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A study of a liquefaction hazard map on groundwater levels and various ground accelerations in the Republic of Korea

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ABSTRACT: The Pohang earthquake, that took place on November 15th, 2017, produced the first liquefaction phenomenon in the Republic of Korea. As a result, the liquefaction phenomenon had grained much focus and attention from the public through the events of the earthquake. In this study, an assessment was performed on the possible liquefaction of the ground in the event of an earthquake. In addition, the entire region of the Republic of Korea calculated the liquefaction potential index using the data of the average annual underground level and various bedrock peak ground acceleration levels with the Arc GIS. The results of this study showed that for ground acceleration of 0.18g or higher, there was a possibility of liquefaction in coastal areas such as Pohang, where liquefaction occurred. From these results, it is expected that the study on the preparation of liquefaction hazard maps will contribute to the preparation of countermeasures against liquefaction by predicting the possibility of liquefaction in the future.

1 GENERAL INSTRUCTIONS

1.1 *Introduction*

The earthquake that occurred on September 12th, 2016 at 8 km southwest of Gyeongju was the largest earthquake ever on the Korean Peninsula since the earthquake that was observed in 1978. The Pohang earthquake, which occurred on November 15th, 2017 at 9 km north of Pohang City, was the first earthquake in Korea to be detected in a region suspected of liquefaction phenomenon.

Economic measures and technical measures against natural disasters in the Republic of Korea concentrate on frequent typhoons, torrential downpours, floods etc, every year. However, due to the series of earthquakes, the government attention has recently been focused onto the earthquake's damage and liquefaction in the Korean Peninsula.

After the Hyogoken Nanbu earthquake (Kobe, 1995), a new academic society, which was EESK and a research center, which was KEERC was established in 1997. This prompted extensive earthquake engineering researches in Korea to analyze the seismic mechanisms and to establish seismic standards and guidelines. In the case of liquefaction studies, research on the proposal of liquefaction evaluation method is given priority. First, Kim et al. proposed this modified Seed and Idriss method which can select the maximum possible earthquake size of 6.5 in the Republic of Korea.

Based on this method, the first design guideline for liquefaction potential assessment was introduced in port and harbor seismic design guideline. Also, using this method, the several liquefaction hazard maps in port and harbor areas were drawn.

Recently, most countries have established and used a national earthquake hazard map for preparing a countermeasure. In 1999, the Technical Committee (TC4) Earthquake Geotechnical Engineering of ISSMGE has issued a revised manual on liquefaction hazard map with the Japanese Geotechnical Society. For countries like Korea who do not have enough data on earthquake damage, stage 3 method is recommended. When using the stage 3 method, it is common to use an index from the simplified method for liquefaction potential. Iwasaki et al. (1978)a 1978b suggested the standard index, liquefaction potential index (LPI).

In Korea, Kwak (2001) has created a liquefaction hazard micro-zonation around port facilities in coastal areas based on the LPIs. Ku (2010) used the site amplification coefficient of Eurocode8 (ECS, 1998) to evaluate the liquefaction risks. Kwak, Ku, and Choi (2015) recommended a reliable site amplification coefficient for mapping for liquefaction potential index. Baek and Choi(2018) have analyzed the liquefaction risk of Pohang using Arc GIS.

1.2 *Groundwater level*

The groundwater level is the depth from the earth surface to the groundwater table. There must be pore water in the ground for liquefaction to occur. Thus, in actual sites, liquefaction occurs in saturated sand or landfill below groundwater. Groundwater levels affecting the occurrence of liquefaction vary day by day with various meteorological and geographical requirements.

The groundwater level varies depending on various external factors, such as groundwater recharge by rainfall, artificial groundwater utilization, and changes in load acting on the indicator.

An increase in the groundwater level during rainfall is a direct factor that increases the pore water pressure and reduces the shear strength of the ground, thereby causing instability of the sloping ground. In result, when the groundwater level rises due to rainfall, the shearing strength of the ground is reduced, and the instability of the ground in the case of the occurrence of an earthquake is further enhanced.

Previous studies have evaluated the possibility of liquefaction in case of an earthquake for mostly in preparation for the dry season, and as a result, there has been a tendency to underestimate the possibility of liquefaction in case of an earthquake.

In order to compensate for these problems, this study mapped liquefaction hazard maps with various groundwater levels of 1m, 3m, and 5m to compare analysis to when the ground dried and to when the groundwater level rised due to rainfall.

2 LIQUEFACTION ASSESSMENT

LPI and LSN are representative indicators of liquefaction risk map. In the Republic of Korea, LPI index proposed by Iwasaki is used in consideration of general liquefaction assessment that estimates liquefaction safety factor. The LPI index is as Figure 1.

2.1 *Liquefaction assessment for micro-mapping*

In the seismic design for new construction, it is known that assessments of liquefaction potential must be performed. In Korea, a simplified method as shown below has been generally used. The characteristics of this method are to include the performance of the site response analysis. An equation to calculate shear stress ratio of an earthquake is shown below.

$$\frac{(\tau_d)\max}{\sigma_v'} = 0.65 \times \frac{a_{depth}}{g} \times \frac{\sigma_v}{\sigma_v'} \tag{1}$$

In the equation, a $_{\text{depth}}$ at a depth is an amplification acceleration obtained from site response analysis using Pro-Shake program. In addition, effective stress and total stress can

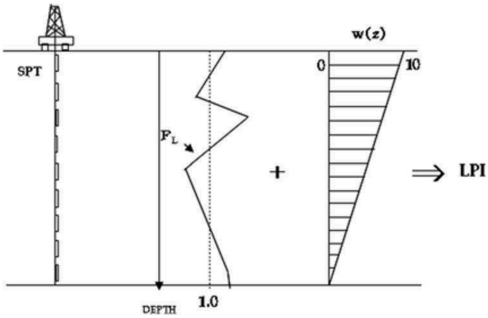

Figure 1. Calculation Method on a site.

be calculated with soil's dry or saturated unit weight. In the site response analysis, shear wave velocities in soils and several dynamic properties of soils are necessary as input parameters.

In the determination on liquefaction resistance strength ratio of soil, a result figure proposed by Seed and Idriss was used and its equation for calculation is as follows.

$$\frac{(\tau_r)}{\sigma_v{}'} = \frac{1}{34-(N1)_{60}} + \frac{(N1)_{60}}{135} + \frac{50}{\left[10(N1)_{60}+45\right]^2} - \frac{1}{2} \tag{2}$$

2.2 *Liquefaction assessment for macro mapping*

To draw macro liquefaction hazard map, a lot of LPIs data are necessary to be pointed on the map. If we choose the above conventional method including the site response analysis, the mapping time needed is too long. In this study, we introduced Euro-code method to reduce the time greatly. The characteristic of this method is to replace the site response analysis with the soil amplification factor. As a result, Eq(1) for shear stress ratio is changed as follows.

$$\frac{(\tau_d)\max}{\sigma_v{}'} = 0.65 \times \frac{a_{bedrock}}{g} \times S \times \frac{\sigma_v}{\sigma_v{}'} \tag{3}$$

In the equation, a $_{\text{bedrock}}$ is a design earthquake acceleration of Korean standard and S is soil amplification factor according to the soil type as shown below.

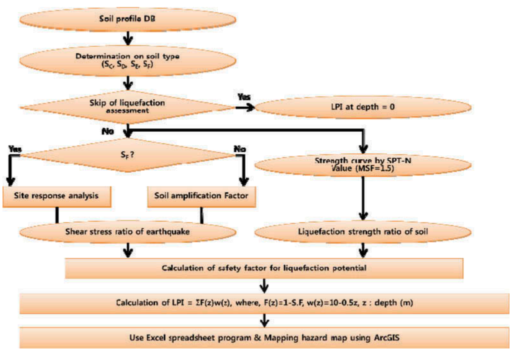

Figure 2. Calculation procedure of LPI for mapping.

N.O	HOLE_CODE	Soil type	γ_t Unit weight	Total stress	Underground Water Level	DEPTH_SPT	SPT_N	Driving Counts	hole_original_tm_x X-Coordinate	hole_original_tm_Y Y-Coordinate
1	B0001BH001		1.8	2.7	0	1.50	15	30	200708.34	422829.16
2	B0001BH001		1.8	5.4	0	3.00	29	30	200708.34	422829.16
3	B0001BH001		1.8	8.1	0	4.50	50	14	200708.34	422829.16
4	B0001BH001		1.8	10.8	0	6.00	50	10	200708.34	422829.16
5	B0001BH001		1.8	13.5	0	7.50	50	8	200708.34	422829.16
6	B0001BH001		1.8	16.2	0	9.00	50	6	200708.34	422829.16
7	B0001BH001		1.8	18.9	0	10.50	50	3	200708.34	422829.16
8	B0001BH001		1.8	Omission	0	30.00	51	4	200708.34	422829.16
9	B0001BH002		1.8	2.7	0	1.50	4	30	200721.09	422867.29
10	B0001BH002		1.8	5.4	0	3.00	50	24	200721.09	422867.29
11	B0001BH002		1.8	8.1	0	4.50	50	18	200721.09	422867.29
12	B0001BH002		1.8	10.8	0	6.00	50	14	200721.09	422867.29
13	B0001BH002		1.8	13.5	0	7.50	50	6	200721.09	422867.29
14	B0001BH002		1.8	16.2	0	9.00	50	7	200721.09	422867.29
15	B0001BH002		1.8	18.9	0	10.50	50	5	200721.09	422867.29
16	B0001BH002		1.8	21.6	0	12.00	50	5	200721.09	422867.29

Figure 3. Input site investigation data.

Table 1. The number of officially reported plague cases in the world.

Soil type	Site Classification	V_s (m/s)	Soil amplification	
			Korea	Euro-code
S_B	Hard Rock	>1500	-	-
S_B	Rock	>760	1.00	1.00
S_C	Very Dense Soil & Soft Rock	>360	1.18	1.14
S_D	Stiff Soil	>180	1.45	1.45
S_E	Soft Soil	≤ 180	2.00	2.00
S_F	Site Specific Analysis			

3 LPI MAPPING METHOD

Based on the above micro and macro methods for liquefaction evaluation, we proposed an analytical procedure for Korean liquefaction hazard map as shown in Figure 3. The Figure 3 mainly shows macro mapping method according to the soil classification.

In soil classification, shear wave velocity is the main criteria to determine the soil type in Figure 1. For example, most sites in Korea were classified with S_C and S_D.

3.1 *Site classification and shear stress ratio*

There are a lot of geotechnical information data stored in the Integrated DB Center for National Geotechnical Information. Thus, only necessary data were extracted. For this study, the data included borehole code, depth, N-value, and borehole location. However, while analyzing the data, the underground water level, and unit weight were missing, thus they were excluded. As a result, the unit weight was set as 1.8γt for all the sites. Figure 3 shows part of input data that needs to be entered into the spreadsheet.

Based on Figure 1 and the data entered as Figure 3, the spreadsheet calculates site classification using the stratigraphic thickness and the shear wave velocity obtained through the equation just as shown in Figure 4.

Once the soil type has been determined, the results go to the result sheet, and the existing geotechnical data changes as the macro automatically changes the location of the site. Here, the entries include 'site name', 'Amax/g', 'using equipment', and 'standard sampler'. Factors such as 'thickness', Vs, site classification, total stress, and overburden pressure are automatically calculated. Following Figure 5 shows the sample of input data and the results.

3.2 *Liquefaction resistance strength ratio and LPI*

Liquefaction resistance strength ratios at every depths for liquefaction evaluation are calculated by Eq(2). The calculated values are all at magnitude 7.5. Therefore, the magnitude

Thickness	Vs Acceleration	Vs*Thick	Process	Vs(avg)	Site Classification	Hole Counts	hole_original_tm_X X-Coordinate	hole_original_tm_Y Y-Coordinate
1.5	197.623	296.435	1					
1.5	258.443	387.664	2					
1.5	360.000	540.000	3					
1.5	360.000	540.000	4					
1.5	360.000	540.000	5					
1.5	360.000	540.000	6					
1.5	360.000	540.000	7					
19.5	760.000	14820.000	8	606.803	SC	1	200708.34	422829.16
1.5	115.400	173.100	1					
1.5	360.000	540.000	2					
1.5	360.000	540.000	3					
1.5	360.000	540.000	4					
1.5	360.000	540.000	5					
1.5	360.000	540.000	6					

Figure 4. Site classification and soil type.

SSR	SRR	MSF	Safety Factor(F)	Fz	Wz	Fz*Wz	Procces	LPI
0.449	0.109	0.164	0.365	0.635	9.250	5.877	5.877	5.877
0.449	Omission	Omission	Omission	Omission	8.500	Omission	Omission	
0.449	Omission	Omission	Omission	Omission	7.750	Omission	Omission	
0.449	Omission	Omission	Omission	Omission	7.000	Omission	Omission	
0.449	Omission	Omission	Omission	Omission	6.250	Omission	Omission	
0.449	Omission	Omission	Omission	Omission	5.500	Omission	Omission	
0.449	Omission	Omission	Omission	Omission	4.750	Omission	Omission	
Omission	0.049	0.074	Omission	Omission	-5.000	Omission	Omission	

Figure 5. Input data sample.

scaling factor (MSF=1.5) must be multiplied to calculate the final factor of safety. Finally, using the following equation, add all factors of safety at a site.

$$\mathrm{SF}_{Final(M=6.5)} = \left\{ \left(\frac{\tau_t}{\sigma_{v'}} \right)_{7.5} / \frac{(\tau_d)max}{\sigma_{v'}} \right\} \tag{4}$$

$$\mathrm{LPI} = \sum\nolimits^{F} (z) W(z) \tag{5}$$

(6)

Using the above equations, calculate an LPI at a site and arrange all data with the developed Macro excel sheet as shown in Figures 6 and 7.

Safety Factor For Liquefaction										
Hole number	1		Underground WL	0.0		Boring N.O			Altitude	
Location			x-coordinate	200708.340		y-coordinate	422829.160			
Closing day				amax/g	0.260	Inspector			Operator	
Hammer	Safety Hamm	Diameter	150	Length of rod	4.0	Sampler	Split spoon sampler			
Hole code	Depth	N-Value	Driving Counts	Thickness	Vs	Vs*Thick	Vs(avg)	Site Classification	Total Stress	Effective Stress
B0001BH001	1.5	15	30	1.5	197.623	296.435			2.70	1.20
B0001BH001	3.0	29	30	1.5	258.443	387.664			5.40	2.40
B0001BH001	4.5	50	14	1.5	360.000	540.000			8.10	3.60
B0001BH001	6.0	50	10	1.5	360.000	540.000			10.80	4.80
B0001BH001	7.5	50	8	1.5	360.000	540.000			13.50	6.00
B0001BH001	9.0	50	6	1.5	360.000	540.000			16.20	7.20
B0001BH001	10.5	50	3	1.5	360.000	540.000			18.90	8.40
B0001BH001	30.0	51	4	19.5	760.000	14820.000	606.803	SC	Omission	Omission

Figure 6. Calculation of LPI.

Hole_Code	N.o	LPI (Liquefaction Potential Index)									Coordinate of borehole	
		0.06g	0.10g	0.14g	0.18g	0.22g	0.26g	0.30g	0.34g	0.38g	X-coordinate	Y-coordinate
B0001BH001	1	0.00	0.48	2.99	4.38	5.26	5.88	6.33	6.67	6.94	200,708.340	422,829.160
B0001BH002	2	1.78	4.77	6.05	6.76	7.21	7.53	7.76	7.93	8.07	200,721.090	422,867.290
B0002BH001	4	2.71	8.52	11.02	12.40	13.28	13.89	14.34	14.68	14.95	206,587.895	417,422.018
B0002BH004	7	0.00	1.74	3.81	4.96	5.70	6.21	6.58	6.86	7.09	206,673.162	417,347.687
B0002BH005	8	0.00	3.31	4.94	5.84	6.41	6.81	7.10	7.33	7.50	206,701.575	417,334.466
B0002BH006	9	0.00	0.47	2.91	4.26	5.12	5.72	6.16	6.49	6.75	206,563.525	417,398.437
B0002BH015	16	0.00	0.00	0.61	2.48	3.66	4.48	5.09	5.55	5.91	206,666.432	417,291.817
B0002BH021	22	1.25	4.35	5.68	6.42	6.89	7.21	7.45	7.63	7.78	206,500.919	417,309.049
B0002BH022	23	1.25	4.43	8.09	10.13	11.42	12.32	12.98	13.48	13.88	206,512.434	417,263.298
B0002BH025	24	1.25	4.43	10.02	13.30	15.38	16.82	17.88	18.69	19.32	206,467.156	417,271.558
B0003BH001	25	0.00	0.03	2.59	4.02	4.92	5.55	6.01	6.36	6.64	207,264.056	418,366.166
B0003BH002	26	0.00	0.90	3.21	4.50	5.32	5.88	6.30	6.62	6.87	207,309.726	418,363.674
B0003BH004	28	0.00	0.00	1.95	3.52	4.52	5.21	5.71	6.10	6.40	207,295.918	418,387.745

Figure 7. Result of LPIs.

4 MACRO LIQUEFACTION HAZARD MAP

For liquefaction risks that can cover the whole Republic of Korea, we collected more than 120,000 borehole data information preferentially. Figure 8 shows the collected borehole data.

Finally, calculating liquefaction potential indexes was completed using more than 120,000 borehole data. Also, since the groundwater level changes depending on the amount of rainfall, three type of 1m, 3m and 5m liquefaction hazard map with the ground acceleration of 0.06g and 0.18g were drawn up.

According to the actual seismic situation of the Republic of Korea, the ground acceleration was set to 0.06g, which is similar to the repetition period of 500 years, and the ground acceleration of 0.18g, which corresponds to the ground acceleration 0.154g of the repetition period of 1000 years.

Figure 9 shows the hazard map of liquefaction of Korea at 0.06g ground acceleration at 1m, 3m, and 5m groundwater level. Figure 10 shows the hazard map of liquefaction of Korea at 0.18g ground acceleration at 1m, 3m, and 5m above groundwater level.

Figure 8. The geographical position of borehole data.

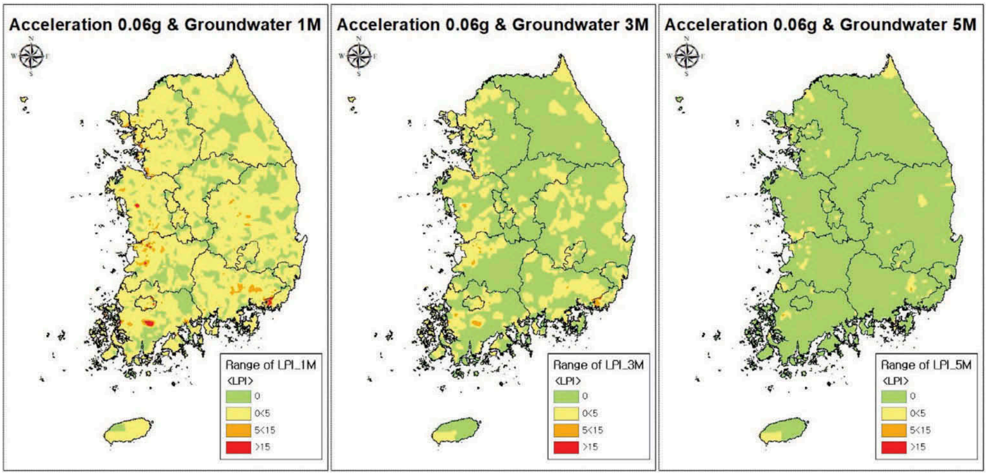

Figure 9. Liquefaction hazard map of the ground acceleration 0.06g of the Republic of Korea

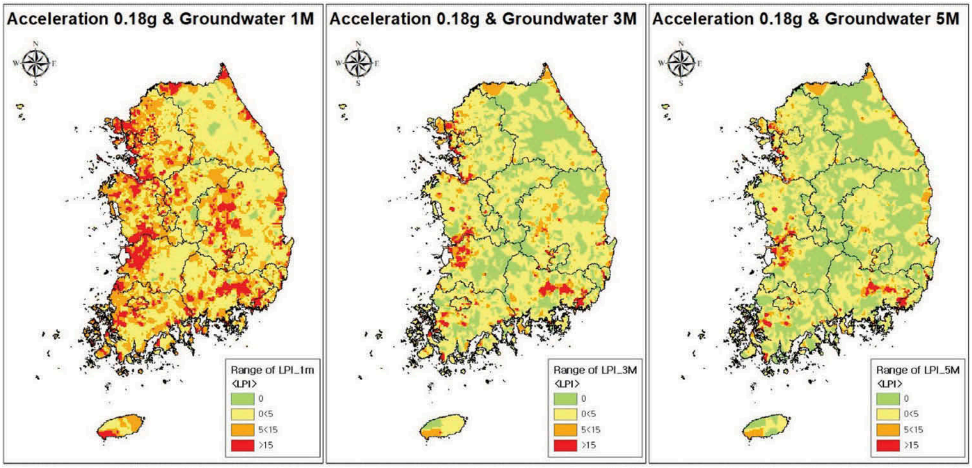

Figure 10. Liquefaction hazard map of the ground acceleration 0.18g of the Republic of Korea

5 CONCLUSIONS

In the case of rainfall, the shear strength of the ground is weakened due to the fluctuation on groundwater, and the possibility of liquefaction phenomenon will be changed accordingly. Even in the case of the same ground acceleration as can be understood in this research, if the groundwater level rises due to rain and the ground becomes saturated, the vulnerability of the liquefaction phenomenon grasped from the liquefaction map above is possible.

As a result of this study, it was found that the liquefaction phenomenon is closely related to the groundwater level. Through future research, a liquid hazard map based on seasonal liquid hazard map and change in groundwater level may be produced through continuous research to conduct a liquefaction risk analysis.

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