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Case Histories of Widespread Liquefaction and Lateral Spread Induced by the 2007 Pisco, Peru Earthquake

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CASE HISTORIES OF WIDESPREAD LIQUEFACTION AND LATERAL SPREAD INDUCED BY THE 2007 PISCO, PERU EARTHQUAKE

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ABSTRACT

Case histories of widespread liquefaction and lateral spread induced by the M_w 8.0, 2007 Pisco, Peru earthquake and observed during a post-earthquake GEER reconnaissance are presented. A long duration of the earthquake over 200 seconds and two phases of strong ground motion induced widespread liquefaction and lateral spread of sand coastal deposits and road embankments over a total length of approximately 100 km of coastal region. Six case histories of liquefaction are presented and discussed including a massive lateral spread of a marine terrace believed to be as large or even larger than that reported along the Shinano River during the 1964 Niigata earthquake in Japan.

INTRODUCTION

On Wednesday, August 15 2007, at 6:40 PM local time, a Mw 8.0 earthquake shook the coastal region of central Peru. The earthquake has been referred to as the Pisco earthquake (Pisco being the most affected city). The earthquake caused severe damage to the cities of Pisco, Ica, Cañete, and Chincha, and was strongly felt in Lima, the capital city of Peru. In response to this event, the Geotechnical Earthquake Engineering Reconnaissance (GEER) organization, with funding from the National Science Foundation (NSF), organized a reconnaissance team to document the geotechnical aspects of the earthquake. The GEER team arrived in Peru on August 20, 2007 and stayed for six days. The team visited the cities of Lima, Paracas, Pisco, and Ica, and traveled the north-south roads connecting these major cities with additional smaller coastal towns (Figure 1). This paper is based on the preliminary report by Rodriguez-Marek et al. (2007).

From a geotechnical perspective, the Pisco earthquake was most significant for the amount of soil liquefaction observed in the mesoseismal zone and the considerable damage to urban areas and transportation infrastructure. Multiple cases of lateral spread of road embankments were observed along the coast of Peru south of Lima. A massive lateral spread of a marine terrace occurred in an area called Canchamana. This paper presents significant observed case histories of liquefaction and lateral spread observed by the post-earthquake reconnaissance mission.

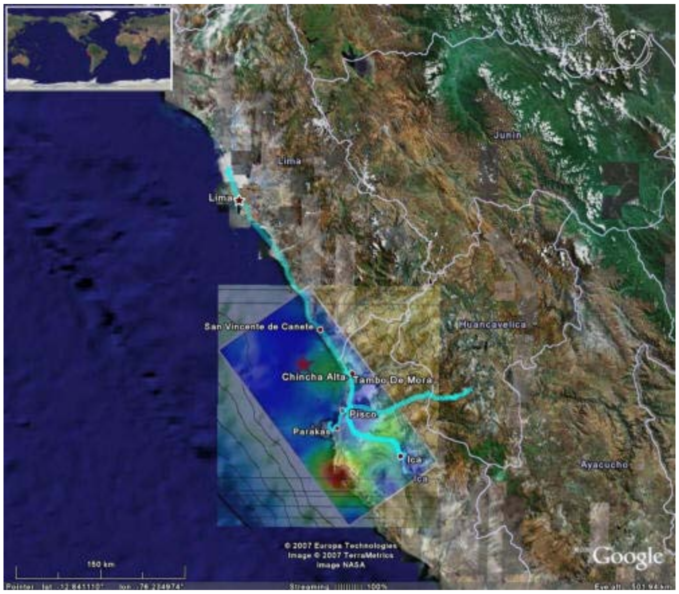

Fig. 1. Overview of affected area. Path in light blue indicates the road coverage of the reconnaissance team. The finite fault solution of Ji and Zeng (2007) is also shown. (Background image from Google Earth).

BACKGROUND INFORMATION

The August 15, 2007 Pisco earthquake was the result of the subduction of the Nazca plate underneath the South American continental plate. This subduction process results in a high rate of seismicity along the coasts of Peru and Chile. The 2007 earthquake was an interface event and occurred on a previously identified seismic gap between the rupture areas of the 1974 Lima and the 1996 Nazca earthquakes (Tavera and Bernal 2005). The 2007 Pisco Earthquake had a moment magnitude (M_w) of 8.0. The hypocenter was located at 13.76S and 76.97W, at a depth of 39 km (USGS 2007). Fault rupture propagated south from the hypocenter (Tavera et al. 2007). The finite fault solution of Ji and Zeng (2007) indicates a rupture plane with a strike of 324º and a dip of 27º, having approximate dimensions of 190 km along strike and 95 km along dip (Figure 2). The locations of aftershock hypocenters match this fault plane (Tavera et al. 2007). The shallow dip and large width of the fault plane implies that the cities most affected by the earthquake (i.e. Pisco and Ica) lie within the ground surface projection of the fault plane. The large duration of recorded ground motions and two phases of strong motion indicate a complex rupture process, with an approximate duration of 210 seconds (Tavera et al. 2007).

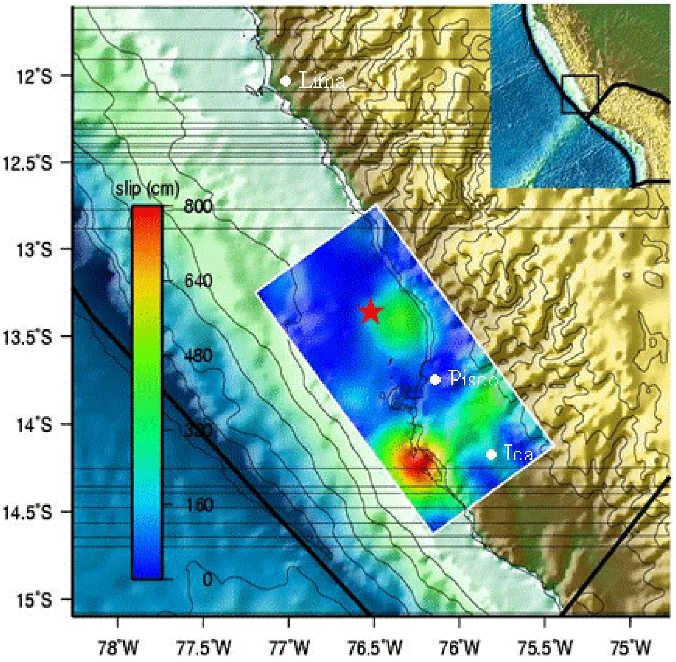

Fig. 2. Finite fault solution by Ji and Zeng (2007).

The Pisco earthquake caused severe damage within its mesoseismal area. As of September 3, 2007, 519 people were confirmed dead, with at least 42 more unaccounted for and 1,874 reported injured. (National Civil Defense Institute, INDECI). INDECI also reports that 54,926 buildings were destroyed and approximately 20,958 buildings were damaged by the earthquake. The majority of the fatalities occurred in the city of Pisco, where by some estimates 80% of the buildings either collapsed or were seriously damaged.

The Geophysical Institute of Peru indicates modified Mercalli intensities of VII in the cities of Pisco, Chincha and Cañete, V to VI in Lima, III in Cuzco, and II in Arequipa (Tavera et al. 2007). In addition, the earthquake was felt as far away as Quito, Ecuador, La Paz, Bolivia, and Manaus, Brazil. The earthquake generated a tsunami that caused considerable damage in the city of Paracas, and inundated portions of many other cities/towns along the coast.

EXTENT OF LIQUEFACTION

The August 15, 2007 Pisco Earthquake spawned a wide variety of liquefaction failures. Notable liquefaction-induced damage included a massive lateral spread extending over approximately 3 km, a 400 m long slope failure induced by liquefaction at the toe, one- to two-story building foundation failures resulting in up to 0.90 m of settlement, numerous highway embankments damaged by lateral spreading, toppling of power poles founded in liquefied soil, rupture of water and sewer lines, and disruption to port facilities. The occurrence of soil liquefaction at each of these sites was confirmed by either the presence of sand boils at the ground surface or wet sand ejecta in open cracks.

The spatial distribution of observed and reported liquefaction features along the Peru central coast ranged from Villa, just south of Lima and approximately 90 km north of the rupture plane (Ji and Zeng 2007), to Paracas in the south, approximately 24 km from the rupture plane, and Ica in the east, about 40 km from the fault plane. Our reconnaissance mission did not extend south of Paracas (Figure 3).

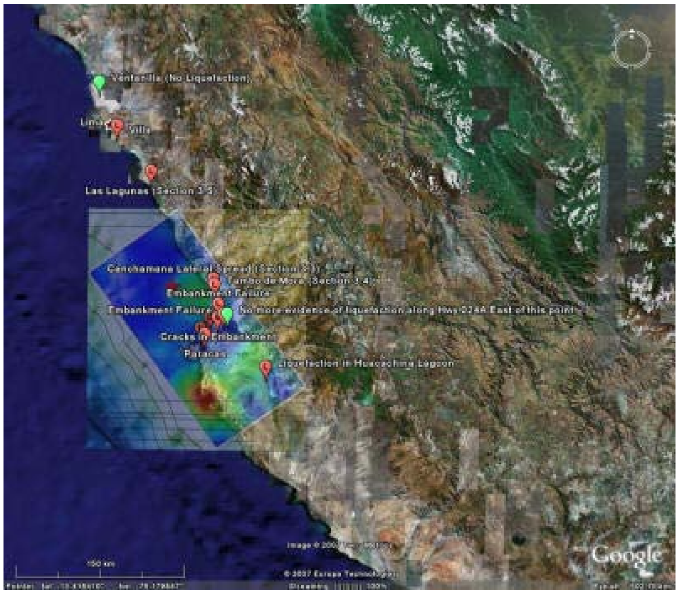

Fig. 3. Overall extent of liquefaction, including one observation of no liquefaction north of Lima in a swamp with saturated sand deposits (green marker). The rupture plane of Ji and Zeng (2007) is overlaid for reference (Background image from Google Earth).

The occurrence of liquefaction along the coast is associated with artificial fills and Holocene marine, eolian and alluvial deposits composed of sands and silty sands with varying angularity and grain size. The marine deposits are stepped terraces that are successively covered by alluvial deposits as they progress inland from the coast. The alluvial deposits are associated with fans and plains from rivers discharging in the ocean. The thickness of these deposits varies from a few meters up to several hundreds of meters. The eolian deposits vary in thickness and are generally composed of dark to light gray sand ranging from coarse- to fine-grained.

The next sections describe significant case histories of liquefaction and lateral spread observed along the coast between Lima, the capital city, and the mesoseismal area.

VILLA SITE

The northernmost liquefaction site, in the Villa neighborhood of Lima, occurred in a swampy area. A similar swampy area located further to the north in the Ventanilla district of Lima, approximately 128 km from the rupture plane, did not show any evidence of liquefaction (Figure 3). Sand volcanoes on the ground surface and lateral spread of road embankments were observed in Villa nonetheless located at approximately 90 km north of the rupture plane.

LAS LAGUNAS SITE

Las Lagunas is a beach housing complex 71 km south of Lima and approximately 51 km from the rupture plane. The area is located in a recent Holocene marine terrace deposit. The complex consists of one- or two-story houses constructed out of brick masonry confined by reinforced concrete columns and beams. Structural damage varied from none to severe and was closely correlated to the degree of foundation settlement and lateral displacement associated with soil liquefaction. Many of the houses are built around manmade freshwater lagoons that were formed by dredging sand and letting the water rise to the natural elevation of the ground water table. The banks of the lagoons were grass-covered slopes with an estimated slope of 1.5H to 1V. There was widespread evidence of lateral displacement of houses towards either the lagoons or the ocean, with displacements ranging from a few centimeters for some ocean-side houses to a case involving 3.9 m of movement towards an inland lagoon (Figure 4).

Fig. 4. Lateral spread with a displacement of 3.9 m. The house located in front of this lateral spread suffered considerable damage due to differential settlements.

Some houses also settled as much as 0.2 m. At least one lateral spread was also observed on the banks of a lagoon where there were no nearby buildings. Additionally, many houses did not show any evidence of movement and performed well in the earthquake, even when located near the open face of a lagoon. In the limited time of our visit, no clear pattern as to the spatial distribution of liquefaction damage within the subdivision could be deciphered. Sand ejecta was present at various places, mainly along cracks in the ground. The ejecta was gray, fine, uniform sand with some non-plastic silt.

JAHUAY SLOPE FAILURE

A 400 m long slope failure was induced at Jahuay by liquefaction at the toe of an approximately 30 to 50 m high, steep-faced slope. The failure occurred near kilometer marker 188 on the Pan American Highway just south of the tollbooth plaza (approximately 40 km from the rupture plane). At this location, the highway runs right along the interface between a Holocene marine terrace deposit and the Pleistocene Cañete Formation (a conglomerate with weak- to medium-cemented sandstone, siltstone, and claystone). The failed slope material consisted of loose, non-plastic, silty sand eolian deposits that covered the stiffer Cañete Formation. The flat, swampy, marine terrace extends approximately 500 m to the coastline on the southbound side of the highway (Figure 5).

Fig. 5. A view of the Pan American highway at the location of the 400 m long Jahuay slope failure. Marine terrace deposits are in the foreground and the Cañete Formation in the background.

The slope failure was induced by liquefaction in the marine terrace deposits at the toe of the Cañete Formation. The shoulder and pavement from the northbound lane of traffic was lifted into a near-vertical face approximately 3 m high; this is thought to have occurred as a result of the failed slope material plowing under the highway embankment. Massive amounts of failed soil were slumped between the highway and the edge of the slope over the entire 400 m length of the failure. A local man reported that the highway south of the slope failure was recently repaired and properly recompacted, and this appears to have prevented an extended failure to the south.

Sand boils were found on both sides of the highway and a man who lived just south of the slide reported water and sand squirting out of the ground approximately 1 m high during the earthquake. A large sand boil feature on the southern end of the slope failure had shrinkage cracks in some of the perimeter material, indicating the presence of plastic fines. The fines were found only on a thin layer on top of the ejecta material. Laboratory tests conducted on the ejecta from this boil indicate it classifies as clayey sand containing approximately 43% fines (11% clay-size particles) with a PI of 8 and a LL of 25. However, until further investigations are conducted at the site it will remain unclear if the fine plastic material was part of the liquefied source layer or if it was mixed in with the liquefied material on its path to the surface. It should also be noted that a sand boil on the opposite side of the road classified as poorly graded sand with less than 3% non-plastic fines.

TAMBO DE MORA TOWN

Liquefaction-induced foundation failures were documented in the northwest portion of Tambo de Mora approximately 0.5 km from the coastline and 38 km from the rupture plane. Tambo de Mora is located on Holocene alluvial and eolian deposits and has a shallow ground water table. While widespread evidence of soil liquefaction (minor settlement and sand ejecta) was present throughout much of the northwest portion of the city, particularly heavy damage (excessive settlement) was observed in one- to two-story buildings along a 300 m stretch of Alfonso Ugarte Street. Along this stretch of road, nearly every building settled substantially (0.3 m plus), with multiple buildings settling between 0.7 and 0.9 m (Figure 6).

Fig. 6. Approximately 0.9 m of liquefaction-induced settlement at a one-story house in Tambo de Mora.

Large quantities of ejecta was observed in cracks that had developed in the road and inside of buildings whose unreinforced slab-on-grade floors had been broken apart and heaved–up into their interiors. In most cases, ejecta was gray, non-plastic, poorly graded sand to silty-sand. One exception was a plastic silt (LL = 48) found in the interior of a house. The depth to the water table along the road was measured at 0.3 m during our visit a week after the earthquake. However, locals reported that the water table existed at a depth between 0.5 to 1.0 m prior to the earthquake. These same residents reported water and sand shooting more than 1.0 m above the ground surface beginning with the second strong phase of the earthquake.

Recent preliminary field exploratory works in Tambo de Mora (Aguilar 2008) indicate that a gravel layer underlies shallow loose, saturated sand. The thickness of the sandy layer ranges between 2.0 and 6.0 meters. SPT N-values were as low as 2 in several cases and the ground water table was close to or at the ground surface. Current efforts aim at defining the thickness of the gravel layer and soil conditions underneath this layer. Reconstruction efforts require deciding whether relocate the town or built on the same place with appropriate and economical foundations.

SAN MARTIN PORT

The General San Martin Port was inaugurated in 1970 and operates with ships as heavy as 25,000 tons of dead weight. It is located in Punta Pejerrey, Pisco Beach, approximately 30 km from the fault. The port is surrounded by granite porfids (intrusive rocks), which are part of the San Nicolas Batholite. The granite porfids have a fine to coarse matrix with colors ranging from pink to dark brownish red. Port facilities were constructed on reclaimed land. The wharf has a reinforced concrete deck that is supported by 780 circular steel pipe piles. The reclaimed land area of the port settled over the years resulting in differential movement between the pile-supported buildings and the surrounding soil. The typical solution to this problem was to place more fill to level the surrounding reclaimed ground surface. The earthquake induced liquefaction in the reclaimed land, as evidenced by sand boils and lateral spreading with significant cracks as wide as 0.25 m and vertical offsets as large as 0.8 m (Figure 7).

Fig. 7. Vertical displacements as large as 0.8 m were observed between the pile-supported wharf and the reclaimed

backfill. The bulge appears to be a pile that was buried in the fill. Although the port was heavily damaged, it had enough functionality to receive relief for earthquake victims

The pile-supported deck appeared slightly inclined seaward, and horizontal offsets in the deck joints were as large as 0.50 m. Ground cracking developed parallel to the deck on the reclaimed land area and was most severe near the waterfront. A pipeline that ran across the port inside of a concrete box was not damaged in the earthquake despite the fact that the surrounding ground settled substantially. It is presumed that the concrete box was supported on piles. No cracks were observed in native ground around the pier.

CANCHAMANA LATERAL SPREAD

A massive liquefaction-induced seaward displacement of a marine terrace occurred in Canchamaná, 2.5 km north of Tambo de Mora. The approximate displaced area was 1 km wide by 3 km long (Figure 8).

Fig. 8. Approximate extent of a massive seaward lateral spread of a marine terrace in Canchamaná. The boundary of the mobilized area on the north is uncertain and could possibly extend further (Background image from Google Earth).

The eastern boundary of the lateral spread was defined by the interface between a Holocene marine terrace and the Pleistocene Cañete Formation (a conglomerate with weak- to medium-cemented sandstone, siltstone, and claystone). The southern boundary appeared to be defined by the interface of the marine terrace with a Holocene alluvial sand deposit. The northern boundary was not firmly established, but appeared to be influenced by the presence of man-made works at a bend in the Pan American highway. The lateral spread could have extended further to the north but it was not verified. The elevation of the Cañete Formation is approximately 10 to 20 m above the marine terrace. The near-surface marine terrace deposits appear to be composed of an upper layer of non-liquefiable soil (weakly cemented sand), and a lower layer of liquefiable soil (silty sand). The thickness of the upper layer tapers from approximately 6 m on the east side to a thin veneer at the beach. The depth of the groundwater table was variable at the two locations where it was measured. Both measurements were made on the eastern side of the marine terrace near the Cañete Formation. In an existing well located approximately at the center (north-to-south) of the displaced area, the ground water was measured at 5.2 m deep, and in an open pit approximately 0.70 km north of this well, the ground water table was measured at 2.0 m deep. The westward slope of the marine terrace surface was approximately 1.6 to 2.1 %.

A clear vertical offset (scarp) of variable magnitude was observed along much of the geological interface between the marine terrace and the Cañete Formation. A maximum vertical displacement of approximately 3 m was measured where a local dirt road links Canchamaná with La Victoria town. In addition to the main scarp at the interface, numerous extensional ground cracks developed across the marine terrace parallel to the coastline. In general, the cracks were largest (both in terms of horizontal and vertical displacement) near the scarp and became smaller towards the coastline. Some crack widths were as large as 1 m and sand ejecta was found inside many of them. In some areas the cracks also ran perpendicular to the beach or in a circular pattern, indicating the effect of topography.

At the northern-most end of the failure, an approximately 8.0 m tall artificial fill embankment for the Pan American highway had been built across a natural drainage feature. Liquefaction and lateral spreading of the marine terrace induced failure of the embankment fill and sheared three concrete box culverts running through the embankment. Sand boils with diameters as large as 2 m were encountered near the base of this embankment. These boils were both found at the base of the Cañete Formation and are only 2 km apart. It is highly likely that the same liquefiable material induced both failures as additional sand boils and small scarps were noted in between these locations.

At present it is very difficult to estimate the total lateral displacement of the marine terrace because it occurred over such a massive area. However, local fishermen showed us traces on the beach of the sea level before and after the event, suggesting that the water line moved about 25 m westward. This measure is not an estimate of the horizontal displacement of the lateral spread, but it is believed that lateral spread contributed to this change in the landscape. A bulge along the beach was also observed, indicating that this could have contributed to the movement of the coastline. Figure 9 shows a sketch of the observed massive displacement of the marine terrace. This massive lateral spread could be as large or even larger than that reported along the Shinano river during the 1964 Niigata earthquake in Japan.

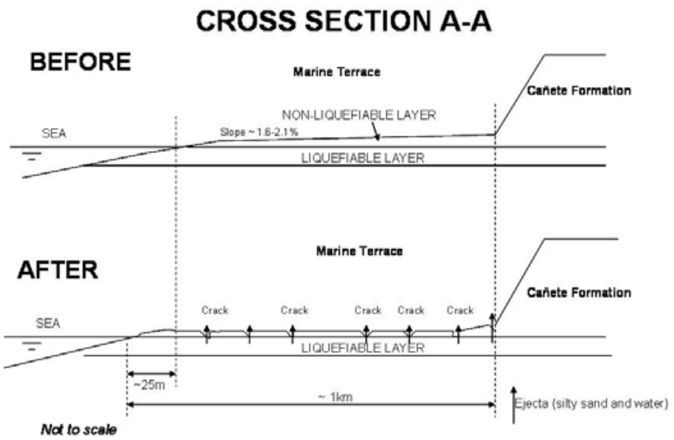

Fig. 9. Interpretative sketch of the massive lateral spread of the marine terrace at Canchamaná at Cross Section A-A from Figure 8.

CONCLUSIONS

Widespread liquefaction and consequent lateral spread caused significant damage to urban areas and transportation infrastructure over approximately 100 km of coastal area. A long duration earthquake of over 200 seconds and two phases of strong ground shaking were the two main causes for the extent of liquefaction of saturated coastal sand deposits. Current field exploratory work in affected areas for reconstruction purposes will unveil soil layering and provide the basis for explanation of physical mechanisms of observed phenomena.

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