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Liquefaction Potential of Pilani Soil

Kamalesh Kumar[1]
[1]*(Civil Engineering Department, Birla Institute of Technology & Science, Pilani, India)*
Corresponding Author: Kamalesh Kumar

Abstract: *Liquefaction takes place when seismic shear waves pass through a saturated granular soil layer. These shear waves distort its granular structure, and cause some of its pore spaces to collapse. This collapse increases pore water pressure and decreases soil's shear strength. If pore space water pressure increases to the point where the soil's shear strength can no longer support the weight of the overlying soil, liquefaction results. In simplified procedure, cyclic stress ratio and cyclic resistance ratio at required depth is determined. These are used to find out factor of safety against liquefaction. It has been suggested that this factor should be more than 2 to ensure safety with respect to liquefaction, excess pore pressure development and ground settlement. Pilani soil is sand till substantial depth below ground surface. Normally water table is at substantial depth. Only during rainfall, soil from ground surface momentarily gets saturated and is below water table. Although this condition of saturation from ground surface with soil below water table is not very likely during earthquake, factor of safety against liquefaction for Pilani soil has been determined for these conditions using simplified procedure. Results have been analyzed and its practical significance has been explained.*

Keywords: *Earthquake, Liquefaction, Pilani soil, Seismic zone, Simplified Procedure.*

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I. Introduction

Liquefaction is a phenomenon in which the strength and stiffness of a soil is reduced by earthquake shaking or other rapid loading. Liquefaction and related phenomena have been responsible for tremendous amounts of damage in historical earthquakes around the world. Liquefaction occurs in saturated soils, that is, soils in which the space between individual particles is completely filled with water. This water exerts a pressure on the soil particles that influences how tightly the particles themselves are pressed together. Prior to an earthquake, the water pressure is relatively low. However, earthquake shaking can cause the water pressure to increase to the point where the soil particles can readily move with respect to each other. Earthquake shaking often triggers this increase in water pressure, but construction related activities such as blasting can also cause an increase in water pressure.

When liquefaction occurs, the strength of the soil decreases and, the ability of a soil deposit to support foundations for buildings and bridges is reduced.

Liquefied soil also exerts higher pressure on retaining walls, which can cause them to tilt or slide. This movement can cause settlement of the retained soil and destruction of structures on the ground surface. Increased water pressure can also trigger landslides and cause the collapse of dams. Lower San Fernando dam suffered an underwater slide during the San Fernando earthquake, 1971. Fortunately, the dam barely avoided collapse, thereby preventing a potential disaster of flooding of the heavily populated areas below the dam.

The term liquefaction has actually been used to describe a number of related phenomena. Because the phenomena can have similar effects, it can be difficult to distinguish between them. The mechanisms causing them, however, are different. These phenomena can be divided into two main categories: flow liquefaction and cyclic mobility.

Flow liquefaction is a phenomenon in which the static equilibrium is destroyed by static or dynamic loads in a soil deposit with low residual strength. Residual strength is the strength of a liquefied soil. Static loading, for example, can be applied by new buildings on a slope that exert additional forces on the soil beneath the foundations. Earthquakes, blasting, and pile driving are all example of dynamic loads that could trigger flow liquefaction. Once triggered, the strength of a soil susceptible to flow liquefaction is no longer sufficient to withstand the static stresses that were acting on the soil before the disturbance. Failures caused by flow liquefaction are often characterized by large and rapid movements.

Cyclic mobility is a liquefaction phenomenon, triggered by cyclic loading, occurring in soil deposits with static shear stresses lower than the soil strength. Deformations due to cyclic mobility develop incrementally because of static and dynamic stresses that exist during an earthquake. Lateral spreading, a common result of cyclic mobility, can occur on gently sloping and on flat ground close to rivers and lakes. The 1976 Guatemala earthquake caused lateral spreading along the Motagua river.

On level ground, the high pore water pressure caused by liquefaction can cause pore water to flow rapidly to the ground surface. This flow can occur both during and after an earthquake. If the flowing pore water rises quickly enough, it can carry sand particles through cracks up to the surface, where they are deposited in the form of sand volcanoes or sand boils. These features can often be observed at sites that have been affected by liquefaction.

II. Simplified Procedure

The first step in liquefaction analysis is to determine whether soil has ability to liquefy during earthquake. Most of the soils that are susceptible to liquefaction are cohesion-less. Cohesive soils liquefy only under specific conditions. Simplified procedure is widely used technique of liquefaction analysis.

For simplified procedure to be applicable, soil must be below groundwater table. Liquefaction analysis can also be performed if it is anticipated that groundwater table will rise in future so that eventually soil will be below groundwater table.

Next step of simplified procedure is to determine the cyclic stress ratio (CSR). Cyclic stress ratio is induced during earthquake. Determination of cyclic stress ratio requires information about peak horizontal ground acceleration. Peak horizontal ground acceleration is caused due to earthquake. Following formula is used to determine CSR [1]:

$$\text{CSR} = 0.65\, r_d \left(\frac{\sigma_{v0}}{\sigma'_{v0}}\right)\left(\frac{a_{\max}}{g}\right) \qquad (1)$$

In above equation, σ_{v0} = total vertical stress at bottom of soil column of depth z, σ'_{v0} = effective vertical stress at bottom of soil column of depth z and a_{max} = maximum horizontal acceleration at ground surface induced by earthquake, expressed in terms of acceleration due to gravity, g. Depth reduction factor, r_d varies with depth below ground surface. It is obtained from standard charts as a function of depth for a particular magnitude earthquake. Sometimes linear relation between depth reduction factor and depth is also assumed. This relation is given as, $r_d = 1 – 0.012z$. z is depth in meters and is measured from ground surface.

From the standard penetration test data, the cyclic resistance ratio (CRR) of the soil is determined. If the CSR induced by earthquake is greater than CRR determined from standard penetration test data, liquefaction of soil will take place during earthquake and vice versa.

Finally factor of safety against liquefaction is determined as FS = CRR/CSR. FS represents factor of safety. It also has been suggested that this factor should be more than 2 to ensure safety with respect to liquefaction, excess pore pressure development and ground settlement at site.

III. Data Analysis

Table 1 shows standard penetration test data, N value for 17 different sites in Pilani region. These N values have been determined based on angle of internal friction (ϕ) – N correlation [2]. As Pilani region soil is sandy, drained direct shear testing has been conducted to determine angle of internal friction. As almost all construction in Pilani region has foundation located 2meters below ground surface, soil prism of 4meters depth has been considered from ground surface for liquefaction analysis. Standard penetration N value, bulk density, dry density, void ratio, specific gravity, saturated density and submerged density reported in Table 1 is for soil samples collected from 2meters from ground surface based on required field and/or laboratory investigation. Values have been assumed constant throughout the 4meters depth.

Normally water table is at substantial depth. Only during rainfall, soil from ground surface momentarily gets saturated and is below water table. Maximum recorded earthquake magnitude in this region is 5.1 on 5th March 2012 in past 20 years [3], which corresponds to seismic zone III [4]. Although this condition of saturation from ground surface with soil below water table is not very likely during earthquake, cyclic stress ratio (CSR) for Pilani soil has been determined for these conditions. Cyclic stress ratio (CSR) in Table 1 has been determined from Equation 1. Depth reduction factor, r_d has been taken equal to 1-0.012z (z in meters from ground surface). In present study, z = 4meters for soil prism of 4meter depth from ground surface. For seismic zone III, $a_{max} = 0.16g$, and this value has been taken in present study.

Table 1: CSR and Pilani soil site properties

N	bulk density (gm/cc)	dry density (gm/cc)	void ratio (e)	specific gravity (G)	saturated density (gm/cc)	submerged density (gm/cc)	CSR
10	1.4	1.341	0.963	2.632383	1.831576	0.831576	0.218069
10	1.49	1.456	0.831	2.665936	1.90985	0.90985	0.207826
15	1.408	1.348	0.978	2.666344	1.842439	0.842439	0.216533
15	1.537	1.428	0.867	2.666076	1.892381	0.892381	0.209956
17	1.492	1.37	0.946	2.66602	1.856125	0.856125	0.214655

17	1.475	1.399	0.907	2.667893	1.874616	0.874616	0.21221
19	1.51	1.466	0.607	2.355862	1.843722	0.843722	0.216355
21	1.47	1.427	0.752	2.500104	1.856224	0.856224	0.214641
22	1.611	1.519	0.717	2.608123	1.936589	0.936589	0.204719
23	1.584	1.454	0.835	2.66809	1.909041	0.909041	0.207923
25	1.557	1.503	0.75	2.63025	1.931571	0.931571	0.205289
25	1.595	1.528	0.657	2.531896	1.9245	0.9245	0.206102
27	1.555	1.473	0.81	2.66613	1.920514	0.920514	0.206565
29	1.547	1.497	0.782	2.667654	1.935833	0.935833	0.204805
31	1.569	1.542	0.691	2.607522	1.950634	0.950634	0.203157
31	1.573	1.502	0.665	2.50083	1.901399	0.901399	0.208846
32	1.546	1.481	0.731	2.563611	1.903299	0.903299	0.208615

Table 2 shows standard penetration test data, N value for same 17 sites in Pilani region as in Table 1. N_{60} in Table 2 is corrected standard penetration test value for field procedure. It is obtained as follows [5]:

$$N_{60} = E_H C_B C_S C_R N/0.6 \qquad (2)$$

As Indian standard specification has been followed, $E_H = 0.6$ for hand dropped donut hammer, C_B = bore hole diameter factor = 1 (bore hole diameter in between 65mm to 115mm), C_S = sampler correction factor = 1 (standard sampler) and C_R = rod length correction factor = 0.75 (rod length less than 3meters).

N_{60} from Table 2 has to be further corrected for overburden pressure to get $(N_1)_{60}$. $(N_1)_{60}$ is obtained as follows:

$$(N_1)_{60} = C_N N_{60} \leq 2N_{60} \qquad (3)$$

Where,

$$C_N = \sqrt{\frac{100}{\sigma'_0}}$$

σ'_0 is effective vertical stress at the base of soil prism in kN/m^2. In present study, depth of soil prism from ground surface = 4meters. Taking submerged unit weight from Table 1 and using 1kg = 9.8N for all 17 soil samples, $(N_1)_{60}$ has been determined using equation 3 and listed in Table 2.

Table 2: Factor of safety against liquefaction for Pilani site soil samples

N	N_{60}	$(N_1)_{60}$	CRR (magnitude=7.5)	CRR (magnitude=5.1)	FS (magnitude=5.1)
10	7.5	13.13613	0.13	0.19929	0.913886
10	7.5	12.55837	0.12	0.18396	0.885164
15	11.25	19.57674	0.205	0.314265	1.451346
15	11.25	19.02104	0.2	0.3066	1.460305
17	12.75	22.00891	0.23	0.35259	1.642592
17	12.75	21.77501	0.2295	0.351824	1.657905
19	14.25	24.77833	0.25	0.38325	1.771397
21	15.75	27.18591	0.27	0.41391	1.92838
22	16.5	27.23118	0.271	0.415443	2.02933
23	17.25	28.89711	0.3	0.4599	2.211879
25	18.75	31.02774	0.5	0.7665	3.733767
25	18.75	31.14618	0.5	0.7665	3.71904
27	20.25	33.71063	0.5	0.7665	3.710691
29	21.75	35.91014	0.5	0.7665	3.74259
31	23.25	38.08669	0.5	0.7665	3.772936
31	23.25	39.11301	0.5	0.7665	3.670167
32	24	40.33224	0.5	0.7665	3.674231

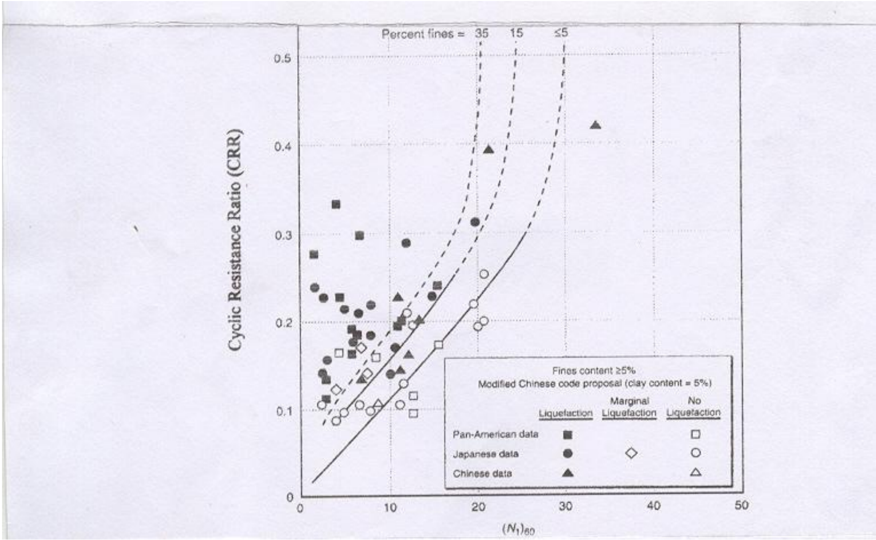

Figure 1: plot used to determine cyclic resistance ratio for clean and silty sands for M = 7.5 earthquake

For 17 samples of Table 2, given $(N_1)_{60}$, CRR has been obtained from Fig. 1 for 7.5 magnitude earthquake [6]. As percent of fines (percent passing 75micron sieve) in Pilani soil is around 5%, rightmost curve of Figure 1 has been used to read CRR values.

Magnitude scaling factor is 1 for 7.5 magnitude earthquake and 1.5 for 5.25 magnitude earthquake. Assuming linear variation, magnitude scaling factor = 1.533 for 5.1 magnitude earthquake. Consequently, CRR values from Table 2 for 7.5 magnitude earthquake has been multiplied with 1.533 to get CRR values for 5.1 magnitude earthquake in Table 2.

As factor of safety against liquefaction = FS = CRR/CSR, using CSR from Table 1 and CRR from Table 2, FS for 5.1 magnitude earthquake has been determined and listed in Table 2 for all 17 different site samples. It has been suggested that this factor should be more than 2 to ensure safety with respect to liquefaction, excess pore pressure development and ground settlement at site.

Variation of FS with $(N_1)_{60}$ has also been plotted in Fig. 2 for 5.1 magnitude (M) earthquake. 6th degree polynomial curve of best fit also has been drawn for this set of data along with its equation. $R^2 = 0.965$, for the equation. This indicates good correlation with data points for 5.1 magnitude earthquake.

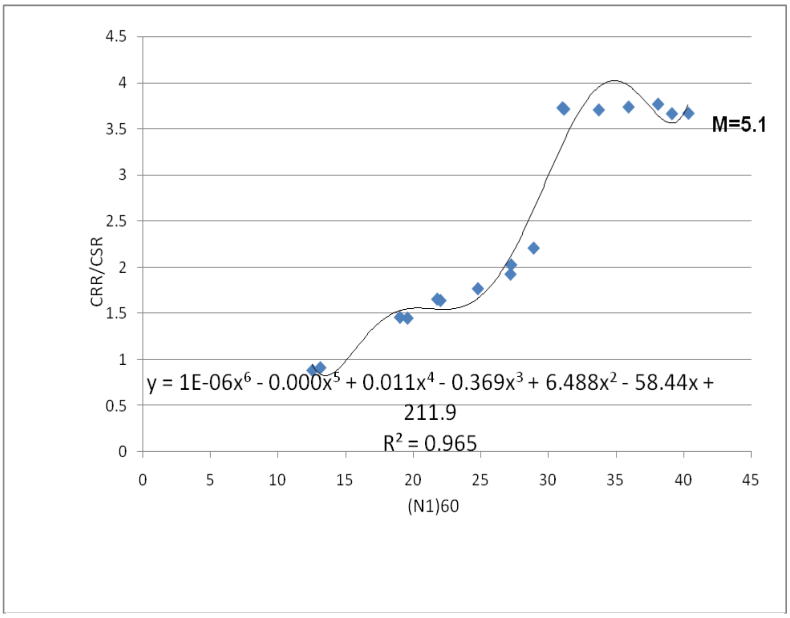

Figure 2: variation of factor of safety against liquefaction with $(N_1)_{60}$

IV. Discussion of Results

From Table 2 and also from Fig. 2, it is clear that if standard penetration testing N value is around 10 or less, factor of safety against liquefaction is less than 1. Also, if standard penetration testing N value is around 21 or less, factor of safety against liquefaction is less than 2.

Although 5.1 magnitude earthquake during the condition in which soil from ground surface is saturated and below water table is not very likely in Pilani region soil, minor tremors due to earthquake are felt once in a while. 15 such have been recorded in last 20 years with maximum magnitude 5.1.

Inspection of most of the buildings and other structures shows minor type of cracks in it in Pilani region. Tremor due to earthquake and low standard penetration testing N value of soil supporting foundation of these seems to be one of the important reasons behind it.

If standard penetration testing N value is kept more than about 21 at sites in Pilani, it will not only ensure safety against liquefaction due to maximum recorded earthquake in last 20 years in the region, there won’t be excess pore pressure development and ground settlement as well. Suitable ground improvement technique can be used for this. It will also ensure minimization of minor type of cracks in buildings and structures of Pilani region.

If site in Pilani already has standard penetration testing N value more than about 21, no ground improvement will be required.

V. Conclusions

For a site in Pilani region, using equation in Fig. 2, factor of safety against liquefaction can be determined if $(N_1)_{60}$ value for the site is known. This can be determined from the standard penetration testing N value using the technique given in present study. If N value is around 21 or less, suitable ground improvement will have to be done to make it more than around 21. This will ensure safety with respect to liquefaction, excess pore pressure development and ground settlement for the earthquake magnitude studied, as well as minimal cracks in buildings and structures with foundation in these soils. If N value is already more than about 21, no ground improvement will be required.

The study is based on simplified procedure of liquefaction analysis. Similar study can be undertaken in other regions also, if soil of the region is similar to Pilani region soil. Present study, thus has great significance.

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