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RAILROAD LIFELINE DAMAGE IN EARTHQUAKES

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SUMMARY

A number of earthquakes have significantly affected railroads. Information regarding these effects is scattered through the literature on earthquake effects. The coverage is uneven, ranging from mention without description to the dedication of an entire volume to a detailed description of earthquake damage to the Alaska Railroad in the 1964 Alaska earthquake. Information, from the literature and from personal observation and correspondence, on the effects of about 90 of these earthquakes, beginning with the 1886 Charleston, South Carolina earthquake and ending with the 2003 Colima earthquake, is summarized and illustrated by examples from specific earthquakes. Characteristics of damaging earthquakes, damage mechanisms, effects on operations and recovery are summarized and illustrated by examples from various earthquakes. Derailments and damage to bridges, tunnels, tracks and roadbed, railroad buildings and signal and communication facilities, are described along with damage to other facilities that affected railroad operations. The extent of the affected regions is summarized for the10 earthquakes for which distances of railroad damage from the epicenters could be determined. Based on available information, it appears that, with some exceptions, recovery planning is likely to be more effective than retrofitting to reduce damage.

INTRODUCTION

A number of earthquakes have significantly affected railroads. The effects range from restriction or suspension of operations on a portion of the railroad, while earthquake effects are assessed by inspection, to extreme damage over large areas. Information regarding these effects is scattered through the literature on earthquake effects. The coverage is uneven since railroad damage is only occasionally covered in separate reports and severe railroad damage has been overlooked in general reports of earthquake damage. The reports on railroad damage range from mention without description to the dedication of an entire volume, by McCulloch and Bonilla [1], to a detailed description of damage to the Alaska Railroad in the March 27, 1964 earthquake.

Information, from the literature and from personal observation and correspondence, on the effects of 89 earthquakes that have damaged railroads, beginning with the 1886 Charleston, South Carolina earthquake and ending with the 2003 Colima, Mexico earthquake, will be summarized and illustrated by examples from specific earthquakes. The earthquakes include 42 in North America with over 1/3 in the California transform zone, 18 in Japan, 12 in Eurasia, 6 in South America, 4 in New Zealand, 4 in Central

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America and one each in Africa, Taiwan and the Philippines. Three additional earthquakes in North America are reported to have caused rolling stock to move on the track without any report of damage. Since about 90 percent of these earthquakes were identified only through the literature, their distribution reflects the completeness of reporting for various regions as well as the regional frequency of damaging earthquakes and the density of railroads in the regions.

DAMAGING EARTHQUAKES

Characteristics of Damaging Earthquakes

Since earthquake intensity depends on both the distance from the fault rupture and local conditions as well as the magnitude and depth of the earthquake, the extent of railroad damage is only indirectly related to the characteristics of the earthquake. However, some trends are apparent in the characteristics of damaging earthquakes.

Forty-six of the 89 damaging earthquakes occurred in subduction zones. Of these, 15 occurred on the interface between the overriding plate and the subducting slab. Nine occurred in the plate and 8 in the slab. Information to define the remaining 14 was not available. Eighteen of the earthquakes occurred in transform zones. Sixteen occurred in plate interiors with 5 of these, arguably, in diffuse plate boundary zones. Six occurred in continental collision zones. Three occurred near triple junctions. One occurred in a continental rift zone. Thirty-two earthquakes were identified as thrust type ruptures, occurring on reverse faults or on the plate interface in subduction zones. Seventeen earthquakes occurred on strike-slip faults and 7 on normal faults. Six of the thrust earthquakes and one of those on normal faults were identified as oblique with slip angles between 30 and 60 degrees. Two earthquakes were complex, involving strike-slip and reverse faults. One complex earthquake involved strike-slip and normal faults.

Forty-nine earthquakes caused severe to extreme damage. Forty-eight of these had magnitudes between 6.0 and 9.5. One of them, the 1899 earthquake near Watsonville, California, had its estimated magnitude reported by different sources as 6.0 and 5.6. Twenty-four earthquakes caused moderate to significant damage. Magnitudes, ranging from 5.8 to 8.9, were reported for 22 of them. Sixteen earthquakes caused slight to minor damage. Magnitudes, ranging from 4.0 to 8.5, were reported for 15 of them. Hypocenter depths were reported for 71 earthquakes. Eleven of these caused only slight to minor damage. Of those causing moderate to extreme damage, 45 had reported depths of 33 km, the USGS default depth for shallow earthquakes, or less. Fourteen had depths in the 40 km to 80 km range. One had a reported depth of 102 km. Hypocenter depths and magnitudes for the 60 earthquakes causing moderate to extreme damage, which had their depths reported, are plotted in Figure 1.

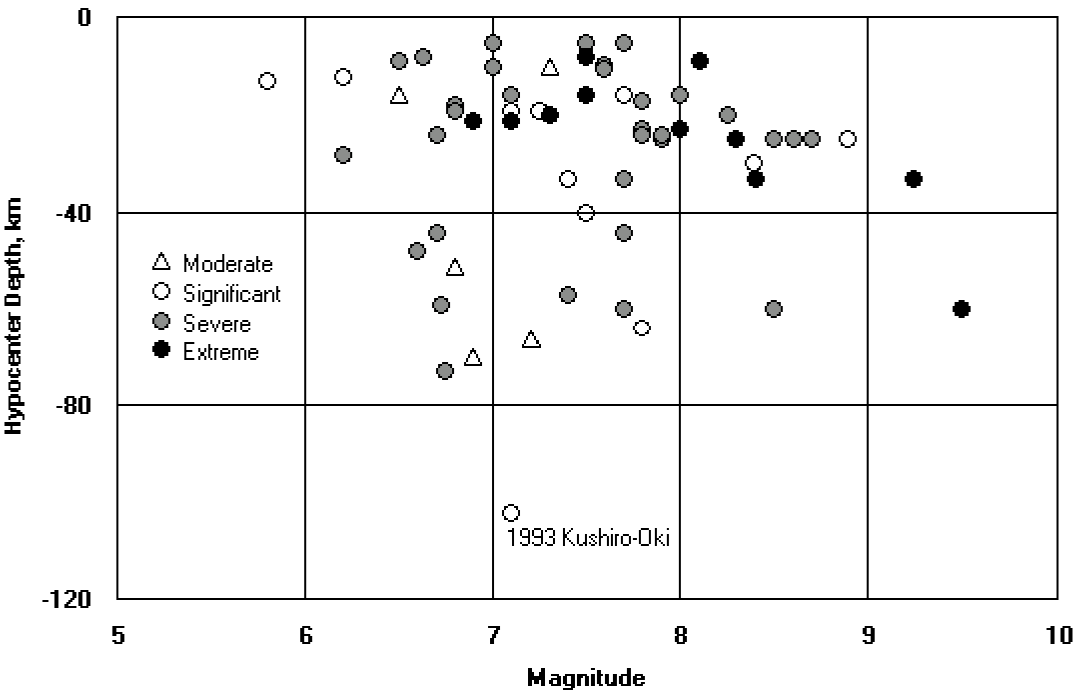

Figure 1. Severity of railroad damage related to magnitude and depth of 60 damaging earthquakes.

Damage Mechanisms

Damage from earthquakes occurs through several mechanisms. Surface displacements across the fault rupture can directly damage facilities that cross the rupture or, if under the ocean can cause tsunamis. Shaking from seismic waves can derail cars and locomotives, can directly damage structures, can produce permanent ground movements related to liquefaction and landslides and can cause damaging floods from dam failures. Appropriate measures to minimize damage or facilitate recovery depend on the mechanism causing the damage.

In 7 earthquakes, the surface trace of the fault rupture crossed the railroad alignment at one or more locations. In the 1906 California (San Francisco) earthquake, it crossed under a bridge at a relatively flat angle causing separation of piers. In the 1999 Kocaeli, Turkey earthquake, tracks were crossed at 3 locations on the line between Haydarpasa (Istanbul) and Ankara causing offsets in alignment at large crossing angles and pulled-apart rail joints at a flat angle crossing. At one large angle crossing, the track alignment was readily corrected but track surface could not be maintained during an extended period of time due to lack of support under the subgrade. In the other 4 earthquakes, tracks were offset horizontally and/or vertically by various amounts. Tsunamis associated with 7 earthquakes caused significant to extreme damage. Damage included bridge spans washed off piers, washed out embankments, and locomotives and cars derailed or overturned by the waves. Flooding from dams ruptured by the 1886 Charleston, SC earthquake washed locomotives and cars of 2 trains off the track, resulting in at least one fatality.

Ground acceleration, without secondary effects, such as liquefaction, caused a significant part of the damage in most of the earthquakes. Locomotives and cars, both standing and in moving trains, were derailed or overturned by earthquake accelerations in 15 earthquakes. In 15 of 49 earthquakes causing bridge damage, the damage resulted from shaking at locations where no permanent ground movement was involved. Shaking resulted in other damage, mainly to signal systems and buildings, in 31 earthquakes. In 4 of these, spans of overpasses fell on the tracks. In one case, the span fell on a passing train. Ballast was sufficiently disturbed by shaking to affect track stability in a number of earthquakes. Earthquake-induced rockfalls and landslides in cuts damaged railroads in 26 earthquakes. Earthquake-induced movement along secondary faults, which crossed the tunnels, caused damage to tunnels in several earthquakes. Liquefaction and associated lateral spreading was a factor in many of the 61 earthquakes that damaged track and embankments, as well as in most of the approximately 30 earthquakes causing bridge damage due to permanent ground displacement. Damage included buckling of trestles, displacement of bridge piers, buckled track, pulled apart rail joints and settlement of embankments.

Distribution of Damage

The geographical distribution of earthquake damage usually assumes a roughly elliptical shape with the major axis parallel to the fault rupture, but the severity is strongly influenced by local conditions. Information on the distribution of railroad damage is available for a limited number of the earthquakes. The distances from the epicenter at which damage occurred are strongly related to the relative position of railroad facilities and directional effects of the earthquake. The maximum distances of railroad damage from the epicenters of 10 strong to great earthquakes are given below.

- M9.2 1964 Alaska – Track and bridge damage up to 150 miles (240 km)
- M8.4 2001 Atico, Peru – Track damage up to 290 km
- M8.0 2001 Gujarat, India – Track damage to 60 km, building damage to 200 km (severe to 130 km)
- M7.8 1999 Kocaeli, Turkey – Minor tunnel damage up to 90 km
- M7.7 1999 Chi-Chi, Taiwan – Track damage from liquefaction to 55 km
- M7.6 2003 Colima, Mexico – Track damage from large rockfalls up to 120 km or 215 km (The location of the epicenter is uncertain.)
- M7.5 1952 Kern County, CA – Extreme tunnel damage to 30 miles (50 km)
- M7.4 1999 Hector Mine, CA–Bridge and track damage to 15 miles (10 km), signal damage to 25 miles (40km),
- M6.9 1995 Kobe, Japan – Extensive track and bridge damage to 45 km
- M6.8 2001 Nisqually, WA – Bridge damage to 35 miles (55 km), signal damage to 70 miles (110 km)

EXAMPLES OF DAMAGE

Derailments and Related Effects

Locomotives and/or cars were derailed or overturned in 23 earthquakes. Standing locomotives or cars were moved on the track without derailing in 4 other earthquakes. A maintenance-of-way inspection vehicle was derailed in one earthquake. In the M6.8 Nisqually, M7.8 Kocaeli (Izmit), M8.0 Gujarat (Bhuj) and M8.4 Atico (southern Peru) earthquakes, there were trains operating in the affected area at the time of the earthquake which did not derail and were able to proceed to an appropriate location to stop. However, 3 loaded tank cars standing in a yard were overturned in the Gujarat earthquake. The crew of one train in Gujarat thought the train had derailed when they felt the earthquake but determined, after inspecting the train, that it had not. Four of the derailments due to earthquake accelerations involved trains in the near field on tracks parallel or sub-parallel to the fault rupture. Two others were in areas where the general alignment was more or less parallel to the fault but the alignment at the point of derailment could not be determined. In 8 additional incidents due to earthquake motion, the relative orientations of the fault and track could not be determined. Two derailments were caused by track conditions resulting from the earthquake. Locomotives or cars were washed off the tracks by 2 tsunamis. Floods from 2 dams, which were broken in the 1886 Charleston, SC earthquake, both washed locomotives and cars of trains off the track. A flash flood caused by an earthquake-induced landslide in the 1923 Kanto earthquake washed a stopped passenger train into the ocean, as reported by the Japanese Bureau of Social Affairs [2]. The

Office of the Engineer, General Headquarters, Far East Command [3] report on the1948 Fukui earthquake describes derailments due to settlement of tracks under standing equipment in addition to the derailment of trains due to ground shaking described by Takahasi [4].

Damage to Bridges

The behavior of railroad bridges in earthquakes varies widely. There was no railroad bridge damage in the M_w 7.5 Kern County, California, the M_s 7.8 Kocaeli, Turkey or the M_w 8.4 Atico, Peru earthquakes. In all 3 of these earthquakes, there was severe damage to other railroad facilities in the immediate vicinity of bridges. On the other hand, bridges are known to have been damaged in 48 of the 91 earthquakes, with severe to extreme damage in 25 and moderate to significant damage in an additional 17. In 40 of the 48 earthquakes for which bridge damage was reported, other railroad damage was also reported. The type and extent of bridge damage was strongly influenced by design details, foundation conditions and liquefaction potential at the bridge site.

In the 1995 Kobe earthquake, there was extensive collapse of concrete rigid frame viaducts up to 45 km from the epicenter but a significantly smaller distance from the fault rupture. This appeared to be largely due to inadequate ductility of the viaduct columns which were reinforced according to detailing standards accepted at the time of their construction but later demonstrated to be inadequate for seismic loading. There were also a number of retaining wall failures.

The Southern Pacific Railroad bridge over the Pajaro River had substructure elements separated about 3.5 ft. (1.2 m) in the 1906 California earthquake by movement along the fault rupture which passed between them at an angle to the bridge of about 45 degrees, as described by Lawson [5]. Movement of an end span relative to the abutment is shown in Figure 2, which was taken from Lawson [5].

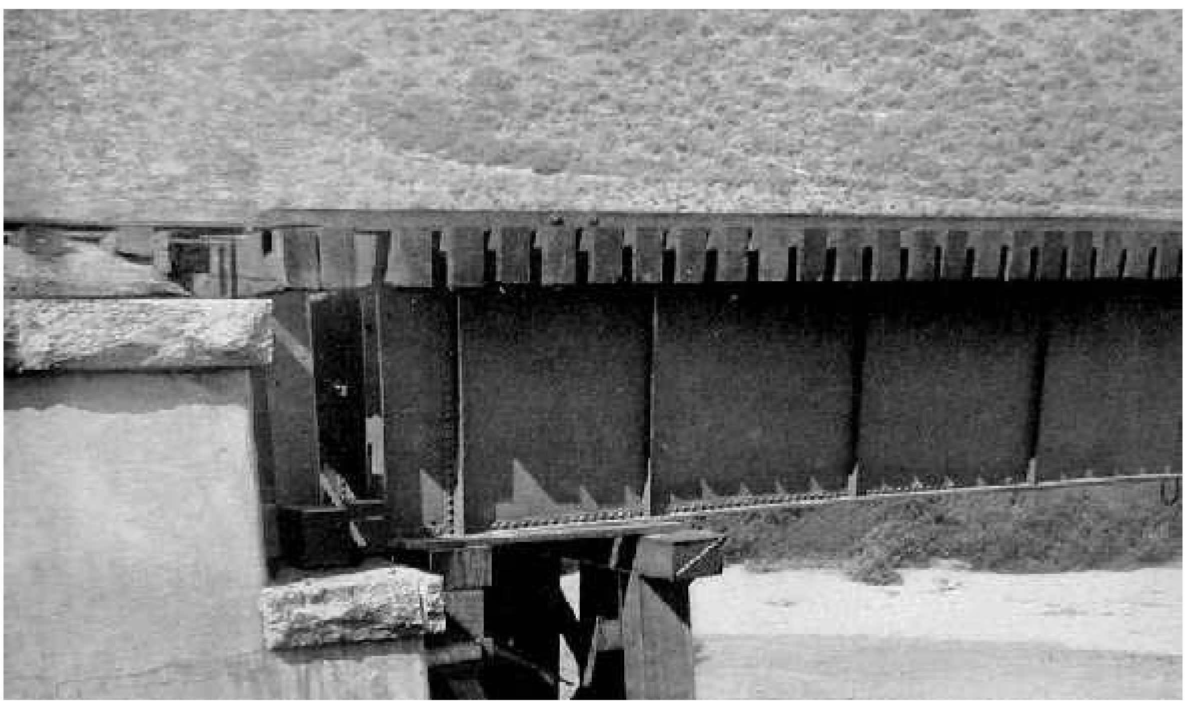

Figure 2. Span displacement due to separation of piers and abutment caused by fault offset at Pajaro River. ***Plate 65.B of Lawson [5]***

Liquefaction-induced lateral spreading of flood plains toward streams caused vertical and lateral buckling of timber trestles and movement of substructure units of steel bridges in the 1964 Alaska earthquake. Vertical buckling of a trestle is shown in Figure 3, from McCulloch and Bonilla [1]. Seventyfive of 81 bridges within 150 miles of the epicenter were damaged. Dutton [6] reports similar, but less extensive, effects in the 1886 Charleston, South Carolina earthquake. There are numerous examples of movement of piers, which are probably related to liquefaction. These include movement of the pivot and rest piers of an open bascule bridge toward the center of the channel, which prevented closing the bridge after the 2001 Nisqually, Washington earthquake.

Figure 3. Vertical buckling of trestle caused by lateral spreading.
Figure 13 of McCulloch and Bonilla [1]

In the 2001 Gujarat earthquake, stone arch bridges and bridges with stone piers were damaged. Arch bridge damage included failures caused by outward earth pressure against parapets and spandrel walls, as shown in Figure 4, cracking in mortar joints of arch rings and displacement of stones in arch rings due to outward movement of abutments. Steel girder bridge damage included movement of girders relative to piers and/or pier displacement resulting in unacceptable track geometry and, in some cases, bearing and/or anchor bolt damage. Cracking of horizontal mortar joints in stone substructure units occurred in both steel girder and concrete slab bridges. Other bridge damage included separation of wingwalls from abutments and other damage to wing walls. Separation of wingwalls from abutments has been observed in other earthquakes and appears to be related to excess earth pressure developed by the earthquake.

Figure 4. Failed spandrel walls of masonry arch bridge. ***Western Railways (India) photo***

Damage to Tunnels

Tunnels were damaged in 16 earthquakes. In 6 of these, tunnel damage was severe to extreme. In one, the 1952 Kern County, California earthquake, there was extreme damage to 4 concrete lined tunnels located approximately 30 miles from the epicenter, primarily where they were crossed by secondary faults. Damage, as reported by Steinbrugge and Moran [7], included collapsed walls and roofs and a location where one rail of the buckled track penetrated or slid under the lining. Restoration of service, on a temporary line, required 26 days. Bridges between these tunnels were undamaged. The tunnels were between 20 and 30 miles from the epicenter. Tunnel damage was slight or minor in 6 earthquakes. In one of these, the 1999 Kocaeli earthquake, one wall of a tunnel, located approximately 90 km from the epicenter and fault rupture, was cracked. The structural connection between the bottoms of the tunnel walls had been removed to lower the track for improvement of the vertical clearance. The vulnerability of the tunnel was increased due to the wall that cracked lacking lateral support because it was close to a steeply sloping hillside. The damage was minor and repairs could be delayed to fit the normal maintenance program. A number of tunnels closer to the fault rupture were not damaged.

Damage to Tracks and Roadbed

Sixty-three earthquakes caused track damage and/or embankment failures. Eighteen of these and 10 other earthquakes caused slides and/or rockfalls in cuts. Track damage ranged from displaced ballast without other track disturbance to broken ties, pulled apart joints as shown in Figure 5, broken rails, buckled track, lateral displacement of up to several meters and loss of vertical support for track over appreciable distances.

Figure 5. Insulated joints pulled apart by ground motion. ***Turkish State Railways photo***

In the 2001 Atico, Peru M_w 8.4 earthquake, severe damage from rockfalls and embankment failures was extensive within distances of about 300 km from the epicenter and 150 km from the rupture surface. Within these distances the extent of damage did not correlate with distance, indicating that, within the region of damage, other factors were more important than distance from the rupture in determining the extent of damage. Slides and rockfalls in cuts buried the track to depths as great as 5 meters as shown in Figure 6. Rockfalls broke rails and ties.

Figure 6. Track buried by rockfall. ***Southern Peru Copper Corp. photo***

Damage to Buildings

Typically, building damage did not prevent running trains. However, destruction of stations, roundhouses and other support facilities had a serious impact on operations and recovery in a number of earthquakes.

In the 2001 Gujarat earthquake, damaged railway-owned buildings numbered in the thousands with about one third damaged beyond repair. To keep this number in perspective, it should be noted that it includes housing units for a large percentage of railway employees, schools, hospitals and other facilities not owned by railroads in many parts of the world. It also includes a large number of minor structures, such as interlocking towers and cabins at road crossings that are protected by gates operated by employees stationed at the crossings.

The most severe damage to railroad facilities in the 1999 Kocaeli earthquake was the nearly total destruction of a major part of a passenger car shop at Adapazari. The shop, in service since 1951, produced about 200 cars per year for the Turkish State Railway at approximately 45 percent of the cost of comparable imported cars. An example of the damage is shown in Figure 7. Some portions of the shop were less severely damaged. Other portions completely collapsed.

Figure 7. Car partially overturned by failed structure in Adapazari shop.

Severe damage to major railroad buildings occurred in other earthquakes including the 1925 Santa Barbara, California, 1948 Fukui, Japan, 1964 Alaska and 1995 Kobe events. Minor structures, particularly the elevated water tanks formerly used to supply steam locomotives, are also vulnerable to earthquake damage.

Damage to Signal and Communication Facilities

Signal systems have suffered limited damage in relatively low magnitude earthquakes due to broken batteries, overturned electrical relays and wrapped wires in pole lines. Such damage is often highly disruptive but can be quickly repaired. Similar damage occurs in larger earthquakes together with more extensive damage such as broken signal masts. In the Gujarat earthquake, where there was significant damage to signal and interlocking systems, operation was resumed with manual operation of switches and reduced speed for facing point moves in accordance with interlocking operating standards. Where signals were inoperative, paper authority was used for track occupancy within absolute blocks. The latter would be similar to track warrant operation in North America, with the track warrants delivered to trains by operators instead of by radio. As repairs were made, speed restrictions were removed until normal operation was restored.

Other Damage

Damage to non-railroad facilities can prevent operation of the railroad. In the 1999 Kocaeli earthquake, a fire in a refinery adjacent to the right-of-way prevented operation of an important line for nearly 6 days after the earthquake and 93 hours after repair of damage to the railroad had made the line otherwise operable. Overpass spans fell on tracks in at least 4 earthquakes. In one of these, the 1964 Niigata earthquake, an overpass fell on a passing train. In other earthquakes, debris from adjacent buildings temporarily blocked tracks. In the 1995 Kobe earthquake, the catenary system was damaged at various locations within 50 km of the epicenter. Damage to facilities of electricity suppliers has affected the operation of electrified lines. In the 1999 Chi-Chi, Taiwan earthquake, an important undamaged line could not be reliably operated for 10 days after the earthquake because of damage to power plants, according to Abe, *et al.* [8]. In the Kocaeli earthquake, one substation supplying power to the railroad was not operable but it was possible to supply power through adjacent substations.

Recovery

The recovery of a railroad from a significant earthquake depends on the severity and extent of damage, the resources available for repair and the urgency of restoring service. As a minimum, inspection to ensure the safety of the track and related systems is required after moderate and larger earthquakes in the vicinity of the railroad. This typically prevents normal operation for 5 hours or more although undamaged lines were returned to operation within 3 hours after the 2001 Gujarat, India earthquake due to a sizeable number of strategically located inspection personnel. Although operation of the railroad was almost immediately known to be impossible, inspection of the Southern Peru Copper Corporation's railroad to evaluate damage after the 2001 Atico, Peru earthquake required 48 hours for inspection on foot due to inaccessibility by road and blockage of the track.

Where track, bridges or signal systems are damaged but restricted operation is possible, repairs are normally made under traffic. Where operation is not possible, partial repairs necessary to allow restricted operation are typically made as rapidly as possible, with permanent repairs for normal operation completed after limited service is restored. After the 2001 Gujarat, India earthquake, some bridges required temporary repairs before they could carry traffic. At others, trains were required to stop before crossing the bridge and to cross at a specified slow speed until repairs were completed. Following the 1952 Kern County, California earthquake, which caused extreme damage to several tunnels, a temporary shoofly with undesirable alignment and grades was opened within 4 weeks and permanent repairs were completed after 21 weeks. After the 1995 Kobe earthquake where there was extensive collapse of long viaducts in a metropolitan area, operation over temporary facilities was not an option but alternate bus service was provided for passengers during a 23-week reconstruction period. Following the 1999 Chi-Chi, Taiwan and 2001 Gujarat earthquakes, main lines were restored to service considerably before branch lines. When only part of a railroad is in the affected area and the damage is extensive, personnel and equipment are usually brought in from other areas to expedite repairs.

Conclusions

Although earthquake damage to railroads is most frequent in highly active seismic areas having a high density of railroads, such as Japan and California, extreme damage to railroads from M7 and greater earthquakes has occurred in other areas. In large earthquakes, the extent of damage may be influenced as much or more by local conditions than by the distance from the fault rupture. Effects beyond the immediate control of the railroad, including structures falling across tracks, fires adjacent to the right-of-way and loss of power, can prevent operation of a railroad after an earthquake. In these situations, the restoration of rail service may depend on the performance of entities beyond the control of the railroad.

With the exception of bridge detailing and securing signal system components and similar equipment to prevent damage from moderate accelerations, recovery planning is likely to be more effective than retrofitting to reduce damage. Retaining walls and earth retaining components of bridges, including wing walls and spandrel walls of filled spandrel arches, are frequently damaged, possibly because of design loads that are not adequate for earthquake conditions. Railroads are subject to major damage at locations where they cross active faults. However, the locations of a number of major cities require crossing active faults. Since appreciable offsets across a fault rupture cannot be avoided, repair strategies for fault-crossing locations should be planed in advance. Where possible, potential repair problems should be considered in selecting the alignment when fault crossings are required. Crossing known faults on bridges or in tunnels should be avoided whenever possible.

Although bridge damage receives much more attention than other earthquake damage to land transportation systems, possibly because bridge replacement can involve large costs and extended time periods and many earthquake engineers have a structural engineering background, other damage was equally or more disruptive to railroads in a number of earthquakes.

REFERENCES

[1] McCulloch, David S.; Bonilla, Manuel G., "Effects of the earthquake of March 27, 1964, on the Alaska Railroad", Geological Survey professional paper 545-D, U.S. Government Printing Office, Washington, DC, 1970, 161 pages

[2] Bureau of Social Affairs, Home Office, Japan, "The great earthquake of 1923 in Japan", 1926

[3] Office of the Engineer, General Headquarters, Far East Command, "Chapter III Transportation Facilities", The Fukui earthquake, Hokuriku region, Japan, 28 June 1948, Volume II, Engineering, prepared by Geological Surveys Branch, Intelligence Division, Office of the Engineer, General Headquarters, Far East 1949, pages 25-55

[4] Takahashi, Ryutaro, "Damage to civil engineering structures", The Fukui Earthquake of June 28, 1948 – Report of the Special Committee for the Study of the Fukui Earthquake", H. Tsuya, Chairman, Tokyo, 1950, pages 190-197

[5] Lawson, Andrew C., "The California earthquake of April 18, 1906", Vol. 1, Carnegie Institution of Washington, Washington, DC, 1908.

[6] Dutton, Clarence Edward, "The Charleston earthquake of August 31, 1886", *Ninth Annual Report, U. S. Geological Survey*, Government Printing Office, Washington, DC, 1889, pages 209-536.

[7] Steinbrugge, Karl V. & Moran, Donald F., "An engineering study of the Southern California earthquake of July 21, 1952 and its aftershocks" (Section 9 Railroad Properties), *Bulletin of the Seismological Society of America*, Vol. 44, 1954, pages 201-462 (Sec. 9: 283-292)

[8] Abe, Masato, *et al.*, "Damage to transportation facilities", *The 1999 Ji-Ji earthquake, Taiwan – investigation into damage to civil engineering structures*, Earthquake Engineering Committee, Japan Society of Civil Engineers, 1999 pages 4-1 to 4-39