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GIS-Based Soil Liquefaction Hazard Zonation due to Earthquake Using Geotechnical Data

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ABSTRACT: Liquefaction is an earthquake ground failure mechanism that occurs in loose, saturated granular sediments and has caused extensive damage to the ground. Liquefaction potential zoning is the process of estimating the response of soil layers under earthquake excitations. Ground conditions play important roles in the prediction of hazards caused by earthquake. Thus to evaluate seismic hazards for a wide area, ground formation history along with soil properties must be known. This paper describes the ground conditions and behavior of Satte city as a result of Earthquake. In this paper, Geographical Information System (GIS) is used to obtain soil liquefaction hazard map. Spatial variations of soil properties are estimated from the available borehole locations where SPT –N values, water table depth and grain size distribution are known. These maps can be useful for assessing the approximate areas affected by hazards and for disaster prevention planning.

Keywords: Soil Liquefaction, GIS, PGA, Satte City.

1. INTRODUCTION

Soil liquefaction is one of the most devastating types of geological effects induced by earthquake. It is well recognized that numerous engineering structures have been severely damaged due to liquefaction of the supporting soils during earthquake.

Japan is situated in a seismically very active zone because of its location in marginal areas of the Pacific, Philippine Sea, North American, and Eurasian plates. This is why it is struck by frequent earthquakes. Past Earthquake history in Japan resembles it.

These frequent earthquake ultimately affect not only human being but also social, cultural and mostly financial status of the region. The 1964 Niigata earthquake and 1995 Kobe earthquake were the most destructive liquefaction effects observed in Japan [1]. However, at most recent March 11'2011 Gigantic Tohoku Pacific Earthquake was the strongest to hit Japan and one of the top five largest earthquakes in the world since seismological record-keeping began. It was followed by a tsunami with waves of up to 10 m. The disaster left thousands dead and inflicted extensive material damage to buildings and infrastructure that led to significant accidents at four major nuclear power stations and 4,460 people missing.

The Satte city of Saitama Prefecture is targeted as a case study in this paper. Saitama Prefecture has been affected by several destroying earthquakes of magnitudes greater than eight in the past times. The great Kanto Earthquake of magnitude 8.3 in 1923 hit this area which was the latest great one before March 11'2011 Gigantic Tohoku Pacific Earthquake. The great Kanto Earthquake devastated Tokyo, the port city of Yokohama, Surrounding prefectures of Saitama, Chiba, Kanagawa, and Shizuoka, and caused widespread damage throughout the Kanto region.
Among the various geomorphological units, the reclaimed land, drained land, river channel, lowland between sand dunes or bars, marginal part of sand dune, natural levee and banking area in swampy lowland are most susceptible to liquefaction [2]. From the Satte city geological map in Fig.4, it is observed that this city is built up in lowland area. Yellow color shows natural levee, an elongate embankment compounded of sand and silt and deposited along both banks of a river channel comprises some major area of the city. Moreover, river plain and old river plain consist of almost the rest of the city.

Around 50 borehole points of Satte city are considered for this research work. Borehole data analyses are done in Excel for different PGA and Liquefaction potential Index refer to (6) is found from Excel calculation at final stage. These values are given as input in GIS according to corresponding latitude and longitude of borehole points and liquefaction potential map are originated accordingly. Following that Geo-statistical analysis is being done for overall surface mapping of Satte area. Finally, the obtained liquefaction potential map is evaluated with geological map (Fig.4) and recent March 11'2011 Gigantic Tohoku Pacific Earthquake liquefaction history (Fig. 8).

1.1 Study area

According to April 1, 2011, the Satte city has an estimated population of 54,444 with household number is 21,449 and the density of 1,603.658 persons per km². The total area is 33.95 km². The city was founded on October 1, 1986. The city is located at 36°04′30″N and 139°43′45″E. Average altitude of the city is 9 meter. The city is almost downstream of Tone River. It is at Saitama prefecture in Kanto region and 43 km from Tokyo at N-W corner.
At March 11'2011 Gigantic Tohoku Pacific Earthquake, the highest PGA observed 3.0 g (USGS 2011) [3] in Japan. However, at Satte City of Saitama Prefecture, the observed PGA was 0.202 g [4]. In this paper, the liquefaction potential has been calculated for 0.202 g and 0.3 g PGA.

2 METHODOLOGY

Liquefaction potential for Satte city is evaluated by using the geotechnical data as type of soil, SPT N-value, depth of water table, mean grain size and unit weight of soil. These geotechnical data were collected from subsoil investigation reports (borehole log) as shown in Fig. 2. The borehole data in the study area were collected from different depths ranging from 10 m to 50 m below ground surface. However, in this study, borehole data parameters are considered up to 20m from ground surface. It is considered that no liquefaction effect on ground for soil properties below 20m depth.

According to [5], an ability to resist the liquefaction of a soil element at an arbitrary depth may be expressed by the liquefaction resistance factor (F_L) identified by the following equation

$$F_L = \frac{R}{L} \tag{1}$$

When the factor F_L at a certain soil is less than 1.0, we evaluated that the soil liquefies during earthquake.

In equation (1), R is the in situ resistance or undrained cyclic strength of a soil element to dynamic loads during earthquakes. The value of R is determined by the following equations based on mean particle diameter (D_{50}) as follows:

For 0.04mm$\leq$ $D_{50} \leq$0.6mm

$$R = 0.0882\sqrt{\frac{N}{\sigma v`+0.7}} + 0.225\log_{10}\frac{0.35}{D_{50}} \tag{2}$$

For 0.6 mm$\leq$ $D_{50} \leq$ 1.5 mm

$$\mathrm{R} = 0.0882\sqrt{\frac{N}{\sigma v`+0.7}} - 0.05 \tag{3}$$

Where N is the number of blows of the standard penetration test, $\sigma v`$ is the effective overburden pressure (in kgf/cm^2) and D_{50} is the mean particle diameter (in mm) illustrated in Table 1.

Due to seismic motion, the dynamic load induced in the soil element can be estimated by the following equation:

$$L = \frac{\Gamma_{\max}}{\sigma v`} = \frac{\alpha_{s\max}}{g}\frac{\sigma v}{\sigma v`} r_d \tag{4}$$

Where $\Gamma_{\max}$ is the maximum shear stress (in kgf/cm^2), $\alpha_{s\max}$ is the maximum acceleration at the ground surface (in gals), g is the acceleration due to gravity (=980 gals), σv is the total overburden pressure (in kgf/cm^2), and r_d is the reduction factor of dynamic shear stress to account for the deformation of the ground. Iwasaki et al. proposed the following equation of r_d from a number of seismic response analyses of the ground:

$$r_d = 1.0 - 0.015\mathrm{Z} \tag{5}$$

Where Z is the depth in meters.

It is evident that the damage to foundations of structure due to soil liquefaction is considerably affected by the severity of liquefaction. An index of liquefaction potential, P_L , can be introduced to express the severity of liquefaction as follows:

$$P_L = \int_0^{20} F \cdot W(Z)dZ \tag{6}$$

Where F = 1.0$-$ F_L for $F_L \leq$1.0, F= 0 for F_L > 1.0 and W (z) =10$-$0.5Z (Z in meters) demonstrated in Fig. (1). For the case of F_L = 0.0 for the entire range from Z= 0 to 20meters, P_L becomes 100, and for the case of $F_L \geq$1.0 for the entire range from Z= 0 to 20meters, P_L becomes 0.

Liquefaction potential sample Excel sheet is attached herewith in Table 2. Stress at every 1m is calculated based upon soil type and average density and the following overburden stress is calculated. Based upon the depth of water level from ground, pore water pressure is calculated and effective stress is found subtracting pore water pressure from overburden pressure. Subsequent that, reduction factor for dynamic shear stress r_d is considered based on depth according to (5). Afterward the in situ resistance of soil R is considered conferring (2) or (3) based on mean particle diameter attached in Table 1. In next step, dynamic load induced in the soil element by seismic motion, L is intended according to (4). Finally an ability to resist liquefaction F_L and Liquefaction potential index P_L is calculated according to (1) and (6) respectively.

The following guideline proposed by [5] is used to assess the liquefaction potential.

$P_L = 0$	: Liquefaction risk is very low
$0 < P_L \leq 5$	: Liquefaction risk is low
$5 < P_L \leq 15$	: Liquefaction risk is high
$15 < P_L$	: Liquefaction risk is very high

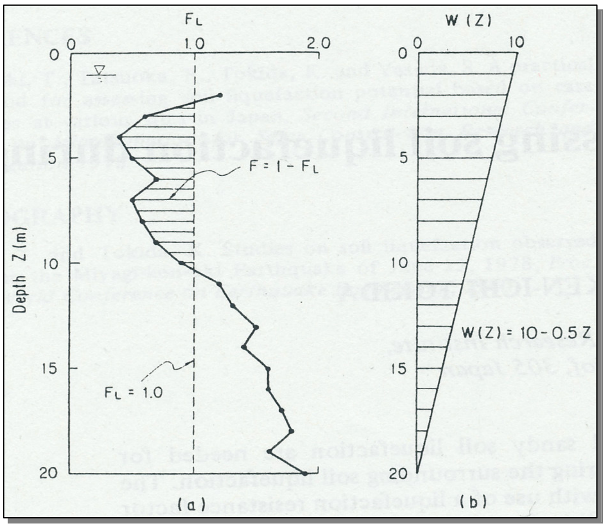

Fig. 1 Definition of F_L

Table 2 Liquefaction Potentuial Index calculation sheet

Table 1 Average values of the Unit Weights and Mean particle Diameters of Different Type of Soil.(This table was used only when these values were not tested) [5]

Soil Type	Unit Weight (t/m3)	Mean Particle Diameter, D_{50} (mm)
Surface soil	1.7	0.02
Silt	1.75	0.025
Sandy Silt	1.8	0.04
Silty Sand	1.8	0.07
Very fine Sand	1.85	0.1
Fine Sand	1.95	0.15
Medium Sand	2.0	0.35
Coarse Sand	2.0	0.6
Gravel	2.1	2.0

Depth(m)	Soil Type	Avg. Density	g	Stress,1m	Ovd. Pres.	D fr. WT	Pore Pres	Eff. stress	kgf/cm^2	N	rd	R	PGA	L	FL	IL
1.3	surface soil	1.7	9.8	16.66	21.658	0	0	21.658	0.21879	4	0.981	0.4637	300	0.3002	1.5449	0
2.3	silt	1.7	9.8	16.66	38.318	0.15	1.47	36.848	0.37224	1.7	0.966	0.368	300	0.3074	1.1972	0
3.3	sand and silt	1.7	9.8	16.66	54.978	1.15	11.27	43.708	0.44154	5	0.951	0.4425	300	0.366	1.2089	0
4.3	silt	1.7	9.8	16.66	71.638	2.15	21.07	50.568	0.51084	0	0.936	0.2579	300	0.4057	0.6356	2.8603
5.3	silt	1.6	9.8	15.68	87.318	3.15	30.87	56.448	0.57024	0	0.921	0.2579	300	0.4359	0.5916	3.0016
6.3	clayey silt	1.7	9.8	16.66	103.978	4.15	40.67	63.308	0.63954	0	0.906	0.2579	300	0.4553	0.5664	2.9699
7.3	clayey silt	1.7	9.8	16.66	120.638	5.15	50.47	70.168	0.70884	0	0.891	0.2579	300	0.4687	0.5502	2.8561
8.3	clayey silt	1.7	9.8	16.66	137.298	6.15	60.27	77.028	0.77814	0	0.876	0.2579	300	0.4777	0.5398	2.6921
9.3	clayey silt	1.7	9.8	16.66	153.958	7.15	70.07	83.888	0.84744	0	0.861	0.2579	300	0.4834	0.5334	2.4962
10.3	sandy silt	1.7	9.8	16.66	170.618	8.15	79.87	90.748	0.91674	0	0.846	0.212	300	0.4866	0.4356	2.7376
11.3	sandy silt	1.7	9.8	16.66	187.278	9.15	89.67	97.608	0.98604	0	0.831	0.212	300	0.4878	0.4345	2.4599
12.3	sandy silt	1.7	9.8	16.66	203.938	10.15	99.47	104.468	1.05534	0	0.816	0.212	300	0.4873	0.4349	2.1756
13.3	sandy silt	1.7	9.8	16.66	220.598	11.15	109.27	111.328	1.12464	0	0.801	0.212	300	0.4856	0.4365	1.8877
14.3	sandy silt	1.7	9.8	16.66	237.258	12.15	119.07	118.188	1.19394	0	0.786	0.212	300	0.4827	0.4391	1.5986
15.3	sandy silt	1.7	9.8	16.66	253.918	13.15	128.87	125.048	1.26323	0	0.771	0.212	300	0.4789	0.4425	1.31
16.3	silt	1.7	9.8	16.66	270.578	14.15	138.67	131.908	1.33253	0	0.756	0.2579	300	0.4744	0.5436	0.8444
17.3	silt	1.7	9.8	16.66	287.238	15.15	148.47	138.768	1.40183	0	0.741	0.2579	300	0.4692	0.5496	0.608
18.3	silt	1.7	9.8	16.66	303.898	16.15	158.27	145.628	1.47113	0	0.726	0.2579	300	0.4635	0.5564	0.377
19.3	silt	1.7	9.8	16.66	320.558	17.15	168.07	152.488	1.54043	0	0.711	0.2579	300	0.4572	0.564	0.1526
20	silt	1.7	9.8	16.66	337.218	17.85	174.93	162.288	1.63943	0	0.7	0.2579	300	0.4453	0.5792	0
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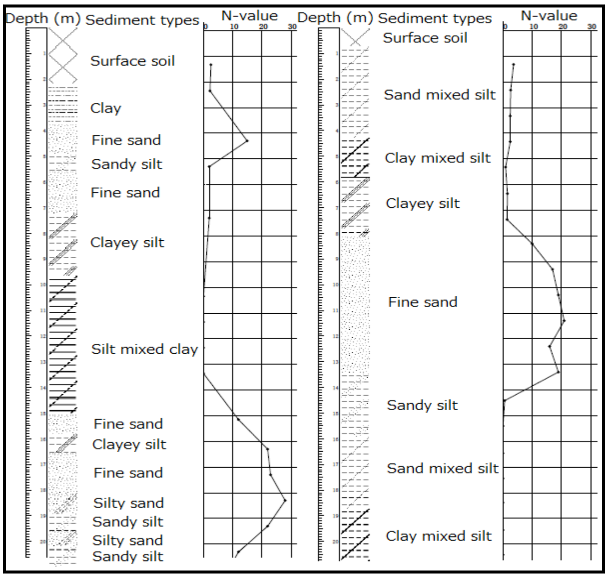

Fig. 2 Typical borehole log of Satte city

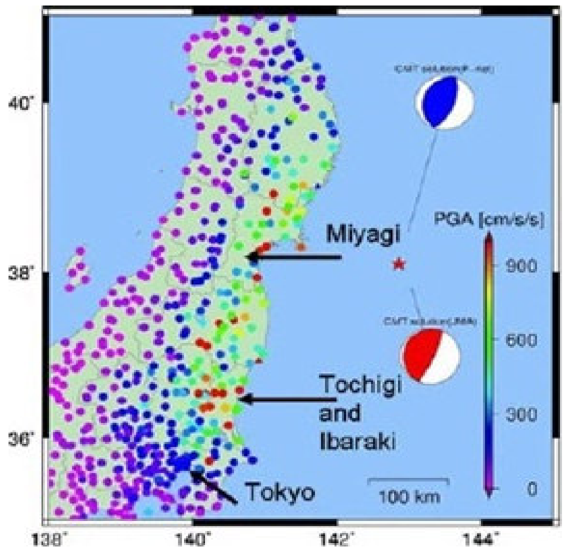

Fig. 3 Distribution of PGA provided by NIED, ERI (The University of Tokyo), AIST, and PARI

3 DATA ANALYSIS AND RESULT

The distribution of peak ground acceleration (PGA) in Fig. 3 implies that the rupture process during the earthquake was not uniform, and contained several asperities radiating strong ground motions. Another point to note is that Tokyo and its surrounding area near the bottom of the Fig. 3 were subjected to strong shaking. Therefore, damage occurred at many places therein. Moreover, according to latitude and longitude of Satte city (36°04′30″N and 139°43′45″E), it is observed that Satte city faces 202 gal of PGA (Fig. 3) during the recent March 11’2011 Gigantic Tohoku Pacific Earthquake.

As a case study, 202 gal PGA corresponding to 2011 Tohoku earthquake is used to assess P_L. Borehole P_L vaues are incorporated in GIS and it is observed that all the borehole points show medium to high risk of liquefaction values ranges from 5 to 38 as shown in Fig. 5& 6. Satte and Kuki city sites are visited just after the March 11’2011 Gigantic Tohoku Pacific Earthquake. Sand boiling through the ground and paved road, house and electric post tilting, manholes coming up the ground are the consequences of liquefaction which match with the analysis. From geological map (Fig. 4), the geomorphological units as shallow valley, river plain and back marsh are more susceptible to liquefaction which is similar to analysis result shown in Fig. 6. Moreover, Seismic Damage and Liquefaction history at March 11’2011 Tohoku Pacific Earthquake attached in Fig. 8 evaluates high to very high risk of liquefaction.

3.1 Ordinary Kriging Method of Interpolation

To find out the liquefaction potential in the zones where borehole data is not available, special statistical analysis is being done. To perform this, Geo-statistical Analyst tool is installed in GIS as an extension. Geo-statistics is intimately related to interpolation methods, but extends far beyond simple interpolation problems to prepare a continuous map [6]. Interpolation is an estimation of a variable at an unmeasured location from observed values at surrounding locations.

In this study a Kriging method of interpolation is used to interpolate the liquefaction potential. This method of interpolation is a geo-statistical technique that considers both the distance and the degree of variation among known data points when estimating values are in unknown areas. Kriging assumes that the distance or direction between sample points reflects a special correlation that can be used to explain variation in the surface. It is a technique of making optimal, unbiased estimates of regionalized variables at un-sampled locations using the structural properties of the semi-variogram and the initial set of data values [7]. It attempts to minimize the error variance and set the mean of the prediction errors to zero so that there is no over or under estimations.

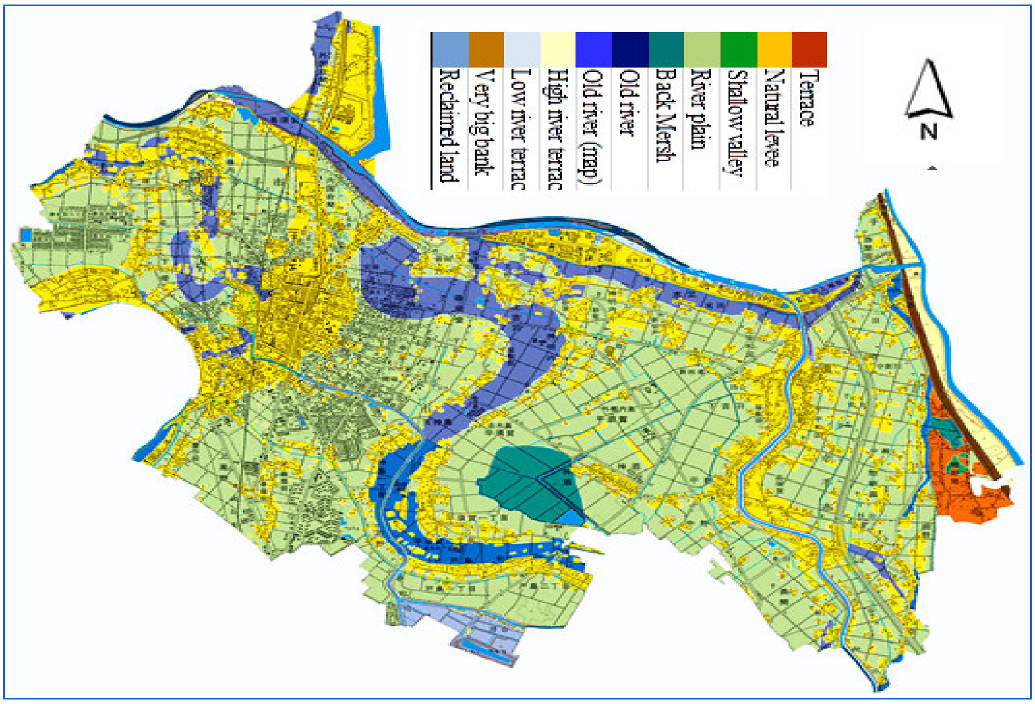

Fig. 4 Satte city Geological map

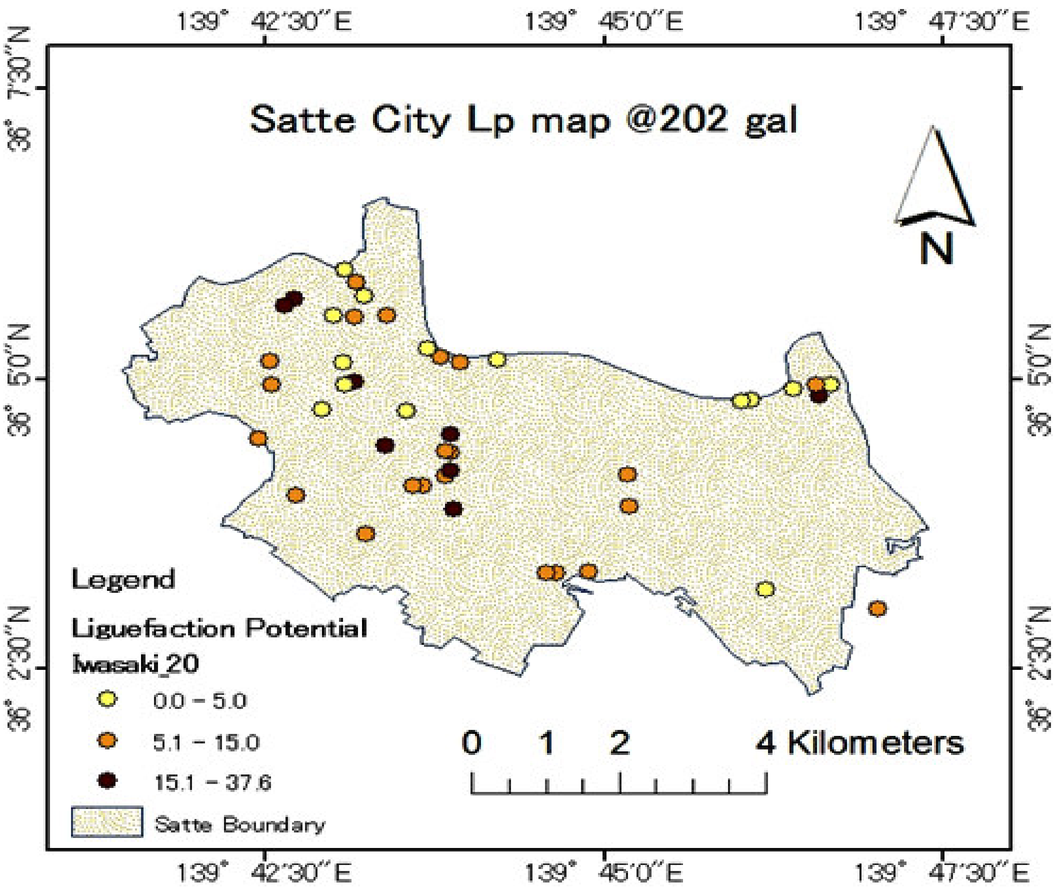

Fig. 5 Satte city Lp Borehole map for 202 gal

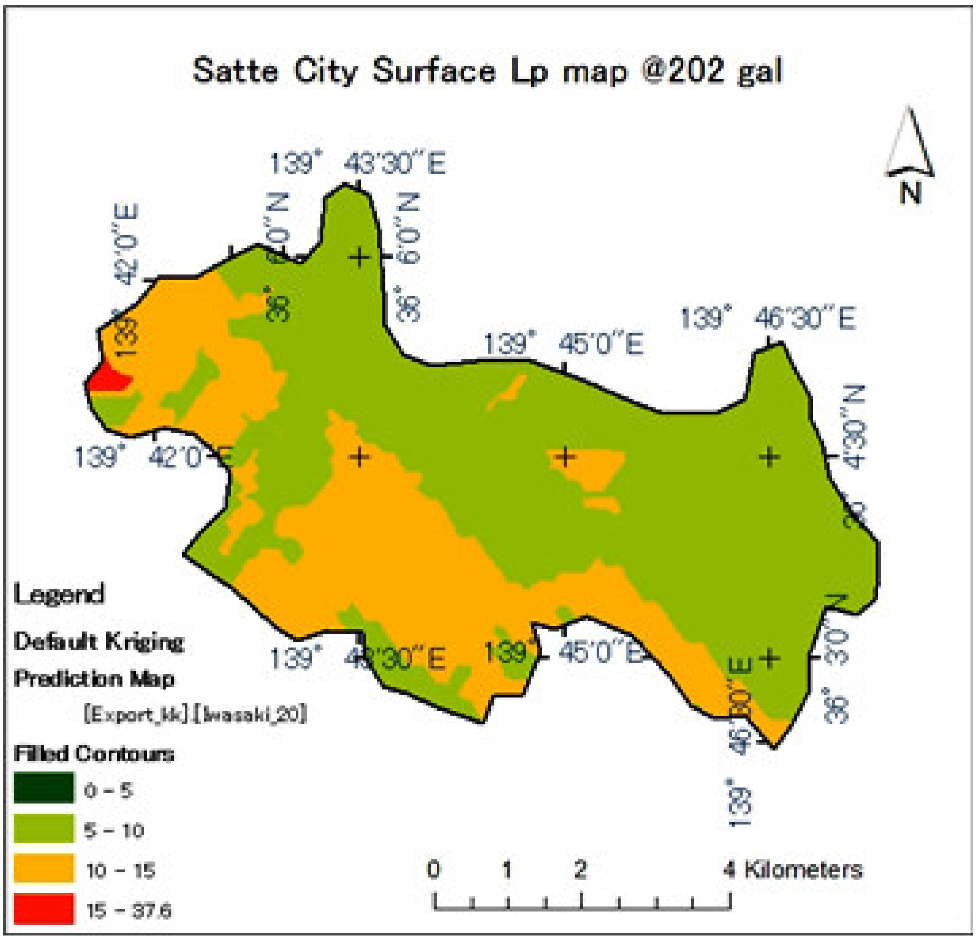

Fig. 6 Satte city Lp Surface map using ordinary Kriging interpolation for 202 gal

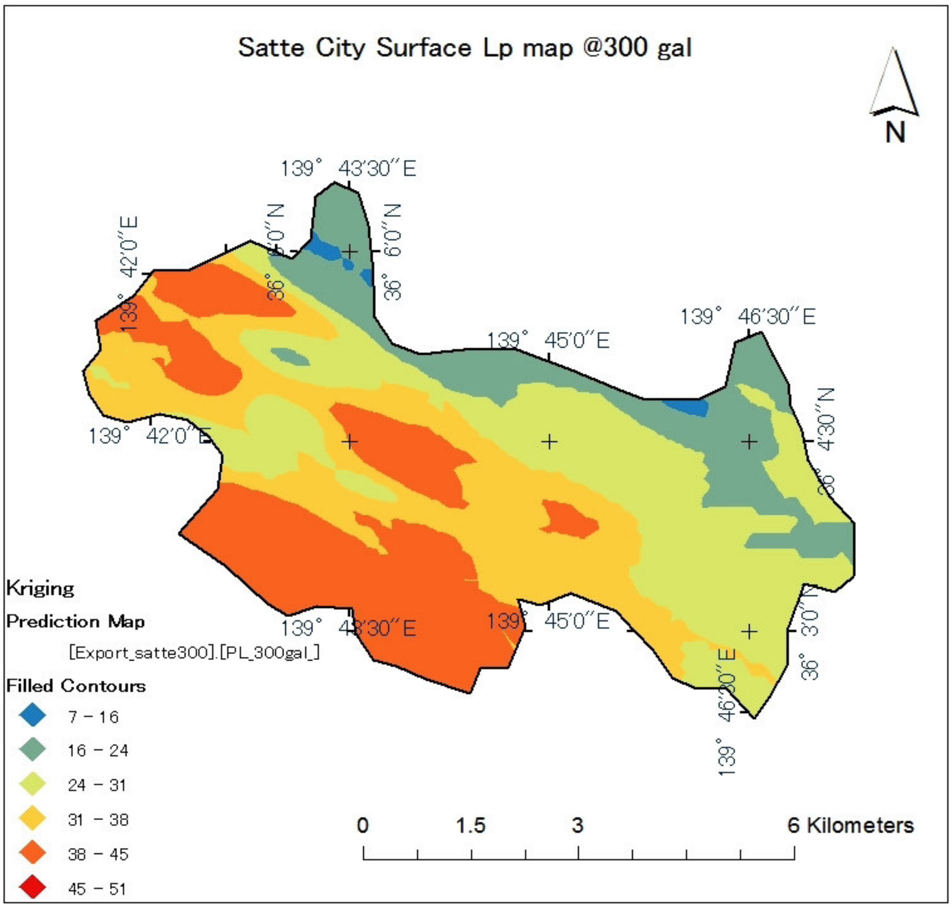

Fig. 7 Satte city Lp Surface map using ordinary Kriging interpolation for 300 gal

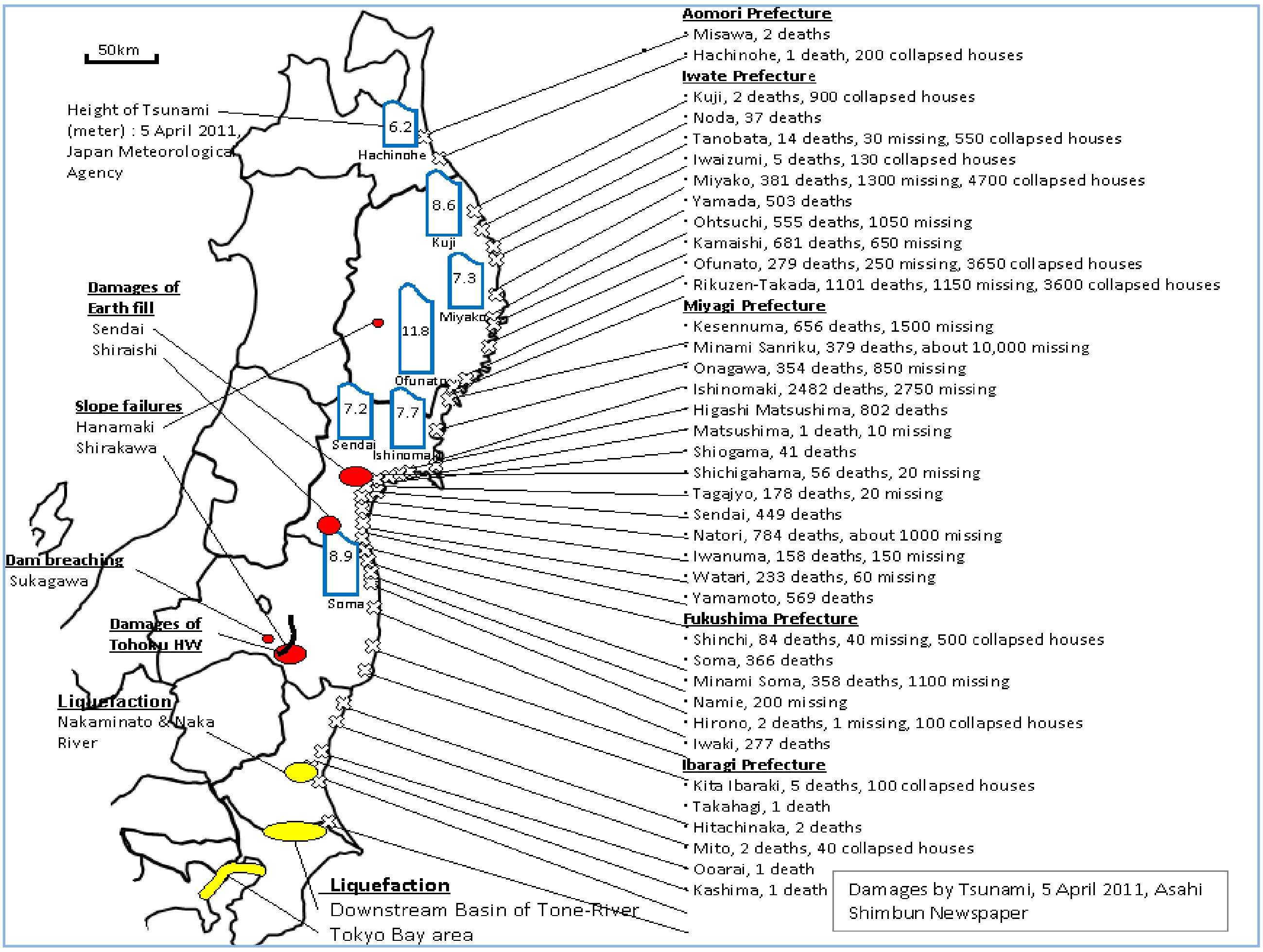

Fig. 8: Damage by Tohoku earthquake associated with tsunami

4 CONCLUSION

Geotechnical problems are made up of liquefaction in foundations and associated ground deformations. Due to damage effect, the post-earthquake response and restoration works have been made difficult and delayed. This is because liquefaction hazard map is necessary for land use development. In this paper, around 50 borehole data are analyzed to draw liquefaction potential map for Satte city.

In case of 202 gal PGA which represents March’2011 Tohoku earthquake, the borehole points display medium to high risk of liquefaction. The borehole P_L values in Fig.5 display the values as well as color to visualize severity. After applying Kriging method of interpolation, continuous liquefaction potential map is produced as Fig. 6. Severity of the Liquefaction hazard map coincides with the geological map and liquefaction history of March’2011 earthquake (Fig. 8).This continuous P_L map is very useful to interpret the approximate areas affected by liquefaction.

Whereas for 300 Gal PGA, the borehole points display high to very high risk of liquefaction. Fig. 7 shows that the south west part of the city shows more likely to liquefaction. It shows that severity of damage increases with increase in P_L value. It means more the PGA value, increase the P_L value. Interpolated result depends on number and distribution of sampled data. More the number of sampled data increase the effectiveness of interpolation.

Water level also plays an important role for liquefaction. The ground where the water level is so close, it’s likely to be liquefied more.

These features have not been considered in the conventional design philosophy and should be discussed from now on for infrastructure development.

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6 REFERENCES

[1] Pokhrel, R.M., Kuwano, J., Tachibana,S., “Liquefaction hazard zonation mapping of the Saitama City, Japan,” Journal of Nepal Geotechnical Society, vol. 40, 2010, pp. 69-76.

[2] Kotoda, K., Wakamatsu, K., and Oya, M., “Mapping Liquefaction Potential based on Geomorphological land classification,” in Proceedings of Ninth World Conference on Earthquake Engineering, August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol. III).

[3] http://earthquake.usgs.gov/earthquakes/eqinthenews/2011/usc0001

[4] Towhata et al., “Earthquake News on Gigantic Tohoku Pacific Earthquake in Japan,”April’2011, ISSMGE Bulletin, Volume 5, 2011, Issue2, pp. 46-66.

[5] Iwasaki, T., Arakawa, T., Todika, K., “Simplified Procedure for assessing Soil Liquefaction during Earthquakes,” in Proc. International Conference on Soil Dynamics and Earthquake Engineering, 1981.

[6] ISSMGE/TC4.1999. “Manual for Zonation on Seismic Geotechnical Hazards,” Technical Committee for Earthquake Geotechnical Engineering TC4, ISSMGE, Japanese Society of Soil Mechanics.

[7] David, M. 1977. Geo-statistical ore reserve estimation. Amsterdam: Elsevier

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