EARTHQUAKE REPORT

TO

COMMITTEE 9
SEISMIC DESIGN FOR RAILWAY STRUCTURES

AMERICAN RAILWAY ENGINEERING
AND
MAINTENANCE-OF-WAY ASSOCIATION

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JUNE 23, 2001 ATICO, PERU EARTHQUAKE

Earthquake Description

An earthquake with a magnitude of 8.4 occurred near the coast of southern Peru at 3:33 PM local time on June 23, 2001. The earthquake, a complex event, occurred at the interface between the Nazca and South American tectonic plates. The initial onset consisted of two events separated by about 6 seconds and was followed by at least one larger complex event occurring about 40 seconds later. According to a model by Kikuchi and Yamanaka, the rupture surface was about 35 km deep under Mollendo, dipping downward toward the northeast at an angle of 21 degrees. The model involved a maximum displacement across the rupture surface of about 4.5 meters in an area 40 to 50 km northwest of Mollendo. The model indicates that the rupture was strongly directional, from northwest to southeast. Figure 1a is a map showing the modeled fault rupture in relation to the affected railroads.

Railway System Description

The railroads of Peru do not constitute a connected network but include the separate entities described below, which are not physically connected. Rolling stock, rail and other track material are imported, reaching each railroad at its port.

Ferrocarril Central Andino S.A. operates 591 km of lines in west-central Peru formerly owned by the Peruvian government and privatized in 1999. A standard gage line runs inland from Callao, the port of Lima, to La Oroya where it divides into north and south branches. The north branch extends to Cerro de Pasco. The south branch divides at Canchayllo to serve Chaucha and Huancayo. A narrow gage line extends from Huancayo to Huancavelica. The railroad handles about

1.4 million tons of general freight per year and rail tours. It was not affected by the earthquake.

PeruRail operates over 1000 km of lines in southern Peru that were privatized in 1999. A 523 km line runs inland from the ports of Mollendo and Matarani, through Arequipa and Juliaca, to Puno. A connecting line with a length of 510 km runs northward from Juliaca, through Cusco and Machu Pichu, to Quillabamba. The railroad has passenger service between Arequipa and Puno and between Puno and Machu Pichu and handles about 0.7 million metric tons of freight per year.

The Southern Peru Copper Corporation operates a 215 km industrial railroad from its smelter and refinery on the coast at Ilo to mines at Toquepala and Cuajone. Annual tonnage is about 5 million gross tons, exclusive of locomotives, and includes copper concentrate moving from the mines and supplies and equipment moving to the mines.

There is also a rail connection between Tacna and Arica, Chile.

Both the Mollendo-Matarani-Arequipa-Puno line of PeruRail and the Southern Peru Copper Corporation (SPCC) railroad sustained extensive damage in the areas indicated in Figure 1b.

PeruRail

PeruRail operates over 1000 km of lines in southern Peru that were privatized in 1999. A 523 km line runs inland from the ports of Mollendo and Matarani, through Arequipa and Juliaca, to Puno. A connecting line with a length of 510 km runs northward from Juliaca, through Cusco and Machu Pichu, to Quillabamba. The railroad handles freight as a common carrier and has passenger service between Arequipa and Puno and between Puno and Machu Pichu. Rolling stock is maintained in shop facilities at Arequipa. The railroad has a track warrant operating system.

Because of large differences in elevation and rough terrain, the lines are characterized by deep cuts, high fills, sharp curvature and, in some locations, side-hill cuts with large elevation differences between the points where the cut slope and the embankment slope at a cross-section intersect the natural ground surface. Because of the terrain, grades are steep, exceeding 4 percent in several locations.

Following the earthquake, the entire railroad was inspected for damage.

The segment between Mollendo and the Matarani-Arequipa line and the portion of the Matarani-Arequipa line between Matarani (KM 0.000) and Guerreros (KM 39.061) are located about 150 km from the epicenter but, probably, over the deeper portion of the ruptured segment. There are 5 tunnels and no bridges in this portion of the railroad. Damage was heavy, involving 81 locations and affecting an aggregate length of 11.56 km in a total of less than 60 km. Damage included settlement of embankments, embankment slides, rock falls, some of which broke rails and/or ties, soil and rock slides which blocked cuts to depths as great as 5 m, disturbed track geometry and fallen rocks in an unlined tunnel.

Between Guerreros and KM 130, damage was limited to a few locations.

Between KM 130 on the Matarani-Arequipa segment and Pampa de Arrieros (KM 71.000 on the Arequipa-Puno segment) the damage was again significant. There were 75 locations with damage affecting an aggregate length of 11.95 km in a total length of 113 km. Distances from the epicenter range from 150 to 180 km. Neither of the two bridges located in this portion of the railroad was damaged. There was minor damage to railroad buildings at Arequipa.

Repairs involved work by both railroad forces and outside contractors. Three days were required to restore service between Arequipa and Puno. Five days were required to restore service between Arequipa and the ports.

A magnitude 7.2 aftershock on July 7, with its epicenter about 50 km south southeast of Mollendo, resulted in additional rock falls. Rocks were cleared and service was restored in about 3 hours as the required equipment was still available at the locations where it was needed.

Southern Peru Copper Corporation Railroad

The Southern Peru Copper Corporation's industrial railroad consists of a 186 km line from its smelter and refinery on the coast at Ilo to its mine at Toquepala and a 29 km branch from El Sargento (KM 183.40) to its mine at Cuajone. The railroad operates 13 Diesel locomotives and approximately 450 cars including most types of freight and maintenance of way cars. Ore cars are typically 100 ton capacity. Tank cars and gondolas are 70 ton capacity. A total of 170 employees operate and maintain the railroad with the assistance of about 80 contractors. Rolling stock is maintained in shop facilities at Ilo. Both on-track and off-track equipment is used for maintenance of way.

Annual tonnage between Ilo and El Sargento is about 5 million gross tons, exclusive of locomotives. Freight includes copper concentrate moving from the mines and supplies and equipment moving to the mines.

The railroad has a track warrant operating system and uses 3 man train crews. Maximum speed is 30 mph with some segments restricted to 15 mph because of the geometry of the line. Two trains per day, typically 35 to 40 cars but up to 50 cars when needed, are operated in each direction with one train between Ilo and Toquepala and one between Ilo and Cuajone. Switching is performed with yard engines at Ilo, Toquepala and Cuajone. The railroad is not signaled but a few grade crossings have crossing signals whose operation was not affected by the earthquake.

Construction of the line from Ilo to Toquepala was started in 1956 and completed in 1959. Because of large differences in elevation and rough terrain, the line is characterized by deep cuts, high fills, sharp curvature and, in many locations, side-hill cuts with large elevation differences between the points where the cut slope and the embankment slope at a cross-section intersect the natural ground surface. The maximum grade is 3 percent and the maximum curvature about 20 degrees. Except for a bridge consisting of 4 through girder spans crossing the Rio de Osmore near Ilo, cross drainage is carried through culverts. The width of the subgrade is 6 meters.

The Cuajone- El Sargento line was built between 1970 and 1975. It has 5 tunnels with lengths of 3590 meters, 5420 meters, 980 meters, 14,720 meters and 2320 meters with intervening sections of open track, each about 200 meters long. Tunnels are reinforced with steel I-beam ribs and lined with shotcrete.

Rail is jointed, originally laid with opposite joints. A program of field welding alternate joints to produce 78 ft rails with staggered joints has been initiated. Ninety pound and 115 lb main track rail is being relaid with 80 ft lengths of 115 lb and 133 lb rail. Rail removed from main track is relayed in yards. Crossties are either wood or concrete. Cut spikes are used with wood ties and Pandrol fasteners with concrete ties. In many wood tie segments, alternate ties, except joint ties, are box anchored. Both rails are braced on the sharper curves. Crushed copper slag is used for ballast.

At the time of the earthquake both trains from Ilo to the mines were in the area of KM 114 and KM 116. They were able to proceed to the siding at KM 124 which is accessible by road. Large segments of the railroad are only accessible by rail and could not be reached because the track was blocked by slides. Therefore, much of the post earthquake inspection had to be done on foot. Inspection was completed about 48 hours after the earthquake. The start of inspection was delayed somewhat because of a tsunami warning at Ilo. Tunnels were a particular concern but had only a small amount of damage in one tunnel.

The railroad was out of service for 7 days following the earthquake. Continued operation of the smelter and refinery depended on stockpiled concentrate and the 15,143 metric tons of concentrate that could be trucked to the smelter during this period. For the first week following opening of the line, speed was restricted to 10 mph. By July 23, 65 percent of the line was being operated at normal speed. Because of safety considerations following the earthquake, the operation was changed from running to the mines during the day and from the mines at night to daytime operation in both directions. This required additional motive power, which could be made available, and dispatching to allow trains to meet at intermediate sidings.

Repairs involved work by both railroad forces and outside contractors. Hiring contractors was complicated by a large demand for their services resulting from the earthquake. There was damage which required repairs at approximately 180 locations.

Between KM 24 and KM 73, about 275 to 295 km from the epicenter, Several slides and rock falls occurred in cuts and longitudinal cracks and slides occurred in fills. Track line and surface were disturbed and ballast was displaced at several locations.

From KM 85 to KM 103, between 290 and 300 km from the epicenter, severe damage was widespread with almost continuous damage between KM 85 and KM 93. Damage included slides and settlement in high fills, shifting of roadbed in side-hill cuts, slides and rock falls into cuts, displacement of ballast and disturbance of track geometry.

There was little damage between KM 103 and KM 142.

Significant slides and rock falls were frequent in cuts between KM 142 and KM 155, between 300 and 310 km from the epicenter. Smaller, less frequent slides and rock falls continued to KM 183, 320 km from the epicenter. Longitudinal cracks in embankment shoulders and damage to shotcrete slope protection in cuts also occurred in this area.

A small amount of material fell from the lining of Tunnel No. 5 at El Sargento about 320 km from the epicenter. There was also a minor slide above the south portal of this tunnel and a few rocks fell from a cut slope near the south portal. There was no other damage between El Sargento and the end of the line at Cuajone, about 300 km from the epicenter.

Analysis of Damage

There was no bridge damage and no important damage to other railroad structures.

Damage to tunnels was minor.

The most severe damage involved material sliding or falling onto the track, as shown in Figures 2 to 4, or embankment failures, as shown in Figures 5 and 6. In some cuts, track was buried under as much as 5 meters of material. There were cases where ballast was displaced without obvious subgrade problems as shown in Figure 7. There were also cases where failures did not occur but longitudinal cracks indicating a potential slide did, as shown in Figure 8. Partially developed slides above the track, as shown in Figure 9, represent a potential future maintenance problem.

Railroad damage was within distances of about 300 km from the epicenter and 150 km from the rupture surface. The damage did not correlate with distance, indicating that other factors were more important than those distances in determining the extent of damage. There appears to be a directional effect consistent with a northwest to southeast progression of rupture. Obvious factors affecting the extent of damage include depth of cuts, height of fills, side slopes and, possibly, the transverse slope of natural ground above cuts and under fills.

Material differences were a factor in performance. Severely jointed rocks and soils that appeared to have little cohesion and uniform gradation performed poorly as would be expected. In cuts through stratified material, loose material under a stratum of sound rock slid into the cut, leaving the sound stratum projecting into the cut beyond the top of the slope of the loose material. In general, conglomerates performed well in cuts. Cuts in what appeared to be volcanic tuff deposits performed poorly.

Many embankments with problems were composed of material that appeared to have little cohesion and uniform gradation. Because of the lack of a shallow water table, liquefaction does not appear to have been a factor in any of the failures. A significant percentage of embankment failures involved slides, or longitudinal cracking indicating a potential slide, as shown in Figure 8, in the region between the ends of ties and the shoulder. It is possible that, over time, traffic loading, combined with a limited amount of moisture penetrating the ballast, increased consolidation and cohesion in the fill under the ties. Such increased cohesion would increase the relative probability of potential failure surfaces beyond the ends of ties. Although the Southern Peru Copper Corporation Railroad was doubtless constructed using modern methods and equipment, the lack of available water would have resulted in compaction at a moisture content far below optimum. At other locations, slides involved the entire width of the fill. Figure 10 shows the top of a minor slide extending under the track. The region to the left has been displaced downward in relation to the track and the region to the right.

Recovery

Although it was determined very soon after the earthquake that lines were impassable, a more detailed assessment of damage was required for planning repairs. This was especially difficult because of the large distances involved and the need to inspect relatively long stretches of track on foot because they were inaccessible by road and rail access was blocked by earthquake damage. This same inaccessibility increased the difficulty of repair work.

The large percentage of the total railroad requiring repair, particularly in the case of the Southern Peru Copper Corporation’s railroad, put extreme demands on railroad maintenance equipment and forces. Resources appropriate for normal maintenance can be inadequate in a disaster. When extensive damage involves only a limited portion of a total rail system, forces and equipment from unaffected areas are nearly always brought in to help with repairs. When the whole system is affected, this is not possible. Although repairs sufficient to allow opening the lines were accomplished within a few days, weeks of additional work were required to restore normal conditions.

Lessons Learned

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 can be more disruptive in some earthquakes. In the case of the Atico earthquake, major rail service interruptions were the result of the displacement of soil or rock due to shaking of the ground.

Where not prohibitively expensive, several measures could reduce the risk of service interruptions and/or reduce their extent and duration. Cuts could be widened to allow accumulation of debris at the bottom of slopes without fouling the track. In cases where rock has been fractured by excessive blasting, fractured rock could be scaled from the sides of cuts. In naturally fractured or jointed formations, grouting of cracks and/or rock bolting to improve stability could be considered. Some of the methods used to prevent other slides in embankments would be beneficial.

Other measures would involve only minor costs. Contingency planning, including establishing relationships with appropriate contractors, developing an earthquake response procedure and having appropriate equipment and material, particularly ballast, available for repairs, can reduce the duration of service interruptions.

Acknowledgement

Without the considerable assistance of officials of the companies involved, Mr. Brooke Ruskin of PeruRail, Mr. William Torres of Southern Peru Copper Corporation and, particularly, Ing. Oscar Bravo of PeruRail and Ing. Raul Merino of Southern Peru Copper Corporation, the investigation resulting in this report would have been impossible. Their willingness to provide information and to arrange the transportation and devote the time required to provide access to damaged areas is very much appreciated.

References

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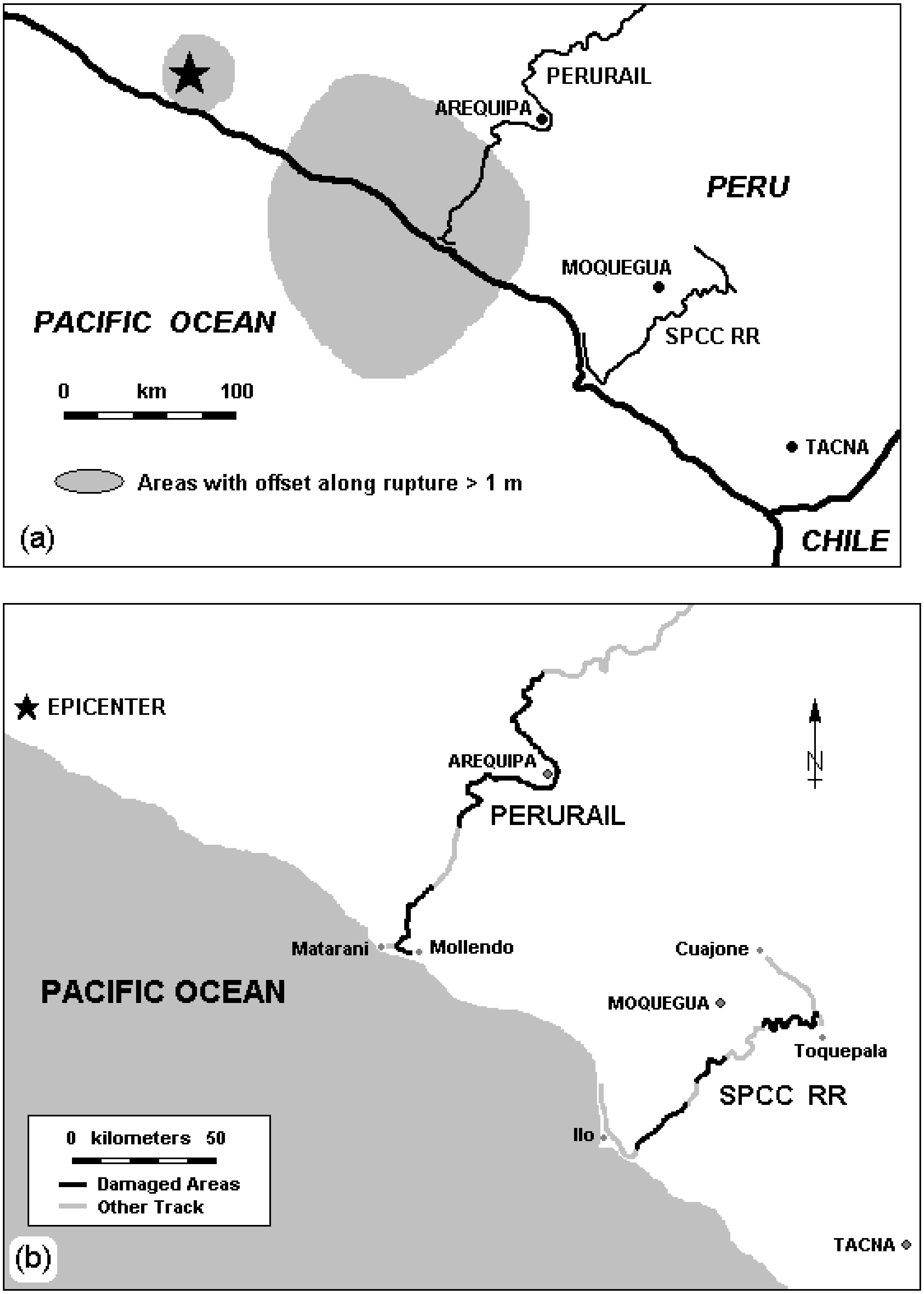

Figure 1. Atico, Peru earthquake and affected railroads

Figure 2. Cut at Matarani-Arequipa KM 17 *(PeruRail photo)*

Figure 3. Rock-fall at Arequipa-Puno KM 35 *(PeruRail photo)*

Figure 4. Rock-fall at SPCC KM 90 ***(Southern Peru Copper Corp. photo)***

Figure 5. Slide at Matarani-Arequipa KM 14 ***(PeruRail photo)***

Figure 6. Slide at SPCC KM 90 ***(Southern Peru Copper Corp. photo)***

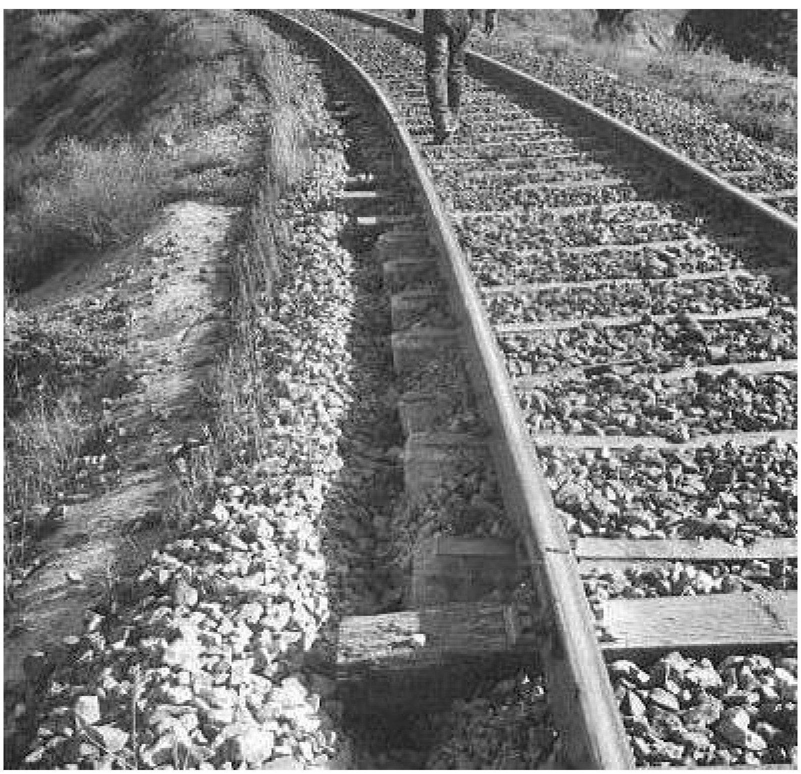

Figure 7. Displaced ballast at Arequipa-Puno KM 49 ***(PeruRail photo)***

Figure 8. Embankment cracks at Arequipa-Puno KM 50 ***(PeruRail photo)***

Figure 9. Slide above track near SPCC KM 40

Figure 10. Slide at SPCC KM 87.6 *(Southern Peru Copper Corp. photo)*