreds of meters minimizing localized stresses. Anchor points (valves of bends) can result in local stress concentrations. By comparison, pipelines readily wrinkle in compression. It may be possible for the pipelines crossing the San Andreas Fault at Cajon Pass to survive if they have been properly designed. If special considerations were not taken into account, it is unlikely the pipelines could accommodate 4.5 meters of offset. The American Lifelines Alliance (2001) estimates that high quality welded steel pipe would have a failure about every 400 meters given these conditions. The Colton-Barstow CalNev pipelines and the Kinder Morgan Colton Yuma pipeline appear to run parallel to and nearly on top of the fault. Depending on the exact fault location, this alignment could put these pipelines into almost pure compression causing them to fail.

Landslides can load buried pipelines in a similar manner to fault rupture. Pipelines crossing block landslide failures (but moving only several meters) laterally are put into shear at both edges of the block. If they run through longitudinally, they are put into tension at the top of the slide, and into compression at the toe. In catastrophic landslide failures, the pipe may be left unsupported. It is difficult to speculate about vulnerability due to landslides without site specific assessments. However for example, pipeline alignments approaching Cajon Pass, the Kinder Morgan pipeline north of Redlands, and the Nogales-Colton pipeline east of Whittier are all in rugged terrain, subject to slides.

Liquefaction and associated lateral spread and settlement occur in alluvial deposits with a shallow groundwater table (less than 10 meters deep). Most of the study area receives minimal rainfall, and as a result has a deep groundwater table. Additional information is required to identify areas that might be vulnerable to liquefaction. If liquefaction does occur, the greatest vulnerability occurs when buried pipelines move as part of large blocks of soil, down gradient. The vulnerable locations are at the block interfaces. The pipelines are subject to similar loading that would be encountered in landslides.

Compression wave propagation along pipelines puts them first in tension and then in compression. Standing on the ground surface, humans feel this as shaking. Pipelines can readily accommodate wave propagation moving the pipe tangential to its alignment.

Historically, steel pipelines with high quality electric arc welded joints perform very well in this shaking environment. Pipelines with joints using oxy-acetylene welds can have failure rates nearly 100 times greater than those with electric arc welded joints.

The most extreme shaking intensity in the study area is expected to be about 250 cm/second, located just north of Cajon Pass and in the Palm Dessert-Coachella area along the Kinder Morgan pipeline. For this level of shaking, the American Lifelines Alliance (2001) estimates failure rates on the order of 0.4/km for high quality welded steel pipelines (Figure 2). Pipelines in the San Bernardino and Palmdale areas would be expected to experience velocities of 150 to 200 cm/sec resulting in failure rates of 0.28/km for high quality electric arc joint welded pipe.

If a pipeline does fail, the consequences are dependent on its contents, its diameter, and the pressure of its contents. The two general categories of contents are “product” including liquid fuels that could be gasoline, jet fuel, diesel fuel, or other liquid fuels, and natural gas. The operating pressure in natural gas pipelines can approach 1,000 psi. Gas released through failures in small diameter low pressure gas mains (distribution mains) will generally dissipate quickly. Failure of large diameter high pressure natural gas pipelines can result in an explosion that can blast a crater in the surrounding soil, and damage nearby and overhead structures and facilities (such as power transmission lines). In any case, an ignition source is required to initiate the explosion. A human caused source could be a vehicle ignition system, cigarette lighter, or spark from a metal on stone impact. There is speculation that pipelines running parallel to overhead high voltage power transmission lines carry an induced current that could cause a spark if the pipeline was ruptured. In any case, there is a high probability that there will be an ignition source in the event of rupture of a high pressure pipeline. As evidenced by the fire that occurred in Washington State, failure and leakage of gasoline can result in an extensive fire if an ignition source exists. For some liquid fuels such as diesel, the potential for a fire is low, but would result in environmental contamination.

Damage Scenario and Lifeline Interaction

Natural gas, gasoline, and diesel pipelines rupture at fault crossings at Cajon Pass, Palm Springs, and Palmdale. A product line carrying gasoline ruptures at Cajon Pass; in the hills east of

Whittier another product line fails spewing jet fuel into the air. The product receiving station tank farm in Colton is heavily damaged.

One of the two Southern California Gas transmission pipelines at Cajon Pass will rupture at the fault and explode (See Figure 3) resulting in a large crater (see Figure 4). The Southern California Gas pipeline-fault interface occurs where the pipeline intersects the CalNev 14-inch product pipeline, so when the explosion occurs the CalNev pipeline ruptures. The CalNev pipeline is transporting gasoline, so the gasoline adds to the fire (see Figure 5). Power transmission lines are overhead, and the fire reaches the lines causing them to fail.

The Southern California Gas pipeline is one of two parallel lines at Cajon Pass. Delayed by highway damage and traffic congestion, operations personnel reach the site and isolate the damaged pipe four hours after the earthquake occurs. Their second pipeline is taken out of service as a precautionary measure to check for damage due to the 5 meter fault offset. The second pipeline is temporarily put back in service until the ruptured one is repaired. CalNev operations personnel reach the site and isolate their line 6 hours after the earthquake. Electrical power is rerouted around the damaged transmission line.

The 20-inch Kinder Morgan product line is ruptured in Palm Springs (Figure 6). The pipeline is aligned directly over the fault. When the earthquake occurs, the pipeline is shortened five meters causing it to wrinkle and rupture (Figure 7). The pipeline is carrying diesel which is sprayed into the air. Ultimately 200,000 gallons of product is discharged into the local drainage until the line can be isolated. A smaller natural gas distribution pipeline is located in the same right-of-way. The fault displacement also ruptures this line. Although the volume of discharging gas is much smaller than that coming from the break at Cajon Pass, the gas hampers response efforts. The Kinder Morgan Pipeline fails at an additional 15 locations due to shaking at locations along the 60 km alignment paralleling the fault trace. Each failure location requires environmental cleanup of the discharged diesel product.

In Palmdale, a natural gas transmission line crosses the fault multiple times. It ruptures when the earthquake occurs, spewing gas into the air. First responders quickly evacuate the area and are able to keep the gas from igniting until a Southern California Gas crew arrives to isolate the break.

A landslide in the hills east of Whittier shears off the 20-inch Nogales pipeline in the hills east of Whittier releasing jet fuel. 100,000 gallons of product is discharged before the line can be shut down. The jet fuel finds its way into a local drainage.

The Colton Receiving Station (Figure 8) is subjected to 40 percent g shaking. The receiving station is a node for distribution of gasoline, diesel and jet fuel. The facility also controls flow of jet fuel to March Air Force Base. Unanchored tanks bounce around breaking connecting pipe. Fuel discharges into the retaining dikes, and is ignited by passing vehicle ignition system.

Southern California Gas has small transmission and distribution piping throughout the impacted area. In recent years, they have replaced most of the cast iron pipe in the distribution system with polyethylene. They still suffer approximately 200 pipeline failures, primarily at fittings and transitions.

Mitigation

To mitigate pipe failures, there is a series of possible mitigation measures that can be considered on a site by site basis. Seismic resistant design of pipelines at fault crossings may be the most effective compared to landslide and liquefaction areas because fault (particularly strike-slip faults) locations can be determined with reasonable accuracy. The same mitigation measures can be employed for areas with high susceptibility to landslides or liquefaction/lateral spreading except that the locations of block interfaces may be less certain. There may be an opportunity to avoid landslide and liquefaction zones when selecting the alignment of new pipelines. Selection of pipe joint design is important in mitigating pipe damage due to wave propagation.

To mitigate damage due to permanent ground deformation (fault movement, landslide, liquefaction) use modern welded steel pipe with butt electric arc welded joints. Replace old pipe that has oxy acetylene welded joints within the fault zones and several thousand feet beyond. The pipeline geometry should be designed so the pipe will go into tension when the fault moves. Install the pipe with a coating/covering to minimize soil-pipe friction allowing the pipe to easily slide through the ground. Avoid use of “anchors” (valves, sharp bends, etc.) to allow the pipe to move so that pipe stresses can be distributed along the pipe. Design the backfill to allow the pipe to move laterally in the trench if required to accommodate the fault movement.

To mitigate damage due to wave propagation (shaking), use modern steel pipe employing electric arc welded joints (the standard in the industry). Replace old (pre-1930) pipe with oxy-acetylene welded joints.

To mitigate the consequence of pipe failure, implement an automated control system to allow quick shutdown of the pipeline systems. Construct parallel (redundant) pipelines in independent alignments so if one fails, the other may remain intact.

Figure 1. Balboa Neighborhood Burned by Exploding Gas Line in Northridge Earthquake (left); Fire ball that Burned the Neighborhood.

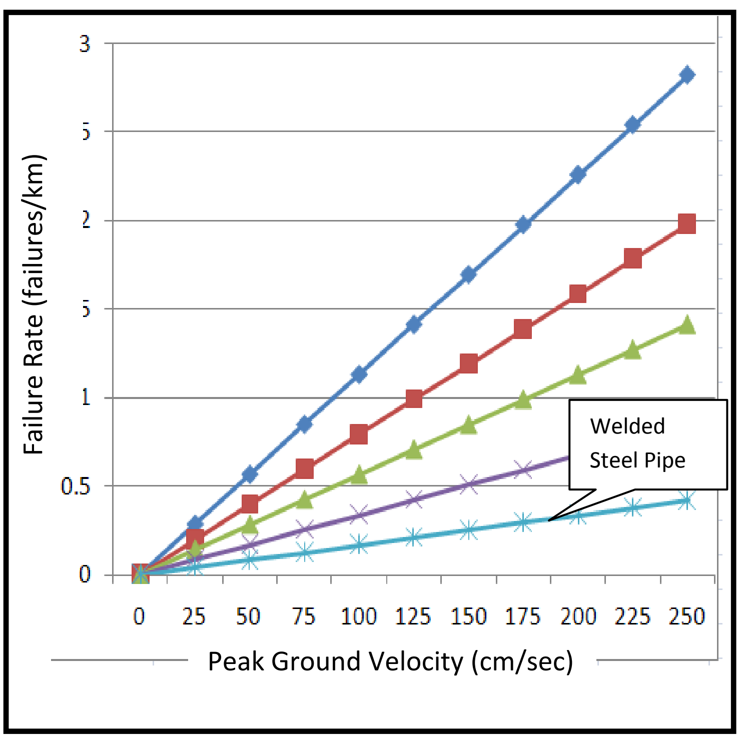

Figure 2. Wave Propagation Pipeline Fragility (After ALA 2001)

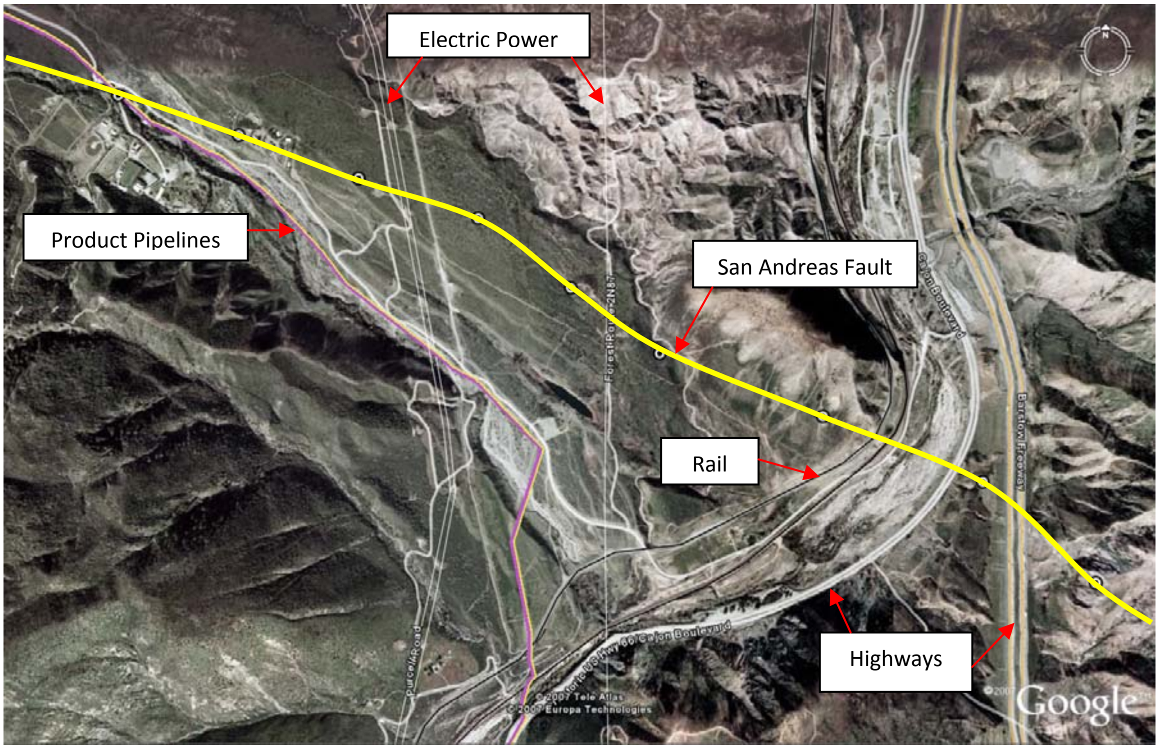

Figure 3. Oil, Electric Power, Highway, and Railway Lifelines in Relationship to the San Andreas Fault at Cajon Pass (Natural Gas Pipelines Not Shown).

Figure 4. Crater Resulting from Williams 26-inch Pipeline Explosion in Washington State, December 13, 2003. (Photo Credit - Washington Utilities and Transportation Commission)

Figure 5. Smoke Plume from 1999 Gasoline Fire in Bellingham Washington resulting from Product Pipeline Failure due to Third Party damage. (Photo Credit – City of Bellingham)

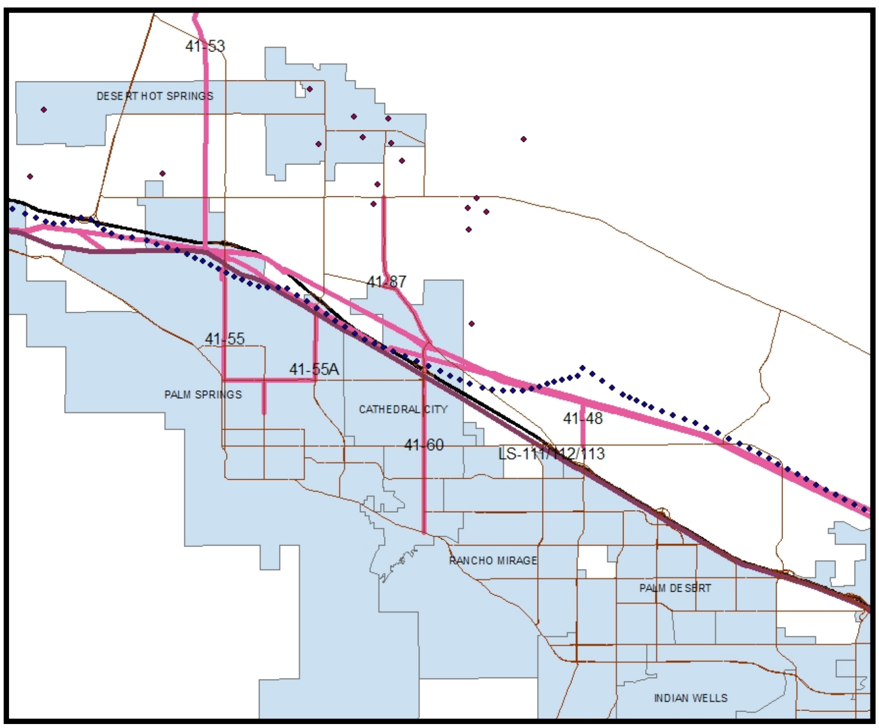

Figure 6. Layout of Kinder Morgan 20-inch Product Line (brown) and Southern California Gas Pipelines (pink). Relative the San Andreas Fault in Palm Springs (dotted).

Figure 7. Wrinkled Pipeline Failed in Compression

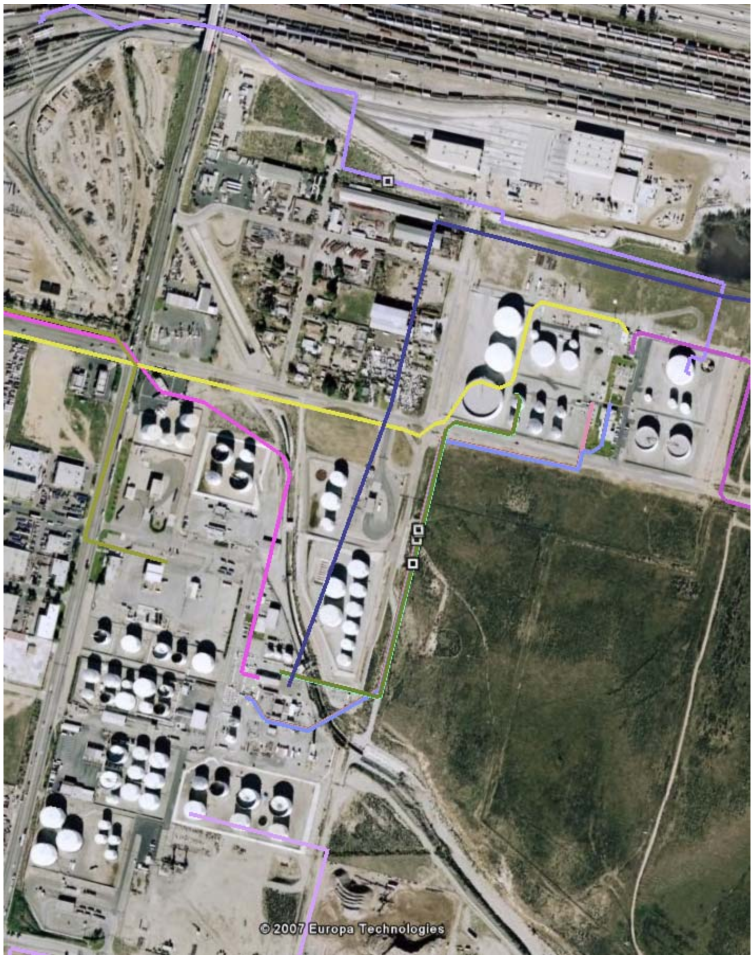

Figure 8. Colton Receiving Facility with Tank Farm Vulnerable to Earthquake Ground Motion