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Collocation Impacts on the Vulnerability of Lifelines During Earthquakes with Applications to the Cajon Pass, California

Study Overview

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COLLOCATION IMPACTS ON LIFELINE EARTHQUAKE VULNERABILITY AT THE CAJON PASS, CALIFORNIA

STUDY OVERVIEW

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STUDY OVERVIEW

EXECUTIVE SUMMARY

Lifelines are those systems and facilities that deliver vital services and products to a community. These include transportation facilities; electric power systems; fuel transmission pipelines and facilities; communication facilities; and such health facilities as drinking water and sewer systems. For a number of reasons, lifelines frequently are collocated or routed in close proximity to each other. The current emphasis on the use of "utility corridors" has increased the likelihood of lifeline collocation.

Under at-risk conditions, such as natural events like earthquakes or large storms or man-made disasters like train derailments or explosions, failures on one lifeline can increase the risks of subsequent damage on a collocated or nearby second lifeline. A 1989 train derailment just south of the Cajon Pass, California, damaged a collocated gasoline transmission pipeline. The subsequent explosion and fire destroyed a number of homes and resulted in several fatalities.

In response to these and similar accidents and disasters, the Federal Emergency Management Agency (FEMA) authorized this study of lifeline systems at the Cajon Pass, California (see Figure 1 on page 3), and how their collocation may influence each lifeline's vulnerability to failure during an earthquake event. The study has produced two important products:

1) the development of a management screening tool that can be used by lifeline owners, designers and providers, operators, users, and regulators to sort through numerous collocation conditions to identify critical locations and to provide an estimate of the increased risk that results when collocated facilities are subjected to an earthquake event; and

2) the analysis of the lifelines in Cajon Pass, California, to demonstrate how the screening tool can be used and to examine specific conditions in the Pass.

Important conclusions developed during the study include:

- Lifeline collocation can produce both benefits and increased risk of failure during earthquake events. For example, a benefit of closely located transportation lifelines is that the second lifeline can provide the detour or access route to the damaged sections of the first lifeline. However, the failure of one intersecting lifeline generally increases the risk of failure of the lifeline(s) it crosses.

- Topographic conditions understandably have led to the routing

of lifeline systems that repeatedly cross over each other. Additionally, Federal and State policies and requirements as well as economic considerations were a significant contributor to the decisions to collocate widely different lifelines in very close proximity to each other.

- o lifeline siting practices have not fully considered the serious impacts that one lifeline may have on another lifeline;

- o special design or routing considerations generally are not required where the lifelines cross known active faults; and

- o although it was found that each lifeline owner has prepared some type of study as to how they would respond to a earthquake event that damaged their lifeline system, the resulting analyses varied significantly in their scope and detail. As a result, lifelines at the same location are designed and operated to significantly different standards and accepted risk levels.

- o A very useful screening tool has been developed during this study. The tool can be used to identify the critical lifeline collocation locations and the conditions that make them critical. It can identify areas of technical uncertainty and poor siting practices, and its use can identify important research and development activities that can lead to lowered risk of collocation-inducted lifeline failures. It will be of value to lifeline owners, designers and providers, operators, users, and regulators. An improvements in earthquake analysis of lifeline systems are developed, they can be easily introduced into the screening tool method.

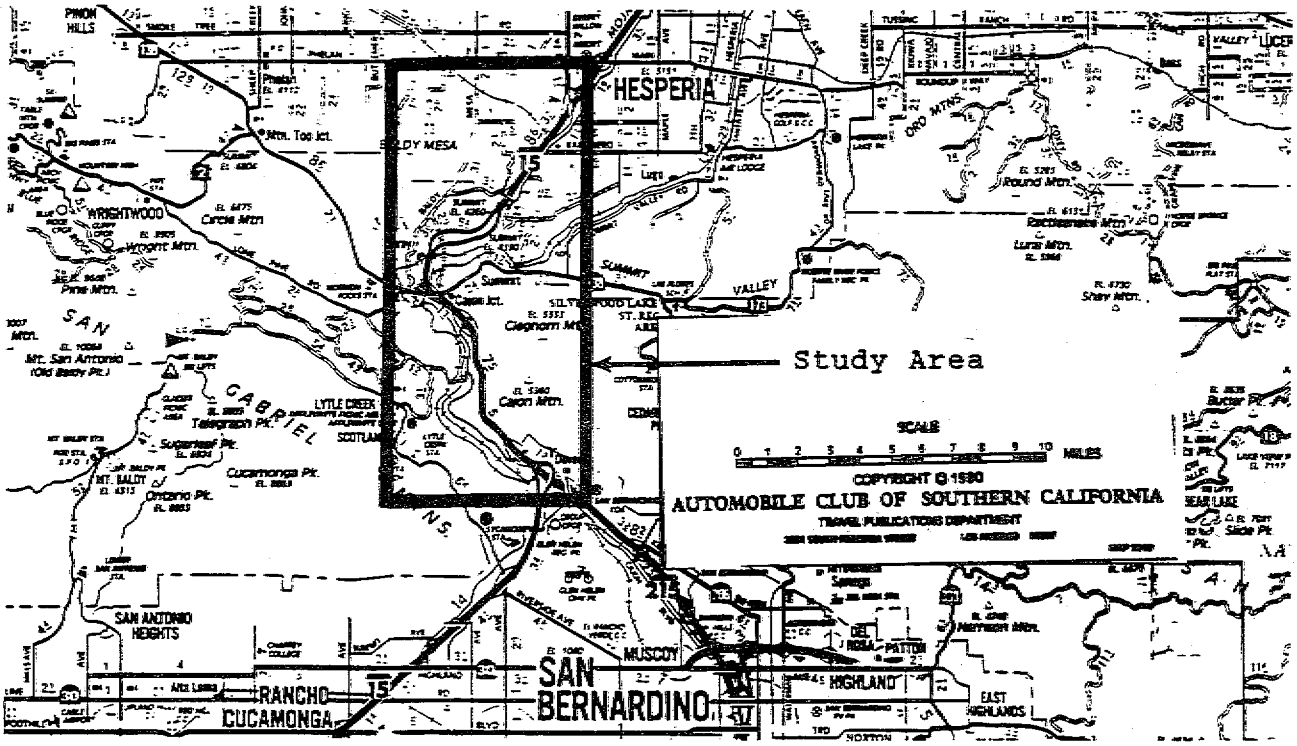
- o At the Cajon Pass over 100 separate collocations involving over 250 potential lifeline interactions were evaluated. The collocations evaluated are identified in Figure 2. In most cases there was a dominant lifeline failure that led to the principal impacts on the other collocated lifelines.

ADDITIONAL CONCLUSIONS

The development of the analysis methodology as well as its test application to the Cajon Pass has highlighted several additional important conclusions.

- o Earthquake shaking is the dominant factor that leads to building damage. Ground movement is more important for lifeline components, especially buried lifelines and electric transmission towers. There is considerable less available data base on earthquake-induced ground movement compared to shaking intensity data. This suggests that future studies need to emphasize obtaining ground movement information.

Figure 1: General Location of the Cajon Pass, California



- The analysis tool has been successfully applied to the Cajon Pass. It has identified for this semi-desert region that:

  The Cajon Junction, Lone Pine Canyon (which contains the San Andreas fault zone), Blue Cut, and the area just south of the interchange between I-15 and I-215 are the critical locations in terms of collocation impacts.

  Fuel pipeline failures have the greatest impact on other lifelines during the immediate recovery period.

  Current siting practices for fiber optic cables and increased reliance on these lifelines indicate that more severe telephone communication failures (than have been experienced in past earthquakes) can be anticipated in future earthquakes.

  Lifeline siting practices have not fully considered the impacts that a new lifeline will have on existing lifelines and visa versa.

  Transportation service restoration is highly dependent on sequential repair since the lifeline itself often provides the access to the next damage site. Parallel repair operations are more probable for the other lifeline systems. When multiple lifelines are collocated, repair times increase because of local congestion and the concern that work on one lifeline component could lead to damage on another lifeline component.

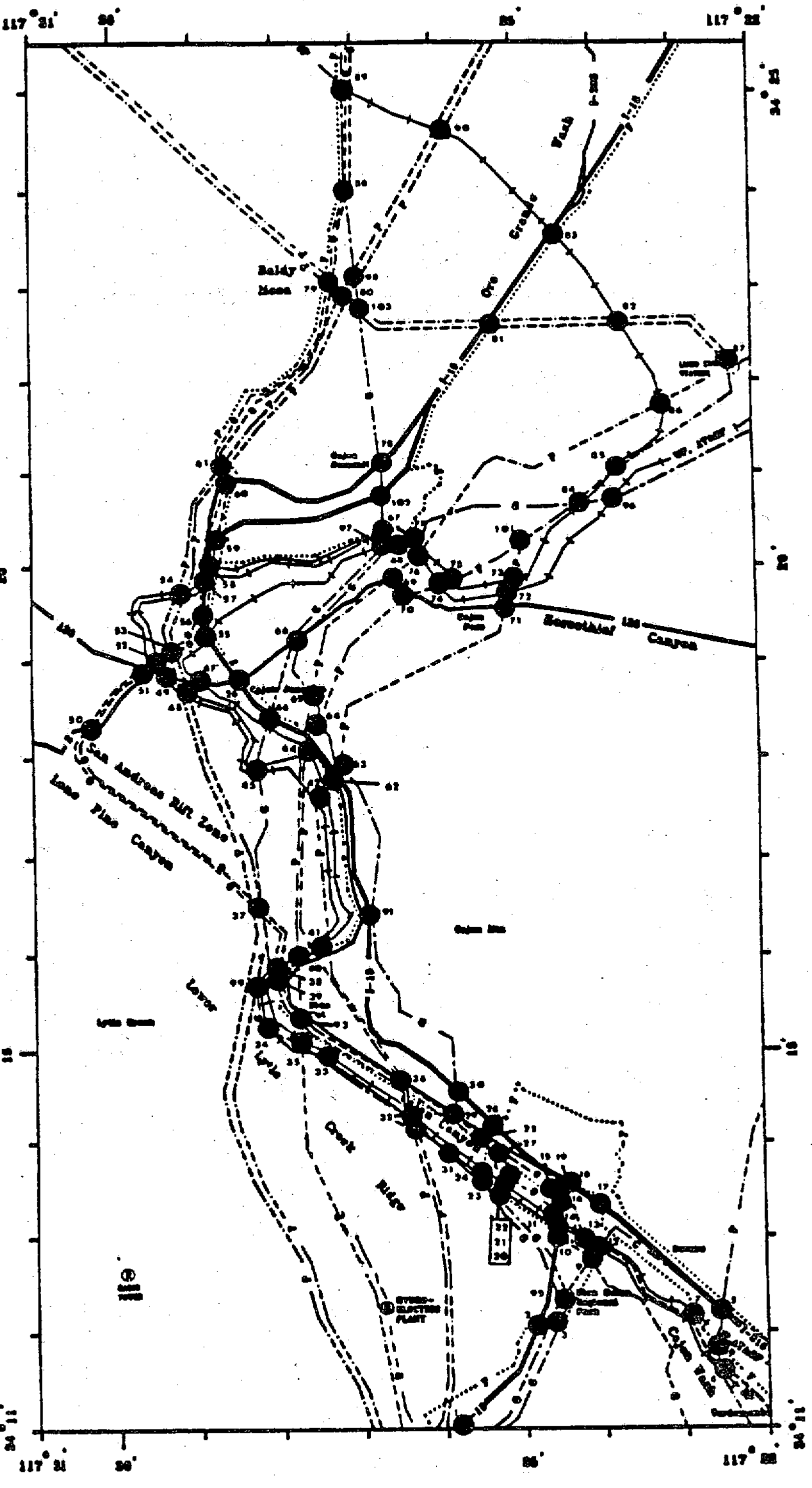
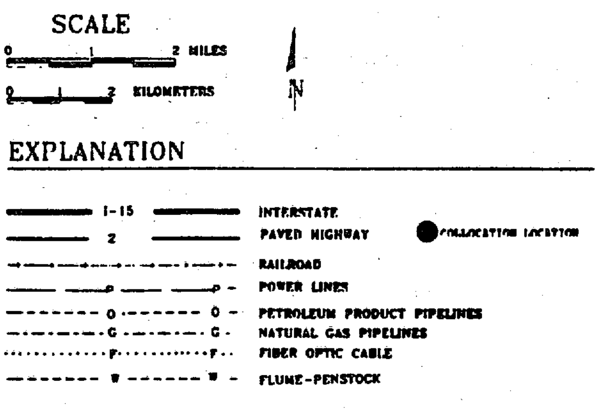


Figure 2: Identification of Lifeline Collocations at Cajon Pass



STUDY RESULTS

The Screening Tool

The screening tool is described in detail in the project report "Collocation Impacts on Lifeline Earthquake Vulnerability With Application to the Cajon Pass, California", August 1991. That report represents the first published work on how to systematically examine collocation impacts on lifeline vulnerability because of earthquakes. The specific details of the method are focused on earthquake response analysis, but the sequence of analysis steps could equally be applied to other regional natural disasters such as floods or hurricanes. In those applications, of course, new details on the response of individual lifeline components and systems to the forces generated during the disaster event would have to be identified and used.

In the case of earthquakes, the screening tool builds upon earlier FEMA studies that used collective expert opinion and actual lessons learned from specific earthquakes to identify the earthquake loadings on individual lifelines and each lifeline's subsequent damage state, the probability that the damage state occurred, and the time required to repair the lifeline back to its needed operational performance level. The analysis method emphasizes the need to conduct detailed site reconnaissance surveys to guide the selection of the specific earthquake/lifeline data from the FEMA-sponsored previous studies and from other local sources.

The screening tool introduces the concept of a "zone of influence" within which one lifeline failure could impact the performance of a second lifeline, and the "most probable restoration time". The latter relates the probability of actual damage occurrence with the sum of: the estimated time to obtain the equipment and material needed to repair a lifeline failure, the estimated time for the equipment and repair personnel to reach the damaged section of the lifeline, and the estimated time to repair the damaged section once the equipment and personnel have been assembled at the damage location. Once the critical collocations have been identified by the screening process, their total impact (which has been defined as the most probable restoration time) can be used to characterize the impact of lifeline collocation during the analyzed earthquake event. However, in many cases it would also be appropriate for subsequent, more detailed analyses of those collocation conditions to be performed to reduce the level of uncertainty and to identify specific, appropriate mitigation approaches that could be applied to each lifeline. This could involve conducting field examinations such as developing soil borings, and conducting detailed stress and equipment response analyses to further define the lifeline damage state.

The screening tool is an important development for several reasons:

1) it is the first documented method for examining multiple collocation conditions and it is applicable to all lifeline

facilities. As improvements are made in the fundamental analysis methods for individual lifelines or earthquake conditions, they can be readily introduced into the screening tool to improve its predictive ability;

2) its use can identify the most critical collocation conditions at a specific study area, thereby allowing limited resources to be focused on the most important conditions for improving the overall ability of the lifelines to survive an earthquake event;

3) its use can identify technical areas of uncertainty and/or poor siting practices. This can identify the need for and lead to further research and studies to reduce the identified technical uncertainty, or it can identify ways to mitigate siting practices that are more vulnerable to inducing collocation failure conditions; and

4) by being documented and made widely available by FEMA, it is anticipated that it will stimulate the earthquake and lifeline communities to developed improvements in the analysis method or even to develop new, improved screening methods.

Cajon Pass, California

The Cajon Pass is a natural opening between the San Bernardino and the San Gabriel mountain ranges. As such, it has been used for years as a major lifeline route between the Los Angeles coastal plain and the high desert regions. Included in the Pass are interstate and state highways, railways, and their bridges; natural gas and petroleum products pipeline systems; hydroelectric power generation, substations, and high voltage electric power transmission lines; and radio towers, fiber optic, and telephone tower systems. There are also a number of smaller, local, water and sewer systems, low pressure natural gas distribution pipelines, low voltage electric power distribution systems, and local wood pole-mounted telephone systems.

Figure 2 is a composite plot of all of the lifelines studied at the Cajon Pass. It shows that the lifelines are concentrated in a band that roughly follows the valley floor of the Pass. However, the close and crossing routings of the lifelines was not imposed by the topology of the Pass, as it varies from about 0.5 miles wide at its narrowest at Blue Cut to over several miles wide at the southern and northern ends of the Pass. The dark circles indicate the 101 collocation locations studied. The figure shows that although there are collocation sites all along the lifeline routes, they are mostly bunched into six or seven groupings. When the estimated earthquake impacts of landslide, ground liquefaction, and fault surface displacement were considered, it was found that the most significant lifeline damage was concentrated at about six locations.

From the study the following general results were identified.

Although there are many collocations for each lifeline, the controlling or major impact locations varied from one to eight, depending on the lifeline. In most cases, there was a dominant lifeline failure that led to the principal impacts on the other collocated lifelines. Thus, all the lifelines do not have to have postulated damage before a collocation effect can lead to problems. Conversely, communication lifeline failures have no immediate effect on the other collocated lifelines, although the collocation itself was judged to be the cause of the communication lifeline failure (for example, a fiber optic cable hung from a bridge as is done in Cajon Pass will fail from shaking intensities that are not strong enough to significantly damage the bridge).

Finally, some collocation may be a benefit since it provides for system redundancy within the lifeline system. However, collocating pipelines in the same trench or power transmission lines from the same towers does not add redundancy, it lowers the separate system reliabilities to the lowest value of the two lifeline (e.g., the weakest link sets the overall reliability of both systems). In general, intersecting different lifeline systems increase the most probable restoration time to return service on each individual lifeline system.

The additional minimum delay, due to collocation, before temporary service can be restored through the Cajon Pass was determined and is given below. The additional time is the increase in time due to collocation impacts compared to the estimated time to restore service if the lifeline were assumed to be isolated from any collocation impacts.

Lifeline	Minimum Additional Delay Before Temporary Service is Restored, days
Fiber Optic Telephone Communication	61
High Voltage Electric Power Transmission	19
Natural Gas Bulk Transmission	25
Petroleum Products Transmission	41
Interstate Highway Traffic	35
Railroad Service	17

Communication Lifelines

Within Cajon Pass there are several communication transmission towers: including radio, microwave, and cellular telephone towers. Since they are isolated from the other lifelines, they have no collocation impacts on the other lifelines. Also, there are wood poll-mounted and hard-wired telephone systems that essentially serve local customers within the Pass. They were not analyzed as this study examined the lifelines that serve regional customers.

From the southern section of the study area north to just below Cajon Junction the old Highway 66 (now a county road called the Cajon Blvd. extension) runs west and parallel to the new I-15 alignment. The eastern side of this divided road has been abandoned, and the western side has been converted to a two lane county road. Four fiber optic conduits (each with a capacity to hold two or three fiber optic cables) and two petroleum products pipelines have been routed in the median strip between the road beds. The fiber optic conduit installation was completed in 1989. In the study area, they were buried next to the two petroleum products pipelines for much of their route. The mechanical trenching equipment used during their installation damaged the pipelines at several location, requiring local pipeline repairs.

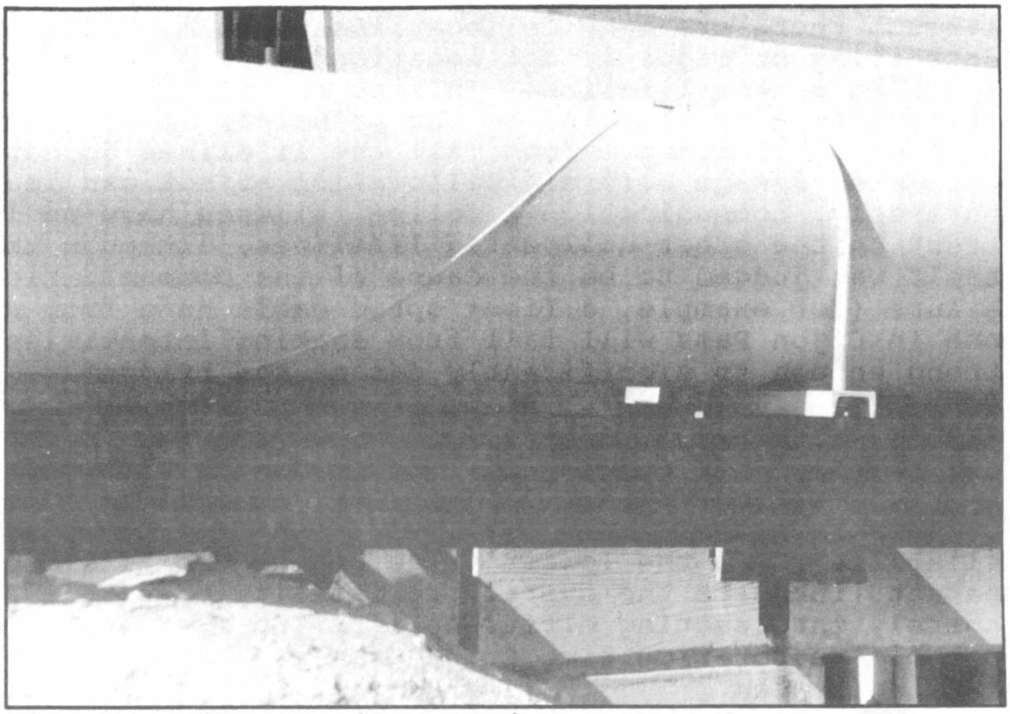


Figure 3 Fiber Optic Conduits Hung Under a Water Distribution Pipe on a Bridge Over a Railroad

At the bridge locations along the Cajon Blvd. extension, the fiber optic conduits are brought to the surface and hung from the bridges, using light anchoring systems. The practice of hanging the fiber optic cables from bridges and other lifeline structures is common throughout the Cajon Pass area, they are on bridges over railroads (see Figures 3 and 4) and on the bridges over the California Aqueduct. They are routed at the foot of a crib wall used to retain the I-15 road bed, after which they are brought to the surface and hung from the wall of a concrete culvert that passes under I-15. Figure 5 shows the details of the typical light wall anchors and supports that are used.

The communication lifelines (the fiber optic cable systems) had no impact on increasing the probable time to restore service for any of the other lifelines. The fact that all four cable conduits are routed together for much of their routes through the Cajon Pass increases the potential that these valuable lifelines will be lost during an earthquake event. The practice of hanging the conduits from bridges and other lifeline structures using very light anchor supports increases the risk of failure of these communication lifelines at earthquake shaking intensities which would not impact them if they had been buried or supported by more robust anchors.

Prior earthquakes have shown that the most vulnerable telephone lifeline component is the switching equipment. The current industry emphasis to shift from hard-wired to fiber optics, coupled with the co-routing of the fiber optic cables, is expected to increase the probability of telephone line failures during earthquakes. The co-routing removes system redundancy since an event that would cause the failure of one cable will probably fail all of the cables. The fact that the fiber optic cables transmit more calls per cable than do hard-wired systems means that the impact of a lost cable will be more significant than the impacts previously experienced when a hard-wired line has been lost. Finally, the construction practices do not appear to have considered earthquake impacts, further

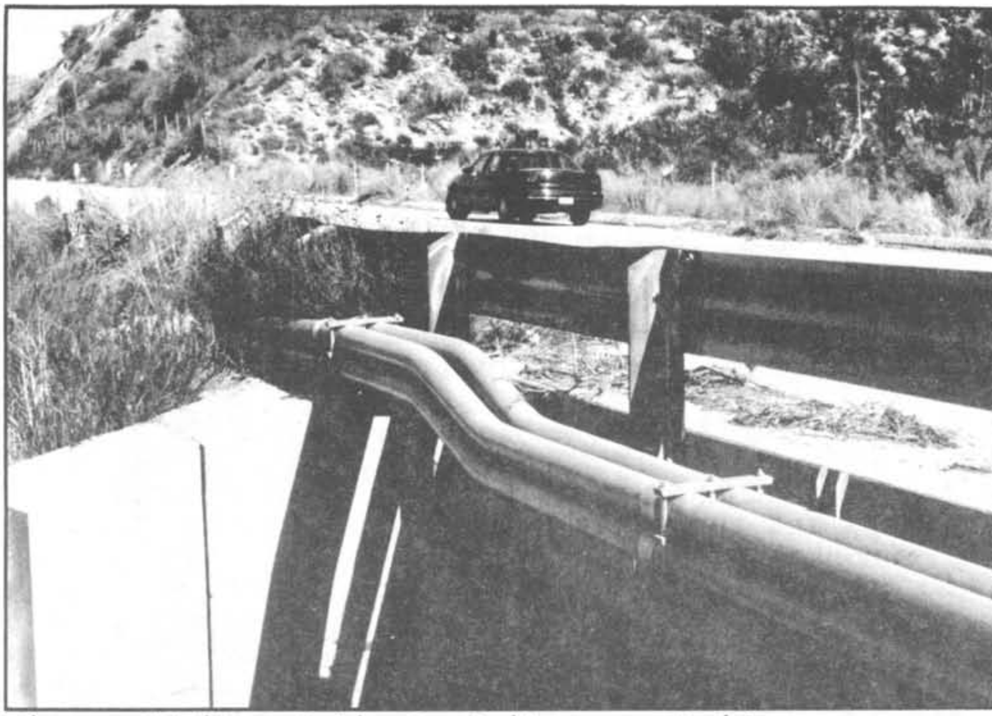


Figure 4 Fiber Optic Conduits on a Bridge on an Abandoned Portion of Highway 66

Figure 5 Details of Fiber Optic Conduit Supports on a Highway Culvert Wall

increasing the risk to the fiber optic systems. However, since these are not problems associated with collocation, they do not necessarily impact the results of the present study. The fact that a fiber optic cable fails on a bridge due to shaking failure of its anchor system is not a collocation impact if the bridge itself does not contribute to the failure.

Of the 55 fiber optic collocation conditions analyzed, nine were estimated to lead to increased probable times to restore the fiber optic systems to their intended service level. Most of the significant time impacts occurred because of ground movements (liquefaction and fault surface displacement) causing significant damage to a collocated fuel pipeline. The earth movement was hypothesized to fail the fiber optic cables, independently of the other collocation lifelines. Thus, the collocation impact was not a change in damage state, but an increase in both the probability of damage and the delay required to mitigate the hazardous environmental conditions so that workers could repair the fiber optic cables without undue risk to themselves. A special case was where the fiber optic cables were buried at the foot of a crib wall used to support the I-15 highway. Although the liquefaction condition was not severe enough to cause the failure of the highway, because the fiber optic cables are routed at the toe of the crib wall, any soil movement could damage them. Thus, the damage at the road was slight, but the delays in being allowed to retrench the cables was found to be significant.

As previously stated, the overall estimate of the impact of collocation was defined as the most probable restoration time, which was the time to restore service compared to the time to restore service if no collocations impacts were considered. For the fiber optic cables this calculated to be:

Lifeline	Increase in Probable Time to Restore Service, days	Increase in Probable Time to Restore Service, %
Fiber Optic Cables	61	86

Electric Power Lifelines

The electric power lifelines in the Cajon Pass include eight separate high voltage transmission lines (two public sector- and six private sector-owned lines), a major power substation (the Lugo substation located in the north east corner of the study area), and a hydroelectric power generation station. However, only the transmission lines are directly involved in collocation situations.

The two public sector-owned 287.5 kV transmission lines (City of Los Angeles owned) were constructed in 1936. Combined, they transmit about 600 MW of power. They are the western most transmission lines in the study area and are isolated from other lifelines through much of their route. They are routed basically from north to south, and they deliver power generated at Hoover Dam to Los Angles. Six private sector-owned high voltage transmission lines (Southern California Edison Company owned) are also routed through the study area. Three 500 kV lines (which transmit approximately 1,700 MW) travel southwest and then south from the Lugo substation to Mira-Loma substation (which is located outside of the study area). Two of these lines (#1 and 2) were installed in the early 1960s and upgraded to 500 kV in the early 1970s. The third line was added in 1983, and just south of the Lugo substation it is collocated on the same transmission tower system as is line #2. These three power lines and the two public sector-owned lines account for all of the significant electric power collocation impacts.

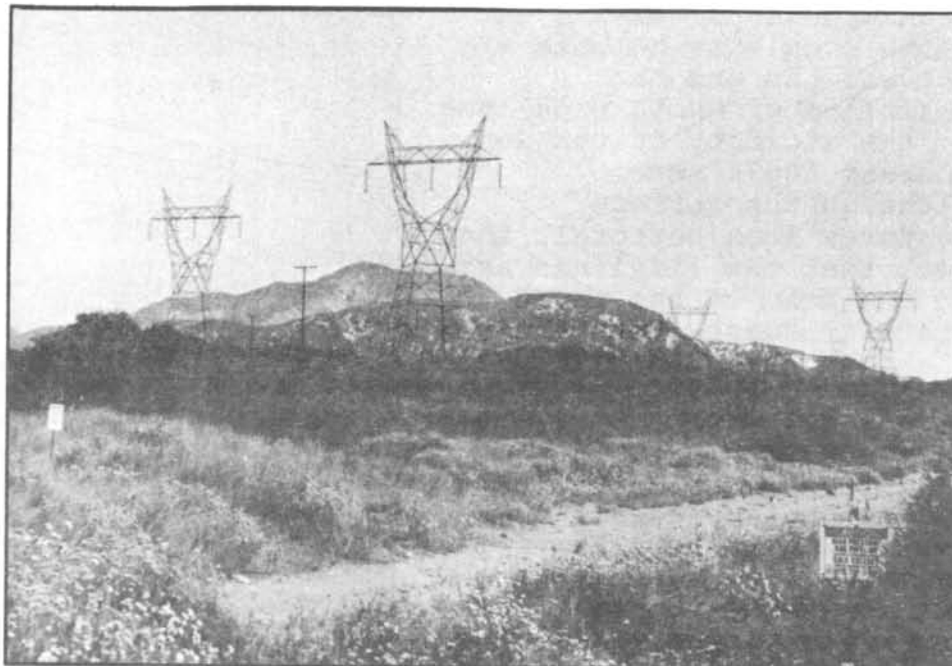


Figure 6 Power Line, Natural Gas and Petroleum Products Pipelines Over the San Andreas Fault

However, there are three additional privately owned high voltage power lines in the study area. Although these three lines have a number of intersections or collocations with other lifelines, the predicted earthquake intensities and lifeline damage are small enough that they have a minor collocation impact compared to the five transmission lines discussed above.

Failure of other lifelines generally will have a small impact on the electric power transmission lines since they are carried on towers well above the other lifelines. However, if fuel pipeline lifelines leak, the power transmission lines can provide an ignition source, and the resulting fire could result in significant damage to both the power lines and the other lifelines located in the flame path. The other earthquake condition of importance occurs when there is ground movement due to landslide, liquefaction, or fault displacement. This could cause the tower foundations to fail, dropping the transmission lines to a height where they could have a direct interaction with the other lifelines. With this in mind, the following describes where there might be such potential interactions.

Figure 6 shows the location where the two separate electric power transmission lines are in close proximity to both a natural gas and the petroleum products pipelines in the vicinity of the San Andreas fault zone. Although the surface features look pastoral, the fact that the lifelines are in the zone of the fault trace increases both their risk and the potential magnitude of the damage that could be induced. Figure 7 is a photograph in the opposite direction to the one shown in Figure 6. It shows an electric power transmission tower located at the edge of a steep embankment, suggesting that a foundation failure may also be a contributing factor to causing the power lines to drop to a height where they could readily interact with spilled fuel.

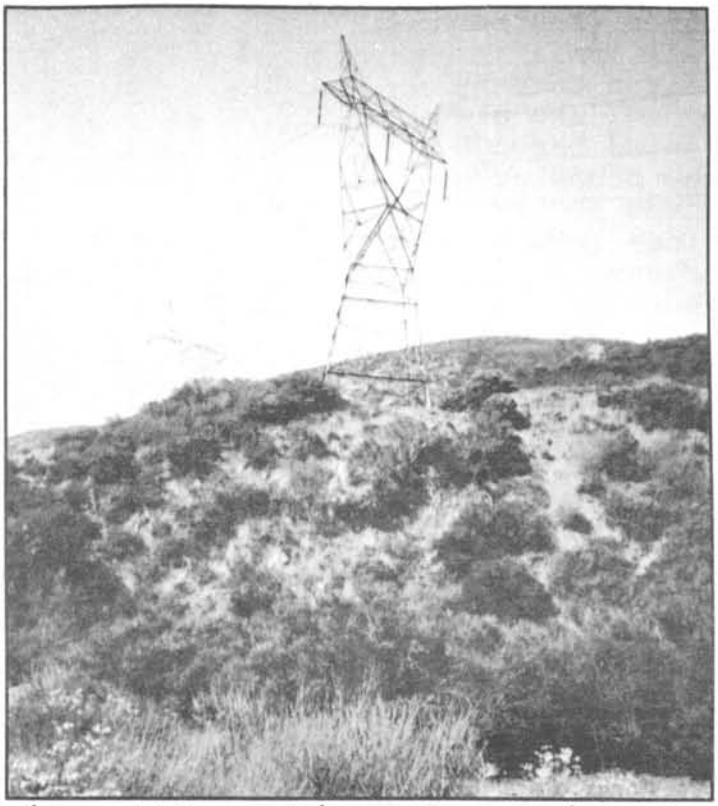


Figure 7 Power Lines At a Ravine Edge at the San Andreas Fault

South of the San Andreas fault zone there are two additional areas where the electric transmission lines pass through a region susceptible to landslides and where there are nearby railroad and buried natural gas pipeline lifelines. Figure 8 shows two transmission towers that were rebuilt when the prior ones were damaged by a local landslide. Not shown at the bottom of the figure are a buried natural gas pipeline and a railroad.

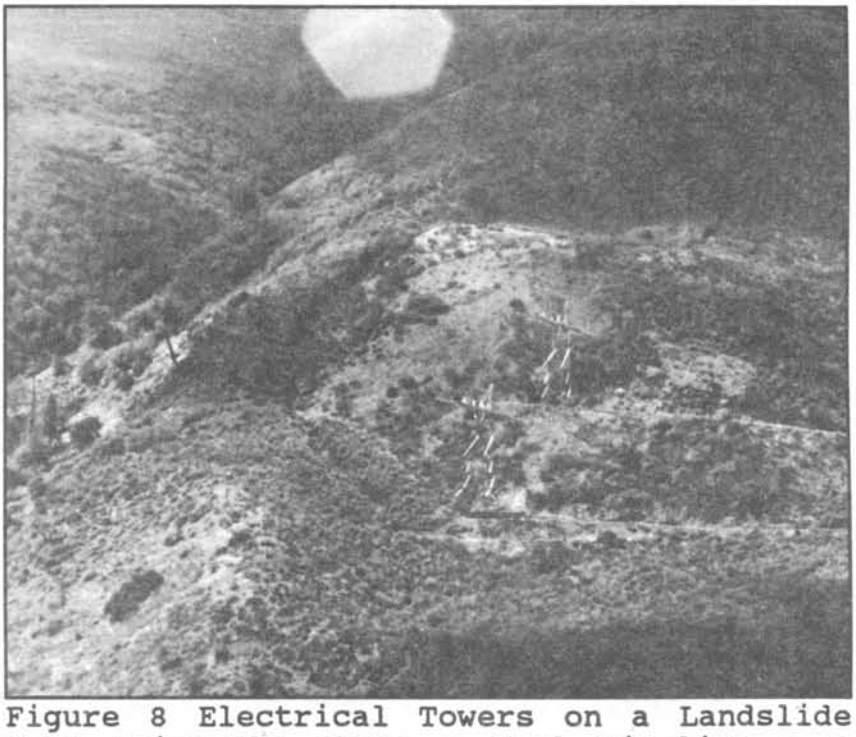


Figure 8 Electrical Towers on a Landslide Scar (Directly Above a Fuel Pipeline & a Railroad)

The electric power

transmission towers are quite resistant to shaking intensity. Although actual earthquakes have demonstrated that line vibration can cause separate circuits on the same pole or support tower to gallop and electrically short by either touching each other or by arcing between adjacent lines, this failure mode has not been characterized in the available data bases. Thus, only tower failure by ground motions was considered in the present analysis. Liquefaction and landslide conditions were identified as causing a light, moderate, and heavy damage state, depending on the local conditions; whereas, the surface displacement at the fault rift zone causes a catastrophic damage.

The collocation impacts at the landslide locations included increasing the damage state when there was a fuel pipeline present as well as increasing the time delay to initiate repairs due to the general congestion and the need to allow for debris removal from collocated railroad beds or environmental cleanup to remove the hazard from spilled fuels.

The overall estimate of the impact of collocation on the electric power lifelines was:

Lifeline	Increase in Probable Time to Restore Service, days	Increase in Probable Time to Restore Service, %
Los Angeles City Lines	49	28
So. California Edison Line 1 (Lugo-Mira Loma)	19	10
So. California Edison Lines 2&3 (Lugo-Mira Loma)	28	13

Fuel Pipeline Lifelines

Within Cajon Pass there are two fuel pipeline transmissions systems: natural gas and petroleum products lifelines.

Natural Gas Pipelines

From the north part of the study area traveling south, there are two 36-inch natural gas pipelines. Sections of the pipeline were installed in 1960, 1966 and 1976. They are operated at 845-936 pounds per square inch gage (psig). They presently supply about 600 million cubic feet of natural gas per day to the Los Angeles Basin, although their combined capacity is up to about 1 billion cubic feet per day.

One pipeline is routed south along Baldy Mesa Rd. (two petroleum products pipelines and two fiber optic conduits are also routed along this road), and the other is routed southwest and south from the eastern boundary of the study area. The two pipelines join at a valve station located between the railroads and Highway 138, north and east of Cajon Junction. From there one pipeline is routed south on the west side of I-15. The other is routed south but on the east side of I-15. The eastern most pipeline is buried throughout its route, the western most pipeline has 18 exposed locations with open spans ranging from 10 to 138 feet.

Figure 9 shows a section (north of Cajon Junction and next to Highway 138) where the two pipelines are routed parallel to each other. A 1990 realignment of Highway 138 (to remove curves) placed the exposed section of the one pipeline about 40 feet from the road bed. The gas line markers shown in the figure identify the route of the buried pipeline.

From that location, the western most pipeline heads south and crosses I-15. It continues south passing across Lone Pine Canyon just north of Blue Cut. The San Andreas earthquake fault zone is in that canyon, and the two petroleum products pipelines also are routed parallel and in the fault zone. Thus, when the natural gas pipeline crosses the petroleum products pipelines, it too is in the fault zone. In addition, two high voltage power lines cross within a few hundred feet from the pipeline intersections (see the discussion for Figures 6 and 7 for additional details about this collocation condition).

South from the San Andreas fault-pipeline-power line intersections, the natural gas pipeline follows the route of the railroad (it is located next to and frequently crosses beneath the track bed). At Blue Cut the railroad and natural gas pipeline are at the foot of a landslide prone region, and directly above them on the mountain (and also in the landslide zone) are high voltage electric power transmission lines. A similar situation exists about 2.5 miles further south.

From the valve station north and east of Cajon Junction, the other natural gas pipeline is routed east of I-15 until about a mile north of the I-15/I-215 intersection, where it crosses under I-15 and it eventually

Figure 9 Two Natural Gas Pipelines, One Exposed One Buried, Next to Highway 138

joins with the other natural gas pipeline. The mountains are steep along the eastern side of I-15, and there has been a prior case where a rain-induced landslide damaged the natural gas pipeline. After crossing under I-15, and about a mile north of the I-15/I-215 junction, the eastern pipeline crosses under the two petroleum products pipelines (which along with the fiber optic cable conduits are located in the median strip of Old Cajon Canyon Rd.). This is a region of high water table subject to possible liquefaction during an earthquake event.

After the two natural gas pipelines join together they are routed under I-15 to a valve station and then south out of the study area. At the valve station a third 16-inch distribution pipeline leaves the valve station to provide gas to cities of Devore and San Bernardino.

The buried natural gas pipelines are relatively insensitive to earthquake shaking. The present study did not estimate the natural period of the 18 exposed sections of the western most 36-inch pipeline, but it is possible that they could be impacted by shaking intensity if their resonant frequency is close to the earthquake vibration frequencies. The principal cause of damage for the pipeline was earth movement due to landslide, liquefaction, and fault displacement. Since the movements result in catastrophic failure of the pipe, the collocation impact does not increase the damage state but it increases the time delays for beginning restoration work. The dry climate of the study area means that the unpaved roads provide sufficient access to the damage sites, freeing these lifelines from dependance on the transportation lifeline availabilities. Of the 61 collocation locations examined, eight contributed to the estimated increase in probable restoration time.

There were two key collocation impacts at locations were ground movement occurred. One was the spilling of petroleum products at liquefaction areas. This was assumed to cause a delay in being allowed access to the damage site while the environmental hazard was removed. At the landslide locations it was assumed that the debris on the railroad bed above the pipeline had to be removed and then the pipeline exposed and inspected for damage. This was required to lower the risk to workers that the construction activities could damage the pipe, causing leaks would be too great a risk to allow them to work with a pressurized pipeline directly below them. Conversely, if a leak had occurred during the landslide, then the collocated high voltage power lines directly above could cause an explosion and fire, increasing the potential damage level. Either case would lead to a delay in the restoration of service.

The triple collocation of high voltage power lines, petroleum pipelines, and natural gas pipeline at the San Andreas fault rift zone caused the largest single delay due to the resulting fire, the need to remove spilled fuel that failed to burn, and the general level of confusion and construction expected at that location.

Petroleum Products Pipelines

There are two petroleum products pipelines in the Cajon Pass. An 8-inch line was installed in 1960, a 14-inch was installed in 1969-1970, and a portion of the 8-inch line was rerouted in 1980 to place it next to the 14-inch line. The two lines operate at 1060-1690 psig and transfer about 80,000 barrels per day of product. They are the primary fuel source for several military air stations and provide the bulk of the gasoline used in the Las Vegas area. The locations where they are routed in close, parallel trenches reduces their overall reliability as a failure to one pipeline is expected to lead to the subsequent failure of the other. A train derailment in 1989 in San Bernardino led to a rupture of the 14-inch pipeline and to subsequent fires and fatalities (this event was specifically identified in the congressional authorization for the present study).

The 14-inch pipeline enters the study area from the south along a railroad right-of-way. It periodically crosses back and forth under the track bed. As previously indicated, just south of the I-15/I-215 intersection it passes through a potentially liquefiable area along with the railroads, a natural gas pipeline, and most of the fiber optic conduits. North of that junction it is joined by the 8-inch petroleum products pipeline and the fiber optic conduits and they all are routed along and within the median zone of the abandoned Highway 66. About a mile north of the I-15/I-215 intersection, the two petroleum products pipelines enter a potentially liquefiable area. There they are crossed at right angles by a 36-inch natural gas pipeline.

At Blue Cut the two petroleum products pipelines separate from the fiber optic conduits, cross the Cajon Creek, continue northwest, and then turn and run parallel to and within the San Andreas earthquake fault zone (this is Lone Pine Canyon). As previously discussed, they cross a 36-inch natural gas pipeline and are near to two high voltage electric power transmission lines collocated in this region.

The petroleum products pipelines are similar to the natural gas pipelines in their response to the earthquake loadings. Thus, they are insensitive to the shaking intensities experienced at the Cajon Pass, but are sensitive to ground movement. Since the movements anticipated generally lead to catastrophic failures, the collocation impact is similar to natural gas pipeline case: an increase in the time delays to initiate restoration work. Of the 32 collocation locations analyzed, eight contributed to the collocation impacts.

In general, the petroleum products pipelines contributed more to the delays in initiating repair for the other collocation lifelines than did the other lifelines' impact the petroleum products pipelines. This is because the spill of the petroleum products was one of the more significant impacts. Liquefaction was the primary cause of the ground displacements that impacted these lifelines, but the probable increase in restoration time only ranged from two to nine days. However, the impact at the San Andreas fault was probably underestimated by the screening tool. There the increase in probable restoration time was estimated at 30 days, but the fact that the pipelines parallels several miles of the fault indicates that there should be multiple pipe failures. There is a strong possibility that the regulatory authorities would not allow the pipeline to be rebuilt along the fault trace, thus the earthquake could lead to the requirement to negotiate new rights-of-ways, further increasing the estimated probable restoration of service delay (but the increase would not be attributable to collocation).

The overall estimate of the impact of collocation on the fuel pipeline lifelines was:

Lifeline	Increase in Probable Time to Restore Service, days	Increase in Probable Time to Restore Service, %
So. California Gas Western 36-inch line	57	64
So. California Gas Eastern 36-inch line	25	83
So. California Gas 16-inch distribution line	8	80
CALNEV Petroleum Products 8- & 14-inch lines	41	63

Transportation Lifelines

Highways

The Cajon Pass contains Interstate Highway I-15 and part of the I-215 connector to San Bernardino. This highway system was originally completed in the late 1960s. It presently carries about 60,000 vehicles per day, on weekends this traffic includes about 28% large trucks. The other major paved highway is the State Highway 138, and the intersection of I-15 and Highway 138 forms Cajon Junction. In addition to these paved roads, there are numerous unpaved roads used for fire equipment access, for maintenance routes for the other lifelines, and for general off-road recreation. The dry climate of the region means that most of the unpaved roads are fully accessible throughout the year.

The highway bridges and road beds, in general, are not subjected to damage from other nearby lifelines. The exception is when a railroad bridge crosses over a highway. At such locations, the failure of the bridge has a direct impact on the highway. Figure 10 shows one such bridge. Because of its skew and simple supports, the bridge was estimated to collapse onto Highway 138, effectively removing that segment of the road as a bypass or detour route for traffic past I-15's damaged sections. It is noted that the bridge span that crosses Highway 138 is the right span in the Figure. Very close to this bridge was a highway bridge over the railroad. Even though it had the same amount of skew with respect to the road alignment, its continuous column design is more robust and it was not estimated to collapse onto the railroad. None of the highway bridges were predicted to completely collapse, although partial collapse is possible. Fortunately, the "diamond" interchange design used in the Pass provides a direct detour route (although one with reduced capacity compared to the I-15 road beds) past any partially damaged bridge.

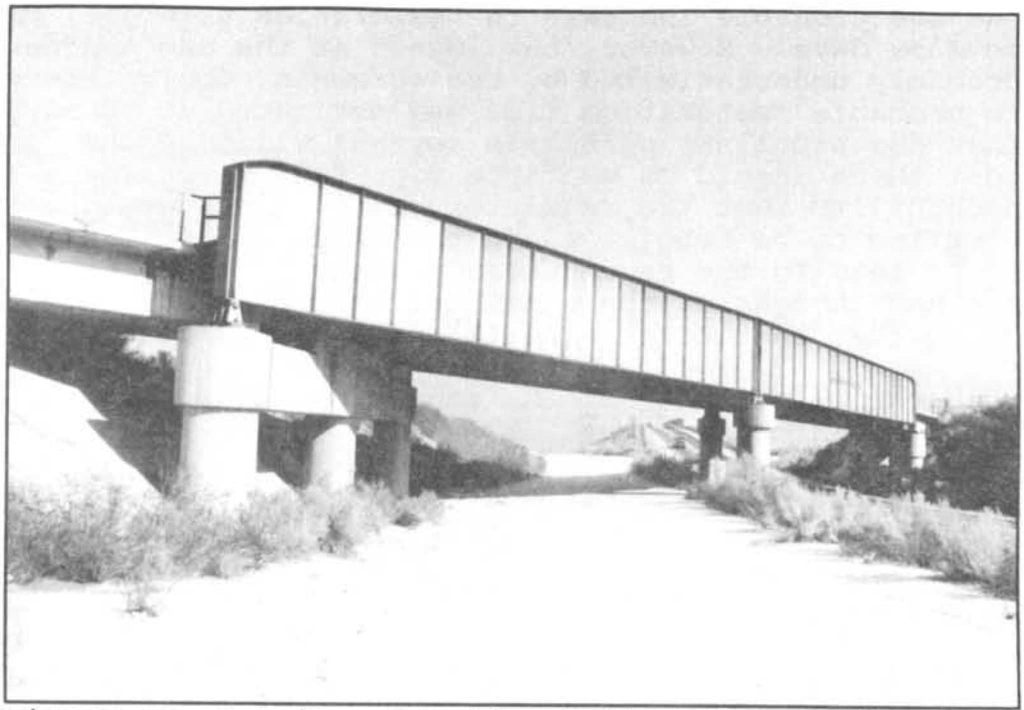


Figure 10 A Railroad Bridge Estimated to Collapse Onto Highway 138 (Highway 138 is located under the right span)

Railroads

Three railroads (the Southern Pacific, the Union Pacific, and the Atcheson Topeka and Santa Fe (Santa Fe)) generally run north-south through the Pass. Most of the bridges are over 50 years old, and the railroads were unable to provide descriptive material on their design or their foundation conditions. The track bed receive regular maintenance, and some realignment has been done to eliminate the need for tunnels. About 75 trains per day travel through the Pass.

The Union Pacific and the Santa Fe actually share track over part of the Pass (sharing track is one of the positive aspects of their collocation, it provides a redundancy for each of the railroads), using one track for south bound traffic for both lines and the other track for north bound traffic.

Buried next to and along side much of the rail track in the southern half of the study area are either a 36-inch natural gas pipeline or a 14-inch petroleum products pipeline (its principal product is gasoline). At several locations the rail bed (along with the buried pipeline) are located at the foot of potential landslide regions, and on the hillside above the railroad and within the landslide zone are high voltage electric power transmission lines. In the northern part of the study area there are a number of small railroad bridges, often with a fiber optic conduit or a natural gas or petroleum products pipeline routed under the rail bed next to the bridge.

The bridges (see Figure 11) over the Cajon Wash (in the southern part of the study area) are in a localized region of high ground water tables, thus the ground could be subjected to liquefaction during an earthquake event. Also in this general area are buried 36-inch and a 16-inch natural gas pipelines, a 14-inch petroleum products pipeline, and fiber optic cable conduits.

The application of the screening tool to the highways and railroads identified that failures of collocated lifelines, other than transportation lifeline components, do not increase the damage level in nearby transportation lifelines. That is, the failure of a fuel pipeline or an electric power transmission line is not expected to increase the damage level sustained by the highways, railroads, or their bridges. Fuel spills can, however, increase the time delay before work on the transportation system can be initiated. That is because there is a delay time required to clean up the fuel so that repair workers on the transportation lifeline are not put at risk due to the potential fire hazard from the spilled fuel. Similarly, in cases where high voltage electric power transmission lines sag or otherwise become close to the transportation lifeline component, the power line must be de-energized or permanently restored before heavy, large equipment needed for the transportation lifeline repair can be used. This too can delay

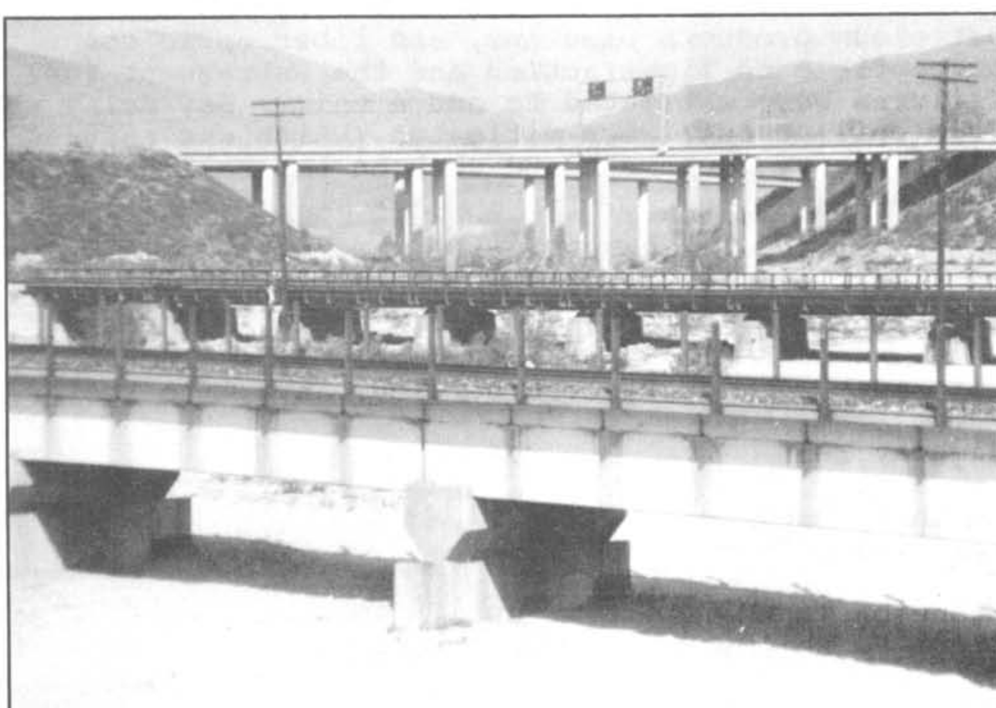


Figure 11 Railroad and I-15 Bridges in Cajon Wash Subject to Liquefaction Damage

the start of repair work on the transportation lifelines.

The collocation of the transportation lifelines is both a benefit and a problem. Nearby roads or railroads can provide the access or detour route for the large equipment needed to repair a damaged bridge or road or rail bed. This redundancy is a benefit. However, the collapse of a bridge over a highway or railroad is a case of one transportation lifeline component interrupting the ability of the collocated transportation lifeline from functioning. This, in fact, was the major cause for the increase in the calculated time to restore the I-15 highway to its needed service level.

In the case of the railroads, two locations were the major contributors to the increase in the time to restore service. One location was at Blue Cut where the railroad is collocated with a buried natural gas pipeline (buried in the railroad right-of-way) and two high voltage power transmission lines. The railroad and pipeline are in the toe of a landslide zone and the power lines are above and also in the slide zone. The major impact on the railroad would occur if the pipeline had no noticeable ruptures. In that case, the railroad repair would be delayed until the pipe could be exposed and inspected to assure that it was not leaking gas. Alternatively, the work on the railroad could continue and the gas line should be shut down until the railroad work had been completed. Then the gas line would be exposed, inspected, and returned to service after it was confirmed that it was safe.

Just south of the intersection of I-15 and I-215 (see Figure 12), the railroads are collocated with a natural gas pipeline, a petroleum products pipeline, and fiber optic conduits. The area is susceptible to liquefaction and the subsequent fuel pipeline failures were estimated to add a thirty day delay while the hazards from spilled fuel were mitigated (which was assumed to be necessary before heavy equipment and work on the railroad bridges could commence).

The overall estimate of the impact of collocation on the transportation lifelines was:

Lifeline	Increase in Probable Time to Restore Service, days	Increase in Probable Time to Restore Service, %
Highway I-15	35	22
Southern Pacific Railroad	17	8
Atcheson Topeka & Santa Fe Railroads	85	33

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