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Observations of Site Amplification and Liquefaction in the Jun 23, 2001, Southern Peru Earthquake

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ABSTRACT

The M_w 8.4 Southern Peru Earthquake of June 23, 2001 caused extensive damage in a widespread area in southern Peru and northern Chile, including several important population centers. Damage in some of these cities was correlated with local soil conditions and topography, suggesting the influence of local site amplification effects in damage distributions. The earthquake caused numerous instances of other types of geotechnical related ground failures, including liquefaction and lateral spreads in river valleys, seismic compression of highway fills, and slope failures. This work focuses on case histories documenting site amplification and liquefaction in the Southern Peru earthquake. Among the liquefaction events observed in this earthquake, the liquefaction of a heap-leach pad is the first reported failure of its type in a seismic event.

INTRODUCTION

The June 23, 2001 M_w 8.4 Southern Peru earthquake provided a unique opportunity to study the effects of a large magnitude subduction event. The Southern Peru earthquake affected a widespread area including several important population centers in southern Peru and northern Chile (Fig. 1). The earthquake was an interface-type event along the subduction boundary of the Nazca and the South American plates. The causative fault plane had an approximate rupture length of 300 km along strike and a width of approximately 100 km.

Damages due to the earthquake were widespread. Structural damage was concentrated on adobe houses and historical construction. However, a significant number of engineered structures also suffered mild to severe damage. The transportation infrastructure suffered considerable damage from landslides, seismic compression, and liquefaction. A tsunami generated by the earthquake was also responsible for considerable damage in coastal towns. A detailed description of the damages caused by the earthquake can be found in Rodriguez-Marek and Edwards (2003). Only a limited number of strong motion instruments recorded the mainshock. The largest registered peak ground acceleration (PGA) was 0.33 g in the northern Chilean city of Arica. The only ground motion station in Peru, located in the city of Moquegua, registered a PGA of 0.30 g.

This paper concentrates on observations of the effects of site amplification on the resulting damages in urban centers, as well as observations of liquefaction occurrence in Southern Peru.

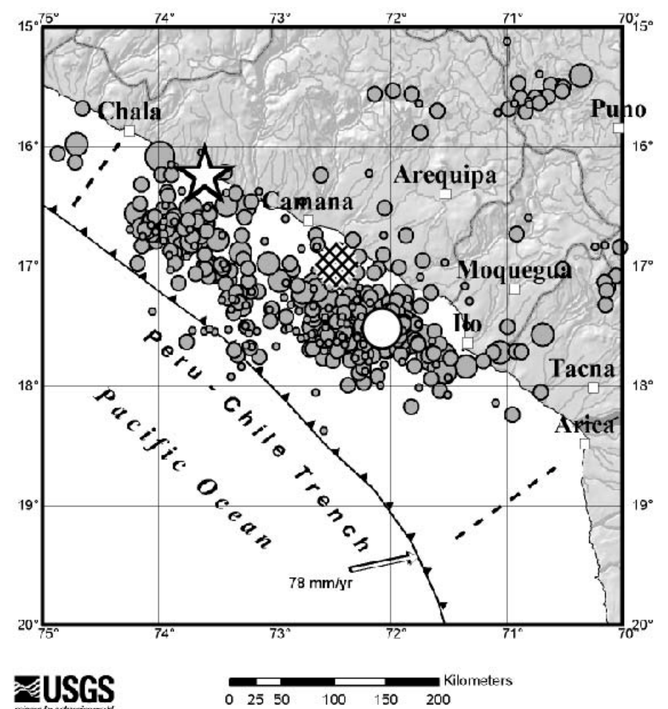

Fig. 1. Seismicity associated with the Southern Peru Earthquake of June 23, 2001, as located by the USGS/National Earthquake Information Center. The epicentre is marked with a star, the largest aftershock (M_w 7.6) is marked with an open circle (modified from Dewey 2003).

SITE AMPLIFICATION STUDIES

Although the lack of recorded ground motions precludes an extensive analysis of site response issues, the documented damage at various population centers (e.g. Tacna and Moquegua) constitute an important database for future study of site effects in subduction zone earthquakes, particularly for the types of soil deposits common to southern Peru, such as stiff alluvial deposits and weathered volcanic rocks. The paragraphs below discuss damage observations in the cities of Tacna and Moquegua, and the correlation of damages with local site conditions.

Moquegua

The city of Moquegua is located at the base of the Andes Mountains near the confluence of the Tulilaca and Torata rivers, about 55 km east of the Pacific coast and at an average elevation of 1400 meters above sea level. The city is located approximately 100 km from the zone of energy release. The recorded PGA at downtown Moquegua was 0.3 g at a recording station located on a stiff gravel deposit of unknown depth. The current population is estimated at about 60,000. The weather in Moquegua is extremely dry, annual precipitation is on average 15 mm. The topography of the city is rugged. The city has expanded from its original location along the Tulilaca River (San Francisco and Cercado districts) into isolated neighborhoods in the surrounding hills (San Antonio, Chen Chen, and Samegua districts). Moquegua had the largest number of affected buildings in the 23 June, 2001 earthquake. Most of the damage occurred in older adobe type construction. Reinforced concrete and brick bearing wall buildings also suffered varying degrees of damage.

Quaternary deposits in Moquegua are dominated by alluvial-type deposits, composed mainly of sandy gravels. These deposits contain large amount of boulders, reflecting a high-energy depositional environment. The density of quaternary deposits varies with depositional age. Elevated terraces have dense to very dense gravels, while more recent fluvial deposits in the river margins are in general looser and can include finer grained sediments, including some silts and clays (Kosaka-Masuno et al. 2001). Bedrock outcrops are mainly late tertiary sedimentary rocks of the Moquegua formation. This formation is composed of conglomerates, sandstones, and tuffs. The Moquegua formation outcrops in the hills surrounding the downtown area and in the communities surrounding Moquegua (San Antonio and Samegua). This formation can show varied degrees of weathering. The Moquegua formation overlies the volcanic Toquepala formation, which is composed of rhyolite, andesite, dacite and piroclastic flows of early tertiary to late cretaceous age. This formation outcrops to the northeast of the city (INGEMET 1999).

Kosaka-Masuno et al. (2001) present results from a series of seismic refraction surveys in various locations of the city of Moquegua. These results indicate the presence of a very stiff alluvial deposit at relatively shallow depths, with reported p-wave velocity values ranging from 600 to 2000 m/s below depths of 2 to 3 m, corresponding to shear wave velocities of approximately 300 to 1100 m/s. The high end of this range represents unusually high shear wave velocities for alluvial deposits at relatively shallow depths. The stiffer profiles are found in the Cercado (downtown) and Los Angeles districts. Relatively softer profiles are found in the San Francisco district (west of the downtown area) and in the Chen Chen and San Antonio districts. At these locations, reported shear wave velocities in the upper 10 m are about half of reported shear wave velocities in other locations of the city. Microtremor measurements by Lermo et al. (2002) and Sato and Konagai (2002) gave similar results. The seismic refraction profiles in the San Antonio district evidenced a large spatial heterogeneity (Kosaka-Masuno et al. 2001). Samples from shallow trenches from around the city indicate a preponderance of gravels and sands throughout the city (Kosaka-Masuno et al. 2001).

Damage Distribution in Moquegua. Given the insufficient number of ground motion recordings in the region affected by the earthquake, evaluation of ground motion intensity and potential site effects and topographic amplification was conducted based on building damage observations. Existing urban construction can be classified within the following three basic types: adobe, brick bearing wall, and reinforced concrete frame with brick infill. Adobe construction is highly susceptible to seismic damage. In an attempt to isolate structural factors in assessing building damage, this type of construction was ignored in the damage assessment. It was assumed that the other two general types of buildings, brick bearing wall and reinforced concrete frame, have a relatively similar performance. While construction quality varies from building to building and a large percentage of the observed damage can be attributed to poor construction practices or lack of adequate design, the overall damage distribution, in particular of buildings with modern design and construction materials, was deemed adequate as a relative measure of ground motion intensity. In particular, the performance of school buildings was a good indicator of potential site effects. These buildings are generally constructed in accordance to two nationwide codes, and construction practices across school buildings are relatively uniform. Thus, variation in their performance is likely due to variations in ground motion intensity and not to structural factors.

In order to follow a uniform procedure to describe and rank the damage level, the structural damage index scale described by Coburn and Spence (1992) was used. In this scale, each building is assigned a damage index, from D0 (no damage) to D4 (complete collapse of structure or one floor). For additional details see Rodriguez-Marek et al. (2003).

Damage to residential housing in the city of Moquegua was widespread. A large percentage of the affected buildings were of adobe-type construction. Damage to adobe structures was especially heavy in the Cercado and San Francisco districts of Moquegua, particularly on the slopes of San Francisco Hill, where adobe construction is prevalent. A few concrete frame institutional buildings were surveyed, and damage ranged from very high (D3) to none (D0). A list of surveyed buildings is given in Table 1. The location of these buildings is shown in Figure 2. Buildings in the Cercado and San Francisco districts had higher damage levels than in other locations. This is consistent with the damage observed in adobe construction. At least one of the buildings in the San Antonio area (San Antonio Health Center) had cracks that were present before the earthquake and, according to local engineers, the building did not suffer additional damage during the earthquake.

Table 1. Damaged buildings in Moquegua.

	Damage Level	**Location**	**Possible Soil Conditions[1] (Kosaka-Masuno et al. 2001, Salas-Cachay 2001)**
1	D1 to D2	Cercado	Alluvial deposits. Superficial layer (about 1.5 m) of low plasticity clay/clayey sand, relatively soft overlying very stiff alluvial material (possibly the Moquegua formation).
2	D0	Cercado	
3	D0 or D1	Cercado	
4	D1	Cercado. Contiguous buildings	
5	D3		
6	D2 and D3	Cercado	Located at higher elevations than other sites in the Cercado district. Possibly in an Alluvial Terrace deposit.
7	D1	Samegua	On Moquegua formation.
8	D2	Samegua	
9	D1 to D2[3]	San Antonio	Gravels and clayey sands and silts. Clay present only in thin strata (about 30 cm). Local engineers report local areas with expansible soils.
10	D1 and D2[3]	San Antonio	
11	D2	San Francisco	Gravelly silt in upper 0.5 to 2 m, overlying the Moquegua formation. Silty clays with expansive properties found at some locations.
12	D2 and D3	San Francisco	

1. Soil conditions obtained from nearby trenches and seismic refraction surveys, as well as observations and inferences from the authors.
2. Cracks were present in the building prior to the earthquake. Based on reports from local engineers, no additional cracking was induced by the earthquake.
3. From Koseki et al. (2002).

Other than the damage in the San Francisco district, which reportedly had softer soils, the relationship between site conditions and observed damage patterns in other areas of the city is not very clear. This is partially due to poor understanding of the site conditions. A hill in the San Francisco neighborhood suffered extensive damage indicating possible topographic effects. It is important to note that damage patterns could also be attributed to construction patterns rather than site effects, given that within each neighborhood construction quality is typically uniform.

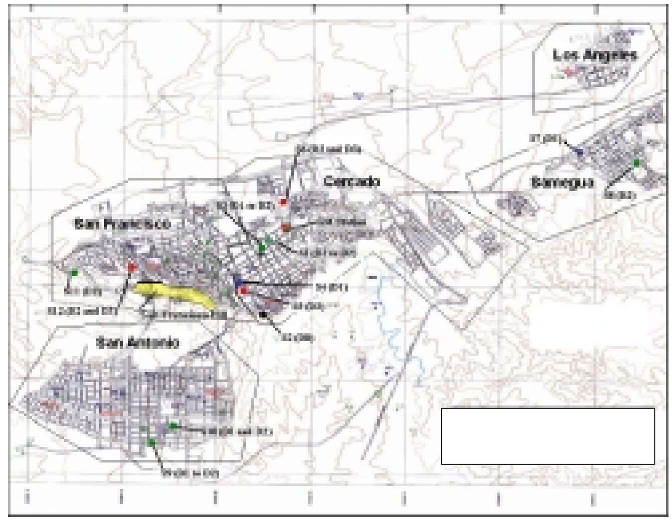

Fig. 2. Map of Moquegua showing locations of evaluated buildings. Damage index is shown in parenthesis. Buildigns are described in Table 1.

Tacna

The city of Tacna is located at the southern end of Peru, near the border with Chile, approximately 38 km northeast of the Pacific coastline on an arid strip of land bounded to the east by the steep chain of the Andes Mountains. The city is located about 135 km from the rupture zone of the earthquake. Elevation ranges between 560 and 650 m above sea level. Precipitation is infrequent, with an annual average of about 20 mm. Current population is estimated at about 250,000. Using the Youngs et al. (1997) attenuation relationship for rocks, the median peak ground acceleration in Tacna is estimated at 0.09 g with a one standard deviation range of 0.06 g to 0.16 g.

The city is divided into five districts: Tacna, Pocollay, Gregorio Albarracín, Alto de la Alianza, and Ciudad Nueva (Figure 3). The district of Tacna, which includes the downtown area, has both old adobe and newer brick and concrete construction. Various levels of damage to older adobe buildings were observed in the downtown area. Most construction in the rest of the city is newer, consisting mainly of 1- to 2-story brick bearing wall buildings. Significant damage to 1- and 2-story brick bearing wall buildings occurred in Alto de la Alianza and Ciudad Nueva districts, located in the northeastern section of the city. Damage to similar buildings was nonexistent to light in other parts of the city.

The central and southern parts of the city (the districts of Tacna, Pocollay, and Gregorio Albarracín) are underlain by alluvial deposits of the Caplina river. These alluvial deposits consist mainly of cobbles and boulders with diameters ranging from 1 to 30 cm and average diameters of 10 to 20 cm. Typical shear wave velocities of deposits from similar depositional environments in Peru range between 500 and 800 m/s, indicating a deposit that would be classified in the boundary of UBC C and UBC B sites. The alluvial deposits are either exposed or at depths of less than 3 m. Surface materials consist of finer sandy, silty, and clayey soils.

The rest of the city, consisting of the north cone (Alto de la Alianza and Ciudad Nueva, and developments on the Intiorko Hill slopes) and part of Pocollay district, lies on volcanic tuffs and silty sands formed from weathering of the tuffs or air fall volcanic ash. These deposits are underlain by a rhyolitic tuff formation (the Huaylillas formation) described as soft to medium hard. The Huaylillas formation is either exposed or at shallow depths in the northern part of the city of Tacna (Ciudad Nueva and Alto de la Alianza). This formation also underlies the dense alluvial deposit in the central and southern portion of the city at a much greater depth.

A seismic microzonation of the city of Tacna was prepared by Cotrado and Siña (1994) based on geotechnical information and site periods obtained from microtremor measurements. This microzonation divides the city in three zones:

Zone III: Sites underlain by more than 3 m of loose soils or sites where the volcanic tuff is at shallow depth and where the site period ranges between 0.25 and 0.32 s.

Zone II: Sites with shallow surface cover (< 1.5 m) over dense alluvial deposits and site periods lower than 0.25 s.

Zone I: Sites with exposed alluvial deposit and site periods lower than 0.25 s.

These zones are mapped in Fig. 3. For details on the microzonation study, refer to Rodriguez-Marek et al. (2003) or Cotrado and Siña (1994).

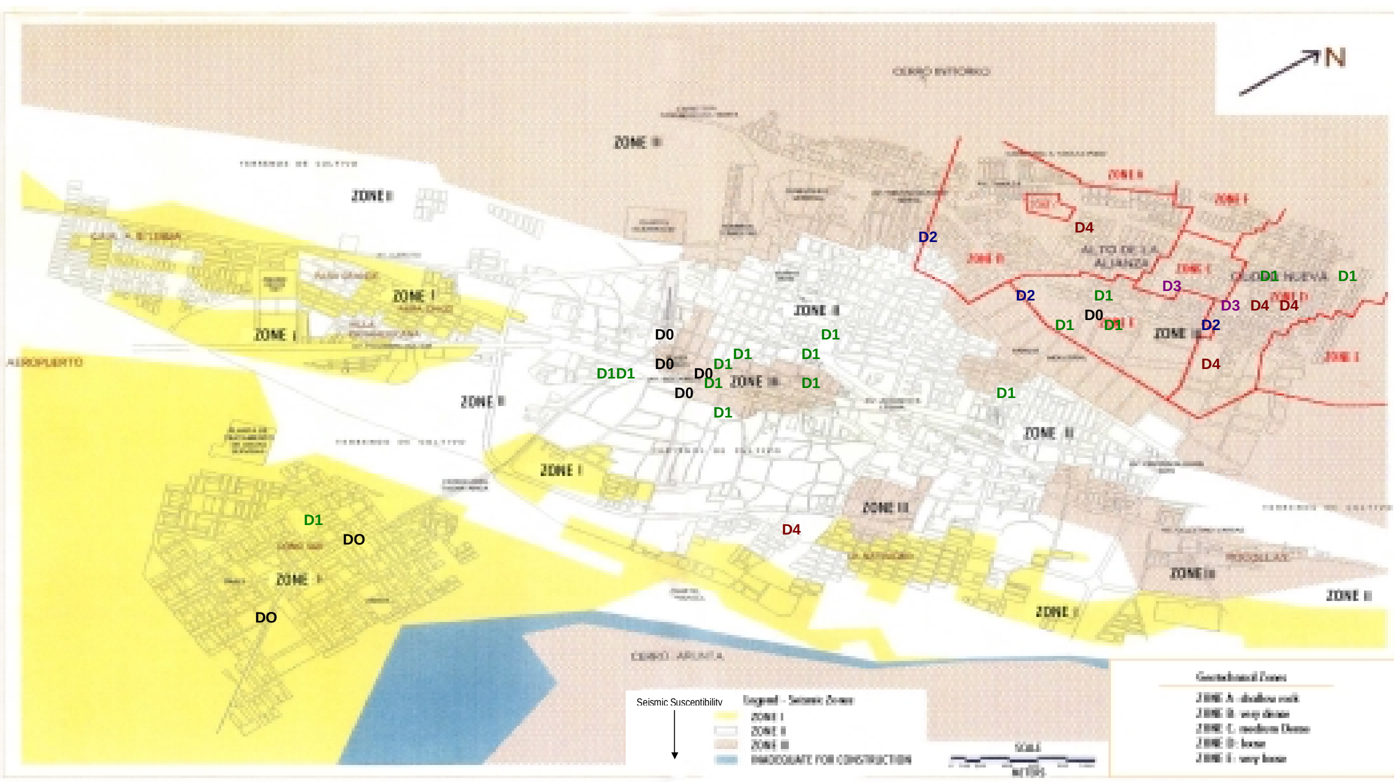

Fig. 3 Damage survey sites in Tacna. Damage scale ranges from no damage, D0, to partial or complete collapse, D4 (base map from Cotrado and Siña 1994).

Damage Distribution in Tacna. The geotechnical reconnaissance team surveyed structural damage at 33 building sites throughout the city. Details of the structural survey are presented in Rodriguez-Marek et al. (2003).

Although there may be some differences in engineering and construction quality between residential and commercial/ institutional buildings, similar types of buildings were compared in different parts of the city. Based on the distribution of damage (Figure 3), it can be seen that more severe damage generally occurred in the northern cone area, and damage in the downtown and southern cone area was generally limited to cracking of nonbearing walls. This is consistent with reports from local engineers, who also indicated the presence of silty sand deposits in areas of concentrated damage. This was also documented by several hand-dug test holes which remained open at the time of the site surveys. The maximum damage index incurred for schools in the downtown and south cone areas was D1. Damage indexes up to D3 were identified for schools in the northern cone. Schools, in general, performed better than residential housing. Several schools located in the northern cone had damage indexes of D0 and D1 only.

A few anomalies of this trend exist. A house in the south part of the Tacna district was classified with a damage level of D4. However, based on observations of the reconnaissance team, it is believed that poor design (i.e. drastically inadequate base shear resistance) influenced this damage more than soil conditions.

The damage distribution clearly indicates that concentration of structural damage was relatively high in areas underlain by the volcanic tuff (Zone III), while areas underlain by the alluvial gravel deposits (Zones I and II) had less damage. By means of a general observation of all structures, it was apparent that a very limited number of structures (less than 1 percent), other than adobe-type construction, suffered damage that would be indexed at the D2 level or greater in the areas underlain by the dense alluvial gravel.

The proportion of damaged structures (D2 to D4) having a similar type of construction in the northern areas, such as Ciudad Nueva and Alto de la Alianza, which are underlain by finer soils, was estimated to be between 60 and 70 percent. The volcanic tuff had varying degrees of weathering and in many places had weathered into a loose silty sand layer. These observations raise the possibility that site effects played an important part in damage distributions. However, it is also possible that construction practices also played a key role. An analysis of site effects in Tacna during the 2001 Southern Peru earthquake is presented in Williams (2002).

The initial geotechnical reconnaissance did not identify occurrences of foundation settlement or foundation failures. Consequently, differences in building performance may be attributed either to structural performance alone, or to a combination of structural performance and ground motion amplification due to site effects. It is noteworthy that the potential site amplification, while observed in deposits apparently looser than most of the soils common to southern Peru, ocurred in soils of relatively high stiffness. Such amplification in stiff soils had been observed in prior earthquakes, including the Lima earthquake in 1974 (Repetto et al. 1980) and the Northridge earthquake of 1994 (Stewart et al. 1994), among others.

LIQUEFACTION

Despite the large magnitude of the earthquake (M_w = 8.4), relatively few instances of soil liquefaction were observed or reported in the region. This is principally due to the significant depth to groundwater in most parts of the region. Groundwater depth varies throughout the affected area, but in many locations, it is in excess of 150 m. Exceptions are many river valleys that cross the affected region. Fig. 4 maps the sites or areas where liquefaction was observed by the geotechnical reconnaissance team or was reported by others (Audemard et al. 2002, Gomez et al. 2002, Koseki at al. 2002). In each case liquefaction was confirmed by the presence of sand boils at the ground surface. It is possible that liquefaction may have occurred at depths great enough to preclude surface expression at other sites that were visited, but where liquefaction was not confirmed. The majority of the mapped liquefaction sites were located near road and highway crossings of rivers. It is reasonable to assume that liquefaction also occurred at other undeveloped river sites not visited by reconnaissance or research teams. A research team from the Geophysical Institute of Peru (IGP) reported occurrences of liquefaction along all of the major river valleys located between the Yauca River in the north to the Sama River near the Peru-Chile border (Audemard et al. 2002, Gomez et al. 2002).

Liquefaction primarily affected bridges, although other types of structures were also damaged. A unique liquefaction failure of a heap leach pad, discussed below, occurred at a local mine. Liquefaction was not observed in the town of Ilo, home to the only major port in the region. Subsurface conditions at the Port of Ilo consist of shallow bedrock.

The local geology at each of the liquefaction sites consisted of Holocene-aged alluvial sediments with shallow groundwater. The alluvial sediments typically consisted of gravelly, coarse to fine sands, often with trace amounts of non-plastic silt. Ejecta found at the liquefaction sites typically consisted of poorly graded medium to fine sands with varying fractions of non-plastic or low plasticity silt.

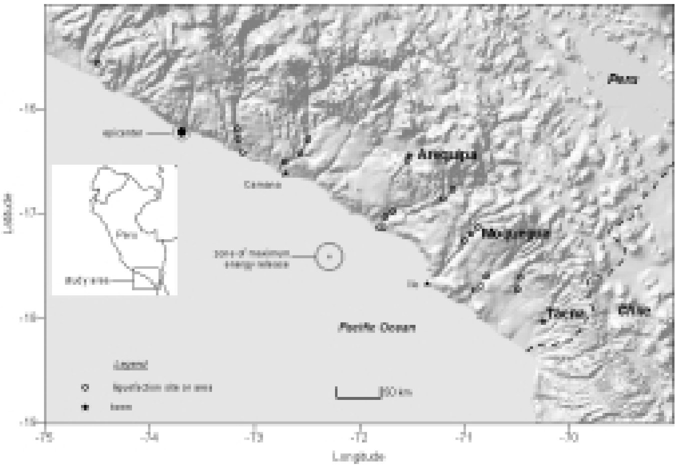

Fig. 4 Distribution of liquefaction in the affected region (compiled from information provided by the NSF reconnaissance team and from, Gomez et al. 2002, Audemard et al. 2002, Koseki at al. 2002).

Fig. 5. Liquefaction-related damage at the Locumba bridge site.

<u>Cuajone Mine Heap Leach Pads</u>

Several heap leach pads exist at the Cuajone mine, one of which failed during the earthquake. Figure 5 shows damage and lateral spreading resulting from liquefaction of the uppermost lift of a heap leach pad liquefied at the Cuajone mine, located about 60 km east of the city of Moquegua (Fig. 4). This uppermost lift was being leached at the time of the earthquake. The pad was lined with a 100-mil high-density polyethylene (HDPE) geomembrane bottom liner. The pad consists of 2-m thick lifts, each of them underlined by a thin (20-mil) geomembrane interlift liner. The ore consists of agglomerated minus 12-in. material (Fig. 6). The liquefied material and leaching solution flowed downstream of the pad. The surface of the liquefied fifth lift suffered considerable deformations (Fig. 7). The likely cause of liquefaction at this heap leach pad was a high solution application rate, combined with the relative fine gradation of the ore and the presence of an underlying interlift liner that inhibited dissipation of pore fluid pressure. To the best of the authors' knowledge, this is the first occurrence of liquefaction in a leach pad and points to the need to consider this potential failure mode due to the potential damages associated with flow failures in leach pads. It is noted that several other geosynthetic-lined heap leach pads exist at Cuajone mine, all of which remained stable.

Fig. 6. . Ore at failed heap leach pad at mine.

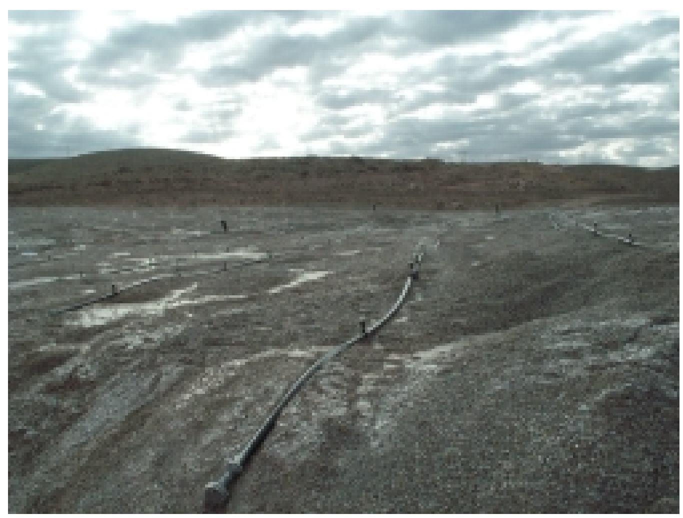

Fig. 7. Failed heap leach pad at Cajone mine.

Liquefaction at the Locumba Bridge

One of the most spectacular liquefaction events occurred at the site of the Locumba Bridge, which is located along the Pan-American Highway. The Locumba Bridge is a 33.5 m long by 9.5 m wide reinforced concrete structure supported by two abutments and a mid-length pier wall. The bridge abutments and wing walls are supported on a shallow foundation system consisting of connected strip footings. Mid-span piers are founded on driven precast concrete piles. The site is underlain by gravelly, sandy alluvium. A complex series of liquefaction-induced ground failures at the site (Fig. 8) resulted in damage that closed the bridge to traffic for at least several months. The vertically displaced road surface, rotated traffic sign and bulging ground below the signposts (Fig. 9) indicate liquefaction-induced strength loss in the foundation soils. A much smaller ground bulge was also observed on the other side of the embankment. Highway crews had removed the damaged pavement before the reconnaissance visit, thereby preventing a detailed survey of the road surface. However, based on references to fixed monuments, it appeared that the road surface was displaced at least 1 m vertically and about the same amount laterally. Less severe, but generally similar, patterns of ground deformation were also observed at the northern approach embankment, where vertical deformations were on the order of 0.35 m. The northern and southern abutment walls of the bridge experienced significant cracking, outward movement, and rotation with consequent damage to the bridge deck supports.

A portion of the site to the west of the bridge spread laterally toward the free face of the river. The magnitude and distribution of the resulting ground movements were captured in a unique manner by rows of corn in a field adjacent to the bridge. The cornrows were offset where a discrete shear zone formed at the ground surface (Fig. 10). The ground surface was relatively flat on this portion of the site, with gradients on the order of about 0.5 percent.

The south river bank spread noticeably toward the free face of the river (Fig. 8). Localized horizontal displacements at the shear zone closest to the river were as large as 1.2 m, and gradually tapered to about zero at a distance of 51 m from the wing wall.

It appeared that the ground southwest of the shear zone experienced little, if any, lateral displacement in this direction, suggesting that the wing wall effectively buttressed the ground, reducing (or eliminating) lateral spread in this area. The eastern limit of lateral spreading could not be determined. Localized lateral offsets and differential ground settlements were observed in the ground surface immediately adjacent to the Locumba River. Sand ejecta were found near many of the ground cracks in this area. Damage to several small structures located along the north bank of the river suggested that lateral spread occurred in this area as well.

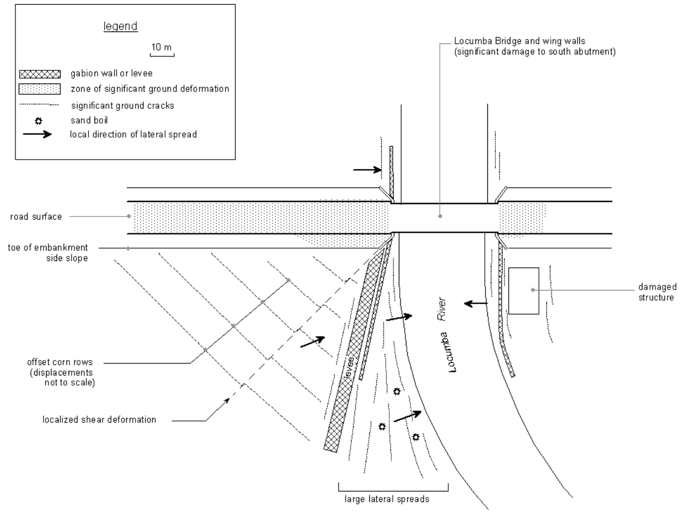

Fig. 8. Liquefaction-related damage at the Locumba bridge site.

Fig. 9. Liquefaction-related damage at the Locumba bridge site.

Other Liquefaction and Lateral Spreading

Additional instances of liquefaction-induced strength loss and lateral spreading damage were observed at other sites in the affected region. An approach embankment of the El Fraile Bridge, a 125 m long steel truss structure located near the town of Mollendo, suffered liquefaction-induced damage (Fig. 11). The presence of sand boils at several locations along the riverbank, along with the general ground deformation patterns, indicated that vertical and lateral embankment deformations resulted from liquefaction of the underlying soil. Comparison of the post-earthquake ground surface with fixed monuments indicated that vertical and lateral deformations were as large as 45 cm and 4.5 m, respectively.

Fig. 10. Southeast view from a levee on the south bank of Locumba River showing ground deformation in a cornfield and damage to the south approach embankment.

Liquefaction was also suspected as the cause of structural distress to the Ocoña bridge on the Pan-American Highway just north of Camaná (Fig. 12). The bridge is a relatively new 5-span reinforced concrete box beam structure. The mid-span support piers were likely founded on driven precast concrete piles, though this was not confirmed. Highway officials closed one lane of the bridge to traffic because of suspected structural damage. Liquefaction in the river valley was confirmed by the presence of numerous sand boils in cornfields upstream from the bridge site. Local residents reported similar occurrences of liquefaction on cornfields further upstream from the river, suggesting widespread liquefaction along the river channel. A drop in the road surface was seen near a mid-length support pier located below the bridge deck. The deformation patterns in the structure suggested that one or more of the middle support piers might have experienced a partial loss of foundation support, causing a significant vertical displacement. It appeared that little, if any, lateral displacement of the support pier occurred.

CONCLUSION

The 2001 Southern Peru earthquake has given the engineering community a great opportunity to study a large subduction event. This paper describes liquefaction observed in the earthquake, and presents observations of potential site effects as evidenced by building damage distributions. Among the liquefaction events observed in this earthquake, the liquefaction of a heap-leach pad is the first reported failure of its type in a seismic event. Observations of building damage distribution in the city of Tacna indicated that there was a higher damage level in areas founded on primarily sandy deposits, while little damage occurred in areas underlain by dense gravels common to southern Peru. Similar observations in the city of Moquegua failed to produce the same degree of correlation. Current research efforts are underway to better characterize local soils both for liquefaction and site effects studies.

Fig. 11. El Fraile Bridge, damaged by liquefaction, was closed to vehicular traffic. A collapsed structure is faintly visible across the river to the right of the bridge.

Fig. 12 Vertical deformation in the Ocoña Bridge probably resulted from liquefaction-induced foundation movements.

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