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LIQUEFACTION POTENTIAL AT PADANG CITY: A COMPARISON OF PREDICTED AND OBSERVED LIQUEFACTIONS DURING THE 2009 PADANG EARTHQUAKE

Adrin Tohari, Khori Sugianti, and Eko Soebowo

ABSTRACT The September 30, 2009 Padang earthquake has resulted in damages to infrastructures and buildings and a death toll of 383 in Padang City. Numerous liquefaction and ground deformations caused by the earthquake were particularly evidence in the areas few kilometers from the coast. The paper presents results of the previous field geotechnical investigations of liquefaction potential and the recent liquefaction observations in Padang City. A microzonation map was created using the data from liquefaction potential analyses and liquefaction potential indexes. The predicted liquefaction susceptibility zones showed a good agreement with site observations. The assessment suggests that the liquefaction susceptibility decreases to the northeast away from the coastal line.

Keywords: the 2009 Padang earthquake, geotechnical investigation, liquefaction index, liquefaction analysis, microzonation

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Adrin Tohari
Research Center for Geotechnology, Indonesian Institute of Sciences, Bandung 40135
Email : adrin@cbn.net.id

Khori Sugianti
Research Center for Geotechnology, Indonesian Institute of Sciences, Bandung 40135
Email : khori_sugianti@yahoo.com

Eko Soebowo
Research Center for Geotechnology, Indonesian Institute of Sciences, Bandung 40135
Email : soebowoeko@yahoo.com

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ABSTRAK *Peristiwa gempabumi yang melanda Kota Padang pada tanggal 30 September 2009 telah menimbulkan kerusakan pada infrastruktur dan bangunan serta menimbulkan korban jiwa sebanyak 383 orang di Kota Padang. Fenomena likuifaksi dan deformasi permukaan tanah yang disebabkan oleh gempabumi tersebut terjadi di wilayah beberapa kilometer dari pinggir pantai. Makalah ini menyajikan hasil investigasi geoteknik terdahulu yang dilakukan untuk mengetahui potensi likuifaksi setahun sebelum terjadi gempabumi tersebut, dan hasil observasi fenomena likuifaksi di Kota Padang. Peta mikrozonasi potensi likuifaksi disusun berdasarkan data dari analisis kerentanan likuifaksi dan indeks likuifaksi. Hasil mikrozonasi prediksi memperlihatkan hasil yang bersesuaian dengan observasi fenomena likuifaksi di lapangan. Kajian ini mengindikasikan bahwa kerentanan likuifaksi berkurang ke arah timurlaut dari pinggir pantai.*

Katakunci*: Gempabumi Padang 2009, investigasi geoteknik, indeks likuifaksi, analisis likuifaksi, mikrozonasi.*

INTRODUCTION

Occurrence of a big earthquake is not only can trigger a tsunami but also liquefaction in areas made up of loose sandy soils with shallow groundwater table. The occurrence of earthquake-induced liquefaction can result in damages of infrastructures, such as bridges, roads, runways, river embankments, and buildings, due to

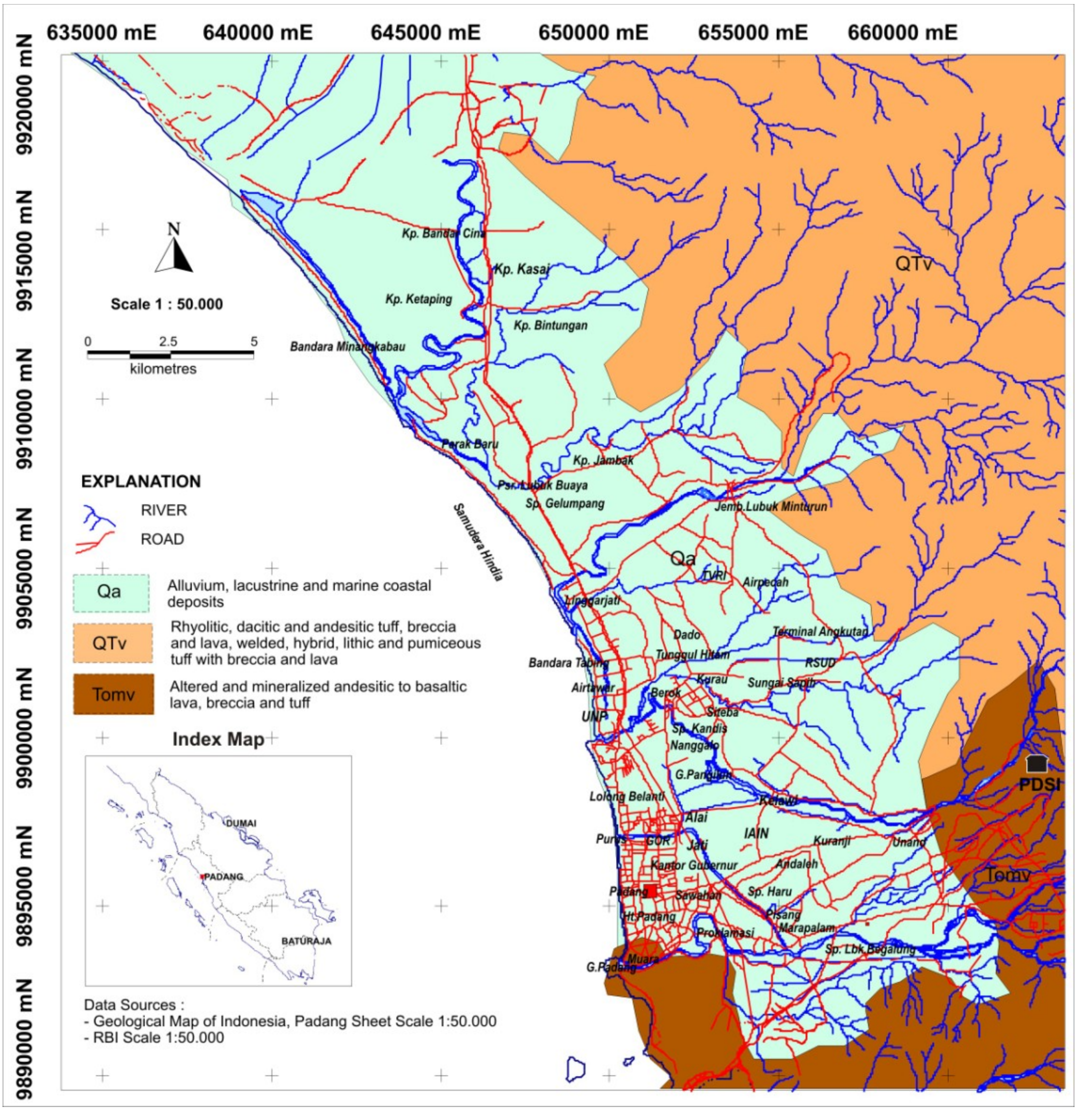

Figure 1. Geological Map of Padang City region (modified from Kastowo et al., 1996).

ground settlement, lateral spreading, sand boiling, loss of bearing capacity, etc.

An earthquake (Mw = 7.6) struck the west coast Sumatra, affecting an area with a population of about 1.2M people in Padang and Pariaman. The earthquake resulted in 383 deaths as well as significant damages in Padang City (Satkorlak, 2009). The casualties were mostly due to ing collapse. It also triggered liquefaction in numerous inland alluvial areas as well along the coast. Lateral spreading, sand boiling and ground settlement were widely observed in Padang City, and along the northern coast of Padang Bay.

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However, a few investigations on the occurrences of liquefaction and associated ground failures have been conducted after the earthquake (e.g., EERI, 2009).

Liquefaction potential of the northern part of Padang City has been studied by the authors after the 2004 Banda Aceh earthquake, for the purpose of government and public awareness on earthquake collateral hazards (Tohari et al., 2006). A subsequent investigation was then conducted to cover the southern part of the city in 2008 (Tohari et al., 2008). The objectives of this paper are to present the results of previous investigations of liquefaction potential in Padang City and to compare the results with the observed liquefaction phenomena occurred during the 2009 Padang earthquake.

GEOLOGICAL AND TECTONIC SETTING

Geological Setting

As seen from the geological map in Figure 1, Padang City is made up of three different geological units. The oldest units are the Tertiary volcanic rock (Tomv), which present in the hill to the southeast. They are composed of altered and mineralized andesitic to basaltic tuff, breccia and lava. They are overlain by the Plio-Plistocene volcanic rocks (QTv), that are composed of rhyolitic, dacitic and andesitic tuff, breccia and lava. They are present in the hill to the northeast. The youngest units are the Quarternary aluvial deposits (Qa) that consist of sand, silt and gravel as well as swamp deposits. Borehole data indicate that the sand layers susceptible to liquefaction are present in the alluvial deposits. The depth of groundwater generally ranges between 0.5 and 5.0 m; the mean groundwater depth near the shoreline is about 1.5 m (Tohari et al., 2008).

Tectonic Setting

The island of Sumatra sits atop the Southeast Asian plate, which overrides the subducting Indian and Australian oceanic plates that converges obliquely at about 50 to 60 mm/yr (Prawirodirdjo et al., 2000). The oblique convergence is partitioned into two components: the dip slip is accommodated on the subduction interface, and the strike-slip component is accommodated largely by the Sumatra fault (McCaffrey, 1992; Sieh and Natawidjaja, 2000). The 1900-km long Sumatran fault zone (SFZ) runs along the back-bone of Sumatra, within or near the active-volcanic arc. The SFZ is highly segmented, and hence consists of 19 major segments ranging in length from 35 km to 200 km. These fault segments are separated by more than a dozen discontinuities, ranging in width from less than 4 to 12 km, mostly are dilatational stepovers (Sieh and Natawidjaja, 2000). The SFZ pose major hazards, particularly to people live on and near the active fault trace. Since 1890, about 21 major earthquakes ruptured the segments of the SFZ with magnitudes ranges from 6.5 to 7.7 (Sieh and Natawidjaja, 2000).

MAIN CHARACTERSITICS OF THE 2009 PADANG EARTHQUAKE

The Padang earthquake, with a magnitude of 7.6 (Mw) occurred on Wednesday September 30, 2009, at 5:16 p.m., affecting an area with a population of about 1.2 M people, including 900,000 in Padang and 80,000 in Pariaman. The epicenter of the earthquake was located offshore about 60 km WNW of Padang, at a depth of about 80 km within the oceanic slab of the Indo-Australian plate (Figure 2). The earthquake produced a compact rupture zone, with a nearly circular shape with a radius of only 15 km (EERI, 2009).

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Figure 2. Location of the September 30 earthquake epicenter on the Sunda thrust fault (Sieh, 2009).

During the earthquake, a peak ground acceleration (PGA) of 0.3g was recorded at the geophysical station, named PDSI, in Padang. Since the station is located at the hills of Limau Manis, 12 km from the coast and on stiff soil (see also Fig. 1), the ground motions in the center of Padang, on softer deeper soil deposits, are likely to have been larger (EERI, 2009).

LIQUEFACTION DAMAGES IN PADANG CITY

Figure 3 show the location of ground settlement, sand boiling and lateral spreading due to the earthquake. The ground settlement and lateral

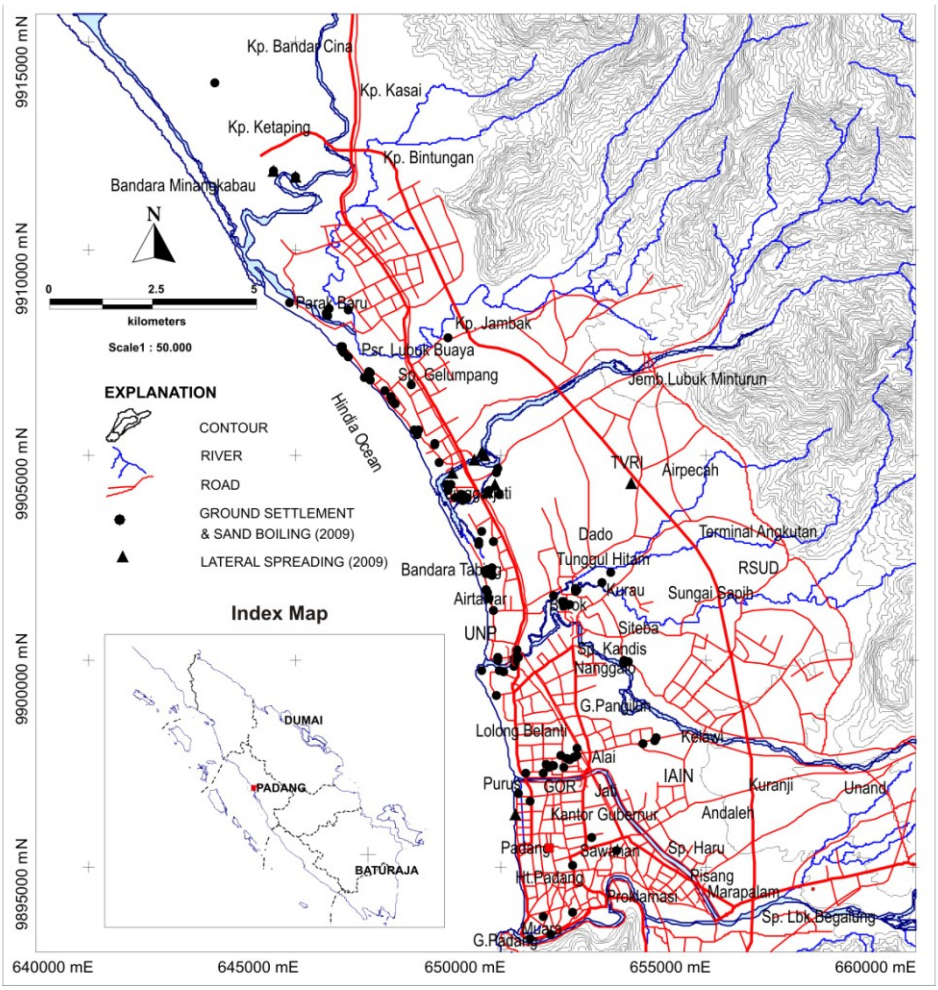

Figure 3. Locations of ground deformation associated with liquefaction due to the September 30 earthquake event.

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spreading generally occurred in the populated areas up to 5 km from the coastal line, with a significant damage to the city infrastructures (roads and bridges), residential housing and buildings. Many buildings, located near the river front experienced foundation movement due to ground settlement. One example of foundation movement was shown by four-story public work building, located near the river front (Figure 4). The building configuration concentrated lateral deformations and residual drift in the first story. In the vicinity of the building, fine sand were commonly ejected out of the ground cracks. Ground settlement also caused the foundation of many residential housing to settle up to 1.0 m (Figure 5).

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These phenomena were well observed in the northern part of Padang City, especially in the Koto Tangah Sub-District.

Lateral spreading mainly occurred in the areas along the swamps and rivers, usually in the road embankments and river dikes. One good example of lateral spreading was evident in Samudera road, which is an embankment road located along the Padang Beach (Figure 6). The presence of weak saturated soil layers at the base of the embankment was a main causative factor for the embankment to experience the lateral spreading during the earthquake.

Figure 4. First-story column damage in the public work building due to ground settlement.

Figure 5. Foundation settlement in brick masonry house building due to liquefaction in Koto Tangah Sub-District, Padang. The total settlement was about 1.0 m.

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Figure 6. Ground cracking at a road embankment in the Padang Bay due to lateral spreading.

EVALUATION OF LIQUEFACTION POTENTIAL PRIOR THE 2009 EARTHQUAKE

Investigation Site and Methodology

In 2006 and 2008, a series of geotechnical investigations was conducted to evaluate and assess the liquefaction potential in Padang City. Figure 7 shows the location of the field geotechnical investigations. The investigations comprised of geotechnical drilling up to 30 m deep at 6 locations, standard penetration tests (SPT) at every 1.5 m at each borehole, cone penetration tests (CPT) at 40 locations up to 30 m deep, mapping of the depth of groundwater table, and laboratory determination of grain size distribution and soil unit weight.

Liquefaction potential analyses were then carried out using a CPT-based method, which requires the calculation of two variables: the seismic demand placed on a soil layer, expressed in terms of cyclic stress ratio (CSR), and the capacity of the soil to resist liquefaction, expressed in terms of cyclic resistance ratio (CRR).
The cyclic stress ratio (CSR) is defined by Seed and Idriss (1971) as:

$$CSR = 0.65\left(a_{\max}/g\right)\times\left(\sigma_{vo}/\sigma'_{vo}\right)r_d \quad (1)$$

where a_{max} is the peak horizontal acceleration at the later interest, g is the acceleration of gravity, σ_{vo} and σ'_{vo} are total and effective vertical overburden stresses, respectively, and r_d is stress reduction factor.

The simplified procedure proposed by Robertson and Wride (1998) were employed to analyze the liquefaction potential based on the CPT data. The 7.6 (Mw) magnitude measured for the Padang earthquake, and the average peak horizontal ground acceleration (PHGA) of 0.40 g estimated from the attenuation relationship (Youngs et al. 1997; Atkinson and Boore, 2003) were used for all analyses.

The liquefaction potential of a site is affected by the severity, thickness and depth of liquefied

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layers in a soil profile. In order to quantify the liquefaction severity of Padang City, the liquefaction potential index developed by Iwasaki et al. (1982) was used. The liquefaction potential index (P_L) is calculated by the following equation:

$$P_L = \int_0^{20} Fw(z)dz \tag{2}$$

which F=1-F_s for F_s <1.0 and F= 0 for $F_s \geq 1.0$ and

$$w(\mathrm{z}) = 10 - 0.5z \tag{3}$$

where w(z) is the function for accounting for soil liquefaction with respect to depth and z is the depth (in meters). The maximum depth considered in this analysis is 20 m. On the basis of P_L values, the liquefaction severity of the site is classified as follow (Table 1)

Table 1. Liquefaction index and associated susceptibility.

Value of P_L	Liquefaction susceptibility
$0 < P_L \leq 5$	low
$5 < P_L \leq 15$	high
$P_L > 15$	very high

Results of Liquefaction Potential Analysis

The results obtained using CPT-based empirical methods are presented in graphical form to show the depth and the thickness of potentially liquefiable soil layers for the NW-SE cross sections to represent the coastal and inland areas (Figures 8 and 9). The potentially liquefiable layers are shown in dashed line on these sections. All the liquefiable zones correspond to layers of loose sand to silty sand, and a mixture of gravel and sand. The cross section of potentially liquefiable layers for the coastal areas (Figure 8) shows that the thickness of liquefiable layers is likely to decrease toward the southeast, due to the presence of clay layer as cap soil overlying the sand layer. Moreover, the depth of liquefiable layers becomes shallow. Meanwhile, compared to the coastal areas, the liquefiable layers in the inland areas (Figure 9) become deeper and thinner toward the southeast due to the presence of thicker fine grained soil layers and denser sand layers. Thus, the liquefaction potential becomes less pronounced toward the southeast part of Padang City.

Microzonation of Liquefaction Susceptibility

Based on the values of liquefaction potential index (P_L) and the classification of liquefaction susceptibility shown in Table 1, a generalized liquefaction susceptibility map for Padang City was established (Figure 10). As seen in this figure, the study area was divided into three zones from low to very high liquefaction susceptibility. The very high susceptibility areas concentrate along the shoreline. The extent of these areas is larger in the northwestern part than in the southeastern part of the city. The liquefaction susceptibility also decreases towards the northeast away from the coastal line.

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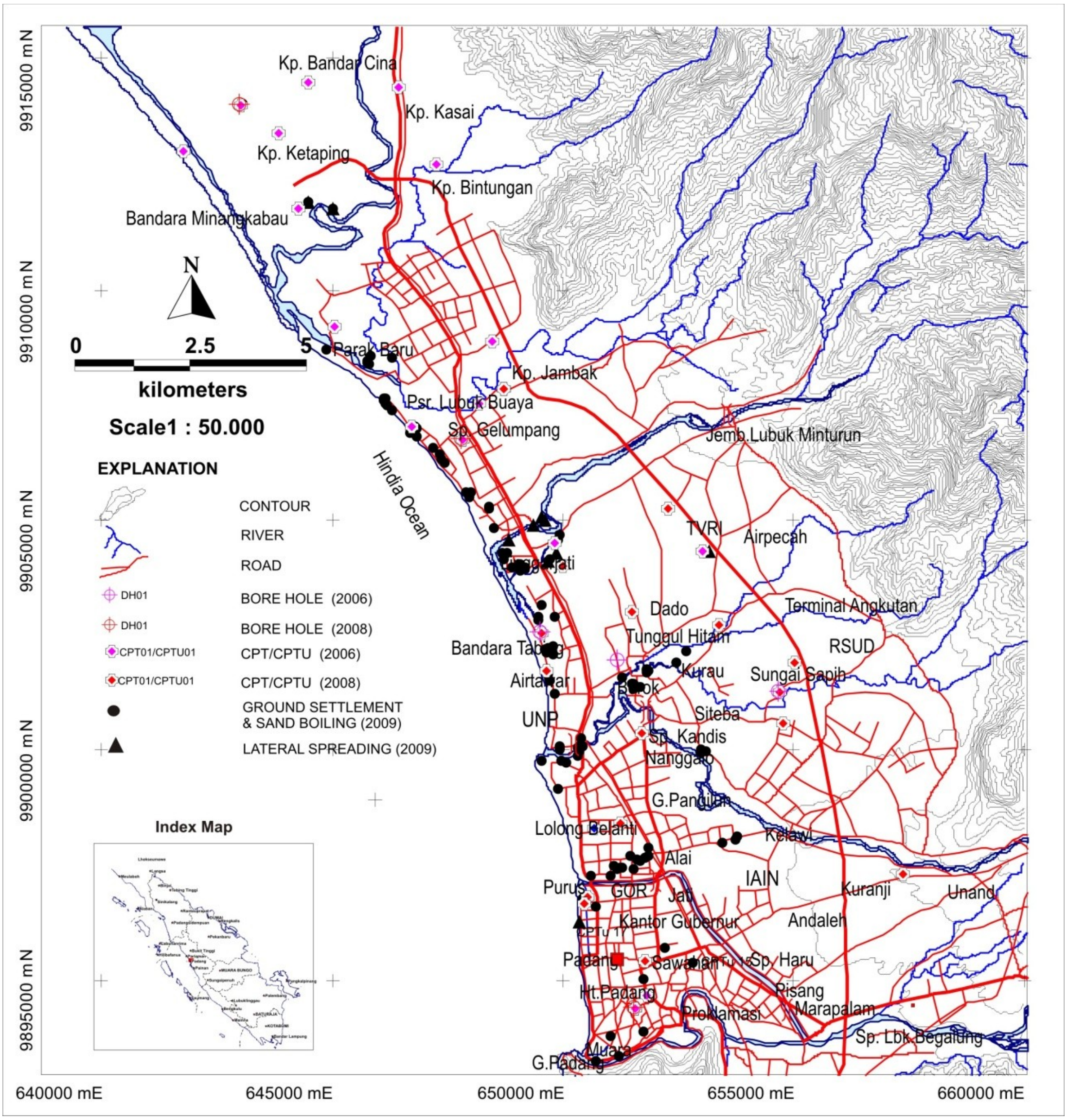

Figure 7. Locations of the sub-surface geotechnical investigation.

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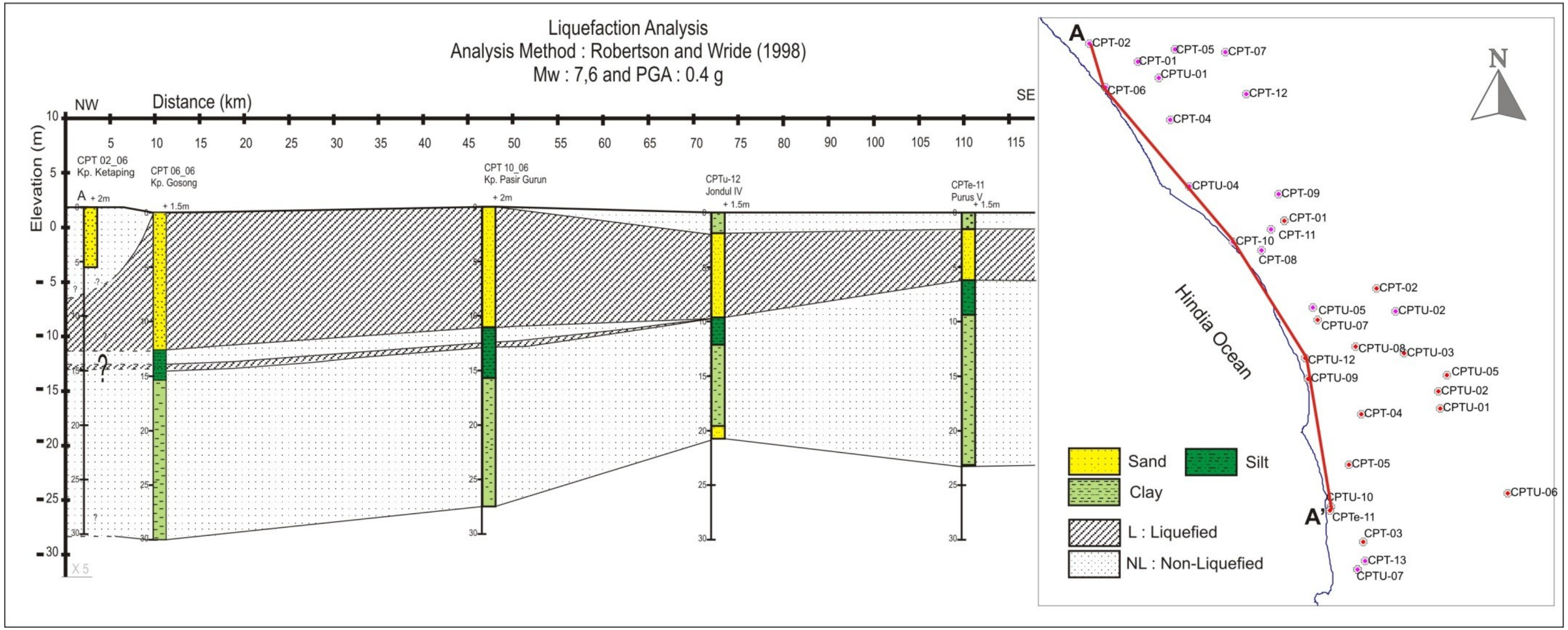

Figure 8. Cross section of potentially liquefiable soil layers across the line A-A'.

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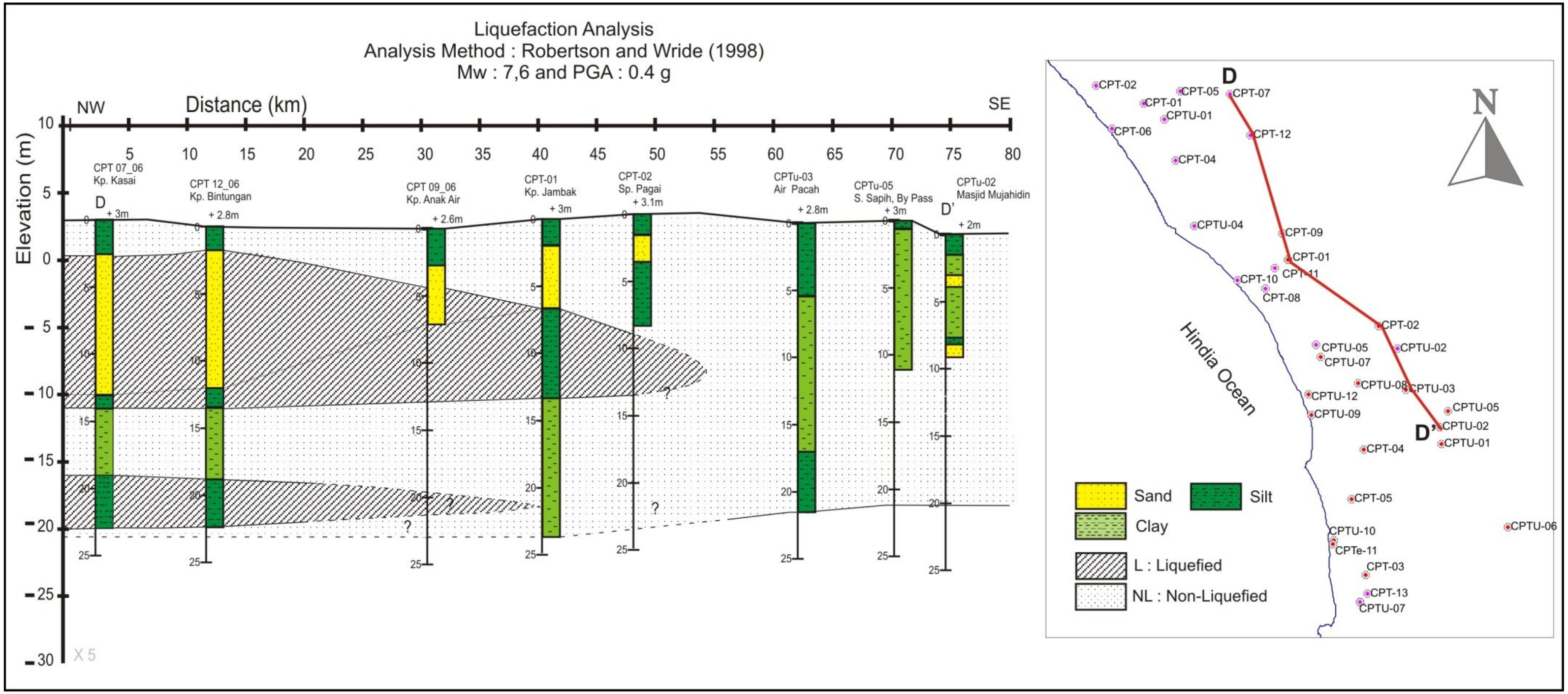

Figure 9. Cross section of potentially liquefiable soil layers across the line D-D'.

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Figure 10 also presents the plot of all the sites of observable liquefactions (i.e., ground settlement, sand boiling, and lateral spreading) due to the 2009 Padang earthquake. It is clear that there is a good agreement between the predicted zones and the sites observed after the earthquake. In particular, Koto Tangah, Padang Utara, Padang Timur dan Padang Selatan Sub-Districts, where sand boiling, ground settlement and lateral spreading were observed, fall into the high to very high liquefaction susceptibility zones.

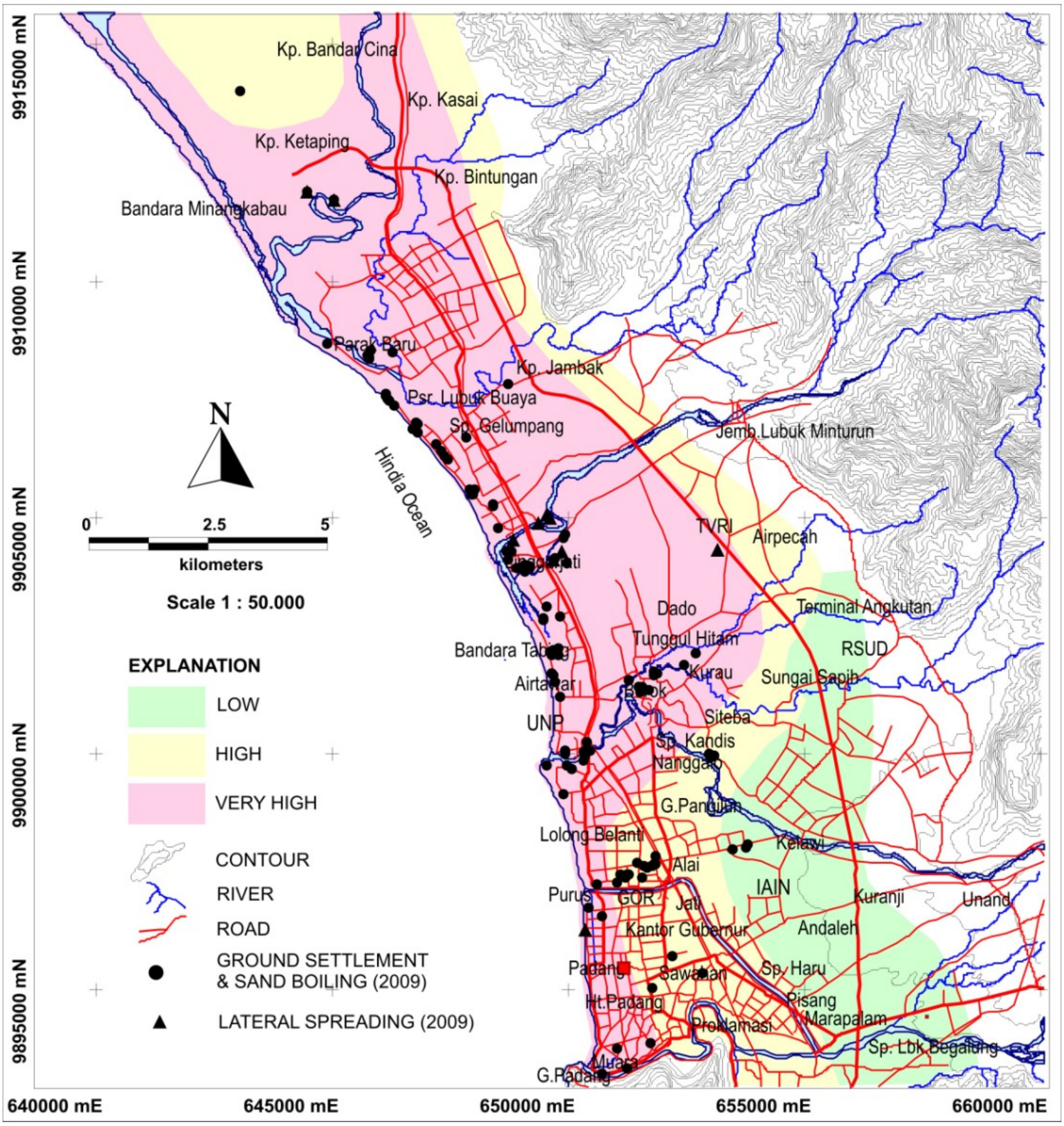

Figure 10. Liquefaction susceptibility map of Padang City.

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Based on the current results, the zones of liquefaction potential, based on the calculated PHGA of 0.4 g, included not only most of the liquefied sites but also non-liquefied sites, suggesting a lower PHGA on the soft soil layer in the city, due to local site effects including strong non-linear soil behavior. Factors like soil stratification and the variation of soil stiffness are believed to produce the non-linearity of soil response to the earthquake wave. Based on previous sub-surface investigations (Tohari et al., 2008), the non-liquefied sites consist of clay layers of 3 m thick, as top soils, overlying dense sand layers. The discrepancy between the observed and the predicted liquefaction phenomena also demonstrates the importance of seismic hazard microzonation to determine the ground acceleration at each site, taking into account the specific site effects.

CONCLUSIONS

Based on the available geotechnical data and information from the site observations following the 2009 Padang earthquake, the liquefaction potential of Padang City was evaluated. The liquefaction potential map established was compared to the liquefaction-affected areas. The main conclusions are:

a. Liquefaction in the Padang City appears to have occurred primarily within the Quarternary alluvial deposit at shallow depth. The major regions of liquefaction and associated ground deformations are mainly located along the shoreline and associated with alluvial sand.
b. A microzonation map of liquefaction susceptibility for Padang City was prepared. The susceptibility map shows a good agreement with the field observations conducted after the 2009 earthquake event. Toward the northeast part of the city, the susceptibility of the soil layers to liquefaction becomes very low, due to the presence of dense sand to gravelly sand, or the presence of thick layers of fine-grained soils as cap soils.
c. Further sub-surface investigations are still required to clarify the influence of site effects on the susceptibility of the Padang City region to liquefaction.

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