UPDATE ON THE OCURRENCE OF THE SOIL LIQUEFACTION PHENOMENON IN PERU

ACTUALIZACIÓN DE LA OCURRENCIA DEL FENÓMENO DE LICUACIÓN DE SUELOS EN EL PERÚ

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ABSTRACT

This paper presents the available information on the soil liquefaction phenomenon induced by seismic action in Peru and its representation on a soil liquefaction hazard map. Such map is drawn at a scale of 1: 5,000,000 and distinguishes between real and probable liquefaction hazards, according to the interpretation of the information available in the literature. All the documentation that provides evidence of the liquefaction phenomenon, such as the formation of small mud and sand boils, the violent expulsion of water from the ground, the presence of intense cracking and the differential settlements triggered by seismic action, has been detailed in this article.

Keywords: Soil liquefaction, Earthquakes, Water table

RESUMEN

Se presenta la información disponible sobre el fenómeno de licuación de suelos en el Perú debido a la acción sísmica y su representación en un mapa de áreas de licuación de suelos. El mapa de áreas de licuación de suelos está dibujado a la escala 1:5'000,000 y presenta distinciones entre casos de licuación seguros y probables, de acuerdo con la interpretación de la información disponible en la literatura. Toda la documentación que presenta evidencias del fenómeno de licuación, tales como la formación de pequeños volcanes de barro y arena, la expulsión violenta de agua del suelo, la presencia de intenso agrietamiento y los asentamientos diferenciales debido a la acción sísmica, ha sido detallada en este artículo.

Palabras Clave: Licuación de suelos, Sismos, Napa freática

1. INTRODUCTION

Soil liquefaction has been one of the main culprits of the damage caused to various infrastructure during earthquakes, damage which ranges from small sand volcanoes to massive landslides. Liquefaction can cause the foundations of the structures of buildings, bridges, retaining works, road works among others to settle, tilt or collapse.

Liquefaction is a term used to describe the loss of strength and stiffness of a soil deposit due to the rise in pore water pressure generally triggered by earthquakes, causing the soil to crack allowing water and sand to erupt. Liquefaction most commonly occurs in loose, saturated, clean to silty sand, but has also been observed in gravels and non-plastics silts.

The main purpose of this article is to present the available information on the occurrence of liquefaction of soils in Peru, a South American country located on the Pacific coast and one of the most active seismic regions in the world.

2. BACKGROUND

Peru is located in a highly seismically active region due to the interaction of the tectonic plates of Nazca and South America, as well as by the activity of surface geological faults. These seismic events have led to considerable and continuous human and material losses throughout the Peruvian territory.

Internationally, problems initially evolved as a result of two devastating 1964 earthquakes, the Niigata and Alaska earthquakes, wherein the liquefaction phenomenon caused devastating effects.

As time went by, the earthquakes continued to provide lessons and data, allowing researchers and professionals to become increasingly aware of the potential additional problems associated with both sandy and gravel soils.

In Peru, several researchers [1], [2], [3], have compiled historical information on the most significant seismic events that have occurred since the 16th century up to the present, one of them being Silgado [4].

There are also soil liquefaction research and evaluations taking place in some areas of the country carried out by researchers and specialists, [5], [6], [7], [8] and [9].

The literature on Peruvian earthquakes that points to the occurrence of the soil liquefaction phenomenon is included in the list of references.

3. METHODOLOGY

This is an investigating qualitative research for which all available information on Peruvian earthquakes [1], [2], was analyzed in detail, compiling both historical data and from this century on the soil liquefaction phenomenon. The purpose was to find evidence of this phenomenon, such as the development of small mud and sand boils, violent expulsion of water from the ground, presence of cracking, differential settlements, loss of bearing capacity and collapse of structures, loss of slope and embankment stability, and the loss of lateral resistance of piles and caissons during earthquakes.

A distinction was made between cases of real and probable soil liquefaction. The distinction was made by the authors, based on experience and existing literature. Probable cases were those generally associated with historical and recent earthquakes where a description of the soil liquefaction phenomenon was not very detailed. Finally, a soil liquefaction map has been prepared and includes the name of the locations and the years in which the phenomenon occurred, as well as the national hydrographic network.

3.1 A BRIEF HISTORY OF THE OCCURRENCE OF THE LIQUEFACTION PHENOMENON

3.1.1. January 22, 1582

Silgado [4], based on Fray Victor Belly's *Los Terremotos de Arequipa*, |Earthquakes of Arequipa|, mentions an earthquake that left the city of Arequipa in ruins. After the earthquake, the entire city was flooded by large amounts of water running through the streets, probably due to the settlement and compression of the water table. On the coast, a stream of water that entered the port of Islay was completely submerged. Reference to this phenomenon is also made in *Historia del Perú* [History of Peru] by Father Ruben Vargas Ugarte, SJ. The maximum intensity of this earthquake was MM X.

3.1.2. February 14, 1619

An earthquake in northern Peru which ruined the buildings in Trujillo. Silgado [4] refers to the chronicle of Father Calancha which reports cracks opening in the ground in various places from which a blackish mud emerged. Feijoo adds that the "viscous and foul-smelling material expelled, covered in clayey water which used to form rivers that ran through the farmlands of Villa of Santa, Barranca and others, stained its currents with such a flood." Based on the stories, it seems that there were other effects on the slopes: water appeared in some dry riverbeds, while in other streams water simply stopped running. The maximum intensity of this earthquake was MM IX.

3.1.3. March 31, 1650

An earthquake in Cuzco that brought down all temples and most of the buildings. According to Silgado [4], cracks opened in the ground in several places, and disturbances could be seen in the water table of the runoff waters near the town of Oropesa. The maximum intensity of this earthquake was IX MM.

3.1.4. May 12, 1664

Earthquake in Ica. Silgado [4] refers to the story of the priest of the Parish Church of San Jerónimo [Saint Jerome], Cristobal Rodriguez Alvarez: "The earth opened once again in several places; the ground around the hills and fields separated forming cracks and great depths which resembled mouths ready to swallow us. The river flowed in over six irrigation channels, overflowing a few of the city's wells and uprooting many large trees, willows and hawthorns." The maximum intensity of this earthquake was X MM.

3.1.5. February 10, 1716

Earthquake in Pisco as described by The Barbinais: "The earth began to shake again fifteen minutes later, opening in some places and expelling jets of dust and water making a frightening noise" [4]. The maximum intensity of this earthquake was IX MM.

3.1.6. October 28, 1746

Earthquake in Lima and Tsunami in Callao. Bachmann [4] says that "the earth parted in the mineral ravine of the Viseca river, in the province of

Lucanas, and out came vermin. A hot water volcano also erupted flooding everything. In the area of the Franciscan Missions of Cajamarquilla, in Pataz, two volcanoes of silt and mud also erupted.” The maximum intensity of this earthquake was X MM.

3.1.7. 1747

In his *Sinopsis de los Temblores y Volcanes del Perú* [Synopsis of the Tremors and volcanoes of Peru] Toribio Polo claims that a strong earthquake occurred in 1747 but as it happened in a remote region in Puno it was hard to get an exact date. It is known, though, to have caused great destruction in Ayapata, province of Carabaya; muddy water sprang from the earth and many people perished [4]. The maximum intensity of this earthquake was MM VIII.

3.1.8. March 30, 1813

Silgado [4] speaks about an earthquake in Ica that destroyed houses and temples, and in which 32 people died. Large cracks opened along the riverbed, from which large amounts of mud emerged. The maximum intensity of this earthquake was MM VII.

3.1.9. August 20, 1857

Silgado [4] talks about a strong earthquake that occurred in Piura and destroyed many buildings. The earth opened from which blackwater emerged. The Port of Paita experienced some minor damage. The maximum intensity of this earthquake was VIII MM.

3.1.10. August 13, 1868

Earthquake and tsunami in Arica. Silgado [4] refers to a story by Toribio Polo: "Various cracks could be seen in the ground, especially in Arica, from which muddy water sprouted". Bachmann [10] reports that in Sama and Locumba much of the crops were lost and the earth opened forming deep cracks which spewed muddy water. The maximum intensity of this earthquake was XI MM.

3.1.11. July 24, 1912

Earthquake in Piura and Huancabamba. Cracks formed along the dry riverbed of the Piura river causing upwelling. Other damages affected the railway embankment. Cracks appeared in the ground at the Port of Paita [4]. The maximum intensity of this earthquake was MM VIII.

3.1.12. December 24, 1937

Earthquake in the eastern slopes of *Cordillera Central* [Central Mountain]. It impacted the peoples of Huancabamba and Oxapampa. Silgado [4] says that a crack opened in Fundo Victoria from which large amounts of water emanated taking with them large trees and increasing the flow of the Chorobamba river. This was a magnitude (Ms) 6.3 earthquake with a maximum intensity of MM IX.

3.1.13. May 24, 1940

Earthquake in the city of Lima and nearby towns. Valencia [11] reports that the effects of the earthquake were felt in Callao, especially in areas formed by hydraulic fill. In these areas the ground cracked and out came large amounts of semi-liquid mud. These cracks even went through constructions. This was a magnitude (Ms) 8.0 earthquake with a maximum intensity of MM IX.

3.1.14. August 6, 1945

Strong tremor in the city of Moyobamba and surrounding areas. According to Silgado [12], a few cracks formed along the Shango ravine. Subsequently, the tremor that occurred on the eighth day produced new cracks adjacent to the first, one of them a 15-cm semicircle with 4-cm of separation, from which silty waters emanated for two days. Cracks also appeared along the edges of the Tahuisco cliffs, near the Mayo river and in the Azungue ravine. New springs appeared about five kilometers away from the sulfur baths and 10 km from the city. The maximum intensity of this earthquake was MM VII.

3.1.15. May 28, 1948

Strong devastating earthquake in Cañete. Several swampland landslides occurred in the vicinity of a place called Calavera. Several cracks formed on the slopes of Cerro Candela where small landslides occurred due to soil saturation [4]. This was a magnitude (Ms) 7.0 earthquake with a maximum intensity of MM VII.

3.1.16. May 21, 1950

Earthquake in the city of Cuzco. Silgado, Fernández-Concha and Ericksen [13] noted an area of extensive cracking on the south side of the Valley, southeast of the town of San Sebastián. They also noted two small fractures in a marshy area located 300 m to the south of San Sebastián, from which water and sand emerged during the earthquake. The holes created by the ejection were about 2 m in diameter and the sand around the fracture was between 1 to 2 cm thick. During the seismic movement, these and other fractures created along the hill were pouring jets of water that reached 1 to 2 m in height. The level of groundwater rose towards the southern side of the Valley. A week and a half after the quake, areas that had been almost completely dry before the earthquake were now covered with 10 to 40 cm of water. Also, after the event, the water in one of Hacienda San Antonio's wells rose to 1.80 m above its normal level. This was a magnitude (Ms) 6.0 earthquake with a maximum intensity of MM VII.

3.1.17. December 9, 1950

Major earthquake in Ica. A few small cracks opened in the ground of Fundo La Vela's sowing field, of which water emanated even hours after the earthquake took place [8]. This was a magnitude (Ms) 7.0 earthquake with a maximum intensity of MM VII.

3.1.18. December 12, 1953

A strong and prolonged seismic movement which affected the north-western part of Peru as well as part of the Ecuadorian territory. Silgado [15] indicates that long cracks opened in the wet ground. Mud ejections were seen in the Bocapán ravine, the estuaries of Puerto Pizarro and elsewhere. Water ran momentarily in Bocapán – which had been dry before the quake – given the water sprouts. Puerto Pizarro saw cracks as well as jets of water 60 cm in height. This was a magnitude (Ms) 7.8 earthquake with a maximum intensity of MM VIII.

3.1.19. January 15, 1958

Earthquake in Arequipa. Silgado [4] indicates ground cracking occurred near the area of Camaná, with ejection of blackwater. This was a magnitude (Ms) 7.0 earthquake with a maximum intensity of MM VIII.

3.1.20. October 17, 1966

The city of Lima was rocked by an earthquake. Numerous cracks appeared in Hacienda San Nicolás, 156 km north of Lima, several of which ejected yellow-colored water [4]. This was a magnitude (Ms) 6.3 earthquake with a maximum intensity of MM VIII.

3.1.21. June 19, 1968

Earthquake in Moyobamba. Kuroiwa and Deza [16] describe cracking in the ground from which sand and water emerged, as well as major landslides in the epicentral region. The phenomena of cracking and emergence of water were the most numerous, especially along the banks of the Mayo river. Martinez Vargas [17] presents views of cone-shaped sand outcrops some 10 to 20 cm in diameter created as a result of the liquefaction phenomenon on the terrace of Moyobamba. This was a magnitude (Ms) 6.9 earthquake with a maximum intensity of MM VIII.

3.1.22. May 31, 1970

Earthquake that affected the entire department of Ancash and southern La Libertad. Ericksen et al [18] and Plafker et al [19] point to the ground lateral spreading caused by the liquefaction of deltaic and beach deposits in Casma, the Port of Casma, and in areas close to the coast in Chimbote, which caused cracks in the ground that ultimately collapsed the structures in their paths.

The largest areas of sand boils formed along the Casma river, between Casma and the Port of Casma. The central crater of the volcanoes measured from several centimeters to 1 m in diameter, surrounded by a mound of sand and silt of up to 15 m in diameter. There were also jets of water reaching a height of up to 1 m. Soil liquefaction was evident in Chimbote's central area, as was the differential compaction of the foundation. The Casma bridge was damaged due to the liquefaction of the foundation of the abutments. Liquefaction-induced ground subsidence could be observed In Chimbote, Casma and along the Pan-American Highway. The residential area of the Port of Casma showed evidence of settlement and water ejection. Cluff [14] reports ground failure in Chimbote due to saturated and loose beach deposits. Liquefaction-induced lateral spreading and differential compaction also occurred in Casma (Fig. 1).

Fig. 1. Concrete-block house affected by differential compaction and lateral spreading due to the liquefaction of beach sand.

Differential compaction caused the land to be flooded by groundwater (Fig. 2). Sand boils and water ejections appeared in many areas because of the high-water table. Berg and Husid [21] report evidence of soil liquefaction in the foundation of the Mundo Mejor school in Chimbote. Carrillo [22] points to the settlement of the access embankments of almost all the bridges along the Pan-American Highway, as well as settlement of the platforms of the Chimbote Port Terminal. There was also evidence of the liquefaction phenomenon in saturated sand deposits along Elias Aguirre street in Chimbote and along km 380 of the Pan-American Highway, near Samanco.

Fig. 2. Flooding of area in southeast Chimbote due to settlement and soil compaction.

Hidrotécnica Corporation and C. Lotti [23] report widespread liquefaction in Port of Casma, producing ground cracking and ejections of sand water. Chimbote saw numerous cases of liquefaction (Fig. 3) and the Port of Casma was completely flooded. Morimoto et al [24] describe the soil liquefaction phenomenon in the city of Chimbote. Widespread liquefaction occurred in the marshlands, in addition to cracking due to differential compaction; subsurface liquefaction occurred in the alluvial zone, as did cracking and sand boils. This was a magnitude (Ms) 7.8 earthquake with a maximum intensity of MM IX, and the maximum acceleration recorded at the Parque de la Reserva station in Lima was 105 cm/s^2.

Fig. 3. Damage to sewer inlets due to liquefaction

3.1.23. December 9, 1970

Earthquake in northwestern Peru. A 500 m-long system of echelon cracks was formed on the fluvial and alluvial terraces of Querecotillo, with 0.30-m openings and 0.25-m echelons. The outpouring of sand forming basins 0.60 to 1.00 m in diameter were also noted. The ground cracked near the La Huaca hamlet, sprouting up sand and mud. Blackwater and sand were seen pouring out through cracks in the fluvial terraces in Tumbes, near the port of El Cura [25]. This was a magnitude (Ms) 7.1 earthquake with a maximum intensity of MM IX.

3.1.24. March 20, 1972

Earthquake in the northeast. According to Perales and Agramonte [26], soil liquefaction occurred in the urban area of Juanjuí with aligned basins of up to 1 m in diameter. Settlement occurred along the Marginal highway. Groundwater varied its static level in more than a meter. Two wells were inspected; at the time of the visit, they were dry and clogged with sand. This was a magnitude (Ms) 6.9 earthquake with a maximum intensity of MM VIII.

3.1.25. October 3, 1974

Earthquake in Lima. According to Huaco et al [27] and Giesecke et al [28], local liquefaction phenomena occurred in the Cañete valley where the water table is very shallow. The most significant local phenomenon happened at Cooperativa La Quebrada, covering an area of 30.000 m^2. Maggiolo [29] indicates widespread liquefaction at Tambo de Mora, caused by either subsidence or sinking, with subsequent densification along 4 km, parallel to the beach line. Sand-water mixture ejected from sand boils in the northern area. Espinosa et al [30] indicate possible differential settlements in El Callao due to soil liquefaction, and Moran et al [31] present a view of possible liquefaction in Ancon. The maximum intensity of the earthquake was of MM VIII, the magnitude (Ms) was 7.5 and the maximum acceleration recorded at the Parque de la Reserva station in Lima was 190 cm/s^2 EW component.

3.1.26. May 29, 1990 and April 4, 1991

On May 29, 1990, at 9:34 pm (local time), a magnitude (mb) 6.0 earthquake shook the southwest of La Rioja. Beginning on April 4, 1991 a series of seismic movements shook the region, the greatest of which occurred at 11:30 pm (local time), with a magnitude (mb) 6.5, the epicenter of which was 30 km northwest of Moyobamba, near Cerro Angaisa. It had a maximum earthquake intensity of MM VII.

Alva [32] observes and describes the soil liquefaction phenomenon at the Port of Tahuishco in Moyobamba. Lateral spreading due to liquefaction occurred at the Educational Center of Tahuishco in 1991, creating cracks 10 cm wide and 50 cm deep (Fig. 4). The floor of a classroom was destroyed. During the 1990 earthquake, the phenomenon did not reach the school building, but it did reach its courtyard where sand boils appeared.

Fig. 4. Ground cracking near the Tahuishco school due to soil liquefaction

Segments of the Moyobamba and Tahuishco highway were damaged during both earthquakes. During the 1990 earthquake the soil liquefaction phenomenon was reported to have occurred at El Chorro and Molino Valencia in La Rioja, as well as in Segunda Jerusalen-Azunguillo, the Negro river and La Conquista.

Ground cracking and lateral spreading occurred in Azunge, located in the Moyobamba lowlands. Cracks were reportedly 100 m long, 40 cm wide and 1 m deep. Most of the houses on the slopes collapsed. The pumping station and sewer lines failed. All the mudwall houses and a few brick houses built on soft ground collapsed (Fig. 5).

Fig. 5. Damage to mudwall houses and ground cracking due to lateral spreading in Azungue.

In Shango, mudwall houses collapsed. 80-cm-long cracks with a 20 cm slope were observed (Fig. 6). Along Miraflores street, cracks were 30 m long and had a depth of 30 cm.

Fig. 6. Ground cracking due to liquefaction going through a brick wall in Shango

3.1.27. November 12, 1996

On Tuesday, November 12, 1996, a moderate earthquake shook the Nasca Acarí region, 450 km south of Lima. The earthquake was caused by the subduction of the Nazca Plate under the South American Plate. The epicenter was located 135 km southwest of the city of Nasca with a focal depth of 33 km. The earthquake had a maximum intensity of 7+ on the MSK scale and magnitude Mw 7.7.

Alva and Vasquez [33] indicate that soil liquefaction occurred along the riverbed of the Yauca river, as did sand boils, mud ejections and cracking. Cracks opened on the top beam and column of one of the bridge's pillars, and the board was displaced. Traffic was interrupted and bridge repair and restoration works began immediately (Fig. 7).

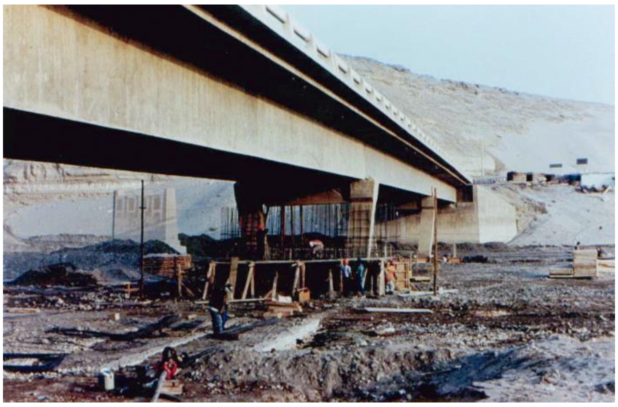

Fig. 7. Soil liquefaction in the foundation of the Yauca Bridge

3.1.28. June 23, 2001

On June 23, 2001, at 15:30 (local time), Peru was hit by a magnitude (Mw) 8.2 earthquake which caused death and destruction mainly in the departments of Arequipa, Ayacucho, Moquegua and Tacna in Peru, Arica and Iquique in Chile, and La Paz in Bolivia; the maximum acceleration recorded at the Moquegua station (CISMID) was 289 cm/s^2 EW component. The maximum intensities in some towns and cities, close to the coast, reached VIII on the Modified Mercalli Scale [34].

Yanqui [35], indicates that liquefaction occurred in the following areas:

Las Magnolias Urbanization: In the district of Socabaya, in the area of Lara, there is a small basin that runs from the Golf Club to the Sabandía river where a few small urbanizations such as Las Magnolias and Los Cristales have settled. These occupy some areas that were liquefied during the most recent earthquake. The effects observed on the ground were as follows: distortion and fracturing of floors, boiling sand water, settlement of a sidewalk by approximately 12 cm, warping of a water tank built with brick and ashlar, ground cracking, lateral spreading of the small slopes of an open drain, tilting and fall of street lights in different directions, cracking of bearing walls of a few houses and of fencing walls, lifting of sewer inlets and collapse of small walls.

Huaranguillo: A small area in Huaranguillo, district of Sachaca, near the Kola Real bottling plant, experienced the earthquake-induced liquefaction phenomenon. Two boiling points appeared: a small one which formed a small sand boil and another larger one that ejected pink sand water. A few longitudinal cracks were also observed along a one-meter-high slope. A fence built pursuant to masonry standards underwent a small settlement.

Semi-Rural Pachacútec: Sand horizons on a small ravine in the Semi-Rural Pachacútec urbanization, in the district of Cerro Colorado, were liquefied and caused the warping and collapse of a few fence walls. Some slopes of small height cracked, and a retaining wall collapsed.

Gomez et al [36] note the presence of soil liquefaction in the valleys of the rivers Yauca, Ocoña, Camaná, Tambo, Osmore, Locumba and Sama. The area of greater evidence of liquefaction was along the Camaná river and the coastal strip between Mejia and Punta de Bombón. Thus, along the Camaná riverbed, the numerous evidences of liquefaction affected the embankment of the left bank of the river. Fine to intermediate-grain sands along the river course were liquefied on those not-very-powerful sandbars. Sand boils measured up to 2 m in diameter. Longitudinal fractures were also measured along the banks with sand ejections a few meters long (individual cracks were no larger than 4 m in length).

Another area with a greater distribution of evidence of soil liquefaction is the deltaic-coastal plain of the Tambo river, with sand ejections and lateral spreading, from the vicinity of Mollendo to El Fiscal, and in the following sections: Mollendo–Mejía, Mejía–El Conto, La Curva–El Arenal, and El Arenal–Puente El Fraile. The sectors located further south, such as at the mouths of the Osmore, Locumba and Sama rivers, showed evidence of sand liquefaction with aligned sand boils, ventilation cracks and small lateral spreading (Fig. 8). Sand boil cones reached a maximum diameter of 50 cm and the volume expelled was also much lower than in critical areas of Camaná and El Tambo.

Fig. 8. Containment wall pulled into the abutment of the bridge over the Sama river

3.1.29. September 25, 2005

On September 25, at 8:55 pm, a strong earthquake rocked the northeastern region of Peru, causing considerable damage mainly in the city of Lamas and surrounding areas in the department of San Martin, as well as in the city of Chachapoyas and surrounding areas, in the department of Amazonas. The magnitude (Mw) 7.5 (NEIC) earthquake, which occurred at a focal depth of 115 km, of intensity MM VI in the epicentral area, and which recorded a maximum acceleration of 132 cm/s^2 EW component at the Moyobamba station, was felt throughout the Northern and Central regions of Peru, perceptible from Lima towards the South and Guayaquil, Ecuador, towards the North. The CISMID team of professionals [37], observe the occurrence of the soil liquefaction phenomenon in the Shango and Azungue sectors, located in the lower part of the city of Moyobamba. (Fig. 9) shows sand boils and ground cracking created by landslides, evidence of soil liquefaction.

Fig. 9. Sand boils, city of Moyobamba

3.1.30. August 15, 2007

On August 15, 2007, at 6:40 pm local time, a strong earthquake shook the coast of central Peru. The epicenter was located 40 km northwest of the city of Chincha, 105 km to the northwest of the city of Ica and 150 km southeast of Lima, the capital of Peru. The epicenter coordinates were 13.354°S 76.509°W, pursuant to the United States Geological Survey (USGS, 2008). The USGS estimated that the Moment Magnitude of this event was M = 8.0 ± 0.1, and the depth of the hypocenter was between 26 km and 39 km. The maximum seismic intensity was VIII degrees on the Modified Mercalli scale, and the maximum acceleration recorded was 483 cm/s^2 at the Parcona station (IGP) in Ica.

Alva et al [38] and Rodríguez-Marek et al [39] note major problems due to the soil liquefaction phenomenon which caused (in addition to damage to the foundations of structures) soil displacement and displacements of slopes, causing damage to roads, bridges, fall of utility poles, rupture of water and sewer lines, failure of port facilities, etc.

Several areas were affected due to this phenomenon, among them, the district of Tambo de Mora, the town of Canchamana, the Jahuay area in Chincha; areas of San Clemente, Independencia and Casalla in Pisco, the area of the Huacachina lagoon in Ica, as well as the Housing Complex Las Lagunas and the Pantanos de Villa sector in the city of Lima.

Alva et al [38] and Rodríguez-Marek et al [39], identify the main areas and detail the main damages caused by the soil liquefaction phenomenon, all of which have been recorded:

Slope failure in Jahuay: The 400-m long, liquefaction-induced failure in Jahuay occurred at the foot of a steep slope, approximately 30 to 50 m in height. It occurred near kilometer 188 of the Pan-American Highway (Fig. 10), just south of the toll booth (approximately 40 km from the rupture plane). Sand cones were found on either side of the highway and a person living just south of where the landslide occurred reported large quantities of water and sand ejecting from the ground during the earthquake, reaching heights of up to 1 m. A sand cone found at the southern tip of the slope failure had contraction cracks in the perimeter material, indicating the presence of fine plastic (Fig. 11).

Lateral spreading in Canchamana: In Canchamana, 2.5 km north of Tambo de Mora, a significant lateral spread occurred towards the sea of a marine terrace which was caused by liquefaction. The approximate area displaced was 1 km wide by 3 km long.

Fig. 10. 400-m slope failure along the Pan-American Highway

Fig. 11. Large sand cone with possibly liquefied fine grains.

Shallow foundation failures in Tambo Mora: Spectacular shallow foundation failures caused by soil liquefaction were documented in the northwestern part of Tambo de Mora, approximately 0.5 km away from the coastline and 38 km from the fault plane. Evidence of liquefaction, such as small dejection cones and minor settlements, were found in most of the area north-west of the city. However, one and two-story houses along Alfonso Ugarte street were particularly affected (due to excessive settlements). The affected area extends 300 m down Alfonso Ugarte street, wherein virtually all the buildings experienced settlements equal to or greater than 0.3 m, several recording settlements between 0.7 and 0.9 m. Large

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quantities of dejection material were found within the cracks that opened along the street and within buildings that had non-reinforced concrete floors; here, the liquefied soil completely destroyed the concrete, lifting it into the buildings.

Las Lagunas: Las Lagunas is a beach house complex located 71 km south of Lima and approximately 51 km from the rupture plane. The structural damage ranged from none to severe and was well correlated with the degree of settlement of foundations and the lateral spreading associated with the liquefaction of underlying soil.

Puerto General San Martín, Pisco: It is located in Punta Pejerrey, Paracas Bay, approximately 30 km from the fault. The earthquake caused the landfill to liquefy, as evidenced by the sand cones found and the lateral spreading with significant cracks of up to 0.25 m wide and vertical distortions of up to 0.8 m. The pile-supported cover leaned slightly towards the sea and the horizontal separations at the cover joints reached 0.5 m. The cracks in the ground developed parallelly to the cover in the area of land reclaimed from the sea and were more severe closer to the shore.

3.1.31. May 26, 2019

On May 26, 2019, at 02:41:12 (local time), a magnitude Mw 8.0 earthquake hit the eastern region of Peru which destroyed homes mainly in the departments of Loreto, Amazonas, San Martin and Cajamarca. The Geophysical Institute of Peru located the epicenter 70 km south-east of Lagunas, Alto Amazonas, Loreto, with a maximum intensity of VI-VII on the Modified Mercalli scale in Lagunas.

The USGS located the epicenter 75.5 km south-southeast of Lagunas (Loreto), 92.0 km east of Yurimaguas (Loreto), 153.0 km in east-northeast of Lamas (San Martín), 165.1 km east-northeast of Tabalosos (San Martín) and 187.2 km east of Moyobamba (San Martin). The maximum intensity reported for the epicentral area was VII-VIII and the maximum accelerations recorded in Moyobamba and Tarapoto were 91 cm/s^2 and 80 cm/s^2, respectively.

There were problems given the soil liquefaction phenomenon, with evidence of sand cones and lateral spreading with cracks along the Huallaga river pier (Fig. 12), at the "El Sauce" Resort (Fig. 13), in the town of Tamarate (Fig. 14), near the Lagunas district and in the 2 de Mayo hamlet in San Martin, Rengifo [40].

Fig. 12. Sand cones found along the pier of the Huallaga river, in the district of Lagunas, province of Alto Amazonas, Loreto.

Fig. 13. Lateral spreading with cracks at the "El Sauce" Resort in Tarapoto

Fig. 14. Town of Tamarate, near the Lagunas District

4. ANALYSIS OF RESULTS

The information presented describes the results of extensive research, concluding that the soil liquefaction phenomenon occurs along the coast, in the mountains and in the jungle areas of Peru, with greater incidence along the coast and on sandy soils.

Upon review, it becomes evident that only six zones had instruments that recorded the values of accelerations of seismic movements. Within these, the areas the presented evidence of liquefaction were located at distances between 37 km to 220 Km from the epicenter, with acceleration values ranging from 91 cm/sec^2 up to 483 cm/sec^2 (see TABLE I).

Finally, a map illustrating the soil liquefaction areas in Peru (see Fig. 15) was prepared based on the information. 14 collected.

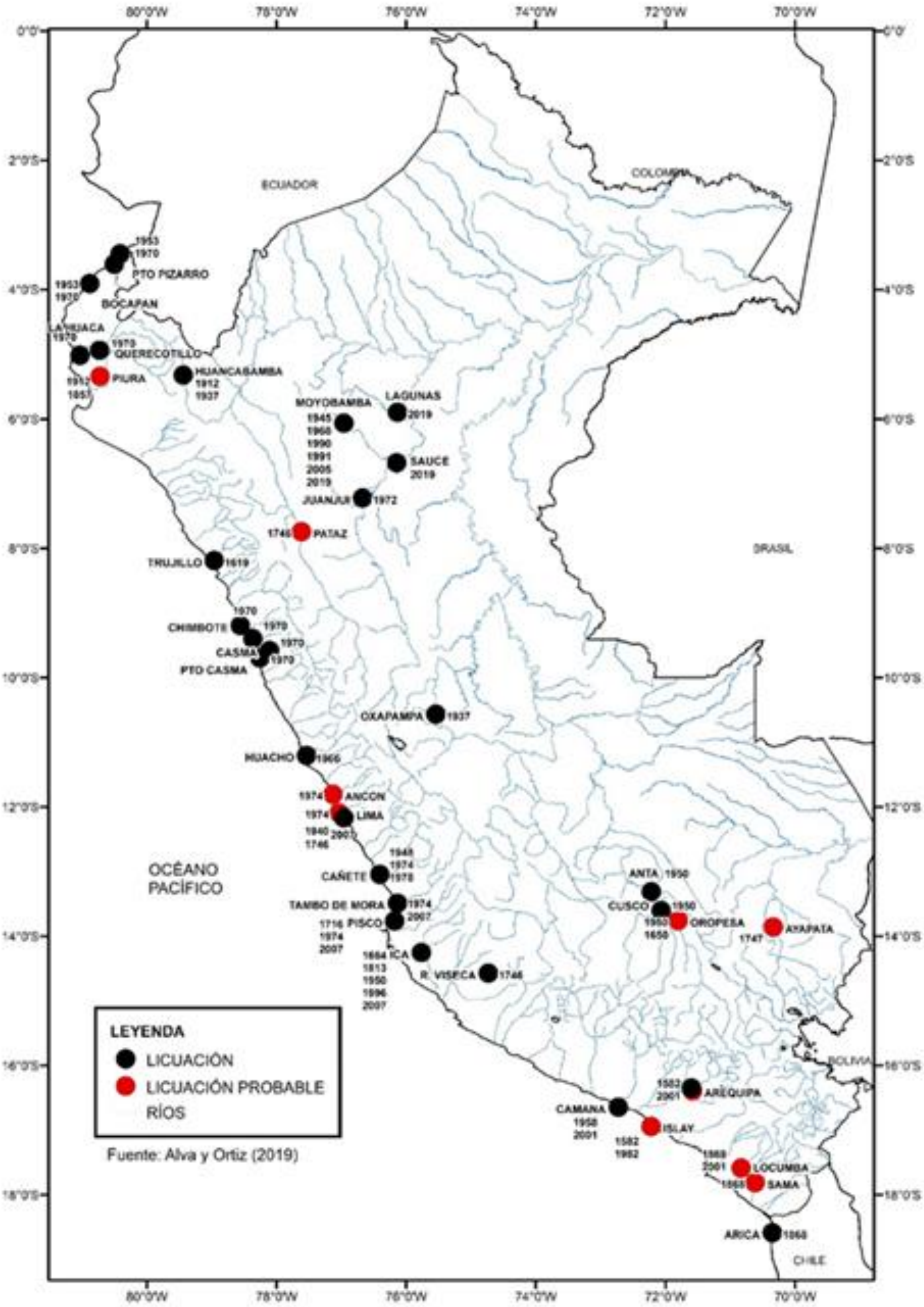

Fig. 15. Map of Soil Liquefaction areas of Peru

TABLE I
Summary of accelerations in areas where liquefaction is present

Date	Station	Location of epicenter.	Magnitude	Max. Accel. (cm/s²)	Distance (Km)		
					1	2	3
31/05/1970	Parque de la Reserva	A 21 Km de Chimbote (Huaraz)	Ms = 7.8	150	37	369	368
3/10/1974	Parque de la Reserva	A 77 Km del Callao (Lima)	Ms = 7.5	190	220	208	73
23/06/2001	César Vizcarra CISMID	A 60 Km de Ocoña (Arequipa)	Mw = 8.2	289	128	202	329
25/09/2005	Moyobamba CISMID	A 39 Km de Yurimaguas (Loreto)	Mw = 7.5	132	90	1	89
15/08/2007	Parcona - IGP	A 51 Km de Chincha (Ica)	Mw = 8.0	483	39	81	119
26/05/2019	CIP Moyobamba	A 70 Km de Lagunas (Loreto)	Mw = 8.0	91	71	170	189

[1] Distance of Liquefaction Zone from Epicenter.
[2] Distance of Liquefaction Zone from Station.
[3] Distance of Station from Epicenter.

4. CONCLUSIONS

A review of the literature indicates that the soil liquefaction phenomenon has occurred in the coastal, mountainous and jungle areas of Peru. There is greater incidence of this phenomenon along the Coast where there is a higher concentration of the population and seismicity is higher. Seismicity has increased over the past few years in the north-eastern region, where the liquefaction phenomenon can be observed. It is possible that soil liquefaction hazard map included herein is incomplete and not be fully representative of this phenomenon in Peru. Further studies are expected to be carried out in the future which will provide new evidence on the occurrence of this phenomenon, and which will serve to modify or supplement the proposed map.

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