行政院國家科學委員會專題研究計畫 成果報告

地下儲槽滲漏監測系統可靠度評估與最佳化設計原則之探討

研究成果報告(精簡版)

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計畫主持人：單信瑜

計畫參與人員：碩士班研究生-兼任助理人員：陳培旼
碩士班研究生-兼任助理人員：劉韋恩

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精簡報告

摘要

加油站地下儲油槽與輸油管線會隨著使用年限的增加，使得老舊之油槽或輸油管線容易出現裂隙並發生油品洩漏。為了避免油品洩漏之量過多與洩漏時間過長而造成嚴重污染，因而必須設置監測設備進行油品洩漏偵測，然而於油品污染團傳輸之過程中會受地質條件、障礙物(油槽)等影響，使得傳輸路徑與距離皆受影響並間接影響監測井之監測效果。為了瞭解監測井於不同洩漏情境與土層狀態間相互關係，因此本研究以數值模擬軟體(TMVOC)模擬各種不同之洩漏情境與地層狀況，以探討監測井可能的最佳配置方式與監測範圍。研究結果顯示地下水位較高者(2 m)之土壤氣體監測井其靈敏度較地下水位低者(5 m)為高；監測井距離油品洩漏點近者(3 m 內)其效果較佳；而土層透水係數大、孔隙率小者其污染團之傳輸速率較快，對於土壤氣體之監測亦能有較大之幫助。地下水體之監測相較於土壤氣體而言其整體效果不佳，然而若監測井距離油品洩漏點較遠處時，則土壤氣體之效果反而不如地下水體監測井。

關鍵字: NAPL、地下儲槽、土壤氣體監測。

Abstract

The potential of leakage of USTs of gasoline station increases with their service life. In order to avoid serious pollution, monitoring measures are employed to provide early warning. Among the monitoring methods, soil gas and groundwater monitoring detect the leaked product directly. The pathway of leaked gasoline flows and diffuses and thus, in turn the effectiveness of soil gas and groundwater monitoring, may be affected by the existence of USTs of gasoline station. In this study, numerical simulation with the software TMVOC was performed in order to assess the effectiveness of soil gas and groundwater monitoring. The results show that both soil gas and groundwater monitoring are more effective if the site has a shallow groundwater table and the soil has higher hydraulic conductivity and lower porosity. The effectiveness of soil gas monitoring is better than groundwater monitoring in general, when soil gas and groundwater monitor well are far away leakage then the groundwater monitoring is better than soil gas.

Keywords: NAPL, underground storage tank, soil vapor monitoring.

1、前言

早期國內加油站設置的規範不完善且土壤地下水污染防範的觀念不如歐美國家先進。因此，當老舊的加油站因儲油設備的損壞、鏽蝕等而產生油品洩漏，其經常直接造成地下不飽和層、地下含水層與地下飽和層等的污染，並且隨著地下水位的升降與水力梯度的帶動而使得污染範圍更為擴散。而依行政院主計處 2010 年 3 月止之統計資料，全台共設置 2,631 家加油站(經濟部能源局， 2010)[1]，而若平均每家加油站以 4 座地下儲油槽估算，全國至少約有 10,524 座地下儲油槽，其中有部分已設置超過 20 年。

然而，根據美國賓州環境資源部研究，地下儲油槽洩漏的機率與其埋設的年代正比例的關係，埋設 10 年以上的儲油槽有 46%之機率會發生洩漏，而設置 15 年以上者，其發生洩漏之機率更達 71%以上。而為減少儲油槽及管線洩漏所造成之污染災害與損失，應要能夠掌握污染物的傳輸與擴散特性及要對於老舊的下儲油槽有適當之監測設備與規範以早期發現污染並防範污染的擴大(Bedient et al., 1993)[2]。

2、文獻回顧

一般加油站皆採用地下儲槽式之儲油系統(Underground Storage Tank System, USTs)如圖 1 所示，由於此型式之儲油槽體是埋設於地下因此於卸、加油時所需之輸油管線亦隨著儲槽埋設於地表下，也因如此一旦儲槽本體或輸油管線因破損而發生洩漏，則對於油品之洩漏點以及所造成之污染範圍是很難能夠確切掌握。而一般加油站油品可能之主要污染途徑分別為:(1) 卸油口及卸油管線洩漏、(2) 地下儲槽洩漏、(3) 輸油管線洩漏、(4) 泵島加油機洩漏。

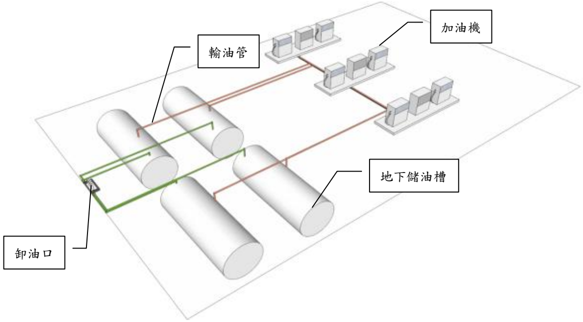


圖 1 一般常見加油站配置圖

2.1 汽油污染物特性

由於汽油的添加物多且複雜，且有各自不同的溶解度、揮發性、吸附性、生物降解性質，因此無法僅以單一揮發性有機物質來代表其整體性質，有鑒於此 Cline et al., (1991)[3] 曾對無鉛與含鉛汽油成分進行分析表 1。而典型之汽油組成成份則如表 2 所示。美國石油學會(1985)[4] 對典型無鉛汽油之平衡濃度進行量測，並列出汽油組成含量百分比結果如表 3。

Gustafson(1997)[5] 為了使得於模擬汽油污染物時更為簡化，故以總石油烴標準(TPHCWG)法來簡化汽油組成份之複雜問題，將汽油成分中的化學性質與物理性質相似者劃分同一區，再依據等碳數(Equivalent Carbon Number, EC)將汽油分類成八個餾分如表 4。如此一來即可以較少之揮發性有機物質來詮釋汽油整體之污染傳輸行為。

表 1 無鉛與含鉛汽油組成成份

組成物	無鉛[1]	含鉛[1]
直鏈烴(Normal /iso- hydrocarbons)	55	59
異戊烷(Isopentane)	9-11	9-11
正丁烷(n-butane)	4-5	4-5
正戊烷(n-pentane)	2.6-2.7	2.6-2.7
芳香烴(Aromatic hydrocarbons)		
二甲苯(Xylenes)	6-7	6-7
甲苯(Toluene)	6-7	6-7
乙苯(Ethylbenzene)	5	5
苯(Benzene)	2-5	2-5
萘(Naphthalene)	0.2-0.5	0.2-0.5
苯基(b)熒蒽(Benzo(b)fluoranthene)	3.9 mg/L	3.9 mg/L
蒽(Anthracene)	1.8 mg/L	1.8 mg/L
烯烴(Olefins)	5	10
環烴(Cyclic hydrocarbons)	5	5
添加劑(Additives)		
四乙鉛(Tetraethyllead)		600 mg/L
四甲基鉛(Tetramethyllead)		5 mg/L
二氯乙烷(Dichloroethane)		210 mg/L
二溴乙烷(Dibromoethane)		190 mg/L

[1] 為體積百分比

本表摘自 Cline, 1991

表 2 汽油之典型組成成份與百分比

<table>
<tr><th colspan="3">汽油組成成分</th></tr>
<tr><th>通稱</th><th>範例</th><th>百分比(%)</th></tr>
<tr><td>脂肪族-直鍊</td><td>庚烷(heptanes)</td><td rowspan="2">30-50</td></tr>
<tr><td>脂肪族-支鍊</td><td>異辛烷(isooctane)</td></tr>
<tr><td>脂肪族-環鍊</td><td>環戊烷(cyclopentane)</td><td>20-30</td></tr>
<tr><td>芳香族</td><td>乙苯(ethylbenzene)</td><td>20-30</td></tr>
</table>

(http://www.elmhurst.edu/~chm/vchembook/514gasoline.html)

表 3 無鉛汽油之成分含量百分比

成份	純化合物之溶解度 (mg/L)	百分比
苯 (Benzene)	1750	1.94
甲苯 (Toluene)	515	4.73
乙苯 (Ethylbenzene)	152	2.00
鄰二甲苯 (o-xylene)	152	2.27
對二甲苯 (p-xylene)	198	1.72
間二甲苯 (m-xylene)	173	5.66
丁烷 (butane)	61	3.83
戊烷 (pentane)	40	3.11
其他(other)	—	74.74

改寫自 API , 1985

表 4 代表汽油性質的 8 個餾分

等碳數區間	重量百分比			等碳數平均值
	最小值	最大值	平均值	
脂肪族				
4-6	25.7	44.2	35.9	5.04
>6-8	7.92	38.1	23.6	7.17
>8-10	1.73	9.6	5.8	8.12
>10-12	0.09	0.31	0.2	11.3
芳香族				
苯 (5-7)	0.12	3.5	1.9	6.5
甲苯				
(>7-8)	2.73	21.8	12.6	7.58
>8-10	5.42	22.3	14.2	9.13
>10-12	2.64	8.76	5.8	10.8

(Gustafson, 1997)

2.2 氣體監測井敏感範圍

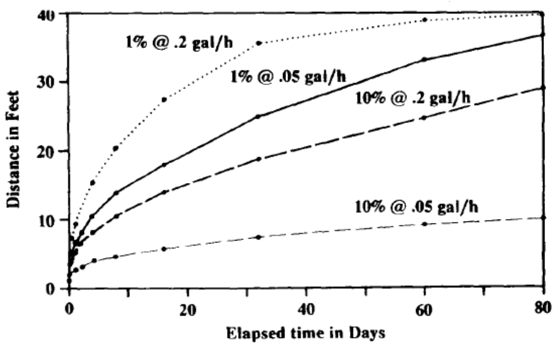
設置在地下儲油槽（USTs）外部位置的被動式蒸汽監測系統包含揮發性碳氫化合物的監測，普遍被視為是一種快速且有效的監測方法。然而對於量測油品洩漏量與蒸汽濃度間之關係仍處於僅止於了解物理過程的認知中，而如此即欲訂定一套定量的網狀系統設計標準幾乎是不可能，並且要能分辨污染來源是由地表之溢流(Spill)或是由地下儲槽洩漏(Leak)所產生之往往需要成熟的監測與分析系統，然而通常難以達成。

為了能對於油品洩漏與蒸汽濃度之關係更加了解 Weber and Schwille (1989)[6] 以模擬軟體 CFEST(Contaminant Finite Element Solute Transport)注入以甲烷、丁烷與 TCE 所混合之污染氣團，模擬汽油汽油揮發後其污染氣團於不飽和層之傳輸，其模擬結果驗證了 Geonomics (1988)[7] 於實驗現地所獲得之結果「如回填於油槽區之回填材為低透水係數者，其汽相濃度消散之速率非常緩慢」。因此認為高透水係數之回填材較低透水係數者更適合設置蒸汽與液體濃度監測與控制設備，然而由於蒸汽相的逸散速率非常緩慢，因此使得該區域之污染濃度長期維持於高值，使得難以區分該區之污染原因是因洩漏或溢流所導致，使得分析背景濃度的變化較為困難，而對於非均質之土壤亦會發生這類難以辨識之困難。

對於一般在設置土壤氣體與地下水監測設備時，習慣以經驗法則作網狀式的佈點，且對於汽油之蒸汽相傳輸一般普遍被接受的經驗法則為「污染氣團傳輸至 15 ft (4.5 m)需歷時 15 天」。然而由 Weber and Schwille (1989) 模擬之結果可知，對於經驗法則使用之正確性須根據可接受之最大洩漏量與最大污染濃度含量管制標準。由圖 2 可發現在洩漏速率為 0.2 gal/h 之情況下，距離洩漏點外 20 英呎處氣體濃度達 1 %時所對應之洩漏時間約為 9 天；而氣體濃度達 10 %所需之洩漏時間則約為 40 天。而若於相同之洩漏條件下，將測漏管距離增加至 30 英呎處，則氣體濃度達 1 %所需之時間約為 18 天；對於氣體濃度為 10 %而言，則是於模擬時間 80 天內無法到達。由此可知，若以較低之氣體濃度門檻值或者

使測漏管距離洩漏點較近之情況下，其兩種情況所對應之洩漏時間均較短，即可以減少洩漏量與污染程度。

由圖 2 亦可知對於洩漏數率較大者，則被檢驗出污染濃度大於警示值所需之時間將可以較為縮短；但對於有效擴散係數較低之情況而言，則又會使得污染濃度大於警示值所需之時間增加，因此若僅以經驗法則作為監測設備之配置依據時則其監測效果較難達預期之情況，除非土層參數有極佳之條件。



(Weber and Schwille, 1989)

圖 2 0.05 與 0.2 gal/hr 油品滲漏造成之油氣濃度 1%與 10%之鋒面移動距離與時間曲線

2.3 數值模擬軟體

目前市面可應用於污染傳輸模擬之商用軟體甚多，且所考慮之機制不外乎包括蒸氣、水、NAPL 在水中之溶解、NAPL 之多相流傳輸及 NAPL 與土壤顆粒之吸附作用，而國內外目前常用於污染物傳輸模擬之數值軟體有: MODFLOW、MT3D、TOUGH2、T2VOC、3DFATMIC 等。

過去有許多學者也曾模擬多相有機污染物的遷徙且發表了許多論文，如:斯克誠(2002)[8] 先以 TOUGH2 模擬五氯酚受熱傳導效應之影響再以 T2VOC 模擬五氯酚之傳輸，其結果顯示在 100 ℃ 等溫線以內的五氯酚濃度甚低，表示五氯酚已由吸附相轉變為溶解相；於 100 ℃ 等溫線外之五氯酚會受到蒸汽之影響而產生推移，若場址之垂直方向滲透係數較高則使得污染氣團易往上移動，高污染區域亦隨之往上移動。顏柏穎(2002)[9] 以 T2VOC 模擬水下空氣注入法(Air Sparging)結合氣體萃取法(Soil Vapor Extraction, SVE)受 NAPLs 污染區域之整治成效與分析。

Fagerlund and Niemi (2003)[10] 將汽油依等碳數分成 8 個餾分，再以 T2VOC 逐步編輯這 8 個餾分的化學參數，並觀察汽油於傳輸過程中汽、液以及油相的變化。Zandin and Niemi (2006)[11] 以 T2VOC 模擬非均質多孔隙介質且考慮入滲水為變動，其 DNAPL 之傳輸影響，其結果顯示污染物所受之影響是由多孔隙介質的非均質性與入滲水的變異性所結合，且會隨著時間尺度而變動。Kererat and Soralump (2010)[12] 以數值模擬軟體 TMVOC 模擬苯於傳輸過程中受到阻隔牆之阻礙，且於模擬過程中考慮(1)地下水流為靜止(即無受水力梯度影響)與(2)受水力梯度為 0.017 之影響，結果發現影響污染物擴散因子為土壤滲透係數與水力梯度，此結果可用來作為設計防滲透牆之尺度與性質。

3、研究方法

本模擬場址是以中型加油站為參考場址其站區範圍為:長 40 m、寬 40 m；而模擬深度至地下 10 m 如圖 3-3，此範圍即為主要模擬區域；模擬區域之三維座標是採卡氏座標(Cartesian System)系統表示之。而為避免邊界效應因此將數值模擬區域之四個邊界往外再延伸一倍模擬範圍，每個模擬範圍長為 40 m，寬為 40 m，因此整個數值模型尺寸長為 120 m、寬為 120 m、深度模擬至地下 10 m。並於 X 軸分割成 29 個網格(grid)、Y 軸分割為 21 個網格、Z 軸依地下水位深度之不同而分別分割為 13、14、16 個網格。於主要模擬區內，油槽區之網格再細分:於 X 軸與 Y 軸分割為 1 m/grid，Z 軸則為 0.5 m/grid。

本研究場址之水文地質狀況假設為:地

表下 0 m 至 10 m 為同一土層，其水平之絕對滲透係數分別為 2.5×10^{-12} m^2 與 2.5×10^{-13} m^2；而一般垂直透水係數約為水平透水係數之 1/5~1/100 間(Noonan and Curtis, 1990)[13]，因此垂直之絕對滲透係數分別為 5.0×10^{-13} m^2 與 5.0×10^{-14} m^2，土壤孔隙率為 0.3，水力梯度均採 0.005，而於模擬進行中須維持上下游水頭不變，因此將上下游邊界設定為定水頭邊界，並且假設地表無逕流。

土層之相對滲透率與三相系統之毛細壓力曲線則參考 Kererat and Soralump (2010)之研究模型，整理如表 5 與表 6；土壤/水-汽油保持曲線如圖 3，由毛細壓力曲線參數 3-4(b) 搭配 TMVOC 中之 Parker's model 即可求得。

本加油站內之儲槽區假定設有儲油量為 55 公秉之儲油槽 4 個，其尺寸為直徑 3 m、長度 8.2 m。並埋設於地表下 1 m 處，以符合規範之油槽頂部距地表至少 0.6 m 之規定，而地下水位部分則假設為有三種情況分別是在地表下 2 m、3 m、5 m 處，亦符合監測井之設置規範中，監測井有效深度不得低於 2 m(即地下水位須於地表下 2 m)；地下水位深度亦不可高過 7 m。

表 5 相對滲透係數參數(Stone's model)

參數 / 材料	S_{wr}	S_{nr}	S_{gr}	n exponent
大氣層	0.1	0.05	0.05	3
土壤	0.1	0.05	0.05	3

註: S_{wr} 為殘餘水相飽和度、S_{nr} 為殘餘 NAPL 相飽和度、S_{gr} 為殘餘汽相飽和度

表 6 毛細壓力曲線參數(Parker's model)

參數 / 材料	S_m	α_{gn}	α_{nw}	n exponent
大氣層	–	–	–	–
土壤	0	100	110	1.84

註: S_m 為極限飽和度、α_{gn} 為強度參數(氣-NAPL 相)、α_{nw} 為強度參數(NAPL-水相)

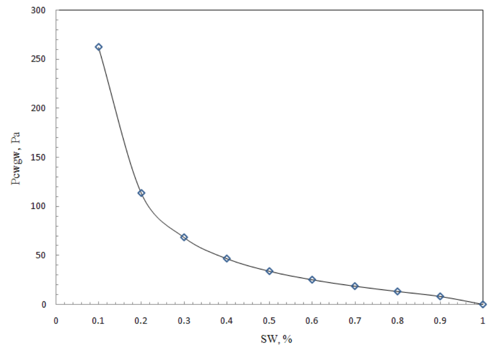


圖 3 土壤/水-汽油保持曲線

3.1 監測井配置

為得到較密集之模擬資料以及為了減少網格數與執行模擬所需之時間，因此將監測井儘量靠近油品洩漏點以及縮小監測井間之間距，因此採每一監測井間之間距為 3 m，共設置 11 支監測井如圖 4。監測井的設置深度，為顧及當地下水位於地表下 5 m 時，仍能獲得不飽和層之氣體濃度與飽和層中之水中濃度，因此設置深度達地表下 6 m 處。

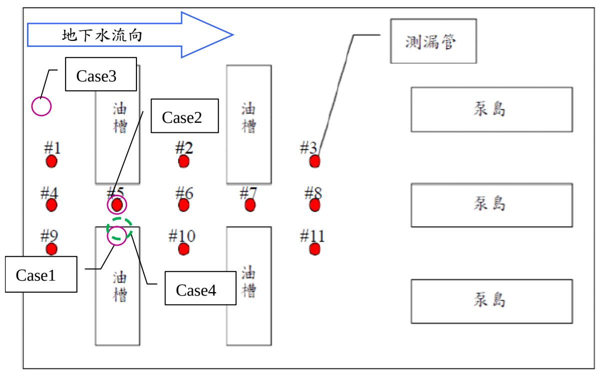


圖 4 監測井與油槽之相關位置示意圖

3.2 汽油污染物參數設定

本研究中綜合各學者之結果，採用 8 種揮發性有機物作為汽油之主要成份，其各成份與含量整理如表 7 所示。

表 7 本研究中所採用之汽油組成成份及百分比

汽油組成成份		
成分	範例	百分比(%)
正烷類	MTBE	18
芳香族	苯	3.5
	乙苯	5.5
	甲苯	7
	二甲苯	1.5
脂肪族	庚烷	20
	異辛烷	20
	環戊烷	24.5

3.3 加油站油品洩漏情況

一般加油站油品的洩漏約以 10 L/day~100 L/day 不等的速率洩漏，而於美國規範中，加油站之測漏管應能於 30 天內測得 150 加侖之油品洩漏事件，即平均每天以 5 加侖之速度洩漏(約為 19 L/Day)；環保署(2006)於「加油站防止污染地下水體設施及監測設備管理辦法」中對於偵測靈敏度要求須能達 0.2 gal/hr 之水準(即為 4.8 加侖/天)。因此於本研究中則假設其油品之洩漏速率為 5 gal/day；並連續注入一年。於本研究中在此假設 4 種不同位置發生油品洩漏分別概述如下:

Case1: 因發生接合不良、鏽蝕或破損等而產生油品洩漏如圖 4 所示。洩漏點於儲油槽上方與輸油管線之連接處，距離入口之地界線 23 m；與左側臨地之地界線距 14 m；深度於地表下 1 m 處。

Case2: 因發生鏽蝕、或外力造成破損而產生油品洩漏，且於下游處受到油槽阻擋如圖 4 所示。洩漏點於加油區內之輸油管線，距離入口之地界線 21 m；與左側臨地之地界線距 14 m；深度於地表下 1 m 處。

Case3:因發生鏽蝕、或外力造成破損而產生油品洩漏，但下游處並無受到儲油槽阻擋如圖 4 所示。洩漏點位於卸油口下方管線，距離入口之地界線 20 m；與左側臨地之地界線距 11 m；深度於地表下 1 m 處。

Case4:因發生破損而產生油品洩漏如圖 4 所示。洩漏點於儲油槽之底部，距離入口之地界線 23 m；與左側臨地之地界線距 15 m；深度於地表下 4 m 處。

4、結果與討論

在油品洩漏速率為 5 gal/day 的注入下當模擬時間(一年)到達後，分別依不同之地下水位深度(2 m、3 m、5 m)、透水係數(2.74×10^{-2}、2.74×10^{-3}、2.74×10^{-4} cm/sec)以及油品洩漏點(Case1-4)等三部分進行資料整理與分類，並以各測漏管之網格資料分別篩選出:不飽和層之平均土壤氣體濃度(X_{Gas})與溶解於地下水中之苯溶解相濃度(X_{Liq})。最後列出各監測井達到規範中「有油氣污染滲漏之虞」之土壤氣體濃度(500 ppmV)時間及達第二類地下水污染管制標準中苯含量達 0.05 mg/L 警戒值之時間。而由於監測井#1、#2、#3 對稱於#9、#10、#11，因此以監測井#9、#10、#11 來表示之，最後再將油品洩漏點(Case1-4)附近之監測井中土壤氣體濃度與地下水含苯濃度值其分別達到警示值之時間與地下水位、透水係數間之關係統整於表 8-表 15，以下分別對模擬場址之地下水位深度、透水係數以及油品洩漏點等各變動參數對於油品污染物傳輸之影響進行分析。

一、地下水位之影響

首先為能凸顯地下水位對於污染團傳輸之影響，因此選定以污染物傳輸狀況最為自由受限最少之洩漏狀況 Case2。在 Case2 之狀況中油品之洩漏點正好位於監測井#5 上，因此先以下游處之監測井#6 來分析地下水位對於污染團傳輸之影響，由監測井#6(表 11)中之 Case2 可看出在土層絕對透水係數同樣為 2.5×10^{-12} m^2 時，當地下水位深度由地表下 2 m 降低為 3 m 時則土壤氣體濃度達管制標準

(500 ppmV)之時間由 140 天增加為 160 天約增加 1.1 倍。而當地下水位再降低至地表下 5 m 時其土壤氣體濃度達管制標準之時間則增加至 230 天約是地下水位於 2 m 之 1.6 倍，然而地下水位深度由 3 m 降低為 5 m 時其土壤氣體濃度達管制標準之時間則相差不大，其原因為當油品之洩漏量為 5 gal/day 且洩漏時間為一年時，其污染團向下傳輸之深度約僅至 3 m 如圖 5，尚未到達 5 m 之地下水位面因此污染團尚未累積於地下水位面上。此外由油品洩漏點之上游處之監測井#4(表 9)中之 Case2 亦可看出地下水位於地表下 2 m 時其土壤氣體濃度達管制標準之時間為 120 天，而地下水為深度降低至 3 m 與 5 m 時，其土壤氣體濃度達管制標準之時間分別為 180 天與 178 天其變化不大，由此可知地下位深度大於 3 m 時且滲漏量少時則需再加上長時間的洩漏否則影響污染團傳輸的現象不大。最後由油品洩漏點 Case2 中監測井#4(表 9)、#6(表 11)及#7(表 12)還可發現於污染團之傳輸路徑不受阻擋之情形下，其監測井之監測能力範圍約在油品洩漏點半徑 3 m 內。

地下水含苯濃度受地下水位深度之影響程度則可由監測井#5(表 10)中之 Case2 看出當地下水位深度為 2 m 時(土層絕對透水係數為 2.5×10^{-12} m^2)其地下水體含苯濃度達管制標準(第二類飲用水標準 0.05 mg/L)之時間為 102 天；而地下水位深度增加至 3 m 時其時間則增加至 238 天約增加 2.3 倍；地下水位深度於 5 m 時則由於污染團傳輸深度僅至 3 m 如圖 6 因此無法監測到地下水體含苯濃度。

二、絕對透水係數之影響

透水係數對於污染團傳輸之影響於本研究中之四種洩漏情境中以油品洩漏點於 Case2 之情況最為顯著，其原因為於 Case2 之洩漏情況中其污染團往下游傳輸之路徑無受阻擋，因此污染團之傳輸行為發展相較於另外三種洩漏情境而言，較為完整，因此於透水係數影響因子中以洩漏點於 Case2 之情況作為討論之案例。

於油品洩漏點為 Case2 之案例，先以洩漏點上游處之監測井#4(表 9)來分析，當土層絕對透水係數為 2.5×10^{-12} m^2(模擬回填料為細砂)情況下且地下水位深度為 2 m 時其土壤氣體濃度值達管制標準之時間為 120 天，然而將土層絕對透水係數提高 10 倍至 2.5×10^{-11} m^2(模擬回填料為粗沙)時，則土壤氣體濃度值達管制標準之時間縮短為 45 天，達管制標準之時間約縮短 2.6 倍。地下水位深度於 3 m 時土壤氣體濃度值達管制標準之時間由 180 天縮短至 80 天(約縮短 2.3 倍)；地下水位深度於 5 m 情況下土壤氣體濃度值達管制標準之時間由 178 天縮短至 80 天(約縮短 2.2 倍)。若與透水係數敏感度分析之結果比較可發現，透水係數之敏感度分析中其監測井之設置間距為了避免間距過大，而受距離因子影響因而以網格之最短間距即為 1 m 來設置，(於場址模擬中其監測井之間距則考慮到油槽間距之關係因而將測漏管之間距增為 3 m)隨著監測井與洩漏點之距離加大使得透水係數較大者對於浮動油相污染團之傳輸速率更為增加，因而各監測井達管制標準之時間差更為顯著。

而若僅比較土層絕對透水係數則發現，對於透水係數為 2.5×10^{-11} m^2 之土層而言其地下水位深度對污染團傳輸之影響不大；但對於土層絕對透水係數為 2.5×10^{-12} m^2 之情況而言，由於土層之垂直向之傳輸速率僅為水平向傳輸速率之 1/50，且地下水位越深則不飽和層越厚如此可供污染氣團擴散之範圍亦較大，使得土壤氣體濃度之累積所需時間較長。如此雙重影響下於土層絕對透水係數為 2.5×10^{-12} m^2 之情況中因而出現地下水位深度越深，則土壤氣體濃度累積所需之時間拉長，如此即可解釋為何增加土層絕對透水係數則

土壤氣體濃度值達管制標準之時間縮短倍數會隨著地下水位深度之增加而增加。

三、洩漏點位置之影響

影響監測井效能之因子除了地下水位深度與土層透水係數外，另一重要因子即為污染物之洩漏點位置，在油品洩漏點於 Case1 如之監測井#5(表 10)中可發現油品污染物之洩漏點下方若有障礙物(油槽)則使得污染團無法直接向下傳輸，會先聚集於障礙物上方（圖 7）最後才經由障礙物邊緣垂直向下傳輸，而此時距離油品洩漏點最近之監測井#5(表 10)在絕對透水係數為 $2.5\times10^{-12}\ m^2$ 之情況下，則地下水位之變化對於監測效果而言並無太大影響。當絕對透水係數增加至 $2.5\times10^{-11}\ m^2$ 時地下水位深度亦對於監測效果之影響不大，然而若以洩漏點之上下游監測井#4(表 9)與#6(表 11)來觀察則可發現，由於傳輸路徑受障礙物阻擋因此絕對透水係數較小($2.5\times10^{-12}\ m^2$)之情況下，無論地下水位為何皆無法測得土壤氣體濃度，僅在絕對透水係數較大($2.5\times10^{-11}\ m^2$)之情況下且地下水位於 2 m 與 3 m 之深度中才能測得土壤氣體濃度達管制標準，其餘監測井則受制於障礙物之影響而無法測得土壤氣體濃度達管制標準之時間。

在地下水含苯濃度部分則因污染團垂直向下傳輸路徑受障礙物阻擋，使得污染團到達地下水位的量較少，因此無論地下水體監測井與油品洩漏點之距離為何皆無法在模擬期間一年內測得地下水體含苯濃度超過管制標準。

最後當油品洩漏點改變至油槽下方 Case4，由於本研究中假設油槽之埋設深度為地表下 1 m 至 4 m。而於地下水位為 2 m 之情況中，此時洩漏點位是位於地下水位面以下 2 m，因此油品之洩漏是直接洩漏於地下水中。然而由於污染物之傳輸路徑上方受油槽阻擋使得傳輸受拘限無法直接垂直向上傳輸(圖 8)，導致於模擬期間(一年)內無任何氣體監測井或地下水體監測井能測得污染濃度高過管制標準。當地下水位降低至 3 m 時，洩漏點則是位於地下水位面以下 1 m 而同樣於污染團傳輸路徑上方受油槽阻擋使得傳輸受拘限(圖 9)，使得無任何土壤氣體監測井能測得土壤氣體濃度超過管制標準，至於地下水體含苯濃度則僅有距離洩漏點旁 2 m 處之監測井#5(表 10)能測得地下水體含苯濃度高過管制標準(於絕對透水係數為 $2.5\times10^{-12}\ m^2$ 時需 89 天；於絕對透水係數為 $2.5\times10^{-11}\ m^2$ 時需 63 天)。當地下水位再降低至 5 m 時，此時洩漏點則是位於地下水位面以上 1 m 處，雖然洩漏點已不在地下水位面之下，但污染團傳輸路徑上方同樣受油槽阻擋(圖 10)使得土壤氣團無法於模擬期間(一年)內達管制標準，僅下游處之地下水體含苯濃度能達管制標準。監測井#10(表 13)於絕對透水係數為 $2.5\times10^{-12}\ m^2$ 時需 107 天；絕對透水係數為 $2.5\times10^{-11}\ m^2$ 時需 60 天；監測井#6(表 11)於絕對透水係數為 $2.5\times10^{-12}\ m^2$ 時需 115 天；絕對透水係數為 $2.5\times10^{-11}\ m^2$ 條件下於第 99 天；監測井#7 表 12)於絕對透水係數為 $2.5\times10^{-11}\ m^2$ 條件下於第 101 天可測得地下水體含苯濃度高過管制標準。

4.1 綜合結論

對於洩漏點 Case3 與 Case4 而言，無論是土壤氣體或地下水體含苯濃度均僅有少部分之監測井監測到有達管制標準，且對大部份之監測井而言監測效果均不佳。因此另外將洩漏點 Case3 周圍之監測井濃度值整理於表 14 ；將洩漏點 Case4 周圍之監測井濃度值整理於表 15。於表 14 中可發現除了監測井#1 可測得土壤氣體濃度達管制標準外，其餘監測井#4 與#5 均須在透水係數較大之情況下才能測得氣體濃度達管制標準，然而地下水體部分則已無法達管制標準。而洩漏點

於 Case4 之情況下(表 15)，則對於地下水位於 2 m 與 3 m 而言由於洩漏點是位於地下水位面以下，因此無論是氣體監測或地下水體含苯濃度之監測均難以發揮其功效，僅於地下水位於 3 m 之情況且監測井#5 正好位於洩漏點旁之地下水監測井才能測得地下水含苯濃度達管制標準。地下水位於 5 m 之情況則稍較前面兩者好一點，但也僅止於洩漏點旁 3 m 之監測井能測得濃度高過管制標準。顯然對於油槽下方發生破損所造成之洩漏，以目前實務上監測井之配置方式而言其監測效果實屬不佳，需配合其他監測設備才能有效監測。

整體而言監測井之監測效果以氣體監測效果優於地下水體之監測；土層透水係數高者(2.74×10^{-2} cm/sec)監測效果優於透水係數低者(2.74×10^{-3} cm/sec) ；地下水位高者(地表下 2 m)其監測效果優於地下水位低者(5 m)，其原因可能為:地下水位高(2 m)則污染物較快遭遇地下水層，則經由地下水層之帶動使得污染團擴散範圍增加、傳輸速度增加等因素；反之當地下水位較低時(5 m)油品於洩漏後則需先向下擴散至地下水位，而因不飽和層較厚使得污染氣團平均分佈於垂直向土層中之孔隙，因此較晚達到 500 ppmV 之門檻值且污染團之擴散範圍亦較小。而當監測井與油品洩漏點間之距離大於 3 m 以上且地下水位深度於 3 m 內者，則僅剩地下水體之監測能發揮監測效果(於油品洩漏時間為一年情況下)，然而地下水體含苯濃度達第二類飲用水管制標準 0.05 mg/L 所需之時間仍過長，由此可知在此情況下，土壤氣體濃度達管制標準之反應時間較地下水體含苯濃度為快，因此預警效果也較快。

另外若以距離洩漏點為 Case2 較遠之監測井#7(表 12)來分析(位於洩漏點下游 6 m 處)，則發現三種地下水位狀況之氣體監測井中之氣體濃度皆甚低，地下水體監測井狀況則僅剩地下水位於 2 m 處之監測井能發揮其功效，但測得地下水體含苯濃度所需之時間較長，同樣較難及時發現有油品洩漏之虞。而若將油槽區之回填材改以滲透係數較佳之回填料回填之，則監測井之模擬結果與上述之現象相似，不過由於滲透係數提高 10 倍使得監測井#4(表 9)與#6(表 11)之土壤氣體濃度達管制標準之時間提早了 2~3 倍。

本研究中汽油之洩漏量設定為 5 加侖/天，而對於本研究中所模擬之測漏管而言，絕大部分之監測效果均不理想。僅在透水係數為 2.74×10^{-2} cm/sec 以及測漏管距離洩漏點較近(1 m)之情況下，才能發揮出較佳之監測效果(土壤氣體濃度最快於 23 天達門檻值) (監測井#5，表 10)。因此可知，若要縮短測漏管土壤氣體與地下水體含苯濃度值到達監測門檻值所需之時間，則污染團之傳輸路徑需與測漏管位置配合才可達到最佳之監測效果。

表 8 監測井#1 之土壤氣體與地下水含苯濃度值

監測井編號 :#1					
油品洩漏點位置	地下水位(m)	氣體濃度達 500ppmV 所需之時間(day)		地下水體含苯濃度達 0.05 mg/L 所需之時間(day)	
		絕對透水係數 (m^2) : 2.5×10^{-12}	絕對透水係數 (m^2) : 2.5×10^{-11}	絕對透水係數 (m^2) : 2.5×10^{-12}	絕對透水係數 (m^2) : 2.5×10^{-11}
Case1	2	—	—	—	—
	3	—	—	—	—
	5	—	—	—	—
Case2	2	—	130	—	—
	3	—	205	—	—
	5	—	—	—	—
Case3	2	110	35	146	98
	3	110	40	—	180
	5	160	47	—	365
Case4	2	—	—	—	—
	3	—	—	—	—
	5	—	—	—	—

表 9 監測井#4 之土壤氣體與地下水含苯濃度值

監測井編號 :#4					
油品洩漏點位置	地下水位(m)	氣體濃度達 500ppmV 所需之時間(day)		地下水體含苯濃度達 0.05 mg/L 所需之時間(day)	
		絕對透水係數 (m^2) : 2.5×10^{-12}	絕對透水係數 (m^2) : 2.5×10^{-11}	絕對透水係數 (m^2) : 2.5×10^{-12}	絕對透水係數 (m^2) : 2.5×10^{-11}
Case1	2	310	76	—	—
	3	—	100	—	—
	5	—	93	—	—
Case2	2	120	45	—	—
	3	180	80	—	—
	5	178	80	—	—
Case3	2	—	89	200	110
	3	—	120	—	350
	5	—	180	—	—
Case4	2	—	—	—	—
	3	—	—	—	—
	5	—	—	—	90

一:於模擬時間內(一年)其土壤氣體或地下水含苯濃度無達管制標準。

表 10 監測井#5 之土壤氣體與地下水含苯濃度值

監測井編號：#5					
油品洩漏點位置	地下水位(m)	氣體濃度達 500ppmV 所需之時間(day)		地下水體含苯濃度達 0.05 mg/L 所需之時間(day)	
		絕對透水係數 (m^2) : 2.5×10^{-12}	絕對透水係數 (m^2) : 2.5×10^{-11}	絕對透水係數 (m^2) : 2.5×10^{-12}	絕對透水係數 (m^2) : 2.5×10^{-11}
Case1	2	46	23	－	－
	3	60	28	－	－
	5	70	33	－	－
Case2	2	1	1	102	85
	3	1	1	238	117
	5	1	1	－	－
Case3	2	－	185	300	118
	3	－	200	－	－
	5	－	－	－	－
Case4	2	－	－	－	－
	3	－	－	89	63
	5	－	－	200	90

表 11 監測井#6 之土壤氣體與地下水含苯濃度值

監測井編號：#6					
油品洩漏點位置	地下水位(m)	氣體濃度達 500ppmV 所需之時間(day)		地下水體含苯濃度達 0.05 mg/L 所需之時間(day)	
		絕對透水係數 (m^2) : 2.5×10^{-12}	絕對透水係數 (m^2) : 2.5×10^{-11}	絕對透水係數 (m^2) : 2.5×10^{-12}	絕對透水係數 (m^2) : 2.5×10^{-11}
Case1	2	300	80	－	－
	3	－	103	－	－
	5	－	130	－	－
Case2	2	140	45	140	102
	3	160	50	－	180
	5	230	61	－	－
Case3	2	－	200	－	120
	3	－	320	－	－
	5	－	－	－	－
Case4	2	－	－	－	－
	3	－	－	－	－
	5	－	－	225	99

－:於模擬時間內(一年)其土壤氣體或地下水含苯濃度無達管制標準。

表 12 (e) 監測井#7 之土壤氣體與地下水含苯濃度值

監測井編號：#7					
油品洩漏點位置	地下水位(m)	氣體濃度達 500ppmV 所需之時間(day)		地下水體含苯濃度達 0.05 mg/L 所需之時間(day)	
		絕對透水係數 (m^2) : 2.5×10^{-12}	絕對透水係數 (m^2) : 2.5×10^{-11}	絕對透水係數 (m^2) : 2.5×10^{-12}	絕對透水係數 (m^2) : 2.5×10^{-11}
Case1	2	－	160	－	220
	3	－	190	－	－
	5	－	－	－	－
Case2	2	－	120	180	105
	3	－	165	－	350
	5	－	－	－	－
Case3	2	－	－	－	－
	3	－	－	－	－
	5	－	－	－	－
Case4	2	－	－	－	－
	3	－	－	－	－
	5	－	－	－	101

表 13 (f) 監測井#10 之土壤氣體與地下水含苯濃度值

監測井編號：#10					
油品洩漏點位置	地下水位(m)	氣體濃度達 500ppmV 所需之時間(day)		地下水體含苯濃度達 0.05 mg/L 所需之時間(day)	
		絕對透水係數 (m^2) : 2.5×10^{-12}	絕對透水係數 (m^2) : 2.5×10^{-11}	絕對透水係數 (m^2) : 2.5×10^{-12}	絕對透水係數 (m^2) : 2.5×10^{-11}
Case1	2	255	50	－	190
	3	260	63	－	310
	5	258	73	－	－
Case2	2	－	80	330	120
	3	－	100	－	210
	5	－	160	－	－
Case3	2	－	－	－	－
	3	－	－	－	－
	5	－	－	－	－
Case4	2	－	－	－	－
	3	－	－	－	－
	5	－	－	107	60

－:於模擬時間內(一年)其土壤氣體或地下水含苯濃度無達管制標準。

表 14 洩漏點於 case3 之土壤氣體與地下水最終污染物濃度值

洩漏點位置：Case3					
監測井編號	地下水位(m)	油品洩漏一年後於土壤氣體監測井中所測得之濃度值(ppmV)		油品洩漏一年後於地下水體監測井中所測得之濃度值(mg/L)	
		絕對透水係數 (m^2) : 2.5×10^{-12}	絕對透水係數 (m^2) : 2.5×10^{-11}	絕對透水係數 (m^2) : 2.5×10^{-12}	絕對透水係數 (m^2) : 2.5×10^{-11}
#1	2	10,626	39,019	13.68	26
	3	5,390	22,252	0	0.67
	5	3,968	8,467	0	0.05
#4	2	243.5	11,747	0.42	4.34
	3	39.7	10,562	0	0.08
	5	2.74	2,095	0	0.01
#5	2	0.11	7,129	0.17	7.03
	3	0.01	5,224	0	0.01
	5	0	8.08	0	0.01
#6	2	0	1,538	0.01	4.11
	3	0	559	0	0
	5	0	0	0	0
#7	2	0	8.07	0	2.26
	3	0	0.95	0	0
	5	0	0	0	0
#10	2	0	0	0	0
	3	0	0	0	0
	5	0	0	0	0

表 15 洩漏點於 case4 之土壤氣體與地下水最終污染物濃度值

洩漏點位置 ：Case4					
監測井編號	地下水位(m)	油品洩漏一年後於土壤氣體監測井中所測得之濃度值(ppmV)		油品洩漏一年後於地下水體監測井中所測得之濃度值(mg/L)	
		絕對透水係數 (m^2) : 2.5×10^{-12}	絕對透水係數 (m^2) : 2.5×10^{-11}	絕對透水係數 (m^2) : 2.5×10^{-12}	絕對透水係數 (m^2) : 2.5×10^{-11}
#1	2	0	0	0	0
	3	0	0	0	0
	5	0	0	0	0
#4	2	0	0	0	0
	3	0	0	0	0
	5	0	5	0	0.03
#5	2	0	0	0	0
	3	0	0	2	1.23
	5	0	9.8	0.18	0.25
#6	2	0	0	0	0
	3	0	0	0	0
	5	0	18.9	0.05	0.25
#7	2	0	0	0	0
	3	0	0	0	0
	5	0	0.02	0	0.26
#10	2	0	0	0	0
	3	0	0	0	0
	5	0	87	0.31	11.7

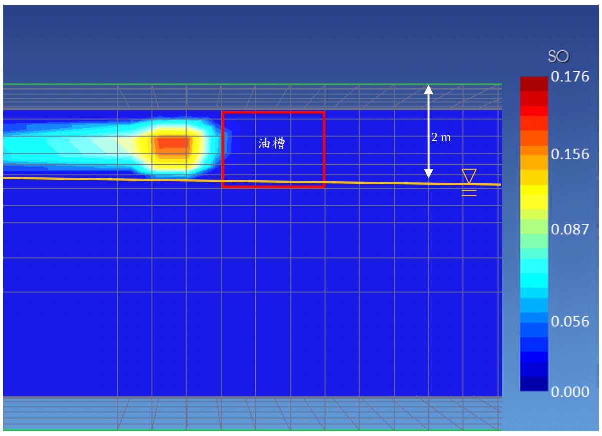


圖 5 污染團下游傳輸路徑受油槽阻擋時之傳輸行為示意圖(地下水位為 2 m)

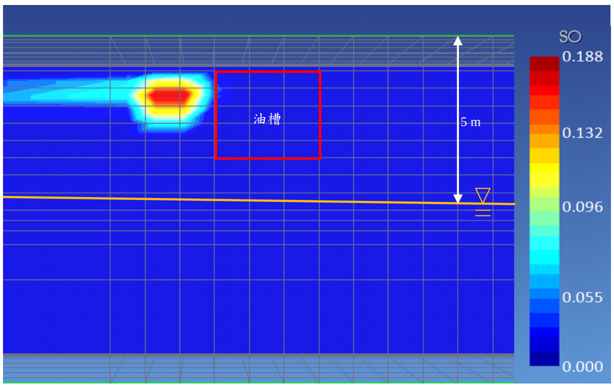


圖 6 污染團下游傳輸路徑受油槽阻擋時之傳輸行為示意圖(地下水位為 5 m)

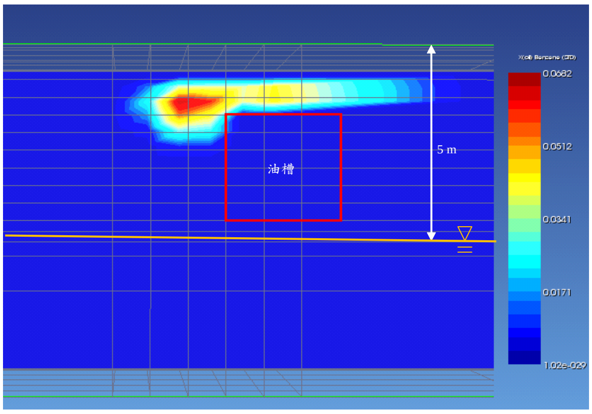


圖 7 污染團正下方之傳輸路徑受油槽阻擋時之傳輸行為示意圖

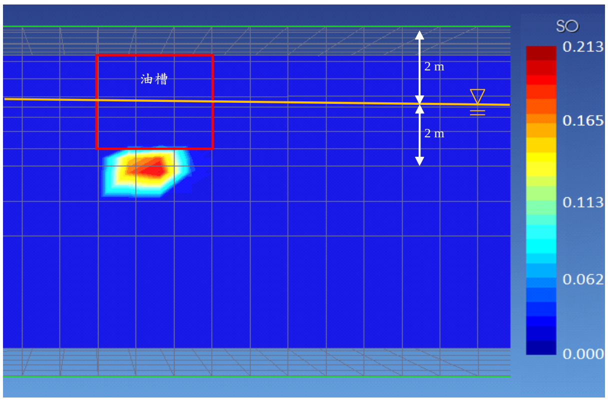


圖 8 洩漏點於地下水位面下 2 m 時之傳輸行為示意圖

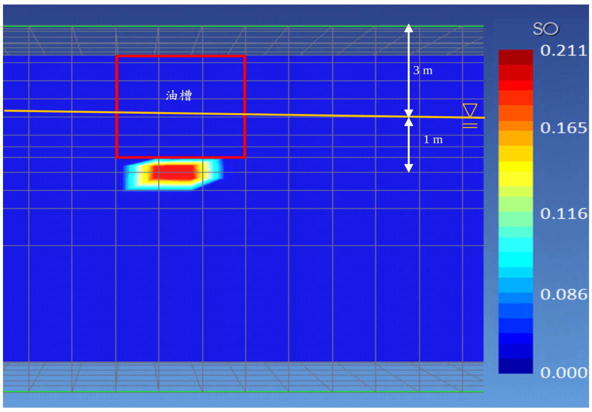


圖 9 洩漏點於地下水位面下 1 m 時之傳輸行為示意圖

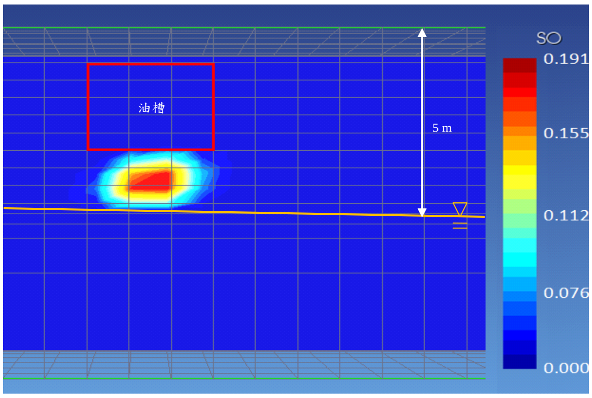


圖 10 洩漏點於油槽底部(於地下水位面上 1 m)時之傳輸行為示意圖

5、結論與建議

1. 整體而言地下水位較高者(地表下 2 m)其土壤氣體與地下水體含苯濃度之監測效果均優於地下水位較低者(地表下 5 m)。
2. 土層之絕對透水係數較大者(2.5×10^{-11} m^2)能提供浮動油相污染團較大之傳輸速率，因此監測效果優於土層絕對透水係數較小者(2.5×10^{-12} m^2)。
3. 於本研究中發現回填材料之若以透水係數較大(約為$\times10^{-2}$ cm/sec)之碎石作為回填材，則能大幅提高監測井之效果。
4. 本研究中對於污染團傳輸路徑受到障礙物阻擋或洩漏點位置發生於油槽底部而言，其整體之監測效果均不佳，建議可以於油槽底部另外增設監測儀器以彌補監測井之監測盲點。
5. 於本研究之結果中發現影響監測井功效之主要控制因子為:洩漏點之位置。而為了確保測漏管均能發揮其功效，建議測漏管之設置盡可能的靠近潛在洩漏機率較高之位置。
6. 於本研究中對於不同之地下水位深度均以同樣之土壤氣體管制標準值來判斷其土壤氣體是否達管制標準，未來可以深入研究土壤氣體濃度、地下水體含苯濃度與不同地下水位深度之相互關係。
7. 實務上監測井會因積水、有效深度不足等因素，致使無法量測土壤氣體濃度值，而改以其他之監測井內濃度值來判定是否達管制標準，然而該監測井與洩漏點之距離因子尚未被考慮，未來應可以考慮監測井與洩漏點之距離因子。

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計畫成果自評

由於我國加油站的設置規範與監測規範均不如國外嚴謹，國內雖加油佔大都以按照規範進行監測，但每年仍發現許多加油佔有滲漏問題，至今列管中之整治場址、控制場址與已解除列管場址已近 100 站，顯然監測方法亦應有缺失才會有此現象。因此對於國內最普遍使用之監測方法應該進行有效性評估，是刻不容緩的工作。

本研究以模擬進行加油站土壤氣體與地下水監測之模擬，結果對於此兩種方法之有效性得出重要之結論。亦即，土壤氣體監測和地下水監測之有效性並不如預期，在許多狀況無法達到法規訂定時所預期的精確度。因為主持人是環保署環訓所加油站監測訓練班的講座，數年來每年定期訓練約五百位加油站的業者與顧問公司和檢測公司工程師；且亦擔任環保署土壤與地下水污染整治基金會各項計畫之審查委員。因而本計畫之研究結果，無論透過期刊或研討會論文發表、或者在主持人參加各種環保署相關的會議與講習時，均將提出來與業界及環保署討論。並據以建議修訂我國的加油站設置規範與監測辦法。這對於環境保護來說，是最直接的貢獻。

由於國內學術界與工程界對於非水相有機液體（NAPL）模擬之經驗非常少，因此本研究在過程中訓練學生使用 TMVOC 進行多相有機物傳輸模擬，對學生和業界來說都非常有價值。

地下儲槽滲漏監測系統可靠度評估與最佳化設計原則之探討

NSC 98-2221-E-009 -133 -

出國報告

一、研討會概要

本計畫主持人利用本年度國科會計畫出國經費參加國際環境地工研討會(International Symposium on Geoenvironmental Engineering, ISGE 2009)。研討會舉行的時間為 2009 年 9 月 8 – 10 日三天。地點位於中國杭州市浙江大學舉。

本研討會之主題為環境地工（Geoenvironmental Engineering），其徵求論文的主題包括環境地工現象模擬、大地環境試驗與監測、一般廢棄物掩埋工程、土壤與地下水保護等，詳細主題如下：

A. Basic and advanced theories for modelling of geoenvironmental phenomena

B. Testing and monitoring for geoenvironment

C. Municipal solid wastes and landfill engineering

D. Sludge and dredging

E. Geotechnical recycling and reuse of industrial wastes

F. Mine sites, tailing dams and sludge ponds

G. Engineering barriers for radioactive waste disposals

H. Contaminated land and remediation technology

I. Applications geosynthetics in geoenvironment

J. Geoenvironmental risk assessment, management and sustainability

K. Ecological techniques and case histories

參加研討會的各國與會人士約三百餘人，發表論文共約一百多篇。在與會者中，中國的與會者約佔了兩百多位。

本計畫主持人發表之論文為：IN-SITU TESTS AND SLOPE STABILITY ANALYSIS OF MUNICIPAL SOLID WASTE LANDFILL（一般廢棄物掩埋場現地試驗與邊坡穩定分析）(國科會計畫成果：NSC 95-2221-E-009-201）。在論文發表後，也和與會人士針對本論文的相關內容進行討論。

研討會主辦單位並安排與會人員參觀杭州市天子嶺掩埋場，該廠佔地面積頗大，收受杭州市之一般廢棄物。由法國 Veolia 公司與杭州市政府組成的公司共同營運。該廠面積雖廣，但工作面僅維持約 100 m^2，其餘面積均用地工膜布暫時覆蓋，以控制氣體排放、臭味，並減少雨水入滲。該廠雖在營運中，但已經開始利用沼氣發電。

二、與會心得

本次參加研討會的環境地工學者專家來自世界各地。由於是中國第一次舉辦環境地工領域之研討會，且浙江大學為中國環境地工研究之重鎮，因此邀請到數位國際知名的環境地工領域學者參與。

因近年來環境地工領域的演進，相關的研究在二十年之間快速成長與成熟，而在國際間以掩埋場為主題的研究逐漸減少。在本次研討會最後投稿與發表的論文可看出端倪：

A. Basic and advanced theories for modeling of geoenvironmental phenomena (15 papers)

B. Testing and monitoring for geoenvironment engineering (10 papers)

C. <u>Applications of geosynthetics in geoenvironment engineering (10 Papers)</u>

D. Ecological techniques and case histories (9 Papers)

E. <u>Municipal solid wastes and landfill engineering (19 papers)</u>

F. Sludge and dredging soils (10 papers)

G. Geotechnical reuse of industrial wastes (9 papers)

H. Contaminated land and remediation technology (8 papers)

I. Geoenvironmental risk assessment, management and sustainability (8 papers)

然而，由於中國的一般廢棄物、事業廢棄物、污泥均以掩埋為主要處理方式，因此在掩埋場相關議題方面來自中國的論文較多。其涵蓋的議題包括廢棄物的性質、掩埋場沈陷的模擬、掩埋場阻水層材料等。另有不少論文實際上與環境地工無關，而實為大地工程領域中的其他子領域，例如：加勁格網、擋土牆等。

另一個值得觀察的是污泥相關的議題。因為在中國，無論是自來水淨水廠的污泥、生活或工業廢水處理廠的污泥、河川整治的底泥都以掩埋方式處理，因此在掩埋之前的固化與安定化是一個極受重視的關鍵議題。

相對地，在國際上環境地工領域近年最受重視的土壤與地下水污染相關的調查、監測、模擬、風險評估、整治等，在本研討會中論文數量較少；係因中國較少相關研究，相對論文產出較少。除了中國以外的論文，有不少與土壤與地下水污染相關的研究成果相關，包括利用以電動勢能(Electrokinetics)原理研發的地工材料可應用於地下水污染整治等。

值得一提的是在本次研討會大會開幕之後，即由我國的前亞新工程顧問公司副總經理秦中天博士報告莫拉克風災災情，其報告內容引起與會人士高度的重視。

International Symposium on Geoenvironmental Engineering

Zhejiang University, Hangzhou, China, Sept. 8-10, 2009

环境岩土工程国际学术研讨会. 2009 年 9 月 8-10 日.中国杭州

ISGE 2009 Program (July 29, 2009 draft)

Organized by

- MOE Key Laboratory of Soft Soils and Geoenvironmental Engineering, Zhejiang University 浙江大学软弱土与环境土工教育部重点实验室
- Chinese Institution of Soil Mechanics and Geotechnical Engineering (CISMGE) 中国土木工程学会土力学及岩土工程分会
- Chinese Chapter of International Geosynthetics Society (CCIGS) 国际土工合成材料学会中国委员会

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Address: Anzhong Building B-412, Zhejiang University, Hangzhou, 310058, P.R. China (浙江省杭州市浙江大学岩土工程研究所安中建工大楼 B412 室, 邮编: 310058)

Program at a Glance (July 29, 2009 draft)

	Monday, September 7, 2009	
08:30-22:30	Registration, Exhibition Setup	
	Tuesday, September 8, 2009	
09:00-09:30	Opening Ceremony	
09:30-09:50	Conference Photo Session	
	Topic: Basic properties and advanced theories for modeling of geoenvironmental phenomena(1)	
09:50-10:10	Invited Lecture: Modeling applied to environmental geotechnics	Mario MANASSERO
10:10-10:30	Invited Lecture: Modeling dominant transport processes in one-dimensional contaminant transport	Madhira R. MADHAV
10:30-10:50	Invited Lecture: The vector sum method: a new approach to calculating the factor of safety of stability against sliding for slope engineering and dam foundation problems	Xiurun GE
10:50-11:00	Coffee Break	
	Topic: Basic properties and advanced theories for modeling of geoenvironmental phenomena(2)	
11:00-11:20	Invited Lecture: Coupled thermo-hydro-chemo-mechanical modeling for geoenvironmental phenomena	Hywel R. THOMAS
11:20-11:40	Invited Lecture: Removal of heavy metal from aqueous solutions using Chinese loess soils	Xiaowu TANG
11:40-12:00	Invited Lecture: Advances on buffer/backfill properties of heavily compacted Gaomiaozi bentonite	Weimin YE
12:00-13:30	Lunch	
	Topic: Testing and monitoring for geoenvironmental engineering	
13:30-13:50	Invited Lecture: An application of centrifuge model in environmental geotechnics: assessment of soft geological barrier subjected to pile constructions in waste disposal site	Jiro TAKEMURA
13:50-14:10	Invited Lecture: Application of electrical resistivity for cement solidified/stabilized heavy metal contaminated soils	Songyu LIU
14:10-14:30	Invited Lecture: TDR measurement system and the application of TDR in geoenvironmental engineering	Renpeng CHEN
	Topic: Applications of geosynthetics in geoenvironment	
14:30-14:50	Invited Lecture: Applications of geosynthetics in geoenvironment	Aigen ZHAO
14:50-15:10	Invited Lecture: In-situ containment for waste landfill and contaminated sites	Takeshi KATSUMI
15:10-15:20	Coffee Break	
15:20-17:20	**Plenary Lectures (6 minutes each)** Topics: (1) Basic and advanced theories for modeling of geoenvironmental phenomena; (2) Testing and monitoring for geoenvironmental engineering; (3a) Applications of geosynthetics in geoenvironment engineering; (3b) Ecological techniques and case histories	
18:00-20:00	Dinner	

Program at a Glance (July 29, 2009 draft)

Wednesday, September 9, 2009		
	Topic: Municipal solid wastes and landfill engineering (1)	
09:00-09:20	Invited Lecture: On recent advances in understanding landfill behaviour	David J. RICHARDS
09:20-09:40	Invited Lecture: Environmental geotechnics related to landfills of municipal solid wastes	Yunmin CHEN
09:40-10:00	Invited Lecture: Full-scale practice of ecologically based landfill of municipal solid waste: to accelerate the biological conversion inside landfill and cover layers	Pinjing HE
10:00-10:20	Invited Lecture: Application of shear strength of solid waste and multilayer interface in landfills	Jianyong SHI
10:20-10:30	Coffee Break	
	Topic: Municipal solid wastes and landfill engineering (2)	
10:30-10:50	Invited Lecture: Challenges associated with the design of covers	Delwyn G. FREDLUND
10:50-11:10	Invited Lecture: Geotechnical aspects of landfill closure and aftercare	Ulrich HENKEN-MELLIES
11:10-11:30	Invited Lecture: A preliminary understanding on performance of barriers for MSW landfills in southern China	Liangtong ZHAN
11:30-11:50	Invited Lecture: Information about standards municipal solid waste sanitary landfill in China	Yixin DONG
11:50-13:10	Lunch	
	Topic: Contaminated land and remediation technology	
13:10-13:30	Invited Lecture: Contaminated land and environmental damage: an analysis of current remedial strategies and future developments	Stephan A. JEFFERIS
13:30-13:50	Invited Lecture: Remediation technologies for contaminated sites	Albert T. YEUNG
13:50-14:10	Invited Lecture: Abandoned mine site rehabilitation strategies used in Canada	Bruno BUSSIERE
	Topic: Sludge and dredged soils	
14:10-14:30	Invited Lecture: Dewatering sludge using electrokinetic geosynthetics	Stephanie GLENDINNING
14:30-14:50	Invited Lecture: Role of soil water in cement-based treatment of dredged materials	Wei ZHU
14:50-15:10	Invited Lecture: Numerical analysis of electro-osmosis in soft clay	Liming HU
15:10-15:20	Coffee Break	
15:20-17:20	**Plenary Lectures (6 minutes each)** Topics: (1) Municipal solid wastes and landfill engineering; (2a) Sludge and dredging soils; (2b) Geotechnical reuse of industrial wastes; (3a) Contaminated land and remediation technology; (3b) Geoenvironmental risk assessment, management and sustainability	

Program at a Glance (July 29, 2009 draft)

Thursday, September 10, 2009		
	The 2009 Zeng Guo-Xi Lecture	
08:30-08:45	Introduction of the Zeng Guo-Xi Lecture	
08:45-09:45	ZGX-1: Static and seismic analysis of solid waste landfills	Pedro S. PINTO
09:45-10:45	ZGX-2: Systems engineering the design and operations of municipal solid waste landfills to minimize contamination of groundwater	R. Kerry ROWE
10:45-11:00	Coffee Break	
11:00-12:00	**Workshop (topic to be announced)**	
12:00-13:30	Lunch	
13:30-17:00	**Technical Visit**	

Plenary Sessions (July 29, 2009 draft)

Tuesday, September 8, 2009		
15:20-17:20, Sept. 8	**Plenary Lectures (6 minutes each)** **(1) Basic and advanced theories for modeling of geoenvironmental phenomena (15 papers)** **(2) Testing and monitoring for geoenvironment engineering (10 papers)** **(3a) Applications of geosynthetics in geoenvironment engineering (10 Papers)** **(3b) Ecological techniques and case histories (9 Papers)**	
	(1) Basic and advanced theories for modeling of geoenvironmental phenomena	
A-2	Numerical simulation of electro-osmosis in soft clay	Liming HU, Weiling WU, Zhaoqun WU
A-3	Research on coefficient of brittle stress drop of brittle-plastic rocks and its application	Gui-Cai SHI, Xiu-Yun GE, Yun-De LU
A-5	Dynamic stability analysis of landfill slope in Dushanbe, Tajikistan	Xue-Tao WANG, Tensay G. BERHE, Stephen WEBB, Wei WU
A-6	High-speed and long range flow analysis model of waste body after sanitary MSW landfills slope unstablilty	Zhan-Hong QIU, Yun-Min CHEN, Xiao-Gang WANG
A-7	One-dimensional consolidation of aquitard considering non-Darcy flow	Zhong-Yu LIU, Jin-Chao YUE, Li-Yun SUN
A-8*	Site effect analysis of Shirvan GTL refinery, using equivalent linear soil behavior (NE of Iran)	Ahmed ADIB, Naser EBADATI, Kobra HEYDARZADEH
A-9	Data division method of sand liquefaction samples based on self-organizing maps	Si-Si LIU, Ming-Hua ZHAO
A-10	GOM-SVM predictor for land subsidence at finished underground mining	Zheng-Wen XIE, Xiao-Yu LIANG
A-11	A fully coupled thermo-hydro-mechanical model for methane hydrate reservoir simulations	Huo-Lang FANG
A-12	Numerical simulation of dynamic responses in transversely isotropic fluid-saturated elastic seabed under wave actions	Zhou-Yuan HENG, Wang-Yong HE, Sun ZHI, Chen-Ming WEI
A-13	Solutions for a completely saturated porous elastic solid with impeded boundaries	Ze-Hai CHENG, Jian-Zhong XIA, Yun-Min CHEN, Dao-Sheng LING, Bing ZHU
A-15	The three dimensional saturated-unsaturated seepage analysis under atomized rain of hydropower project with high slope	Huan-Ling WANG, Wei-Ya XU
A-16	Study on unloading rock mass constitutive relationship	Jie LIU, Jian-Lin LI, Xiao-Hu WANG, Jian-Jun QU, Ting ZHU
B-1	Destructuration constitutive model for soft clay	Xiao-Jun YU, Zhi-Hong QI
B-10	Identification of damping ratios of soil-structure system subjected to ambient excitation	Zhi-Ying ZHANG, Qiang PAN, Chong-Du
		CHO, Zhan-Chao GAO
	(2) Testing and monitoring for geoenvironment engineering	
B-4	Laboratory flume studies on consolidation of soft silty seabed soil under wave actions	Ying LIU, Hong-Jun LIU, Xiu-Hai WANG, Min-Sheng ZHANG
B-5	Characteristics of shear strength of unsaturated weak expansive soils	Wei-Min YE, Ya-Wei ZHANG, Bao CHEN, Shi-Fang ZHANG
B-6	On the determination of the soil-water characteristic curve using the pressure plate extractor	Hui CHEN, Chang-Fu WEI, Rong-Tao YAN, Pan CHEN, Pan-Pan YI
B-8	Zero valent iron to remove the arsenic contamination from natural groundwater: Batch and Column Experiment	M. A. ABEDIN, Takeshi KATSUMI, Toru INUI and Masashi KAMON
B-9	Simulation tests of biodegradation and compression of municipal solid waste	Jun-Long LIU, Han KE, Tony L.T. ZHAN, Yun-Min CHEN
B-11	Compatibility of tropical soil and bentonite mixtures subjected to chemical solutions	Thiago Luiz Coelho MORANDINI; Adilson do Lago LEITE
B-12	Development of sediment monitoring during heavy rainfalls	Chih-Ping LIN, Chih-Chung CHUNG, Yu-Chia CHANG, Tzong-Shen CHANG
B-13	Research on relationship of engineering indexes and microstructural feature value to saturated soft soil	Yong XU, Ji-Chao ZHANG, Wu-Ping Li, He YI
B-14	Shear strength behavior of bentonite modified by tetramethylammonium cations	B. BATE, S.E. BURNS
B-15	Monitoring of landfill settlement by means of horizontal inclinometers	Xiao-Bing XU, Hai-Yun WEI, Tony L.T.ZHAN Yun-Min CHEN, Yao-Shang WANG
	(3a) Applications of geosynthetics in geoenvironment engineering	
I-1	Applications of geogird reinforced soil retaining wall with wrap-around facing in railway	Guang-Qing YANG, Qiao-Yong ZHOU, Bao-Jian ZHANG, Jun-Xia DING
I-2	Test study on engineering properties of gabion structures	Guo-Lin YANG, Xiang-Jing HUANG, Yu-Liang LIN
I-3	Pullout test study on interface friction characteristics of reinforcements with red sandstone as filler	Yu-Liang LIN, Guo-Lin YANG, Yun LI, Xiang-Jing HUANG
I-4	Application of geomembrane as carbon capture at Palm Oil Mill	Andryan SUHENDRA, Amelia MAKMUR
I-5	Interface frictional property between sand and geomembranes	Junli GAO, Mengxi ZHANG, Wenjie ZHANG
I-7	Covered anaerobic lagoons with HDPE geomembrane experiences in developing Asian countries	Hoe-Boon NG , Chang-Wei QI and Xiao-Ming

		TAN
I-8	Durability analysis of reinforced Gabion retaining wall material	Gui-Lin XU, Guo-Lin YANG, Xiang-Jing HUANG
I-9	Lessons learned from the numerical modeling of a retaining wall with non-uniform reinforcements	Xiang-Jin HUANG, Ze LIU, Vicari M
I-10	Experimental studies of arching effect and geosynthetic deformation in local subsidence problem	Deng GAO, Bin ZHU, Yun-Min CHEN, Tony L.T. ZHAN, Xiang-Zhi WANG
I-11	A large-scale ramp model test on composite liner systems	Wei-An LIN, Tony L.T. ZHAN, Yun-Min CHEN, Sheng HE
	(3b) Ecological techniques and case histories	
K-1	Sustainable design based on near nature construction method – a case study	Huat-Yoo CHUA,Hsiao-Chou CHAO, Chung-Tien CHIN
K-2	Engineering geological properties of the saturated clay foundation at the southern edge of Mu Us Desert in China	Sheng-Rui SU, Fang-Qiang SUN
K-3	Geology consideration influential in urban development and vulnerability of the Gorgan Region (NE Iran)	Naser EBADATI , Ahmad ADIB, Reza MAGHSOODLOORAD
K-5	Protection technology and applications of Gabion	Guo-Lin YANG, Zhe-Zhe LIU, Gui-Lin XU, Xiang-Jing HUANG
K-6	A parametric study on evaluation of stability of column type DM improved ground	Masaki KITAZUME
K-7	Case study on geoenvironmental effects of press-in piles installation	Jian-Xue SONG, Tong-He ZHOU, Yuan-Cheng GUO
K-8	A construction case of ramps located on the expansive soil for highway interchange	He-Ping YANG, Xiao NI, Jie XIAO
K-9	Analysis of the deep-seated concrete slab for settlement control at bridge approach embankment	Yun SUN, Yi-Qiang XIANG, Dong-Mei GUO, Ting-Ting ZHANG
K-10	Application of geocell in the ecological protection of rock slope	Xin-Jun ZOU, Ming-Hua ZHAO

Plenary Sessions *(July 29, 2009 draft)*

	Wednesday, September 9, 2009
15:20-17:20, Sept. 9	**Plenary Lectures (6 minutes each)** **(1) Municipal solid wastes and landfill engineering (19 papers)** **(2a) Sludge and dredging soils (10 papers)** **(2b) Geotechnical reuse of industrial wastes (9 papers)** **(3a) Contaminated land and remediation technology (8 papers)** **(3b) Geoenvironmental risk assessment, management and sustainability (8 papers)**

	(1) Municipal solid wastes and landfill engineering	
C-1	Effect of thickness of hydraulic barrier on the integrity of a cover system subjected to differential settlements	Bhamidipati V.S. VISWANADHAM and Sathiyamoorthy RAJESH
C-2	Seismic response characteristics of municipal waste landfill	Xue-Jing DENG , Xian-Jing KONG , De-Gao ZOU
C-3	Study on soil properties of the early ecological restoration for a chemical landfill in Huainan	Wen FAN, Jia-Ping YAN, Hui-Ping LIU
C-4	Geotechnical site characterization of municipal solid waste landfill in Uzbekistan	Kobiljon KHOLMATOV, Diana KHASHIMOVA, Wei WU , Marufdjan MUSAEV
C-5	Ambient noise site investigation of a representative MSW landfill in Bishkek, Kyrgyzstan	Thiep DOANH, Xue-Tao WANG, Stephen WEBB, Wei WU
C-6	Analyses on applicability of ET covers in humid areas	Wen-jie ZHANG, Yun-Min CHEN
C-7	In-situ tests and slope stability analysis of municipal solid waste landfill	Hsin-Yu SHAN, Tsuo-Hsien FAN
C-9	Effect of municipal solid waste composition on permeability	Harris RAMLI, Mastura AZMI, F. AHMAD, M.M. ALI
C-10	Study on the Duncan-Chang model parameters of stress compression for municipal solid waste	Zhen-Ying ZHANG, Chang-Fu WU, Yun-Min CHEN
C-11	Study on parameter sensitivity of the combination failure of landfill with a dam	Fan Tu, Fang-Qiang CHANG, Zhao-Yun XIAO, Xiao-Jie WU
C-12	Model tests on deformation behavior of Bentonite mixed soil layer subjected to a local subsidence in landfill	Shigeyoshi IMAIZUMI, Yasuto SHINOZAKI, Kengo KUDO and Takuya YOSHINAO
C-14	Factors affecting slope stability of landfill covers	Manoj DATTA

C-15	One-dimensional settling behavior of a group of soil materials in static water assuming coastal landfill	Shuichi NAGAOKA, Yuta NABESHIMA, Kenichi SATO, Shotaro YAMADA, Tomoaki HACHIMURA and Tetsuya MIYAHARA
C-17	Experimental study on the nonlinear change of saturated hydraulic conductivity of waste soil	Ying ZHAO, Qiang XUE, Bing LIANG, Lei LIU
C-18	Landfill gas generation and transport in bioreactor landfill	Qi-Lin FENG, Lei LIU, Qiang XUE and Ying ZHAO
C-19	Development of a computer software for predicting landfill settlement and its storage capacity	Yao-Shang WANG, Han KE, Tony L.T. ZHAN, Xue-Chen BIAN, Yun-Min CHEN, Zhe FU
C-20	Influence of rainfall pattern on the infiltration into landfill earthen final cover	Guan-Wei JIA, Tony L.T. ZHAN, Yun-Min CHEN, D.G. FREDLUND
C-21	Municipal solid waste management after Wenchuan earthquake	Hua TAO
C-22	Field investigation on the feasibility of leachate recirculation in Chengdu MSW Landfill, China	J.W. LAN, Tony L.T. ZHAN, Y.M. CHEN, H. KE, Z. LIU, G.Q. LU
	(2a) Sludge and dredging soils	
D-1	Reuse of pond sediment by mixing with stabilizers and shredded paper	Yasuyuki NABESHIMA, Seishi TOMOHISA
D-2	Laboratory study on electrokinetic dewatering of sewage sludge	Yuan FENG, Tony L.T. ZHAN, Yun-Min CHEN, Quan-Fang ZHANG
D-3	Hydraulic conductivity evaluation of vertical cutoff walls bearing filter cake from slug test analysis	The-Bao NGUYEN, Chulho LEE, Yonghoon AHN and Hangseok CHOI
D-4	Filtration performance of two-layered nonwoven geotextiles	Li-Fang LIU, Lian-Ying JI, Fa-Wen GUO , Qian-Li WANG , Xiao-Jie YANG
D-5	Reasonable construction management in fill loading with vacuum consolidation method based on FEM analyses	Mohammad SHAHIDUZZAMAN, Yoshihiko TANABASHI, Hiroshi KAWABATA,Yujing JIANG, Satoshi SUGIMOTO
D-6	Finite element numerical analysis to interaction of buried spiral steel plastic composite pipe with surrounding soils	Xiang-Yong ZENG, An-Fu DENG, Bing ZHENG, Xiaodong GUO
D-7	Experimental study on engineering properties of a dredged sediment solidified by common cementitious materials	Ping CHEN, Bangmin QIN
D-8	Improving soft ground and sludge by over-pressure vacuum consolidation system	Ya-Wei JIN , Ben NIU
DF-3	Changing in the physical parameters of dumps of the coal-mining industry of Kansk-Achinsk (Siberian) coal field and possibility of their remediation	E.V. STANIS, E.N. OGORODNIKOVA, E.A. KARPUKHINA
DF-5	Dynamic reaction analysis of tailing dams under earthquake	Bao-Lin XIONG, Xi-Liang WANG, Chun-Jiao LU
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E-2	Experimental study on the engineering properties of two incineration bottom ash of municipal solid wastes	Jian-Ming ZHANG, Min-Yun HU, Si-Fa XU
E-4	Utilization of coal ash as recycling material options in view point of geoenvironment	Ahmad RIFA'I, Noriyuki YASUFUKU, Kiyoshi OMINE, Kazuyoshi TSUJI
E-5	Study on engineering property of mixed-soil fly ash	Ya-Sheng LUO, Jing LI, Andrew CHAN
E-6	Experimental study on treatment of over-wetted clays using calcium chloride	Ying-Ying ZHANG, Yan-Jun DU, Song-Yu LIU, Fan ZHANG
E-7	Mechanical and chemical properties of ash molten slag mixed with Bentonite	Fujio IGARI, Shigeyoshi IMAIZUMI
E-8	An applicability of dehydrated cake produced from quarry to impermeable material with heavy metal adsorption	Ryo SUETAKE, Kenichi SATO, Miyako TAKEDA, Morimoto TATSUO
E-9	Unconfined compressive strength of mixture of phosphogypsum-fly ash-lime-clay	Zhi-Hong QI, Xue-Yuan XU, Mi-Lin ZHU, Yang HU
E-10	Adsorption behavior and mechanism of Cu(II) on activated firmiana simplex leaf	Qiang TANG, Xiao-Wu TANG, Man-Man HU, Yun-Min CHEN, Yan WANG, Nai-Yu KOU
	(3a) Contaminated land and remediation technology	
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H-2	An overview of stabilization/solidification technique for heavy metals contaminated soils	Yan-Jun DU, Song-Yu LIU, Zhi-Bin LIU, Lei CHEN, Fan ZHANG, Fei JIN
H-4	Case study on influences of oil contamination on geotechnical properties of coastal sediments in Yellow River Delta	Yong-Gang JIA, Qiong WU, Xiang-Mei MENG, Xiu-Juan YANG, Zhong-Nian YANG, Geng-Cheng ZHANG
H-5	Bioremediation of water contaminated with BTEX, TPH and TCE under different environmental conditions	C.K. LEI, J. H.LI, S.S. DONG, and H. SHIM
H-6	Hysteretic retention of Pb(II) in kaolin column	Zhen-Ze LI, Yun-Min CHEN, Xiao-Wu TANG, Yan WANG and Qiang TANG
H-9	Experimental study on the mechanism of action of ionic soil stabilizer on red clay of Wuhan	Wei XIANG, De-Shan CUI, and Fei AI
H-10	Effects of surface-active agent on mechanical behaviors of loess	Nai-Yu KOU, Xiao-Wu TANG, Quan-Fang

		ZHANG, Yun-Min CHEN, Qiang TANG
H-11	EDTA-enhanced electrokinetic extraction of cadmium from a natural clay of high buffer capacity	Ying-Ying GU, Albert T. YEUNG, Hong-Jiang LI
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J-1	Urban night soil transportation and treatment in China	Ting LIU, Zhu-Lei CHEN, Lie YANG
J-4	Study on the relationship between landslides, debris lows and the modern river geological processes	Ming-Xin ZHENG
J-5	Seismic damage characteristics of rural adobe-wood building in Gansu Province induced by the Wenchuan Great Earthquake	Ai-Lan CHE, Zhi-Jian WU, Jun-Jie SUN, Jing-Hua QI
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J-12	Geoenvironmental risk assessment in Albania	L. BOZO, G. J. IKONOMI
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IN-SITU TESTS AND SLOPE STABILITY ANALYSIS OF MUNICIPAL SOLID WASTE LANDFILL

Hsin-yu Shan[1], Tsuo-Hsien Fan[2]

ABSTRACT: Due to the limitation of population density and availability of land, a large portion of Taiwan's landfills are located in mountainous area. Current regulations do not require slope stability analysis for these landfills. As a result, almost all of the landfills were not designed to maintain a suitable factor of safety against failure. The composition of Taiwan's solid waste differs considerably from that of the United States or any other country in the world. However, the lack of data of local solid waste poses a great limitation to engineers. The objectives of this research are to collect shear strength data from in-situ tests and perform a series of stability analyses. The results show that the cohesion and friction angle of the MSW at Chu-nan and Hu-kou landfills are 34.9 kPa and 37.9°, 33.6 kPa and 32.1°, respectively. In addition, the coefficients of subgrade reaction, kv, are 875.25 kN/m3 and 494.33 kN/m3, respectively. Results of 2-D and 3-D slope stability analyses show that the factor of safety increases with lower height of wastes, longer length of waste body, smaller slope angle of the back of the excavation, and steeper face slope of final cover. In addition, 3-D analysis indicates that the factor of safety decreases with the widening of the mouth of the landfills on slopes.

KEYWORDS: landfill, in-situ test, shear strength, compressibility, slope stability

INTRODUCTION

Prior to 1980's when direct disposal in landfill was the only appropriate method allowed, there were more than 300 landfills in operation at the same time. There are still more than 130 landfills in use currently although incineration has become the major approach for treating municipal solid wastes (MSW). These active landfills receive nonhazardous industrial wastes along with bottom ash and stabilized fly ash generated by the incinerators. In 2008, more than 4 million tons of MSW was incinerated, which generated about 1.2 million tons of incinerator ash, and approximately 240,000 tons was directly disposed in landfills. Over the time, more landfills will be close while the ones still operates will be limited to the landfills that located in distant rural areas where incineration is inhibited by high cost and those that solely used for disposal of incinerator ash. The closed landfills will be covered with low permeability soil and top soil for vegetation. The Environmental Protection Administration encourages redevelopment of the closed landfills as public recreational facilities such as parks, basketball courts, golf training courses, and croquet courts.

However, a large portion of the landfills in Taiwan are located in hilly area due to the difficulty in finding suitable locations for landfills as a result of the NIMBY effect. Furthermore, many landfills are dumped with much more MSW than they were designed. Therefore, it is very common for these landfills to experience slope failures of various magnitude in the typhoon season, where accumulation of leachate should be the trigger of such failures.

The objective of this study is to investigate the stability of the landfills with shear strength parameters determined by large scale in-situ tests and 2D/3D slope stability analysis. The results of the study will provide valuable information for future design and operation of the MSW landfills.

BACKGROUND

Unit Weight of MSW

The unit weigh of MSW can be determined by a range of approaches including field methods such as filling a large measuring box with MSW, excavating a test pit, estimation by the weight of MSW dumped and

[1] Associate Professor, Department of Civil Engineering, National Chiao Tung University, Taiwan, hyshan@mail.nctu.edu.tw
[2] Former graduate student, Department of civil engineering, National Chiao Tung University, Taiwan, woodguy1007@yahoo.com.tw

the resulted volume, and laboratory methods such as determining the unit weight of remolded MSW (Merz and Stone, 1962; Schumaker, 1972; Sower, 1973; Bromswell, 1978; Dvinoff and Munion, 1986; Sargunan et al., 1986).

The unit weight of MSW ranges from 3.92 to 8.83 kN/m^3 depending on the degree of compaction (Table 1) (Dixon and Jones, 2004). The unit weight measured in the field fell between 4.91 and 6.87 kN/m^3.

In Taiwan, the average unit weight of MSW is approximately 1.60±0.05 kN/m^3 according to limited data (Taiwan EPA, 2005). This value is much smaller than those listed in Table 1, since the method for measuring the unit weight is different from those used in geotechnical studies.

Table 1 Unit Weight of Municipal Solid Wastes (Dixon and Jones, 2004)

Country	Unit Weight (kN/m^3)	Notes	Literature
United Kingdom	5.98	Compacted by 21-ton hammer falling from 2 m above ground	Watts and Charles (1990)
	8.04	Compacted by 21-ton hammer falling from 0.6 m above ground	
Belgium	5.00~10.01	Various degree of compaction	Manassero et al. (1996)
France	6.97	Freshly buried MSW	Gourc et al. (2001)
United States	5.98~6.97	Freshly buried MSW	Kavazanjian (2001)
	14.03~20.01	Highly decomposed	

The data collected by Kavanzanjian et al. (1995) showed that the unit weight of MSW near the surface of the fill was about 6 kN/m^3 and increased with depth to around 13 kN/m^3 at a depth of 80 m. Fassett et al. (1994) showed that the unit weight of MSW near the ground surface to be approximately 3.53 to 6.47 kN/m^3 and increased with depth to about 12.5 kN/m^3 and remained relatively constant after the depth reached 50 m.

Shear Strength of MSW

The shear strength parameters of MSW are difficult to determine given the wide variety of the type of materials in it and the variation of composition with time due to bio- and/or chemical degradation. The shear strength of MSW has been obtained by large scale direct shear tests or triaxial tests in the laboratory, in-situ direct shear tests, and back-analysis from slope failures. Shear strength parameters available from the literatures are listed in Table 2.

Landva and Clark (1990) conducted large-scale direct shear tests on crushed and shredded MSW in the laboratory and the resultant cohesion and friction angle ranged between 0 to 23 kPa and 24 to 42°, respectively.

Table 2 Shear Strength Parameters of MSW (Sadek and Manasseh, 2004)

Shear Strength Parameters		Literature	Shear Strength Parameters		Literature
c (kPa)	ϕ (°)		c (kPa)	ϕ (°)	
Direct Shear (LAB)			**Back analysis**		
19	42	Landva and Clark (1986)	29	22	Pagotto and Rimoldi (1987)
19	38		78	0	Singh and Murphy (1990)
10	33.6		80	8.5	
16	33	Landva and Clark (1990)	60	15	
19	39		57	3	
22	24		40	13	
35	0	Singh and Murphy (1990)	0	35	
70	20		0	38	
65	3		35	14	
0	38		20	20	
0	42		18	20	
15	31		27	19.5	
0	39		**Misc.**		
0	53		0	35	Martin and Genthe (1993)
0	41	Golder Assoc.(1993)	10	25	Cowland (1993)
7	42	Jessberger et al. (1994)	15	35	Singh and Murphy (1990)
28	26.5		23.5	20	
50	35	Pelkey (1997)	0	35	
27.5	20	Gabr & Valero (1995)	10	23	Fasset et al. (1994)
0	39		10	32	
0	26	Kavazanjian et al. (1999)	7	38	Jessberger et al. (1994)
43	31		0	30	
24	18	Mazzucato et al. (1999)	0	40	
In-situ tests			15	15	Kolsh (1995)
			18	22	
80	0	Singh and Murphy (1990)	5	25	Jones et al. (1997)
100	0	Richardson and Reynolds (1991)	0-50	35	Eid et al. (2000)
10	18		**Triaxial tests(LAB)**		
10	43	Whitiam et al. (1995)	100	0	Gabr & Valero (1995)
10	30		40	0	
22	18.2	Thomas et al. (2003)	16.8	34	(c_u, ϕ_u) (c', ϕ')

Singh and Murphy (1990) determined shear strength of MSW by laboratory tests, in-situ tests, and back-calculation and concluded the shear strength $c = -2.35\phi$ (°)+81±17 kPa. Kavazajian et al. (1995) suggested an MSW shear strength envelop where cohesion is 24.0 kPa and friction angle is 0 when normal stress is less than 30.0 kPa and cohesion is 0 and friction angle is 33° when normal stress is greater than 30.0 kPa.

Eid et al. (2000) concluded from the results of large-scale direct shear tests and back-analysis on landfill slope failure that the cohesion and friction angle of MSW to be 25.0 kPa and 35°, respectively. Furthermore, based on the data presented by Eid et al. (2000), Kavazajian et al. (2001) suggested that when normal stress is greater than 150 kPa friction angle of MSW decreased significantly, such that it is not appropriate to use a straight line for the failure envelope of MSW.

In addition, the stress-strain behavior of MSW is very different from that of soil. Results of triaxial compression tests showed that shear stress continued to increase even after axial strain had already reached 30% (Singh and Murphy, 1990; Machado et al., 2002).

Three-Dimensional Effect of Slope Stability

It is generally believed that the factor of safety resulted from three-dimensional slope stability analysis is often larger than that from two-dimensional analysis. Chang (2005) has quantified the 3D effect of slope stability by the index E_3, which is defined as:

$$E_3 = (F_3 - F_2) / F_2 \qquad (1)$$

where F_2 and F_3 are the factor of safety determined by 2D and 3D stability analysis, respectively. He concluded that 3D effect depends on geometric parameters such as the width to height ratio of the sliding mass, the opening and dipping angles of the slope on the two sides. When the mouth of the slope opens wider than the rest of the slope, 3D analysis gives a smaller factor of safety than 2D analysis. In addition, 3D effect is more pronounced for slopes with width to height ration less than 5 to 10.

METHODOLOGY

Landfills Selected for Study

Two MSW landfills were selected for this study. In-situ direct shear tests and plate load tests were conducted at both landfill, but only the Huko landfill was analyzed for slope stability.

The Huko landfill is located in Hsinchu County. The landfill was in service during 1993 to 2007, which was a year after the in-situ tests were conducted at the site. The Huko landfill covers an area of 3.96 hectare and situated on a mild slope of approximately 10 - 15°. The solid wastes disposed in Huko landfill include MSW and nonhazardous industrial wastes and averaged amount was 40 ton per day.

On the other hand, Chunan landfill is a landfill constructed on flat ground. Concrete and reinforced retaining walls had been constructed as the containing structure of the wastes. The total area of Chunan landfill facility was 31.5 hectare but only a quarter of the area is actually used for disposal of solid wastes. Chunan landfill has been in service since 1987. Nowadays, it only receives around 100 tons of incombustible wastes and 200 tons of nonhazardous industrial waste per day.


(a) General View


(b) Reinforced Retaining Wall at the Toe of Slope

Fig. 1 Huko Landfill


Fig. 2 Chunan Landfill

Physical Properties of MSW

The unit weight of undisturbed MSW samples were measured with a metal sampling box of 500 mm×500 mm×400 mm. Care was taken when trimming samples into the box. Once the samples had been obtained, they were removed from the sampling box and weighed. The samples were taken back to the laboratory to determine their water content.

The compositions of the MSW samples were determined after they were oven dried. Combustible wastes were categorized into plastic, paper, wood and bamboo, and fiber; while non-combustible wastes were categorized into metal, glass, and miscellaneous materials.

In-Situ Tests of MSW

In order to obtain the shear strength parameters of undisturbed MSW samples, large-scale in-situ direct shear tests were conducted. The tests were conducted in accordance with the inclined load direct shear test suggested by ISRM for testing of weak interface of rock (Lama and Vutukuri, 1978; Brown, 1981) and ASTM D4554-90. Four specimens of 800 mm×800 mm×400 mm were sheared under various normal stresses.

Plate load tests were performed to determine the compressibility of the MSW. Steel plate with a diameter of 750 mm was used as the footing. The tests were conducted following the procedures suggested by ASTM D1194-72.

Slope Stability Analysis

The 3D slope stability analysis was carried out with the software program CLARA-W developed by O. Hungr Geotechnical Research, Inc. The program allows the user to choose from the following methods for analysis: Bishop's simplified method, Janbu Simplified, method, Spencer's method, and Morgenstern-Price method.

Four types of 3D failure surface can be selected: ellipsoid, wedge, general, and composite.

RESULTS AND DISCUSSION

Physical Properties of MSW

The unit weight of MSW of Huko landfill ranges between 4.41 – 5.40 kN/m^3 with an average of 5.02 kN/m^3. The most significant component of the wastes is plastics, which accounts for 72% of the total weight.

On the other hand, the average unit weight of MSW of is 6.37 kN/m^3 while the maximum value reaches 7.36 kN/m^3. The most significant component is also plastics, which reaches for 26%. The rest of the portion consists of construction debris, food wastes, household wastes, papers, and miscellaneous materials.

Shear Strength and Deformation Properties of MSW

The stress-strain curves of MSW of Huko and Chunan landfills are shown in Figs. 3 and 4, respectively. The normal stresses labeled in the figures are the normal stresses at the start of the tests. The normal stress at failure was computed as the vertical component of shear force increased as shearing took place. It can be seen that the shear stress kept increasing with the shear strain, especially for MSW specimens subject to lower normal stress. For some specimens the shear stress continued to increase even when the shear strain reached 25%. Part of the increase of shear stress can be accounted for by the elevated normal stress, while the majority of the increase should be the result of continuous compaction of MSW during the shearing process. Since the MSW was very loose, dilatancy effect had not been observed.

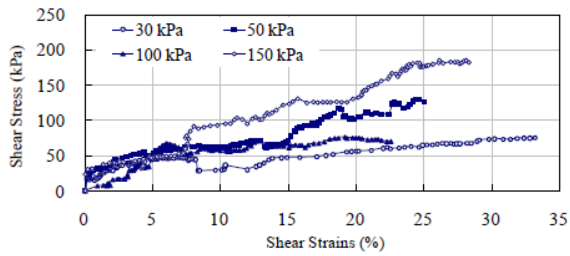


Fig. 3 Stress-Strain Curves of MSW of Huko Landfill

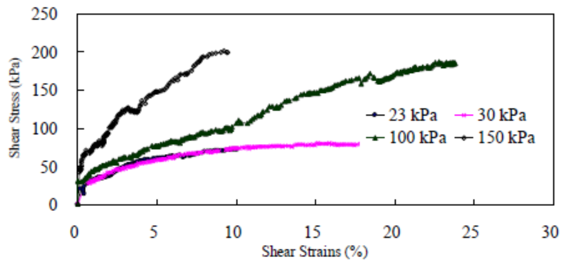


Fig. 4 Stress-Strain Curves of MSW of Chunan Landfill

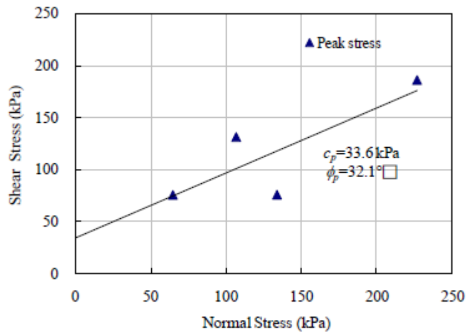


Fig. 5 Failure Envelope of MSW of Huko Landfill

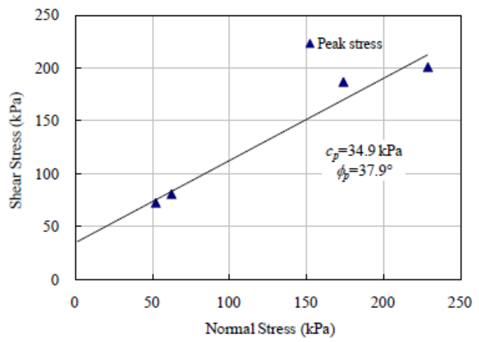


Fig. 6 Failure Envelope of MSW of Chunan Landfill

The Mohr-Coulomb failure envelopes of the MSW are shown in Figs. 5 and 6. The cohesion and friction angles of MSW of Huko and Chunan landfills are 33.6 kPa and 32.1° and 34.9 kPa and ϕ=38.0°, respectively. It is likely that the cohesion is an artifact of linear regression. For linear failure envelopes with zero cohesion, the friction angle of Huko and Chunan MSW are 39.9° and 44.5°, respectively. These shear strength parameters are on the higher side when compared with those tabulated in Table 2.

The load-settlement curves of plate load tests are shown in Figs. 7 and 8. It is difficult to determine the ultimate bearing capacity of the MSW with the relatively linear relationships between settlement and loading. The MSW of Chunan landfill is less compressible and the settlement curve starts to level off after the settlement reached 180 mm. Nevertheless, by following the procedure of data reduction suggested by ASTM D1194 and establish the bearing capacity as loading corresponds to a settlement of 0.5 in., the ultimate bearing capacity, q_u, of MSW of Huko and Chunan landfills are 5.69 and 11.87 kPa, respectively. These bearing capacity values correspond to those of loose sand and soft clay.

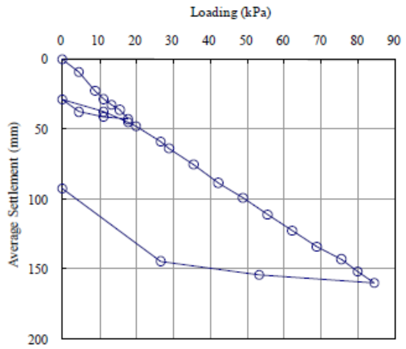


Fig. 7 Load-Settlement Curve of MSW of Huko Landfill

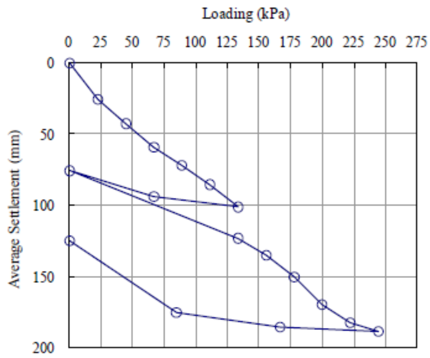
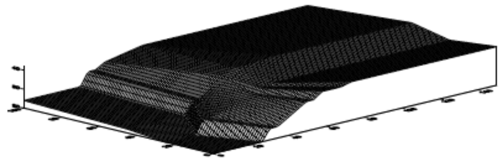


Fig. 8 Load-Settlement Curve of MSW of Chunan Landfill

3D Slope Stability Analysis

The 3D models of the Huko landfill just after construction and before final closure are shown in Fig. 11. The horizontal distance from the geogrid-reinforced retaining wall at the toe of the slope to the top of the slope is approximately 150 m. (Y direction) The width of the landfill is about 100 m (X direction). The maximum height of the MSW approaches 15 m. The height of the retaining wall ranges varied from 6 to 7 m from south to north.

(a) Before Dumping of MSW



(b) After Closure

Fig. 11 3D Model of Huko Landfill

The factor of safety against slope failure were computed by setting the center of the failure ellipsoidal surface at the profile of minimum and maximum slope, which are X = 25 m and X = 50 m (from northern boundary), respectively. Factors of safety for ellipsoidal failure surface of various ellipticity, R_e, which is defined as the ratio of major axis to minor axis (X axis/Y axis), were computed. The shear strength parameters were assumed based on the results of in-situ tests with c and ϕ being 30 kPa and 30°. The unit weight was assumed to be 10 kN/m^3 in order to take the effect of consolidation in the future into account.

As tabulated in Table 3, the steepest cross-section of the landfill has a lower factor of safety. It is also interesting to find that for the X = 25 m cross-section with a rather flat slope 3D analysis gave a lower factor of safety. On the contrary, 3D analysis gave a higher factor of safety for the steepest slope at X = 50 m.

The index E_3 is listed in Table 4. For steeper slopes, the shear resistance at the lateral boundary has a positive effect on the factor of safety. In contrast, for gentler slopes the smaller normal stress on the 3D slip surface might lead to a lower shear resistance and thus a low factor of safety.

Table 3 Factor of Safety against Slope Failure

3D Analysis					
Re \ X	25 m	50 m	Re \ X	25 m	50 m
1.0	2.52	2.67	2.4	2.42	2.72
1.2	2.43	2.64	2.6	2.43	2.72
1.4	2.43	2.64	2.8	2.45	2.70
1.6	2.37	2.66	3.0	2.52	2.69
1.8	2.41	2.66	4.0	2.49	2.68
2.0	2.40	2.69	100.0	2.60	2.60
2.2	2.42	2.71			
2D Analysis	**2.63**	**2.27**			

Table 4 3D Effect on Factor of Safety (E_3)

Re \ X	25 m	50 m	Re \ X	25 m	50 m
1.0	-3.82	17.62	2.4	-7.63	19.82
1.2	-7.25	16.30	2.6	-7.25	19.82
1.4	-7.25	16.30	2.8	-6.49	18.94
1.6	-9.54	17.18	3.0	-3.82	18.50
1.8	-8.02	17.18	4.0	-4.96	18.06
2.0	-8.40	18.50	100.0	-0.76	14.54
2.2	-7.63	19.38			

RESULTS AND DISCUSSION

After conducting large-scale in-situ tests in two MSW landfills in Taiwan and performing slope stability analysis, the following conclusions can be drawn from the results. Firstly, the unit weight of MSW in Taiwan's landfills is in agreement with those obtained in landfills worldwide provided that the MSW characteristics might differ significantly. The shear strength parameters obtained from this study are slightly higher than those found from the literatures. The most likely reasons for the difference could be the high percentage of plastic wastes found in the two landfills and the large shear strain reached in the direct shear tests. Furthermore, the compressibility determined with plate load tests is very large and exhibits a linear load-settlement relationship even at very large settlement. In addition, it is difficult to determine the ultimate bearing capacity from the results of the tests. Finally, 3D effect on factor of safety of slope stability may reach as large as 20%. For landfill cross-sections on steeper slopes, factor of safety of 2D analysis is on the conservative side.

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無衍生研發成果推廣資料

98 年度專題研究計畫研究成果彙整表

計畫主持人：單信瑜	計畫編號：98-2221-E-009-133-
計畫名稱：地下儲槽滲漏監測系統可靠度評估與最佳化設計原則之探討	

<table>
<tr><th colspan="3" rowspan="2">成果項目</th><th colspan="3">量化</th><th rowspan="2">單位</th><th rowspan="2">備註（質化說明：如數個計畫共同成果、成果列為該期刊之封面故事...等）</th></tr>
<tr><th>實際已達成數（被接受或已發表）</th><th>預期總達成數(含實際已達成數)</th><th>本計畫實際貢獻百分比</th></tr>
<tr><td rowspan="12">國內</td><td rowspan="4">論文著作</td><td>期刊論文</td><td>0</td><td>1</td><td>100%</td><td rowspan="3">篇</td><td>題目戰訂為：加油站土壤氣體與地下水基測之有效性評估模擬</td></tr>
<tr><td>研究報告/技術報告</td><td>0</td><td>0</td><td>100%</td><td></td></tr>
<tr><td>研討會論文</td><td>0</td><td>2</td><td>100%</td><td>題目暫訂為：1.地下水位對加油站土壤氣體監測之影響。2.加油站土壤氣體與地下水監測之精確度評估</td></tr>
<tr><td>專書</td><td>0</td><td>0</td><td>100%</td><td></td><td></td></tr>
<tr><td rowspan="2">專利</td><td>申請中件數</td><td>0</td><td>0</td><td>100%</td><td rowspan="2">件</td><td></td></tr>
<tr><td>已獲得件數</td><td>0</td><td>0</td><td>100%</td><td></td></tr>
<tr><td rowspan="2">技術移轉</td><td>件數</td><td>0</td><td>0</td><td>100%</td><td>件</td><td></td></tr>
<tr><td>權利金</td><td>0</td><td>0</td><td>100%</td><td>千元</td><td></td></tr>
<tr><td rowspan="4">參與計畫人力（本國籍）</td><td>碩士生</td><td>0</td><td>2</td><td>100%</td><td rowspan="4">人次</td><td></td></tr>
<tr><td>博士生</td><td>0</td><td>0</td><td>100%</td><td></td></tr>
<tr><td>博士後研究員</td><td>0</td><td>0</td><td>100%</td><td></td></tr>
<tr><td>專任助理</td><td>0</td><td>0</td><td>100%</td><td></td></tr>
<tr><td rowspan="2">國外</td><td rowspan="2">論文著作</td><td>期刊論文</td><td>0</td><td>1</td><td>100%</td><td rowspan="2">篇</td><td>題目暫訂為：Assessment of Performance of Soil Vapor and Groundwater Monitoring for Underground Storage Tanks</td></tr>
<tr><td>研究報告/技術報告</td><td>0</td><td>0</td><td>100%</td><td></td></tr>
</table>

		研討會論文	0	2	100%		論文題目暫訂為：1.Effect of Groundwater Table on Soil Vapor Monitoring of Underground Storage Tanks 2. Assessment of Leak Detection by Soil Vapor and Groundwater Monitoring for Underground Storage Tanks
		專書	0	0	100%	章/本	
	專利	申請中件數	0	0	100%	件	
		已獲得件數	0	0	100%		
	技術移轉	件數	0	0	100%	件	
		權利金	0	0	100%	千元	
	參與計畫人力（外國籍）	碩士生	0	0	100%	人次	
		博士生	0	0	100%		
		博士後研究員	0	0	100%		
		專任助理	0	0	100%		
其他成果 (無法以量化表達之成果如辦理學術活動、獲得獎項、重要國際合作、研究成果國際影響力及其他協助產業技術發展之具體效益事項等，請以文字敘述填列。)		本論文之成果已於環保署環境訓練所之加油站地下儲槽與管線監測訓練班課程中對全國加油站業者講授，並在數個縣市環保局舉辦之加油站土壤與地下水污染講習會中講授，對於加油站業者和顧問公司選擇有效之監測方法有重要之影響。未來將在研討會與期刊發表論文，並與環保署環境檢驗所在未來更新加油站監測辦法和各項監測標準作業方法時討論法規修正方向與條文。					

	成果項目	量化	名稱或內容性質簡述
科教處計畫加填項目	測驗工具(含質性與量性)	0	
	課程/模組	0	
	電腦及網路系統或工具	0	
	教材	0	
	舉辦之活動/競賽	0	
	研討會/工作坊	0	
	電子報、網站	0	
	計畫成果推廣之參與（閱聽）人數	0	

國科會補助專題研究計畫成果報告自評表

請就研究內容與原計畫相符程度、達成預期目標情況、研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性）、是否適合在學術期刊發表或申請專利、主要發現或其他有關價值等，作一綜合評估。

1. 請就研究內容與原計畫相符程度、達成預期目標情況作一綜合評估

■達成目標

□未達成目標（請說明，以 100 字為限）

　　□實驗失敗

　　□因故實驗中斷

　　□其他原因

說明：

2. 研究成果在學術期刊發表或申請專利等情形：

論文：□已發表 ■未發表之文稿 □撰寫中 □無

專利：□已獲得 □申請中 ■無

技轉：□已技轉 □洽談中 ■無

其他：（以 100 字為限）

3. 請依學術成就、技術創新、社會影響等方面，評估研究成果之學術或應用價值（簡要敘述成果所代表之意義、價值、影響或進一步發展之可能性）（以 500 字為限）

本論文之成果已於環保署環境訓練所之加油站地下儲槽與管線監測訓練班課程中對全國加油站業者講授，並在數個縣市環保局舉辦之加油站土壤與地下水污染講習會中講授，對於加油站業者和顧問公司選擇有效之監測方法有重要之影響。未來將在研討會與期刊發表論文，並與環保署環境檢驗所在未來更新加油站監測辦法和各項監測標準作業方法時討論法規修正方向與條文。