

## A DETERMINISTIC APPROACH OF GENERATING EARTHQUAKE LIQUEFACTION SEVERITY MAP OF MINDORO, PHILIPPINES

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**ABSTRACT:** An essential component in decision making for site planners is the availability of risk maps to various geological hazards. Liquefaction in particular can be devastating and impose disastrous damage to existing structures built in earthquake prone areas like the province of Mindoro. Through the aid of in situ data, a simplified method of evaluating earthquake induced liquefaction potential was carried out in this study. This is to address the difficulty and high cost necessary to carry out the development of a liquefaction risk map. Borehole data were collected from different locations in Mindoro and the earthquake liquefaction severity index in each location were calculated using deterministic approach. Results showed that different levels of liquefaction severity were obtained in various areas of Mindoro. There were locations exhibiting manifestations of surface liquefaction due to 7.1 Mw earthquake with a peak ground acceleration of 0.4g. The generated liquefaction severity maps can be utilized as baseline information in selecting appropriate geotechnical intervention for soil improvement and stabilization. Further, the indices can be used as additional dimension of evaluating the holistic reliability of existing engineering structures.

*Keywords: Borehole, Liquefaction, Liquefaction Severity Index, Risk Map*

### 1. INTRODUCTION

The Philippine Archipelago is located within the Pacific Ring of Fire. For this reason, the country is vulnerable to two natural hazards characteristic of this region that are significant to this study – earthquakes and soil liquefaction. Earthquakes, which is the shaking of the earth's surface due to the sudden release of energy in the lithosphere, often causes soil liquefaction. Soil liquefaction takes place when ground movements or earthquakes cause an increase in water pressure that turns the solid ground into a liquid-like state. The shaking of the ground disrupts the soil by increasing the spaces between grains, which in turn lessens soil cohesion, making the soil lose its bearing capacity or strength [1]. These disturbances in the ground lead to a significant problem for areas at risk for soil liquefaction - multi-story buildings and other infrastructures experience the sudden loss of support of the soil underneath it that may cause buildings to collapse. Owing to the Philippines' location in the Pacific Ring of Fire, a record number of earthquakes occurs almost every day in parts of the Philippines, but most are imperceptible tremors that people are entirely unaware of. Because of this, the impact and risks brought upon by soil liquefaction often have devastating results due to people being unaware that they are in risk zones.

There are a number of measures that can be done to lessen the impact and risk that this hazard can

incur to a community. This phenomenon can be mitigated, through soil stabilization and a number of ground improvement techniques. Such as accelerating the dissipation of pore water pressure by inducing radial drainage through sand or stone columns, inducing cohesion into the soils or jet-grouting which also increases the density and strength, injection of chemical additives, and liquefaction mapping through hazard indexing. There are several approaches on how to develop liquefaction map by means of: First, Probability of Liquefaction by Chen and Juang [2], Iwasaki et-al. Liquefaction Potential Index [3], Sonmez, Liquefaction severity index by Sonmez and Gokceoglu [4]. In this study, the approach of liquefaction severity index proposed by Sonmez and Gokceoglu will be used for probability and severity mapping. This introduces the probability of liquefaction equation by Juang et al. [2] based on the factor of safety to the liquefaction potential index concept. Rearranging the classification of liquefaction severity by considering Chen and Juang's probability of liquefaction classes based on  $P_L$  values [2]. For this research, the Mindoro province were evaluated for generation of the liquefaction severity map by considering earthquake scenario of Mw=7.1 based from the destructive 1994 Mindoro earthquake.

Mindoro in particular is the seventh largest island in the Philippines by land area with a total of 10,571 square kilometers and is prone to

Earthquakes [5]. Although there are models being developed to assess the structural health of buildings [6-8], no disaster mitigating methods due to earthquake liquefaction was carried out in the province. The absence of a liquefaction map might impose devastating impact on built environment resulting to damage to structures and intangible losses [9-13].

To address this, this study aims to develop earthquake liquefaction severity map to identify liquefaction prone areas and measure the severity of liquefaction when an earthquake of various magnitudes occurs in the province. The generated map can be utilized as baseline information to develop appropriate mitigation techniques to lessen the risk of earthquake liquefaction. A rapid and inexpensive assessment of the degree of liquefaction can be carried out in a timely and convenient approach with the aid of the generated maps.

## 2. EXPERIMENTAL PROGRAM

This presents the procedures that the researchers have undergone to achieve the objectives of this study. The data gathered from the geotechnical reports were used for the calculation of the factor of safety against liquefaction ( $F_L$ ) to the calculation of the probability of liquefaction ( $P_L$ ) and the liquefaction severity index (LSI) as shown in Fig. 1. These will be used to determine if the soil in the Province of Occidental Mindoro is liquefiable or not liquefiable using earthquake magnitude 7.1 and to determine the severity of liquefaction in each location.

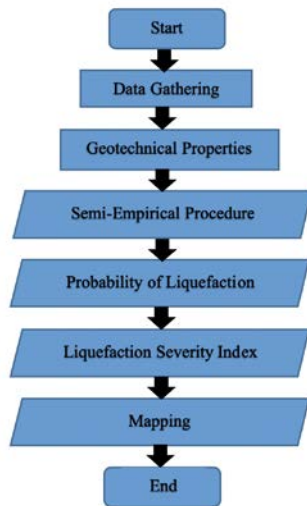


Fig. 1 Liquefaction Mapping Flowchart

A quantitative research that focused on computational techniques for the investigation with regards to liquefaction is used in this study. The geotechnical properties gathered from geotechnical

reports was tabulated in Microsoft Excel to obtain the vertical pressure, pore water pressure, effective pressure, and the factor of safety against liquefaction at every 1.5 m layer. The susceptibility of liquefaction was based on the factor of safety against liquefaction by Idriss and Boulanger [10]. The Probability of Liquefaction ( $P_L$ ) and the Severity of Liquefaction at each location was based on the Liquefaction Severity Index by Sonmez and Gokceoglu which uses  $P_L$  values by Chen and Juang.

The Probability of Liquefaction by Chen and Juang based on  $P_L$  values were considered in rearranging the classification of liquefaction severity [3]. An equation proposed by Juang et al. was introduced by Sonmez and Gokceoglu to overcome the use of linear relation for impact of the factor of safety on liquefaction potential. Table 1 shows the classification of the severity index by Sonmez and Gokceoglu.

Table 1 Liquefaction Severity Index Classification

Severity Index	Classification
$L_s = 0$	Non-Liquefiable
$0 < L_s < 15$	Very Low Liquefaction Severity
$15 < L_s < 35$	Low Liquefaction Severity
$35 < L_s < 65$	Medium Liquefaction Severity
$65 < L_s < 85$	High Liquefaction Severity
$85 < L_s < 100$	Very High Liquefaction Severity

$$FS = \frac{CRR_m}{CSR} \quad (1)$$

$$L_s = \int_0^{20} P_L(z) W(z) dz \quad (2)$$

$$P_L(z) = \frac{1}{1 + \left(\frac{F_L}{0.96}\right)^{4.5}} \text{ for } F_L \leq 1.411 \quad (3)$$

$$P_L(z) = 0 \text{ for } F_L > 1.411 \quad (4)$$

$$W(z) = 10 - 0.5z \text{ for } z < 20m \quad (5)$$

$$W(z) = 0 \text{ for } z > 20m \quad (6)$$

## 3. RESULTS AND DISCUSSION

### 3.1 Geotechnical Assessment

Considering the geotechnical properties of Occidental, Mindoro, this study analyzes the factors of safety against liquefaction ( $F_L$ ), the probability of liquefaction ( $P_L$ ) and corresponding liquefaction severity indices for an earthquake having magnitude 7.1. The number of borehole logs on each municipalities of Occidental Mindoro are shown in Fig. 2.



Fig. 2 Map of Occidental Mindoro

The data gathered from the Province of Occidental Mindoro was evaluated based from the water content, number of blows, N-values, and the depth of soil. The number of blows is the most dominant geotechnical characteristic because it affects the whole computation for Cyclic Resistance Ratio (CRR). The water content, specific gravity of soil and the depth of soil is important for computing the Vertical Pressure, Pore Water Pressure, and Effective Pressure which will contribute to the computation of the Cyclic Shear Ratio (CSR). The CSR and CRR values will help us obtain the factor of safety for each 1.5 m layer. Considering different factors needed in this study, a total of 73 boreholes were used as shown in Table 2. Based from the geotechnical report, the water content and n-values were used to solve the vertical pressure, pore water pressure, and effective pressure as shown in Table 3.

Table 2 Borehole Distribution in Occ. Mindoro

List of Municipalities	No. of Boreholes
Abra de Ilog	11
Calintaan	4
Magsaysay	9
Mamburao	12
Paluan	9
Rizal	1
Sablayan	13
San Jose	8
Sta. Cruz	6
Total No. of Boreholes	73

Table 3 Geotechnical Properties

DEPTH	WATER CONTENT	N-VALUE	VERTICAL PRESSURE	PORE WATER PRESSURE	EFFECTIVE PRESSURE
1.5	100	22	14.07	4.41	9.65
3.0	100	18	35.54	19.13	16.41
4.5	98	28	57.12	33.84	23.27
6.0	100	11	78.59	48.56	30.03
7.5	100	11	100.07	63.27	36.79
9.0	100	7	121.55	77.99	43.56
10.5	100	6	143.02	92.70	50.32

Based from the geotechnical report, the water content and n-values were used to solve the vertical pressure, pore water pressure, and effective pressure as shown in Table 3.

### 3.2 Semi-Empirical Procedure

A Semi-Empirical Procedure based on Idriss and Boulanger was used in this study to calculate the safety factor against liquefaction refer to Eq. (1). In determining the Factor of Safety, the values of the reduction factor ( $r_d$ ), Magnitude Scaling Factor (MSF), equivalent clean sand standard penetration resistance value ( $N_{1(60)CS}$ ), cyclic shear stress ratio (CSR), and cyclic resistance ratio (CRR) will be obtained as shown in Table 4. The soil is susceptible to liquefaction if  $FS \leq 1$  or otherwise, it is not susceptible to liquefaction if  $FS > 1$ .

Table 4 Result of Factor of Safety at Magnitude 7.1

DEPTH	CSR	CRR <sub>m</sub>	FS
1.5	2.51	1.41	0.56
3.0	3.73	0.27	0.07
4.5	4.23	0.49	0.12
6.0	4.51	0.13	0.03
7.5	4.68	0.12	0.03
9.0	4.80	0.10	0.02
10.5	4.89	0.09	0.02

The table above shows the result of the factor of safety at magnitude 7.1. This table shows that with an increasing depth the reduction factor decreases and as CSR is greater than that of CRR<sub>m</sub>, the value of the factor of safety against liquefaction is less than 1 and is identified as a liquefiable layer, or otherwise, a non-liquefiable layer.

### 3.3 Liquefaction Severity Index

The factor of safety against liquefaction can be used to calculate the probability of liquefaction and the liquefaction severity index refer to Eq. (2), (3), (4), (5), (6) and as shown in Table 5.

Table 5 LSI corresponding to Mw=7.1

DEPTH	Z	H	w(z)	P <sub>L</sub> (z)	LSI
1.5	0.75	1.50	9.63	0.13	1.81
3.0	2.25	1.50	8.88	0.73	9.65
4.5	3.75	1.50	8.13	0.60	7.31
6.0	5.25	1.50	7.38	0.87	9.66
7.5	6.75	1.50	6.63	0.88	8.79
9	8.25	1.50	5.88	0.91	8.02
10.5	9.75	1.50	5.13	0.92	7.05
$\sum LSI =$					52.29
Level of Liquefaction Severity: MODERATE					

### 3.4 Mapping

The probability of the soil to liquefy and the severity of liquefaction for each location was obtained in terms of LSI values of 9 municipalities having 73 boreholes around Occidental Mindoro.

The maps of LSI values were generated for the province to show the distribution of the probability and severity of liquefaction as shown in Fig. 3 and Fig. 4. The probability map and the severity map will help identify liquefaction prone areas and measure the severity of liquefaction when a 7.1 magnitude earthquake occurs in the province. The levels of severity as shown in Table 1. Abra De Ilog has 100% probability of liquefaction though the severity level varies from low to moderate, Calintaan has 0-28.88% probability of liquefaction and the severity level varies from very low to low, Magsaysay has 0.05-100% probability of liquefaction and the severity level varies from very low, low, and moderate, Mamburao has 0.42-100% probability of liquefaction and the severity level is moderate, Paluan has 9.02-99.91% probability of liquefaction and the severity level varies from low to moderate, Rizal has 89.24% probability of liquefaction and the severity level is moderate, Sablayan has 0-100% probability of liquefaction and the severity level varies from very low, low, and moderate, Sta. Cruz has 1.15-100% probability of liquefaction and the severity level is moderate, San Jose has 0.05-100% probability of liquefaction and the severity level varies from low to moderate. Based on the analysis, Abra De Ilog, Magsaysay, Mamburao, Paluan, Rizal, Sablayan, Sta. Cruz, and San Jose has high probability of liquefaction while Calintaan has low probability of liquefaction. Sablayan has the highest probability of liquefaction due to a smallest value of FS and as observed from the data, the least number of blows results to a smaller value of FS. Also, the effective pressure and depth of the soil affects the probability of liquefaction. The deeper the depth, the larger the pressure and at the same time has the least number of blows results to a higher probability of liquefaction as observed in the data. The factors that contributed to the level of liquefaction severity is the LSI value at every 1.5 m layer. The summation of all LSI values at each location results to the level of liquefaction severity.

As a result, the category of high to very high liquefaction severity were not observed for the earthquake scenario  $M_w=7.1$ . The factors that affects the severity of liquefaction are the depth of the midpoint of the soil layers, the thickness of the soil layer, and the probability of liquefaction. The higher the probability of liquefaction at a certain layer and the nearer it is to the ground results to a higher chance of having larger LSI values. Majority of the studied areas in the province are in moderate liquefaction severity as described by the LSI values. Furthermore, the severity of liquefaction in Occidental Mindoro ranges from very low to moderate liquefaction severity although it is susceptible to liquefaction. Municipalities with low chance of liquefaction is because of the not existing

ground water table at a depth of 10.5 m which means a dry soil in that certain depth and a shallow ground water table has very high chance to liquefy. It can be observed in the probability map that a high chance of liquefaction would likely to occur in some of the areas in Occidental Mindoro while it can be observed in the severity map that most of the areas is not that severe when liquefaction would occur during seismic events.

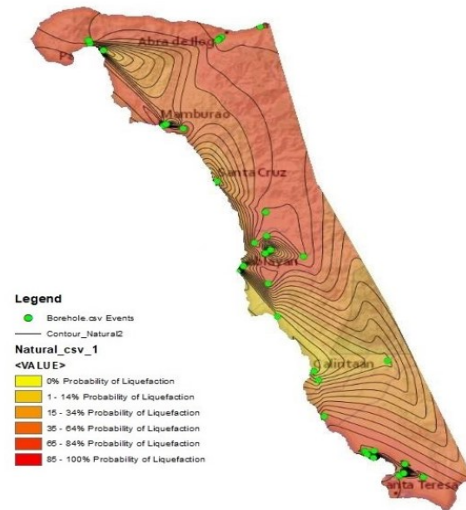


Fig. 3 Liquefaction Probability Map of Occidental Mindoro at EQ Magnitude 7.1

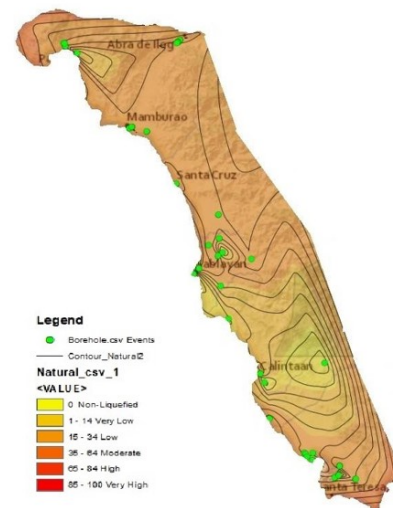


Fig. 4 Liquefaction Severity Map of Occidental Mindoro at EQ Magnitude 7.1

#### 4. CONCLUSION

The soil properties were investigated in the Province of Occidental Mindoro to show manifestation of soil liquefaction during seismic events. It was observed that majority of the municipalities have high degree to liquefaction as described by  $P_L$  values, and the severity of

liquefaction is not that severe in a 7.1 earthquake magnitude as described by LSI values. The Probability and Severity Map were able to provide a rapid and inexpensive assessment of the degree of liquefaction in a timely and convenient approach, which are essential to structural engineers in improving the safety matters of any structures to be built and developed in the Province of Occidental Mindoro.

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