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FINES CONTENT EFFECTS ON LIQUEFACTION POTENTIAL EVALUATION FOR SITES LIQUEFIED DURING CHI-CHI EARTHQUAKE, 1999

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SUMMARY

The purpose of this paper is to present the effect of fines content on the evaluation of liquefaction potential while using Seed's method (1985) and Tokimatsu and Yoshim's method (1983). The data used in the paper were bored in the liquefied sites during Chi-Chi earthquake, 1999. The fines content of soil is the major influence factor that affects the factor of safety of stability and is the target discussed in these methods. The results from Student t-Test in Statistics show that the factor of safety calculated from the Seed's method and the T&Y's method could be regarded as the same amount as fines content less than 35%. However, the results of T&Y's method will overestimate the liquefaction resistance as the fines content greater than 35%. An appropriate correction factor for the fines content greater than 35% is proposed from back-calculated analysis using the liquefied site data. The result show the proposed correction factor will improve the effect of the fines content on liquefaction potential evaluation in the T&Y's method.
Keywords: Earthquake, soil liquefaction, liquefaction potential, fines content.

I. INTRODUCTION

An earthquake scaled as Richter magnitude of 7.3 hit central Taiwan at the mountainous village called Chi-Chi at 1:47:12 a.m. on September 21, 1999. The earthquake is the strongest ever recorded in Taiwan for the past 100 years. The destructive earthquake caused a serious disaster throughout the six counties of central Taiwan, especially in Yunlin, Zhanghua, Nantou, and Taichung County. Many areas and structures, including free fields, building foundations, riversides, embankments, retaining walls, harbor structures, etc., were liquefied and caused much damage during the soil liquefaction. The fines content of soil stratum is much higher in the central Taiwan shown in the boring report. This stimulates researchers to re-check or to calibrate the effectiveness of the existing the liquefaction potential evaluation (LPE) methods and to develop a modified factor to improve the accuracy of the existing LPE to mitigate the damage from soil liquefaction.

There are many methods to assess the liquefaction potential (LP), and simplified methods using standard penetration test N (also called SPT_N or N_{SPT}) value are more popular (Ni [1] [2]). The simplified

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methods include Seed's method (Seed [3], [4]), method of Japan Road Association (1990, JRA method), new method of Japan Road Association ([5], NJRA method), Tokimatsu and Yoshimi's method (Tokimatsu and Yoshimi [6] is called T&Y's method later), method of Chinese Building Codes (CBC method, National Standards of the P. R. of China [7]), and Arias intensity method (Kayen [8]). The factors of liquefaction resistance considered in these methods are N_{SPT} value and fines content except that the CBC method uses clay content instead of fines content. As described in Ni and Lai's paper, the LP results obtained from analyzing the same site liquefied during Chi-Chi earthquake depend highly on the method selected. They also described that the major factor to cause the variation is the factor of fines content, a highly empirical parameter used in the different methods. The purpose of this paper is to present the effect of fines content on the evaluation of liquefaction potential while using the simplified methods for the central Taiwan area. However, in this paper only the Seed's method (1985) and the T&Y's method (1983) will be discussed in.

In the paper Student t-Test using in Statistics will be used to present the effect of the fines content on the factor of safety calculated from the Seed's method and the T&Y's method. The boring data used and analysis results from those two methods are shown as Table 1. Also, an appropriate correction factor for the fines content will be determined from back-calculated analysis using boring data by NCREE in the liquefied site during Chi-Chi earthquake in the central Taiwan area.

Ⅱ. THE FACTORS AFFECT SOIL LIQUEFACTION

The term soil liquefaction is used to describe deformations caused by monotonic, transient, or repeated disturbance of saturated cohesionless soils under undrained conditions. The generation of excess pore water pressure under undrained loading conditions is the hallmark of all liquefaction phenomena. When saturated cohesionless soils are loaded rapidly under undrained conditions, the excess pore pressure induced by densification will increase and the effective stress will decrease. It is called "initial liquefaction" (Seed [9]) when the effective confining pressure progress to the point of essentially zero effective confining pressure. When a soil element reaches the condition of zero effective confining pressure, it does not have any strength and large deformation can occur during cyclic loading in almost loose cohesionless soils. This situation is called soil liquefaction. However, cyclic mobility will occur in the medium to dense sand.

According to many researchers' report and literatures, many factors affect the soil liquefaction. The major factors as listed in Table 2. However, the main factors considered in both the Seed's and the T&Y's method are relative density (or void ratio), effective confining pressure, the characteristics of soil grain, fines content.

Relative density or void ratio

The soil element is more difficult to develop pore pressure as the relative density becomes denser. Based on the observation from Seed [10] in Niigata Earthquake happen in 1964, the soil liquefaction was found obviously where the relative density was about 50%. However, it did not find the soil liquefied in the soil stratum where the relative density greater than about 70%. Mulilis [11] presented that the liquefaction resistance of soil has linear relationship with the relative density as the relative density of soil is less than 70%, and the relationship is a function of confining pressure.

Effective Confining Pressure

The liquefaction resistance of soil is a function of the effective confining pressure, i.e., the soil liquefaction is easier to develop at shallow stratum than that at the deeper stratum. The liquefaction resistance of soil increases with increasing the effective confining stress of soil element, i.e., liquefaction potential of soil decreases with increasing the effective confining stress of soil element.

Based on the results of the cyclic triaxial test by Peacock [12], the required cyclic shear stress to develop liquefaction increases with increasing the effective confining pressure, however, the required cyclic shear stress ratio to develop liquefaction decreases with increasing the effective confining pressure.

Table 1 The boring data and analysis results from Seed's and T&Y's method of liquefied and unliquefied sites during Chi-Chi Earthquake in Central Taiwan

Loaction	a_{max}/g	Depth	Soil Type	N_{SPT}	σ'_v	$(N_1)_{,60}$	$(N_1)_{fc}$	FC	PC	FS-	FS-
NT-1-1	0.428	2.80	ML	4	5.90	6.0	19.9	98	44.7	0.40	0.61
NT-1-1	0.428	4.30	ML	7	7.69	9.2	18.7	54	13.9	0.46	0.51
NT-1-1	0.428	5.80	ML	10	9.54	11.8	24.7	89	15.5	0.52	0.66
NT-1-2	0.428	7.20	SM	11	12.15	11.5	17.3	21	7.0	0.61	0.58
NT-2-1	0.428	5.80	SM	7	11.57	7.5	13.9	25	7.0	0.50	0.56
NT-2-1	0.428	8.80	SC	12	14.71	11.4	19.1	43	13.0	0.65	0.60
NT-2-1	0.428	17.80	ML	35	23.70	26.2	34.2	80	13.0	2.11	1.49
NT-2-1	0.428	19.20	SM	45	25.15	32.7	34.1	29	9.0	2.19	1.38
NT-2-2	0.428	3.80	SM	10	5.25	15.9	23.0	30	6.0	0.70	0.55
NT-2-2	0.428	5.80	SM	10	7.18	13.6	20.8	30	7.0	0.55	0.47
NT-2-2	0.428	7.20	SM	17	8.62	21.1	22.3	6	3.0	0.59	0.48
NT-2-2	0.428	17.80	SM	31	19.32	25.7	30.5	36	9.0	1.77	0.85
NT-3-1	0.428	3.20	SM	10	4.54	14.6	23.7	27	11.7	0.66	0.59
NT-3-2	0.428	2.80	SM	6	3.79	11.8	17.7	22	5.0	0.43	0.40
NT-3-2	0.428	4.30	SM	14	4.88	23.1	31.9	48	7.0	1.29	0.80
NT-3-2	0.428	5.80	SM	11	6.52	15.7	22.7	28	5.0	0.56	0.45
NT-3-2	0.428	7.20	SM	23	8.13	29.4	36.3	25	5.0	1.28	1.19
NT-3-2	0.428	10.20	SM	17	11.21	18.5	24.2	20	5.0	0.64	0.50
NT-3-2	0.428	11.80	SM	39	13.08	39.3	44.0	21	3.0	1.36	2.46
NT-3-2	0.428	13.20	SM	35	14.67	33.3	38.1	26	4.0	1.44	1.59
NT-3-2	0.428	20.80	SM	54	23.72	40.4	40.9	27	5.0	1.97	2.58
ZH-1-1	0.192	2.80	SM	8	4.72	11.5	19.1	36	9.5	1.45	1.36
ZH-1-1	0.192	4.50	SM	10	6.44	12.3	19.0	25	10.1	1.24	1.18
ZH-1-1	0.192	5.80	SM	17	7.97	18.8	24.9	18	8.1	1.70	1.55
ZH-1-1	0.192	7.30	SW-SM	18	9.75	18.0	23.0	10	7.9	1.30	1.31
ZH-1-1	0.192	8.80	ML	12	11.40	11.1	23.8	89	35.2	1.11	1.41
ZH-1-1	0.192	10.30	ML	8	12.73	7.0	19.7	89	31.8	0.80	1.14
ZH-1-1	0.192	11.80	ML	14	14.20	11.6	24.7	97	38.6	1.17	1.49
ZH-1-1	0.192	13.30	ML	17	15.46	13.5	24.2	76	24.5	1.38	1.45
ZH-1-1	0.192	14.80	CL-ML	16	17.05	12.1	23.4	83	27.8	1.33	1.40
ZH-1-2	0.192	4.28	SM	4	8.06	4.4	11.6	31	4.0	0.68	0.94
ZH-1-2	0.192	6.00	SM	5	9.37	5.1	13.7	46	17.0	0.70	0.94
ZH-1-2	0.192	7.28	ML	4	11.40	3.7	13.5	59	5.0	0.57	0.91

Loaction	a_{max}/g	Depth	Soil Type	N_{SPT}	σ'_v	$(N_1)_{,60}$	$(N_1)_{fc}$	FC	PC	FS-	FS-
ZH-1-2	0.192	10.28	SM	6	14.04	5.0	11.9	31	5.0	0.62	0.84
ZH-1-2	0.192	11.78	ML	6	12.98	5.2	16.0	70	6.0	0.67	0.98
ZH-1-2	0.192	15.05	SP-SM	18	16.35	13.9	16.9	9	0.0	1.08	1.04
ZH-1-2	0.192	16.28	SP-SM	18	17.86	13.3	16.1	9	0.0	1.09	1.03
ZH-1-2	0.192	17.78	SP-SM	17	19.25	12.1	13.8	8	0.0	1.03	0.97
ZH-1-2	0.192	20.78	ML	14	22.58	9.2	17.4	55	6.0	1.32	1.17
ZH-1-2	0.192	22.28	SM	16	23.99	10.2	17.1	45	6.0	1.48	1.19
ZH-1-2	0.192	23.78	SW-SM	16	25.47	9.9	10.2	7	0.0	0.97	0.93
ZH-1-2	0.192	25.28	SW-SM	16	27.08	9.6	8.8	6	1.0	0.94	0.89
ZH-1-2	0.192	26.78	SP	19	29.09	11.0	12.8	9	3.0	1.23	1.12
ZH-1-3	0.192	2.28	SM	6	4.43	8.9	14.3	15	2.0	1.12	1.26
ZH-1-3	0.192	4.28	ML	3	6.41	3.7	17.7	99	22.0	0.64	1.16
ZH-1-3	0.192	5.78	ML	4	7.70	4.5	14.0	54	4.0	0.65	0.95
ZH-1-3	0.192	7.28	SW-SM	11	9.24	11.3	15.3	9	0.0	0.81	0.97
ZH-1-3	0.192	10.28	SM	13	12.25	11.6	18.7	34	2.0	1.13	1.08
ZH-1-3	0.192	11.78	SM	21	13.72	17.7	22.7	18	4.0	1.50	1.31
ZH-1-3	0.192	13.28	SW-SM	24	15.39	19.1	19.9	7	3.0	1.34	1.16
ZH-1-3	0.192	14.78	SM	26	17.16	19.6	24.0	20	3.0	2.03	1.46
ZH-1-3	0.192	16.28	SW-SM	18	18.98	12.9	16.6	10	5.0	1.11	1.07
ZH-1-3	0.192	17.78	SW-SM	23	20.66	15.8	14.9	6	2.0	1.28	1.03
ZH-1-3	0.192	19.28	SM	11	22.14	7.3	13.2	29	8.0	1.04	0.99
ZH-1-3	0.192	20.78	ML	11	24.08	7.0	19.1	92	9.0	1.13	1.27
ZH-1-3	0.192	22.28	ML	12	25.64	7.4	19.2	91	15.0	1.21	1.31
ZH-1-4	0.192	2.28	ML	4	3.81	6.4	16.1	59	7.0	0.84	1.06
ZH-1-4	0.192	3.78	SM	6	4.53	8.8	14.5	17	2.0	0.77	0.87
ZH-1-4	0.192	5.28	ML	6	5.92	7.7	17.9	61	6.0	0.78	0.95
ZH-1-4	0.192	6.78	SM	7	7.46	8.0	13.6	15	4.0	0.65	0.81
ZH-1-4	0.192	8.28	SM	12	9.28	12.3	17.9	15	6.0	0.93	0.96
ZH-1-4	0.192	11.28	SM	17	12.04	15.3	20.9	20	8.0	1.19	1.10
ZH-1-4	0.192	12.78	SW-SM	22	13.64	18.6	19.8	7	2.0	1.19	1.07
ZH-1-4	0.192	14.33	SM	18	15.45	14.3	19.2	18	4.0	1.24	1.08
ZH-1-4	0.192	17.28	SW-SM	22	18.90	15.8	19.2	10	0.0	1.33	1.14
ZH-1-4	0.192	21.78	ML	11	23.40	7.1	16.1	61	5.0	1.11	1.10
ZH-2-1	0.211	4.28	SM	6	6.08	7.6	15.0	33	5.0	0.78	0.86
ZH-2-1	0.211	5.78	SM	48	7.79	53.7	60.5	21	4.0	2.91	5.24
ZH-2-1	0.211	8.78	SM	37	11.35	34.3	40.7	29	5.0	2.85	5.25
ZH-3-1	0.192	5.80	ML	4	8.06	4.4	18.2	97	54.4	0.69	1.18

Loaction	a_{max}/g	Depth	Soil Type	N_{SPT}	σ'_v	$(N_1)_{,60}$	$(N_1)_{fc}$	FC	PC	FS-	FS-
ZH-3-1	0.192	7.30	ML	7	9.22	7.2	21.0	98	39.5	0.87	1.27
ZH-3-1	0.192	8.80	ML	6	10.80	5.7	19.3	97	59.4	0.73	1.15
ZH-3-1	0.192	10.30	MH	12	12.04	10.8	24.4	99	77.6	1.10	1.48
ZH-3-1	0.192	11.80	ML	11	13.35	9.4	21.0	80	18.1	1.01	1.22
ZH-3-2	0.192	4.77	SM	5	5.12	6.9	15.8	49	5.0	0.71	0.85
ZH-4-1	0.192	2.78	SM	5	3.81	8.0	13.6	18	4.0	0.70	0.82
ZH-4-1	0.192	13.28	SM	16	12.73	14.0	19.7	21	7.0	1.11	1.00
ZH-4-1	0.192	16.23	SM	13	15.84	10.2	14.8	13	4.0	0.87	0.89
ZH-4-1	0.192	17.23	SM	18	16.83	13.7	18.2	16	3.0	1.25	1.03
ZH-4-1	0.192	18.73	SM	19	18.75	13.7	17.9	16	3.0	1.34	1.06
ZH-4-1	0.192	26.78	ML	9	27.08	5.4	18.2	98	45.0	1.01	1.28
CY-1-1	0.227	2.80	SM	6	4.97	8.4	14.0	16	8.5	1.02	1.21
CY-1-1	0.227	4.40	SP-SM	6	6.59	7.3	12.4	10	10.2	0.66	0.98
CY-1-1	0.227	5.80	ML	11	7.93	12.2	22.9	65	20.4	1.28	1.31
CY-1-1	0.227	7.30	ML	8	9.51	8.1	18.7	66	8.5	0.88	1.10
CY-1-1	0.227	8.80	MH	6	10.80	5.7	19.6	99	23.6	0.67	1.11
CY-1-1	0.227	14.80	SM	18	16.59	13.8	19.7	30	6.9	1.43	1.13
CY-1-1	0.227	16.30	ML	11	17.98	8.1	19.6	82	31.5	0.99	1.15
CY-1-1	0.227	17.80	SM	48	19.66	33.8	37.7	36	18.8	3.44	4.19
CY-1-1	0.227	19.80	SM	42	21.78	28.1	31.1	27	17.1	3.68	2.19

Notice:

1. Location symbol meanings:

NT-1: Chenshin village, Nantou city. ZH-1: Lunya village in YuanLin town, Zhanghua county.
NT-2: Jungongliao, Nantou city. ZH-2: ShanHu village in Shetou, Zhanghua county.
NT-3: Lumei Bridge, Nantou city. ZH-3: Huangtsuo village in Datsun, Zhanghua county.
ZH-4: Meigang village in Datsun, Zhanghua county.
CY-1: Chinliao village in Hobi, Chaiyi county.

2. the measured PGA from the nearest seismometer.
3. $(N_1)_{60}$ is the corrected N_{SPT} value used in Seed's methods.
4. $(N_1)_{fc} = N_1 + \Delta N_f$ used in T&Y's methods.

The characteristics of soil grain

The dynamics strength of soil is affected strongly by the characteristics of soil grain such as grain size, grain shape, grain distribution and mineral composition. Seed [14] presented the relationship between the liquefaction resistance and the mean grain size (D_{50}). The liquefaction resistance increases with increasing with the D50 of soil specimen.

Ishibashi [15] show that for a given mean grain size (D_{50}), soil specimen with well-graded grain distribution have lightly greater liquefaction resistance than that with uniform grain size distribution.

Fines content

Several studies have shown that the liquefaction resistance of silty sand will initially decrease as the silt content increases until some minimum resistance is reached, and then increase as the silt content continues to increase.

Uyeno [16] suggested that liquefaction resistance of silty sand increases with increasing fines content as fines content of soil is 20% about. It is due to that void ratio of silty sand structure will be greater than the maximum void ratio of pure sand (e_{max}) as fines content greater than 15% to 17.5%, i.e., some sand grain suspended in a silt matrix at the time, and the significance of cyclic strength of fines will be greater than that of sand grain.

Based on the suggestion by Polito [17], for silty sands and sandy silts there is a large decrease in cyclic resistance that occurs when the silt content of the soil becomes greater than the limiting silt content, and the largest amount of silt that can be accommodated in the voids created by the sand skeleton has been called the limiting silt content and occurs between 25 and 45% for most sands. If the silt content is greater than the limiting silt content, the cyclic resistance of these soils is also controlled by either the relative density of the specimen and is markedly lower for that it is for soils below the limiting silt content at similar relative densities. Additionally, the increase in cyclic resistance that occurs with an increase in relative density occurs at a slower rate.

Table 2 The Factors Effects on Cyclic Strength (After Chen [13])

Effect Factors	Level of Effect	
	Pure Sand	Sand with fines
Average Effective Confining Pressure， $\bar{\sigma}_0$	R	R
Void Ratio，e	V	V
Saturated degree，S_r	V	V
Overconsolidation Ratio，OCR	L	V
Pre-strain history	V	V
Sample Prepared Method	V	V
Grain Size, Distribution and Mineral Contents	V	V
Frequency of Loading, H_Z	R	L
Time Effect	R	R
Volume change during shear strain($\gamma < 0.5\%$)	U	U

Note： V：Major effect factor L：Minor effect factor

R：Light effect factor U：Significance unknown

Ⅲ. COMPARISON OF SEED'S METHOD AND T&Y'S METHOD

Because there are many similarity between the Seed's method and the T&Y's method, they are discussed in this paper. Table 3 are shown the comparison with the Seed's method, JRA's method, NJRA's method and the T&Y's method. The main difference of the Seed's method and the T&Y's method are the consideration of effect of fines content.

3.1 Effect of Fines Content

The main difference of the Seed's method and the T&Y's method is the consideration of the effect of the fines content on the liquefaction resistance of soil. The maximum amount of fines content is counted up to 35% in the Seed's method. Lai [18] presented his study that the consideration will underestimate the soil cyclic resistance as soil with the high fines content, e.g. FC> 35%.

The fines content of soil stratum for most cases used to create the T&Y's method is less than 35%. This causes the limitation of the T&Y's method to predict the liquefaction behavior of soil as the fines content of soil is greater than 35%. Furthermore, mean of the value of N_1 of soil has obvious difference between that had been investigated in Japan used in the T&Y's method and that had been investigated in the central Taiwan during Chi-Chi Earthquake, 1999.

Table 4 shows that the mean of $(N_1)_{60}$ of soil at liquefied site in the central Taiwan is generally much greater than the soil that has been investigated in the T&Y's method, in particular, for the soil stratum with the fines content greater than 35%. Therefore, the count for the fines content in the T&Y's methods should be modified as the method is used in Taiwan.

Table 3 Comparison of the Seed's method, JRA's method, NJRA's method and T&Y's method

Method		NCEER(1998) (Seed's method)	JRA's method	NJRA's method	T&Y's method
CSR	CSR eq.	$\tau_{ave} = 0.65\gamma h \frac{a_{\max}}{g} r_d$	$\left(\frac{\tau_{\max}}{\sigma'_v}\right)_L = r_d \cdot C_Z \cdot C_G \cdot C_I \cdot k_{s0} \cdot \frac{\sigma_v}{\sigma'_v}$		$\tau_{ave} = 0.65\gamma h \frac{a_{\max}}{g} r_d$
	MSF	$r_m=(15/N_{eq})^{0.2}$	$c_2=(15/N_{eq})^{-0.2}$		$r_n= 0.1(M-1)$
	r_d value	Seed [14]	Iwasaki [19]		Iwasaki [19]
CRR curve	From	According to the in-situ boring data	According to the results from laboratory test	According to the results from laboratory test	According to the results from laboratory test
	Parameters	$(N_1)_{60,cs}$	N_a	N_a, c_w	N_a, K_0, C_s
The correction of the effect of soil grain		NCEER [20]: $(N_1)_{60,cs} =\alpha+\beta(N_1)_{60}$	R_2 , R_3	$N_a =C_1+ C_2N_1$	$N_a =N_1+\Delta N_f$
		$\Delta N_f= f\,[(N_1)_{60}\,,\text{FC}]$	$R_2 + R_3= f\,[D_{50},\text{FC}]$	$\Delta N_f= f\,[(N_1)_{60}\,,\text{FC}]$	$\Delta N_f= f\,[\text{FC}]$

In order to understand the variation of factor of safety between the Seed's method and the T&Y method as the fines content of soil changes. Statistics method is used to analyze the result obtained from using the two methods to test the data of liquefied area in the central Taiwan during Chi-Chi earthquake (the area includes Nantou, Changhua, and Taichung during Chi-Chi Earthquake (the data were bored by NCREE), and Hobi village during 1022 Earthquake). The result obtained from Student t-Test in Statistics is shown in Figure 1.

Table 4 Comparison of *N* value with sample used by Tokimatsu [6] and sample bored in liquefied site during Chi-Chi Earthquake

FC(%)	$N_{1,60}$ (From Lai [18])	N_1 (From Tokimatsu[6])
0-5	—	12
10-20	12	7
20-60	16	5
>60	9	3

There are three descriptions in the hypotheses which is used in the Student t-Test:
(1). Null hupothesis: H_0: the factor of safety between the two methods is the same.
(2). Alternative hypothesis: H_1: the factor of safety between the two methods is different.
(3). 95% confidence interval is used, i.e., the factor of safety between the two methods is different as the value α from testing less than 0.05, or it can be assumed to be the same.
It can be found in Figure 1 that the factor of safety between the two methods has obvious variation as the fines content greater than 35%. On the other hand, the result obtained from the two methods can be regarded as the same as the fines content is less than 35%.

3.2 The variation of results obtained from the two methods
According to the study of Lai [18] and Li [21], the Seed's method has higher accuracy to evaluate the liquefaction potential of soil stratum. Let the difference of the factor of safety obtained from the Seed's and the T&Y's method be the value of ΔFS. The relationship of the value of ΔFS and the fines content of soil is shown in Figure 2. The equation for the upper and the lower bound for the relationship between the value of ΔFS and the fines content is:

Upper bound: $\Delta FS = (1.40 - 0.01FC)^4 - 0.16$ (1)

Lower bound: $\Delta FS = (1.30 - 0.01FC)^6 - 0.60$ (2)

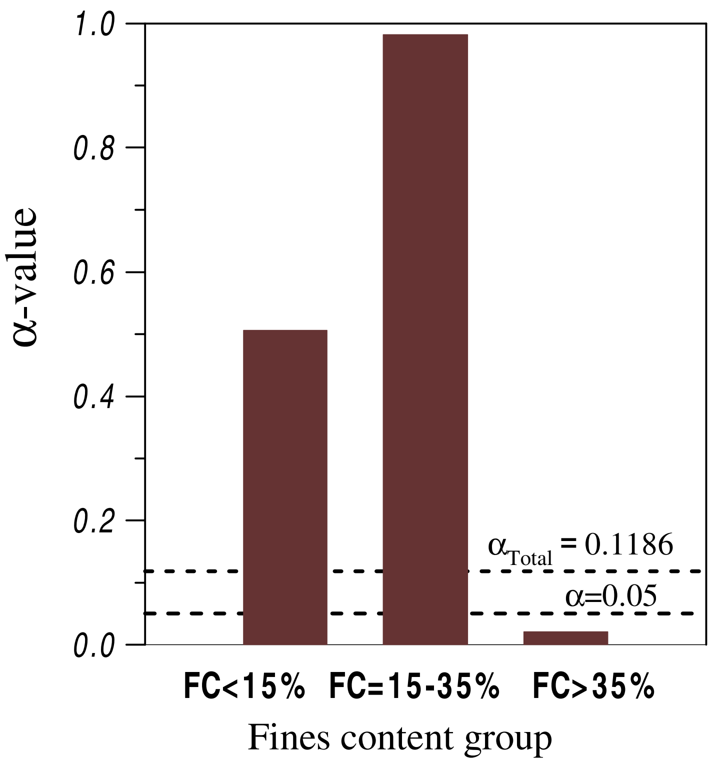


Fig. 1 Result by using Student t-Test in Statistics

The scattering of the value of ΔFS versus the fines content is due to the analyzing depth below ground surface in the liquefied site is different. The different depth below ground surface will cause the depth correction factor (stress reduction factor) variance, but the amount of liquefaction potential variances due to the depth correction factor variance is much less than that due to the fines content variance for the higher fines content. Therefore, all of the value of ΔFS versus the fines content becomes approximately a bound distribution.

The correction factor for the factor of safety in the T&Y's method can be calculated using the mean value of the upper and the lower bound equations which are shown in Eq. (1) and Eq. (2). The correction factor for the factor of safety in the T&Y's method decreases with increasing the fines content. It is approximately to be zero as the fines content at 50%, and the result shows that correction factor of the fines content (ΔN_f) does not increase linearly with increasing the fines content.

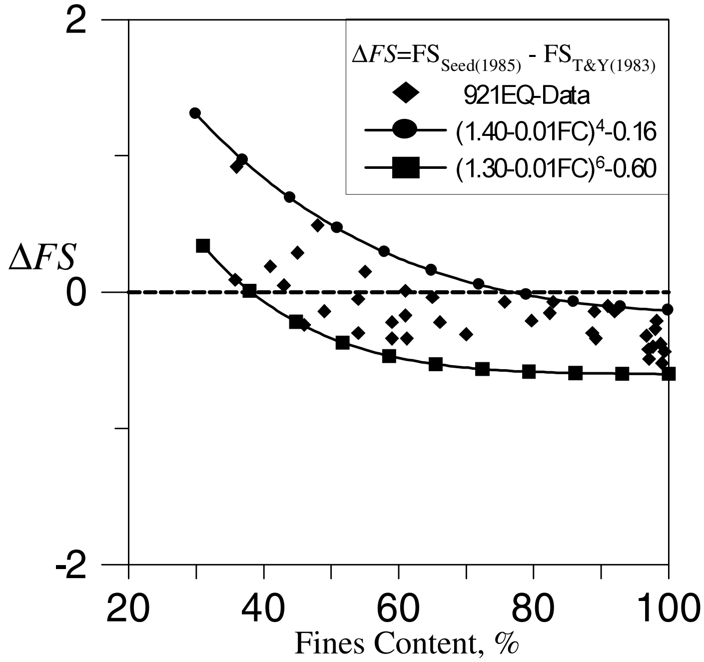


Fig. 2 Variation of ΔFS based on fines content

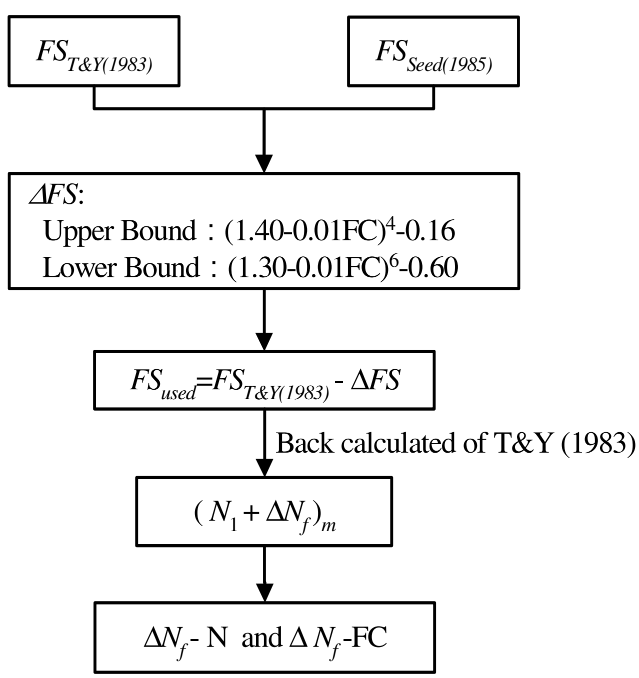


Fig. 3 Flowchart used to modify the T&Y's method

3.3 Proposed correction factor for the fines content

In order to improve the accuracy of the T&Y's method for the soil stratum with the higher fines content. This study uses a procedure to determine the correction factor of the fines content for the T&Y's method. The flowchart of the procedure is shown in Figure 3. The first step in the flowchart is to find the reasonable factor of safety of the soil element in the liquefied site. The reasonable factor of safety of liquefaction (called $FS_{T\&Y,m}$ later) is to subtract ΔFS from $FS_{T\&Y}$. After the value of $FS_{T\&Y,m}$ is found, the back-calculated procedure in the T&Y's method is used to find the modified value of $N_1 + \Delta N_f$ (called $(N_1 + \Delta N_f)_m$ later) and the modified value of ΔN_f (called $\Delta N_{f,m}$ later). Finally, the relationship between $\Delta N_{f,m}$ and the fines content can be found. The relationship between $(N_1 + \Delta N_f)_m$ and N_1 of the data in liquefied site during Chi-Chi Earthquake for the unit value of $FS_{T\&Y,m}$ is shown in Figure 4.

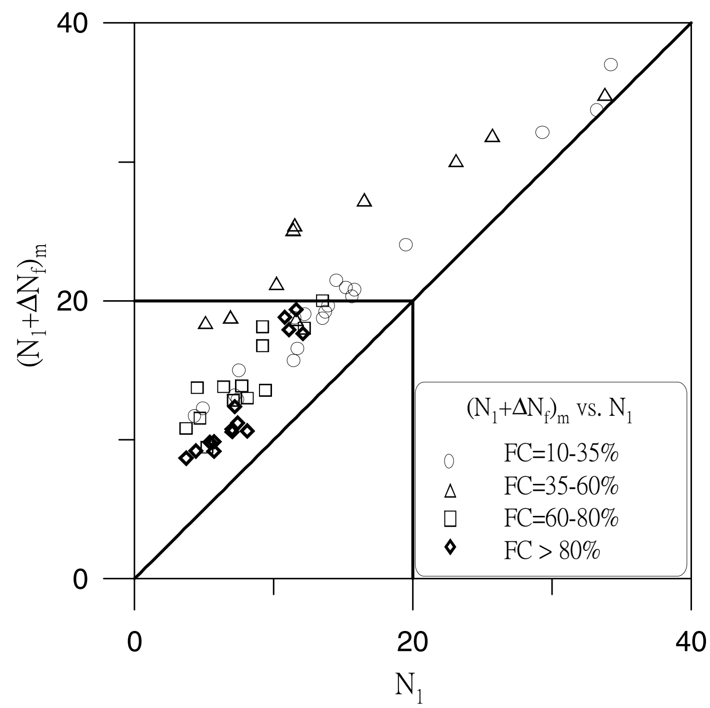


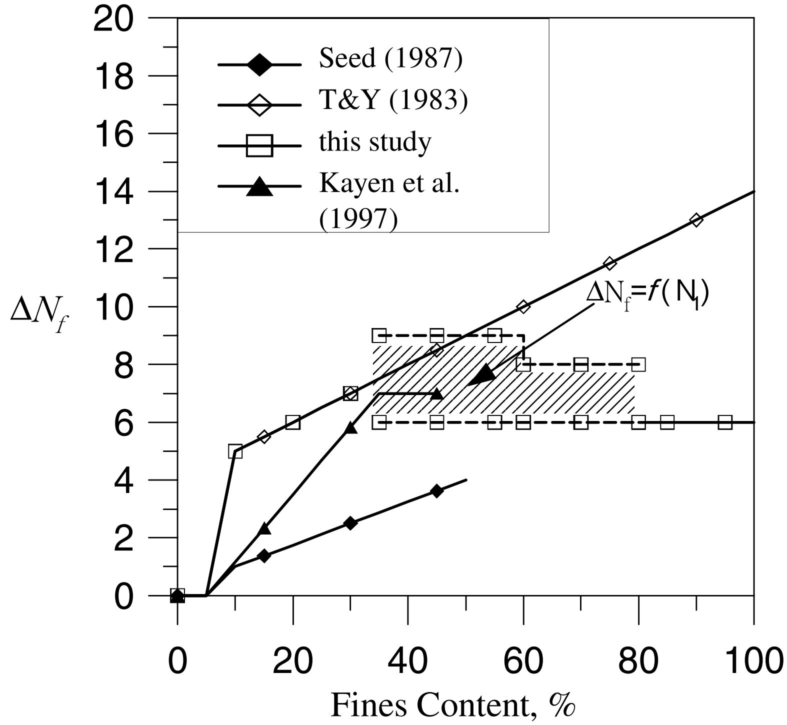
Fig. 4 Relationship between $(N_1 + \Delta N_f)_m$ and N_1

Based on the observation in Figure 4, the value of $(N_1 + \Delta N_f)_m$ has the maximum value when the fines content of soil element is between 35% and 50%. And, the value of $\Delta N_{f,m}$ decreases with increasing the fines content as the fines content is greater than 50%. It can also be found from the result obtained from the data in the liquefied site during Chi-Chi Earthquake in Figure 4 that the value of $(N_1 + \Delta N_f)_m$ is less than 20 as the fines content is greater than 50%. The correction factor of the fines content of this study is determined from the regression of data in Figure 4. The correction factor for the variant fines content group is shown as following:

FC=35-60% , $\Delta N_{f,m} = -0.10 N_1 + 9$ (3)

FC=60-80% , $\Delta N_{f,m} = -0.10 N_1 + 8$ (4)

FC > 80% , $\Delta N_{f,m} = 6$ (5)



* - for the soil element with mean grain size (D_{50}) less then 0.15 mm, Seed [22] suggested that correction factor of the fines content of soil element is 7.5.

Fig. 5 Relationship between ΔN_f and fines content

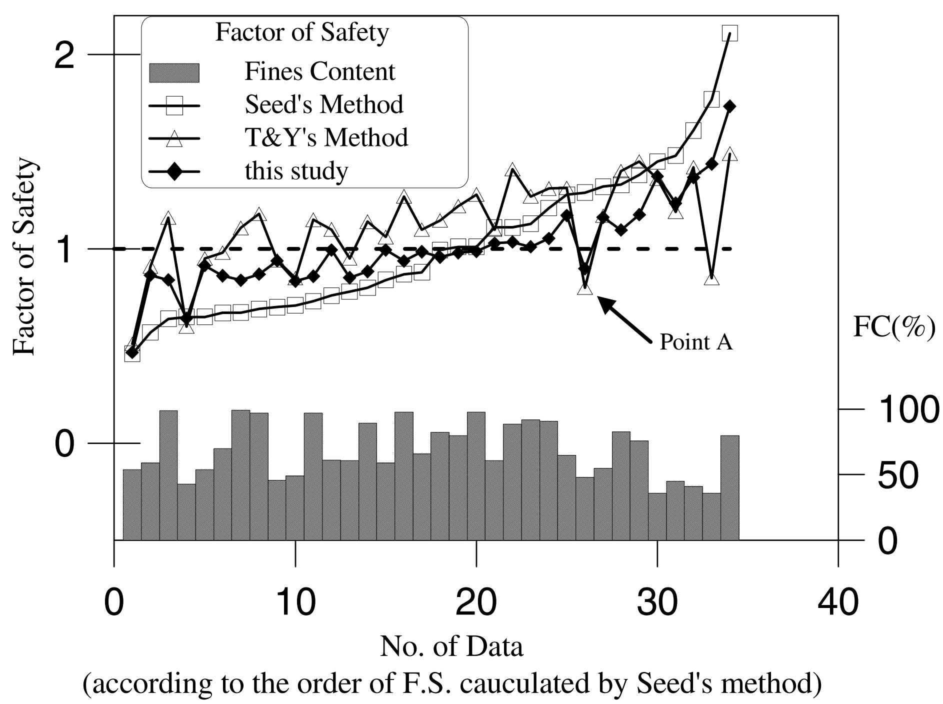


Fig. 6 Comparison of the Factor of safety calculated from three methods

3.4 Performance of the correction factor for the fines content

The correction factor for the fines content has been suggested by several studies, however, most of these studies is used for the fine content less than 50%. The data suggested by Seed [4], Tokimatsu [6], Kayen [8] and this study are plot in Figure 5 for the purpose of comparison.

Figure 5 shows that the variation of the correction factor for the fines content among the several methods. As shown in the figure, the correction factor for the most of the methods increases with increasing the fines content. The correction factor for the fines content of this study has the greater value as the fines content between 30% and 60%. And, the amount of the value is similar to the value correspond to FC in the vicinity of 50% suggested by Kayen [8]. The amount of correction value for the fines content between 35% and 60% is similar to the value correspond to FC in the vicinity of 50% suggested correction by Seed [4]. However, the contribution of the fines effect on liquefaction resistance should be reduced as the fines content is greater than 80%.

Figure 6 shows that the factor of safety in this study is very similar to that of Seed's method. The number lies, generally, between the result of Seed's method and the result of T&Y's method. the factor of safety of this study tends to be closed to that of Seed's method as the factor of safety approaches 1. The factor of safety shows greater difference between this study and Seed's method when the factor of safety is greater than 1. This mean s that the value obtained from this study will be more conservative, compared to Seed's result.

The samples with the higher fines content, which were bored at sites liquefied during the Chi-Chi Earthquake, are used to verify the correction factor suggested for the fines content shown in Eq. (3) to Eq. (5). The results (the factor of safety) obtained from Seed's method and T&Y's method are shown in Fig. 6 for the purpose of comparison.

It notes that result of the point A in Figure 6 is slightly conservative, this is because the soil sample of point A was bored in the shallow depth. In this situation the stress reduction coefficient r_d has greater variance between the Seed's method and the T&Y's method in the shallow depth. The factor of safety using Chinese Building Code to analyze the soil element at the point A in Figure 6 is 1.06. This implies that the suggested correction factor for the fines content in this study does not seriously underestimated.

IV. THE DISCUSSION OF THE EFFECT OF FINE CONTENT

4.1 The observations of the SPT-*N* value

The values $N_{1,60}$ and fines content of soil which are shown on Figure 7 are bored from the site at the liquefied area after Chi-Chi Earthquake in the central Taiwan, and the coefficients of the regression lines of that are shown on the Table 5There are some results from the regression:

1. The correlation coefficient between the values $N_{1,60}$ and fines content in section I (i. e., fines content ranges from 20 percent to 60 percent) is greater than that in section II (i. e., fines content is over 60 percent).
2. The slope of regressive line is steeper when the fine content is in section I., whereas it is gentle in section II.

Based on the upper results, the values $N_{1,60}$ will be decreasing with the increasing of the fine content increasing, however it will approximate a stationary value as fines content greater than 60%.

4.2 The forms of the correction factor of fines content

In the Table 3, the equation of correction factor of fines content can be divided into three forms, such as :

A. The fines content is used to correct the value of liquefaction resistance. It is assumed in JRA's method that there is a direct relationship between the grain size and liquefaction resistance. The correction factor of fines content will be only influenced by fines content. However, it is not reasonable that there will be the same amount of correction (Liquefaction resistance) whether the relative density of soil is high or low.

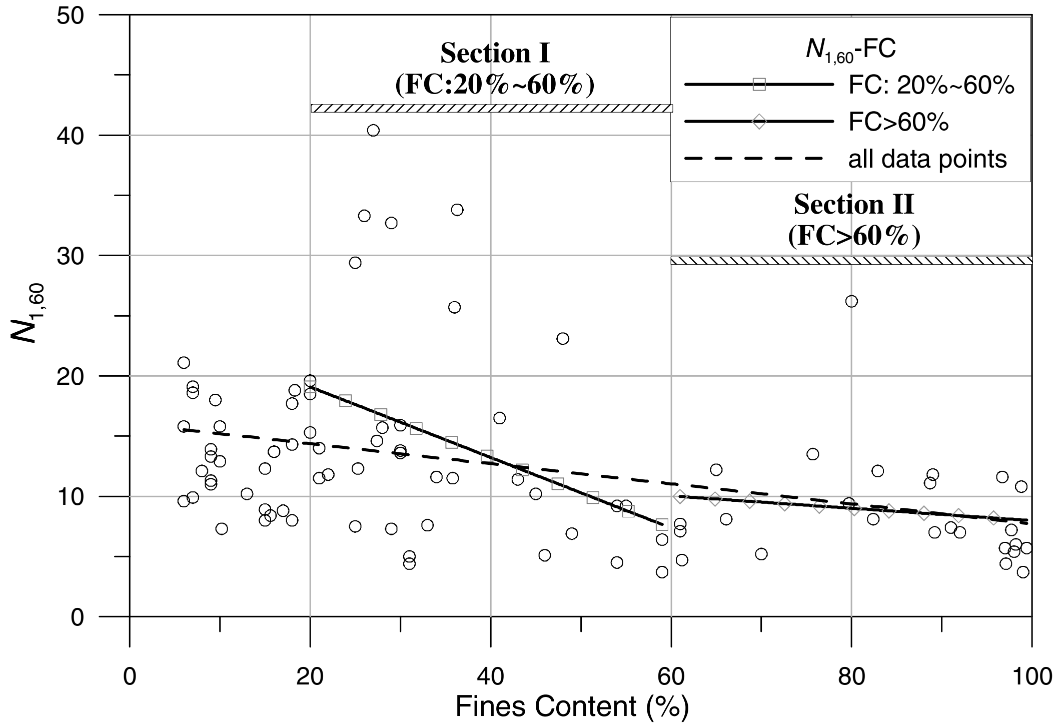


Fig. 7 The relationship between $N_{1,60}$ and fines content from in-situ boring data(Ni, [23])

Table 5 The correlation coefficients of the relationship between the value $N_{1,60}$ and fines content (Ni, [23])

		All data point	Section	Section
Fines Content		6-99%	20-60%	＞60%
Correlation Coefficient, r^2		0.1249	0.1311	0.0235
Regressive	Slope	-0.0832	-0.3077	-0.0512
equation	Intercept	16.0325	25.5908	13.1029

B. The fine content is used to be the parameter to correct the value of N_1 (or $N_{1,60}$) to become $N_{1,f}$ (or $N_{1,60cs}$). It is assumed that there is a direct relationship between the fine content and values ΔN_f, and the correction factor of fines content (ΔN_f) will be only influenced with fines content in T&Y's method. However, it will overestimate the weighting value of fines content in the correction equation when the fines content is higher.

C. The fines content is used to correct $N_{1,60}$ to become $N_{1,60,f}$, and both the fines content and $N_{1,60}$ are the parameters to determine the amount of correction. This form is used in the NJRA's method and the NCEER's method.

Eq(6) to Eq(8) are suggested by Ni [23]:

$$\left(N_1\right)_{60cs} = K_s \left(N_1\right)_{60} \tag{6}$$

$$K_s = 0.0167FC + 0.8582 \tag{7}$$

$$\Delta N_f = \left(0.0167FC - 0.1418\right) N_{1,60} \tag{8}$$

The amount of correction factor of fines content will be similar to results form using the Eq. (3) and Eq. (8). For example, suppose that the fines content is 50% and the $N_{1,60}$ (or N_1) is 12, the amount of correction factor for fines content (ΔN_f) will be 7.8 from using Eq. (3) to calcute, and that will be 8.3 from using Eq. (8) to calculate.

V. CONCLUSIONS

Analyzing soil strata data from site liquefied during the Chi-Chi Earthquake using Seed's method and T&Y's method, the following conclusions can be drawn:

1. The major factor to cause the analytic result variance between the Seed's and the T&Y's method is the weighting consideration of the fines content.
2. The results from Student *t*-Test in Statistics show that the factor of safety calculated from the Seed's method and the T&Y's method can be regarded as the same as fines content less than 35%. However, the results obtained from the T&Y's method will overestimate the liquefaction resistance as fines content greater than 35%.
3. The value of ΔN_f in the T&Y's method does not increase linearly with increasing fines content of soil. The ΔN_f has maximum value as the fines content is somewhere between 30% and 50%.
4. To improve the accuracy of the T&Y's method, the study suggests to use Eq. (3) to Eq. (5) to correct the effect of the fines content, and Eq. (6) to Eq. (8) are suggested to be the correction factor of fines content of Seed's method.

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