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Liquefaction-induced damage, and geological and geophysical conditions during the 1990 Luzon earthquake

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ABSTRACT: The Luzon, Philippines Earthquake of July 16, 1990, caused extensive soil liquefaction in a wide-spread area. One of the most significant features of liquefaction damage is the bearing failure of multi-story reinforced concrete buildings in Dagupan city located about 100 km from the epicenter. This paper discusses the damage patterns of buildings and their relation to the geological and geophysical conditions. For this purpose, field investigations including microtremor measurements are conducted within the city, then Rayleigh wave dispersion characteristics and V_s structures are determined. These characteristics are compared with the damage features of buildings. It is found that the buildings that suffered extensive settlement and tilting concentrated in banks of active rivers and fills built on recently abandoned river channels. It is also found that there is a fairly good correlation between the shear wave velocity of surface soils and the extent of damage to structures.

INTRODUCTION

The Luzon, Philippines Earthquake of July 16, 1990, (M_s=7.8) affected a widespread area and caused extensive damage to various structures in the Central Luzon, the Republic of the Philippines. More than 25,000 houses were totally destroyed and over 60,000 houses were partially damaged, affecting 280 thousand people. Over 1,600 fatalities resulted and more than 900 were missing. Damages resulting from this event were estimated at 10 thousand million pesos.

Fig. 1 shows the geological map showing the affected region of the Central Luzon, together with the epicenter and the trace of surface faulting of the earthquake. Most parts of the northern Central Plains are alluvial deposits of the Agno River that flows into the Gulf of Lingayen. No strong motion records were registered for the main shock. The modified Rossi-Forel intensities resulting from the event were VIII-IX in Baguio, and VIII in Agoo and Dagupan, and VI-VIII in Cabanatuan and Tarlac.

The major cause of the damage is associated either with a combination of strong shaking and inadequate design and construction of buildings or with ground problem including soil liquefaction. The damage classified into the former category concentrated mostly in Baguio and Agoo. More than 50 multistory reinforced concrete buildings collapsed in Baguio city. As a result, over 600 persons were killed or missing.

The ground problem associated with the earthquake includes (1) ground surface distress due to tectonic movements along the fault, (2) slope failures in the mountain region in or near the fault rupture zone, and (3) soil liquefaction in deltaic deposits. The roads, bridges, and embankments crossing the fault zone were extensively damaged due to lateral movements up to 6 meters of the surface faulting. A large number of slope failures triggered by the earthquake, its aftershocks, or subsequent rainfalls shut off many roads in the mountainous region. For example, all the three main roads leading to Baguio city were closed for three days after the earthquake.

Soil liquefaction occurred in the epicentral region as well as in the northern part of the Central Plains from Tarlac to the Gulf of Lingayen. One of the most significant features of the liquefaction damage during this earthquake is the bearing failure of reinforced concrete buildings in Dagupan city. This paper describes liquefaction-induced damage during the earthquake with emphasis on that in Dagupan city. Also described and discussed are the geological and geophysical conditions, and their relation to the damage patterns of buildings in Dagupan city.

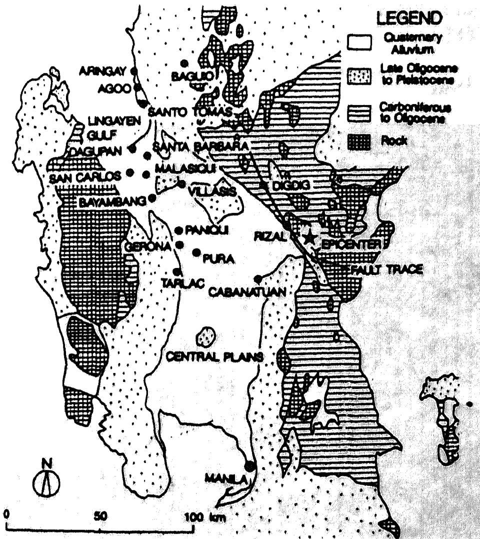

Fig. 1 Map showing affected area in the Central Luzon

DISTRIBUTION OF LIQUEFACTION DAMAGE

The July 16 event caused soil liquefaction in alluvial deposits of river delta, sandbars and artificially fills, which in turn caused extensive damage to reinforced concrete buildings, wooden houses, embankments, roads, and bridges not only in the epicentral region but also the Central Plains between Tarlac and the coastline of the Gulf of Lingayen (Tokimatsu et al. 1991).

Extensive liquefaction that occurred in the river delta along the coastline of the Gulf of Lingayen affected such towns as Aringay, Agoo, Santo Tomas, Dagupan, San Carlos, Santa Barbara, and Malasiqui (Punongbayan and Umbal 1990; Tokimatsu et al. 1991) and caused severe damage to numerous wooden houses. Sandbars along the coastline liquefied extensively in some of these villages. These include Alaska in Aringay, and Narvacan and Rawis in Santo Tomas. Large ground settlement and lateral ground spreading triggered by soil liquefaction, making many of the homes in these villages submerged below sea level (Photo 1). In addition to the severe damage to wooden houses, some 500 reinforced concrete buildings in Dagupan city suffered large settlement and tilting.

Liquefaction also occurred in many alluvial sandy deposits in the middle part of the Central Plains and in the sparsely populated epicentral region, causing extensive damage to private homes, school buildings, roads, and embankments. Many buildings in Paniqui, Pura, and Gerona were badly damaged (Punongbayan and Umbal 1990; Tokimatsu et al. 1991) and some places in these villages had been inundated for several months until the beginning of a dry season. Several bridges across the Agno River collapsed due to soil liquefaction. These include the Carmen Bridge near Villasis and the Carvo Bridge near Bayambang.

The maximum epicentral distance of the liquefied site for this event (Japan Society of Civil Engineers 1990) is about 140 km which is consistent with the empirical chart by Seed et al. (1984), as shown in Fig. 2. The correlation between maximum epicentral distance, R_{max}, and earthquake magnitude, M, drawn in the figure is given by the following equation (Yoshimi 1991):

$$R_{max} = 10^{0.464M-1.14} \qquad (1)$$

Photo 1 Submerged Village called Narvacan

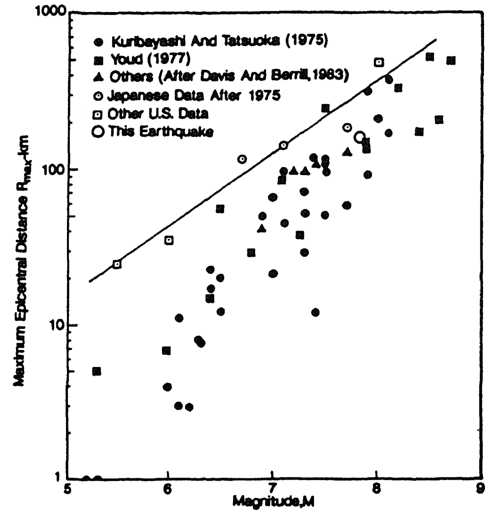

Fig. 2 Relationship between maximum epicentral distance of liquefied site and earthquake magnitude

LIQUEFACTION DAMAGE IN DAGUPAN CITY

Dagupan city is located at the southern end of the Gulf of Lingayen and extends over the delta of several tributaries of the Agno River. The city has a population of about 110,000. The altitude of the city is only about 1 meter, and the water table is very shallow.

Fig. 3 shows a map of Downtown Dagupan through which the Pantal River meanders from the south to the northwest. Most of the commercial buildings concentrated in the area from Burgos Ave. to M. H. Del Pilar St. and from A. B. Fernandez Ave. to Perez Blvd.

Also shown in Fig. 3 are the approximate zones of liquefaction and of lateral ground spreading. Most of the reinforced concrete buildings in the liquefied area settled considerably often accompanied by severe tilt, whereas the buildings outside the liquefied area appeared unaffected.

Fig. 3 also shows the distribution of the reinforced concrete buildings that settled more than 75 cm and/or

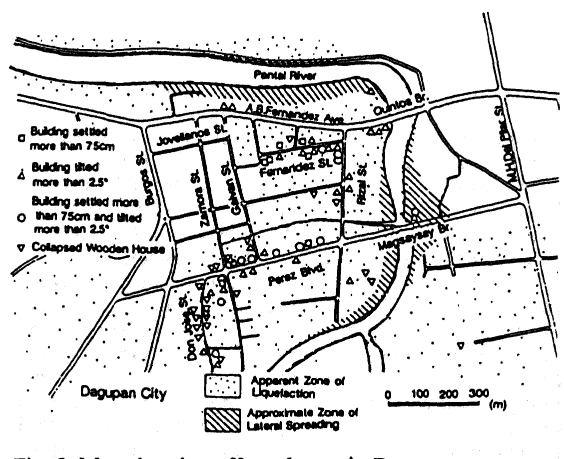

Fig. 3 Map showing affected area in Downtown Dagupan

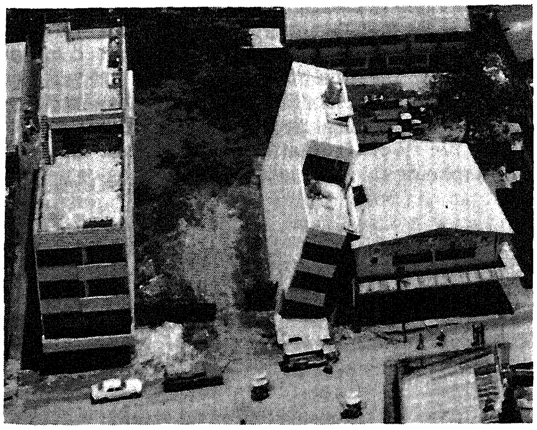

Photo 2 Building that suffers large settlement and tilting along Perez Blvd.

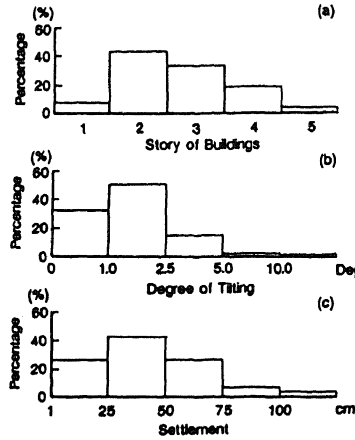

Fig. 4 Damage statistics of rcinforced concrete buildings

tilted more than 2.5 degrees and of collapsed wooden houses. Many of the buildings on Perez Blvd. and some buildings on Fernandez and Rizal Streets settled and tilted considerably (Photo 2), whereas the buildings on A. B. Fernandez Ave. generally suffered smaller settlement. Damage to superstructure was significant in many reinforced concrete buildings on A. B. Fernandez Ave.

Several reinforced concrete buildings distributed within wooden houses along Don Jose St. suffered extensive settlement and tilting. Many wooden houses in this area were also badly damaged. The ground surface along Don Jose St. settled about 50 cm. The damage to reinforced concrete buildings on the east side of the river was also extensive (Photo 3) but almost restricted within the sliding zone along the river.

Fig. 4 summarizes damage statistics of about 220 reinforced concrete buildings in the affected area. Most of the buildings are two to four storied with shallow footings. It appeared that very few buildings had pile foundations and that no consideration was made in the foundation design to mitigate liquefaction hazards.

Over a half of the buildings in the liquefied area tilted more than 1 degree. The average differential settlement of the buildings relative to the ground surface was about 50 cm.

In the liquefied area, uplifts and/or breaks of buried light-weight utilities such as gas storage tanks in automobile service stations, sewage tanks, and water and sewer pipes, and resulting pavement damage can be seen everywhere. Many electric poles tilted considerably due to foundation bearing failure.

The bridge on Perez Blvd., called the Magsaysay Bridge, which has seven spans collapsed due to lateral movement and bearing failure of its piers. Photo 4 shows the collapsed bridge and the river which has been narrowed due to lateral spreading of both sides of the river. The Quintos Bridge on A. B. Fernandez Ave. appeared unaffected.

It is interesting to note that Dagupan experienced liquefaction during the earthquake of March 16, 1892 (Series on Seismology 1985). This was the only earthquake that shook Dagupan with Intensity XIII or greater in the last 100 years (Table 1).

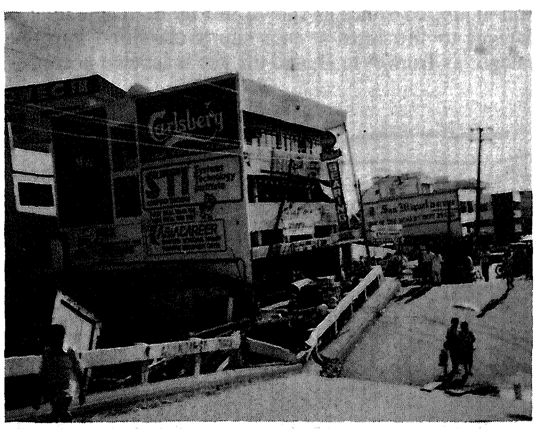

Photo 3 Damage to buildings on the east side of the river near Magsaysay Bridge

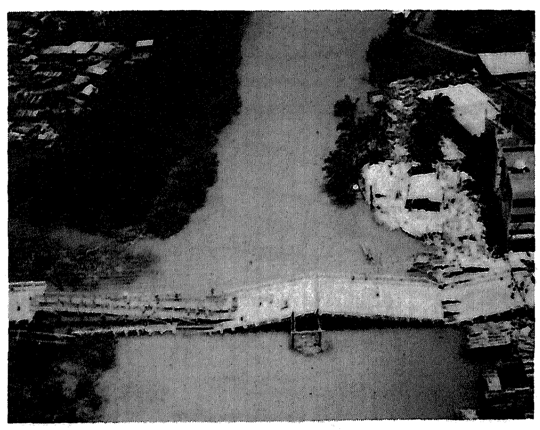

Photo 4 Magsaysay Bridge collapsed due to bearing failure and lateral ground spreading

Table 1 Characteristics of Earthquakes that shook Dagupan after 1880

Date	Earthquake Magnitude	Intensity in Dagupan	Occurrence of Liquefaction
7/18/1880		7	No
3/16/1892		8	Yes
8/24/1932	6.3	5-6	No
8/01/1968	5.9	7	No
4/07/1970	6.5	7	No
7/16/1990	7.8	8	Yes

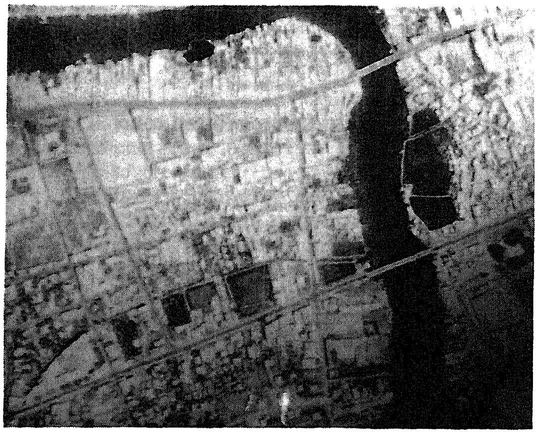

Photo 5 Aerial photo taken in between 1966 and 1974

EFFECTS OF GEOMORPHOLOGICAL CONDITIONS ON DAMAGE TO BUILDINGS

Most parts of the affected area are considered artificial fills and/or alluvial deposits of fine to silty sands which are underlain by clay at depths below 10 to 15 meters. The fills were reportedly built on recently abandoned river channels, fishponds or swampy lands after 1900's with fine sand. Photo 5 shows an aerial photo taken in between 1966 and 1974. Most parts of the north of Perez Blvd. were still swamps or fishponds at that time.

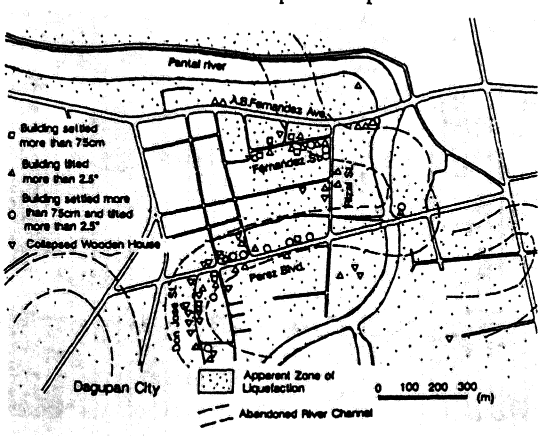

Fig. 5 Map showing relation between geological condition and damage to buildings

From this photo, Punongbayan and Torres (1990) have detected the location of recently abandoned river channels as shown in Fig. 5. Superimposed on the figure is the location of the buildings that suffered severe damage. Most of the damaged buildings concentrate in the abandoned river channels and the banks of the active river, indicating a significant effect of geomorphological conditions on the building damage.

EFFECTS OF V_s PROFILES OF SURFACE SOILS ON DAMAGE TO BUILDINGS

V_s Determination from Microtremor Measurements

To estimate V_s structures in the city, short-period microtremors were measured using arrays of sensors and dispersion characteristics of Rayleigh waves were determined. This method is based on the principles that microtremors consist of predominant Rayleigh waves and that their dispersion characteristics reflect the V_s structure of the site.

A portable system developed by Tokimatsu et al. (1992) was used for this investigation. It consists of several sensors, amplifiers, and a laptop computer. The sensors are vertical velocity transduces with a natural frequency of 1.0 Hz. The computer is equipped with an A/D converter having a resolution of 12 bits.

Six vertical sensors are distributed on the ground surface to form a circular array with a sensor in the center. The radius of the array is originally set at 5 meters and expanded or contracted by a factor of about two so that the range of array radius covers the range of wavelengths to be measured.

With each array, the vertical ground surface motions of either microtremors or forced vibrations are observed. If the signal-to-noise (S/N) ratios of microtremors in the frequency range of interest are low, forced vibrations are generated artificially with a known distance from the array to improve the S/N ratio of the measured motions. It took about 30 to 45 minutes to measure microtremors and forced vibrations at a site. The details of the test apparatus and test procedure have been described elsewhere (Tokimatsu et al. 1992).

The test sites were distributed over liquefied and non-liquefied zones as shown in Fig. 6. The extent of damage to structures at each site is classified into four categories from A to D, and the site is labeled accord-

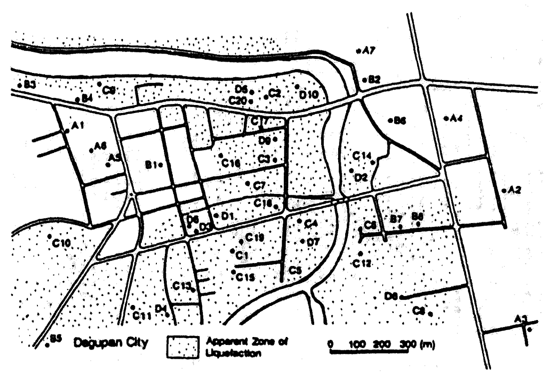

Fig. 6 Map showing location of test sites

ingly. Sites A1 to A7 are in the non-liquefied zone with no structural damage, Sites B1 and B8 near the boundary separating liquefied from non-liquefied zones with little or no structural damage, and Sites C1 to C20 and Sites D1 and D10 are in the liquefied zones with moderate and heavy structural damage, respectively.

The spacial auto-correlation analysis (Aki 1957; Okada and Matsushima 1986) is used to calculate dispersion curves from the data measured at each site. An inverse analysis using the dispersion data can result in the V_s profile of the site (Tokimatsu et al. 1992). From a theoretical point of view, the auto-correlation analysis is applicable only to the cases where observed waves are unidirectional or isotropic. However, with this analysis, Okada and Matsushima (1986) have successfully determined Rayleigh wave dispersion curves. Besides, dispersion curves can readily be determined with a personal computer.

Effects of Geophysical Conditions on Damage to Buildings

The dispersion curves for Sites A5, B1, C4, and D1 are compared in Fig. 7. The phase velocities at wavelengths longer than 40 m are on the order of 200 m/s regardless of the site conditions. The variation of phase velocity with wavelength, however, depends on site conditions at wavelengths shorter than about 40 m. Namely, the phase velocities in this wavelength range at Sites B1, C4, and D1 are consistently less than those at Site A5 for the same wavelength. Besides, the phase velocities at wavelengths less than 10 m are lower than 100 m/s at Sites C4 and D1, whereas it is equal to or more than 100 m/s at Sites A5 and B1. Considering the fact that the effective sampling depth for each wavelength is approximately equal to 1/3 or 1/2 of that wavelength, the difference in dispersive trend with site suggests that the V_s structures at depths less than 5 to 10 m might have had significant effects on the damage to structures.

The V_s structures at all sites are determined through an inverse analysis using the computed dispersion data. Fig. 8 shows the V_s structures thus obtained for the

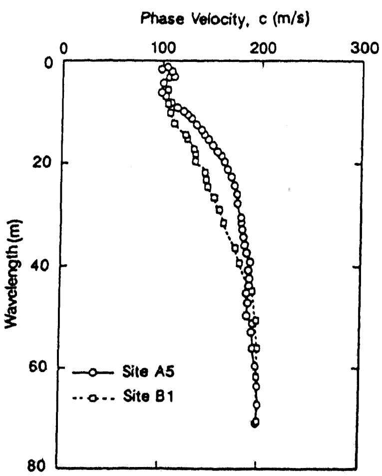

Fig. 7 (a) Dispersion curves at Sites A5 and B1

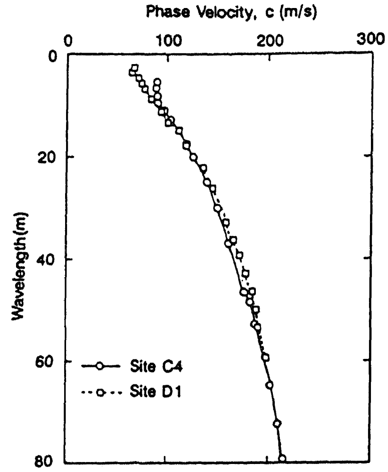

Fig. 7(b) Dispersion curves at Sites C4 and D1

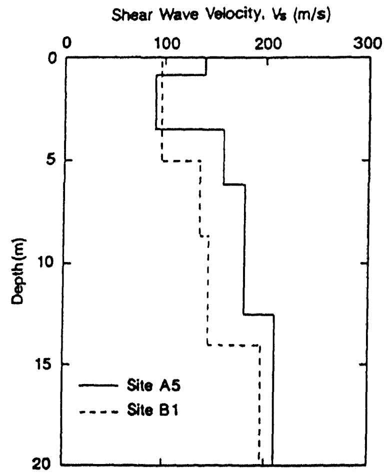

Fig. 8(a) V_s structures at Sites A5 and B1

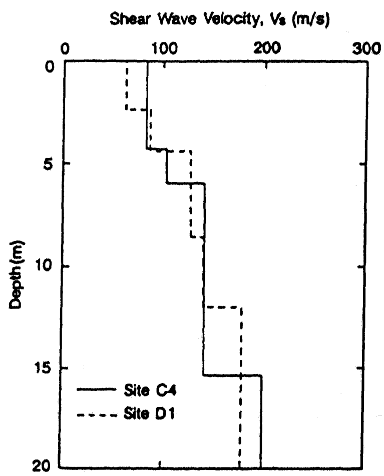

Fig. 8(b) V_s structures at Sites C4 and D1

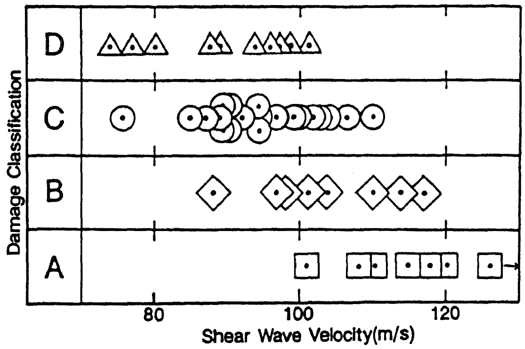

Fig. 9 Relation between average V_s of surface soils and damage classification

sites. As expected, the shear wave velocities at depths less than 10 m for Sites B1, C4, and D1 are significantly lower than those for Site A5, and the shear wave velocities at depths less than 5 m for Sites C4 and D1 are less than those for Sites A5 and B1.

For preliminary considerations, the average shear wave velocity to a depth of 5 m of surface soils at each site, $(V_s)_{ave}$, is plotted in Fig. 9 against the damage classification of buildings. There is a well-defined trend in which the damage to structures increases as the average shear wave velocity decreases. No damage to structures would be expected at sites with $(V_s)_{ave}$ greater than about 105 m/s, whereas extensive damage is provable at sites with $(V_s)_{ave}$ less than about 105 m/s. The relatively good separation of damaged from non-damaged sites indicates that the microtremor measurements used in this study appears promising as a simple means of seismic zonation.

CONCLUDING REMARKS

The Philippine earthquake of July 16, 1990 (M_s=7.8), caused extensive liquefaction in artificially fills and alluvial deposits of sandy soils, which in turn caused extensive damage to reinforced concrete buildings, wooden houses, embankments, roads, and bridges not only in the epicentral region but also the Central Plains between Tarlac and the coastline of the Gulf of Lingayen. One of the most significant features associated with the earthquake is the liquefaction induced bearing failure of buildings in Dagupan city. Extensive field investigation including microtremor measurements was made in Dagupan city to explore soil conditions and their relation to the building damage during the earthquake.

It has been found that the buildings that suffered extensive settlement and tilting concentrated in banks of active rivers, in fills built on recently abandoned river channels, and in soil deposits of which average V_s is less than about 105 m/s. These findings suggest that the Rayleigh wave investigation using microtremors is promising as an effective and yet simple means of seismic zonation, though refinements are needed in some points.

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