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Liquefaction potential evaluation: Under and over-estimation hazards

S.M.Simeonov & K.D.Hadjiyski
Central Laboratory for Seismic Mechanics & Earthquake Engineering, Bulgarian Academy of Sciences, Sofia, Bulgaria

ABSTRACT: A critical survey, aimed at pointing out some peculiarities and shortcomings in various procedures applied in Bulgaria for estimation of liquefaction potential of water saturated sands (LPS) has been made. The authors have accomplished a large number of numerical experiments and carefully analyzed them to infer that overestimation of the equivalent number of cycles (Ne) is observed, when time history of shear stress (acceleration) obtained by the total stress method (TSM) of analysis is used. That is why an improved procedure is suggested. It has also been ascertained that the frequency content of earthquake motions can't be neglected and has to be considered when factor of safety against liquefaction (FS) is computed.

1 INTRODUCTION

The procedures for estimation of LPS, used in Bulgaria, can be generalized in three major groups. The first one is based on simple criteria, relating the main parameters of earthquakes - epicentral distance (R), magnitude (M), peak ground acceleration (PGA), mean cyclic stress ratio etc., with some characteristics of sands - maximum (initial) shear modulus (G_{max}), shear wave velocity (V_s), relative density (Dr), standard penetration test value (N) etc.. The following criteria are usually applied: Kuribayashi and Tatsuoka (1975); Dobry, Powell, Yokel and Ladd (1980); Iwasaki, Tatsuoka, Tokida and Yasuda (1978); Yegian and Vitteli (1981), Seed, Mori and Chan (1977). The second group of procedures is based on comparison of stress conditions in field, during an earthquake & laboratory determined stress conditions causing liquefaction, Simeonov (1990). The third one requires an investigation on the dynamic site response to a set of earthquakes with representative quantitative parameters, assuming the effective stress method (ESM) of analysis, Simeonov (1986).

2 HAZARDS FOR THE FIRST GROUP OF PROCEDURES

The choice of an appropriate criterion for LPS depends on the available seismological data for the investigated site and the soil characteristics. It is preferable to use criteria based on characteristics of sands determined by in-situ tests. That is so, because the field techniques do not eliminate the influence of the cimentation between sand grains and the natural water content. They take into account also the influence of seismic history on LPS, which is considerable, Seed, Mori and Chan (1975). By our experience from investigations carried out for many building sites in Bulgaria, we could infer that assessments based on simple criteria are scattered in a rather broad range and sometimes may be contradictory and even inconsistent. As an illustration of this fact the results from an investigation of a typical building site in North Bulgaria are presented hereafter. The thickness of the surfacial sand layer is 4.7m. The following sand characteristics are determined by laboratory and in-situ tests: $\rho = 18.8kN/m^3$, $G_{max} = 84700kPa$, $V_s = 210m/s$, $D_r = 65\%$, $N = 11$. The LPS is evaluated for depth of 2.35m. The boundary seismic excitation, expressed by boundary peak acceleration (BPGA), in terms of acceleration of gravity, over which the water saturated sand can be liquefied is derived by three widely used methods. The respective results are given in table 1.

Table 1. Computed BPGA by three methods

#	Method used	BPGA (g)
1	Dobry et al.	0.225
2	Iwasaki et al.	0.132
3	Seed et al.	0.167

The differences for the three methods are 70%, 35% and 27% respectively.

The under- and over-estimation hazards for this group of procedures is quite obvious.

Nevertheless such criteria are likely to be used for sites of non-critical structures. As for sites of critical structures (class A, according the Bulgarian Seismic Code) this approach is admissible only for preliminary tentative assessments.

3 HAZARDS FOR THE SECOND GROUP OF PROCEDURES

The procedures belonging to this group comprise the following: computation of time history of shear stresses, $\tau(t)$, in sands excited by site-dependent accelerogrammes; obtaining the curve of shear stress ratio (τ/σ'_{vo}) versus number of cycles causing liquefaction; transformation of $\tau(t)$ in Ne with constant amplitude; comparison of Ne with the number of cycles necessary for liquefaction (N_1); determination of generated excess pore pressure and evaluation of FS. Time history of shear stresses may be obtained by TSM and ESM of analysis. ESM provides the possibility for direct evaluation of LPS. An iterative procedure based on TSM may be incorporated too. For practical purposes Ne is usually calculated by transforming of $\tau(t)$, obtained by TSM of analysis. The effect of increase of pore pressure is not taken into account in this case. It is considered too, that the application of an iterative procedure is not warranted, Seed, Martin & Lysmer (1975). The TSM over-estimates ground response because of neglecting the progressive decrease of sand's stiffness due to permanent generation of excess pore pressure. Because of this Ne calculated on the bases of $\tau(t)$, obtained by TSM is over-estimated also. A numerical example is set forth underneath. The $\tau(t)$ in a sand layer excited by seismic input, obtained by TSM and ESM are shown in Fig. 1 and Fig. 2.

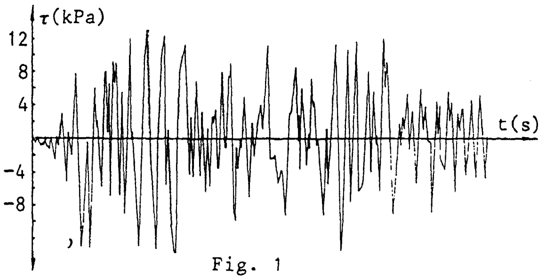

Fig. 1

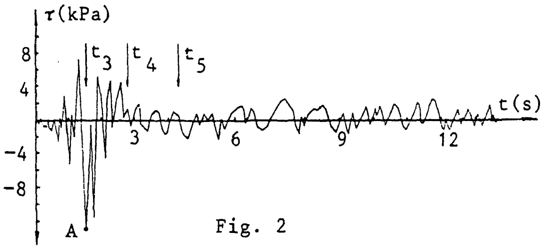

Fig. 2

Table 2. Occurrence moments of PGA, phase transformation and liquefaction.

#	t_1	t_2	t_3	t_4	t_4-t_2	t_4-t_1	t_1-t_2
	s	s	s	s	s	s	s
1	0.93	1.56	1.53	3.38	1.82	2.45	-0.63
2	0.96	1.00	1.58	3.61	2.61	2.65	-0.04
3	0.98	1.60	1.57	2.75	1.15	1.77	-0.62
4	1.42	1.50	1.48	5.01	3.51	3.59	-0.08
5	1.44	2.25	1.57	5.01	2.76	3.57	-0.81
6	1.64	1.32	1.28	3.80	2.48	2.16	0.32
7	1.94	1.50	1.44	4.78	3.28	2.84	0.44
8	1.99	2.14	1.56	4.24	2.10	2.25	-0.15
9	2.22	2.24	2.22	4.52	2.28	2.30	-0.02
10	2.24	2.26	2.28	5.66	3.40	3.42	-0.02
11	2.24	2.28	2.26	3.86	1.58	1.62	-0.04
12	2.82	2.58	1.32	3.78	1.20	0.96	0.24
13	2.84	1.62	1.38	3.78	2.16	0.94	1.22
14	4.28	1.48	1.50	3.08	1.60	-1.20	2.80
15	4.30	1.52	1.48	2.76	1.24	-1.54	2.78
16	4.32	1.54	1.52	2.80	1.26	-1.52	2.78
17	4.74	3.66	3.52	4.46	0.80	-0.28	1.08
18	6.23	3.48	3.46	4.42	0.94	-1.81	2.75
19	6.24	4.68	3.74	4.66	-0.02	-1.58	1.56
20	6.25	3.48	3.76	6.20	2.72	-0.05	2.77
21	9.12	3.47	3.26	4.16	0.69	-4.96	5.65
22	9.13	9.23	3.22	4.15	-5.08	-4.98	-0.10
23	9.14	3.51	3.50	6.32	2.81	-2.82	5.63
24	10.14	10.04	6.92	8.44	-1.60	-1.70	0.10

It is evident that up to the moment of phase transformation (point A in Fig. 2) the two signals are almost identical. After that the $\tau(t)$, obtained by TSM, attenuates due to decrease of sand's stiffness. The Ne specified by transforming of $\tau(t)$ through the TSM and ESM are 24 and 3 respectively. The difference is more than significant and the LPS will be unrealistic if the first value of Ne is adopted. Because of this and to avoid the iterative procedure a new proposition deduced from numerical experiments is recommended in this paper. The response of real deposits of water saturated sands to different seismic inputs is analyzed. For every case the moments of occurrence t_1 and t_2 of PGA for the sand layers are computed by TSM and ESM of analysis. The moments of phase transformation and liquefaction are designated as t_3 and t_4. Some of the results are listed in table 2. They imply that in case of seismic vibrations with distinguished initial, strong and attenuating phases (accelerogrammes with $t_1 > 4$ s) liquefaction takes place before the occurrence of PGA, i.e. $t_4 < t_1$. This ragularity makes it possible to use a fragment of $\tau(t)$, obtained by TSM, for evaluation of Ne, i.e. the fragment from the origin to the moment t_5, defined as

$$t_5 = t_1. \qquad (1)$$

For accelerogrammes with strong initial phase ($t_1 < 3$ s), $t_4 > t_1$ and t_5 may be expressed by the equation

$$t_5 = t_1 + t_c \qquad (2)$$

Having fulfilled a great number of numerical experiments, followed by a careful analysis, we have good reasons to recommend the value of 3 for t_c. Of course, this value of t_c needs to be further on verified in the process of compiling additional input data.

Such an estimation of Ne has the following advantages.

1. The time-consuming iterative procedure for computing $\tau(t)$ is avoided.
2. The initial fragment of $\tau(t)$, obtained by the TSM, is used only, i.e. the fragment of $\tau(t)$ that is almost identical to the closed form ESM solution, especially up to the occurrence of phase transformation.

4 HAZARDS FOR THE THIRD GROUP OF PROCEDURES

Here an investigation of the response of soil deposits to site-dependent accelerogrammes is presumed. A very important stage of this analysis is the choice of input motions for soil models. The object of this division is to analyze the influence of the frequency content of seismic inputs on the evaluated LPS/FS.
A numerical approach is adopted. The response of sand deposit of thickness 33 m is analyzed with seven different accelerogrammes as input: Vranchea 04.03.1977, record Buchurest, E-W component (BUC); El Centro 1979 (EC79); El Centro 1940 (EC40); San Fernando 1940 (SF40); Monte Negro 1979, N-S component (MN); Vranchea 04.03.1977, computed accelerogramme for rock at Bucharest (BRC) and a synthesized accelerogramme (SA). Their spectral content is visualized in Fig. 3 by their Amplitude Fourier Spectra. The accelerogrammes are scaled linearly to maximum amplitude of 1.0 m/s². The values of Housner's spectral intensity (S), mean velocity ($\bar{v}$) and MM intensity (J) are computed by the formulae

$$S = \int_{0.1}^{2.5} PSV_\zeta \, dT; \qquad (3)$$

$$\bar{v} = S/2.4; \qquad (4)$$

$$J = \lg 14\bar{v}/\lg 2; \qquad (5)$$

where PSV_ζ is the pseudo-spectral velocity for natural period T and damping ratio $\zeta = 0.02$. The results are given in Table 3. Afterwards the accelerogrammes are normalized to S = 50 cm. The new values of PGA are listed in the last column of Table 3. The response of the soil deposit to these inputs is computed then. The respective curves of initial effective vertical stresses (σ'_{v0}) and the excess pore pressure (u) are drawn in Fig. 4. There is no liquefaction in case of low frequency excitations (BUC & BRC). The SF40 & EC79 inputs (their spectra are almost identical for $f > 0.8$ Hz) cause liquefaction of sands at depth from 10 m to 12 m. The high frequency SA produces liquefaction at depth from 6 m to 8 m and from

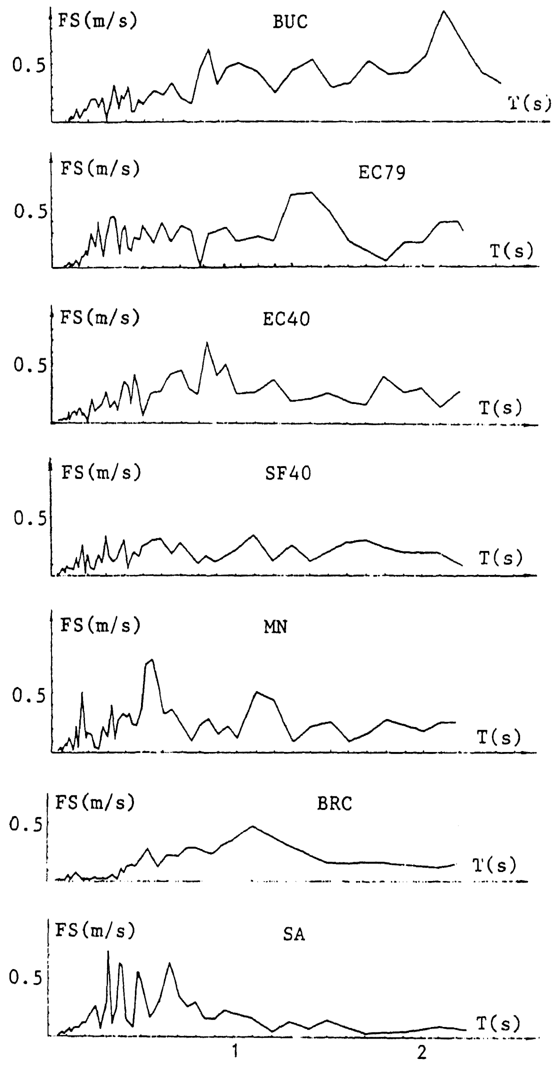

Fig. 3

Table 3.

accelero-gramme	S cm	$\bar{v}$ cm/s	J	PGA m/s²
BUC	96.8	40.3	9.14	0.5165
EC79	63.7	26.5	8.54	0.7849
EC40	52.6	21.9	8.26	0.9506
SF40	52.9	22.0	8.27	0.9452
MN	51.8	21.6	8.24	0.9647
BRC	50.1	20.9	8.19	0.9980
SA	35.3	14.7	7.69	1.4164

10 m to 12 m. The range from 6 m to 12 m is liquefied by EC40 and MN excitations. The factor of safety against liquefaction (FS) varies with depth and the maximum difference in percents for these seven input motions are given in Table 4.

Table 4. FS versus depth.

Depth from - to m	FS from - to	Maximum difference in %
2 - 4	2.60 - 6.10	135
4 - 6	2.05 - 4.10	100
6 - 8	1.00 - 3.25	225
8 - 10	1.00 - 3.30	230
10 - 12	1.00 - 2.40	140
12 - 14	2.20 - 5.20	136
14 - 16	2.00 - 3.50	75
16 - 18	2.60 - 5.75	121
18 - 21	2.30 - 5.80	152
21 - 24	1.90 - 5.75	203
24 - 27	1.75 - 5.90	237
27 - 30	1.55 - 5.80	274
30 - 33	1.50 - 6.00	300

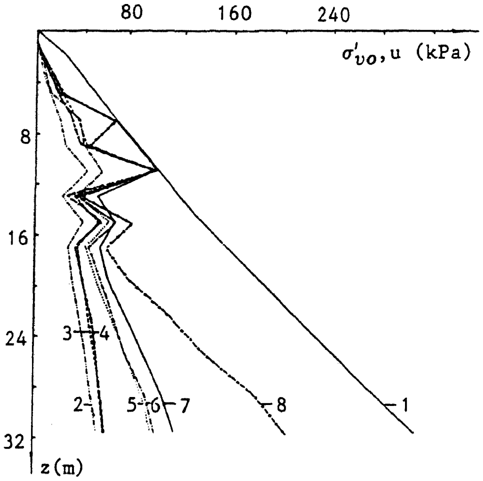

Fig. 4. 1 - σ'_{vo}; u computed from input BUC - 2, EC79 - 3, SF40 - 4, MN - 5, BRC - 6, EC40 - 7, SA - 8

Liquefaction takes place when FS is equal to 1.00. FS changes from 1.00(liquefaction) to 3.30(considerable resistance to liquefaction) for sands at depth from 6 m to 12 m. For some layers differences in FS are up to 300%. These numerical results apparently are in support of our statement for the significant influence of seismic input frequency content on LPS. The excess pore pressure, generated by BRC, SF40, MN and EC40 inputs with almost equal PGA (range from 0.9452 m/s^2 to 0.9980 m/s^2, maximum difference 5.6%), are illustrated in Fig. 5. The range of variation of FS and the corresponding differences may be seen in Table 5.

Table 5. FS versus depth.

Depth from - to m	FS from - to	Maximum difference in %
2 - 4	2.60 - 4.45	71
4 - 6	2.05 - 3.60	76
6 - 8	1.00 - 2.15	115
8 - 10	1.00 - 2.20	120
10 - 12	1.00 - 1.85	85
12 - 14	2.20 - 4.20	91
14 - 16	2.00 - 2.45	22
16 - 18	2.80 - 4.55	62
18 - 21	2.80 - 4.55	62
21 - 24	2.65 - 4.55	72
24 - 27	2.60 - 4.90	88
27 - 30	2.50 - 5.00	100
30 - 33	2.55 - 5.25	106

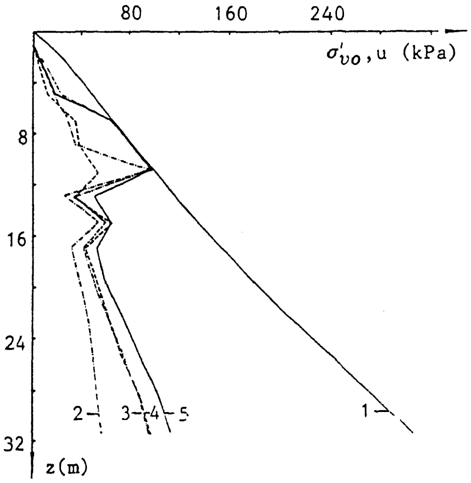

Fig. 5. 1 - σ'_{vo}; u computed from input SF40 - 2, MN - 3, BRC - 4, EC40 - 5

The results for SF40 and EC79 accelerogrammes with maximum amplitudes of 0.9452 m/s^2 and 0.7849 m/s^2 (difference 20.4%) and with almost identical spectra for f $>$ 0.8 Hz are given in Fig. 6 and Table 6 respectively.

Table 6. FS versus depth.

Depth from - to m	FS FS40	 EC79	Difference in %
2 - 4	3.45	3.05	13.1
4 - 6	2.70	2.30	17.4
6 - 8	2.15	1.90	13.2
8 - 10	2.20	2.05	7.3
10 - 12	1.00	1.00	0.0
12 - 14	4.20	3.60	16.7
14 - 16	2.45	2.60	6.1
16 - 18	4.55	4.50	3.3
18 - 21	4.55	4.75	4.4
21 - 27	4.70	4.95	5.3
27 - 33	5.10	5.35	4.9

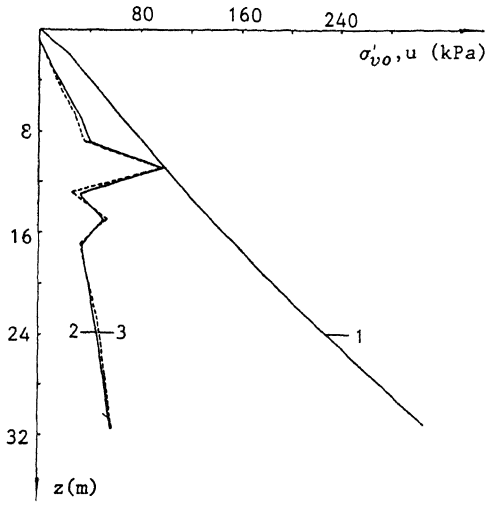

Fig. 6. 1 - σ'_{vo}; u computed from input EC79 - 2, SF40 - 3

So in case of similarity in the frequency content of seismic inputs (SF40 & EC79 - Fig. 6 and Table 6), maximum amplitude difference of 20.4%, causes a difference of 17.4% for the FS. But in case of diversity in frequency content (BRC, SF40, MN & EC40 - Fig. 5 and Table 5), regardless of the similarity in maximum amplitude values (maximum difference of 5.6%), the differences in the FS are appreciable (up to 120%). Therefore these numerical results ascertain that:

1. The influence of the frequency content on LPS is not negligible but rather significant.

2. The PGA only, cannot be used as a reliable seismic parameter for evaluation of factor of safety against liquefaction.

5 CONCLUSIONS

After a considerable number of numerical experiments have been analyzed (here above had been demonstrated only some typical cases), the following is concluded:

1. The results for LPS, obtained by simple criteria, usually vary in a wide range and sometimes are controdictory or even inconsistent.

2. It is recommended these criteria to be applied for sites of critical structures about preliminary tentative estimation only.

3. For sites of noncritical structures they might be applied, but final assessment should be based on coincidence of results from more than two criteria.

4. Use of the entire time history of shear stresses (accelerations), obtained by TSM, for calculation of Ne may bring about unacceptable hazard in evaluation of LPS.

5. When $\tau(t)$, obtained by TSM of analysis, is applied for evaluation of Ne the following is recommended:

5.1. In case of seismic input with well expressed phases (initial, strong and attenuating), the fraction of $\tau(t)$ from the origin to the occurrence of peak amplitude to be used.

5.2. When the seismic input is without initial phase (recorded on site near the source), the 3 s after the occurrence of peak amplitude (value of t_c in equation 2) have to be taken into account too.

6. The frequency content of seismic input has an influence on the estimated LPS that cannot be neglected.

7. A reliable assessment of LPS for sites of critical structures requires a detailed evaluation of frequency content of seismic motions.

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