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ABSTRACT: Factors affecting liquefaction are analysed. Qualitative factors along with liquefaction itself are conceived to be of fuzzinesses the common methods cannot deal with. A new method -- the Multiple-Stage Multifactorial Evaluation is introduced to evaluate the liquefaction potential of sand which can take into account not only the factors considered by the common methods but also these qulaitative factors which otherwise cannot be considered by the explicit mathematic evaluation methods and can treat each fator according to its importance to liquefaction. Tests with the method show a higher correct evaluation rate over other methods. Concludion is drawn about the liquefaction potential of the upper lens in the ground of the Pubugou Power Station under an earthfquake of the seventh degree.

ANALYSES OF THE FACTORS AFFECTING LIQUEFACTION

Many factors affect the liquefaction potential of a sandy deposite, such as soil characteristics, drainage condition, static stress condition, and seismic loading properties. Each category of these factors can be specified by the following subfactors, as shown in the factor tree in Fig.1. Among the factors affecting liquefaction relative density, maximum acceleration, critical depth, and earthquake magnitude etc. are explicit in their conecpts although the ground exploration and the earthquake monitoring may conflict with the complicated system of ground liquefaction. It is on these explicit factors that the common liquefaction evalution methods based. Other factors, such as the intensity of earthquake, the type of soil, the uniformity of soil, and the drainage condition of soil layer, on the other hand, are defined by personal experiences or common agreement. No absolute differences exist between each subdivided factor, eg., an earthquake of the seventh degree and an earthquake of the eighth degree show no absolute differences. Factors with the characteristics are called fuzzy factors which cannot be taken into account by common methods with explicit variables. Liquefaction of soil was defined as the state at which the ratio of the pore-water pressure to the confining pressure equals an unity, ie., $\gamma=1.0$, whereas sand boiling occured when $\gamma<1.0$, which behaved as the so-called macroliquefaction. Just as the concept of "safe" and "unsafe", the likelihood of liquefaction is a concept depends on a valve value. Neglect of the complexities and the fuzzinesses of the factors will result in a lower corret evalution rate and an inaccurate description of evaluation. A new liquefaction potential evaluation method, the multiiple-stage multifactorial evalution , is put forward here to handle the problems involing fuzzy factors.

MATHEMATIC MODEL

Assuming V is a variable set. P is a partition of V which divide V into n subsets.

$$\bigcup_{i=1}^{n} V_i = V$$

$$V_i \cap V_j = 0 \quad i=j$$

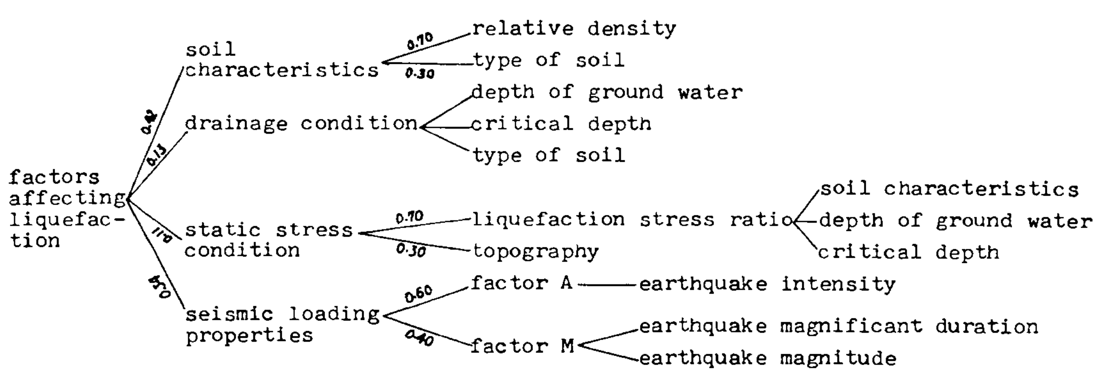

Fig.1 Factor tree and the weights of factors

The set V under partition P is $V/P=(V_{1},V_{2},\ldots,V_{n})$, while the substage factor is $V_i=(V_{i1},V_{i2},\ldots,V_{ik})$, $i=1,2,\ldots,n$. The multifactorial evaluation of V_i is,

$$B_i = A_i\, R_i = (b_{i1}\ b_{i2}\ \ldots\ldots b_{in})$$

$$i=1,\ 2,\ \ldots\ldots n$$

in which. b_{im}=evaluation result of V_{ik}; A_i=weight vector of V_i; R_i=evaluation matrix of V_i.

$$A_i = (a_{i1}\ a_{i2}\ \ldots\ldots a_{ik})$$

$$R_i = \begin{bmatrix} u_{i11} & u_{i12} & \cdots u_{i1n} \\ u_{i21} & u_{i22} & \cdots u_{i2n} \\ \cdots\cdots & & \\ u_{ik1} & u_{ik2} & \cdots u_{ikn} \end{bmatrix}$$

in which, a_{im}=weight of the factor V_{ik}; u_{ikm}=membership degree of V_{ik} to the mth evaluation resultant set. The calculation rule $M(\cdot,\oplus)$ is used.

$$b_{im} = \sum_{l=1}^{k} a_{im}\cdot u_{ilm}$$

The resultant B_i is the evaluation of V_i in the partition V/P. If the weight vecter of V/P is A, the general evaluation matrix will be,

$$R = \begin{bmatrix} B_1 \\ B_2 \\ \vdots \\ B_n \end{bmatrix} = (b_{ij})_{m\ n}$$

The two-stage multifactorial evaluation of all the factors of V is then,

$$B^* = A\cdot R$$

In this paper, the factors are divided into two stages Models of more than two stages should be used if the affecting factors are divided further.

DETERMINATION OF MEMBERSHIP DEGREES

Seven factors are chosen for liquefaction analysis from the factor tree in Fig.1, viz. relative density, type of soil, drainage condition, lique- faction stress ratio τ/σ_0, topography, earthquake intensity, the ground water, the crictive vertical stress and factor $A=a_m\ \sigma/\sigma_0$ (σ= total vertical stress, σ_0= effective vertical stress) . The significant earthquake duration is closely related to the earthquake magnitude M.

Liquefaction potential increases with decreasing relative density. By the Aseismic Design Code(1978), no liquefaction will occur if the relative density of sand is larger than 70%, whereas a sand with relative density less than 40% is susceptible to liquefaction. The membership functions suggested by Kaufmann(Zhongxiong Ho.1983) are recmmended here for relative density Dr. Similar functions are recommended for A, M, and τ/σ_0, as shown in Fig.2 and Tab. 1. The parameters in these functions are the results of the exaggerated common scopes of variables, as shown in Tab. 3. The values of membership degrees of qualitative factors come from experts' estimates, as listed in Tab.2.

Tab.1 Membership Functions of Dr, A, M, and τ/σ_0

factor	membership of 'liquefaction'	membership of 'no liquefaction'
D_r and $\frac{\tau}{\sigma_0}$	$f(x)=\begin{cases} 1 & 0\le x\le a \\ \frac{1}{2}-\frac{1}{2}\sin\frac{\pi}{b-a}(x-\frac{a+b}{2}) & a<x<b \\ 0 & x=b \end{cases}$	$f(x)=\begin{cases} 0 & 0\le x\le a \\ \frac{1}{2}+\frac{1}{2}\sin\frac{\pi}{b-a}(x-\frac{a+b}{2}) & a<x<b \\ 1 & x=b \end{cases}$
A and M	$f(x)=\begin{cases} 0 & 0\le x\le a \\ \frac{1}{2}+\frac{1}{2}\sin\frac{\pi}{b-a}\ x-\frac{a+b}{2} & a<x<b \\ 1 & x=b \end{cases}$	$f(x)=\begin{cases} 1 & 0\le x\le a \\ \frac{1}{2}-\frac{1}{2}\sin\frac{\pi}{b-a}(x-\frac{a+b}{2}) & a<x<a \\ 0 & x=b \end{cases}$

Table 2 Membership degrees of qualitative factors

type of soil	membership		drainage	membership		topography	membership	
	Liq.	No Liq.		Liq.	No Liq.		Liq.	No Liq
gravel	0.00	1.00	open	0.00	1.00	inclined	0.40	0.60
sandy gravel	0.30	0.70	very good	0.40	0.60	slightly inc	0.50	0.50
coarse sand	0.50	0.50	good	0.50	0.50	level	0.55	0.45
medium sand	0.60	0.40	average	0.55	0.45			
fine sand	0.75	0.25	poor	0.60	0.40			
silty sand	0.75	0.25	confined	0.60	0.40			

Table 3 Parameters of membership functions

valve value	A	M	D_r	τ_L/σ_0
a	0.1	5.0	40	0.0
b	0.5	9.0	80	0.4

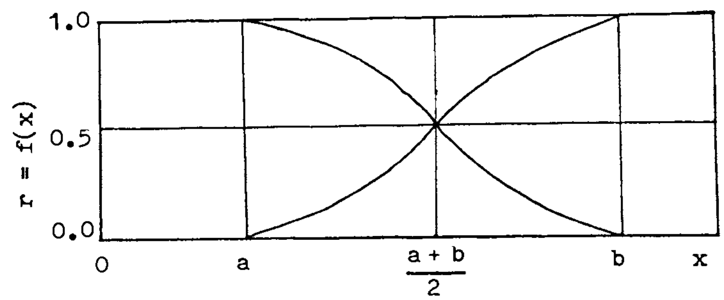

Fig.2 Membership functions of D_r, A, M, and $\frac{\tau_L}{\sigma_0}$

EVALUATION OF LIQUEFACTION POTENTIAL

The evaluation matrix can be set up after the values of the membership degrees have been determined. The weights of each factor are the averages from experts' estimated, as shown in Fig.1. Typical procedures can be seen from the following example case.

The in-situ information of the Jensen Power Station during the San Francisco Earthquake, 1971, are listed in Tab.4. The evaluations of the first stage factors are,
for the soil characteristics

$$B_1 = (0.7\ 0.3)\begin{bmatrix}0.794 & 0.206\\ 0.750 & 0.250\end{bmatrix} = (0.62\ 0.38)$$

for the drainage condition

$$B_2 = (0.4\ 0.6)$$

for the statio stress conditions

$$B_3 = A_3\ R_3 = (0.7\ 0.3)\begin{bmatrix}0.655 & 0.345\\ 0.550 & 0.450\end{bmatrix} = (0.55\ 0.45)$$

for the seismic loading properties

$$B_4 = A_4\ R_4 = (0.6\ 0.4)\begin{bmatrix}0.690 & 0.310\\ 0.345 & 0.655\end{bmatrix} = (0.55\ 0.45)$$

The general evaluation of all the factors is,

$$B^* = A\ R = (0.34\ 0.11\ 0.13\ 0.42)\begin{bmatrix}0.78 & 0.22\\ 0.40 & 0.60\\ 0.62 & 0.38\\ 0.55 & 0.45\end{bmatrix} = (0.62\ 0.38)$$

The ground of the power station would liquefy under the effect of the earthquake because of $b_l > b_n$. This conclusion accorded with the case study. Information in Tab.4 were compiled partly by Seed and Christian. The drainage conditions are determined in terms of ratio of the depth of ground water to the critical depth and the type of soil. Tests with the similar procedure show that the results of 36 cases out of 38 cases agree with the in-situ investigations, with the correct evaluation rate P=92.1%, as shown in Tab.4.

The method presented above is based mainly on the accumulated experience of sand liquefaction studies. The powerful mathematic tool can take into account not only the factors considered by the common methods but also these qualitative factors which otherwise cannot be considered by a explicit mathematic evaluation method. It is capable of considering the general effects of many factors without leaving out the effects of some minor factors by allocating a weight to a factor. Compared with the accmulated failure procedure (Valera, 1977), P=85.4%, the statistic method (Tanimoto,1976), P=83.2%, and the method in the Chinese Aseismic Design Code (1978) , P is approximately 80% for cases during the Tangshan earthquake, 1976, and the Haichen earthquake, 1975, the presented theory is more reliable.

For the case of the upper stream lens in the ground of Pubugou Power Station, the in-situ information are listed in Tab.4. The seismic loading propertis are, M=6.5, a_s=0.1g, A=0.2, the revised in-situ liquefaction stress ratio τ_l/σ_0=0.125(N_s=8) . The evaluation results of the first stage factors are,
for the soil characteristics

$$B_1 = (0.7\ 0.3)\begin{bmatrix}0.15 & 0.85\\ 0.75 & 0.25\end{bmatrix} = (0.33\ 0.67)$$

for the drainage condition

$$B_2 = (0.6\ 0.4)$$

for the static stress conditions

$$B_3 = (0.7\ 0.3)\begin{bmatrix}0.78 & 0.22\\ 0.55 & 0.45\end{bmatrix} = (0.71\ 0.29)$$

for teh seismic loading properties

$$B_4 = (0.6\ 0.4)\begin{bmatrix}0.69 & 0.31\\ 0.15 & 0.85\end{bmatrix} = (0.47\ 0.53)$$

The general evaluation of all teh factors is,

$$B^* = (0.34\ 0.11\ 0.13\ 0.42)\begin{bmatrix}0.33 & 0.67\\ 0.60 & 0.40\\ 0.71 & 0.29\\ 0.47 & 0.53\end{bmatrix} = (0.47\ 0.53)$$

Because 0.47<0.53, macorliquefaction will not occur if the upper lens is subjected to an earthquake of the seventh degree. Further computation result in the conclusion that if the relative density of a part of the lens is larger than 62%, the part will not liquefy under an earthquake of the seventh degree, and the persent sand lens will liquefy if earthquake intensity equal or larger than 8 degree.

It should be noted that macroliquefaction doesn't mean by its fuzzy concept, a pore-water pressure ratio of one and the conclusion of no macroliquefaction doesn't mean a very low pore-water pressure. So, it is necessary to reexamine the possible effects of the high pore-pressure on the general stability of the

Table 4 In-situ information and predicted liquefaction

Site	Magnitude	Date	Depth to ground water in feet	Critical depth in feet	a in g	A in g	Dr in %	τ/σ_0	Type of soil	Drainage condition	Topography	In-situ liquefaction	Predicted liquefaction
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
Niigata	6.6	1802	3	20	0.12	0.22	53	0.14	sand	poor	level	No	No
Niigata	6.6	1802	3	20	0.12	0.22	64	0.14	sand	poor	level	No	No
Niigata	6.1	1887	3	20	0.08	0.15	53	0.09	sand	poor	level	No	No
Niigata	6.1	1887	3	20	0.08	0.15	64	0.09	sand	poor	level	No	No
Mino Owari	8.4	1891	6	30	0.35	0.68	65	0.39	sand	poor		Yes	Yes
Mino Owari	8.4	1891	6	25	0.35	0.61	55	0.37	sand	average		Yes	Yes
Mino Owari	8.4	1891	8	20	0.35	0.59	75	0.35	gravel			No	No
Mino Owari	8.4	1891	8	20	0.35	0.52	72	0.35	sand	average		Yes	Yes
Sheffield dam	6.5	1935	15	25	0.20	0.26	40	0.16	sand	good	incline	Yes	Yes
Brawley	7.0	1940	15	15	0.25	o.25	58	0.16	sand	very good		Yes	Yes
All american canal		1940	20	25	0.25	0.28	43	0.20	sand	good		Yes	Yes
Sofatara canal	7.0	1940	5	20	0.25	0.42	32	0.26	sand	average		Yes	Yes
Komii	8.3	1944	5	13	0.08	0.12	40	0.08	sand	average		Yes	Yes
Meiko street	8.3	1944	2	8	0.08	0.14	30	0.09	silt	average		Yes	Yes
Takaya	7.2	1948	11	23	0.30	0.42	72	0.30	sand	average		Yes	Yes
Shonenji temple	7.2	1948	4	10	0.30	0.45	40	0.29	sand	average		Yes	Yes
Agricultural union		1948	3	20	0.30	0.55	50	0.33	silt	poor		Yes	Yes
Lake Merced	5.5	1957	8	10	0.18	0.20	55	0.15	sand	very good		Yes	Yes
Puerto Montt	8.4	1960	12	15	0.15	0.17	50	0.15	silt	average		Yes	Yes
Puerto Montt	8.4	1960	12	15	0.15	0.17	55	0.15	silt	silt		Yes	Yes
Puerto Montt	8.4	1960	12	20	0.15	0.19	75	0.15	silt	good		No	No
Niigata	7.5	1964	3	20	0.16	0.29	53	0.20	sand	poor	level	Yes	Yes
Niigata	7.5	1964	3	25	0.16	0.30	70	0.20	sand	poor	level	Yes	Yes
Niigata	7.5	1964	3	20	0.16	0.29	64	0.20	sand	poor	level	No	Yes
Niigata	7.5	1964	12	25	0.16	0.23	53	0.12	sand	average	level	No	Yes
Snow river	8.3	1964	0	20	0.15	0.31	50	0.18	sand	poor	slightly inc.	Yes	Yes
Snow river	8.3	1964	8	20	0.15	0.22	40	0.15	sand	average	slightly inc.	Yes	Yes
Quarts creek	8.3	1964	0	25	0.12	0.23	1	0.15	sand	poor	slightly inc.	No	No
Scott glacier	8.3	1964	0	20	0.16	0.33	65	0.19	sand	poor	slightly inc.	Yes	Yes
Valdez	8.3	1964	5	20	0.25	0.42	68	0.25	gravel			Yes	Yes
Hachinohe	7.8	1968	3	12	0.21	0.35	78	0.23	sand	average		No	No
Hachinohe	7.8	1968	3	12	0.21	0.36	58	0.23	sand	average		Yes	Yes
Hachinohe	7.8	1968	5	10	0.21	0.29	80	0.19	sand	average		No	No
Hakodate	7.8	1968	3	15	0.18	0.31	55	0.21	sand	average		Yes	Yes
Huachipato	6.6	1960	10	30	0.25	0.38	1			average		No	No
Huachipato	6.6	1960	10	75	0.25	0.43	1			average		No	No
Jensen plant	7.7	1971	55	55	0.35	0.35	52		silt	very good		Yes	Yes
Pubugou plant	6.5		0	164	0.10	0.20	70	0.13	sand	poor	level		No

structure system in which the studied sand layer acts as a part even if the sand layer is identified " no liquefaction".

CONCLUSION

Some major factors affecting liquefaction and macroliquefaction itself are of fuzzinesses the common evaluation methods cannot deal with. The persented theory in this paper, the Multiple-Stage Multifactorial Evaluation, is capable of incorporating both quantitative and qualitative factors into consideration and rsults in a higher correct evaluation percentage than the common methods.

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