Liquefaction Susceptibility Plot of Gerona, Central Luzon Philippines

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***Abstract*—The 1990 earthquake in the Central Luzon, Philippines manifested sand boils and land deformations in Gerona, Tarlac signifying the town's susceptibility to soil liquefaction. Liquefaction-susceptible sediments are water-saturated, loose, fine-grained sand deposits. Ocular inspection was done to survey and select the sites to be considered. Standard penetration test (SPT) was employed to establish the geotechnical profile, subsurface conditions, and the soil bearing pressure of the underlying soil formation. Seven boreholes were drilled in selected areas namely Tagumbao (BH1), Danzo (BH2), Apsayan (BH3), Poblacion (BH4), Matayungcab (BH5), Salapungan (BH6), and San Antonio (BH7). The method of Seed and Idriss was applied to compute for the liquefaction potential index (LPI) of selected sites in Gerona. MathCAD was used to generate the liquefaction susceptibility plots at varying earthquake magnitudes. At earthquake of magnitude 5.0, the area within the vicinity of BH 7 has low liquefaction potential. At earthquake of magnitude 6.0, all areas within the vicinity of the SPT sites will liquefy except on areas near BH 3 and at earthquake of magnitude 7.5, the entire area within the vicinity of the SPT sites is highly liquefiable.**

***Index Terms*—liquefaction, susceptibility, mapping, SPT, USCS, LPI**

I. Introduction

In 1990, Central Luzon was hit by one of the strongest earthquake in the Philippines. An earthquake magnitude of 7.8 with epicenter at 15.6° N and 121.0° E near the town of Rizal, Nueva Ecija was recorded by the Philippine Institute of Volcanology and Seismology (PHIVOLCS). Manifestations of liquefaction occurrences were observed in the form of tilting of structures, sinking foundations, sand boils, lateral spreading, and rise of subsurface structures [1].

Liquefaction failures are the result of geologic formation of soil strata, pore water pressure, density and characteristic of the soil grains [2]. However, a driving force equivalent to an earthquake magnitude of at least 5.5 is needed within an area approximately hundreds of kilometers from the epicenter [1].

There have been studies about the liquefiable sites within the Philippines. However, the bases of this mapping were usually geographical observations and historical or geological data [3]. A new perspective was suggested in this study using a geotechnical approach which focuses on a simple method known as the Standard Penetration Test (SPT).

Manuscript received January 15, 2016; revised April 8, 2016.

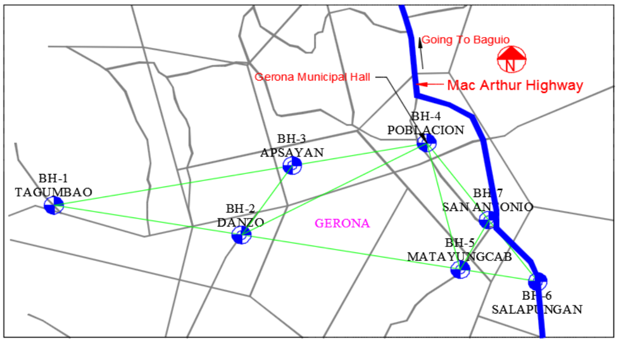

Figure 1. Standard Penetration Test Locations at Gerona, Tarlac.

This study evaluates the town's susceptibility to liquefaction considering the sites of Tagumbao, Danzo, Apsayan, Poblacion, Matayungcab, Salapungan and San Antonio (Fig. 1) which were selected based on manifestations of liquefaction during the destructive 1990 earthquake. Liquefaction Susceptibility Plots (LSP) for selected sites of Gerona, Tarlac were generated.

II. Methodology

A. Geological Mapping

Geological assessment of soil with potentially liquefiable nature was first undertaken to identify plottable boundaries. Prior to the actual soil exploration, a preliminary site survey by ocular inspection of the liquefiable sites was conducted in coordination with Gerona's municipal officials and the locals. The three main boundaries considered as the reference points used in mapping were Tagumbao, Poblacion and Salapungan. MathCAD was employed for all computations and in the generation of the Liquefaction Susceptibility Plots (LSP) of Gerona, Tarlac.

B. Geotechnical Exploration Using Standard Penetration Test

As shown in Fig. 1, four Standard Penetration Test (SPT) sites were added to the three main boundaries to provide seven points of reference. Seven boreholes namely, Tagumbao (BH 1), Danzo (BH 2), Apsayan (BH 3), Poblacion (BH 4), Matayungcab (BH 5), Salapungan (BH 6) and San Antonio (BH 7), were drilled to establish

doi: 10.18178/ijscer.5.4.292-295

the geotechnical profiles and subsurface conditions of the underlying soil formation using the Unified Soil Classification System (USCS).

C. Liquefaction Susceptibility Analysis

Liquefaction susceptibility analysis was applied to determine the factor of safety against liquefaction using Seed and Idriss method [2]. Initially, the values of the SPT blowcounts, $(N_1)_{60}$, were determined using Eq. (1).

$$(N_1)_{60} = (N_{SPT})(C_N)(C_E)(C_B)(C_S)(C_R) \quad (1)$$

where C_N, C_E, C_B, C_S, and C_R, are the correction factors used. C_N is the correction factor to normalize the measured blow count under 1atm of effective overburden pressure as expressed in Eq. (2).

$$C_N = \sqrt{\frac{P_{ATM}}{\sigma}} \quad (2)$$

where P_{ATM} is the atmospheric pressure. C_E is the correction factor for the level of energy delivered by the SPT hammer, defined in Eq. (3).

$$C_E = \frac{ER}{60} \quad (3)$$

where ER is the actual energy ratio delivered to the top of drill rod. In this case, the value used for ER is 45 since the hammer used is a donut-type with a hammer-pulley release. Thus, the value of C_E is equal to 0.75. C_B is the correction factor for borehole diameter and the value used is 1.0 which is applicable for borehole diameters ranging from 65 to 115 mm. C_S is the correction factor for sample liner. The value used for C_S is 1.2 which is applicable for samplers without a liner. Lastly, C_R is the correction factor for drill rod length in which the value varies depending on the sampling depth, z. C_R is equal to 0.75 for $z \leq 3$ m, $(15 + z)/24$ for $3 < z < 9$m, or 1.0 for $z \geq 9$m.

After determining N_{SPT}, the clean-sand equivalent of $(N_1)_{60}$ was computed following Eq. (4),

$$(N_1)_{CS60} = (N_1)_{60} + \Delta(N_1)_{60} \quad (4)$$

where $\Delta(N_1)_{60}$ is 0 for FC ≤ 5%, 7(FC-5)/30 for 5% < FC < 35%, and 7.0 for FC ≥ 35%. Note that FC is the fines content (percent finer than 0.075 mm or no. 200 sieve).

The cyclic resistance ratio (CRR) for an earthquake moment magnitude, $CRR_{M=7.5}$, was then determined for the soil based on the computed $(N_1)_{CS60}$ using Eq. (5).

$$100CRR_{M=7.5} = \frac{95}{34-(N_1)_{CS60}} + \frac{(N_1)_{CS60}}{1.3} - \frac{1}{2} \quad (5)$$

For $(N_1)_{CS60}$ value exceeding 30, CRR approaches infinity which corresponds to a very dense sandy soil where liquefaction is unlikely to occur.

More so, a magnitude scaling factor (MSF) is used to adjust $CRR_{M=7.5}$ for the magnitude of earthquake under consideration. The resulting CRR is expressed in Eq. (6) and the MSF value is obtained using Eq. (7) or (8).

$$CRR = (CRR_{M=7.5})\,(MSF) \quad (6)$$

$$MSF = \left(M_W^{-3.46}\right)\left(10^{3.0}\right), \text{ for } M_W < 7.0 \quad (7)$$

$$MSF = \left(M_W^{-2.56}\right)\left(10^{2.24}\right), \text{ for } M_W \geq 7.0 \quad (8)$$

The cyclic stress ratio, CSR, is computed to determine average cyclic shear generated by an earthquake of specific magnitude. The CSR is given by Eq. (9).

$$CSR = 0.65\left(\frac{\alpha_{max}}{g}\right)\left(\frac{\sigma_{vo}}{\sigma'_{vo}}\right)r_d \; n \quad (9)$$

The factor of safety, FS_{liq}, at each SPT location was determined using Eq. (10).

$$FS_{liq} = \frac{CRR}{CSR} \quad (10)$$

where the soil at the depth of the measured SPT blowcount is susceptible to liquefaction if $FS_{liq} \leq 1.0$. Otherwise, not susceptible to liquefaction if $FS_{liq} > 1.0$.

Finally, the acquired FS_{liq} is used to solve for the liquefaction potential index (LPI), given in eq. (11). LPI was used to determine the susceptibility of a soil column of specified thickness [4]. The severity of liquefaction was evaluated using the criteria established from the previous studies of Iwasaki et al where LPI= 0 is not liquefiable (NL), 0<LPI≤5 is low liquefaction potential, 5<LPI≤15 is moderate liquefaction potential, and LPI>15 is high liquefaction potential [5].

$$LPI = \int_0^{20m} F * w(z)\,dz \quad (11)$$

where F = 1 − FS for FS ≤ 1, and F = 0 for FS > 1, and w(z) = 10 − 0.5z.

TABLE I. SUMMARY OF SPT DATA AND LIQUEFACTION ANALYSIS RESULTS AT EARTHQUAKE OF MAGNITUDE 5.0

Borehole no. and Site	Factor of Safety FS = CRR/CSR							LPI	Liquefiable layer	Remarks
	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7			
1. Tagumbao	1.50	1.36	1.31	1.72	1.79	DENSE	DENSE	0.00	NONE	NL
2. Danzo	1.32	1.31	1.21	1.59	2.05	DENSE	DENSE	0.00	NONE	NL
3. Apsayan	1.92	DENSE	DENSE	DENSE	DENSE	DENSE	DENSE	0.00	NONE	NL
4. Poblacion	1.34	1.02	1.39	1.47	DENSE	DENSE	DENSE	0.00	NONE	NL
5. Matayungcab	1.10	1.22	2.24	DENSE	DENSE	DENSE	DENSE	0.00	NONE	NL
6. Salapungan	2.20	1.88	1.80	1.97	DENSE	DENSE	DENSE	0.00	NONE	NL
7. San Antonio	0.95	0.89	DENSE	1.97	DENSE	DENSE	DENSE	1.96	1-2	LOW

TABLE II. SUMMARY OF SPT DATA AND LIQUEFACTION ANALYSIS RESULTS AT EARTHQUAKE OF MAGNITUDE 6.0

Borehole no. and Site	Factor of Safety FS = CRR/CSR							LPI	Liquefiable layer	Remarks
	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7			
1. Tagumbao	0.80	0.72	0.70	0.92	0.95	DENSE	DENSE	9.72	1-5	MODERATE
2. Danzo	0.70	0.70	0.64	0.84	1.09	DENSE	DENSE	12.10	1-4	MODERATE
3. Apsayan	1.02	DENSE	DENSE	DENSE	DENSE	DENSE	DENSE	0.00	NONE	NL
4. Poblacion	0.71	0.54	0.74	0.78	DENSE	DENSE	DENSE	13.29	1-4	MODERATE
5. Matayungcab	0.59	0.65	1.19	DENSE	DENSE	DENSE	DENSE	9.78	1-3	MODERATE
6. Salapungan	1.17	DENSE	0.96	1.05	DENSE	DENSE	DENSE	0.42	NONE	LOW
7. San Antonio	0.51	0.47	DENSE	1.05	DENSE	DENSE	DENSE	12.97	1-2	MODERATE

TABLE III. SUMMARY OF SPT DATA AND LIQUEFACTION ANALYSIS RESULTS AT EARTHQUAKE OF MAGNITUDE 7.5

Borehole no. and Site	Factor of Safety FS = CRR/CSR							LPI	Liquefiable layer	Remarks
	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7			
1. Tagumbao	0.39	0.36	0.34	0.45	0.47	DENSE	DENSE	28.58	1-5	HIGH
2. Danzo	0.35	0.34	0.32	0.42	0.54	DENSE	DENSE	29.54	1-5	HIGH
3. Apsayan	0.50	DENSE	DENSE	DENSE	DENSE	DENSE	DENSE	6.91	1	MODERATE
4. Poblacion	0.35	0.27	0.36	0.39	DENSE	DENSE	DENSE	27.86	1-4	HIGH
5. Matayungcab	0.29	0.32	0.59	DENSE	DENSE	DENSE	DENSE	21.64	1-3	HIGH
6. Salapungan	0.58	0.49	0.47	0.52	DENSE	DENSE	DENSE	20.19	1-4	HIGH
7. San Antonio	0.25	0.23	DENSE	0.52	DENSE	DENSE	DENSE	22.78	1-2,4	HIGH

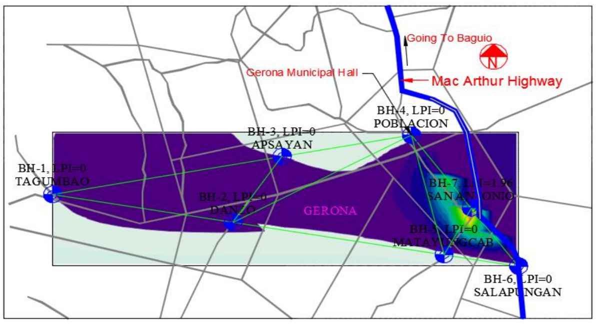

Figure 2. Liquefaction Susceptibility Map of Gerona, Tarlac at earthquake of magnitude 5.0.

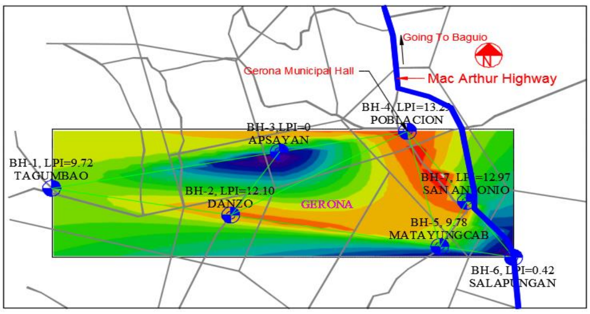

Figure 3. Liquefaction Susceptibility Map of Gerona, Tarlac at earthquake of magnitude 6.0.

III. RESULTS AND DISCUSSION

A. Computer-Aided Liquefaction Susceptibility Analysis

The Seed and Idriss method is a deterministic approach to evaluate the liquefaction potential on the basis of a factor of safety. The FS_{liq} and LPI values for each borehole were summarized in Table I, II, and III at earthquake magnitude 5.0, 6.0, and 7.5 respectively. The areas showing liquefaction potentials were identified using shaded contours based on the LPI values as shown in Fig. 2, Fig. 3, and Fig. 4.

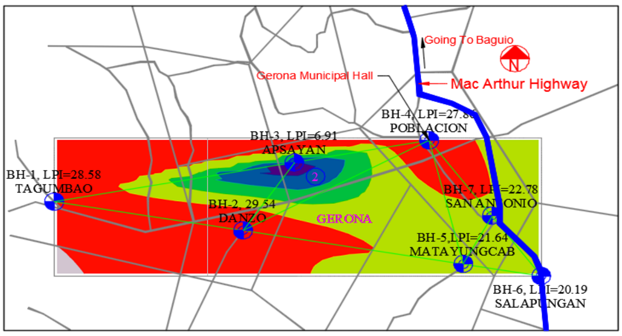

Figure 4. Liquefaction Susceptibility Map of Gerona, Tarlac at earthquake of magnitude 7.5.

B. At Earthquake of Magnitude 5.0

As shown in Table I, BH 1 to 6 are not liquefiable at all layers of exploration. However, BH 7 was remarked to have low liquefaction potential with LPI equal to 1.96. Similar analyses were done to boreholes at earthquake magnitude 6.0 and 7.5.

C. At Earthquake of Magnitude 6.0

As shown on Table II, at magnitude 6, all the boreholes are liquefiable except Apsayan (BH 3). However, BH 6 has low liquefaction potential with LPI equal to 0.42 while the others are moderately liquefiable with LPI between 5 and 15.

D. At Earthquake of Magnitude 7.5

As shown on Table III, all boreholes are highly liquefiable (LPI >15) except for BH 3 with LPI equal to 6.9 which is moderately liquefiable at the surface. The condition of BH 3 being liquefiable only near the surface is attributed to the clean-sand equivalent on depths below that layer which are relatively high [2]. Inconsistencies on the effect of fines on liquefaction susceptibilty are worth noting, though it has been accepted that relatively clean sandy soils, with few fines, are susceptible to earthquake induced liquefaction [6], [7]

E. Effect of Liquefaction around Gerona SPT Sites

The determination of the LPI based on specific locations (ie. boreholes) together with the thickness of liquefiable soil layer served as basis for the generation of liquefaction susceptibility plot. As shown in Fig. 2, at earthquake magnitude of 5.0, liquefiable layers, although not highly susceptible, can be seen around the vicinity of San Antonio to a depth up to 3m (layer 1 and layer 2 of Table I).

Fig. 3 shows that at earthquake magnitude 6.0, almost the entire area is prone to liquefaction except those near the vicinity of Apsayan (BH 3). The behavior of such occurrence is already risky around Tagumbao, Danzo and Poblacion since the depth of liquefiable layers can extend from 6m up to 7.5m (layers 1 to 5 of Table II). Moreover, at extreme conditions where an earthquake reaches a magnitude of 7.5, the only less-liquefiable area is that near the vicinity of Apsayan (BH 3) as shown in Fig. 4.

LSP was generated to represent the minimum values of FS in terms of LPI. A curvilinear mesh was fitted into the values of LPI at the test sites. The thickness of underlying liquefiable soil is directly related to post liquefaction failures [8]. Hence, thicker liquefiable strata would mean an area more prone to liquefaction [5].

In the absence of surface evidence of liquefaction, a site can only be classified as one with non-apparent liquefaction since there is some possibility that liquefaction may have occurred at some depth below the ground surface but its effect were not seen at the ground surface. This is evident in the case of Salapungan (BH 6) at magnitude 6.0 where the potential for liquefaction is not seen at the uppermost layer.

IV. Conclusion

Liquefaction potential index and liquefaction susceptibility plots of seven sites in Gerona, Tarlac were successfully computed and generated at varying earthquake magnitudes using MathCAD. At earthquake of magnitude 5.0, the vicinity of San Antonio (BH 7) is barely susceptible to liquefaction at a depth of about 1.5 to 3.0m from the ground surface. At earthquake of magnitude 6.0, all areas are moderately liquefiable except for Salapungan (BH 6) which is barely liquefiable while the vicinity of Apsayan (BH 3) is still not liquefiable. Lastly, at earthquake of magnitude 7.5, all areas near the test sites are found to be highly susceptible at a depth of 4.5m to 7.5m except for Apsayan (BH 3) which has moderate liquefaction potential.

Acknowledgment

This work was supported by Tarlac State University Research Office and the Municipal Government of Gerona. The author also wishes to thank the assistance of his colleagues and students.

References

[1] R. C. Torres, M. L. O. Paladio, R. S. Punongbayan, and R. A. Alonso, "Mapping of areas affected by liquefaction during the 16 July 1990 earthquake," *The July 16 Luzon Earthquake - A Technical Monograph*, pp. 43-46, 2001.

[2] A. F. Rauch, "EPOLLS: An empirical method for predicting surface displacements due to liquefaction-induced lateral spreading in earthquakes," Ph.D. dissertation, Dept. Civil Eng., Virginia Tech., Blacksburg, VA, 1997.

[3] M. A. A. Beroya and A. Aydin, "First-Level liquefaction hazard mapping of Laoag City, Northern Philippines," *Nat. Hazards*, vol. 43, pp. 415-430, June 2007.

[4] T. L. Holzer, S. Toprak, and M. J. Bennett, "Liquefaction potential index and seismic hazard mapping in the San Francisco bay area, California," presented at the 7th National Conference on Earthquake Engineering, Boston, USA, July 21-25, 2002.

[5] T. Iwasaki, K. Tokida, and F. Tatsuoka, "Soil liquefaction potential evaluation with use of the simplified procedure," in *Proc. 1st International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*, Missouri, 1981, pp. 209-214.

[6] A. Marton and T. C. Soon, "Short review on liquefaction susceptibility," *International Journal of Engineering Research and Applications*, vol. 2, no. 3, pp. 2115-2119, May-Jun 2012.

[7] R. B. Seed, *et al*, "Recent advances in soil liquefaction engineering: A unified and consistent framework," in *Proc. 26th Annual ASCE Los Angeles Geotechnical Spring Seminar, Keynote Presentation*, H.M.S. Queen Mary, Long Beach, California, April 30, 2003.

[8] T. D. Orourke and J. W. Pease, "Mapping liquefiable layer thickness for seismic hazard assessment," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 123, no. 1, 1997.

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