LIQUEFACTION OF CALCAREOUS SANDS AND LATERAL SPREADING EXPERIENCED IN GUAM AS A RESULT OF THE 1993 GUAM EARTHQUAKE

Shahriar Vahdani
Associate Engineer, Treadwell & Rollo, Inc.
San Francisco, California

Robert Pyke
Independent Consultant, Lafayette, California

Ukrit Siriprusanen
President, Geo-Engineering, Tamuning, Guam

ABSTRACT

The August 1993 magnitude 8.1 (moment magnitude, M_w 7.7) Guam earthquake caused soil liquefaction and associated ground failures (lateral spreading and settlement) in the harbor and port areas and along the free-faces of stream channels. Soil liquefaction caused severe damage to the commercial and the U.S. Navy port facilities, where uncontrolled fill had been placed to reclaim land.

The epicenter of the earthquake was adjacent to the Mariana Trench, about 60 kilometers (km) south of the island. Unfortunately, there were no operable strong ground motion instruments in Guam at the time of the earthquake. According to eyewitnesses, the strong ground shaking lasted up to about 60 seconds. Based on published attenuation relationships appropriate for subduction zone earthquakes in the region, for a M_w of 7.7, the island must have experienced a peak ground acceleration (PGA) in the range of 0.20 gravity (g) to 0.3g.

The earthquake provided a unique opportunity to study the behavior of calcareous soils during strong ground shaking caused by a large magnitude earthquake. This paper presents our observations regarding liquefaction-induced ground failures and damage to various facilities. The study was supported by the National Science Foundation (NSF Grant No. CMS-9413272).

INTRODUCTION

The island of Guam is located at the southern end of the Mariana Islands, within the Pacific Rim (Figure 1).

In this region, the relative movement between the Pacific Plate and the Philippine Plate creates a highly active seismic environment; it is characterized by the subduction and underthrusting of the Pacific Plate beneath the Philippine Plate along the Mariana Trench.

As can be seen from Figure 1, the north-south trending Mariana Trench is east of the Mariana Islands; near the island of Guam, it turns westward and approaches the Yap Trench. The 8 August 1993 Guam earthquake occurred adjacent to the Mariana Trench, about 60 km south of Guam.

Three accelerographs are located on the island; however, none of them were operational at the time of the earthquake. The eyewitnesses interviewed indicated that the quake resulted in a rolling motion that lasted more than 90 seconds, with 60 seconds of strong shaking.

The earthquake caused little damage to low-rise, stiff structures and significant damage to some of the high-rise buildings. This indicates that the predominant period of the earthquake must have been between 0.5 and 1.5 seconds.

Using the attenuation relationships appropriate for subduction earthquakes in this region, for a M_w of 7.7, a PGA in the range of 0.2g to 0.3g is computed.

The northern half of the island is relatively flat, and is underlain by limestone. The subsurface conditions in the southern half of the island consist of a thin layer of highly plastic silt (residual volcanic rock) and volcanic rock with intruding layers of limestone. Near the shoreline, there are lagoon deposits consisting of a heterogenous mixture of particles ranging from silt- to gravel-size. Because of their unique depositional environment, the lagoon deposits can be found in soft (loose) states even at great depths. The shorelines are blanketed by a layer of coral sand beach material.

The soil liquefaction and related ground failures, as evidenced by sand boils, ground subsidence, lateral spreading, and differential settlement between pile-supported structures and adjacent areas occurred in the southern half of the island, mostly near the shorelines of Apra Harbor. Soil liquefaction occurred in both the naturally-deposited, loose and silty sand of the lagoon deposits and in the loose sand fill in the reclaimed areas.

Liquefaction-related ground failures resulted in damage to the port facilities, electric power plants, pavements, utilities, oil storage tanks, and other structures in Guam. Our observations of the damage to these facilities are presented in the remainder of this paper.

COMMERCIAL PORT FACILITIES

At the commercial port on Cabras island, the liquefaction-related damage was concentrated in an area between Berth No. 3 and Berth No. 6. This area was reclaimed by:

1) dredging the lagoonal deposits and raising the ground surface from its original grade at Elevation[1] -3 feet to Elevation +1 foot

2) driving the sheet piles to Elevation -45 feet (tip elevation)

3) driving the 15-foot-long deadman sheet piles and installing the tie rods

4) placing additional fill, compacting the fill to 95 percent relative compaction, and raising the grade to Elevation +9 feet at the bulkhead location and to Elevation +10 feet at the deadman location about 100 feet from the bulkhead

5) dredging the material in front of the bulkhead to approximately Elevation -35 feet.

During the first stage of fill placement, the dredged materials were placed below water and directly over the lagoon deposits. The results of a post-earthquake geotechnical investigation in this area indicate that the lagoon deposits contain a layer of loose, silty, fine sands containing about 15 to 25 percent fines. The penetration resistance measured within this layer was less than 10, mostly in the range of 2 to 8. It should be noted that some of the blow counts were obtained through a non-standard penetration testing procedure (i.e., the holes were drilled using a hollow stem auger, and the sampler size was larger than that of the Standard Penetration Test sampler). The blow counts were then converted to the SPT N-values by applying a correction factor to account for the larger-sized sampler.

Figure 2 presents an aerial view of the commercial port facilities. Significant soil liquefaction occurred in the area between Berth Nos. 3 and 6. Soil liquefaction resulted in failure of the bulkhead, and caused up to 24 inches of lateral movement and up to 18 inches of settlement of the ground behind the bulkhead (Figures 3 and 4).

Figure 5 presents the liquefaction-induced differential settlement between the pile-supported crane railing system and the adjacent filled areas. Figure 6 shows the disruption of the surface drainage by the differential ground settlement.

The movement of the bulkhead and lateral spreading resulted in several pavement cracks parallel to the shoreline; the most significant of which occurred near the deadman, about 100 feet from the bulkhead.

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[1] Mean Low Low Water

Our team is in the process of performing additional field investigations in areas adjacent to but outside of the zone that experienced soil liquefaction. We will attempt to identify critical SPT N-values by comparing the penetration resistances at sites that experienced soil liquefaction and those which did not.

SHELL OIL TERMINAL

The Shell Oil Terminal is on a spit of land branching out from Cabras island near Berth F at the commercial port (Figure 8).

Soil liquefaction resulted in settlement and lateral spreading near the shoreline. No significant damage to the tank or its foundation was reported as the result of the ground failures.

Figure 9 shows that about six inches of settlement and six inches of lateral movement that occurred near the shoreline where the smaller oil tanks are located.

The subsurface condition generally consists of 9 to 10 feet of fill made up of silty, sandy, limestone gravel. The upper 3 to 4 feet of fill appears to be medium-dense, but the lower portion, which was placed below water, is loose. The natural soil underlying the fill is medium-dense to dense, silty, gravelly sand of coral origin.

It is surmised that the mat foundations supporting the oil tanks influenced the pattern of ground failure (i.e., ground settlement and lateral movement were pushed to the landside of the tanks), and performed satisfactorily by maintaining the tanks in a relatively level condition.

PITI ELECTRIC POWER PLANTS

There are two electric power plants (EPP) in Piti (Figure 10). The new EPP belongs to the U.S. Navy and is supported on steel H piles; the older EPP belongs to the government of Guam and is supported on wood piles.

Soil liquefaction resulted in ground settlements (locally up to several inches), and minor lateral movements, except near the stream channel.

The subsurface conditions consist of a 5- to 8-foot-thick silty, sandy, gravel fill underlain by a medium-dense, relatively clean, coral sand layer about six feet thick. The coral sands are, in turn, underlain by coralline limestone at depths ranging from 12 to 14 feet.

As can be seen from Figure 11, lateral spreading caused the power poles to lean towards the stream channel. Figure 12 shows typical ground settlements adjacent to buildings supported either on shallow foundations founded on dense sands below the liquefiable sands or on deep pile foundations.

U.S. NAVY PORT FACILITIES

Figure 13 presents an aerial view of the U.S. Navy port facilities in Apra Harbor and the inner harbor areas. Similar to the commercial port facilities, soil liquefaction, ground settlement, and lateral spreading caused significant damage to the port facilities.

Although the ground failures at each wharf exhibited unique characteristics, soil liquefaction generally resulted in a series of pavement cracks parallel to the shoreline. In all cases, the lateral movements were coupled with ground settlements, making determination of volumetric strain very difficult, if not impossible.

At Wharf V, there was a concentration of lateral ground movement at the deadman location (Figures 14 and 15). Failure of the bulkhead resulted in bulging of the ground surface on the front and about a 24-inch drop on the backside, of the deadman. Upon further investigation, it became apparent that the upper portion of the deadman was embedded within soil that did not liquefy. As a result of soil liquefaction and loss in strength of the lower material, the deadman moved laterally and pushed against the upper, more competent material, and caused the ground surface to bulge.

At Wharf O, soil liquefaction resulted in failure of the bulkhead, lateral movements in the bulkhead and backfill of up to three feet, and ground settlement of up to 24 inches (Figure 16). In addition to a major crack parallel to the shoreline, a classical, circular ground failure also occurred behind the deadman (Figure 17). Our team is in the process of performing a geotechnical field investigation within areas where failure occurred and in the adjacent areas where soil liquefaction did not occur. Again, the purpose of this work is to identify critical SPT N-values by comparing the penetration resistances at sites that experienced soil liquefaction and those which did not.

Figures 18 and 19 show aerial and close-up views of Wharf S, where the maximum lateral movement of the bulkhead (about eight feet) and ground settlement behind the bulkhead (about 30 inches) occurred within the U.S. Navy port facilities.

Lateral ground failure, as manifested by cracking of the pavement, occurred at a relatively large distance (up to 250 feet) away from the shoreline near Wharf S. Available subsurface information from a geotechnical investigation performed for a site about 150 feet away from the shoreline indicates the site is underlain by a layer of granular fill that is 8 to 11 feet thick. Below the fill, down to a depth of 80 feet, the site is underlain by lagoon deposits consisting of alternating layers of loose clean sand, loose silty sand, medium-dense gravel, coralline limestone, and soft sandy silt.

It is clear that settlement and lateral movement in this area are indicative of soil liquefaction within the lagoon deposits, and is not necessarily limited to the surficial fill material. Indeed, the reported lateral movements along the Dry Dock island shorelines and the U.S. Navy fuel pipeline were the results of soil liquefaction within the lagoon deposits consisting of loose silty sand and soft sandy silt.

Of particular interest is the apparent influence of the presence of the Laundromat building on the pattern of lateral ground movement (Figure 20). As indicated in this photograph, as the ground surface crack approached the building, it changed direction, and instead of breaking through the slab, it separated the slab from the wall, then continued its natural course on the other side of the building. This indicates that even the stiffness offered by a building of substandard design and construction could significantly affect the pattern of ground failure.

Figure 21 shows typical settlement and cracking of the pavement immediately behind the bulkhead at the U.S. Navy port facilities.

OTHER SITES WHICH EXPERIENCED SIGNIFICANT SOIL LIQUEFACTION

The largest lateral movement caused by soil liquefaction occurred near the former Andy's hut at the north shoreline of Apra Harbor. Lateral spreading of up to 15 feet caused failure of the sheet piles (Figures 22 and 23) and collapse of the building. The building had been demolished and removed before these photographs were taken.

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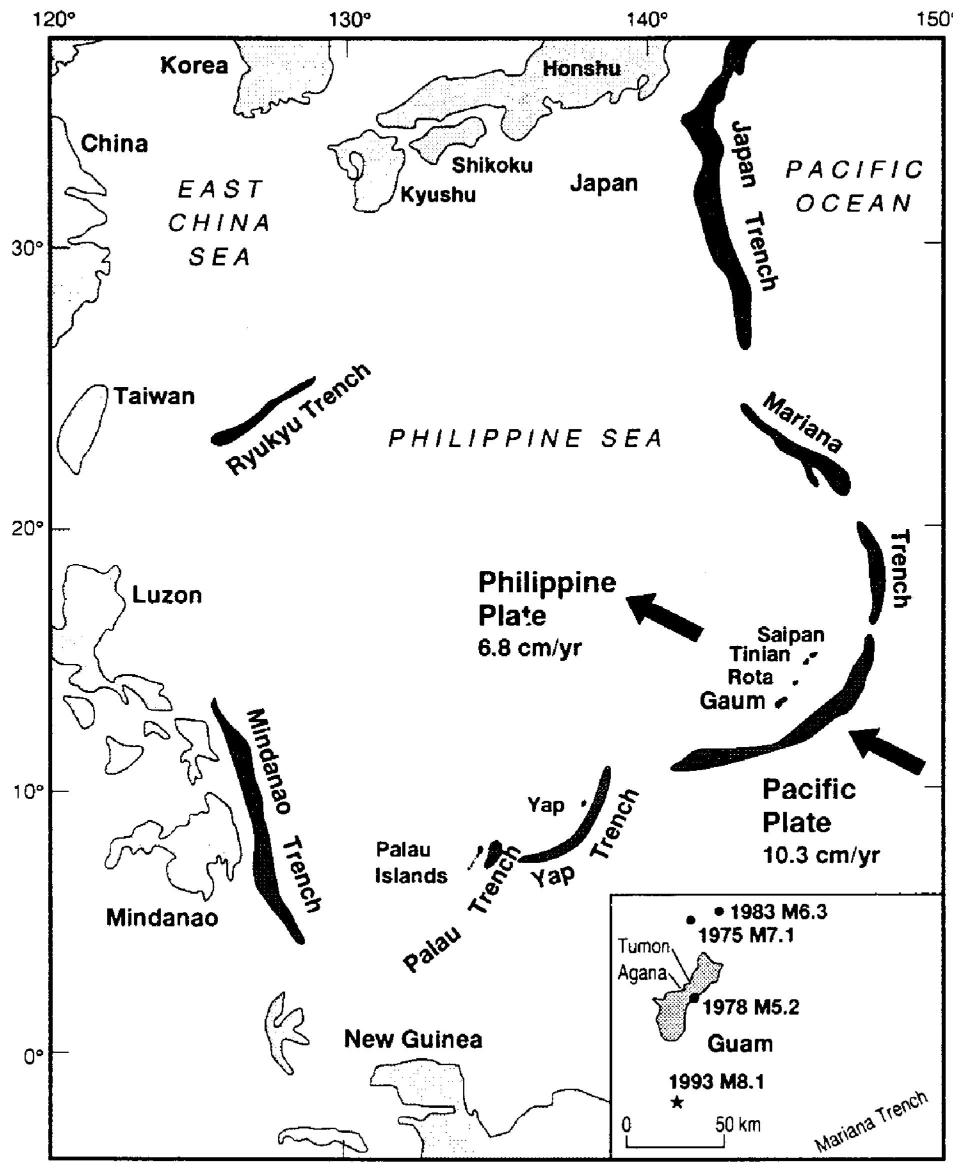

Figure 1: Location map, island of Guam, Mariana Trench, and epicenter of the 1993 earthquake within the Pacific Rim Reference: EERI Newsletter, v. 27, n. 10, October 1993