行政院國家科學委員會專題研究計畫 成果報告

水庫淤泥應用於多功能流填料之研究
研究成果報告(精簡版)

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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

水庫淤泥應用於多功能流填料之探討

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水庫淤泥應用於多功能流填料之探討

摘要

台灣地區由於環境因素、地質狀況及人為條件之不良影響，致使水庫淤泥淤積嚴重且處置、清除十分困難，研發淤泥資源化利用技術實屬當務之急。國內回填工程之施工品質控制不良，常導致施工回填後發生沈陷與孔洞，對市容及行車安全皆造成不良之影響。使用流填料(flowable fill，亦稱CLSM)回填可有效改善此種缺點。

為使水庫淤泥有效資源化利用，本研究針對水庫淤泥取代流填料骨材之可行性進行探討其應用係以淤泥取代骨材，執行配比試驗，觀察淤泥流填料之工程性質。試驗項目包含水庫淤泥之基本物理性質及流填料之單位重、流度、強度及大地工程之滲水性、壓縮性、濕陷性等。

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，淤泥流填料之配比建議為水固比為 0.7~0.8；灰水比為 0.5~0.6。本研究之成果初步證實水庫淤泥應用於流填料可行性高，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、CLSM

一、前 言

1.1 研究動機

近年來，台灣由於環境因素、地質狀況及人為條件之不良影響，致使水庫嚴重淤積，除造成水庫使用壽命折減外，亦衍生許多政治、社會與民生問題(魏子翔，2004；周贊祐，2004)。然而水庫淤泥之處置、清除十分困難，遂使水庫無法有效清淤，因此研發淤泥資源化利用技術實屬當務之急(吳素禎等人，1999；范國晃，2001；Elkins and Thompson, 1997)。鑑於水庫淤泥實為一種高含水量之細粒土壤，若能將其資源化再利用，不惟可以解決淤泥過剩的問題亦可紓緩粒料缺乏的窘境。

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)。

1.2 研究目的

鑑於水庫淤泥淤積嚴重，淤泥有效資源化處理極其重要，而提昇回填品質及砂石替代材料之發展亦刻不容緩，因此本研究以石門水庫淤泥為試驗土樣，使用不同材料之配合比例，探討水庫淤泥流填料之物理及工程性質，希望藉由實驗結果，確認水庫淤泥流填料應用於回填工程的可能性。

1.3 研究方法與流程

以石門水庫淤泥為骨材，以試驗方式觀察不同配比淤泥流填料試體其工程性質之變化，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

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）與摻料執行配比設計試驗。觀察淤泥流填料不同配比之工程性質，探討淤泥於此方面應用之可行性並求其最佳配比。研究內容以大地工程性質為主，驗證其於回填工程應用之適用性。研究首先進行淤泥之基本物理性質觀察並依土壤統一分類法予以分類；其次進行淤泥流填料之配比設計試驗，針對各種不同配比之試體，執行流度(ASTM D6103)、泌水率(ASTM C940)、濕陷性、壓縮性、單軸壓縮強度(ASTM D2938)及透水性試驗(ASTM D5856)。試驗之詳細項目及試驗方法說明如下：

2.1 淤泥基本物理性質試驗

試驗土樣之基本物理性質試驗，包括比重(ASTM D854)、阿太保限度(ASTM D4138)、土壤粒徑分析(ASTM D422)等。

2.2 淤泥流填料之配比設計

淤泥流填料之齡期 28 天設計目標強度為小於 2,100kPa。配比設計之重點為儘可能提昇淤泥資源化之比例並同時兼顧必要之回填材料工程性質。

淤泥流填料之配比設計用量係依下列公式計算：

灰水比（C/W）＝水泥重/水重　　(1)

水固比（W/S）＝水重/固體重　　(2)

淤泥粒料重＝固體重－水泥重　　(3)

用量計算以下例說明：

假設控制參數為 C/W＝0.4、W/S＝0.4。

1. 試驗固體重假設為 1,000g。
2. 將假設之固體重代入式(2)中可求得用水量為 400g。
3. 將用水量代入式(1)中可求得拌合所需水泥量為 160g。
4. 最後將水泥量 160g 代入式(3)中可得淤泥粒料重 840g。

故淤泥流填料C/W＝0.4、W/S＝0.4，所需之各種材料使用添加量即可求得。

2.3 試驗材料

1. 水庫淤泥 - 本研究之試驗淤泥材料取自石門水庫沈澱池。試樣顏色成黑色黏稠狀，烘

乾後淤泥呈灰色，且具團塊之現象。

2. 水泥 - 採用台灣水泥公司生產之第 I 型波特蘭水泥，其性質符合CNS 61-R2001之規定。
3. 拌合水 - 在相關規範中對拌合水無特別規定，普通自來水即可符合試驗要求，因此本試驗採用一般純淨自來水作為拌合水。

2.4 泌水率試驗

將烘乾之淤泥與水泥量於拌合盆內先行乾拌均勻後，依照所需實驗配比加入適當拌和水調勻。試驗步驟說明如下：

1. 首先將銅模底部以橡皮套封住，倒入已拌和好之流填料直到填滿為止，以鏝刀依試體高度將頂部刮平，靜置 24 小時。
2. 將試體由銅模內以頂土器頂出，以游標卡尺量測試體高度並記錄之。
3. 泌水率為泌水高度（試體之高度與銅模之高度差）與銅模高度之比值。

2.5 流動性試驗

依照 ASTM D 6103 之要求，以 7.5cmϕ×15cmH 圓柱鋼模量測其流動性。將烘乾之淤泥與水泥量於拌和盆內先行乾拌均勻後，依照所需實驗配比加入適當拌和水調勻。試驗步驟說明如下：

1. 以濕抹布將鋼模內側壁潤濕並置於鋼鈑上，以手固定鋼模，防止鋼模底部滲水。
2. 將拌和好流填料倒入鋼模內，直至填滿為止。
3. 以鏝刀刮平頂部，並立即以穩定的速度將鋼模垂直向上提起，其速度約為 5±2 秒內 30cm。
4. 以游標卡尺量測流填料之流度值。流度值即為流填料流動範圍之直徑。

2.6 單軸壓縮試驗

本研究之試驗儀器為計測企業有限公司製造之單軸壓縮試驗試驗儀。主要包括壓力機、荷重儀表與垂直應變計等。試驗速率為電子調速，本研究是以 1%/min 之加載速率進行試驗。試驗步驟說明如下：

1. 依照各種配比拌和後，澆置於銅模（3.5cmϕ×7cm）內，靜置 24 小時，再以頂土器將試樣小心取出後編號歸類進行養護。
2. 依照齡期將試體取出，置於單軸壓縮試驗試驗儀上進行單軸壓縮試驗。

2.7 滲透試驗

本研究所使用之儀器為六聯式透水試驗儀，可同時量測六個試體。量測滲透係數時，以變水頭方式進行，並依土體滲透性大小，選擇不同管徑之量測管進行試驗。試驗步驟說明如下：

1. 拌合完成之流填料，倒入透水模具中，直至填滿為止，並以刮刀將頂模多餘之拌合料刮平。
2. 將試體靜置於室內 24 小時，進行室內變水頭試驗。

2.8 單向度壓密試驗

本研究依據 ASTM D2435 所使用之儀器為四聯壓密試驗機，可同時量測四個試體。壓密環的尺寸為直徑 6.35cm，高度 2.5cm，對土體進行雙向排水壓密試驗。試驗步驟說明如下：

1. 拌合完成之流填料，倒入壓密環中，直至填滿為止，並以刮刀將頂模多餘之拌合料刮平。
2. 將試體靜置於室內 24hr，進行雙向排水壓密試驗。

2.9 單向度單式濕陷試驗

本研究依據 ASTM D2435 所使用之儀器為四聯壓密試驗機，作為濕陷觀測儀器。濕陷環的尺寸為直徑 6.35cm，高度 2.5cm。試驗步驟說明如下：

1. 拌合完成之流填料，倒入濕陷環中，直至填滿為止，並以刮刀將頂模多餘之拌合料刮平。
2. 將試體靜置於室內 24hr，進行濕陷試驗

三、試驗結果與分析

本研究以試驗方式探討淤泥流填料應用於都市道路回填之可行性。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，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。粒徑分析結果如圖 1 所示。顯示其通過 200 號篩之細料為 56.77%。細料之液性限度(LL)為 39%、塑性指數(PI)為 14%，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

淤泥流填料之配比設計目標為以淤泥取代所有骨材，添加適量之水泥執行配比試驗。觀察淤泥流填料之工程性質，以探討淤泥於流填料此一方面應用之可行性。為簡化各種變異因素對流填料之影響，本研究以流度為控制因素，比較各不同配比之工程性質。

3.3 流動性試驗

如圖 2 所示，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(陳怡伶，2006；黃政昭，2005；蔡慕凡，2003；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。就試驗結果顯示，淤泥流填料當水固比為 0.7、灰水比為 0.6～0.75，水固比為 0.8、灰水比為 0.3～0.5 及水固比為 0.9、灰水比為 0.2～0.3 時，具有較理想之流度值。

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 養護條件與單軸壓縮強度之討論

養護條件對於水泥固化物強度之發育至關重要。本研究對相同試體分別施予不同養護方式，包括封存養護(sealed curing)、覆土養護(underground curing)與水中養護(under water curing)，以觀察養護條件對強度之影響。代表性結果如圖 3 所示。比較三種養護條件，其中以封存與水中養護之強度較高。顯示試體含水量之保存對其強度之發育至關重要，惟考量現地施工之狀況仍以覆土養護較為接近。

3.4.2 水固比、灰水比與單軸壓縮強度之關係

綜合試驗結果如圖 4 所示。水固比於 0.7 增至 0.9 時，淤泥流填之單軸壓縮強度(q_u)隨之而降低，但水固比大於 0.8 後，q_u 產生折減之現象，而就水固比 0.7 至 0.8 與水固比 0.8 至 0.9 相較，前者較後者折減小，由此可知水固比有其一定之適用範圍。用水量過多易使強度折減及骨材析離，但用水量過低亦具有不易拌合、流動性及強度過高不利於開挖等缺點(李銘哲，2000；蔡慕凡，2003)。依據試驗結果，淤泥流填料之建議水固比以 0.7 至 0.8 較為理想。

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，增加水泥用量有助於 q_u 值之提升，然水固比為 0.7、灰水比為 0.6 時，其 28 天強度已高達 2,400kPa～2,900kPa，不符合開挖性之要求；而水固比為 0.8、灰水比小於 0.5 時則強度甚低。由此可知，淤泥流填料之水固比有一定之適用範圍，且高灰水比易造成強度過高不符再開挖之要求，因此若設計強度為 2,000kPa 時，建議水固比(w/s)應≦0.9 且灰水比應≧0.5，可符合規範之要求。

3.4.3 齡期與單軸壓縮強度之關係

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(圖 5)，惟於水固比及灰水比較小時，齡期之影響較不明顯。依據試驗結果，並考慮長期強度之變化，建議最佳之水固比為 0.7、灰水比為 0.6，水固比為 0.8、灰水比為 0.5 較符合回填料之長期強度要求。

3.5 設計配比之大地工程性質

依據前述試驗所得之配比設計建議，本研究近一步探討淤泥流填料之大地工程性質。試驗結果探討如次。

3.5.1 滲透性試驗

淤泥流填料之滲透性試驗結果如圖 6 所示。淤泥流填料之滲透係數介於 1×10^{-7} 至 1×10^{-8} cm/sec 之間，與黏土相當，屬低透水性材料。試驗結果亦顯示，淤泥流填料在水固比為 0.7、灰水比為 0.6 時，滲透係數較無明顯變化；但於水固比為 0.8、灰水比為 0.5 時，滲透係數則產生較明顯的變化。由固化反應產生之膠體，填充試體顆粒間之孔隙，使滲透路徑受阻造成滲透性降低。灰水比愈高，固化反應膠體愈多，故滲透性亦隨之降低。

3.5.2 單向度壓密試驗

淤泥流填料之單向度壓密試驗結果如圖 7 所示。由於水泥固化作用之影響，淤泥流填料之壓縮指數與壓密係數皆隨水固比之增加而增加，灰水比之增加而減少。原因為水固比較高且灰水比較低時，試體易造成骨材顆粒析離，使固化反應產生之膠體減少，填充試體顆粒間之孔隙也隨之減少，引發壓縮較大之現象。

3.5.3 單向度單式濕陷試驗

淤泥流填料之單向度單式濕陷試驗結果如圖 8 所示。淤泥流填料之濕陷量隨著水固比之增加而增加。於較低之荷重時(200kPa)時，濕陷狀況較為明顯，惟其最大值亦僅為 0.04%，對結構不具危險性。當荷重增加至 800kPa 與 1,600kPa 時，濕陷值甚微。變化之原因，推測於乾燥狀態時，較高荷重可使試體中產生較高應力，使粒料在未浸水前即趨於壓實，產生預壓密作用，使得粒料間的互制力較強，可提供較大之抗剪力，因此試體浸潤時較不會產生濕陷。

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，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，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(2,100kPa)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. 建議配比試體之滲透性介於 1×10^{-7} 至 1×10^{-8} cm/sec 之間，與黏土相當，屬低透水性材料。壓縮指數與壓密係數皆隨水固比之增加而增加，灰水比增加而減少，惟預壓密壓力達 800kPa，故於一般回填工程應用時應無沈陷之虞。濕陷量隨著水固比之增加而增加。於較低之荷重時(200kPa)時，濕陷狀況較為明顯，惟其最大值亦僅為 0.04%，對結構不具危險性。當荷重增加至 800kPa 與 1600kPa 時，由於較高荷重產生之預壓密作用，故濕陷值甚微。

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. 由於來源變異性之影響，淤泥成份亦產生變化，極可能造成流填料之產製性質無法一致。建議於現地淤泥取樣時，宜多方取樣試驗，最後再以統計迴歸方法取得一致性。

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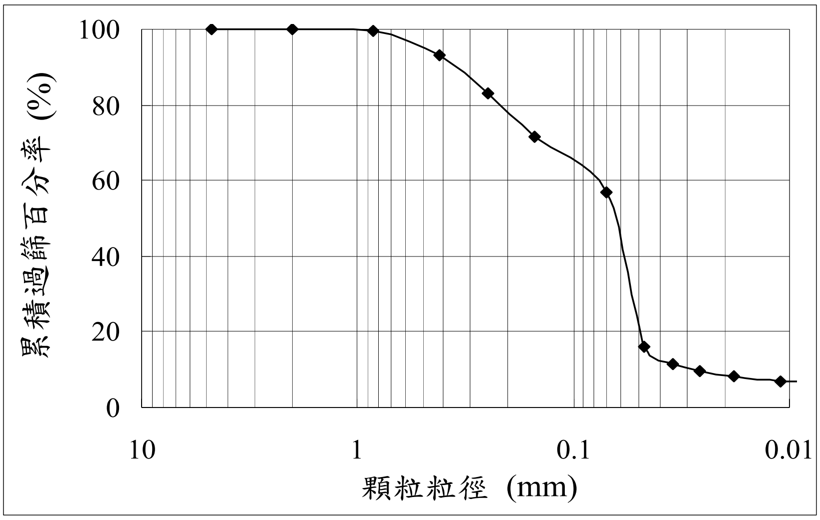

圖 1 水庫淤泥之粒徑分佈

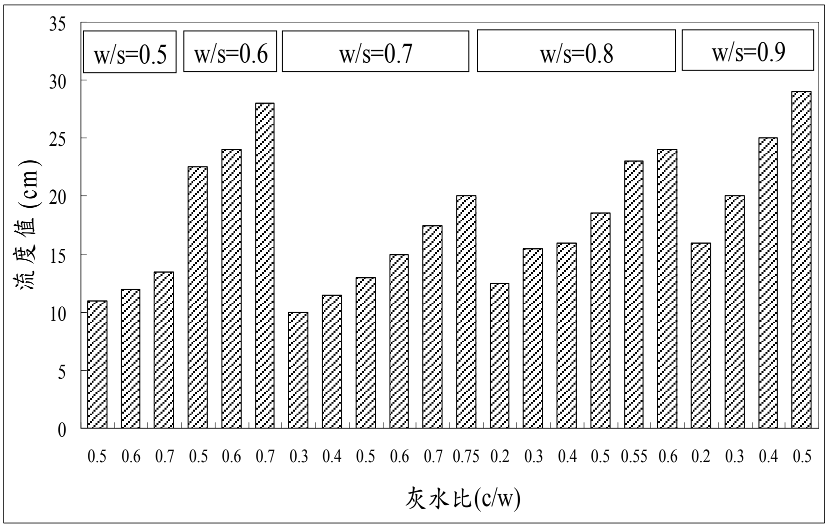

圖 2 淤泥流填料之流度值與各控制參數之關係

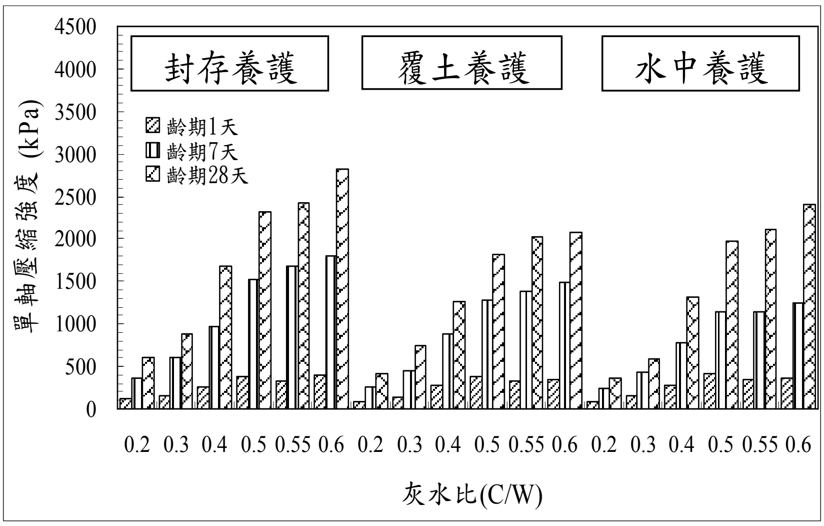

圖 3　淤泥流填料之單軸壓縮強度與養護條件之關係 (水固比＝0.8)

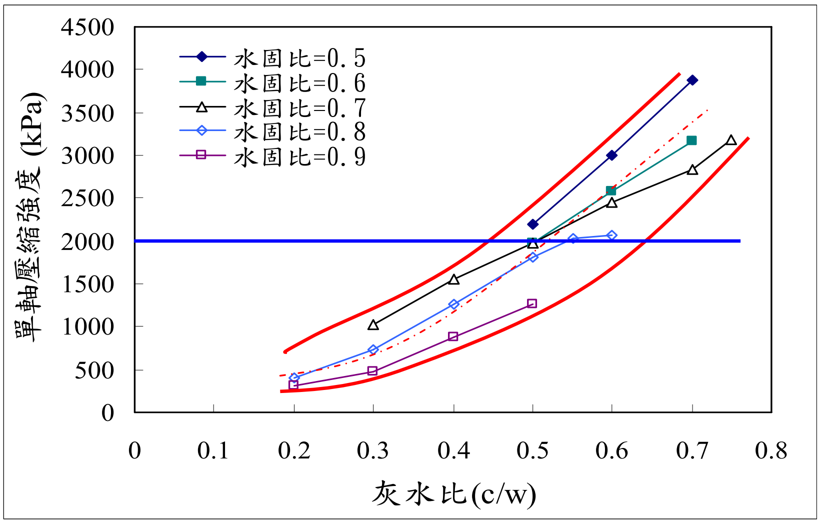

圖 4　單軸壓縮強度與水固比、灰水比之關係

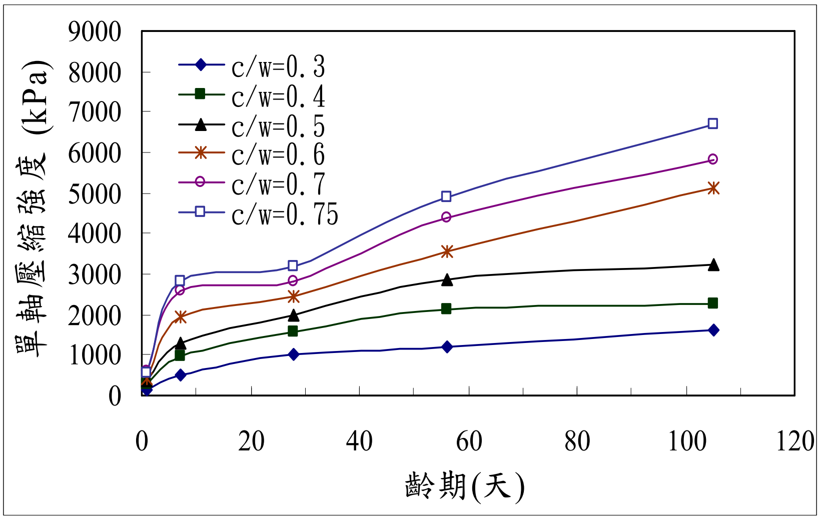

圖 5　淤泥流填料之單軸壓縮強度與齡期之關係 (水固比＝0.7)

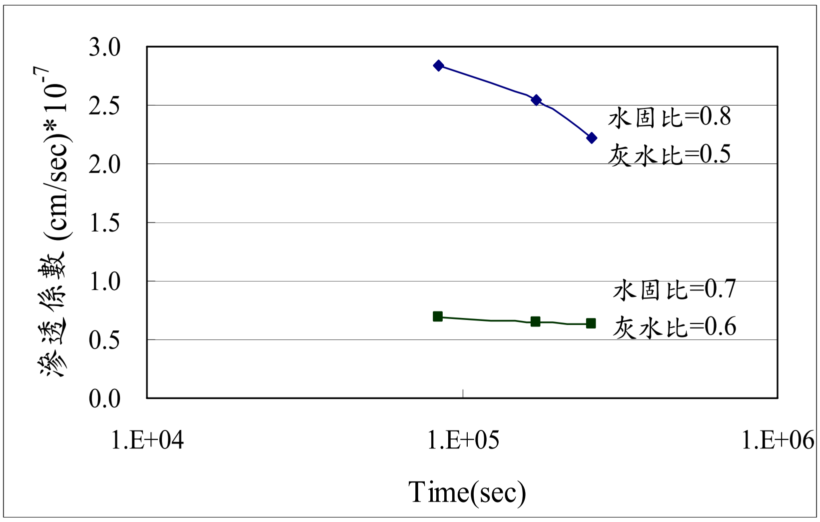

圖 6 淤泥流填料之設計配比與滲透性之關係

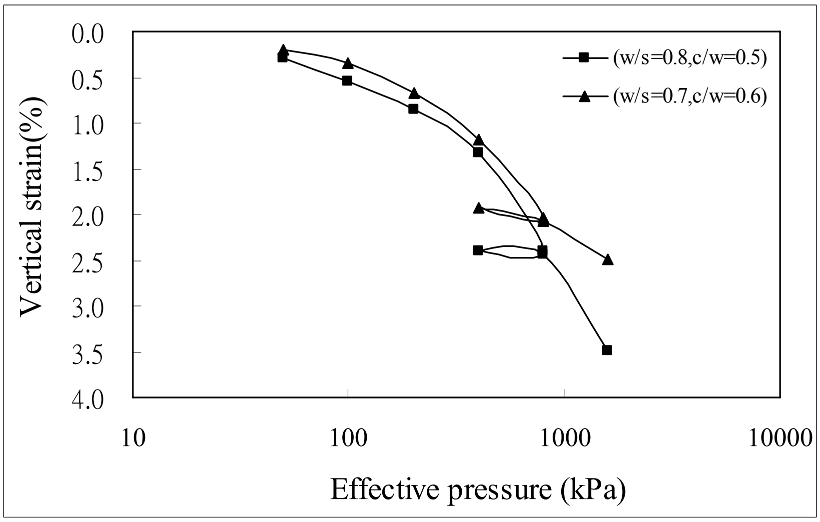

圖 7 淤泥流填料之設計配比與壓密性之關係

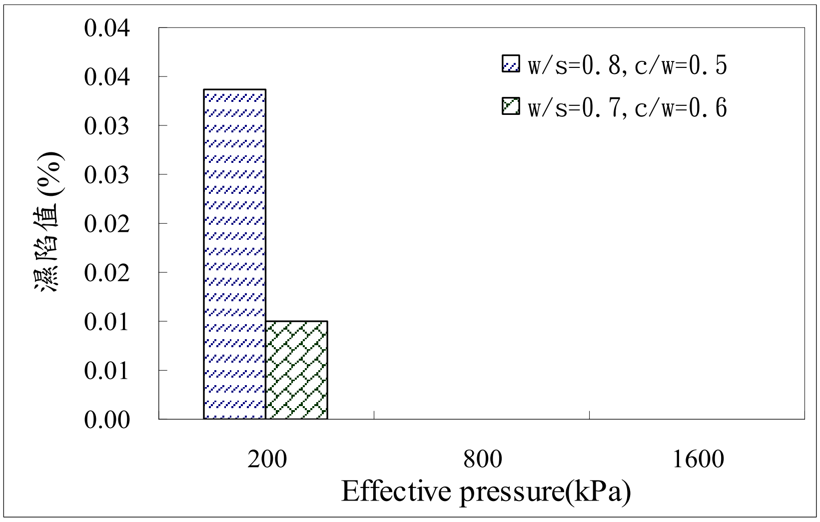

圖 8 淤泥流填料之設計配比與濕陷性之綜合關係

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

95 年 10 月 5 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
時間 會議 地點	2006/9/18-2006/9/22 日本橫濱市	本會核定 補助文號	NSC 95-2211-E-216-004
會議 名稱	(中文) 第八屆國際地工合成材料研討會 (英文) Eighth International Conference on Geosynthetics		
發表 論文 題目	(中文) 加勁擋土結構破壞之案例探討 (英文) Case Studies of Geosynthetic Reinforced Earth Structure Failures		

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，每隔四年均會主辦全球性之國際地工合成材料學術研討會(International Conference on Geosynthetics, ICG)，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

ICG 今年輪由 IGS 日本分會於亞洲區首度舉辦，地點選擇距離日本首府東京市郊之國際海港橫濱市，會議自 9/18/2006 開始至 9/22/2006 結束。報名參與會議人數達 806 人，參展相關廠商亦達 58 家，接受發表之論文達 400 餘篇，為 ICG 舉辦 30 年以來最多者。我國參加者，學界包括臺灣大學、成功大學、暨南大學、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、慧光等共計 42 人。人數僅次於地主國日本，堪稱陣容龐大。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。9/18 為訓練課程，正式會議則分別於 9/19~9/22 次第展開。會場設於橫濱市之 Pacific Yokohama 會議中心。

報告人與台大陳榮河教授、地工材料協會理事郭勝雄等人於 9/18 自臺灣啟程赴日，於當地時間 9/18 夜晚抵達橫濱市下榻 Pan Pacific Hotel，次日即至會場報到，領取會議資料。會議正式展開，早上 9:30 至 10:30 首先進行大會開幕式(照片 2)，由大會主席日本 Tatsuoka 教授主持並邀請國際土壤力學及大地工程學會會長 Pinto 教授等貴賓致詞。

照片 2 第八屆國際地工材料研討會之開幕式

10:30-11:30 由 Giroud 論文獎得主 Lawson 先生進行開幕專題演講，介紹地工容器於水力及環境工程之應用；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 60 家，除來自美、歐、日等先進地區國家外，亦包括泰國、中國大陸、紐西蘭等國；台灣亦有盟鑫、七洲等五家廠商參展。午休之後，隨即同步展開各場次之議程。報告人分別參加了「基礎加勁」及「排水案例探討」等場次。報告者分別來自美、日、義大利、中國大陸、葡萄牙、新加坡、香港、伊朗與韓國等地區與國家。各場演講中以新加坡大學 T. P. Leong 教授報告之「創新電傳導垂直排水帶應用於新加坡廢棄物之處理」，令報告人印象最為深刻。作者提出結合電傳導與垂直排水帶技術應用於高含水量污泥等廢棄物之脫水，達到廢棄物減量及資源化應用之優異效果。Leong 教授以實驗証明電傳導技術確實可與垂直排水帶結合，藉由陰陽電極與水之正負極性相吸之原理，加速淤泥中含水量之移除，對於淤泥之處理發揮立竿見影之功效。國內水庫淤泥問題相當嚴重，因此此種創新工法實值得國人再進一步蒐集資料加以學習。

9/20 上午開場專題報告由日本 Koseki 教授主講「加勁擋土牆之地震穩定性」。首先回顧近年來世界各地發生強震地區之加勁擋土結構行為表現；其次以實驗室模型說明加勁擋土結構之耐震行為；最後再以數值分析方法分析加勁擋土結構之破壞行為並提出加勁擋土結構耐震規範之修正建議。報告清晰、精闢入理。我國與日本同處強震區，加勁擋土結構具有優異耐震性能，極為適用於台灣山坡地之邊坡工程。Koseki 教授之報告實值得國內加以參考引用。議程主題包括襯層界面、加勁邊坡及擋土牆案例探討、祛水、加勁擋土牆地震行為。上午 10:30~12:00 報告人出席「加勁邊坡與加勁擋土牆」議程並發表論文：「加勁擋土結構破壞之案例探討」(照片 3)。以十一個台灣加勁擋土結構破壞案例之統計分析與探討，說明台灣特殊的環境與工程因素與加勁擋土結構破壞之關係，並指出工程規劃不當與施工品管不良為我國加勁擋土結構破壞之主因，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(照片 4)。下午及 9/21 全日參加之議程均為「加勁邊坡與擋土牆」之案例探討。依據大會報告，本次研討會共接受將近 100 篇之案例探討論文，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。例如韓國慶應大學 Han 教授以一加勁擋土結構破壞案例，說明目前雖然設計規範堪稱完整，但因大地工程之不確定性，使得在分析方面仍有欠缺，甚至導致破壞之發生。泰國、馬來西亞、義大利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。參展廠商中，台灣廠商多達五家，數量僅次於地主國，顯現我國於地工合成材料發展之雄厚實力。。研討會最後一日(9/22)之專題演講係由美國亞利桑納大學 Kavazanjian 教授主講「地工膜布於掩埋場之應用」。說明地工皂土布(GCL)及不透水膜(geomembrane)於各類型掩埋場應用時之最新觀念與技術亦以實例指出目前相關技術之困難所在及亟待改進之處。專題報告結束後隨即返回旅館整理行李束裝啟程返國，結束此次日本 2006 第八屆國際地工材料研討會學習之旅。

照片 3 報告人發表論文

照片 4 與會者提問研討

二、與會心得

本次研討會參加者達 800 餘人，對於一個單一工程主題的會議，竟然可吸引如此眾多的與會者，其主要原因當係主辦單位素負權威、規劃週詳，且會議主題切合潮流，使得會議內容豐富精彩；其二則為產官學界之全力支持，由此可見得日本工程界對整合研究與實務方面之重視及用心。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。日本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、Kohata 教授、美國西雅圖華盛頓大學 Holtz 教授、新加坡 Leong 教授、南非 KayTech 工程顧問公司經理 Davis 先生，以及墨西哥、伊朗、韓國、中國大陸廠商代表等 20 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)

本次會議因行程時間限制未參加任何工程參觀活動。

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

「第八屆國際地工材料研討會會議論文集」光碟片及大會各參展廠商提供之資料等。

Proceedings of the 8th International Conference on Geosynthetics, Yokohama, Japan, pp. 1105-1108.

Case studies of geosynthetic reinforced earth structure failures

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Keywords: reinforced earth structure, slope stability, failure, intense rainfall.

ABSTRACT: This paper collected eleven cases of failure for geosynthetic reinforced earth structures (RES) in northern Taiwan. Qualitative forensic studies were conducted to explore the causes of the structure failures. The results of the research indicated that intense rainfall was the primary natural influence causing the RES failure. Incorrect engineering practices also were relevant in the failure of RES. However, inadequate planning and poor construction workmanship were the most important causes. In addition, the study also showed that the RES failures were due to a lack of essential trainings on traditional slope stability analysis instead of deficient RES know-how. Lessons learned in this study can be valuable to technical development and safety improvement for engineering practices related to geosynthetic reinforced earth structures.

1 INTRODUCTION

Reinforced earth structure (RES) consists of reinforced soil slope (RSS) and mechanically stabilized earth wall (MSEW). RES has been used widely with a variety of applications in hundreds of thousands of projects implemented around the world. It presents many advantages and makes it attractive for infrastructure development and often becomes the first choice for many embankments or earth retaining projects. However, with the increased use of RES, the number of RES failures has also increased. These incidents are not only directly jeopardizing the relevant facilities around the structure, but also distressing the confidence of potential clients regarding the safety and application of RES (Scarborough 2005).

Failure plays an important role in engineering practices. Through the forensic study of failures, engineers can learn to avoid similar technical errors, allowing them to build more efficient, safer structures. For the engineer, knowledge of engineering failure is just as important as knowledge of its successes. To avoid any additional RES failure, it is necessary to conduct a forensic study to explicate the common mistakes that have caused the collapse of the RES and offer guidance for future engineering practices. A number of RES failures have occurred in the past decades, however, only a few case studies of failure have been analyzed (Mitchell and Zornberg 1995, Chou 2000, Yoo 2002, Huang et al. 2003, Scarborough 2005, Ling and Leshchinsky 2005). This research collected eleven cases of failure for RES in northern Taiwan occurring within the past three years. These live cases and eight additional cases reported by Chou (2000) were then compiled and studied. Qualitative forensic investigations were conducted and the most frequent causes of RES failure along with the evidence and mechanisms were explored and examined. The post failure studies serve as lessons for practicing engineers and engineering students concerning the difficult technical, professional, and procedural issues that may arise during engineering practices for geosynthetic reinforced earth structures.

2 CAUSES OF FAILURE

Based on site observations and engineering studies for each failed case, the causes of failure generally can be distinguished as natural influences and professional mistakes. Each category can be further classified into detailed sub-issues. The influence of each sub-issue was then rated based on the evaluation of its significance in causing the failure. Figure 1 summarizes the rated weight of all items that were related to the failures. Frequency is defined as the total occurrences of each observed cause divided by the quantity of total cases studied. Due to the limitation of this paper's length, detailed information of all the studied cases and their statistical results can be found in Tang (2005) and are not presented here.

2.1 *Natural Influences*

2.1.1 *Intense Rainfall*

The research indicates that about 89.47% of the failures were related to intense rainfall (rated weight ≥1). Failures significantly affected by intense rainfall were up to 63.15% (rated weight ≥4). Numerous worldwide studies have reported that intense rainfall has been the major factor responsible for many slope failures including reinforced earth structures (Huang 1994, Rahardjo et al. 2001, Pando et al. 2005). When rainfall initiates an unstable man-made slope, the mechanism is that water infiltration reduces soil suction in the unsaturated compacted soil. This causes a decrease in the effective stress on the potential failure surface reflected in a decrease in the soil strength to a point where equilibrium cannot be sustained in the slope (Abramson et al. 2002). In addition to the loss of shear strength, surface erosion, seepage force, and hydraulic gradients caused by surface run-off or groundwater also have a significant adverse effect on the slope stability.

2.1.2 *Earthquake*

There are only two cases in the study that failed during the 1999 Ji-Ji earthquake in Taiwan. Both cases collapsed due to strong seismic motion. The statistical frequency is 10.53%. Since then several significant earthquakes have occurred around the island, however, no more RES damage has been reported. In comparison with the greater amount of damages of conventional concrete walls during earthquakes, RES presents better dynamic performance. Huang et al. (2003) indicated similar findings. In their study, Ling and Leshchinsky (2003) reported that the failure of a modular-block RES was due to inadequate design in resisting compound failure during the presence of horizontal and vertical accelerations.

2.2 *Professional Issues*

2.2.1 *Planning*

Prior to the design of the RES, the engineers should conduct necessary site investigations to identify potential problems and site compatibility and perform essential countermeasures to ensure the safety of the RES. Detailed subsurface information should be obtained to support accurate analysis and design. In addition, the engineers should also communicate with the client to clearly identify the safety requirements and avoid misuse of the structures. Based on the evaluation of this research, 52.63% of the cases failed due to improper planning. Evidence indicates that the most critical problem would be ignorance of the importance of a detailed site exploration. Without correct site information, all the following engineering practices are highly likely lead to incorrect consequences.

2.2.2 *Analysis and Design*

The accuracy of analysis and design ensures the safety of the RES. The inclusion of an erroneous design or miscalculation can cause a variety of failures ranging from a simple malfunction to a total collapse. This type of cause could be the direct result of a lack of experience, negligence, a lack of education, incompetence, or the inability to communicate (Greenspan 1989). Based on the study, the frequency of this type of error was 36.85%.

The results of the evaluation indicate that the most common errors made in the analysis are using incorrect strength parameters. The common practices for RES analysis include using effective stress parameters deduced from triaxial consolidated undrained tests. However, for embankment construction, a total stress analysis using unconsolidated undrained values of shear strength would be more appropriate to access the stability of the slope during and immediately after construction (Abramson et al. 2002). In addition, the effective stress parameters also cannot truly reflect the stress condition of unsaturated soils. As described earlier, matric suction plays an important role in an unsaturated soil slope. The stability of the RES during and shortly after the construction is highly dependent on the changes in matric suction. The analysis that totally ignores the effect of matric suction is risky for the structure. Most of the observed RES failures occurred after a relatively short period following the construction. Such a phenomenon may be considered as an evidence of such an error.

The analysis for RES usually has been conducted by using computer programs developed based on the limit equilibrium theory. STEDwin is the most common one used in Taiwan. Generally, this program is easy to work with and engineers use it for typical RES analysis without difficulty. However, many reinforced earth structures are widening configurations from the existing slope. The fill structure placed on a slope presents a potential for downward movement not to mention other adverse site effects such as seepage, earthquake, and geological dip formation. The interface stability is therefore important to the RES safety. Unfortunately, STEDwin does not assess translational failure for the RES in a convenient manner. As a result, engineers rather assume failure goes through the circular slip surface and take advantage of the auto search of the program. The calculated safety factor is therefore may not be the correct minimum value of the structure. Ignorance of the importance of interface stability would be one of the key causes of RES failure in Taiwan.

As described earlier, intense rainfall has activated many a RES to fail. In a tropical area, intense rainfall frequently occurs. Therefore, it is the responsibility of the engineers to account for such unfavourable conditions in the analysis and make the structure safe. The failures after intense rainfall indicate the negligence or incompetence of the engineers. It has become a common problem for the RES professional in Taiwan. Evidences indicate that instead of deficient RES know-how, the failures of the RES were due to a lack of essential trainings on traditional slope stability analysis.

2.2.3 *Materials*

The safety of any structure is highly dependent on its material's stability and durability. Therefore, the selection of reinforcement for RES must consider the performance, service life, and the environmental conditions of the structure. The reinforcements used in Taiwan are predominantly geogrid made of a variety of geosynthetic materials. Because of its complexity, the quality verifications of geogrid on site are always problematic. Disputations regarding the selection and the installations of a geogrid are quite common during the engineering practice for RES. However, despite the complexity of the material, failures mainly caused by a geogrid in this research are insignificant. The frequency is only 5.26%. It was also observed that those geogrid materials that caused failures were all made of fibreglass. Such material has a brittle characteristic not favourable with the flexibility of the RES. Strain compatibility between reinforcement and structure must be evaluated if this type of geogrid material is proposed for use.

The majority of reinforced earth structure consists of compacted fill. The study indicated that about 31.58% of the failures were caused by the poor quality of the fill. Many engineers believe that reinforcement would be the major support system for the RES service loads. The stronger the reinforcement is, the more loading the RES can sustain. In reality, compacted fill offers most of the support for a service load. Reinforcement only provides additional improvement. The ignorance of the importance of the fill leads to negligence in the selection of fill materials. In addition, the site conditions or the financial burdens of the project often limit the probability of selecting suitable fill materials. As a result, virtually all kinds of fill materials such as silt, clay, or crushed shale have been used for RES in Taiwan. Although the use of fine-grained poorly draining materials in RES may not warrant damages of structure, proper safety measures must be specified to ensure the performance of the RES (Mitchell and Zornberg 1995). Good structure performance is strongly dependent on maintaining a low water content in the poorly draining fill. Therefore, an appropriate drainage system must be installed to dissipate surface run-off or seepage in a timely manner for the RES. Large movements occur in the RES when pore water pressures were generated, and failures were reported in marginal backfills reinforced with impermeable inclusions that became saturated after rainfalls (Mitchell and Zornberg 1995, Scarborough 2005). The designers or the geosynthetic material distributors who favour the use of RES must realize that the safety of the structure is highly dependent on the availability of qualified fill materials.

2.2.4 *Construction*

The performance of compaction controls the quality of fill material. Also, the placement of reinforcements has to follow certain procedures. Although contract documents clearly specify the construction procedures, acceptable construction quality may not be achieved unless reliable construction performance is exactly followed.

Poor construction workmanship certainly warrants higher probability of instability not to mention the technical difficulties inherited from the unsuitable materials. The frequent rainfalls in a tropical area further reduce the chances for a better compaction performance. As a result, failures caused by poor filling quality are as high as 44.44%. Improvement of construction workmanship becomes mandatory to ensure the safety of the RES. Independent construction surveillance should be engaged for compaction verifications to ensure fill quality.

2.2.5 *Service and Maintenance*

Many owners of RES ignore the importance of overuse or maintenance of a facility. A typical example is the placement of a surcharge or loading in excess of the capacity of the structure. Other problems such as neglecting routine clean-up of the drainage system, paying no attention to cracks, deformation, or settlement lead to much worse damage. The research indicates that about 15.79% of the observed cases failed due to negligence of service and maintenance.

3 CONCLUSIONS

Based on the forensic diagnosis of the observed RES failures, intense rainfall was the most important natural influence to causing the RES failures. Incorrect engineering practices also were relevant to the RES failures. However, inadequate planning and poor construction workmanship are primarily responsible for the RES failures. The study also showed that the failures of the RES were due to insufficient trainings on traditional slope stability analysis and design rather than deficiency in professional RES know-how.

The findings presented in this research provide essential lessons for RES professionals. It is beneficial to the technical development and safety improvement for engineering practices with reinforced earth structures.

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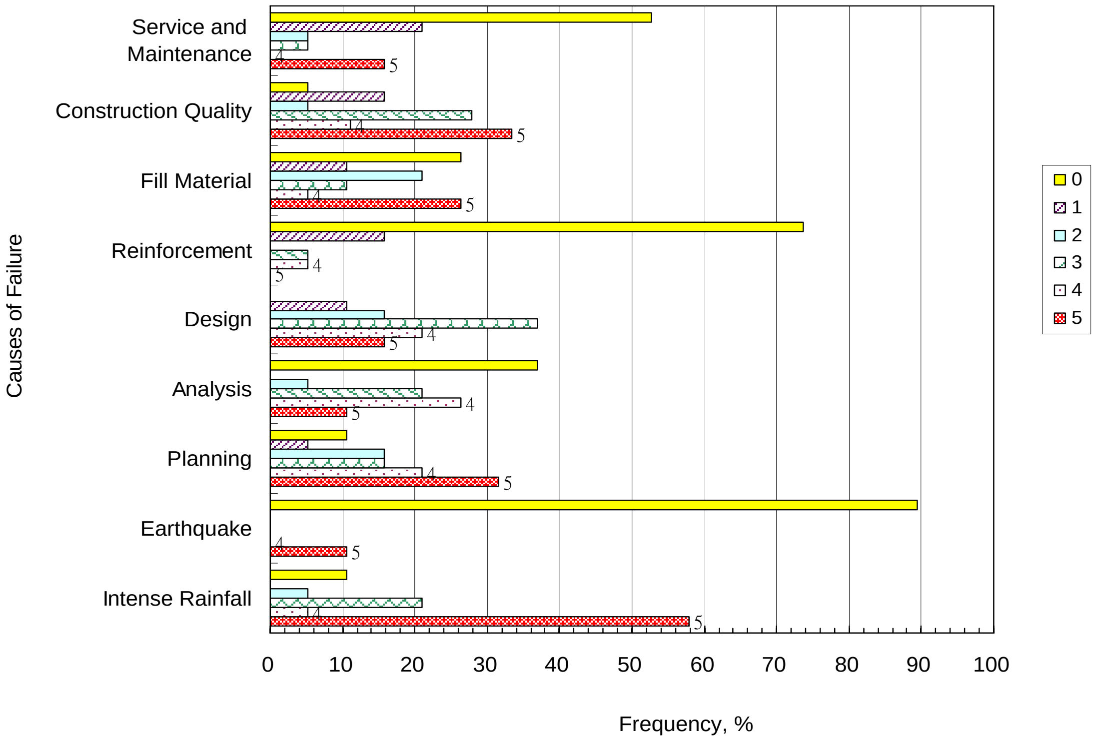

Rate of Significance:
0 - negligible, 1 - extremely slight, 2 - slight, 3 - moderate, 4 - considerable, 5 - extremely considerable

Figure 1. Causes of failure and their statistical ratings for the studied geosynthetic reinforced earth structures.

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

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時間 會議 地點	2006/9/18-2006/9/22 日本橫濱市	本會核定 補助文號	NSC 95-2211-E-216-004
會議 名稱	(中文) 第八屆國際地工合成材料研討會 (英文) Eighth International Conference on Geosynthetics		
發表 論文 題目	(中文) 加勁擋土結構破壞之案例探討 (英文) Case Studies of Geosynthetic Reinforced Earth Structure Failures		

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，每隔四年均會主辦全球性之國際地工合成材料學術研討會(International Conference on Geosynthetics, ICG)，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

ICG 今年輪由 IGS 日本分會於亞洲區首度舉辦，地點選擇距離日本首府東京市郊之國際海港橫濱市，會議自 9/18/2006 開始至 9/22/2006 結束。報名參與會議人數達 806 人，參展相關廠商亦達 58 家，接受發表之論文達 400 餘篇，為 ICG 舉辦 30 年以來最多者。我國參加者，學界包括臺灣大學、成功大學、暨南大學、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、慧光等共計 42 人。人數僅次於地主國日本，堪稱陣容龐大。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。9/18 為訓練課程，正式會議則分別於 9/19~9/22 次第展開。會場設於橫濱市之 Pacific Yokohama 會議中心。

報告人與台大陳榮河教授、地工材料協會理事郭勝雄等人於 9/18 自臺灣啟程赴日，於當地時間 9/18 夜晚抵達橫濱市下榻 Pan Pacific Hotel，次日即至會場報到，領取會議資料。會議正式展開，早上 9:30 至 10:30 首先進行大會開幕式(照片 2)，由大會主席日本 Tatsuoka 教授主持並邀請國際土壤力學及大地工程學會會長 Pinto 教授等貴賓致詞。

照片 2 第八屆國際地工材料研討會之開幕式

10:30-11:30 由 Giroud 論文獎得主 Lawson 先生進行開幕專題演講，介紹地工容器於水力及環境工程之應用；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 60 家，除來自美、歐、日等先進地區國家外，亦包括泰國、中國大陸、紐西蘭等國；台灣亦有盟鑫、七洲等五家廠商參展。午休之後，隨即同步展開各場次之議程。報告人分別參加了「基礎加勁」及「排水案例探討」等場次。報告者分別來自美、日、義大利、中國大陸、葡萄牙、新加坡、香港、伊朗與韓國等地區與國家。各場演講中以新加坡大學 T. P. Leong 教授報告之「創新電傳導垂直排水帶應用於新加坡廢棄物之處理」，令報告人印象最為深刻。作者提出結合電傳導與垂直排水帶技術應用於高含水量污泥等廢棄物之脫水，達到廢棄物減量及資源化應用之優異效果。Leong 教授以實驗証明電傳導技術確實可與垂直排水帶結合，藉由陰陽電極與水之正負極性相吸之原理，加速淤泥中含水量之移除，對於淤泥之處理發揮立竿見影之功效。國內水庫淤泥問題相當嚴重，因此此種創新工法實值得國人再進一步蒐集資料加以學習。

9/20 上午開場專題報告由日本 Koseki 教授主講「加勁擋土牆之地震穩定性」。首先回顧近年來世界各地發生強震地區之加勁擋土結構行為表現；其次以實驗室模型說明加勁擋土結構之耐震行為；最後再以數值分析方法分析加勁擋土結構之破壞行為並提出加勁擋土結構耐震規範之修正建議。報告清晰、精闢入理。我國與日本同處強震區，加勁擋土結構具有優異耐震性能，極為適用於台灣山坡地之邊坡工程。Koseki 教授之報告實值得國內加以參考引用。議程主題包括襯層界面、加勁邊坡及擋土牆案例探討、祛水、加勁擋土牆地震行為。上午 10:30~12:00 報告人出席「加勁邊坡與加勁擋土牆」議程並發表論文：「加勁擋土結構破壞之案例探討」(照片 3)。以十一個台灣加勁擋土結構破壞案例之統計分析與探討，說明台灣特殊的環境與工程因素與加勁擋土結構破壞之關係，並指出工程規劃不當與施工品管不良為我國加勁擋土結構破壞之主因，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(照片 4)。下午及 9/21 全日參加之議程均為「加勁邊坡與擋土牆」之案例探討。依據大會報告，本次研討會共接受將近 100 篇之案例探討論文，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。例如韓國慶應大學 Han 教授以一加勁擋土結構破壞案例，說明目前雖然設計規範堪稱完整，但因大地工程之不確定性，使得在分析方面仍有欠缺，甚至導致破壞之發生。泰國、馬來西亞、義大利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。參展廠商中，台灣廠商多達五家，數量僅次於地主國，顯現我國於地工合成材料發展之雄厚實力。。研討會最後一日(9/22)之專題演講係由美國亞利桑納大學 Kavazanjian 教授主講「地工膜布於掩埋場之應用」。說明地工皂土布(GCL)及不透水膜(geomembrane)於各類型掩埋場應用時之最新觀念與技術亦以實例指出目前相關技術之困難所在及亟待改進之處。專題報告結束後隨即返回旅館整理行李束裝啟程返國，結束此次日本 2006 第八屆國際地工材料研討會學習之旅。

	
照片 3 報告人發表論文	照片 4 與會者提問研討

二、與會心得

本次研討會參加者達 800 餘人，對於一個單一工程主題的會議，竟然可吸引如此眾多的與會者，其主要原因當係主辦單位素負權威、規劃週詳，且會議主題切合潮流，使得會議內容豐富精彩；其二則為產官學界之全力支持，由此可見得日本工程界對整合研究與實務方面之重視及用心。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。日本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、Kohata 教授、美國西雅圖華盛頓大學 Holtz 教授、新加坡 Leong 教授、南非 KayTech 工程顧問公司經理 Davis 先生，以及墨西哥、伊朗、韓國、中國大陸廠商代表等 20 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)

本次會議因行程時間限制未參加任何工程參觀活動。

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

「第八屆國際地工材料研討會會議論文集」光碟片及大會各參展廠商提供之資料等。

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Case studies of geosynthetic reinforced earth structure failures

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Keywords: reinforced earth structure, slope stability, failure, intense rainfall.

ABSTRACT: This paper collected eleven cases of failure for geosynthetic reinforced earth structures (RES) in northern Taiwan. Qualitative forensic studies were conducted to explore the causes of the structure failures. The results of the research indicated that intense rainfall was the primary natural influence causing the RES failure. Incorrect engineering practices also were relevant in the failure of RES. However, inadequate planning and poor construction workmanship were the most important causes. In addition, the study also showed that the RES failures were due to a lack of essential trainings on traditional slope stability analysis instead of deficient RES know-how. Lessons learned in this study can be valuable to technical development and safety improvement for engineering practices related to geosynthetic reinforced earth structures.

1 INTRODUCTION

Reinforced earth structure (RES) consists of reinforced soil slope (RSS) and mechanically stabilized earth wall (MSEW). RES has been used widely with a variety of applications in hundreds of thousands of projects implemented around the world. It presents many advantages and makes it attractive for infrastructure development and often becomes the first choice for many embankments or earth retaining projects. However, with the increased use of RES, the number of RES failures has also increased. These incidents are not only directly jeopardizing the relevant facilities around the structure, but also distressing the confidence of potential clients regarding the safety and application of RES (Scarborough 2005).

Failure plays an important role in engineering practices. Through the forensic study of failures, engineers can learn to avoid similar technical errors, allowing them to build more efficient, safer structures. For the engineer, knowledge of engineering failure is just as important as knowledge of its successes. To avoid any additional RES failure, it is necessary to conduct a forensic study to explicate the common mistakes that have caused the collapse of the RES and offer guidance for future engineering practices. A number of RES failures have occurred in the past decades, however, only a few case studies of failure have been analyzed (Mitchell and Zornberg 1995, Chou 2000, Yoo 2002, Huang et al. 2003, Scarborough 2005, Ling and Leshchinsky 2005). This research collected eleven cases of failure for RES in northern Taiwan occurring within the past three years. These live cases and eight additional cases reported by Chou (2000) were then compiled and studied. Qualitative forensic investigations were conducted and the most frequent causes of RES failure along with the evidence and mechanisms were explored and examined. The post failure studies serve as lessons for practicing engineers and engineering students concerning the difficult technical, professional, and procedural issues that may arise during engineering practices for geosynthetic reinforced earth structures.

2 CAUSES OF FAILURE

Based on site observations and engineering studies for each failed case, the causes of failure generally can be distinguished as natural influences and professional mistakes. Each category can be further classified into detailed sub-issues. The influence of each sub-issue was then rated based on the evaluation of its significance in causing the failure. Figure 1 summarizes the rated weight of all items that were related to the failures. Frequency is defined as the total occurrences of each observed cause divided by the quantity of total cases studied. Due to the limitation of this paper's length, detailed information of all the studied cases and their statistical results can be found in Tang (2005) and are not presented here.

2.1 *Natural Influences*

2.1.1 *Intense Rainfall*

The research indicates that about 89.47% of the failures were related to intense rainfall (rated weight ≥1). Failures significantly affected by intense rainfall were up to 63.15% (rated weight ≥4). Numerous worldwide studies have reported that intense rainfall has been the major factor responsible for many slope failures including reinforced earth structures (Huang 1994, Rahardjo et al. 2001, Pando et al. 2005). When rainfall initiates an unstable man-made slope, the mechanism is that water infiltration reduces soil suction in the unsaturated compacted soil. This causes a decrease in the effective stress on the potential failure surface reflected in a decrease in the soil strength to a point where equilibrium cannot be sustained in the slope (Abramson et al. 2002). In addition to the loss of shear strength, surface erosion, seepage force, and hydraulic gradients caused by surface run-off or groundwater also have a significant adverse effect on the slope stability.

2.1.2 *Earthquake*

There are only two cases in the study that failed during the 1999 Ji-Ji earthquake in Taiwan. Both cases collapsed due to strong seismic motion. The statistical frequency is 10.53%. Since then several significant earthquakes have occurred around the island, however, no more RES damage has been reported. In comparison with the greater amount of damages of conventional concrete walls during earthquakes, RES presents better dynamic performance. Huang et al. (2003) indicated similar findings. In their study, Ling and Leshchinsky (2003) reported that the failure of a modular-block RES was due to inadequate design in resisting compound failure during the presence of horizontal and vertical accelerations.

2.2 *Professional Issues*

2.2.1 *Planning*

Prior to the design of the RES, the engineers should conduct necessary site investigations to identify potential problems and site compatibility and perform essential countermeasures to ensure the safety of the RES. Detailed subsurface information should be obtained to support accurate analysis and design. In addition, the engineers should also communicate with the client to clearly identify the safety requirements and avoid misuse of the structures. Based on the evaluation of this research, 52.63% of the cases failed due to improper planning. Evidence indicates that the most critical problem would be ignorance of the importance of a detailed site exploration. Without correct site information, all the following engineering practices are highly likely lead to incorrect consequences.

2.2.2 *Analysis and Design*

The accuracy of analysis and design ensures the safety of the RES. The inclusion of an erroneous design or miscalculation can cause a variety of failures ranging from a simple malfunction to a total collapse. This type of cause could be the direct result of a lack of experience, negligence, a lack of education, incompetence, or the inability to communicate (Greenspan 1989). Based on the study, the frequency of this type of error was 36.85%.

The results of the evaluation indicate that the most common errors made in the analysis are using incorrect strength parameters. The common practices for RES analysis include using effective stress parameters deduced from triaxial consolidated undrained tests. However, for embankment construction, a total stress analysis using unconsolidated undrained values of shear strength would be more appropriate to access the stability of the slope during and immediately after construction (Abramson et al. 2002). In addition, the effective stress parameters also cannot truly reflect the stress condition of unsaturated soils. As described earlier, matric suction plays an important role in an unsaturated soil slope. The stability of the RES during and shortly after the construction is highly dependent on the changes in matric suction. The analysis that totally ignores the effect of matric suction is risky for the structure. Most of the observed RES failures occurred after a relatively short period following the construction. Such a phenomenon may be considered as an evidence of such an error.

The analysis for RES usually has been conducted by using computer programs developed based on the limit equilibrium theory. STEDwin is the most common one used in Taiwan. Generally, this program is easy to work with and engineers use it for typical RES analysis without difficulty. However, many reinforced earth structures are widening configurations from the existing slope. The fill structure placed on a slope presents a potential for downward movement not to mention other adverse site effects such as seepage, earthquake, and geological dip formation. The interface stability is therefore important to the RES safety. Unfortunately, STEDwin does not assess translational failure for the RES in a convenient manner. As a result, engineers rather assume failure goes through the circular slip surface and take advantage of the auto search of the program. The calculated safety factor is therefore may not be the correct minimum value of the structure. Ignorance of the importance of interface stability would be one of the key causes of RES failure in Taiwan.

As described earlier, intense rainfall has activated many a RES to fail. In a tropical area, intense rainfall frequently occurs. Therefore, it is the responsibility of the engineers to account for such unfavourable conditions in the analysis and make the structure safe. The failures after intense rainfall indicate the negligence or incompetence of the engineers. It has become a common problem for the RES professional in Taiwan. Evidences indicate that instead of deficient RES know-how, the failures of the RES were due to a lack of essential trainings on traditional slope stability analysis.

2.2.3 *Materials*

The safety of any structure is highly dependent on its material's stability and durability. Therefore, the selection of reinforcement for RES must consider the performance, service life, and the environmental conditions of the structure. The reinforcements used in Taiwan are predominantly geogrid made of a variety of geosynthetic materials. Because of its complexity, the quality verifications of geogrid on site are always problematic. Disputations regarding the selection and the installations of a geogrid are quite common during the engineering practice for RES. However, despite the complexity of the material, failures mainly caused by a geogrid in this research are insignificant. The frequency is only 5.26%. It was also observed that those geogrid materials that caused failures were all made of fibreglass. Such material has a brittle characteristic not favourable with the flexibility of the RES. Strain compatibility between reinforcement and structure must be evaluated if this type of geogrid material is proposed for use.

The majority of reinforced earth structure consists of compacted fill. The study indicated that about 31.58% of the failures were caused by the poor quality of the fill. Many engineers believe that reinforcement would be the major support system for the RES service loads. The stronger the reinforcement is, the more loading the RES can sustain. In reality, compacted fill offers most of the support for a service load. Reinforcement only provides additional improvement. The ignorance of the importance of the fill leads to negligence in the selection of fill materials. In addition, the site conditions or the financial burdens of the project often limit the probability of selecting suitable fill materials. As a result, virtually all kinds of fill materials such as silt, clay, or crushed shale have been used for RES in Taiwan. Although the use of fine-grained poorly draining materials in RES may not warrant damages of structure, proper safety measures must be specified to ensure the performance of the RES (Mitchell and Zornberg 1995). Good structure performance is strongly dependent on maintaining a low water content in the poorly draining fill. Therefore, an appropriate drainage system must be installed to dissipate surface run-off or seepage in a timely manner for the RES. Large movements occur in the RES when pore water pressures were generated, and failures were reported in marginal backfills reinforced with impermeable inclusions that became saturated after rainfalls (Mitchell and Zornberg 1995, Scarborough 2005). The designers or the geosynthetic material distributors who favour the use of RES must realize that the safety of the structure is highly dependent on the availability of qualified fill materials.

2.2.4 *Construction*

The performance of compaction controls the quality of fill material. Also, the placement of reinforcements has to follow certain procedures. Although contract documents clearly specify the construction procedures, acceptable construction quality may not be achieved unless reliable construction performance is exactly followed.

Poor construction workmanship certainly warrants higher probability of instability not to mention the technical difficulties inherited from the unsuitable materials. The frequent rainfalls in a tropical area further reduce the chances for a better compaction performance. As a result, failures caused by poor filling quality are as high as 44.44%. Improvement of construction workmanship becomes mandatory to ensure the safety of the RES. Independent construction surveillance should be engaged for compaction verifications to ensure fill quality.

2.2.5 *Service and Maintenance*

Many owners of RES ignore the importance of overuse or maintenance of a facility. A typical example is the placement of a surcharge or loading in excess of the capacity of the structure. Other problems such as neglecting routine clean-up of the drainage system, paying no attention to cracks, deformation, or settlement lead to much worse damage. The research indicates that about 15.79% of the observed cases failed due to negligence of service and maintenance.

3 CONCLUSIONS

Based on the forensic diagnosis of the observed RES failures, intense rainfall was the most important natural influence to causing the RES failures. Incorrect engineering practices also were relevant to the RES failures. However, inadequate planning and poor construction workmanship are primarily responsible for the RES failures. The study also showed that the failures of the RES were due to insufficient trainings on traditional slope stability analysis and design rather than deficiency in professional RES know-how.

The findings presented in this research provide essential lessons for RES professionals. It is beneficial to the technical development and safety improvement for engineering practices with reinforced earth structures.

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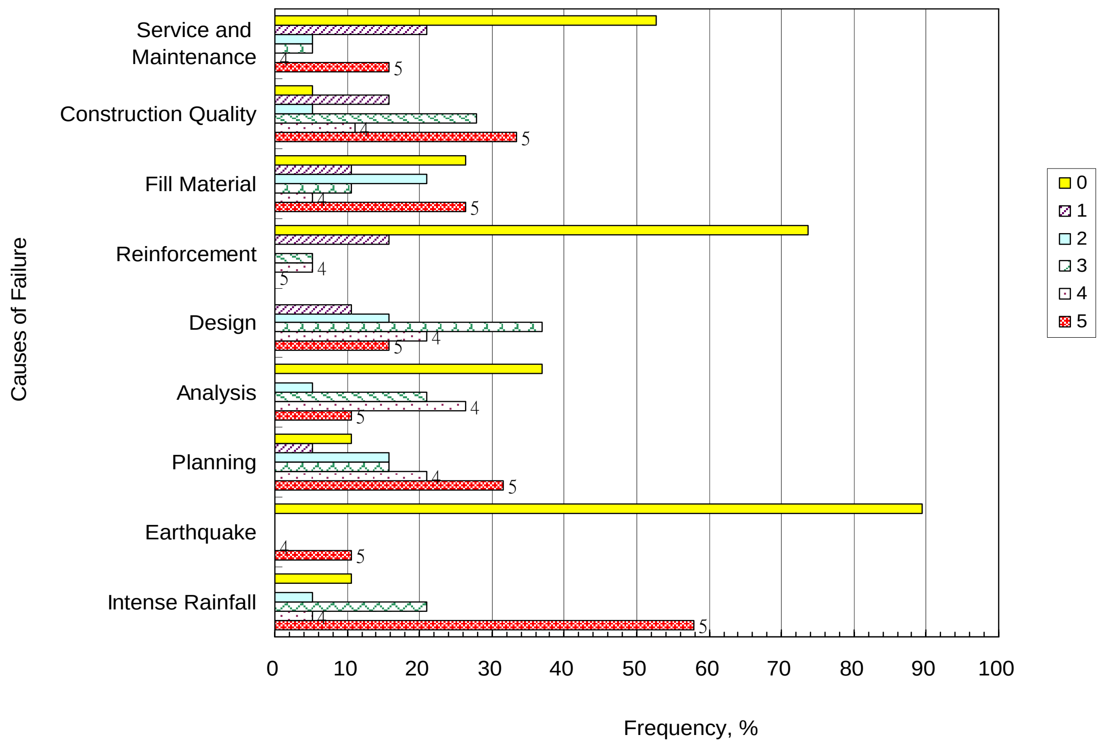

Rate of Significance:
0 - negligible, 1 - extremely slight, 2 - slight, 3 - moderate, 4 - considerable, 5 - extremely considerable

Figure 1. Causes of failure and their statistical ratings for the studied geosynthetic reinforced earth structures.