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Evaluation of Soil Swelling and Liquefaction Potential Using a GIS Software: a Case Study of Tabriz, Iran

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Abstract

Worldwide research on inflation and soil liquefaction is in nowadays a hot cake. Critical issues on soil liquefaction can cause irreparable effects to surface and undersurface installation the results which could be easily realized through the accidents like, derailment of rail, distortion in the roads, bend building, damage to the pipelines and an even close cross-section of the tunnel and reversal structures. Thus maintaining some specific patterns is always felt necessary to identify such points to avoid these destructive phenomena, and the structures would remain safe in coming future from vulnerabilities of hazards. We aimed this study to forward some guidance to identify and modifies regions having critical issues relating to the high liquefaction. From 50 excavated bores, total standard influence numbers and the Atterberg limits at different depth have been calculated. Further, by using of Arc GIS application, geostatistics analysis tool and by using of interpolation Kriging method, zoning maps of liquefaction and critical situation have been estimated. The obtained results hope to be useful in future plans to decrease the relevant accidents.

Introduction:

Liquefaction is a phenomenon where a saturated soil which is under severe stresses, completely loses its strength and stiffness and behaves like a liquid. This stress could be an outcome of earthquakes or sudden changes in soil conditions. If the water pore pressure would be high enough to exceed the ability of soil grains to withstand the load, then the soil grains would get separated by water and soil status become like liquated sand. This phenomenon has been seen more in saturated soils, loose (low-density or non-compacted soils) and sandy soil. Loose sand tends to be compacted under these loads, but compacted sand tends to increase in volume under such conditions (Bengt, 1993). If the soil would be saturated with water; conditions such as groundwater or soil below the sea level, then the water fills the space between the solid particles (pore space). If a pressure would be applied to the soil, the water pressure will increase in these spaces. In contrast, water tends to get out of the pore spaces and flow to where the pressure would be less (usually water moves up the ground or upward). However, if this pressure comes fast and big enough or repeatedly in large numbers (like earthquake

condition or a pressure from the hurricane) so that water cannot find enough time to exit until the next round (next cycle) then by the result of this pressure, grains from the soil flows out. Indeed the contact between soil grains is the only way to transmit the weight of the building and its layers to the lower layers of soil or bedrock at a higher depth.

However, when soil loses its structure and contacts between solids then the whole profile of soil would not show any resistance (Abdullah *et al.*, 1999). Some expansive soils are that soils which may encounter a significant increase in volume as a result of the moisture content changes. The best description of this phenomenon is the physical and chemical reactions in between the soil and its environment and the amount of swelling depends on the severity of the reactions in between the physical and chemical forces of attraction and repulsion (Sridharan & Gurtug, 2004). Changes in moisture content due to seasonal changes in weather or some other artificial factors, alter the mechanical properties of the soils, especially on the clay soils. The degree of swelling depends on the activity of the minerals

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of clay soil. Pre-consolidated clays, Quaternary and Tertiary sedimentary layers, basalt and weathered shales, are the known components of the expansive soils. Expansive soil can be found in most parts of the world such as Argentina, Spain, Australia, America, Iran, Turkey, Palestine, Canada, and India (Kramer, 1996). In the Iranian provinces of Khuzestan, Fars, Kerman, Yazd, and parts of Khorasan, this type of clay exists more than any other place of the world (Seed *et al.*, 1962).

By keeping in mind that Iran is located in the earthquake-prone belt of Alpine - Himalayan, it can be said that earthquakes are the most destructive natural disasters in this country. The destructive effects of natural disasters such as earthquakes, floods, and slope movements such as avalanches, rock fall, and landslide in all regions of the world have catastrophic results in the destruction of human settlements pose. The destructive effects of natural phenomena in the developing countries are more vulnerable compared to developed nations. In the case of soil swelling, it can be said that change in soil moisture content can change the volume of the soil, especially those in arid and semi-arid climatic zones (Williams & Donaldson, 1980). Change of soil volume can cause damage to the road pavement, rails, and building. For example, damage caused by soil swelling in America is about seven billion dollars annually which is nearly the double of the damages caused by floods, storms, and earthquakes (Kramer, 1996).

For soil swelling and liquefaction assessment, a detailed report of subsurface explorations and geotechnical field with laboratory tests are required in addition to the earlier reports. The liquefaction potential estimation method comprises the following steps:

- Estimation of soil resistance against liquefaction.
- Estimation of the maximum or equivalent shear stress cycle by the earthquake which is likely to occur in the soil.
- Potential estimation of liquefaction based on information about deposits Resistance against the liquefaction may be calculated based on vitro tests on intact samples such as cyclic triaxial shear tests and field tests such as SPT (standard penetration test) and CPT (dynamic penetration test), which are usually in use today (Youd & Hoose, 1977).

Excellent restructuring of undisturbed samples and laboratory testing are the most accurate evaluation process for prediction of periodic resistance of sand. However, obtaining samples of sand from the aquifer sediments is an expensive task and could be recommended only for the administrative project. Therefore it is important to make the process easier and economically and also it is better to consider a viable alternative for determining the resistance of sand. During the last three decades a method called "simplified procedure" was

randomly used to evaluate the potential of soil liquefaction. It was founded by Seed & Idriss (1971) and also was corrected over the time according to the information about the previous earthquakes (Youd & Idriss, 2001; BSSC, 2003). In this study, the amount of the maximum ground acceleration was 0.3g ($a_{max} = 0.3g$). Based on earthquakes occurred in the region and regulations for the 2800 earthquake code, it was assumed that the magnitude of a probable earthquake is 7.5 Richter. In general, the philosophy of soil liquefaction assessment is presented in five sections (Joyner & Boore, 1981).

The prescribed formula has been used for:

- Calculation and correction of standard penetration test number (Fardis *et al.*, 2005).
- Soil mass cyclic shear stress ratio (CSR) (ASCE, 1922) followed by Idriss (1999).
- Cyclic shear strength of the soil mass and its correction (CRR) (Burrough, 1986).
- Factor of safety (Fs) (BSSC, 2004).
- Liquefaction index (PL) (Joyner & Boore, 1981).

There are several ways to evaluate the potential of soil swelling, but the "Plastic Index" method to evaluate the potential for swelling gives the better results (Soroohan & Ryabova, 1988). The relationship between soil plasticity index and the index of swelling is mentioned below:

Table-1: Relation between swelling potential and plasticity index

Plasticity index	Swelling Potential
0 to 15	low
15 to 30	medium
30 to 45	high
More than 45	Very high

Earthquake vibrations or dynamic loads cause liquefaction in loose saturated granular soils the most important reason for this phenomenon is the occurrence of delay in drainage procedure and sudden increase in water pore pressure. The major common methods to deal with such situation are as follow (Bengt, 1993):

- Excavation and replacement of soils susceptible to liquefaction.
- Drainage.
- Changing the nature of the soil by injection.
- Densification of the available soil.

One method to deal with soil swelling is soil stabilization with lime which will improve soil geotechnical properties for a specific purpose. The use of lime improves the strength properties. Reaction with lime for soil stabilization achieves high strength more than the reaction of the cement. Use of lime for swelling soil stabilization occurs for three reasons:

- 1) Strong calcium ions will be exchanged with sodium ions in limestone or clay.
- 2) Using lime soil, the texture becomes scattered;

3) Swelling soil would be replaced with lime.

Percentage of lime should be determined by testing, but it is about 2 to 8 percent. It is worth on using the lime, liquid limit and plasticity index with decrease and finally plastic characteristics will be improved (Oates, 2008).

Methodology:

Study area: Tabriz is one of the major cities in Iran and the capital of East Azerbaijan province. The city is a largest economic center in the northwestern area of Iran and is known as administrative, communication, commercial, political, and cultural center in the northwest of Iran. Tabriz experiences devastating earthquakes and thus there is always a probability for another big earthquake in this region which is the purpose we have to evaluate the liquefaction and also soil swelling potential in the area of this city. For this purpose, SPT test data and Atterberg Limit experiments which were conducted by Padir company for 50 drilled holes were used. The following image (Fig.-1) shows the exact location of each borehole. Table-3, shows the initial data for each borehole.

Figure 1: Location of bore holes around the city
(The map is prepared by Padir. Company).

Following the figure and table, the average number of SPT (NSPT) in three depth ranges of 0 to 7 meters, 7 to 14 meters and 14 to 20 meters was calculated. The reason for choosing of the aforementioned values is that the phenomenon of liquefaction is probably only up to a maximum depth of 20 meters. In addition, the mean values of plastic and liquid limits were calculated in depth range of 0 to 10. According to a previous sentence, the reason for choosing this value was this fact that soil swelling is only probably up to a depth of 10 meters.

In order to evaluate the potential of soil liquefaction and swelling, standard penetration test data, liquid limit and the plastic limit is mandatory. However, using the available empirical relationships, swelling and liquefaction potential were calculated and then the same was compared with the standard values. In this study, the potential of liquefaction and soil swelling was calculated through liquefaction index (PL) and swelling index (S).

The calculated values of liquefaction and soil swelling potential can be seen in Table-4. In order to have a better understanding of the situation in the drilled boreholes, the calculated values of swelling and the liquefaction potential have been compared with standard values (Table 1 & 2).

For Zoning maps of liquefaction and soil swelling an introduction to the ArcGIS software and Geostatistical analyzer tool was employed. ArcGIS is comprehensive software for design and management of solutions, this software is based on knowledge of geography. This software able to perform in-depth analysis, to gain a greater understanding of their data and make more informed decisions at high levels. ArcGIS software makes it simple to conduct a geographical analysis, without the need for GIS expertise. The most important aspects of this version (10.2) is that the users of ArcGIS can be a source of GIS, maps, pictures, location information, and tools, as a web service access. Sample points provide height, depth or have pollution levels. Geostatistical modeling of spatial analysis can also be used in various applications such as Spatial Information System. One advantage of the tools and methods is that the sample points are mostly fitted to the model surface. In this study, we used ArcGIS software and the geostatistical analyzer to produce zoning map of liquefaction and soil swelling potential. (Hengl *et al.*, 2004; Johnson & Wichern, 1992).

Results:

In the previous part of the research, quantities needed for liquefaction and soil swelling assessment were provided (Kramer, 1996). Then, after a brief introduction of the ArcGIS software and its capabilities in the preparation of zoning maps, now, it is time to produce the zoning maps. Kriging interpolation method used for this purpose. At first step of zoning process, all tables and maps has been introduced by Arc Catalog module. Then in Arc MAP module maps and tables have been added. Using the Geo-statistical Analyzer tool and choosing Kriging interpolation method the liquefaction and soil swelling zoning maps has been produced. The left side of each map is also given instructions that can be compared with standard values (Table 1 & 2). Zoning maps are shown in Figures 2 to 5.

Table-2: Classification of liquefaction potential

PL	Liquefaction Hazard and Measures needed
0	Liquefaction risk is very low and generally do not feel the need to research more accurate
0 to 5	Liquefaction risk is low and needs more detailed studies.
5 to 15	Liquefaction hazard is moderate, recommended research and corrective methods are necessary.
>15	High liquefaction hazard and it is important to do more detailed studies and appropriate methods should be adopted.

Figure-2: zoning map of soil swelling

Figure-3: zoning map of liquefaction in the depth range of 0-7 meters

Figure-4: zoning map of liquefaction in the depth range of 7-14 meters

Figure-5: zoning map of liquefaction in the depth range of 14-20 meters

Table-3: Characteristics of all boreholes

Bore Hole	Latitude	Longitude	NSPT (0-7)	NSPT (7-14)	NSPT (14-20)	PL	LL
BH1	610995	4215346	12	20	22	43	31
BH2	615103	4216043	14	35	80	41	17
BH3	614066	4217176	106	110	100	39	18
BH4	611586	4217437	18	28	65	45	22
BH5	621296	4212480	31	70	100	63	33
BH6	620495	4214579	14	15	45	49	27
BH7	617807	4215510	55	140	100	69	37
BH8	618664	4213798	40	50	75	26	13
BH9	617860	4211419	30	75	90	57	35
BH10	615414	4211862	33	78	110	32	17
BH11	611134	4211996	120	79	78	41	17
BH12	605708	4210801	38	59	100	27	17
BH13	604292	4211896	18	28	30	34	14
BH14	607250	4214257	33	19	25	57	32
BH15	607944	4216088	12	22	28	52	19
BH16	612830	4212566	33	40	45	47	29
BH17	608956	4217210	7	24	70	43	20
BH18	607807	4219815	34	40	45	43	31
BH19	611133	4219337	30	47	84	63	34
BH20	610973	4223664	24	80	85	25	14
BH21	615087	4218880	30	75	90	42	25
BH22	603079	4225402	30	27	40	33	17
BH23	600932	4226131	90	130	120	37	14
BH24	604276	4224252	130	130	140	39	17
BH25	606360	4221618	35	70	125	52	29
BH26	624211	4210817	31	68	70	54	31
BH27	621951	4209130	25	27	36	39	28
BH28	623252	4208456	11	15	19	47	29
BH29	624974	4208403	21	28	38	43	26
BH30	626999	4210057	15	27	41	52	39
NB1	628291	4211465	18	18	17	43	29
NB2	622694	4211095	26	28	77	38	29
NB3	619885	4211095	48	79	75	44	30
NB4	620290	4210861	61	76	97	62	30
NB5	616378	4213110	28	41	77	32	21
NB6	615370	4214078	43	42	54	52	29
NB7	615040	4215349	30	45	60	51	28
NB8	619090	4213534	32	55	82	29	19
NB9	613115	4214872	16	34	68	51	31
NB10	612589	4216256	24	39	55	30	19.5
NB11	610431	4214087	17	32	45	24	20
NB12	616383	4216520	45	76	45	27	20
NB13	608464	4216735	45	76	87	31	20
NB14	613128	4214022	16	19	48	31	19
NB15	605836	4218700	45	72	81	45	24
NB16	609327	4213268	40	109	125	39	21
NB17	609334	4218821	29	40	47	35	25
NB18	605487	4220484	96	158	100	41	30
NB19	601337	4224231	22	40	45	25	19.8
NB20	603389	4225386	37	46	51	26	18

PL: Plastic limit ; LL: Liquid limit; NSPT: average number of standard penetration test

Table-4: Calculated values of liquefaction and soil swelling potential

Bore hole	PL 14-20	Cat.- 14-20	PL 7-14	Cat.- 14	PL 0-7	Cat.- 0-7	S.pl	Cat. S.pl
BH1	0.37134	v L	5.71327	L	15.26843	H	12	L
BH2	0.23605	v L	4.55590	v L	15.90392	H	24	M
BH3	0.34158	v L	3.92757	v L	5.79882	L	21	L
BH4	0.33242	v L	4.98315	v L	14.48844	M	23	M
BH5	0.20381	v L	3.51010	v L	16.93078	H	30	M
BH6	0.28990	v L	5.67563	L	15.03013	H	22	M
BH7	0.28244	v L	2.42414	v L	11.43767	M	32	M
BH8	0.30189	v L	3.85028	v L	12.3142	M	13	L
BH9	0.36739	v L	7.62280	L	2.76747	v L	22	M
BH10	0.19324	v L	4.82936	v L	13.52568	M	15	L
BH11	0.41787	v L	5.23410	L	4.36549	v L	24	M
BH12	0.22536	v L	4.52737	v L	12.40191	M	10	L
BH13	0.36445	v L	4.96182	v L	14.42643	M	20	L
BH14	0.38870	v L	6.20162	L	12.30283	M	25	M
BH15	0.35359	v L	5.09509	L	15.69218	H	33	H
BH16	0.33062	v L	4.58678	v L	13.31238	M	18	L
BH17	0.24959	v L	4.84938	v L	17.52507	H	23	M
BH18	0.33467	v L	4.64291	v L	12.91289	M	12	L
BH19	0.40657	v L	6.72304	L	2.88332	v L	29	M
BH20	0.25698	v L	3.43706	v L	14.48934	M	11	L
BH21	0.40153	v L	5.94978	L	3.02464	v L	17	L
BH22	0.52671	v L	8.18262	L	2.59344	v L	16	L
BH23	0.27699	v L	3.15070	v L	7.49828	L	23	M
BH24	0.28127	v L	3.83651	v L	4.31796	v L	22	M
BH25	0.18155	v L	3.93093	v L	13.51642	M	23	M
BH26	0.28098	v L	3.53498	v L	16.65972	H	23	M
BH27	0.35602	v L	5.27620	L	12.80167	M	11	L
BH28	0.38583	v L	5.48498	L	15.61538	H	18	L
BH29	0.33927	v L	5.08014	L	13.80407	M	17	L
BH30	0.31472	v L	4.94748	v L	15.19332	H	13	L
NB1	0.41831	v L	5.52215	L	13.97671	M	14	L
NB2	0.26139	v L	5.34131	L	12.72485	M	9	L
NB3	0.31775	v L	3.83543	v L	11.19866	M	14	L
NB4	0.26981	v L	4.23064	v L	9.61000	L	32	M
NB5	0.27722	v L	4.75751	v L	12.22783	M	11	L
NB6	0.31500	v L	4.82332	v L	11.27500	M	23	M
NB7	0.37656	v L	6.99015	L	2.85992	v L	23	M
NB8	0.24465	v L	4.75385	v L	14.03129	M	10	L
NB9	0.28579	v L	4.63663	v L	15.25562	H	20	L
NB10	0.28442	v L	4.64228	v L	13.57319	M	10.5	L
NB11	0.30788	v L	4.75596	v L	14.90337	M	4	L
NB12	0.37734	v L	3.83975	v L	11.45414	M	7	L
NB13	0.27417	v L	3.90187	v L	11.63943	M	11	L
NB14	0.28624	v L	5.47857	L	14.72082	M	12	L
NB15	0.28892	v L	4.03347	v L	11.52291	M	21	L
NB16	0.19993	v L	2.91823	v L	13.27482	M	18	L
NB17	0.34768	v L	4.94564	v L	10.99909	M	10	L
NB18	0.35526	v L	2.54721	v L	7.21217	L	11	L
NB19	0.32393	v L	4.49393	v L	14.00011	M	5.2	L
NB20	0.32334	v L	4.37789	v L	12.42742	M	8	L

Cat.- Category; PL: Plastic limit; LL: Liquid limit; SPI: Swelling plasticity index; vL- very Low; L- Low; M-Medium; H-High

Discussion:

The soil type in the study area is made of fine sand and in some parts, clay, and silt. The major geological formation in this area is of the Qom formation. Due to the high level of water and fine sand in this area, the probability of liquefaction always remains high. The soil density is classified as medium density class, that's why liquefaction is expected to occur less in deep parts.

In general, in the East and Southeast parts of the city, as well as a small area in the center of the study area, there is a moderate to high risk of liquefaction. Whereas in other areas, the possibility of occurrence is low. This is due to the lower density of soil in these areas and also high levels of underground water (Fig.-5).

Liquefaction is predicted to occur in the depth range of 0-7 meters. In the case of swelling, it can be said that, within the north and north-eastern region, especially due to the presence of a certain type of red clay and silt, soil swelling is prone phenomena. But the probability of its occurrence was low or medium (Fig.-4). The study area in this research has a significant population and also it is one of the important political and commercial cities of Iran. Thus a periodic detailed study is always necessary.

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