行政院國家科學委員會專題研究計畫 期中進度報告

砂土受一維與二維振動之液化與沈陷(2/3)
期中進度報告(精簡版)

計 畫 類 別 ：個別型
計 畫 編 號 ：NSC 95-2221-E-002-259-
執 行 期 間 ：95 年 08 月 01 日至 96 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

報 告 附 件 ：國外研究心得報告
出席國際會議研究心得報告及發表論文

處 理 方 式 ：期中報告不提供公開查詢

中 華 民 國 96 年 05 月 26 日

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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共同主持人：
計畫參與人員： 陳家漢、陳益成、曾永成
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中文摘要

為考慮二維地震波作用下之砂土液化與沈陷行為，使用自行研發之大型雙軸向多層剪力試驗盒，在國家地震工程研究中心之振動台進行大尺寸物理模型試驗，以模擬實際地震力作用下砂土的受震反應行為。同時亦在試體表面上裝設沈陷盤，以觀察振動時試驗砂土表面沈陷量之變化，並在試驗前後量測試體表面高程。根據水壓計及框架加速度量測結果，可了解並分析受震時孔隙水壓激發情況，並探討在一維單向與二維多向振動作用下砂土之液化行為之不同，亦可用以判定發生液化土層之厚度，依此計算液化砂土層之體積應變與沈陷。由純淨越南砂振動台試驗結果可看出砂試體在未發生液化時其表面之沈陷量相當小，而液化後土層之體積應變與相對密度及振動延時間呈現良好關係。其他因素如:一維或二維振動、振動強度與頻率等關係不大。本研究並由此關係發展一估計不同規模之地震作用所引致純淨砂之沈陷關係。

關鍵詞: 砂、地震、振動台、多層剪力試驗盒、液化、沈陷

Liquefaction and ground settlement of sand under one- and two-dimensional shakings (2/3)

ABSTRACT

In order to study the behavior of saturated sand, including liquefaction and settlement, under multidirectional earthquake shakings, physical model tests using a large biaxial laminar shear box on the shaking table at the National Center for Research on Earthquake Engineering (NCREE) were performed. Pore pressures and accelerations of the specimen were measured during tests under both one- and multi-directional shakings. The settlement of the sand surface was measured after each shaking. The results of shaking table tests on clean Vietnam sand showed that multidirectional shaking caused easier liquefaction of the sand and a deeper liquefaction depth than those under one-dimensional shaking. Significant settlements occurred only when there is liquefaction of the soil. With consideration of the depth of liquefied sand, the test results showed a nice relationship between volumetric strain after liquefaction and relative density of sand and the shaking duration. Relations for estimate of settlements of clean sand under earthquakes of different magnitudes were developed based on the shaking table test results in this study.

Key words: earthquake, sand, shaking table, laminar shear box, liquefaction, settlement.

一、 前言

當砂性土壤受到振動之時，土壤顆粒會有緊密化的趨勢。若在飽和不排水的情況下，土壤空隙縮小的趨勢會使顆粒和顆粒間的接觸應力傳遞到孔隙水上，而激發超額孔隙水壓，若振動強度夠大或延時夠長時，當孔隙水壓力上升到與土壤的有效應力相等時，土壤會失去強度有如液體般，此時即稱為液化。液化後的土壤失去承載力，致使上部結構物下沉、傾斜，且斜坡砂土層會向低處滑移與側潰。1999 年集集地震使台灣中部許多砂性土層地區發生液化，顯示出砂性土壤液化問題在台灣局部地區有進一步研究之必要性。土壤受振沉陷的問題在近幾年來一直是相當重要的課題，一般而言，土壤受振液化發生與否是影響沉陷量大小的主要因素。相對於室內小試體土壤元素試驗而言，大型振動台試驗之試體比較符合現地土壤狀況。

目前土壤動態試驗方法多將土壤之受震反應行為簡化為單向受剪振動問題，而現地土層所受之二維乃至於三維振動對於土壤動態反應行為之探討，不論是小元素試體或是大尺寸試體之試驗仍相當有限。因此本研究使用國家地震工程研究中心所研發之大型雙軸向多層剪力試驗盒[1]，並以中心之大型振動台進行大尺寸物理模型振動試驗，以模擬並了解在一維與二維地震力作用下土壤之受震反應、液化及沈陷行為。本年度為此計畫之第二年，接續第一年之初步成果，進一步發展純淨砂受不同規模地震作用下之沈陷估計，以為實際工程評估之用。同時亦進行台灣西部海岸沖填新生地區之麥寮砂試體準備方法的探討。

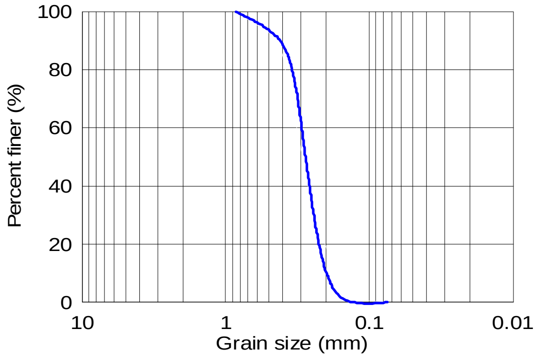
二、 試體準備與量測儀器

2.1 純淨越南砂試體準備

本研究採用濕沈降法(wet sedimentation method)進行純淨砂大型試體準備。有關大型砂土試體準備的詳細探討可參考翁作新等人的研究報告[2]。目前採用較容易大量取得而且均勻之進口越南石英砂作為試驗用砂，其基本物理性質及粒徑分佈曲線分別如表一及圖一所示。

表一 越南石英砂之基本物理性質

Shape	G_s	D_{50} (mm)	C_u	e_{max}	e_{min}	ρ_{max} (kg/cm^3)	ρ_{min} (kg/cm^3)
Subangular	2.65	0.32	1.52	0.912	0.612	1644	1386



圖一 越南石英砂之粒徑分佈曲線

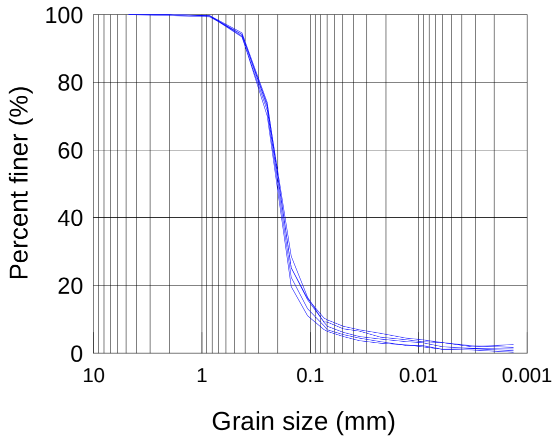
2.2 麥寮砂試體準備

天然麥寮砂之顆粒形狀多為次角與薄片形，其工程性質與一般石英砂相較則具有較高壓縮性及較低的膨脹性。麥寮砂之基本物理性質如表二所示。而其土樣之粒徑分佈曲線則如圖二所示。

表二 麥寮砂土之基本物理性質

G_s	D_{50} (mm)	C_u	e_{max}	e_{min}	FC (%)
2.71	0.20	2.66	1.162	0.586	6.49

本計畫依評估結果[3]以分階濕沉降法（staged sedimentation method）準備大型麥寮砂試體。為配合剪力盒之尺寸與試體準備方法，本研究研發一旋轉葉片型式之霣落器準備含有自然含水量之麥寮砂土試體。此霣落器在設計上主要考量以下兩點：(1)霣落器能裝載足夠土量並能提供足夠之勁度防止容器變形；(2)霣落器底部由八只葉片構成，藉由兩側傳動軸控制葉片同步開啟使得土壤可均勻霣落至剪力盒中。其照片如圖二所示。



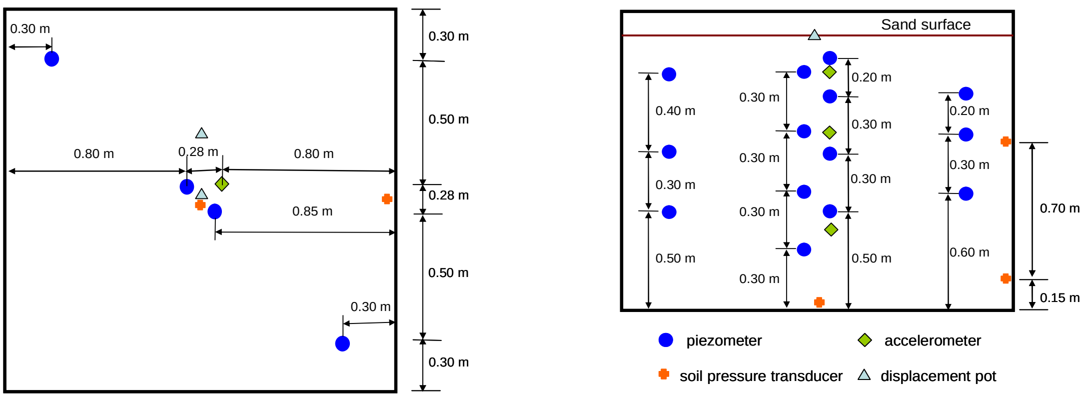
圖二 麥寮砂土之粒徑分佈曲線

圖三 葉片式霣落器照片

分階濕沉降法主要分為兩個步驟：(1)先緩慢注水至一預定高度；(2)利用霣落器將砂土霣落至剪力盒中，並靜置試體約 30 分鐘待。重複上述方法直到試體預定高度為止。本研究每階段霣落約 1 ton 之土量，共分為七階段進行，完成試體之高度約為 1.35m。當試體霣落完成之後，則進行試體水平向之壓力波波速量測以檢驗試體之飽和度。測試結果顯示採用分階濕沉降法配合特殊設計之霣落器可得到符合要求均匀度及飽和度試體。

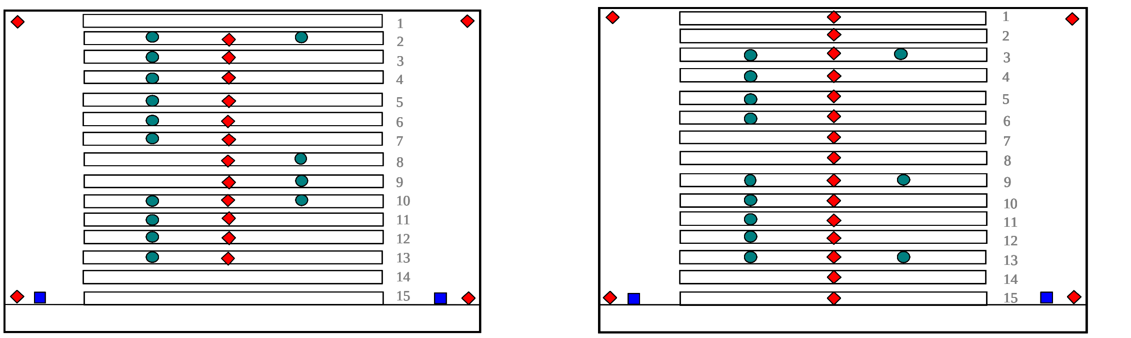
2.3 量測儀器裝置

除了在土壤試體內部不同深度與位置埋設水壓計、加速度計與土壓計之外，在剪力盒的內、外框架上則裝設有 X，Y 兩方向之位移計、速度計及加速度計，同時也在試體表面上裝設沈陷盤，以觀察振動試驗進行中的土層表面沈陷量之變化。剪力盒內部量測儀器的配置則如圖二所示。圖三顯示剪力盒框架上之儀器配置。



(a) plan view (b) vertical view

圖二 剪力試驗盒砂試體內部量測儀器配置圖



(a) Inner frame (b) Outer frame

圖三 剪力試驗盒框架上儀器配置圖

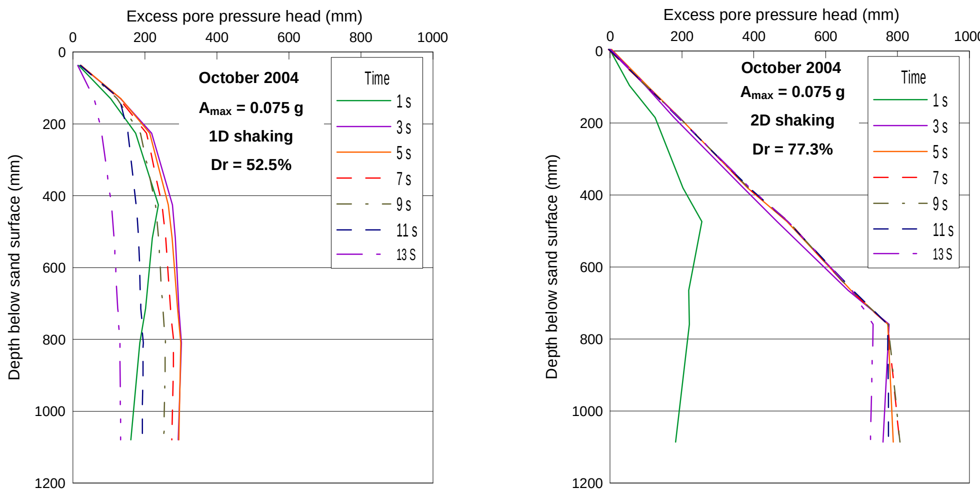
三、 振動台試驗

本研究利用國家地震工程研究中心之振動台為地震力來源，進行大尺寸物理模型試驗來模擬水平向二維地震力作用下土壤之受震反應行為。翁作新等人自 2002 年 8 月起至本年度共進行了九次純淨越南砂的振動台試驗，其試驗的項目及振動模式列於[4]。而至目前也已進行兩次麥寮砂之振動台試驗。一般試驗輸入振動模式為先進行一維振動後，再是二維振動；先施加 8~30 秒之正弦波，並變化其頻率（1Hz、2Hz、4Hz 與 8Hz）和加速度（0.03g~0.20g），然後施加不同之實際地震記錄；先以小振幅振動，再加大振幅振動。每次振動試驗中皆量測不同深度內外框 X、Y 向的加速度、速度與位移、土體中之水壓力與加速度以及土層表面之沈陷量。振動停止後，仍繼續水壓計之記錄，以觀測孔隙水壓之傳播與消散情形。而且也在每次振動前後量測水面與砂面高度，以得到砂土沈陷量與試體密度的變化。

四、 試驗結果

4.1 一維與二維振動作用之水壓力變化與液化深度

圖五(a)與(b)為分別在一維與二維振動作用下（振幅 A_{max} = 0.075g），砂試體不同深處之孔隙水壓力變化情形。圖五顯示在相同的加速度下，二維振動作用下所激發之超額孔隙水壓較一維振動試驗高，且其液化深度(760 mm)也比一維振動所引起之液化深度(≈ 200 mm)深。



(a) 一維振動　　　　(b) 二維振動

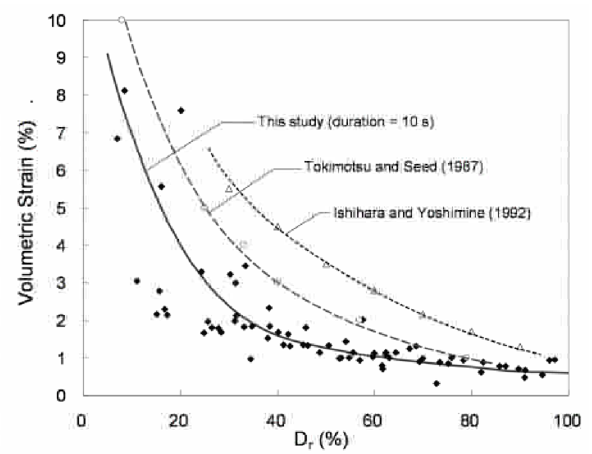
圖五 振動台試驗試體不同深度超額孔隙水壓變化

4.2 試體受振之沈陷反應

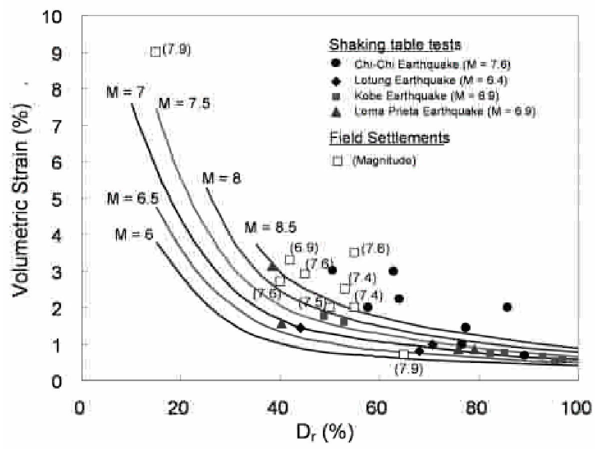
根據試體表面所裝設之沈陷盤可以量測在試驗進行過程中砂土表面沈陷量之變化。量測結果顯示當砂土試體受振動時振動延時愈長則沈陷量愈大，且二維振動所產生的沈陷量比一維振動的沈陷量大。

試驗結果顯示在未發生液化之振動試驗，砂土試體表面的沈陷量相當小，其值大致小於 2 mm，而發生液化之振動試驗則會引起顯著較大的沈陷量。本研究根據水壓計及框架加速度量測結果判定液化土層之厚度，依此方式來計算液化土層之體積應變。由初步分析結果顯示在 10 秒的正弦波振動作用下，液化土層的體積應變會隨著試體的相對密度增加而減小，而且皆不受所輸入之加速度振幅、頻率與振動方向的影響，其關係如圖六所示。換句話說，加速度大小與振動方向之影響會反應在砂土層之液化厚度上，而使得飽和砂土之液化後之體積應變只與其相對密度有關。此關係亦與他人結果(如 Tokimatsu and Seed[5])有不錯的比較。

本研究又依據延時越長引致液化後之體積應變越大之試驗數據，發展出純淨砂受不同規模之地震作用引致液化後體積應變與相對密度之關係，如圖七所示。與現地觀察之結果比較，有實用價值之可能。



圖六 液化土層體積應變與相對密度之關係



圖七 不同地震規模液化土層體積應變與相對密度之關係

五、結論

根據本計畫目前之試驗與分析結果可歸納以下幾點結論：

1. 在相同的加速度作用下，二維振動時所引致之超額孔隙水壓較一維振動時高，其引致之液化深度也較深。

2. 砂土層受振動而未發生液化時之沈陷量相當小，只有在發生液化時才有顯著之沈陷量。不論試體是否有發生液化，砂土表面沈陷量會隨著振動延時增加而增加。而且，二維振動所造成試體沈陷量皆比一維振動作用大。
3. 由本研究結果，可得在不同規模之地震作用下，純淨砂土液化後產生之體積應變與其相對密度之關係。
4. 麥寮砂採用分階濕沉降法配合特殊設計之霣落器可得到符合要求均勻度及飽和度之大型剪力盒試體。

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[2] 翁作新、陳家漢、彭立先、李偉誠，「大型振動台剪力盒土壤液化試驗(Ⅱ)--大型砂試體之準備與振動台初期試驗」，國家地震工程研究中心，No. NCREE-03-042 (2003)。

[3] 鄒承府，「振動台大型剪力盒麥寮砂試體準備之評估」，國立台灣大學土木工程學研究所，碩士論文(2006)。

[4] Ueng, T.S., Wu, C.W., Cheng, H.W. and Chen C.H., "Settlements of Saturated Clean Sand Deposits in Shaking Table Tests," Submitted for possible publication, (2007).

[5] Tokimatsu, K. and Seed, H.B., "Evaluation of settlements in sands due to earthquake shaking," *Journal of Geotechnical Engineering*, ASCE, Vol. 113, No. 8, pp.861-878 (1987).

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。本年度除整理並發展純淨砂液化後沉陷評估之關係以為工程設計應用外，並繼續進行台灣本土麥寮砂之大型試體準備與振動反應之探討。在振動台試驗中，亦配合國立暨南大學土木工程系張文忠教授，在大型砂試體中安裝其所研發之現場土壤水壓與加速度量測儀器。本計畫儀器之量測數據與張教授所得者，有很好的驗証。本計畫之第三年度中，將繼續與張教授合作，在試驗之進行、量測儀器之配合、數據與分析結果之分享，可有更佳成果。此外本研究計畫亦供應部份振動台試驗數據，給國立成功大學土木工程學系倪勝火教授，以便其進行研究與驗証工作。同時將應用本計畫振動台試驗之經驗，從事有關液化土壤中結構土壤互制行為之探討。此後將繼續與國內外學者共享試驗數據、分析與驗証等成果。

本年度與本計畫有關之成果發表如下:

[1] T. S. Ueng and C. H. Chen, "Liquefaction of Sand Under Multidirectional Shaking Table Tests," Physical Modelling in Geotechics—6th ICPMG’06, Ng, Zhang & Wang (eds), Vol. 1, pp. 481-486, Hong Kong, August 2006.

[2] T. S. Ueng, 2006, "Inference of Behavior of Saturated Sandy Soils during Earthquakes from Laboratory Experiments," Journal of GeoEngineering, TGS, Vol. 1, No.1, pp. 1-9.

[3] J. S. Chiou, C. H. Chen and T. S. Ueng, "Evaluation of Dynamic Properties of Large Saturated Sand Specimen in the Shear Box," 4th International Conference on Earthquake Engineering, paper No. 041, Taipei, October 2006.

[4] 翁作新、陳家漢、程漢瑋、吳繼偉，「大型振動台剪力盒土壤液化試驗(III)—飽和越南砂試體受振沉陷之探討」，國家地震工程研究中心，報告編號:NCREE-06-019，民國 95 年 12 月。

[5] T. S. Ueng, C. L. Yeh, S. H. Wu and C. H. Chen, "Liquefaction of Soils with High Fines Contents in Laboratory Tests," Proceedings, 16th Southeast Asian Geotechnical Conference, Subang Jaya, Malaysia, May 2007.

[6] Ueng, T.S., Wu, C.W., Cheng, H.W. and Chen C.H., “Settlements of Saturated Clean Sand Deposits in Shaking Table Tests,” Submitted for possible publication, (2007).

更正

無赴國外出差或研習心得報告。

出席 2007 第十六屆東南亞大地工程會議報告

一、參加會議經過

第十六屆東南亞大地工程會議(16th Southeast Asian Geotechnical Conference)為東南亞大地工程學會每大約三年一次舉辦的國際性學術會議，輪流由其會員國(目前包括台灣、泰國、新加坡、馬來西亞)主辦。這是少數台灣為正式會員國的國際性組織。此次會議由馬來西亞工程師學會(The Institution of Engineers, Malaysia)主辦，於 2007 年 5 月 8 至 11 日在馬來西亞 Subang Jaya (吉隆坡)舉行。共有來自 15 國家近 500 人參與此次會議，也有 24 參展廠商。台灣共有 10 人參加，發表兩場專題演講及多篇論文，並主持會議場次。

本次大會之主題為「大地工程在工程實務、海嘯及土石流方面之新發展」(Geotechnical Innovations in Practice, Tsunami and Debris Flow)。研討之領域包括工址調查與土壤性質、設計分析與模擬、室內試驗、地盤改良與穩定、工程地質、深基礎、地工環境、邊坡與開挖、地工材料及堤壩等。共 19 場專題及邀請演講與分別 11 會議場次，所有文章皆以口頭報告形式發表。本人發表與室內試驗有關之成果，“Liquefaction of Soils with High Fines Contents in Laboratory Tests”。

本年恰為莫若楫博士發起東南亞大地工程學會成立 40 週年，故特編有一紀念專輯(Special Commemorative Volume)，“Development, Advancement and achievements of Geotechnical Engineering in Southeast Asia”，介紹東南亞大地工程學會之緣由與發展，並敘述台灣、馬來西亞、新加坡、泰國、香港等國，四十年來在大地工程方面之發展與成就。

台灣亞新顧問工程公司之秦中天博士獲選為下屆東南亞大地工程學會會長，值得慶賀。下次第十七屆東南亞大地工程會議將於 2010 年在台灣舉行。

二、與會心得與建議

此次會議所發表論文內容理論與工程實務並重，由這些文章可了解東南

亞地區大地工程之近況。多場專題及邀請演講對工程實務與學理皆有助益。本人亦與研究主題類似之作者互相討論，並交換資料。

此次會議，台灣僅有 10 人參加，在少有台灣為正式成員的國際會議中，人數似偏少。台灣有關大地工程方面之工程與發展很多，也有許多特殊的成果，應多鼓勵參加國際會議，增加能見度。

會中亦與數位曾在台灣就讀大學的馬來西亞僑生交談。他們在當地很有成就，對台灣在東南亞的發展應有助益。

三、攜回資料名稱及內容

本次出席 2007 第十六屆東南亞大地工程會議，共計攜回會議論文集一冊及論文光碟片乙片，並有東南亞大地工程學會成立 40 週年專輯一冊及其光碟片。

Liquefaction of Soils with High Fines Contents in Laboratory Tests

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Abstract: Cyclic triaxial tests and miniature cone penetration tests (MCPT) on Maoluo River soil with various fines contents (FCs) were conducted. Because of the compliance of the measuring system and the lower permeability of soils with higher FCs, the measured water pressure changes at different locations within the specimen could be different from those measured at the ends of specimen during a cyclic triaxial test. This could affect the assessment of the liquefaction resistance of the soil. The non-uniformity of the triaxial specimen and the variations of the measured pore pressure changes should be evaluated for soil with high FCs. The laboratory MCPT shows that the cone penetration resistance decreases with increasing fines content, and there is a very low sleeve friction even with FC > 50%. Comparing with the liquefaction resistances in the cyclic triaxial tests, the results can be used for assessing the use of CPT in liquefaction evaluation of soils with high FCs.

Keywords: Earthquake, liquefaction, fines content, cyclic triaxial tests, CPT

1 INTRODUCTION

Previous studies on the soil liquefaction characteristics are mostly based on the laboratory test results of clean sands with little fines (< 0.075 mm). Current methods of evaluation of liquefaction potential of soils during earthquakes was developed mainly from the field penetration test data of liquefied/non-liquefied soils with fines contents (FCs) usually less than 5%. It was considered that soils with higher fines content should have a higher liquefaction resistance, and the soil is unlikely to liquefy with a FC higher than 35%. However, in many recent earthquakes, soils containing high fines contents were often found liquefied, for example, liquefaction of sandy silts in Nantou City during the 1999 Chi-Chi Earthquake. Therefore, the liquefaction resistance of sand with fines was studied extensively in the recent year, e.g. Prakash, *et al.* (1998), Thevanayagam, *et al.* (2000) Yamamura & Kelly (2001).

Cyclic triaxial test apparatus, e.g. Chan & Mulilis (1976), is one of the most used testing devices in the soil liquefaction studies. In a typical undrained cyclic triaxial tests, it is assumed that no volume change of the specimen and the measuring system. As a result, the values of water pressure changes measured by the sensors should be the pore pressure changes throughout the soil specimen. In fact, there exists a volume change in the triaxial measurement systems, including tubing and sensors, when the water pressure changes. Therefore, when the pore water pressure changes in a certain location of the specimen, the soil in other locations or at another end of the measuring pipeline senses the pressure changes with a water flow according to the compliance of the test system. For sand with a high FC, the pressure measured at the ends of specimen cannot immediately reflect the pore water pressure changes within the specimen due to the low permeability of the soil. This can render inaccurate test results for the purpose of liquefaction assessment.

In the recent years, cone penetration test (CPT) results were frequently used for the liquefaction evaluation of the ground under earthquake loading (Olsen 1997, Robertson & Wride 1998). The sleeve friction ratio, $R_f = f_s/q_c$, is adopted to take into account of the effect of FC on the liquefaction resistance, where f_s is the sleeve friction and q_c is the cone tip resistance in CPT. However, the results of the liquefaction assessment using CPT are often inconsistent with the field observations (Seed *et al*., 2003), especially, for soils with high FCs. Furthermore, it is not well understood whether the fines reduces the field cone penetration resistance, or it actually increases the liquefaction resistance of the sand (Youd, *et al.*, 2001).

This paper attempts to clarify the above points by performing laboratory cyclic triaxial tests and mini cone penetration tests (MCPT).

2 CYCLIC TRIAXIAL TEST SETUP

The cyclic triaxial test apparatus was modified, as shown in Fig. 1, to provide three holes at the base platen of the triaxial cell for installing three 3-mm rigid stainless steel tubes with filters at the tips (Chan 2000). The heights of these tubes are 40 mm, 80 mm, and 120 mm. They are corresponding respectively to approximately 1/4, 1/2, and 3/4 of the specimen height of about 160 mm. The pore water pressure changes at the tip of each stainless steel tubes can be measured with the miniature pressure sensors (6.4 mm in diameter and 11.4 mm in length) directly beneath the metal pipe. Due to the limitation of the measuring system, only two metal tubes were used at the same time in each test. The water pressure changes at both ends of the specimen are measured as in the ordinary triaxial test with an external differential pressure transducer connected by stiff Teflon tubes with a total tubing length of approximately 1000 mm for the cyclic testing apparatus at Department of Civil Engineering, National Taiwan University. Thus, the pore water pressure changes at both ends, mid height, and 1/4- or 3/4-height of the specimen can be measured simultaneously during a cyclic triaxial test.

The soils used in this study were obtained from Maoluo River bank in Nantou City where extensive soil liquefaction occurred in the 1999 Chi-Chi Earthquake. Fig. 2 shows the grain size distribution curves for the Maoluo River soils obtained from two near-by locations on the river bank. The soils varies from ML (NP) to CL (PI = 8) containing low-plastic fines (PI = 7−14).

The portions of sand (> 0.075 mm) and fines (< 0.075 mm) of these soils were separated using wet sieving method. Soils with various fines contents were obtained by remixing different proportions of sand and fines. The triaxial specimen was prepared using the moist tamping method to obtain a dry density of 1400 kg/m^3.

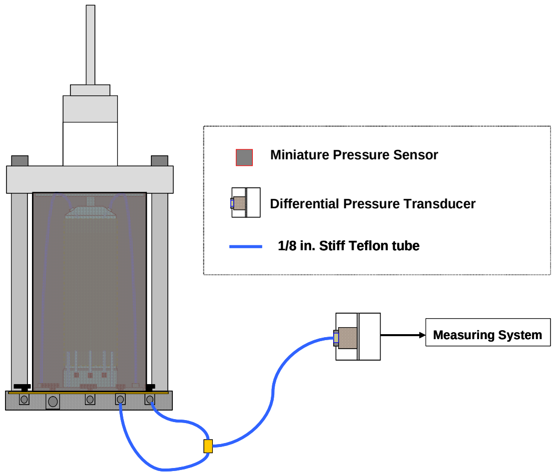
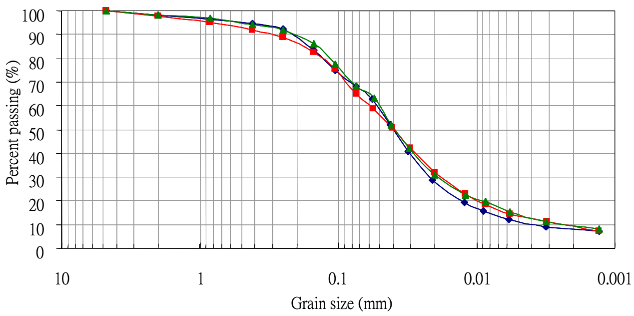
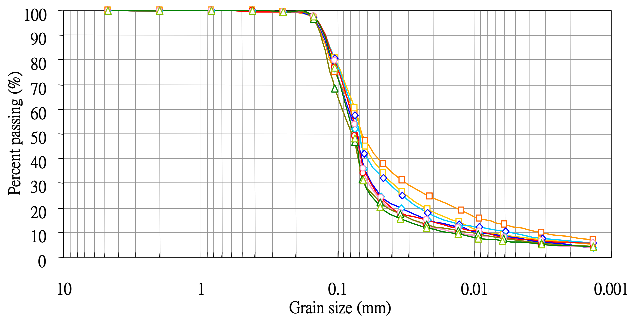


Fig. 1. Modified cyclic triaxial testing apparatus.



(a) Soil 1



(b) Soil 2

Fig. 2. Grain size distribution curves for the Maoluo River soils.

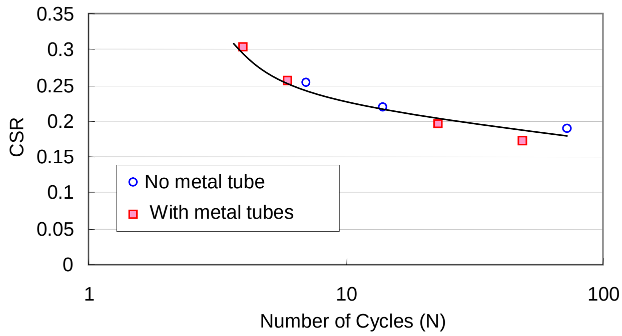
3 CYCLIC TRIAXIAL TEST RESULTS

3.1 *Liquefaction Resistances of Specimens with and without Metal Tubes*

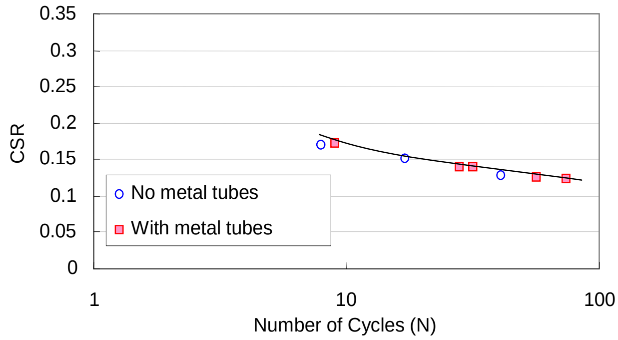
Cyclic triaxial tests on specimens with and without metal tubes were conducted to evaluate the effect of the metal tubes within the specimen on the liquefaction resistance. Fig. 3 indicates that there is little difference of liquefaction resistance between specimens with and without the inner metal tubes.

3.2 *Pore Pressure Changes at Different Locations within the Specimen*

Cyclic triaxial tests on soils with different FCs were conducted and the pore water pressure changes at different locations were measured (Yeh 2005, Wu 2006). Fig. 4 shows the comparison of water pressure measurements at various locations. It can be seen that for the clean sand (FC = 0), the pore water pressure changes during the cyclic triaxial test are essentially the same at different locations within the specimen. For the sandy silts (FC = 60% and 65%), the measured pore pressure changes are the highest at 3/4 height of the specimen, followed by those obtained at mid height, 1/4 height, and the ends of the specimen. This indicates an earlier liquefaction of the soil at 3/4 height where the necking of specimen usually occurs.

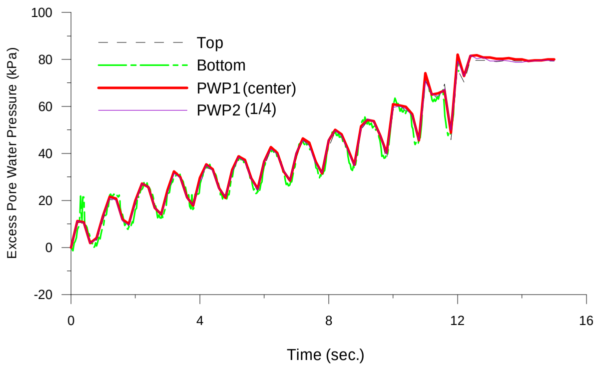


(a) FC = 0

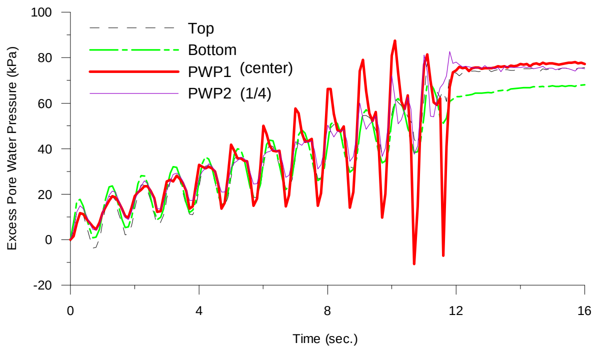


(b) FC = 60 %

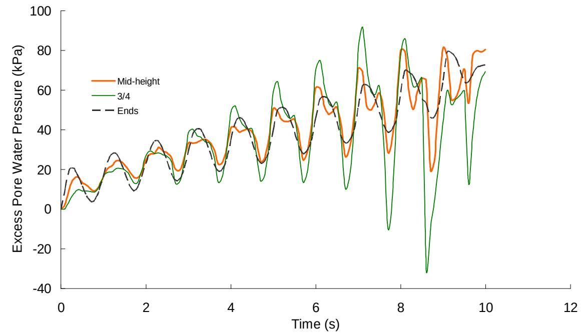
Fig. 3. Comparison of liquefaction resistance between triaxial specimens with and without inner metal tubes.



(a) Soil 1, FC = 0



(b) Soil 1, FC = 65%



(c) Soil 2, FC = 60%

Fig. 4. Comparison of pore water pressure changes at various locations in the triaxial specimen.

A correction for the number of cycles to liquefaction can be obtained by comparing the number of cycles to reach pore water pressure ratio, r_u = 1.0 at the ends and the 3/4 height or mid height of the specimen. A correction of number of cycles (Cn) to reach liquefaction can be expressed by:

$$Cn = N_i / N_o \tag{1}$$

where N_o = number of cycles to liquefaction based on the water pressure measured at the specimen ends, and N_i = number of cycles to liquefaction based on the pressure measured within the specimen.

3.3 *Permeability and Correction of Liquefaction Resistance*

Permeability of the soil with different fines contents were measured as shown in Table 1. The effect of soil permeability on Cn is shown in Fig. 5, based on the ratio between the pressure measurements at the mid height and the ends of the specimen. It can be seen that, according to the test results in this study, correction is needed for soil permeability lower than about 10^{-4} cm/s.

Table 1. Permeability of soils (dry density = 1400 kg/m^3) with different fines contents.

(a) Soil 1

FC (%)	Permeability (cm/s)
0	2.98×10^{-3}
15	1.87×10^{-3}
48	3.57×10^{-4}
65	4.44×10^{-5}
100	1.32×10^{-5}

(b) Soil 2

FC (%)	Permeability (cm/s)
0	3.07×10^{-3}
20	1.09×10^{-3}
40	1.40×10^{-4}
60	3.62×10^{-5}
100	1.10×10^{-5}

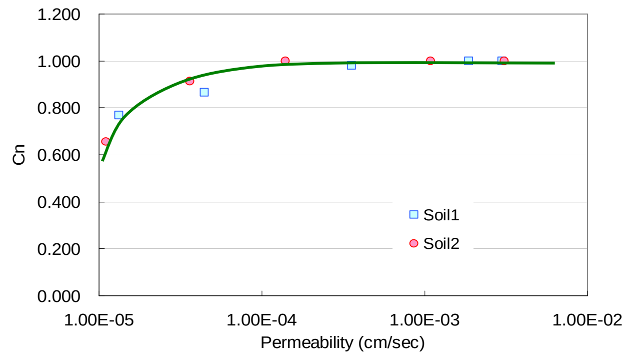


Fig. 5. Cn versus soil permeability.

4 MINI CONE PENETRATION TESTS

The laboratory MCPT was performed using a test system as shown in Fig. 6. The Maoluo River Soil 2 with FCs of 0%, 35%, and 54% was used in a specially designed stainless steel calibration chamber of 400 mm in diameter and 950 mm in height. The mini cone is about the half size of the ordinary standard electronic cone penetrometer (ASTM D5778-95) with a diameter of 17.8 mm and the friction sleeve length of 66.8 mm.

The soil specimens, 800 mm in height, were prepared by the moist tamping method, except the clean sand specimen which was prepared by the dry compaction method, to a dry density of 1400±30 kg/m^3 for all different FCs. Vacuum was first applied on the compacted specimen, and then the de-aired water was introduced to saturate the specimen. A mass surcharge of 60 kg was placed on top of the specimen to provide a K_o condition under a vertical effective stress of approximately 46 kPa. Mini piezometers were also placed at three depths of 160, 400, and 640 mm.

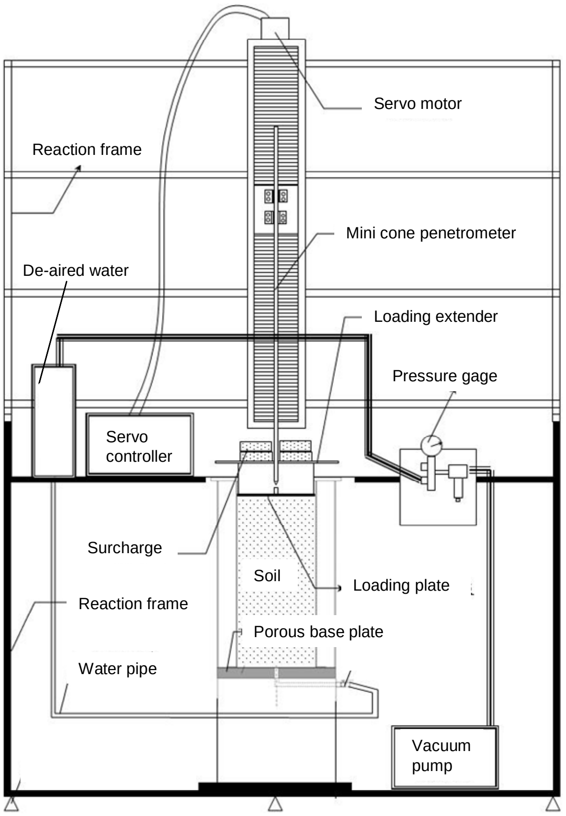


Fig. 6. Schematic drawing of MCPT system.

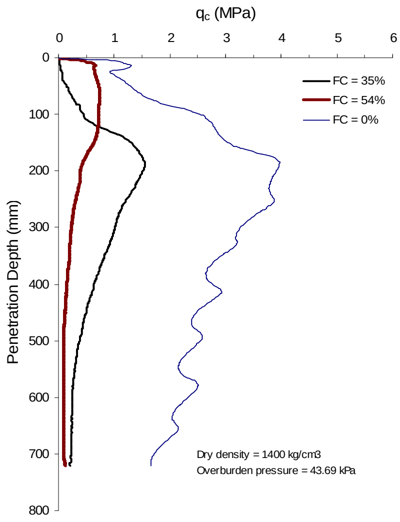


Fig. 7. q_c versus penetration depth in MCPT.

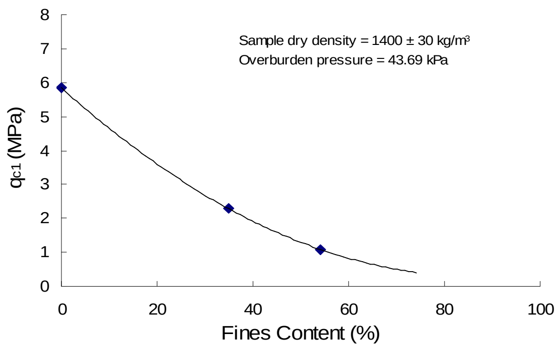


Fig. 8. Maximum q_{c1} for different FC in MCPT.

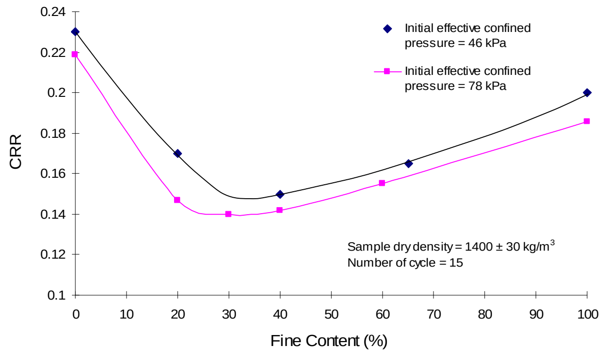


Fig. 9. CRR under number of stress cycles = 15 for Maoluo River soil of various FC.

The MCPT was conducted at a penetration rate of 20 mm/s until the cone reached a depth of 720 mm. The cone penetration resistance, sleeve friction force, and pore water pressures changes were measured during the penetration test.

Details of the MCPT system, instrumentation, sample preparation, and test procedures are presented in Chen (2006).

5 MCPT RESULTS

5.1 *Cone Penetration Resistance*

Fig. 7 shows the cone penetration resistance, q_c, versus the depth of penetration for FC = 0%, 35%, and 54%. The values of q_c were normalized according to $q_{c1} = q_c/(\sigma_v')^{0.5}$. The relationship between the maximum q_{c1} in a penetration test and FC is shown in Fig. 8. It depicts that q_{c1} decreases consistently with increasing FC, even with FC > 50%. The liquefaction resistance (cyclic resistance ratio, CRR, under number of stress cycles = 15) obtained in the cyclic triaxial tests (Fig. 9), shows that CRR decreases from FC = 0 to a minimum value at FC ≈ 30%, and then CRR increase slightly with FC > 30%. Obviously, the correction of FC should be applied when we assess the liquefaction resistance based on CPT results, especially for soils of high fines contents.

5.2 *Sleeve Friction*

Partly due to the sensitivity of the MCPT friction measurement and partly due to the very small sleeve friction resistance in the saturated Maoluo River soil of low plasticity, no sleeve friction could be measured for soil with FC = 0% and 35%. Less than 8 kPa friction resistance (Rf ≈ 1−5%) was obtained in the soil with FC = 54%. Therefore, there are difficulties and uncertainties in the use of the sleeve friction for FC correction in the liquefaction evaluation of soil with high FCs.

5.3 *Pore Water Pressure Responses during Penetration Tests*

The measured pore water pressure increases reached a maximum value when the cone tip passing the depth of that piezometer. The increase of pore water pressure during the penetration tests in soils of various FCs is plotted on Fig. 10. It can be seen that the higher the FC the more pore water pressure generation during the penetration test. This increase of pore pressure or decrease of effective stresses might be one of the reasons for the lower q_c in soils of high FCs and very low sleeve frictions.

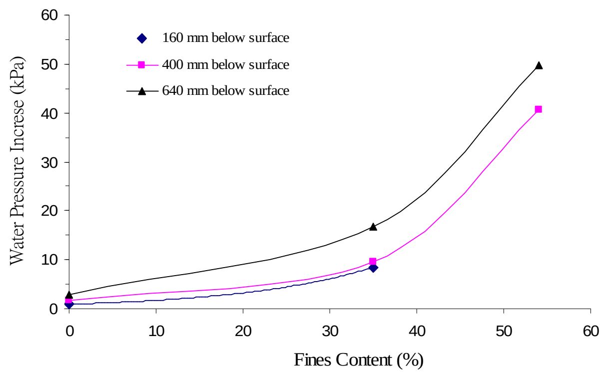


Fig.10. Pore water pressure increases during MCPT.

6 CONCLUDING REMARKS

The major findings in this study on measurements in the laboratory cyclic triaxial tests and MCPT for the Maoluo River soil with high FCs are:

– Because of the compliance of the pressure measuring system and the lower permeability of a soil with a higher FC, the measured water pressure changes at different locations within the specimen could be substantially different from those measured at the ends of specimen during a cyclic triaxial test.
– The higher the FCs, the lower the permeability of a soil. The true pore water pressure changes within the specimen of permeability less than about 10^{-4} cm/s cannot be obtained correctly by the pore pressure measurements at the specimen ends.
– The increase of FC reduces the cone penetration resistance, q_c, in CPT for the saturated the Maoluo River soil of high FCs.
– There is a very low sleeve friction measured in CPT on the Maoluo River soil even with a FC > 50%.
– Although a FC correction must be applied for the liquefaction evaluation of soils based on CPT data, there are uncertainties and difficulties to use the sleeve friction in CPT for this purpose.

It should be noted that the quantitative results in this study were obtained using the test apparatus at Department of Civil Engineering, National Taiwan University. Different testing devices with different system characteristics in other laboratories can give different results. However, the qualitative trend obtained in this study should be applicable to the liquefaction evaluation for soils with high FCs.

ACKNOWLEDGMENTS

This study is supported by the National Science Council, Taiwan, ROC. The uses of facilities in the National Center for Research on Earthquake Engineering (NCREE), Taiwan for MCPT are greatly appreciated. The authors wish to thank the assistances of Mr. C.H. Chen, and engineers at NCREE.

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Youd, T.L. *et al*., 2001, "Liquefaction Resistance of Soils: Summary Report from the 1996 NCEER and 1998 NCEER/NSF Workshops on Evaluation of Liquefaction Resistance of Soils," *Journal of the Geotechnical and Geoenvironmental Engineering*, ASCE, 127(10): 817-833.