

First-level liquefaction hazard mapping of Laoag City, Northern Philippines

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Abstract During the 1990 Luzon earthquake (M_s 7.8), the central part of Luzon Island, Philippines suffered much from liquefaction-related processes. Examination of inventories shows that the affected areas lie on certain geological environments that are characteristically vulnerable to liquefaction. Based on this local experience and the findings of earlier workers correlating geological setting with liquefaction susceptibility, a first-level map of liquefaction hazard for Laoag City, Northern Philippines, was produced. Distinct geomorphological units were identified within the mainly fluvio-deltaic setting of the study area. The liquefaction susceptibility of each unit was then ranked as high, moderate, low or non-liquefiable, taking also the geomorphological evolution of the area into account. The geomorphological model of the fluvio-deltaic basin was tested against the results of the georesistivity survey carried out in this study. Moreover, compatibility of the liquefaction susceptibility map with historical liquefaction records supported the validity of the proposed ranking. The study showed that microzonation based on geomorphological criteria is indeed very useful in less-developed countries like the Philippines, where funds for a more rigorous determination of liquefaction potential are limited and not always available.

Keywords Liquefaction · Hazard mapping · Susceptibility ranking · Microzonation · Geomorphological criteria · Laoag City · Philippines

1 Introduction

Owing to its geotectonic framework, the Philippines is an earthquake country. At least five earthquakes hit the country daily, making it one of the most tectonically active regions in

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the world. As such, it is prone to various earthquake-related hazards such as liquefaction. In fact, the country's record is replete with historical liquefaction occurrences. However, it was not until the 1990 Luzon earthquake that the public had a clearer grasp of the phenomenon and the threats it poses. This earthquake of magnitude 7.8 on the Richter scale caused widespread liquefaction in the central part of the Luzon Island, affecting 13 towns and cities in 4 provinces, including Dagupan City, which is an important commercial center in central Luzon (Fig. 1). The effects included sandboils, relative ground settlement and lateral spreading, which in turn caused flooding of coastal villages, severe tilting of houses and buildings, buckling of floors and pavements, collapse of bridges and uplift of buried buoyant structures such as gasoline storage tanks, septic tanks, and drainage pipes (Fig. 2).

Despite recognition of potential damage due to liquefaction, progress in relation to the mitigation of the problem is slow. Liquefaction hazard zonation maps, for instance, rarely exist in the country. This study aims to help to address the issue by formulating a first-level liquefaction hazard zonation map of Laoag City that is based mainly on geomorphological criteria. Past earthquake experiences, including that of the 1990 July Luzon earthquake, show that liquefaction occurrence is specific to recent and/or active depositional environments, each with distinct geomorphological features. Consequently, geomorphological information has been proposed to be a basis for the preliminary assessment and mapping of liquefaction hazard (TCEGE 1999; Iwasaki et al. 1982; Youd and Perkins 1978). Since the procedure involved is simple and can be completed relatively quickly and inexpensively over a wide area, the method is deemed very useful especially for less-developed countries like the Philippines where resources for more rigorous methods are limited.

TCEGE (1999) classifies the methods for liquefaction zonation into three groups, depending on the sources and nature of the data utilized in the evaluation process. The Grade-1 methods are based on pre-existing data from standard published sources while Grade-2 methods also incorporate other available but generally unpublished data from public and private sources. The first-level map presented in this article, which is based on Grade-2 methods, allows a preliminary assessment of the relative susceptibility of the delineated geomorphological units to liquefaction should an earthquake of strong enough intensity occur in the study area. As such, it can serve as a guide for planning urban



Fig. 1 The areas affected by liquefaction during the 1990 July Luzon earthquake in Central Luzon, Philippines. (PFZ: Philippine Fault Zone)



Fig. 2 Effects of liquefaction caused by the 1990 July Luzon earthquake

expansion and identifying zones that require a more detailed and site-specific determination of liquefaction potential.

2 Description of the study area

Laoag is an old Spanish colonial city located on the northwestern coast of Luzon Island, Philippines and covers a total land area of 127.47 km² (Fig. 3). The capital of the Ilocos Norte Province, Laoag City is a densely populated area with critical buildings and infrastructure. The city is undergoing rapid expansion and economic growth, and programed under the North Luzon Growth Quadrangle Plan (NORTHQUAD) to be an international commercial/tourism center.

Laoag City was chosen for this study as it is situated in the same geological environment (i.e., fluvio-deltaic) as Dagupan City, which was hardest hit by liquefaction during the 1990 July Luzon earthquake. It is also surrounded by several geological structures capable of triggering ground motion of comparable magnitude as that of the said earthquake. It was noted that historical occurrences of liquefaction have been reported in certain areas of the city (Fig. 3), particularly toward the southwest where the infrastructural expansion is planned according to the city's 10-year comprehensive land use plan (Laoag City Development Council 2002), making the hazard study more warranted.

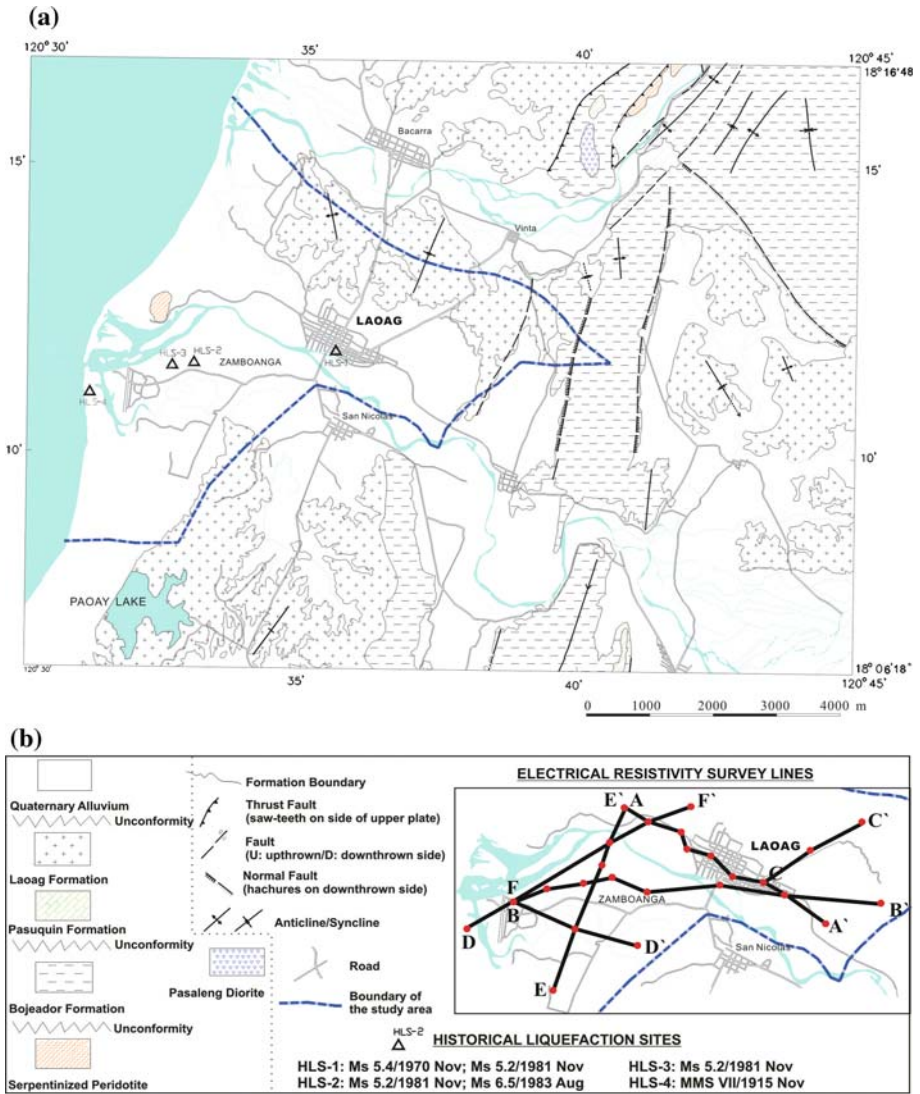


Fig. 3 Location map of the study area (redrawn from 1:50,000 scale topographic map sheets of Laoag). Also shown are (a) historical liquefaction sites with corresponding dates and magnitudes (or intensities) of the triggering earthquakes and (b) resistivity survey lines

3 Methodology

Soil deposits that are susceptible to liquefaction are formed within a relatively few geological environments (Youd 1991). Soils formed by processes that lead to a uniform grain size distribution and deposition in loose state are likely to liquefy when saturated. Thus, it is possible to conduct an initial screening for liquefaction susceptibility based on the geological origin of the soil deposits.

In this study, distinct micro-geomorphological units were identified within the general fluvio-deltaic environment of Laoag City. This was mainly based on examination of

topographic maps (1:250,000; 1:50,000), geologic maps (1:50,000), aerial photographs (1:30,000; 1:10,000), and a radar image (1:100,000). Results of the desk study were subsequently checked in the field. Using the criteria set forth by various authors (e.g., TCEGE 1999; Iwasaki et al. 1982; Youd and Perkins 1978), and considering the 1990 Luzon earthquake experience, the liquefaction susceptibility of each unit was then categorized as high, moderate, low, or non-liquefiable. In ranking the units, the geomorphological evolution of the area was considered. For instance, the present floodplain identified behind the southern bank of the Laoag River was used to be the site of active delta front progradation. Therefore, thick sand deposits were expected to be found underneath silty/clayey layers typical of a floodplain deposit.

To check for such buried features and boundaries, as well as to validate the geomorphological model assumed for the study area, resistivity survey was conducted along six selected lines (Fig. 3). The Schlumberger technique, known as vertical electric sounding (VES), was selected as it is known to be superior over other techniques in distinguishing lateral from vertical variations in resistivity and field operations are faster. The instrument used was OYO McOHM Mark-2 Model 2115A resistivity instrument. It is a compact digital averaging resistivity meter that contains a transmitter and receiver functions packed in one unit. It is designed to measure extremely weak electrical signal. Measurements at each ground level were repeatedly stacked to eliminate ground noise and other electrical interferences that can hamper the survey. This stacking feature automatically cancels spontaneous potential in resistivity measurement. The instrument can transmit up to 200 mA under more or less 200 V, which is sufficient enough for ordinary resistivity surveying.

As in usual field procedure, the computed apparent resistivity values were plotted at logarithmic scale paper to gain an initial view of the resulting curve. This is undertaken prior to interpretation or at the sounding site to preclude unwanted curve, which results when errors are committed in readings and in distances set up. The interpretation of the measured values is facilitated through the use of a computer. A resistivity sounding interpretation software was used for database management and sounding interpretation including plotting of sounding curves. The software is designed to automatically fit the theoretical curve to that of the master curves of Orellana and Mooney using iterations and test for convergence/divergence processes. The resulting interpretation was then compared with and adjusted based on drilling and test pit data available in the area.

Furthermore, confirmation of the assigned ranking and distribution of liquefaction susceptible units was accomplished by sifting through the historical earthquake records for possible indication of liquefaction occurrences in the study area. Sites of historical liquefaction were then plotted on the map to see if they fall within areas classified as prone to liquefaction.

4 Seismicity and seismic sources in the study area

Like most parts of the Philippines, the northern Luzon region is characterized by high seismicity. Figure 4 shows distribution of the epicenters of past earthquakes occurring in the vicinity of the study area from 1907 to 2002. It can be noted that most of the earthquakes were generated at shallow (0–65 km) to moderate depths (66–150 km). The shallow earthquakes are generated in the brittle part of the crust while deeper earthquakes occur along the subducted slabs.

Several seismotectonic elements are responsible for the present-day activity in the region. However, only those lying within about 150 km are considered capable of triggering

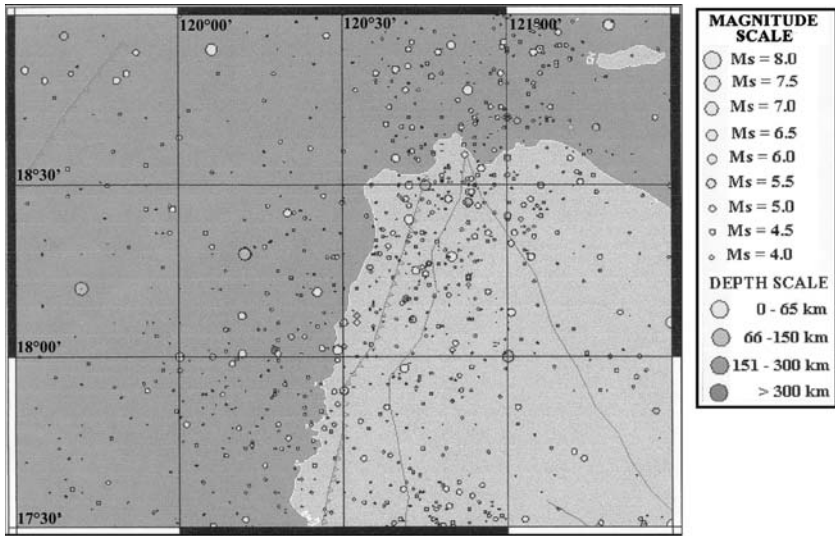
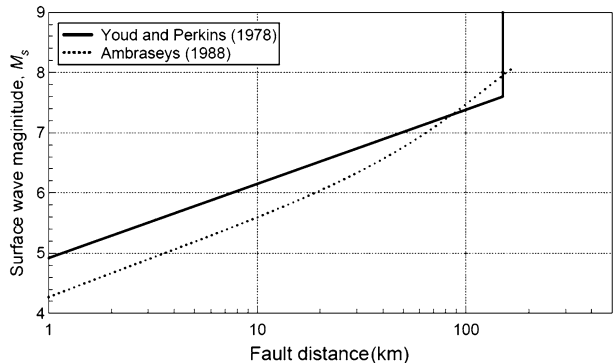


Fig. 4 Location of historical earthquake epicenters in the vicinity of the study area (PHIVOLCS, 2002)

liquefaction in the study area, assuming a worst-case scenario of an $M_s = 8.0$ earthquake and following the relationship formulated by Ambraseys (1988) for shallow earthquakes correlating magnitude with the shortest horizontal distance from the causative fault to the farthest indication of liquefaction. Note that Ambrasey’s (1988) correlation considered all manifestations of liquefaction, including minor fissures and sand boils, and is thus more conservative compared to that of Youd and Perkins (1978) (Fig. 5). Accordingly, three major structures or group of tectonic structures are relevant in this study: the Manila Trench, the North Luzon Ridge Fault Zone, and the Philippine Fault Zone (PFZ) with its various splays (Fig. 6).

Located about 150 km to the west of the study area, the Manila Trench represents the morphologic expression of the subduction of the Sunda Plate under the Philippine archipelago. It is an elongated bathymetric depression with depths reaching 5,100 m in the latitude of Manila (Ludwig et al. 1967). The corresponding Wadati-Benioff zone is steep in the south but flattens off towards the north and is well-defined by dense seismicity to depths of more than 200 km (Pinet and Stephan 1990), implying that towards the north in

Fig. 5 Two widely-used relationships between the distance (from a causative fault plane to the farthest liquefied site) and the surface wave magnitudes M_s of earthquakes (TCEGE, 1999)



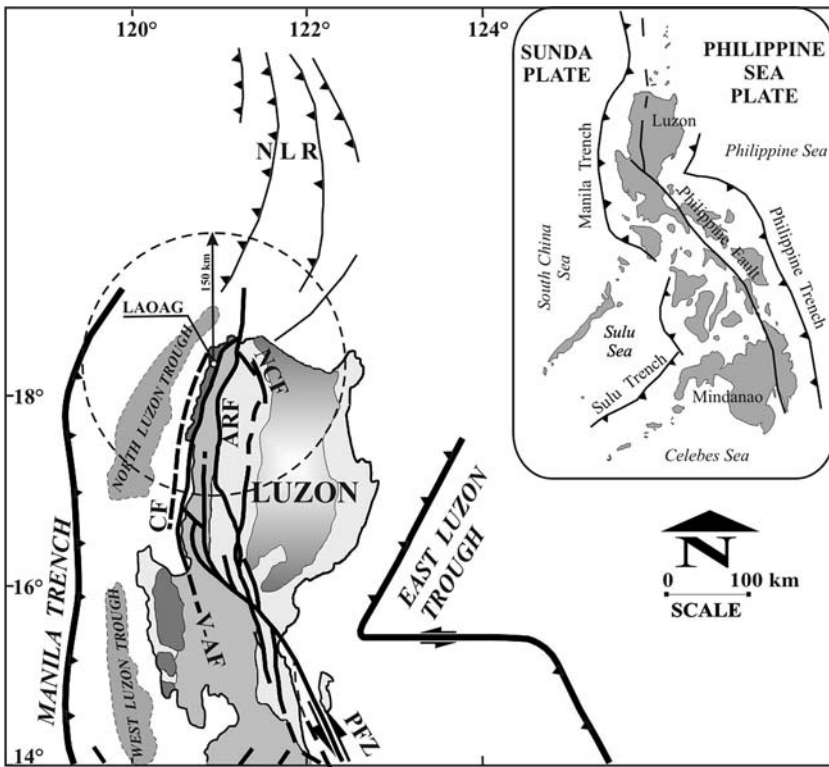


Fig. 6 Major tectonic structures capable of triggering liquefaction in the study area. ARF: Abra River Fault; NCF: North Cordillera Fault; CF: Coastal Fault; V-AF: Vigan- Aggao Fault; NLR: North Luzon Ridge; PFZ: Philippine Fault Zone (after Pinet and Stephan, 1990 and Bautista et al., 2001)

the vicinity of the study area, earthquakes associated with this trench are expected to be shallower and of greater frequency. Two destructive earthquakes, the 1934 M_s 7.6 and 1948 M_s 8.2 events, are believed to be generated by this structure (Hamburger et al. 1983).

About 100 km north of Laoag City, offshore of Luzon Island, is the North Luzon Ridge region characterized by a series of parallel faults. In this region, a 200-km-wide zone of dense shallow seismicity is observed (Bautista et al. 2001). The nature of this fault zone (e.g., orientation, direction of movement) is still controversial. An M_s 7.9 earthquake that occurred in 1979 is believed to originate in this region (Hamburger et al. 1983).

The PFZ, on the other hand, is a 1,200-km long left-lateral strike-slip fault that cuts through the entire archipelago from north to south. Given such dimension, the structure is considered to be one of the World’s major strike-slip faults. PFZ have been responsible for a number of damaging earthquakes, including the July 1990 earthquake. To the north, in the vicinity of the study area, the fault separates into a number of generally N–S trending splays. These northern extensions of PFZ have a significant thrust component in contrast to its extension in the central and southern Philippines, where movement is nearly pure strike-slip. Primary among these northern splays are the: (a) *Coastal Fault* which passes along the coastline of northeastern Luzon, and thus along the eastern boundary of the study area; (b) *Vigan-Aggao Fault*, which is approximately 350 km long and manifests as narrow elongated ridges, with its nearest trace just about 7 km east of Laoag City. Farther north of

the study area, it is found thrusting the recent coral reefs over the Holocene alluvium in northwestward direction (Pinet and Stephan 1990). A minimum fault velocity of 1 cm/year for the last 1 m.y. was estimated from the displacement of a broad syncline (Pinet 1990, *in* Ringenbach et al. 1993); (c) *Abra River Fault* which, like the Vigan-Aggao Fault, is a prominent structure in Northern Luzon, located approximately 30 km to the east of the study area. This fault runs for about 200 km and joins the Vigan-Aggao Fault at the northern coast of the Luzon Island. At its southern termination, the fault separates into several minor parallel splays. The fault is marked in the field by about 200-m wide zone of intense shearing developed in intrusives and volcanic rocks (Pinet and Stephan 1990); and (d) *Northern Cordillera Fault*, which is located about 75 km east of Laoag City and can be traced for about 60 km. Like the Coastal Fault, the nature of this structure is less known.

While the magnitudes of the past earthquakes associated with the Manila Trench and North Luzon Ridge Fault System confirm their potential to induce liquefaction at the site area, there are no historical records to evaluate the potentials of the smaller scale faults (i.e., the northern splays of the PFZ). However, considering their close proximity to the site, earthquakes generated along these faults would be capable of causing liquefaction at magnitudes much less than M_s of 8.0 (Fig. 4). Investigating the statistical relations between fault rupture length and magnitude for worldwide data set, Bonilla et al. (1984) proposed the following relationship:

$$M_s = 6.04 + 0.78 \log_{10} L \quad (s = 0.306) \quad (1)$$

where M_s is surface wave magnitude and L is fault rupture length and s is the standard deviation. Using this correlation and assuming rupture along full length, the Vigan-Aggao, Abra River and North Cordillera Faults are predicted to be capable of generating an M_s 7.8, 7.7, and 7.3 earthquakes, respectively. These predicted magnitudes are well above those of the liquefaction triggering earthquakes (Fig. 5).

Activity of these structures must have caused the liquefaction incidents that were documented in the study area. Based on historical accounts compiled by SEASEE (1985), liquefaction may have been triggered in at least four sites (two of which liquefied twice) during four different earthquake events. Figure 3 shows the sites of historical liquefactions with corresponding dates and magnitudes (or intensities) of the triggering earthquakes. Liquefaction effects include ground fissures, cracks on floors, differential settlement, partial collapse of houses and sand boils.

5 The fluvio-deltaic environment of Laoag City

Laoag City lies along the lower reaches of Laoag River system, which drains a total land area of 1,332 km². The river system originates in the high mountains of Central Cordillera with peak elevation of more than 2,000 m, and finally empties its load into the South China Sea at Laoag City. The main channel is about 50 km long.

5.1 Laoag River delta

The Laoag River delta is wave-dominated as evident from the smooth and regular shoreline and the bathymetric contours that parallel the shoreline (Reading 1982). Strong wave action redistributes the sediments supplied by Laoag River forming elongate beach ridge complexes that likewise parallel the shoreline. Abandoned beach ridges occur behind the

active shoreline. Since wave processes is dominant, delta front progradation is slow. Looking at Fig. 7, a linear feature can be traced bounding the hills on both sides of the river mouth, extending for about 5 km further to the south where it bounds the western margin of Paoay Lake. This linear feature suggests the possible position of the former shoreline.

Due to abundance of beach sand and sufficient wind velocity for aeolian processes to take place, dune fields were developed along the beach on both sides of the river mouth, occupying an estimated area of 100 km². Moving landward from the active sand dunes, older dunes are immobilized by vegetation and infrastructure development. Behind the series of beach barriers that bound the river mouth, a backswamp area formed that is currently being used as fishponds. Channel bars also formed along the distributary channels.

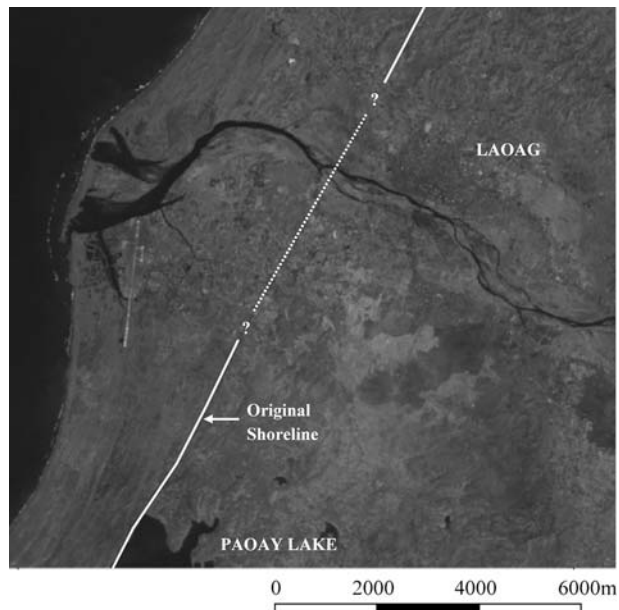
5.2 The meandering Laoag River

The Laoag River has a meandering pattern with a low sinuosity of about 1.2–1.5. Aerial photograph interpretation shows that the main river channel shifted several times in the past as indicated by abandoned meanders, point bar deposits, and natural levees. Abandoned meanders and point bars are marked by concentric bands associated with meander scrolls, which are reasonably well-preserved and prominent in the photographs (Fig. 8).

In the old point bar deposit at the southeastern boundary of the city is a possible old chute cut-off, which formed from the natural tendency of streams to straighten the course of their main flow across meander bends, thereby cutting chutes into the point bar or deepening swales on the point bar top (Reading 1982). The levee associated with this point bar/meander appears to be locally breached by a crevasse (Fig. 8a).

Along the active river channel, sand to gravelly sand point bar deposits that gently slope towards the channel are found on the convex side of the river curves. Bordering the channel on both banks are the floodplains of the present river channel, with elevations that

Fig. 7 Landsat image showing a lineament suggesting the position of the former shoreline



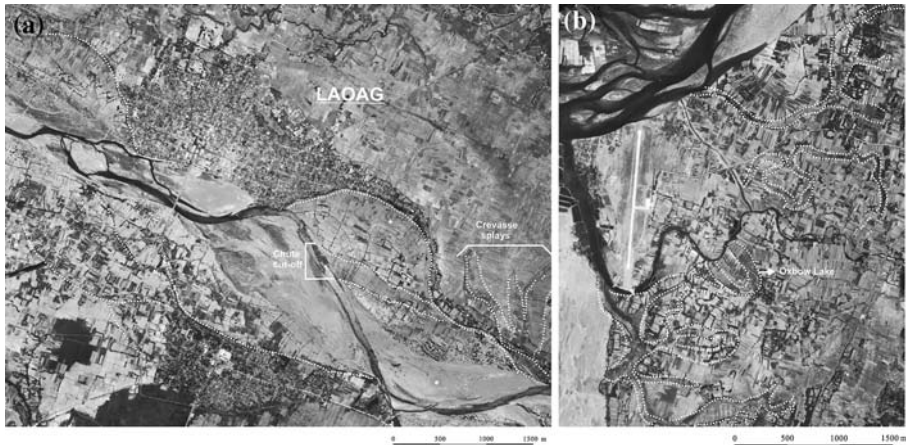


Fig. 8 Aerial photographs of the study area (a) showing well-preserved abandoned meanders and point bars and (b) recently abandoned channels in the SW floodplain (NAMRIA, 1979)

are a few meters higher than the existing channel. These areas are not submerged by small-scale floods. The floodplain behind the northern bank, which covers the city proper, appears to be a historical floodplain. In contrast, the southern floodplain, in the vicinity of Barangay Zamboanga (Fig. 3), is believed to be former site of delta front progradation. On this floodplain, several recently abandoned channels were identified (Fig. 8b). Once the main channel is flooded, the flood water tends to rush down along these old river channels. A minor filled-in oxbow lake was also recognized in the area.

Figure 9 shows the distinct micro-geomorphological units identified in the study area.

6 Discussion

The correlation between geological setting and liquefaction susceptibility of deposits has long been recognized. Youd and Hoose (1977) estimated the qualitative influence of several geologic factors on liquefaction and ground failure susceptibility of various sedimentary deposits. Results of their study with some additional data were summarized by Youd and Perkins (1978) as shown in Table 1. On the other hand, Iwasaki et al. (1982) analyzed the data presented by Kuribayashi and Tatsuoka (1975) from several hundred sites that liquefied as a result of 44 earthquakes in Japan with reference to the geomorphological conditions on these sites. This analysis led to a set of microzonation criteria based on geomorphological information as shown in Table 2.

In the Philippines, the validity of these criteria was confirmed during the 1990 Luzon earthquake, when the central part of Luzon Island suffered much from liquefaction-related processes. Examination of the inventories reveals that the affected areas are situated in recent sedimentary environments that exhibit characteristic vulnerability to liquefaction: (1) backswamps in Gerona, Pura, Paniqui and Ramos, Tarlac; (2) river channels and point bars in Dagupan City, San Carlos, and Malasiqui, Pangasinan; (3) sandspits in Agoo and Sto. Tomas, La Union; and (4) deltas in Aringay, La Union and Lingayen, Pangasinan (Torres et al. 1994) (Fig. 1). Figure 10 shows that most of the buildings affected by liquefaction in Dagupan City lie on abandoned river channels. Buildings most heavily damaged are also confined to these features which are common at Laoag City as well.

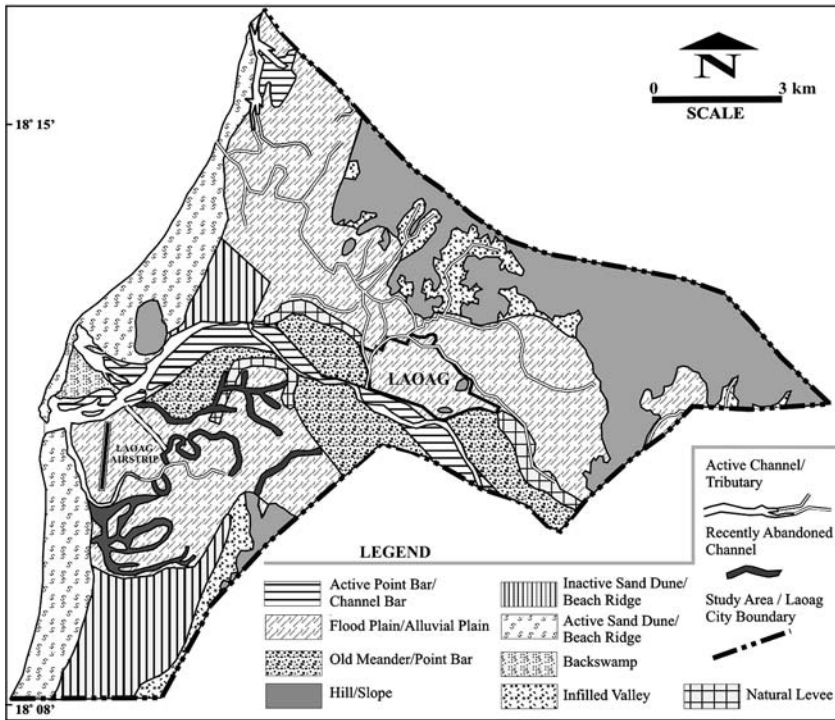


Fig. 9 Micro-geomorphological units identified within the study area

Taking from the Philippine experience, as well as the results of the studies mentioned, a first-level liquefaction hazard map of Laoag City is presented in Fig. 11. The susceptibility of the different units to liquefaction was classified as high, moderate, low and non-liquefiable (Table 3). Under the high category are included the active and recently abandoned river channels and point bars, and the delta-associated active sand dunes, channel bars and backswamp, where loose, granular deposits are expected. Susceptibility of abandoned beach ridges/inactive sand dunes, and old meanders, point bars and natural levees are considered moderate. Although these units would normally consist of cohesionless sediments, they should have been compacted through time, thus gaining increased resistance against liquefaction. The floodplains on both sides of the river are also considered moderately susceptible to liquefaction. Apparently a historical floodplain, the northern floodplain is expected to be underlain mostly with clay/silt layers that result from the vertical accretion of suspended sediments during flooding. Thus, the vulnerability of this unit to liquefaction is reduced. On the other hand, thick sand deposits of a series of abandoned shorelines are expected to be found underneath the southern floodplain. However, the deposits are still considered moderately liquefiable since these are buried beach ridges, and therefore must have undergone some degree of compaction. Valley infills comprised mainly of fine-grained sediments have low susceptibility, while the low-lying hills that bound the study area to the north are considered non-liquefiable.

Representative profiles from the resistivity survey are shown in Fig. 12. As predicted, clayey to silty layers of considerable thickness, interpreted as floodplain deposits, underlie the Laoag City proper and the area north of the city’s southeastern termination (VES-11 to

Table 1 Susceptibility to liquefaction of sedimentary deposits during strong shaking (Youd and Perkins 1978)

Type of deposits	General distribution of cohesionless sediments in deposits	Likelihood that cohesionless sediments, when saturated, would be susceptible to liquefy (by age of deposit)			
		<500 years	Holocene	Pleistocene	Pre-Pleistocene
Continental deposits					
River channel	Locally variable	Very high	High	Low	Very low
Flood plain	Locally variable	High	Moderate	Low	Very low
Alluvial fan and plain	Widespread	–	Low	Very low	Very low
Marine terrace and plain	Widespread	Moderate	Low	Low	Very low
Delta and fan- delta	Widespread	High	Moderate	Low	Very low
Lacustrine and playa	Variable	High	Moderate	Low	Very low
Colluvium	Variable	High	Moderate	Low	Very low
Talus	Widespread	Low	Low	Very low	Very low
Dunes	Widespread	High	Moderate	Low	Very low
Loess	Variable	High	High	High	Very low
Glacial till	Variable	Low	Low	Very low	Very low
Tuff	Rare	Low	Low	Very low	Very low
Tephra	Widespread	High	High	?	?
Residual soils	Rare	Low	Low	Very low	Very low
Sebkha	Locally variable	High	Moderate	Low	Very low
Coastal zone					
Delta	Widespread	Very high	High	Low	Very low
Estuarine	Locally variable	High	Moderate	Low	Very low
Beach					
High wave energy	Widespread	Moderate	Low	Very low	Very low
Low wave energy	Widespread	High	Moderate	Low	Very low
Lagoonal	Locally variable	High	Moderate	Low	Very low
Fore shore	Locally variable	High	Moderate	Low	Very low
Artificial					
Uncompacted fill	Variable	Very high	–	–	–
Compacted fill	Variable	Low	–	–	–

Table 2 Susceptibility to liquefaction of geomorphological units (Iwasaki et al. 1982)

Rank	Geomorphological units	Liquefaction potential
A	Present River Bed, Old River Bed, Swamp, Reclaimed Land, and Interdune Lowland	Liquefaction likely
B	Fan, Natural Levee, Sand Dune, Flood Plain, Beach, and Other Plains	Liquefaction possible
C	Terrace, Hill, and Mountain	Liquefaction not likely

VES-17 of Resistivity Profile A-A'). In the area of old point bar (VES-2), thick sand deposits are found. From VES-16 going seaward, marine and fluvial deposits intercalate with each other forming thick sand layers. Resistivity profiles D-D' and E-E' pass along

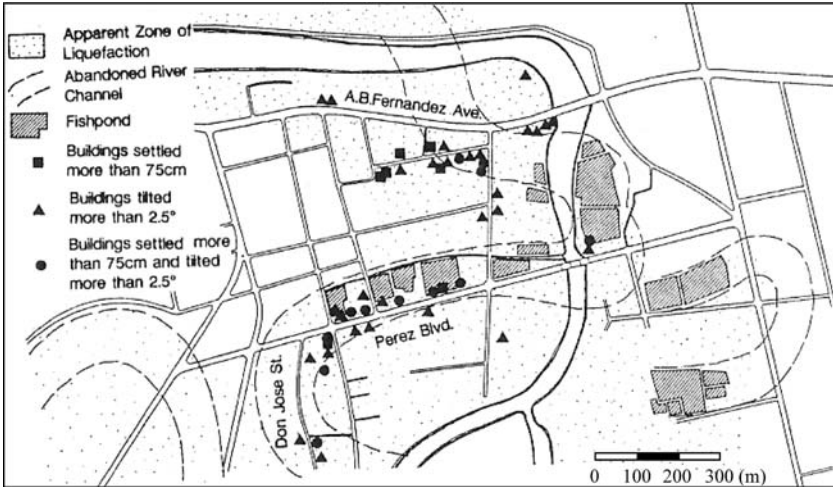


Fig. 10 Distribution of buildings in Dagupan City affected by liquefaction during the 1990 July Luzon earthquake (Tokimatsu et al., 1994). Note that most of these buildings lie on the abandoned meanders of Pantal River

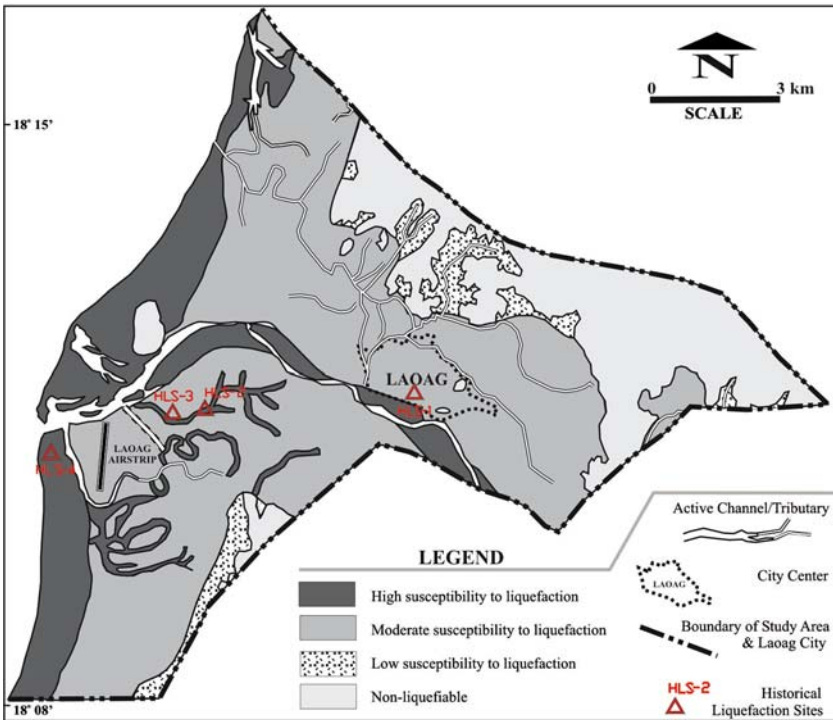


Fig. 11 Microzonation of liquefaction susceptibility based on depositional environments of surficial deposits as suggested by geomorphological units (Fig. 9) and ranked according to Table 3

Table 3 Susceptibility to liquefaction of micro-geomorphological units identified in the study area

Geomorphological Unit	Liquefaction potential
Active and recently abandoned channel and point bar; delta-associated active dune, channel bars and backswamp	High
Abandoned beach ridge/inactive sand dune; old meander, point bar and natural levee; floodplain	Moderate
Valley in-fill	Low
Hill, mountain, slope	Non-liquefiable

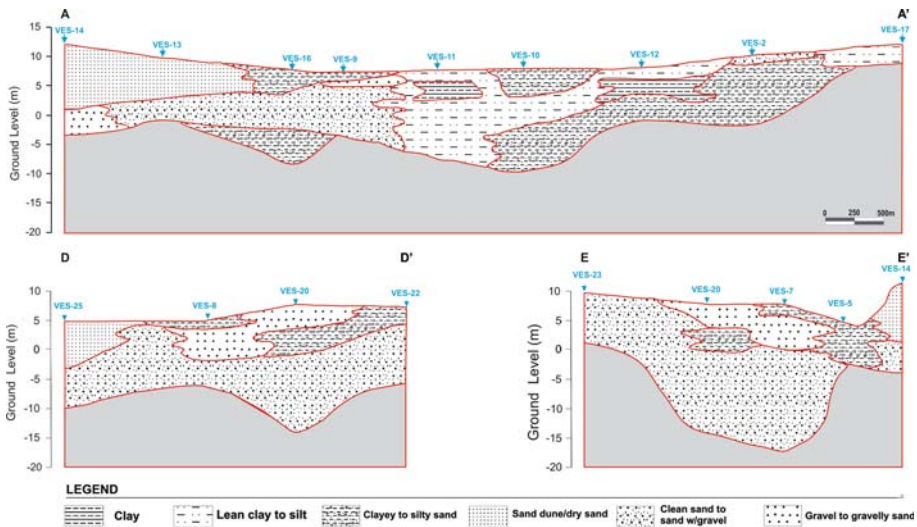


Fig. 12 Resistivity profiles along the selected lines A–A', D–D' and E–E'

the southern floodplain. As can be seen from these sections, thick sand deposits of mixed marine and fluvial origin underlie the area. In general, results of the resistivity survey confirm the geomorphological model proposed for the study area.

The sites of historical liquefaction occurrences plot on the zones predicted to be of high to moderate susceptibility, thereby supporting the validity of the ranking developed in this study (Fig. 11). More specifically, historical liquefaction occurred within recently abandoned river channels (or within adjacent zones where their point bar deposits are expected to exist). Worth noting is the recurrence of liquefaction at the same location during different seismic events.

Also interesting to note is the repeated occurrence of liquefaction in the church tower area (VES-10, Profile A–A', Fig. 12) located in the northern floodplain, which was classified as only moderately susceptible to liquefaction. Although thick clayey/silty layers generally underlie the floodplain, local sand layers of significant thickness are also found at shallow depth, which might be at a loose state. Furthermore, recent studies show that depending on the state of the soil, even fine-grained soils can also liquefy (e.g., Guo and Prakash 1999; Perlea 2000).

7 Conclusions

This study showed that microzonation based on careful geomorphological evaluation (especially when supported by simple geophysical surveys) could be an effective tool for general screening of liquefaction susceptibility. This approach is obviously most useful where funds for a more rigorous study are limited.

The results were presented in the form of a microzonation map, which is regarded as one of the most influential means of transferring information from the scientific community to the planning and decision-making community, and the public in general. As such, the proposed map should serve as a valuable guide in the formulation of policies and regulations regarding hazard and risk management and mitigation in the Laoag City. In particular, critical structures lying on moderately to highly susceptible areas must be re-evaluated for proper mitigation. A more detailed and quantitative assessment of liquefaction hazard must be required prior to the approval of new construction projects particularly in these areas. These recommendations are critical, in that the city administration plans developing Laoag City as a “metropolis in the northern part of the country” and aims to maximize “the socio-economic and physical growth of the city” expected to become an industrial center (Laoag City Development Council 2002). As already mentioned, expansion of the city is planned towards the southwest portion, which was identified in this study as highly liquefiable.

As a final note, the use of the results of this study as a general guide must be emphasized and they should not be used in lieu of a detailed and more site-specific investigation. As seen in the northern floodplain, a particular unit may generally have low to moderate susceptibility to liquefaction but certain parts within the unit may have higher susceptibility depending on local conditions, thus the repeated occurrences of liquefaction. In the same manner, the presence of potentially liquefiable layers does not mean that liquefaction is imminent. The shear stress that can develop in the soil in the event of an earthquake must be compared with the resistance of that soil to liquefaction. Both factors (i.e., shear stress and resistance) depend on a large number of ground motion and site characteristics, which can only be determined through a detailed survey.

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