行政院國家科學委員會專題研究計畫　成果報告

土壤液化評估中細料含量界定與特性之考量

計畫類別：個別型計畫
計畫編號：NSC92-2211-E-002-045-
執行期間：92 年 08 月 01 日至 93 年 07 月 31 日
執行單位：國立臺灣大學土木工程學系暨研究所

計畫主持人：翁作新

計畫參與人員：余定縣、孫家雯

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行政院國家科學委員會補助專題研究計畫 ■ 成 果 報 告
□期中進度報告

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計畫主持人：翁作新
共同主持人：
計畫參與人員： 余定縣、孫家雯

成果報告類型(依經費核定清單規定繳交)：■精簡報告 □完整報告

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執行單位：國立台灣大學土木工程學系

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中文摘要

本研究取南投市貓羅溪岸出現液化現象之工務所與第二條高速公路高架橋下附近土壤，分別以 200 號篩與 400 號篩作為細粒料之界定標準，藉由控制試體乾密度相同，改變試體中之細粒料含量，利用 C.K.C.動力三軸儀以及中空圓柱試體扭剪儀進行動力試驗，求得不同細粒料含量土壤之抗液化強度，以便探討不同細粒料界定標準與特性對土壤抗液化強度之影響。根據動力試驗結果顯示，不論其細料之界定為何，當細料含量不超過 30 %時，土壤整體的行為偏向與一般砂性土壤的行為相似，呈現較小的變形性、剪力模數維持定值以及孔隙水壓力在破壞前出現激增等現象，而對純細粒料試體，會出現變形量大、剪力模數隨反覆作用次數增多而改變等動態特性。當土壤處於疏鬆狀態之條件下，具相同乾密度之試體，其抗液化強度會隨著細粒料含量的增加，出現先下降後上升的趨勢，土壤在細粒料含量約為 20-30%時出現最小的液化阻抗強度。純細粒料試體抗液化強度約為此最小抗液化強度的 1.28 至 1.45 倍。

根據本研究中之試驗結果與他人之研究結果相比較，可以發現貓羅溪岸土壤在疏鬆狀態下，以 400 號篩作為細粒料界定標準時，其細料含量對抗液化強度之影響，比以 200 號篩為界定標準更顯著，而且所得細料含量與液化強度關係較有一致性。

關鍵詞： 砂、地震、液化、細料、細料界定、動力試驗

Definition of Fines and Liquefaction Resistance of Maoluo River Soil

ABSTRACT

Two definitions of fines, soil particles finer than the No. 200 sieve (0.075 mm) and No. 400 sieve (0.038 mm), are adopted to evaluate the effect of fines content on the liquefaction resistance of the silty soil in the Maoluo River area of Nantou City. The specimens of different fines contents according to these two definitions of fines were prepared by moist tamping to a dry density of 1400 kg/m^3. The liquefaction resistance of these specimens were tested using the cyclic triaxial test apparatus and the cyclic torsional shear device. Comparisons were made between the liquefaction resistances of soils containing fines according to different definitions. The results show that the effect of fines on the liquefaction resistance of Maoluo River soil is more pronounced and consistent based on the fines content defined as the portion finer than the No. 400 sieve than that with fines defined as soil passing the No. 200 sieve. .

Key words: earthquake, liquefaction, fines content, fines definition, cyclic tests, sand

一、　前言

早期研究土壤液化的學者專家大都侷限於純淨砂土的研究，對於含細粒料土壤的液化研究較少。其主要的原因是早期學者認為，高細粒料含量的土壤具有較高的抗液化強度故難以發生液化。但是現地沉積土層或多或少都含有細粒料，而且從近年地震案例的研究中可以發現，含高量細粒料的土壤也會有發生液化的可能。

關於砂土細粒料含量對液化潛能的影響，目前較常使用的土壤液化簡易評估法[1,2]，通常都是考慮通過 200 號篩(<0.075 mm)之土壤含量百分比，少數評估法則採以顆粒平均粒徑大小或細粒料塑性指數作為修正參數，且對於高細粒料含量的土層常常給予較高之抗液化強度的評定。但是在集集大地震中，南投貓羅溪沿岸發生液化之土層中，通過 200 號篩的細粒土壤含量甚高[3]，理應具有較高之抗液化強度，但事實卻不然，由此可見土壤依照傳統 200 號篩分類，其中細粒料含量與土壤抗液化強度之關係仍有再研究的必要性。本研究中嘗試比較以不同顆粒尺寸，即 200 號篩(0.075 mm)與 400 號篩(0.038 mm)，界定細粒料，探討不同細粒料界定及細料特性對土壤抗液化強度之影響。

本研究選自於南投市貓羅溪岸出現液化現象之工務所與第二條高速公路高架橋下附近土壤，控制試體的乾密度，依據不同細料界定改變試體之細粒料含量，利用 C.K.C. 動力三軸儀試驗，以及中空圓柱形試體動態扭剪試驗，求取試體之液化阻抗強度，以求瞭解細粒料含量及其界定對土壤抗液化強度之影響。研究中同時也對細粒料含量與土壤整體之動態特性的影響關係，及乾密度對高細料含量土壤液化強度之影響做更進一步的探討。藉此研究成果可提供研究學者與工程界，評估台灣本土高細粒料含量砂土液化潛能，以及工程設計或研究之參考。

二、　試驗內容

本試驗所使用的重模試體土樣，乃取自南投市貓羅溪岸第二高速公路高架橋下區域之土壤與工務所附近之土壤，取樣深度距離地表面約 1 至 1.5 公尺。其中工務所區域，根據試驗結果得到其現地土壤之平均含水量為 18.3 %，乾密度值為 1400 kg/m^3。該兩區域的土壤，由試驗結果之粒徑分佈曲線顯示於圖一及基本性質示於表一。經統一土壤分類法工務所土壤屬於粉質砂土（SM），橋下土壤屬於低塑性土壤（CL）。

如依一般土壤分類法將土樣以 200 號篩為界，分為粗粒料與細粒料兩部份，分別進行土壤基本物理性質試驗，由試驗結果發現兩處粗粒料與細粒料各自之粒徑分佈曲線(圖二)與基本性質試驗數值相近。根據統一土壤分類法橋下與工務所土樣之粗粒料部分，均可判定為不良級配砂土 SP，細粒料部份橋下土樣與工務所土樣也皆屬於低塑性黏土 CL。另外以 X 光繞射分析儀進行半定量分析，求取土壤礦物種類與其含量，兩區域礦物含量以石英所佔的比例最高。動態強度試驗結果亦顯示，相同細料含量之兩

處土壤的抗液化強度相同。綜合上述，橋下與工務所土樣中的粗粒料與細粒料土樣其實各自應為同一種土壤。

表 一.橋下與工務所土壤之基本性質

項目	工務所土樣	橋下土樣
比重	2.68	2.69
現地乾密度(kg/m^3)	1400	—
現地含水量(%)	18	—
最大空隙比	1.02	1.26
最小空隙比	0.56	0.74
最大乾密度(kg/m^3)	1716	1547
最小乾密度(kg/m^3)	1330	1191
液性限度LL	20.5	27.78
塑性限度 PL	17	19.48
塑性指數 PI	3.5	8.3
平均粒徑 D_{50}(mm)	0.078	0.04
均勻係數Cu	43	37
曲率係數Cc	2	5
細粒料含量FC(%)	48	74
統一土壤分類	SM	CL

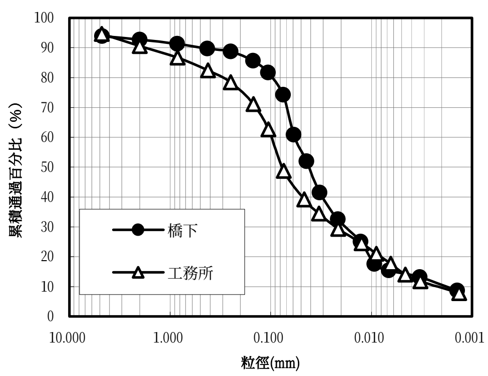
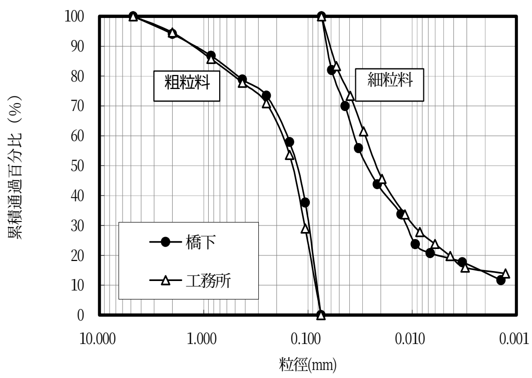


圖 一. 貓羅溪岸第二高速公路高架橋下、工務所附近之粒徑分佈曲線圖



圖二. 橋下、工務所之粗粒料與細粒料粒徑分佈曲線圖

本研究之液化強度試驗, 係採用美國加州大學柏克萊分校 C. K. Chen 及 J. P. Mulilis 所設計之動力三軸儀，與美國 GCTS(Geotechnical Consulting and Tesing Systems) 公司所設計製造之動態中空圓柱試體扭剪試驗儀，進行動態加載試驗（Dynamic Test）。其加載為頻率 1 Hz 之正弦載重波（Sine Wave），並且依照試體之有效應力及所

欲施加之反覆剪應力比（Cyclic Stress Ratio, CSR），設定進行動態加載試驗所需之反覆軸差應力值(三軸試驗)及扭剪力矩(扭剪試驗)[4,5,6]。

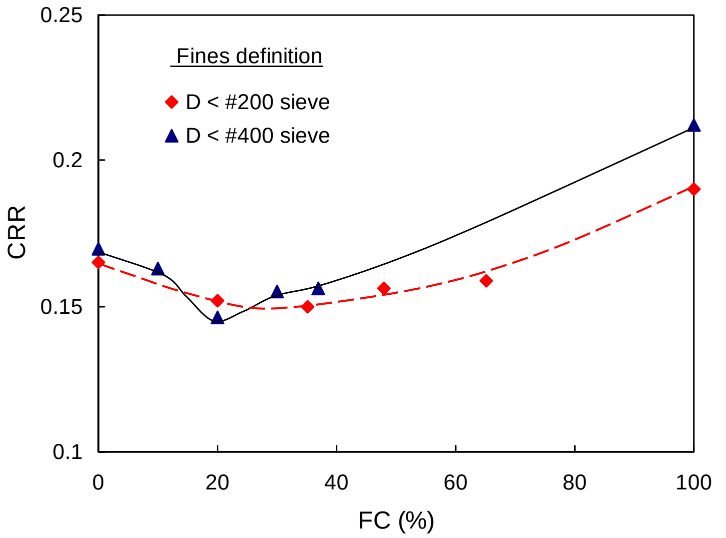
三、 試驗結果與討論

為確保中空圓柱試體扭剪試驗結果與動力三軸試驗結果之對應正確度，故進行測試與驗證試驗，以利用 CKC 動態三軸試驗儀對工務所土樣之粗粒料部份為本試驗之驗證對象。以相同控制參數及相同試體初始有效應力 78 kPa 下，施加不同反覆應力。將中空圓柱形試體扭剪試驗與動力三軸試驗結果之液化強度曲線，取相同引致液化之作用次數下，兩者反覆應力比之比值可得 $(CSR)_{扭剪} = 0.666(CSR)_{三軸}$。其中 0.666 就是反覆三軸與反覆扭剪試驗之反覆應力修正係數 C_r。本研究採用 Fine et al. (1971)[7]、Seed and Peacock (1971)[8]與 Castro (1975)[9]三個建議公式進行計算 C_r 值後取平均，求出修正係數 C_r 約略為 0.68，與本試驗所求出的結果相當接近。可驗證在整個中空圓柱形扭剪試驗過程，包括重模試體的製作、試驗步驟、控制與操作、以及量測系統之可信度。

本研究依據通過 200 號篩 與 400 號篩$(FC)_{400}$ 之細粒料界定，對土壤的動態特性與抗液化強度之影響進行研究。以通過 200 號篩為細料之試體細料含量$(FC)_{200}$ 包括 0 、10 、20 、35 、48、65、74 以及 100 %，而以通過 400 號篩為細料之試體細料含量$(FC)_{400}$ 包括 0 、10 、20 、30 、37 以及 100 %。這些土壤依統一土壤分類法分別屬於粉土質砂土（SM）、粉土（ML）以及低塑性粘土（CL），除了本身的顆粒組成與塑性性質不同外，其對砂土受動態應力時所導致的液化行為之影響亦有所不同。

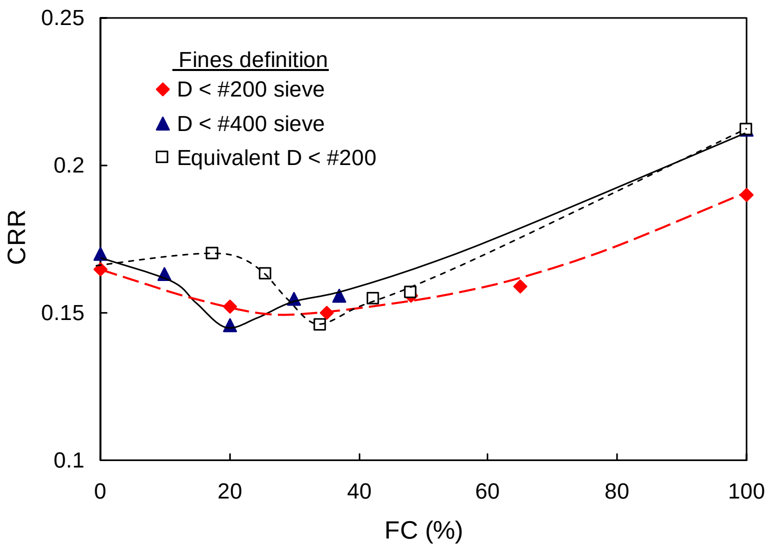
在土壤的動態特性方面，當細粒料含量比較小時，土壤整體的行為偏向與一般砂性土壤的行為相似，呈現較小的變形性、剪力模數維持定值以及孔隙水壓力在破壞前出現激增等現象；但對於純細粒料試體而言，試體則會出現變形量大、剪力模數隨反覆作用次數增多而改變等不同於砂性土壤而比較接近粘土的動態特性。純細粒料試體在動力三軸試驗中雖有大變形量，但其孔隙水壓之激發，卻未能使其有效應力趨於零，或初始液化現象。

本研究中係以試體軸向應變達 5 %時即定義該試體發生液化破壞。圖三則顯示不同細料界定時，貓羅溪岸土壤受到反覆作用次數等於 15 時，細料含量與液化阻抗強度(CRR)之關係。由此試驗結果得知，在相同乾密度條件下，試體的細粒料含量大約在 20-30 %時會出現最低的抗液化強度。由圖三中也可看出純細粒料成分的試體會有最高的抗液化強度，其強度在以通過 200 號篩為細料時，約為最低強度之 1.28 倍；而以通過 400 號篩為細料時，則約為最低強度之 1.45 倍。

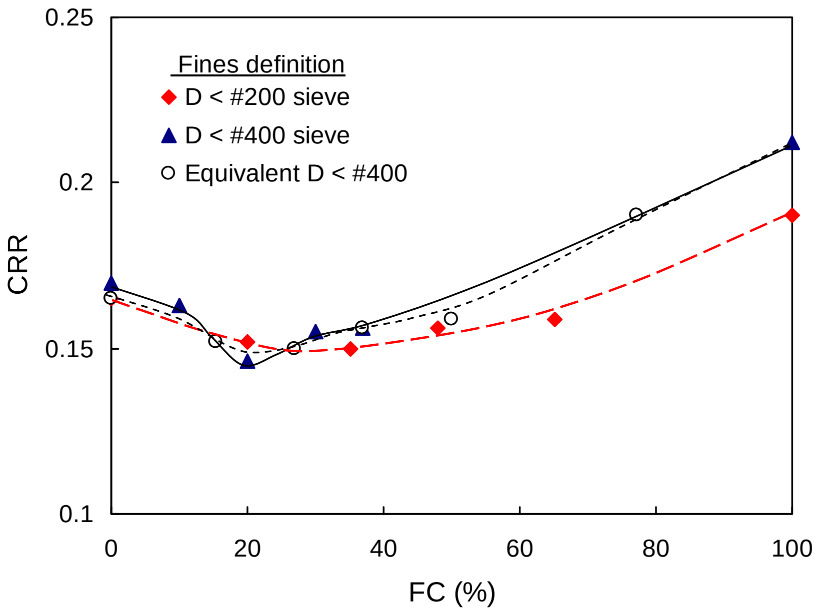


圖三　貓羅溪岸土壤反覆作用次數等於 15 時，細料含量與液化阻抗強度之關係

藉由上述之比較結果，可以發現以 200 號篩界定之純砂試體與以 400 號篩界定之純砂試體兩者之抗液化強度大小相近。但若以小於 400 號篩為細料時，其細料含量對土壤液化強度之影響比較顯著。若將以 400 號篩為界定之試體的細料含量，轉換為相當$(FC)_{200}$，則可比較細粒料不同時，$(FC)_{200}$之影響。同樣也可將以 200 號篩為界定之試體的細料含量，轉換為相當$(FC)_{400}$，比較不同粗粒料時，$(FC)_{400}$之影響。圖四與圖五各為將$(FC)_{400}$轉換為相當$(FC)_{200}$與將$(FC)_{200}$轉換為相當$(FC)_{400}$時，細料含量對土壤液化強度的影響。可見以小於 400 號篩為細料界定時，不論粗料如何，可有較一致的細料含量與土壤液化強度的關係。



圖四　相當$(FC)_{200}$對液化強度的影響



圖五　相當$(FC)_{200}$對液化強度的影響

四、　結論

(1) 動力三軸試驗與中空圓柱試體扭剪試驗結果，經適當修正，所得的液化強度相同。
(2) 根據試驗結果，當細粒料含量不超過 30 %時，土壤整體的行為偏向與一般砂性土壤的行為相似，呈現較小的變形性、剪力模數維持定值以及孔隙水壓力在破壞前出現激增等現象；對於純細粒料試體，試體會出現變形量大、剪力模數隨反覆作用次數增多而改變等動態特性。
(3) 在相同乾密度條件下，試體的細粒料含量大約在 20-30 %時會出現最低的抗液化強度；純細粒料成分的試體會有最高的抗液化強度，其強度在以通過 200 號篩為細料時，約為最低強度之 1.28 倍，而以通過 400 號篩為細料時，則約為最低強度之 1.45 倍。
(4) 以 400 號篩作為細粒料界定標準時，其細料含量對抗液化強度之影響，比以 200 號篩為界定標準更顯著，而且所得細料含量與液化強度關係較有一致性。

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成果自評

本計畫研究內容與成果與原計畫本年度預期目標相符，所得研究成果對使用不同細料特性為界定時，對液化評估之影響，可有相當了解。對後續研究也可給以探討方向。本研究計畫之成果除於 92 年 11 月舉行之台美液化研討會中發表，並已於 93 年 10 月在”Soil Dynamics and Earthquake Engineering” (SCI)期刊中發表[10](附件一)。

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Definition of fines and liquefaction resistance of Maoluo River soil

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Abstract

Two definitions of fines, soil particles finer than the No. 200 sieve (0.075 mm) and No. 400 sieve (0.038 mm), are adopted to evaluate the effect of fines content on the liquefaction resistance of the silty soil in the Maoluo River area of Nantou City. The specimens of different fines contents according to these two definitions of fines were prepared by moist tamping to a dry density of 1400 kg/m^3. Comparisons were made between the liquefaction resistances of soils containing fines according to different definitions. The results of cyclic triaxial tests show that the effect of fines on the liquefaction resistance of Maoluo River soil is more pronounced based on the fines content defined as the portion finer than the No. 400 sieve than that with fines defined as soil passing the No. 200 sieve.

Keywords: Fines content; Fines definition; Liquefaction; Cyclic triaxial tests; Earthquake

1. Introduction

In the evaluation of liquefaction potential of a sandy soil, the effect of fines is an important factor [1]. It is usually considered that soil with higher fines content (FC) will have a higher liquefaction resistance. However, in the recent earthquakes, e.g. 1999 Kocaeli earthquake and Chi–Chi earthquake, liquefaction occurred in the soils with very high FC [2,3]. Therefore, the liquefaction behavior of fines and the effect of fines on the liquefaction resistance of a soil were extensively studied recently [4–6].

The fines of a soil is presently defined as the portion of soil particles finer than the No. 200 sieve (0.075 mm) [7], which was determined arbitrarily regardless of soil behavior. It is not clear whether this definition of fines is suitable in the evaluation of liquefaction potential or possibly, other definitions of fines can better reflect the effect of fines on the liquefaction resistance of the soil. In this study, the portion of a soil finer than the No. 400 sieve (0.038 mm) is considered as an alternative definition for FC of a soil and the effect of FC on liquefaction resistance were evaluated. The silty soil liquefied during the 1999 Chi–Chi earthquake in the Maoluo River area in Nantou City was selected for the study. Dynamic triaxial tests were performed on the specimens with various FCs based on the new definition of fines. The results of the liquefaction resistances of these specimens were compared with those of the specimens in which the FC are defined as the portion finer than the No. 200 sieve.

2. Soil samples

The soil used in the study was taken about 1.5 m below ground surface from the bank of Maoluo River where severe liquefaction occurred during the 1999 Chi–Chi earthquake. The SPT *N*-values of the liquefiable soils in this area are around 2–5. The grain size distribution curve of this soil is shown in Fig. 1. The properties of this soil are given in Table 1. It can be seen that 48 and 37% of the soil are finer than the No. 200 sieve and No. 400 sieve, respectively. The maximum density was tested according to ASTM D4253 test method 1B (wet method) that gives a higher maximum density than the dry method. The minimum density was obtained according to ASTM D4254 test method A. Even though these test methods are not recommended for soils with a FC higher than 15%, these results still can indicate the probable range of densities that could be obtained for this soil. The maximum and minimum densities of the coarse-grained material with the grain size (D) > 0.075 mm are 1590 and 1320 kg/m^3, respectively, according to ASTM standard methods D4253 and D4254. The soil in the field is in a loose state with a dry density of 1400 kg/m^3 (Dr ≈ 31%). The soil is a silty sand (SM) according to the Unified Soil Classification System (USCS), but with such a high FC, it is like a sandy silt (ML).

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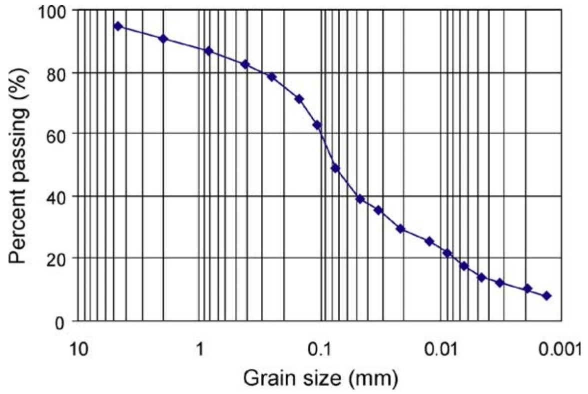

Fig. 1. Grain size distribution of Maoluo River soil.

Two series of dynamic triaxial tests were performed on the Maoluo River soil, one with the fines defined as the soil finer than the No. 200 sieve and another with fines defined as the soil finer than the No. 400 sieve. For the study of the properties of the fines and preparation of the test specimens with different FCs, the fines were separated from the soil using the wet sieving method by washing the soil particles through the No. 200 and 400 sieves. The portion of soil particles larger than the No. 4 sieve (4.75 mm) was replaced with the coarse-grained material passing the No. 4 sieve. The properties of the coarse-grained portion and fines according to these two definitions are presented in Table 2. Table 3 also shows the mineral compositions for three different ranges of grain sizes, i.e. (a) coarser than the No. 200 sieve ($D > 0.075$ mm), (b) between the No. 200 and 400 sieves (0.038 mm $< D <$ 0.075 mm), and (c) finer than the No. 400 sieve ($D < 0.038$ mm). It can be seen that the portion of soil passing the No. 400 sieve resembles a clayey soil of some plasticity, while soil passing the No. 200 sieve is low-plastic silt. There is mainly quartz and very little clay minerals in the portion of Maoluo River soil between the No. 200 and 400 sieves. It is essentially very fine sand. That is, this portion of fines will probably not significantly affect the liquefaction resistance of the soil.

The triaxial test specimens were prepared by the moist tamping method for it can give consistent specimens of the desired density with a rather uniform distribution of fines within the soil. Based on the definitions of fines, the coarse-grained materials were mixed with different amounts of fines according to the FCs of the specimens. An 8% of moisture content was added and the soil was sealed at least 4 h before the soil was placed in the mold to form a specimen of 72 mm in diameter and 148 mm in height. The specimen was saturated and consolidated under the estimated field effective stress of 78 kPa to a dry density of 1400 kg/m^3 that is the in situ density of the original Maoluo River soil. The saturation of the specimen was performed by passing through the specimen with CO_2 followed by de-aired water and by applying a back pressure of 120 kPa during consolidation to reach a minimum value of 0.95 for the pore water pressure parameter B. Since, the differences of specific gravity between the coarse-grained material (Gs = 2.67) and fines (Gs = 2.69–2.70) are not large, for the same $\rho_d = 1400$ kg/m^3, the variations of void ratios of the soils with different FCs are mostly small with the extreme values of 0.907 for $(FC)_{200} = 0$ and 0.929 for

Table 1
Properties of Maoluo River soil

Specific gravity	2.68
In situ ρ_d	1400 kg/m^3
D_{50}	0.078 mm
Cu	43
Maximum ρ_d	1720 kg/m^3
Minimum ρ_d	1290 kg/m^3
LL	23
PI	NP
FC (<0.075 mm)	48%
USCS	SM

Table 2
Properties of soils of different grain size ranges

Grain size	>200 Sieve (>0.075 mm)	<200 Sieve (<0.075 mm)	>400 Sieve (>0.038 mm)	<400 Sieve (<0.038 mm)
Gs	2.67	2.69	2.68	2.70
LL	–	36	29	38
PI	–	8	–	15
USCS	SP	ML	SM	CL

Table 3
Mineral compositions in percent of soils of different grain size ranges

Grain size	Rock fragments	Quartz	Feldspar	Mica	Illite	Chlorite	Kaolinite
>200	24	68	5	3	0	0	0
<200, >400	0	87	7	3	3	0	0
≤400	0	41	3	0	28	3	25

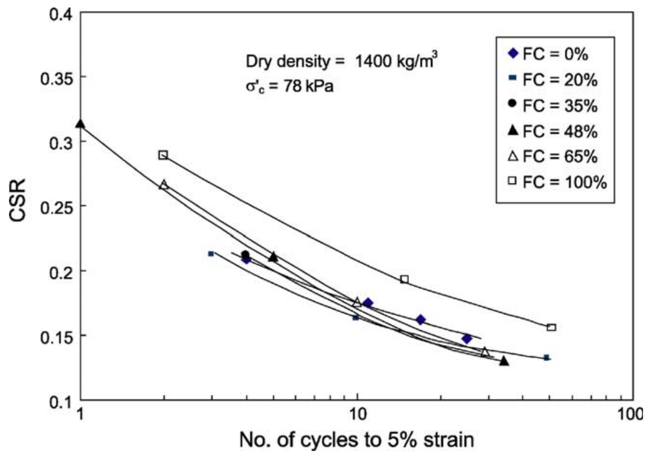

Fig. 2. Cyclic stress ratio (CSR) versus No. of cycles to 5% axial strain for Maoluo River soil with fines defined as $D <$ 200 sieve.

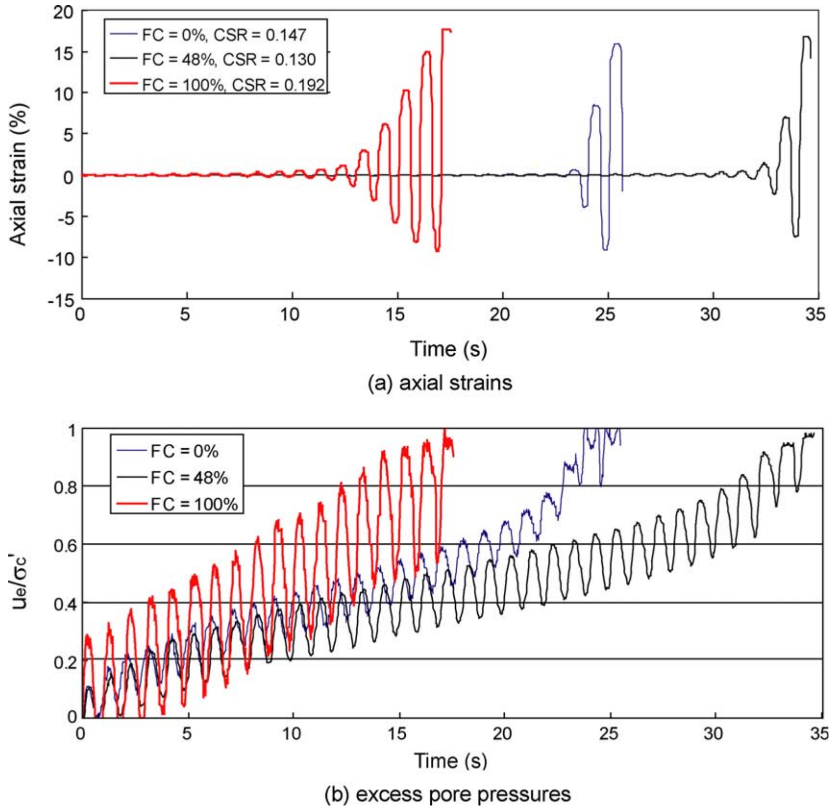

Fig. 3. Axial strains and pore pressure generations in specimens with various $(FC)_{200}$s.

$(FC)_{400} = 100\%$. The cyclic axial load at a frequency of 1 Hz was applied in the cyclic triaxial tests. More details of the sample preparations and testing procedures can be found in [8,9]. The deviator stresses, pore water pressure changes, and axial deformations were recorded during the cyclic loading tests.

3. Test results

For convenience of discussions hereafter, $(FC)_{200}$ and $(FC)_{400}$ represents the FCs of a specimen with fines defined as soil finer than the No. 200 sieve ($D < 0.075$ mm) and the No. 400 sieve ($D < 0.038$ mm), respectively.

3.1. Fines defined as $D < 0.075$ mm

For the specimens with fines defined as soil finer than the No. 200 sieve ($D < 0.075$ mm), six different $(FC)_{200}$s were considered, i.e. 0, 20, 35, 48, 65, and 100%. The soil with $(FC)_{200} = 48\%$ is the original soil from the site. The relations of cyclic stress ratio (CSR) versus number of cycles to 5% single amplitude axial strain for different $(FC)_{200}$s are presented in Fig. 2. It appears that the responses to the cyclic loading are different for soils with different FCs. In fact, they are no longer the same soil even though they were derived from the same parent material. Fig. 3 shows the axial strain and the pore water pressure generations in specimens with $(FC)_{200} = 0$, 48, and 100% under cyclic loadings. It can be seen that the deformation of the 100% fines increases gradually during the cyclic loading test, and the strain reaches a substantial value (>10%) before the effective stress reaches zero, i.e. initial liquefaction. Whereas, the strains of specimens with $(FC)_{200} = 0$ and 48% remain rather small and increase rapidly when they reached initial liquefaction. The number of stress cycles to 5% axial strain (N_L) appears more sensitive to the change of CSR for sand with $(FC)_{200} = 0\%$. N_L increases less rapidly for soil with higher FC when CSR decreases. Without fines

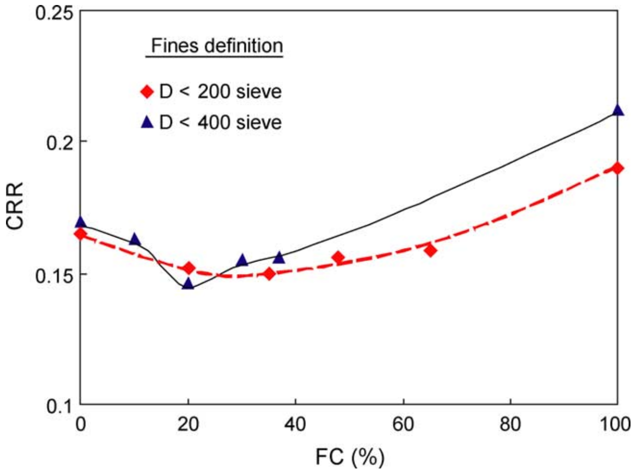

Fig. 4. Cyclic resistance ratio (CRR) causing 5% axial strain under15 cycles of loading.

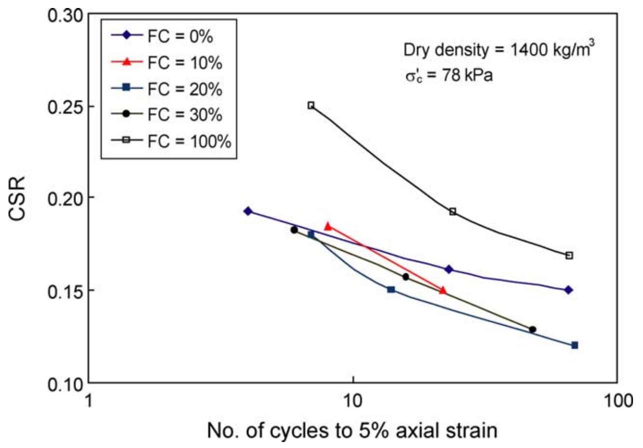

Fig. 5. Cyclic stress ratio (CSR) versus No. of cycles to 5% axial strain for Maoluo River soil with fines defined as $D < 400$ sieve.

at contacts between coarse particles in sand with $(FC)_{200} = 0\%$, when CRS decreases, the slips between particles and accordingly the shear strain would reduce more rapidly than those in soils with fines at the contacts. This would cause the lesser pore pressure generation and softening of the soil. As a result, more number of stress cycles are required to induce liquefaction for sand with $(FC)_{200} = 0\%$ than those for soils with higher FCs when CRS is reduced. Considering an earthquake of a magnitude of 7.5, an equivalent number of stress cycles of 15 are usually taken to represent the duration of the earthquake loading. The liquefaction resistances (CRR) under 15 cycles of loading for Maoluo River soil with different $(FC)_{200}$s are given in Fig. 4. The CRR of the soil decreases when its $(FC)_{200}$ increases from 0% and reaches the minimum value when $(FC)_{200}$ is around 30%. The liquefaction resistance increases when $(FC)_{200}$ increases beyond 30%.

3.2. Fines defined as $D < 0.038$ mm

Six different $(FC)_{400}$s, i.e. 0, 10, 20, 30, 37 and 100%, were prepared for the specimens with fines defined as soil finer than the No. 400 sieve ($D < 0.038$ mm). Here, the coarse-grained material is the soil with $D > 0.038$ mm which is different from that for fines defined as $D < 0.075$ mm above. The relations between CSR and number of cycles to 5% single amplitude axial strain for different FCs are also shown in Fig. 5. As for the fines defined as $D < 0.075$ mm, Fig. 5 also shows that N_L is more sensitive to the changes of CSR for specimens with a lower $(FC)_{400}$. The relation for soil with $(FC)_{400} = 37\%$, which is the original in situ soil, is the same as that with $(FC)_{200} = 48\%$ for fines defined as $D < 0.075$ mm. Fig. 6 shows the axial strain and pore pressure generations in specimens with $(FC)_{400} = 0$, 30, and 100% under cyclic

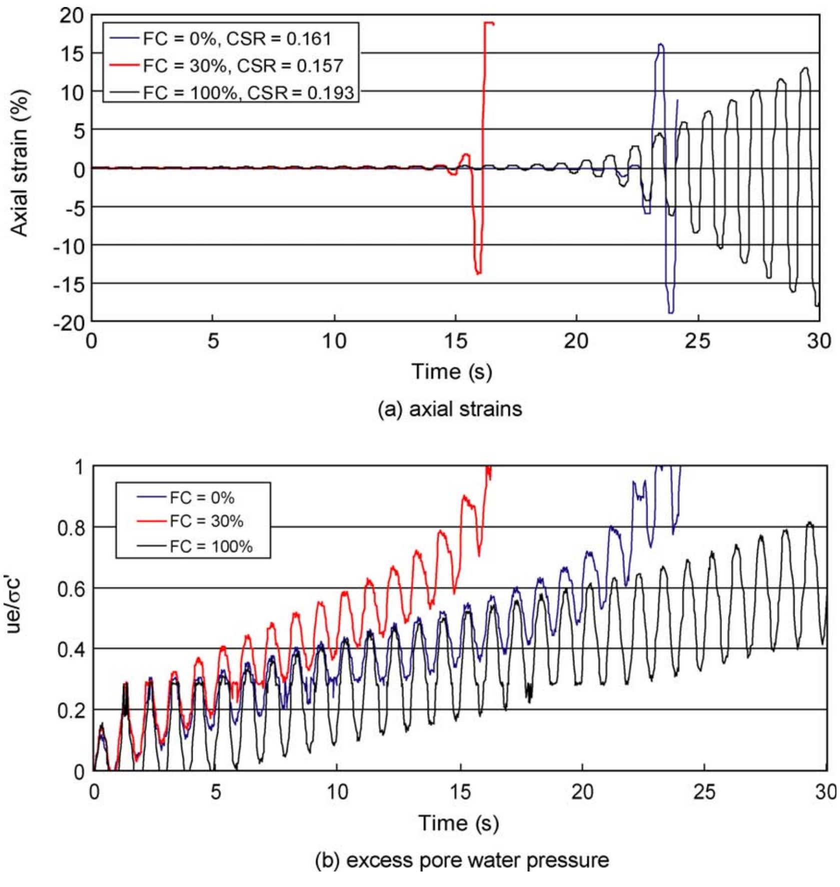

Fig. 6. Axial strains and pore pressure generations in specimens with various $(FC)_{400}$s.

loadings. The results show that for $(FC)_{400} = 0$ and 30%, the behavior of soil under cyclic loading is quite similar to that of clean sand, i.e. there is very little deformation developed before initial liquefaction, but large strains occurred rapidly at initial liquefaction. Examining the stress–strain relationship, it was found that for $(FC)_{400} = 100\%$, the soil behaved like a clayey soil with degradation of modulus under cyclic loading; and the excess pore water pressure and strain developed gradually and no initial liquefaction occurred even when the axial strain reached over 10%. The values of CRR under 15 cycles of loading for Maoluo River soil with different $(FC)_{400}$s are also given in Fig. 4 that shows greater differences of CRR for specimens with different $(FC)_{400}$s. There is also a minimum liquefaction resistance for this soil with FC near 20%.

4. Comparison of liquefaction resistance between different fines definitions

The differences of liquefaction resistance between soils with fines defined as $D < 0.075$ and < 0.038 mm can be evaluated by comparing the relations of CRR versus FC for these two fines definitions given in Fig. 4. It shows that the effect of fines on the liquefaction resistance of Maoluo River soil is more pronounced using the definition of fines of $D < 0.038$ mm, but the trends of the effect of FC on liquefaction are quite similar, and there exist minimum liquefaction resistances for both definitions of fines when FC is around 20–30%. The liquefaction resistances of the specimens with $FC = 100\%$ are approximately 1.28 and 1.45 times those minimum values for fines defined as $D < 0.075$ and < 0.038 mm, respectively. The differences in grain size and plasticity of fines filling between the coarse particles might cause the difference of effect on the liquefaction resistances.

For the specimens with fines defined as $D < 0.038$ mm, we can recalculate $(FC)_{200}$ of each specimen considering the portion of soil with $D > 0.075$ mm as the coarse-grained material. Thus, for each $(FC)_{400}$ of the soil specimen with fines defined as $D < 0.038$ mm, there is a correspondent equivalent $(FC)_{200}$ if we define fines as $D < 0.075$ mm, only the compositions of fines are different for specimens of different equivalent $(FC)_{200}$s. That is, the higher the equivalent $(FC)_{200}$, the less portion of grains between 0.038 and 0.075 mm. Table 4 shows the proportions of soil

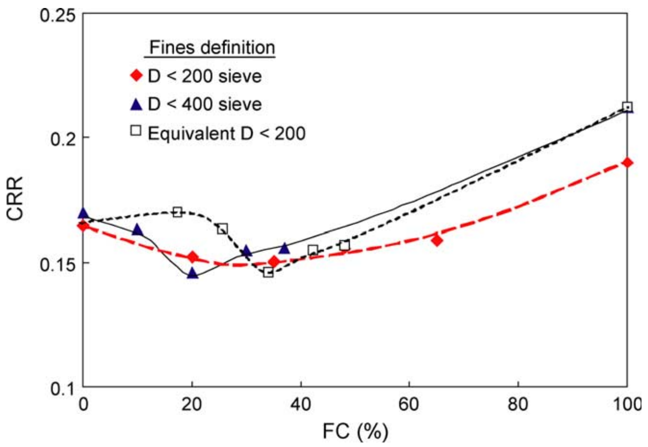

Fig. 7. Cyclic resistance ratio (CRR) versus equivalent $(FC)_{200}$.

in the three grain size ranges for each $(FC)_{400}$ and its correspondent equivalent $(FC)_{200}$. The CRR of these specimens can then be plotted against the equivalent $(FC)_{200}$s as shown in Fig. 7. The relations for CRR versus FC for different fines definitions given in Fig. 4 are also shown in Fig. 7 for comparison. Fig. 7 indicates that with different fines compositions, CRR are substantially different even though $(FC)_{200}$ are the same.

For $(FC)_{400} = 0\%$ or equivalent $(FC)_{200} = 17.5\%$, the fines with grain size only in the range of $0.038 < D < 0.075$ mm is essentially a very fine sand as shown in Table 3. There is a very slight difference in liquefaction resistance between this soil and the clean sand with only particles larger than the No. 200 sieve. It depicts that fines between the No. 200 sieve and the No. 400 sieve may not affect the liquefaction resistance of sand significantly.

On the other hand, for the specimens with fines defined as $D < 0.075$ mm we can also obtain the equivalent $(FC)_{400}$s by considering the coarse material as $D > 0.038$ mm. In this case, the compositions of coarse material are different for different equivalent $(FC)_{400}$s. Table 5 shows the proportions of soil in the three grain size ranges and the corresponding equivalent $(FC)_{400}$ for each $(FC)_{200}$. The relation of CRR versus equivalent $(FC)_{400}$ is plotted in Fig. 8 together with the relations for CRR versus $(FC)_{200}$ and $(FC)_{400}$ from Fig. 4. It is interesting to find that the relation of CRR versus equivalent $(FC)_{400}$ is quite close to the relation for CRR versus $(FC)_{400}$ even though the compositions of the coarse materials are different in these two fines definitions. That is, soil with the same proportion of fines with $D < 0.038$ mm,

Table 4
Grain size compositions in percent of specimens with various $(FC)_{400}$

$(FC)_{400}$	0	10	20	30	37	100
Equivalent $(FC)_{200}$	17.5	25.7	34	42.2	48	100
$D > 0.075$ mm	82.5	74.3	66	57.8	52	0
0.075 mm $> D >$ 0.038 mm	17.5	15.7	14	12.2	11	0
$D < 0.038$ mm	0	10	20	30	37	100

Table 5
Grain size compositions (%) of specimens with various $(FC)_{200}$

$(FC)_{200}$	0	20	35	48	65	100
Equivalent $(FC)_{400}$	0	15.4	27	37	50.1	77.1
$D > 0.075$ mm	100	80	65	52	35	0
0.075 mm $> D >$ 0.038 mm	0	4.6	8	11	14.9	22.9
$D < 0.038$ mm	0	15.4	27	37	50.1	77.1

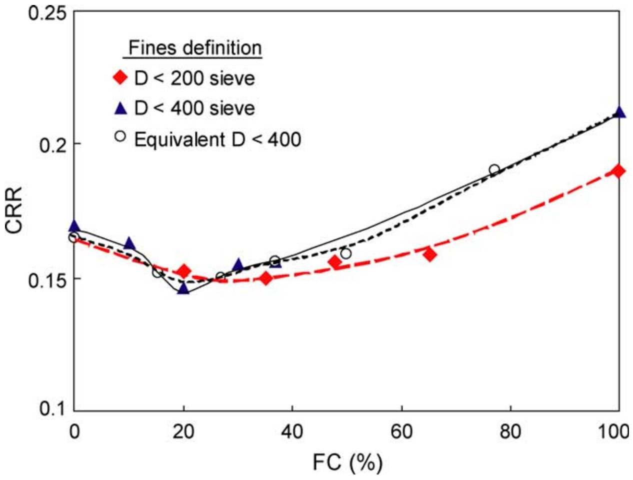

Fig. 8. Cyclic resistance ratio (CRR) versus equivalent $(FC)_{400}$.

regardless of the composition of the coarse material of $D > 0.038$ mm, will have about the same liquefaction resistance. This infers that $(FC)_{400}$ might be a better parameter for considering the effect of fines on the liquefaction resistance of a soil.

It should be noted that the comparisons of the effect of FC are based on the same dry density of 1400 kg/m^3 for all specimens. Similar results of comparison might hold for a denser soil, but further studies are needed.

5. Concluding remarks

Two definitions of fines for Maoluo River soil, i.e. $D < 0.075$ and < 0.038 mm, are considered to evaluate the effect of FC on the liquefaction resistance subjected to cyclic loading. The soil with the grain size between 0.038 and 0.075 mm is essentially a very fine sand and its presence will probably not significantly affect the liquefaction resistance of Maoluo River soil. The results of dynamic triaxial tests show that the effect of fines on the liquefaction resistance of the soil is more prominent using $(FC)_{400}$ than $(FC)_{200}$, probably due partly to the difference in plasticity of the fines. Even though $(FC)_{400}$ is probably a better indicator for the effect of FC on liquefaction resistance of a soil, there is no sure overall benefit yet to change the present definition of fines, i.e. $D < 0.075$ mm. However, in liquefaction potential evaluation, corrections of CRR solely based on $(FC)_{200}$ without considering the properties of fines (e.g. grain sizes and plasticity) cannot truly reflect the effect of fines on the liquefaction resistance of a soil. Further studies are needed for a better way of considering the effect of fines on liquefaction resistance.

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