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水庫淤泥處置及資材化應用之最佳化探討
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水庫淤泥處置及資材化應用之最佳化探討

摘要

台灣地區各主要水庫目前均面臨極為嚴重之淤泥沈積問題，因此水庫淤泥之清除及有效資源化處理對我國民生安全與經濟發展具有重大意義且屬刻不容緩。控制性低強度材料(CLSM)亦稱流填料(flowable fill)為一優良填方替代材料，可有效解決國內填土工程品質低劣及砂石料源日益短缺之問題，惟目前國內外CLSM之拌製均未曾應用具有塑性之水庫淤泥。本研究擬將此二項深具環保與經濟意義之議題結合，探討水庫淤泥於多功能流填料之應用可行性。參考CLSM之原理，以水庫淤泥為骨材，摻加固化劑再與水混合使之形成具有自流性之填方材料，配合地工砂袋應用於各種可能填方工程。研究內容以實驗室試驗為主，觀察水庫淤泥流填料之工程性質及地工織物之加勁圍束影響。試驗項目包括一般物理性質、流動性、凝固時間、單軸強度等，以期此一具有環保價值之工法得予實際應用，除可紓解國內水庫淤泥處理困難之窘境，亦可具體提昇填土之工程品質。

試驗結果顯示，水庫淤泥成分為高含水量之細料，屬低塑性黏土；以淤泥拌製流填料，藉由適當配比設計，可得合理之工程性質。考量回填工程之需求，淤泥流填料之最佳配比建議為水固比 0.7、灰水比 0.4。使用地工織物可具體提昇淤泥流填料之強度，其增量最高可達 86%，惟其影響有其限制。淤泥流填料初始強度愈高者，其增量愈低。一般而言，初始強度超過 1,000kPa 者，使用地工織物已不具有加勁效應。本研究之成果證實水庫淤泥應用於流填料確實可行，由此不但可以解決水庫淤泥之問題、增加填方工程之品質，亦可紓解台灣天然砂石資源不足之窘境，值得工程界參考。

關鍵詞：水庫淤泥、回填工程、流填料、地工織物、控制性低強度材料

ABSTRACT

Most of the reservoirs in Taiwan have experienced serious sediment accumulation problems. Therefore, the clean-up of reservoir sediments (RS) and its resource recovery becomes critical issues for national security and economical development. Controlled low strength material (CLSM) or AKA flowable fill is an excellent alternative for backfill construction. It is an ideal solution for poor backfill workmanship and shortage of aggregate materials in Taiwan. However, RS has never been used in backfill construction or CLSM because of its high water content and plasticity. This research studied the possibility of using RS in flowable fill together with geobags for backfill applications. The study will base on laboratory experiments to observe the engineering properties of the proposed CLSM and the effect of confinement supported by geotextile. Tests include specimen preparation, physical properties, flowability, set time, bleedings, and unconfined compression tests. The test results showed that RS contains plastic fines with high water content. However, it can be used for producing of acceptable flowable fill thorugh proper mix design procedures. Considering the requirements of backfill applications, this study recommends a W/S ratio of 0.7 and a C/W ratio of 0.4 can be used for the design. Geotextile presents strong confining effect on the strength increase for the hardened flowable fill. The highest increment observed was 86%. However, the stronger of the sample, the lower increment it will have. For samples with strength over 1,000 kPa, the geotextile no longer presents noticeable confinement. The results tend to reuse reservoir sediment, save natural

resource of granular fill, and ensure the quality of backfill constructions in most cases.

Key Words: reservoir sediment, backfill, flowable fill, CLSM

一、前 言

1.1 研究背景與動機

台灣地區各主要水庫目前均面臨極為嚴重之淤泥淤積問題。依據相關統計資料，台灣水庫之總淤積量已近五億立方公尺，平均淤積率達 20%，且每年仍以二千萬立方公尺之淤積量持續淤積之中，相當於每年損失一座明德水庫之蓄水量(張孟弘，2004)。水庫淤泥不但嚴重減少水庫容量，同時亦與颱風豪雨季節原水濁度之增加具有密切關聯，降低公眾供水之水量與品質，屢屢造成嚴重之民生、社會與政治問題(許盈松，2003)。例如石門水庫於 2003 至 2005 年間連續數度發生因颱風或豪雨造成之大桃園地區停水事件，導致當時政治、民生及社會極度之不安。此外，水庫淤泥由於含泥量與含水量極高，故其堆置、運棄與處理均極為困難。以石門水庫為例，其淤泥之清除與運棄，長年以來一直未能有效解決。問題癥結在於淤泥始終無法獲得妥善之最終應用或棄置。石門水庫淤泥多屬細粒土壤(ML 或 CL)且含水量極高，工程性質低劣，因此不適合作為工程材料，再利用性不高；且本身強度甚低，不具自立性，故無法如同一般土壤堆置成山丘狀，僅能儲存於沈澱池中。由於佔地遼闊，極為浪費土地資源。石門水庫目前興建之 13 座大型沈澱池容量均己告用罄，其所蓄存之淤泥仍無處棄置，而週邊地區亦無適當地點可供另闢沈澱池，導致水庫淤泥之清除作業因而停頓。在颱風豪雨之持續侵襲下，淤積量日益增加，水庫壽命己岌岌可危，對北台灣水資源未來之供應與發展產生立即而顯著之負面影響。由此可知，水庫淤泥整治方案應以解決淤泥之儲存與處置為當務之急，俾使庫底淤泥之清除作業得以恢復，紓解水庫壽命立即之威脅。長期而言，水庫淤泥之防治則必須重視集水區崩塌地之整治。依據歷年來學者與專家之調查與研究，各水庫淤泥產生之來源以自然崩塌為主，其餘則為地表沖蝕。例如石門水庫於艾利颱風期間產生之總土砂量約有 64%來自邊坡崩塌；明德水庫於桃芝颱風期間產生之總土砂量則高達 85%係來自邊坡崩塌。另依據統計，崩塌地所產生之泥砂，約佔全水庫淤積量之 75%。由此可知防治淤泥正本清源之道應為集水區崩塌地之治理(水利署，2005a)。

就回填工程而言，回填為施工過程所必須且重要之作業項目，而夯實即為確保填土作業達成最佳化目標之手段。由於天然砂石材料具有施工便捷且壓密快速等優點，應用於新闢或全路寬道路改善之基層，施工效果良好。故道路管理機關為確保回填工程之品質，規定將開挖後之剩餘土石方運棄不用，而以天然砂石材料回填，非但使天然砂石匱乏之問題日益嚴重且使工程成本大幅提昇，任意棄置之廢棄土方對生態環境亦造成嚴重衝擊(張育容，2006；蔡政欣、張源銘，2006)。此外部分回填施工空間狹小，例如管溝工程，夯實作業困難，事實證明經壓實後，路面仍產生大量沉陷，不易達成預期施工效果並造成維護成本增加(吳盛昆等人，2000)。

為尋求解決當前道路回填工程品質不佳所造成之問題，以工地實務之觀點，使用具有自流性、免夯實、高強度、低沈陷、低滲透等優良工程性質之流填料 (flowable fill，亦稱控制性低強度材料 control low strength material, CLSM)，取代傳統天然砂石級配回填料，可確實提昇回填品質不良之弊病。若以水庫淤泥作為流填料之骨材，不但可以解決水庫淤泥之問題、增加填方工程之品質，亦可紓解台灣天然砂石資源不足之窘境(李維峰等人，2002；

Lin et al., 2007)。

以土石填入各種天然纖維材料編製而成之砂袋(sandbag)，數百年來曾被廣泛應用於各種臨時堆填防護狀況且發揮具體顯著的效果，例如堤壩之防汛搶險、隧道湧水之緊急防堵、低窪地區之抗洪擋水，以及軍事設施、掩體之防護等(Gadd, 1988; Koerner, 1999; Matsuoka, 2002)。由於天然材料之耐久性不佳，故多數傳統砂袋僅具有臨時功能，較少長期之應用。然而近年來因塑料及紡織工業技術之發展，使得地工織物之品質與性能獲得大幅改進，耐久性得以改良，其中抗紫外線性能更具有顯著的提昇。以之編製成地工砂袋(geobag)，裝填各類土石、水泥漿或混凝土，即可長期用之於許多大地工程之中，例如管溝、路基、擋土牆，以及軟弱地盤之局部加固回填等，成為近年來極具推廣價值之創新工法(Matsuoka, 2002)。然而由於水庫淤泥為高含水量之細粒土壤，以其直接填充地工砂袋仍具有強度不足及大量體積縮減之缺點，不利地工砂袋加勁結構之長期穩定與安全。

綜合上述可知，水庫淤泥存在亟須處理之急迫性與無法處理之複雜性；而傳統工法亦難以克服填土工程品質弊病，以及山區道路路基災害之重複發生，因此若能將流填料與地工砂袋加勁工法之觀念與原則加以結合，並以之應用於水庫淤泥之處置、儲運並將其資材化發展成為應用於填土工程之材料與山區道路路基搶險救災之創新工法，對於我國環境保護永續發展及土木工程技術之提昇均具有積極意義。

1.2 研究目的

鑑於水庫淤泥之預防、處置及資源化產品應用之研發極其重要，而填方工程品質之控制及道路填方邊坡擋土結構災害之防治功效向為國人之詬病亦亟須改善，因此本研究擬將此二項深具環境保護與民生永續發展意義之議題結合，探討水庫淤泥之處置、儲運改善對策及應用於填方、擋土結構資材之最佳化可行性。以實驗室試驗（bench scale）觀察水庫淤泥流填料之工程性質及其與地工砂袋加勁工法之可行性。結合地工材料新科技，研發具體實際可行之非傳統工法與施工應用方案，以期紓解國內水庫淤泥處置之難題並有效提昇填方工程之品質，提供山區道路路基災修、復建另類選擇，同時亦達到水庫淤泥資源化應用之國家環境保護與永續發展之目標。

1.3 研究方法與流程

以石門水庫淤泥為骨材，以實驗室試驗方式觀察不同配比淤泥流填料試體及以此種材料填充之地工砂袋其工程性質之變化，探討此種材料作為回填應用之可行性與適用性，並提出最佳建議配比。

二、研究計畫與試驗方法概述

為增加水庫淤泥之有效應用，本研究以淤泥取代所有流填料之骨材，配合適量之水泥（Type I）執行配比設計試驗。觀察淤泥流填料不同配比之工程性質及地工織物之圍束效應(effect of confinement)，探討淤泥流填料及地土砂袋於此方面應用之可行性並求其最佳配比。研究參考前人之研究成果，以實驗室方法進行配比設計，首先進行淤泥之基本物理性質觀察包括比重(ASTM D854)、阿太堡限度(ASTM D4138)、土壤粒徑分析(ASTM D422)等並依土壤統一分類法予以分類；其次觀察各種成份組合之物理性、工作性與檢測強度關係之發展，針對各種不同配比之試體，執行流度(ASTM D6103)、泌水率(ASTM C940) 及單軸壓縮強度(ASTM D2938)，求其最佳配比；最後針對地工織物對於淤泥流填料強度之圍束影響加以驗證與探討。確認固化後之淤泥之大地工程性質，評估水庫淤泥流填料實際應用時之大地工程性質變化，以確認其應用之可行性。各項試驗方法均參照 ASTM 相關規範執

行。

三、試驗結果與分析

本研究以試驗方式探討淤泥資材化應用之可行性，因應水庫淤泥高含水量之特性，以淤泥產製流填料可避免脫水乾燥之需要，可直接作為管溝或擋土牆等結構之回填材料，具有節省成本及實務直接應用之優點。為求淤泥之最大資源化再利用，本試驗係以全淤泥拌製流填料之方式進行。研究重點為探討淤泥流填料之工程性質及地工織物對其強度之影響，依實際工程考量求出適當且合理之配比設計並提出相關之結論與建議。

3.1 淤泥基本物理性質試驗結果

淤泥試樣之平均比重值為 2.71。粒徑分析結果顯示其通過 200 號篩之細料為 56.77%。細料之液性限度(LL)為 34、塑性指數(PI)為 9，故淤泥試樣依統一土壤分類法屬於低塑性之黏土 CL。試驗進行時亦發現，可能因為沈積來源變異之影響，不同批次取樣之淤泥，其細粒料含量略有不同。當黏土含量較多時，其物理性質如上所述；粉土含量較多時，液性限度及塑性指數則略低，惟兩者之分類仍均屬低塑性之黏土（CL）。

3.2 淤泥流填料之配比設計

流度與強度為流填料最重要的二項特質，前者為其於流態(fluid state)時之施工控制要項；後者則為流填料於硬固後安全與否之所繫。因此淤泥流填料之配比設計目標以流度及強度為控制因素，作為各不同配比之優劣比較基準。

3.3 流動性試驗

試驗結果顯示，淤泥流填料與前人研究之一般流填料類似，其流度值隨水固比與灰水比之增加而增加，惟其中以水固比之影響較為明顯(吳淵洵、蔡慕凡，2004；李銘哲，2000)。良好流動性對工作性極具助益，然而拌合水較多易造成顆粒離析、泌水率增加，影響流填料之品質，故流度應於符合強度與施工性能要求之前提下，降低至最小限度。根據 ASTM D6103 建議，適當之流度值應介於 15cm 至 20cm 之間，惟若流填料未發生析離，則流度小於 30cm 者亦可接受(Pierce and Blackwell, 2003)。依據試驗結果，淤泥流填料於水固比為 0.7~0.8 時，其流度值為 16~28cm 較為理想。

3.4 單軸壓縮強度試驗

強度影響回填品質及日後可能在開挖之施工性能，本研究針對不同試驗條件進行分析與探討，以下分別就灰水比、水固比與養護齡期等影響因子加以討論。

3.4.1 水固比、灰水比與單軸壓縮強度之關係

綜合試驗代表性結果如圖 1 所示，淤泥流填之單軸壓縮強度(q_u)隨水固比及灰水比之增加而增加。一般而言，淤泥流填料中添加之水泥量愈多，試體之強度愈高。填塞於淤泥顆粒間孔隙之水泥，藉膠結作用使淤泥顆粒緊密結合而發揮固化效果。由綜合比較可知，增加水泥用量(灰水比增加)確實有助於 q_u 值之提升。於混凝土中，含水量增加可造成強度降低，然而在淤泥流填料中卻呈現相反之變化，其原因可能係淤泥之塑性較高，增加之含水量可增加淤泥顆粒之水化分解，提昇淤泥與水泥之結合程度，從而增加整體固化效果。依據相關文獻，流填料之 28 天設計強度一般介於 345 至 1,380 kPa 之間(ACI, 1999; Pierce and Blackwell, 2003)。試驗結果顯示，所拌製之三種淤泥流填料配比，其強度皆符合需求，惟

考量成本、安全與使用需求，淤泥流填料之配比建議以水固比為 0.7、灰水比為 0.4 較佳。

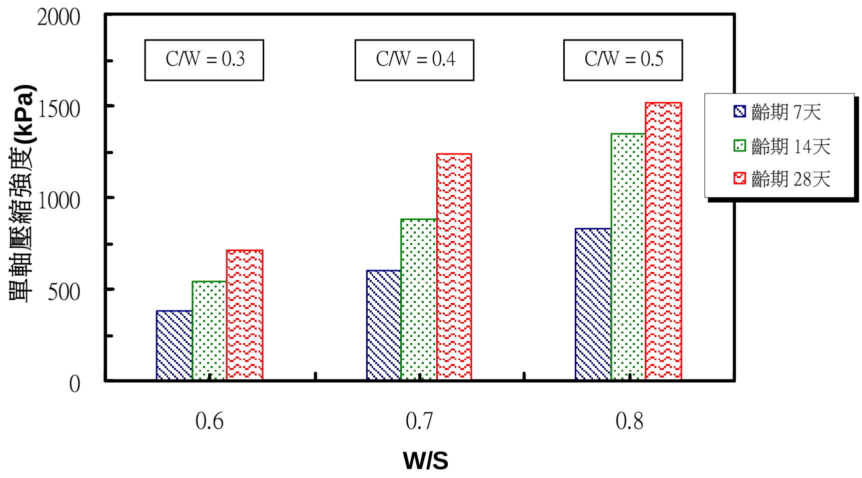

圖 1 淤泥流填料之強度與灰水比、水固比之關係

3.4.2 齡期與單軸壓縮強度之關係

由圖 1 亦可知，淤泥流填料因水泥之水化作用隨齡期持續發揮，故無論水固比及灰水比之變化 q_u 值均隨著齡期的增加而增加，且依據圖 2 之迴歸分析，齡期 7 天之強度與齡期 28 天者具有良好之線性關係，由此可依據短期強度預測 28 天之設計強度，有利於工程品質之控制。

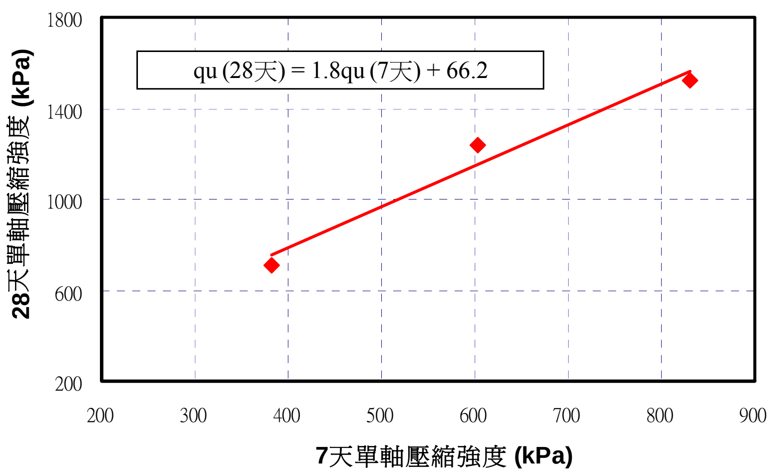

圖 2 淤泥流填料之齡期 7 天與 28 天強度之關係

3.5 地工織物之加勁圍束效應

綜合相關文獻之探討，地工砂袋加勁結構具有下列優點(Matsuoka and Liu, 2003; Matsuoka et al., 2003a; Matsuoka et al., 2004)：

- ✧ 可顯著提昇抗壓強度
- ✧ 若砂袋內充填無凝聚性材料則整體沈陷量低微
- ✧ 砂袋成本低廉且易於採購
- ✧ 與土壤具有相同單位重
- ✧ 地工砂袋內可充填各種類土壤(soil-like)廢棄物，因此可提昇此種廢棄物資材化應用機率
- ✧ 施工簡易毋須特殊機械

✧ 無公害、低噪音、低震動且與環境生態相容

為觀察地工織物對於固化淤泥流填料之強度影響，本研究依前述配比設計結果，分別選擇 W/S = 0.6、C/W = 0.3 及 W/S = 0.7、C/W = 0.4，二種代表性配比進行試驗。每種配比均複製二個相同試體。其一為控制組，未以地工織物加以圍束；對照組之複製試體則以與試體相同尺寸之地工織物予以包覆(如圖 3)。所使用之地工織物為 ACETex GTP 40/40 聚丙烯材質之織布(woven geotextile)，極限抗拉強度(ASTM D 4595)為 40kN/m。由於研究時程之限制，僅能試驗一種地工織物。試體之養護與前述一般試體之方式相同，並同樣於齡期 7 天、14 天與 28 天將試體分別進行單軸強度試驗，觀察此二組試體之強度差異。代表性試驗結果如圖 4 與圖 5 所示，由圖可知，未以地工織物加以圍束時，淤泥流填料之強度隨齡期之增加而增加，應力與應變關係呈脆性破壞且破壞應變均不超過 2.5%。當試體以地工織物圍束後時，其應力與應變不但轉變為塑性破壞模式，且破壞強度具有明顯差距之雙峰值，其最終應變量可達約 30%。Matsuoka and Liu, (2003)以實驗觀察不同填充物地工砂袋之強度變化亦得到類似之結果(圖 6)。

圖 3 觀察地工織物加勁圍束對淤泥流填料試體強度之影響

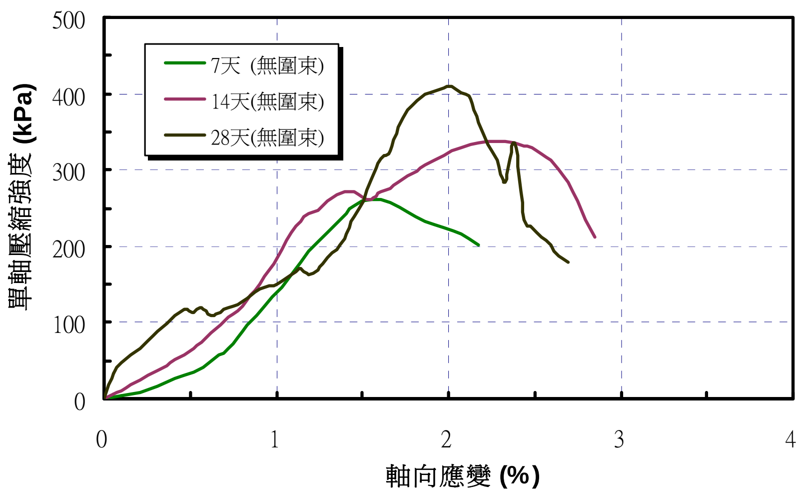

圖 4 未加勁圍束之淤泥流填料試體其應力與應變之關係
(C/W = 0.3、W/S = 0.6)

比較圖 4 與圖 5 亦可知，於較小應變產生之第一次破壞強度應為淤泥流填料試體其固體粒料之原有強度。當試體破壞後，由於地工織物加勁圍束之影響使得破壞之試體得以再度產生剪力阻抗，因而造成強度再次增加直至地工織物破壞為止。由圖 7 可知，加勁圍束影響之強度增量變化極大，介於 2%~86%之間。一般而言，其中以初始強度較低者，增量較大，齡期長短之影響則較無規則。若以齡期 28 天之試體為比較標準，水泥量較低者(C/W = 0.3)，其強度增量可達 72%，惟若水泥量增加至 C/W = 0.4 則增量趨近於零。由此可知，使用地工織物對於淤泥流填料強度之增加的確可產生正面助益，惟其成效需視淤泥流填料之初始強度而定。依據初步試驗結果，初始強度超過 1,000 kPa 者，地工織物之加勁圍束效應已降至最低。

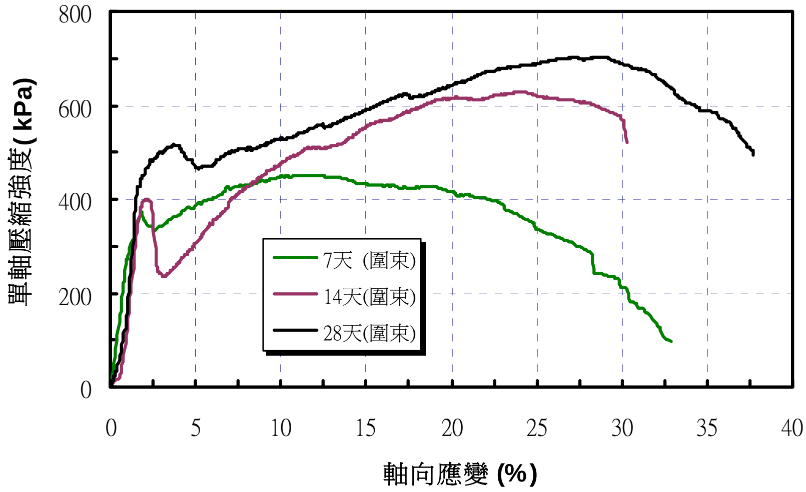

圖 5 以地工織物加勁圍束之淤泥流填料試體其應力與應變之關係
(C/W = 0.3、W/S = 0.6)

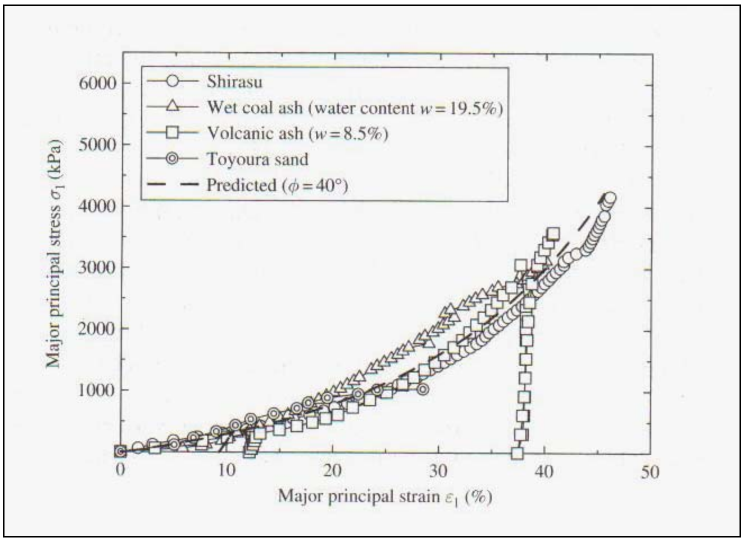

圖6 不同填充物之地工砂袋無圍壓縮強度試驗結果(Matsuoka and Liu, 2003)

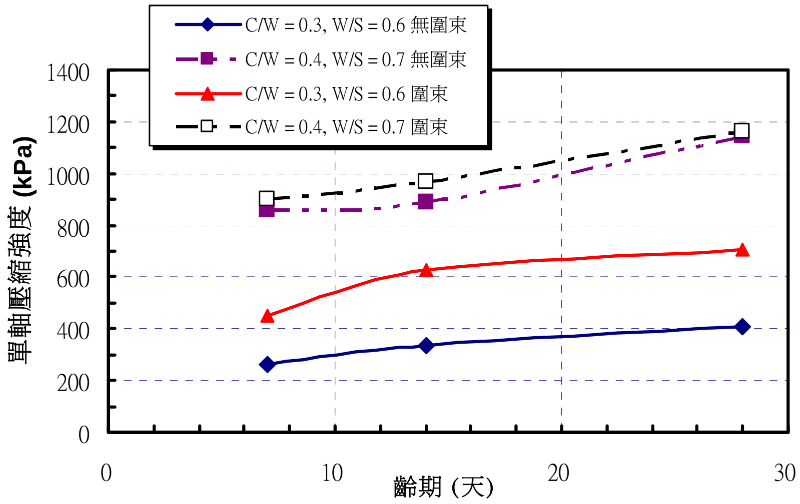

圖 7 地工織物加勁圍束對淤泥流填料強度影響之比較

四、結論與建議

本研究以試驗方式探討水庫淤泥應用於流填料之工程性質，並觀察使用地工織物對於淤泥流填料強度增量之影響，藉以提昇淤泥資源化之再利用。研究之主要目的為評估水庫淤泥於回填工程應用之可行性，依實際工程考量以試驗方式求出適當且合理之配比設計及實務可用之加勁材料，綜合試驗結果可獲得以下結論與建議：

4.1 結論

1. 以淤泥拌製流填料，於實驗室觀測所得之性質與一般流填料所表現者類似。流度隨水固比與灰水比之增加而增加，且以水固比之影響較為明顯。強度則隨灰水比之增加、水固比之降低而增加。依據回填施工之流度與單壓強度要求，淤泥流填料之配比建議水固比為 0.7、灰水比為 0.6 或水固比為 0.8、灰水比為 0.5。
2. 使用地工織物加以圍束時，可使淤泥流填料之應力與應變關係由脆性破壞轉變為塑性破壞模式，且破壞強度具有明顯差距之雙峰值。破壞應變量於初始強度時為 2.5%，但達極限強度時其應變量增加至約 30%。地工織物對於強度增量之影響，以初始強度較低者其影響較大，齡期長短之影響則較無規則。若以齡期 28 天之試體為比較標準，水泥量較低者(C/W = 0.3)，其強度增量可達 72%，惟若水泥量增加至 C/W = 0.4 則增量趨近於零。由此可知，使用地工織物對於淤泥流填料強度之增加的確可產生正面助益，惟其成效需視淤泥流填料之初始強度而定。依據初步試驗結果，初始強度超過 1,000 kPa 者，地工織物之加勁圍束效應已降至最低。。

4.2 建議

1. 本研究僅針對石門水庫淤泥進行試驗及探討，故研究成果之普遍性較為不足，為確實水庫淤泥應用於流填料之可行性，未來應針對其他水庫淤泥進行探討。
2. 地工織物之類別甚多，故其加勁圍束之影響可能因不同材料或不同產製方式而具有不同之影響，建議未來應針對不同類別之地工織物持續加以探討以確認其對強度之影響。

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行政院國家科學委員會補助國內專家學者出席國際學術會議報告

97 年 6 月 30 日

報告人姓名	吳淵洵	服務機構及職稱	中華大學 土木與工程資訊系副教授
會議 時間 地點	2008/6/16-2008/6/21 中國上海市	本會核定補助文號	NSC 96-2211-E-216-021
會議名稱	(中文) 第四屆亞洲區地工合成材料研討會 (英文) The 4th Asian Regional Conference on Geosynthetics		
發表論文題目	(中文) 降雨浸潤引致加勁邊坡破壞之探討 (英文) Wetting-induced geosynthetic reinforced slope failure		

報告內容應包括下列各項：

一、參加會議經過

國際地工合成材料協會(International Geosynthetics Society, IGS)與世界各地區分會合作，每隔四年均會主辦區域性之地工合成材料學術研討會(Regional Conference on Geosynthetics)，作為產官學各界交流之平台，廣邀世界各地之專家、學者及業者與會交流討論，為地工合成材料領域之國際盛事，故每次研討會多吸引世界各地產官學界菁英與會，蔚為風潮(照片 1)。

照片 1 IGS 為地工合成材料學術地位最高之國際組織

亞洲區之區域地工合成材料學術研討會繼上第三屆(2004)於韓國首爾舉辦後，本屆今年輪由中國主辦，地點為各項地工合成材料應用實例極多之上海市。會議自 6/16/2008 開始至 6/20/2008 結束。報名參與會議人數達 420 人，參展相關廠商亦達 38 家，接受發表之論文達 157 篇。我國參加者，學界包括中原大學、屏東科技大學、中華大學等校師生；廠商則有營建研究院、盟鑫、七洲、卓氏等共計 18 人。會議內容涵蓋地工合成材料於各領域之應用包括掩埋場、基礎加勁結構、排水、模型與與實驗室試驗、襯層穩定、加勁擋土結構(邊坡與擋土牆）案例探討、排水案例探討、拉拔試驗、襯層界面、祛水、加勁擋土牆地震行為、防漏層、反濾行為、新加勁材料之應用、地工膜布性質、地工合成材料耐久性、沖蝕控制、輕質土壤

材料、加勁邊坡及擋土牆之有限元素分析等總計達 28 項議題，以及四場專題演講。6/17 為訓練課程，正式會議則分別於 6/18~6/20 次第展開。會場設於上海市之上海展覽中心國際會議廳。

報告人於 6/15 上午自臺灣啟程赴上海，於當地時間夜晚抵達上海市下榻新錦江酒店，次日(6/16)即至會場報到參加由 IGS 教育委員會主辦之訓練課程，講員分別來自美、法、澳洲、韓、泰及地主國，針對地工合成材料之重要觀念、原則及實務應用加以介紹與說明。6/17 上午領取會議資料。會議正式展開，早上 9:00 至 10:40 首先進行大會開幕式(照片 2)，由大會主席清華大學教授李廣信主持並邀請國際土壤力學及大地工程學會會長 Pinto 教授、IGS 會長 Tatsuoka 教授等貴賓致詞，Tatsuoka 教授隨後並進行幕專題演講，報告地工合成材料之國際研發近況。

照片 2 第四屆亞洲區地工合成材料研討會之開幕式

10:40-11:50 由 Mercer 講座獎得主 Palmeira 教授進行專題演講，介紹 Soil-geosynthetic interaction 地工加勁材料之界面摩擦與剪力阻抗之最新發展；專題演講之後，隨即舉行參展廠商之開幕式。此次參展廠商近 40 家，地主國廠商佔多數，其餘分別來自美、歐、日、泰、紐西蘭等國；台灣亦有盟鑫、七洲等四家廠商參展。午休之後，仍為專題演講。報告者分別來自日本、新加坡、中國與韓國等國家。各場演講中以日本 Yasufuku 教授報告之「Confining effect of geogrid reinforced soils」，令人印象最為深刻。作者針對圍束應力對加勁格網產生之束制影響進行長期觀察，提出土壤膨脹角觀念，對於加勁擋土結構之分析設計與安全預測具有極大貢獻。隨即

6/18 上午仍為專題報告。報告者分別來自法國、美國、義大利、中國與泰國等國家。其中由中國浙江大學 Y.M.Chen 教授主講之「Expanded old landfill」較具有吸引力。垃圾掩埋場佔地遼闊，在長期使用後容積日減。由於都會地區人口稠密土地昂貴，因此老舊垃圾掩埋場之更新或延壽，對於都市之長期發展極為重要。本篇論文以實驗成果說明如何應用地工合成材料之優點進行老舊垃圾掩埋場之擴建，並指出目前若干分析上仍待探討之重點。報告清晰、精闢入理。我國垃圾掩埋場也面臨類似問題，因此本篇論文成果極為適用於台灣之狀況。下午 13:30~15:00 同步展開各場次之議程。報告人參加了「Reinforcement」場次。議程主題包括加勁邊坡及擋土牆案例探討、加勁擋土牆地震行為。於本場次中報告人發表論文：「降雨浸潤引致加勁邊坡破壞之探討」，以實驗及分析結果，說明台灣加勁擋土結構破壞特殊的環境與工

程因素與加勁擋土結構破壞之關係，最後再以案例加以驗證並與探討，相關研究成果可供工程界之參考。與會者對於本篇論文至感關注，且對台灣近年來頻頻發生之豪大雨及其與加勁擋土結構破壞之密切關聯性提出廣泛討論，並一致認為不飽和土壤浸水軟化之力學行為與加勁擋土結構之破壞具有必然關係，值得進一步加以探討。下午 15:30~17:00 為第二場次，報告人參加「Physical Test and Centrifuge Test」，並擔任會議主持人。本場次總共有八篇論文發表，報告者分別來自泰國、日本、希臘、土耳其及中國。其中以日本 Izawa 博士之「Centrifuge shaking table tests」最具有特色，且探討重點亦為浸潤對於加勁擋土結構之影響，其實驗結果也更可以佐證本人前述論文之觀點。該場次地主國之協同主持人並未參加，大會亦未指派任何工作人員協助計時，由本人獨撐全局，好在與會各論文發表人及觀眾相當合作，會議圓滿結束，不過大會之規劃疏忽與協調不週實令人難以苟同。

6/19 全日參加之議程均為「加勁邊坡與擋土牆」之案例探討，共計 19 篇論文。多數論文在探討加勁擋土結構之變形與穩定性分析，顯示地工合成材料應用至今，雖然材料品質與施工技術迭有進步，但仍有諸多盲點亟待探討並加以克服。泰國、新加坡、韓國與巴西等地之學者和專家亦分別提出加勁擋土結構位於軟弱地基時所造成之工程難題及改善建議對策。在各場次議程休息時間，報告人亦利用時間參觀各參展廠商所展示之最新產品蒐集資料。本次研討會參展廠商眾多，展示商品種類及內涵包括材料、設計、施工及電腦程式等均極為豐富。報告人如入寶山收獲甚多。研討會最後一日(6/20)為工程現場參觀，報告人參加之行程為上海洋山深水港航道工程。工程參訪結束後隨即返回旅館整理行李結束此次上海 2008 第四屆亞洲區國際地工材料研討會學習之旅。

二、與會心得

本次研討會參加者約 400 餘人，以國際研討會而言，規模不算龐大，惟會議主題切合潮流，主辦國，故會議內容尚稱豐富精彩。我國地工合成材料發展至今已將近 20 年，材料生產規模與品質亦已具有國際水準且已打開外銷市場，惟產學各界仍欠缺整合。各材料廠商因削價競爭產生心結，更無合作意願。而材料之複雜性亦使得公共建設之應用遠不如民間。中國、日本等地工合成材料產官學各界之合作模式實值得國內相關單位之參考。

地工合成材料具有性能佳、易施工、低成本、可耐久等多項優點，可應用於各種土木工程專業領域，但其中仍以大地工程佔主要部分。由於大地工程之高度不確定性以及地工合成材料之材料複雜性等因素之影響，使得地工合成材料之應用雖經迭次改進，惟目前仍具有諸多風險，歷年來在世界各地均已造成不少輕重不等的事故。而此點亦在此次會議中眾多發表之論文得到印証。在所有場次中，不少論文相當精闢且意義重大，值得令人學習與深思。對個人而言，當以加勁擋土結構破壞案例探討這一部分價值最為重要。俗諺:「失敗為成功之母。」大地工程之成功實踐，正確之本土經驗影響至鉅，因此藉由失敗案例之研討，可供工程人員汲取教訓，累積經驗，體認失敗的孕育、發生、發展及消亡規律，進而採取科學、有效、適時與積極之相應對策，提昇工程水準，預防失敗之發生。經過本次研討會之研習，不但印証報告人過去數年來於國科會支持下，針對此一研究方向努力之正確性，符合世界潮流與趨勢，同時亦增加不少關於地工合成材料之新知。感謝國科會與中華大學對於相關研究計畫及對於參加本次研討會經費之支持。

此次參加會議亦得以認識大會主席日本 Tatsuoka 教授、Izawa 博士、美國西德拉瓦大學 Leshchinsky 教授、新加坡 Phoon 教授，以及美國 Durham、TRI、中國大陸聯誼、泰興廠商代

表等 30 餘位世界各地的專家與學者並就研究所知與工程經驗交換心得。綜合言之，本次參加研討會研習收獲豐碩，鑑於 ICG 之學術研討會價值與地位倍受世界各地之重視，報告人至盼未來仍有機會再度與會研習新知。

三、考察參觀活動(無是項活動者省略)

研討會最後一日(6/20)為工程現場參觀，報告人參加上海洋山深水港航道工程。該工程為中國正在建設的最大的專業貨櫃集散港區，工區面積遼闊。主辦單位介紹了航道工程的設計規模、平面佈置、航道疏浚回淤研究等基本情況。工程規模浩大，令人印象深刻，對於中國近年來致力於經濟發展，提昇各項工程建設，獲得世界工廠之名實非偶然。

四、建議

依據報告人之研習與參訪所得，建議：

1. IGS 主辦之 ICG 國際研討會學術與實務價值極高，對整合工程理論、實務技術與市場行銷均極具成效，落實研發成果與技術之推廣，國內工程界應引為借鏡。建議地工材料協會應參照此種模式例行性的舉辦研討會，廣邀國內外產官學各界參與，推廣地工合成材料之應用與發展並提昇我國地工合成材料之國際地位，協助增加國產品外銷之市場。
2. ICG 相關主題之研討會吸引世界各地菁英與會，國人不應缺席，應儘量爭取出席，提高國人知名度與國際地位，此次會議國人參與者眾多自然形成力量，博取表現機會殊為值得，建議國科會或政府相關部會宜寬列預算，儘量鼓勵國內學者專家參加此種大型國際研討會以累積我國地工合成材料之國際地位。

五、攜回資料名稱及內容

「第四屆亞洲區地工合成材料研討會會議論文集」訓練課程教材及大會各參展廠商提供之材料樣品、資料等。

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WETTING-INDUCED GEOSYNTHETIC REINFORCED SLOPE FAILURE

J.Y. Wu[1] and A.H. Tang[2]

ABSTRACT: Failures of geosynthetic reinforced soil slope (RSS) initiated by intense rainfall have been often reported recently. These incidents were likely to be the effect of strength reduction upon wetting for unsaturated fill. This paper proposes a practical approach to evaluate the probable erroneous in analysis that responsible for such failures. A case study for a collapsed highway RSS was conducted to verify the developed protocol. The results were consistent with those observed in the field. The rational procedures found in this research offer a quick and simple way to estimate the stability of RSS upon wetting.

Keywords: Reinforced soil slope, intense rainfall, failure.

INTRODUCTION

Geosynthetic reinforced soil slope (RSS) technology has been widely used in Taiwan for the past decades. However, with its increasing uses, observed failures also have been often reported. Based on a comprehensive forensic survey, most of the RSS failures were initiated by intense rainfall or poor dissipation of seepage (Wu & Tang 2006). It appears to be anomalous as these structures all had shown sufficient safety factor under severe rainstorm conditions based on their safety analyses. Thus, studies of wetting-induced failures and back analyses are essential to substantiate the accuracy used in the design.

Conventional safety design of RSS under rainstorm condition is based on the limit equilibrium approach, which generally assumes a condition of rising groundwater level. However, the accuracy of the analysis depends on whether or not the assumed mode of failure adequately represents the conditions actually leading to collapse. Numerous studies for slope stability have indicated that the failure mechanism upon wetting involves moisture infiltration into the slope surface that leads to decreases in matric suction and soil strength (Chen et al. 2004, Collins & Znidarcic 2004, Crosta 2004, Sako et al. 2006). Although many researches have been conducted on the effect of wetting-induced slope instability, standard procedures have not been established to predict the corresponding slope safety. Available researches for RSS also seldom address to the effect of wetting on the stability. The sophisticated failure mechanisms and time-consuming analyses for unsaturated soils also make most engineers difficult to integrate theory into practice.

This study proposes a practical approach to the problem, in which a modified direct simple shear test was derived to observe the strength loss of compacted fill upon wetting. Computer limit equilibrium analyses were then performed using the observed strength parameters for rainstorm conditions. The practicability of the procedures was then verified by using an actual case of failure in which a geosynthetic reinforced slope collapsed after it was attacked by a typhoon.

EXPERIMENTAL PROGRAM

Testing Material and Specimen Preparation

The soil studied was a yellowish sandy material collected at the site where a highway RSS collapsed after it was attacked by a typhoon. The sand can be classified as poorly graded sand with silty clay (SP-SC) according to the Unified Soil Classification System (ASTM D2487). Table 1 presents their detailed physical properties. To observe the effect of infiltration on the stability of RSS with different moisture contents, specimens were compacted to 90% of standard Proctor maximum density with three moisture contents, namely OMC-2%, OMC, and OMC+2%.

Test Procedures

Determining the shear strength parameters of an unsaturated soil involves a sophisticated and time

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-consuming testing program (Cabarkapa and Cuccovillo 2005). For most of the geotechnical engineering firms in practice, their testing laboratories usually do not have the capability to measure the shear strength of unsaturated soils. There is a general lack of familiarity as regards equipment, procedures, and results (Abramson et al. 2002).The experiment in this research was therefore designed specifically to develop a simple protocol using current available equipment for the practicing engineers. Considering the influences of cost, times, and simplicity of the test, simple direct shear test (ASTM D 3080) was used to observe the effect of wetting on the variations of shear strength for sandy material compacted with different values of moisture content.

To examine the effect of wetting on the strength reduction of compacted sand, sample was vertically loaded without inundation to simulate the fill construction. Each sample was then soaked for 4, 12, or 24 hours to observe the effect of different time of soaking on the strength variations. Hydrocollapse due to wetting was recorded with time. The sample then was sheared to failure. Test procedures were similar to those described by Melinda et al. (2004) except shearing was not initiated until soaking of the sample was completed for the specified time. This was to simulate a rainfall-induced landslide of a fill slope under its self-weight. The primary object of the test was to observe the reduction of strength upon wetting and also keep simplicity of the testing protocol; suction was therefore not monitored throughout the test. Such arrangements were easy to perform yet able to acquire reasonable test results in relevant to the effect of wetting on unsaturated soils.

Table 1. Physical properties of tested soil.

Property	Value
Specific gravity	2.6
Coefficient of curvature, C_c	0.76
Coefficient of uniformity, C_u	9.1
% of fines (%)	8.24
Liquid limit (%)	26
Plastic limit (%)	12
USCS soil classification	SP-SC
Maximum dry density (kN/m^3)	17.6
Optimum moisture content (%)	17

RESULTS AND DISCUSSIONS

Effect of Wetting on the Shearing Behavior

Figures 1 to 3 illustrate the effect of wetting on the shearing behavior of sandy fill compacted to 90% of standard Proctor maximum density with varying moisture contents and soaking periods. The normal stress applied was 100 kPa. Detailed results of other testing schemes can be found in Tang (2005). It can be seen that the as-compacted moisture content and the soaking periods presented significant effects on the shear strength of compacted sand. Specimen compacted dry-of-optimum (OMC-2%) demonstrated the highest strength and a brittle behavior before wetting. However, its strength reduced to about 40% of its initial value and became the lowest after water was introduced to the specimen. Although the infiltration caused the strength to vary with the time of soaking, the final strength varied little for specimens compacted at higher moisture contents (OMC and OMC+2%).

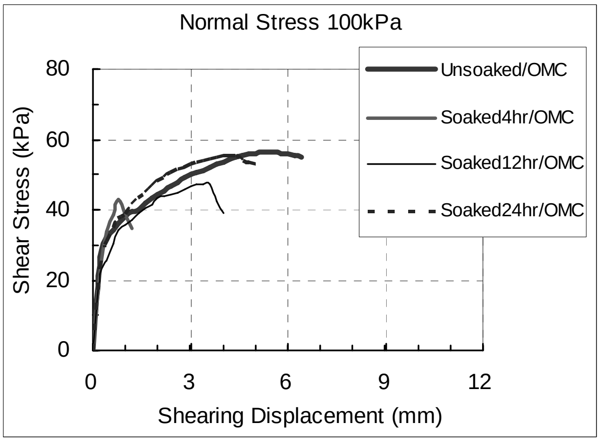

Fig. 1 Effect of wetting on the shearing behavior of a compacted fill (90% compaction, OMC)

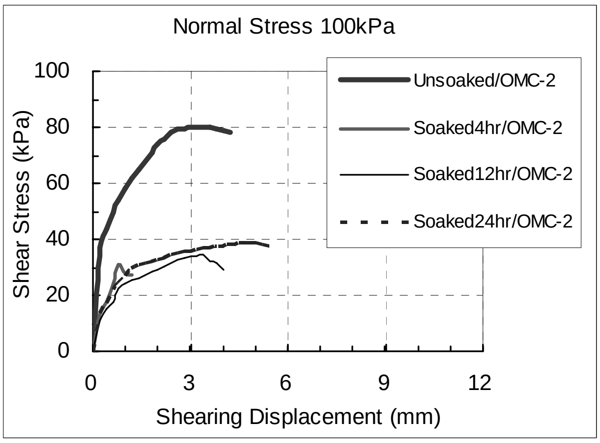

Fig. 2 Effect of wetting on the shearing behavior of a compacted fill (90% compaction, OMC-2)

Strength Parameters

Strength parameters are the crucial input in order to analyze the safety of a slope. The determinations of these parameters in a truly manner corresponding to those conditions at the site are thus vital to an accurate prediction for the slope safety. Abramson et al. (2002) stated that the shear strength of unsaturated soils can be readily accommodated within conventional slope analyses by using a concept of total cohesion. With this approach a modified value of total cohesion is used to include the effect of matric suction within the slope.

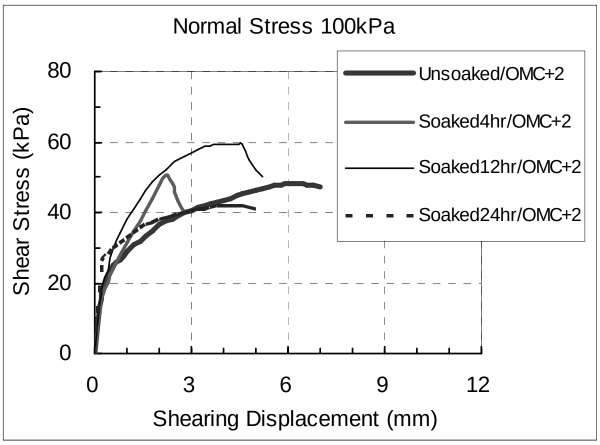

Fig. 3 Effect of wetting on the shearing behavior of a compacted fill (90% compaction, OMC+2)

Figure 4 summarizes all strength parameters tested for samples compacted to 90% of standard Proctor maximum density with varying moisture contents. In general, the infiltration caused the cohesion to decrease with the increase of soaking times. The cohesion was totally vanished after 24 hours of infiltration for samples compacted with less moisture contents (OMC and OMC-2%). The reduction was up to 100% in comparison with its initial value before wetting.

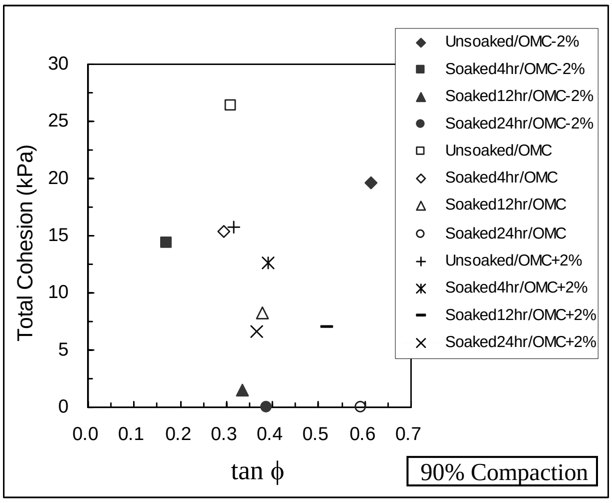

Fig. 4 The effect of wetting on the reduction of strength parameters for soils with varying moisture contents

According to Fredlund and Rahardjo (1993), the decrease of cohesion can be attributed to the loss of matric suction due to infiltration. Conversely, the friction angle increased with the increase of soaking time. It appears to be anomalous as research findings have indicated that friction angle is effectively independent of matric suction (Fredlund and Rahardjo 1993). Such phenomenon should be the effect of further consolidation of soil particles triggered after the hydrocollapse of soil sample. A longer consolidation promotes greater increases in the effective stress. It can be seen that samples compacted with less moisture content (OMC-2%) presented significant strength weakness upon wetting. It is logical to conclude that fill slope compacted dry-of-optimum will be more vulnerable to fail after intense rainfalls. Rehardjo et al. (2003) and Chen et al. (2004) reported many landslides of man-made slopes coincided with such behaviors.

Stability Analysis

Almost all traditional slope stability analyses are conducted using computer programs based on limit equilibrium methods. ReSSA has been the one on the market recently used by practicing engineers. It is relatively easy, simple, and user-friendly. To reduce the annoyance of facing unknown challenges for engineers, this paper proposes that conventional program such as ReSSA still can be used for unsaturated slope stability analyses. However, the reduced strength parameters observed using the above modified simple direct shear test must be used to account for the effect of infiltration on the strength loss. For normal and earthquake conditions, drained or undrained strength parameters applied for stability analyses of fill slope remain unchanged as those would be used in the conventional procedures. For intense rainfall condition, boundary of infiltration should be established first and the strength parameters for soil strata within the range of wetting band should be revised using the reduced values.

High-intensity rainfall induced landslides of fill slope often occurred on relatively shallow slip surfaces. The depth of the wetting front can be approximated based on soil characteristics and rainfall conditions (Abramson et al. 2002) or in terms of pore pressure (Collins & Znidarcic 2004). A more practical alternative would rather assume a reasonable depth of wetting front. The landslides in the unsaturated fill slopes are generally shallow and the failure surfaces are usually parallel to the slope surface. Therefore, for a short-term intense rainfall condition, the depth of wetting front of a sandy fill typically for RSS can be assumed reasonably within a range of 2 to 6m. For long-term condition, a worst case can be assumed that the phreatic surface rises to coincide with the slope surface and that the slope is completely saturated.

FHWA (2001) indicated that the interaction behavior between soil and geosynthetics in the anchorage zone determines the stability of reinforced earth structures. The pullout resistance of the embedded geosynthetic is a function of soil-geosynthetic interface shear resistance. It can be described by the following equation (Moraci and Recalcati 2006):

$$P_R = 2L\sigma'_v\ f_b\ tan\phi' \quad (1)$$

where P_R is the pullout resistance; L is the reinforcement length in the anchorage zone; σ_v' is the effective vertical stress; f_b is the soil-geosynthetic interface apparent coefficient of friction; and ϕ' is the soil shear strength angle. Based on Moraci and Recalcati (2006), the value of f_b are largely influenced by the value of shear strength of the fill material. Therefore, a reduction of soil shear strength certainly causes f_b to decrease as well.

CASE STUDY

To evaluate the usefulness and the practicability of the developed protocols, a case study was performed using site conditions and soil parameters from an actual case of failure. The site consisted of typical cut and fill constructions for a 15-m wide highway winding through a mountainous area. A 19-m high tiered reinforced slope was used to support the widening of the highway. The fill material for the RSS construction was the same as those described earlier.

Pre-construction stability analysis based on the traditional groundwater rising procedures indicated that the slope presented a safety factor of 1.63 for intense rainfall condition. However, the RSS collapsed during an attack of typhoon with an enormous rainfall and caused serious traffic interruption of the highway (Figure 5).

Fig. 5 RSS collapsed during an attack of typhoon

Forensic field investigation after the failure had observed that the collapsed fill was totally saturated because of the infiltration of rainfall. The saturation also caused the shear strength of the fill material dropped significantly. This happens to be the situation essentially similar to those inundated samples observed in the laboratory as described earlier. The designer ignored the effect of strength reduction upon wetting for unsaturated fill material. Therefore, it has shown reasonable evidence that the collapse was likely because of the erroneous stability analysis.

The safety of the RSS was examined further using the protocols developed in this study. Strength parameters of the fill material were reduced in stages to simulate the effect of infiltration resulting from the downward movement of wetting front. The reductions of pullout resistance of geogrid also can be simulated using reduced values of f_b in ReSSA.

Figure 6 presents a summarized result showing the variations of the factor of safety (F_s) with the depth of wetting front and the reduction of pullout resistance. The analyses were obtained using strength parameters after 24 hours of infiltration. Detailed results of all analyses can be found in Tang (2005). It can be seen that the values of F_s decreased with the increase of depth of wetting front. The reductions of pullout resistance of the reinforcements also presented significant negative effect on F_s.

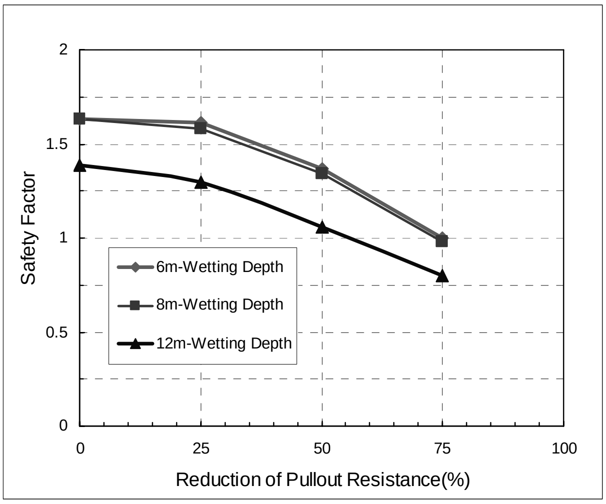

Fig. 6 The variations of factor of safety with the depth of wetting front and the reduction of pullout resistance

Based on the results of the simulations, failure of RSS will be highly likely when the wetting depth increases to 12-m and the pullout resistance drops over 50%. The failure plane essentially passes along the interface of cut and fill. The calculated factor of safety and the predicted mode of failure have shown a good agreement with what was observed in the field (Figure 7).

The illustrated case study shows that sophisticated infiltration and slope stability analysis may not always necessary for analyzing rainfall induced slope failure. Rational results also can be available using traditional analysis with proper experimental simulations. Further studies are underway to verify the presented method.

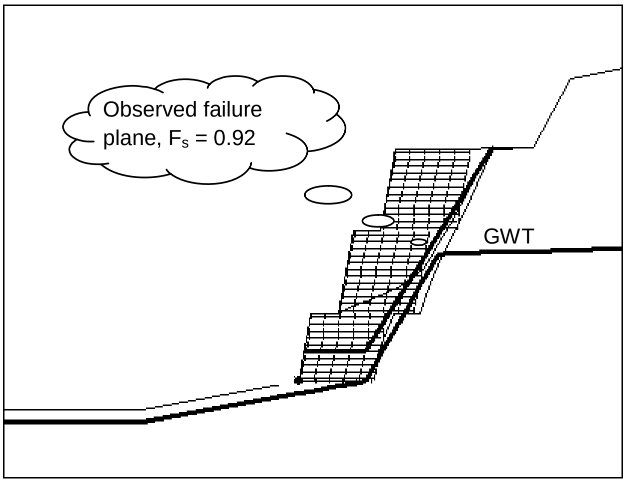

Fig. 7 Result of stability analysis showing a wetting depth of 12-m caused the RSS to collapse

CONCLUSIONS

Based on the study, the following conclusions can be drawn:

- The modified simple direct shear tests developed in this research appropriately simulate the strength reduction upon wetting in the field.
- In general, the infiltration caused the cohesion to decrease with the increase of soaking times. For samples compacted with less moisture contents, the cohesion could be vanished completely after 24 hours of infiltration.
- Samples compacted with less moisture content presented significant strength weakness upon wetting. Common practices for RSS compacted dry-of-optimum thus will be more vulnerable to have failures after intense rainfall.
- The results of a case study demonstrated that the calculated safety factor and the predicted mode of failure agreed reasonably with what was observed in the field.
- The proposed method in this study offers a simple and practical way to evaluate the stability of RSS upon wetting.

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