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Evaluation of Effectiveness of Soil Gas and Groundwater Monitoring for Underground Storage Tanks

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ABSTRACT

Potential of leakage of a underground storage tank (UST) of gasoline station increases with its service life. In order to avoid serious pollution caused by the dissolution of toxic constituents in LNAPLs (Light non-aqueous phase liquids), 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: LNAPL, underground storage tank, soil vapour monitoring.

1 INTRODUCTION

1.1 UST leakage potential and monitoring

USTs of gasoline stations have been a major source of groundwater contamination in Taiwan. There are more than 2,600 gasoline stations with at least 10,500 USTs nationwide (MOE 2010). The leakage potential of USTs increases with their age. The locations that most likely to leak fuel are dispensers, refilling ports, tanks, and pipeline (Figure 1).

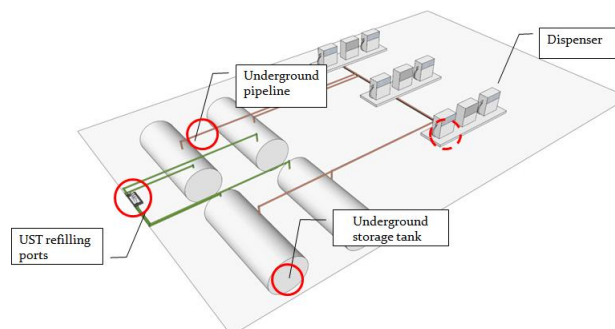


Figure 1. Typical layout of a gasoline station

It is imperative to install proper monitoring system for early detection of UST leakage to control contamination of soil and groundwater. Currently, there are four types of monitoring that are permitted by the regulatory agencies in Taiwan, which are: (1) Soil vapour monitoring, (2) Groundwater monitoring, (3) Tank tightness testing, (4) Interstitial monitoring (TWEPA 2011). Among them, soil vapour monitoring is most widely used due to the relative low cost of installation and monitoring. The vapour monitoring wells must be installed in the UST zone and pipeline zone (TWEPA 2006a). On the longitudinal sides of each UST, there must have at least two vapour monitoring wells. For USTs larger than 60,000 litres, six vapour monitoring wells are required for each tank. The vapour monitoring is conducted monthly. The concentrations of the volatile organic compounds (VOC) are measured with a combustible gas detector and flame ionization detector (FID) or photoionization detector (PID). When

the LEL (Lower Explosive Limit) value is greater than 25% or when the VOC concentrations are greater than 500 ppmV, further investigation is required and, in the meantime, the regulatory agencies must be notified. Soil vapour monitoring cannot be used if the depth to the groundwater table below the gasoline station is less than 2 m.

If groundwater monitoring is selected as the major monitoring method, the depth to groundwater table must be less than 7 m. At least a total of 3 groundwater monitoring wells is required, one installed at the upstream of groundwater flow direction and at least two downstream. The hydraulic conductivity of the soil between the USTs and the monitoring wells must be greater than 0.01 cm/s. If free product is found in the monitoring well or the concentrations of BTEX (Benzene, toluene, ethyl benzene, xylenes) are above the regulatory limits, further investigation is required (TWEPA 2006b).

For gasoline stations with a depth of groundwater table between 2 to 7 m, both soil vapour monitoring and groundwater monitoring are allowed for leak detection monitoring. However, it is difficult to assess the equivalency of the two methods based on their effectiveness or sensitivity of detection of leakage.

1.2 Gasoline vapour transport

Weber and Schuille (1991) simulated the VOC transport in the vadose zone with the software CFEST (Contaminant Finite Element Solute Transport) to evaluate the effectiveness of soil vapour monitoring. The injected vapour for simulating gasoline is a mixture of methane, butane, and trichloroethylene (TCE). For soil vapour monitoring, a rule of thumb is that the time for gasoline to travel 4.5 m (15 ft) is about 15 days (Weber and Schuille, 1991). However, the results of their simulation show that for a leakage rate at 0.2 gal/h in to sand backfill, it takes 9 and 40 days for the VOC vapour to reach a contaminant level of 1% and 10% at the monitoring well 6.7 m (20 ft) away from the leakage source, respectively. In the meantime, when leakage rate is reduced to 0.05 gal/h, the time to reach 1% and 10% at a monitoring well 6.7 m (20 ft) away is 22 days and more than 80 days, respectively.

The results of their simulation show that transport of organic vapour is very slow if the soil in the vadose zone has a low hydraulic conductivity and thus soil vapour monitoring will be less effective. In addition, Weber and Schuille (1991) suggest that in vadose zone of soils of low hydraulic conductivity, the background concentration of VOCs is constantly quite high due to the slow dissipation of small quantity of VOCs enters the vadose zone due to normal operation of gasoline stations.

1.3 Models for LNAPL transport simulation

Currently, the most widely used LNAPL distribution model is the API/Charbeneau model developed by Charbeneau and Chiang (1995) to characterize the vertical distribution of LNAPL. It was later improved and executed as spreadsheets and specialized software (Charbeneau, 2007; Charbeneau and Beckett, 2007). However, it does not simulate transport of vapour and dissolved VOC constituents. There is only very few commercially available software than can simulate multiphase transport, such as 3DFATMIC, MODFLOW-Surfact, T2VOC, and TMVOC. Among them, TMVOC is most versatile. TMVOC belongs to MULKOM family of codes including TOUGH2, TOUGHREACT, T2VOC, and TMVOC, which were developed in the Earth Sciences Division of Lawrence Berkeley National Laboratory. TMVOC simulates three-phase non-isothermal flow of water, soil gas, and a multicomponent mixture of up to 19 species of VOCs in 3D heterogeneous porous media.

Fagerlund and Niemi (2003) simulate the multiphase transport of gasoline in porous media using T2VOC by combining the physical and chemical parameters of 8 constituents they selected. Zandin and Niemi (2006) studied DNAPL transport in heterogeneous porous media while infiltration varied with time by simulation with T2VOC. Kererat and Soralump (2010) evaluated the effectiveness of cut-off wall to impede the migration of benzene with TMVOC. Rasmusson and Rasmusson (2009) used TMVOC to simulate free product recovery by skimmer pumping of a 700 m³ of gasoline and the results were in reasonably good agreement with field data.

2 UST LEAKAGE SIMULATION

2.1 Modelling gasoline station with TMVOC

The gasoline station modelled for TMVOC simulation is 40 m x 40 m (X and Y direction) in area and the depth is 10 m (Z direction) (Figure 2). Four scenarios of leakage modelled are shown in Figure 3. There are 4 55,000 litre underground storage tanks of 3 m x 3 m x 8.2 m buried at 1 m below the ground surface. Three cases of depths of groundwater table were studied, which are 2 m, 3 m, and 5

m, respectively. The monitoring points are the locations of concentration of VOC vapour and dissolved VOCs computed. The vapour concentration from ground surface to a depth of 2.5 m is averaged to represent the results that can be obtained by FID or PID measurement. On the other hand, the VOC concentration above 6 m to the groundwater table is averaged to represent the values that are determined by groundwater sampling and analysis. In order to minimize the boundary effect, the total area modelled is 120 m x 120 m with the gasoline station in the middle. Below the gasoline station, the vadose zone and aquifer close to the groundwater table is discretised as 1 m (X) x 1m (Y) x 0.5 m (Z) grids, the grids in the zone outside the gasoline station are set larger to save computation effort.

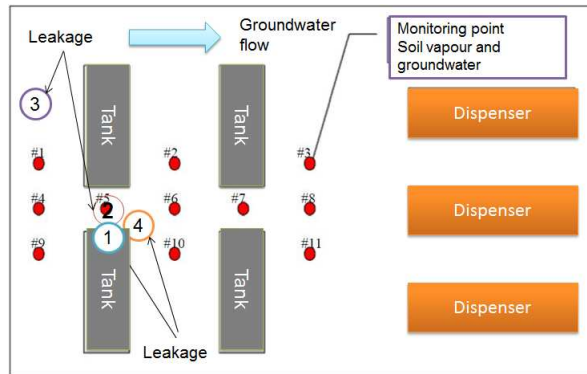


Figure 2. Layout of the model gasoline station

In most cases, USTs' gasoline leakage rate ranges from 10 L/day to 100 L/day. The regulation in Taiwan requires the monitoring system to have a sensitivity of 0.2 gal/hr (4.8 gal/day) (TWEPA 2011). In this study, a leakage rate of 5 gal/day (18.93 L/day) is assumed. The total time of leakage simulated is one year. Four scenarios with different points of leakage is simulated (Figure 3).

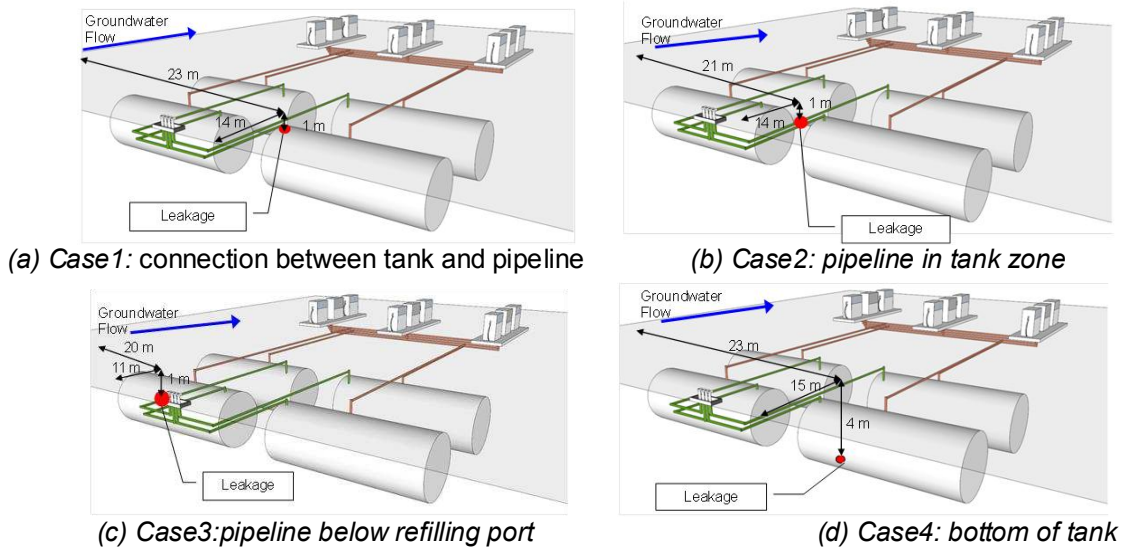


Figure 3. Scenarios of leakage simulated

2.2 Properties of soil and gasoline

The same geological material is assumed for the vadose zone and the aquifer. The porosity is assumed to be 0.3. Two intrinsic permeability values assumed for studying the effect of hydraulic conductivity, which are $2.5 \times 10^{-12} \text{ m}^2$ and $2.5 \times 10^{-13} \text{ m}^2$, respectively. The equivalent hydraulic conductivity, k_h , is thus 2.74×10^{-3} and $2.74 \times 10^{-4} \text{ cm/s}$, respectively. The intrinsic permeability in the vertical direction is set to 1/5 of those in horizontal direction. A hydraulic gradient of 0.005 is imposed by setting constant head boundaries at the upstream and downstream side of the site. Stone's relative permeability model and Parker's capillary-suction model are selected from a group of models available in TMVOC to describe the multiphase retention and flow of air, water, and gasoline. The parameters

are listed in Table 1, where S_{wr} , S_{nr} , and S_{gr} are residual liquid content of water, NAPL, and gas phase, respectively. The gasoline is simulated as a mixture of 8 major organic compounds (Table 2).

Table 1: Parameters for Stone's model and Parker's model

Stone's model	S_{wr}	S_{nr}	S_{gr}	n exponent
Parameter value	0.1	0.05	0.05	3
Parker's model	S_m	α_{gn}	α_{nw}	n exponent
Parameter value	0	100	110	1.84

Table 2: Composition of gasoline simulated

Group	Compound	Composition (%)
Ether	MTBE	18
Aromatics	benzene	3.5
	ethyl benzene	5.5
	toluene	7
	xylene	1.5
Aliphatic - straight chain	heptane	20
Aliphatic - branched	isooctane	20
Aliphatic - cyclic	cyclopentane	24.5

3 RESULTS AND DISCUSSION GUIDELINES ON REFERENCING

For all cases simulated, the time soil vapour and groundwater to reach regulatory limit is listed in Table 3. The effect of depth of groundwater table is best demonstrated by the results of case 2, where gasoline is free to migrate downward and along the direction of groundwater flow. However, since monitoring point #5 is located where leakage occurs in case 2, the discussion will exclude its data. For sand backfill with a permeability of $2.5 \times 10^{-11} \text{ m}^2$, when the depth of groundwater table is at 2 m, it takes 45 days for VOC vapour to reach 500 ppmV in monitoring well #6 which is 3 m downstream. When the groundwater table is at 3 m or 5 m deep, the time to reach 500 ppmV are 50 and 61 days, respectively. Obviously, VOC vapour will be more concentrated when the groundwater table are higher and the space for VOC to migrate is smaller. On the other hand, it takes 102 and 180 days for benzene concentration in the groundwater to reach the regulation limit of 0.05 mg/L for groundwater table of 2 m and 3 m, respectively. It can be seen in Figure 4 that even when groundwater table is 2 m deep, the LNAPL plume had just reached the groundwater the 180 day. For the groundwater located 5 m deep, the LNAPL was still far above it after 180 days.

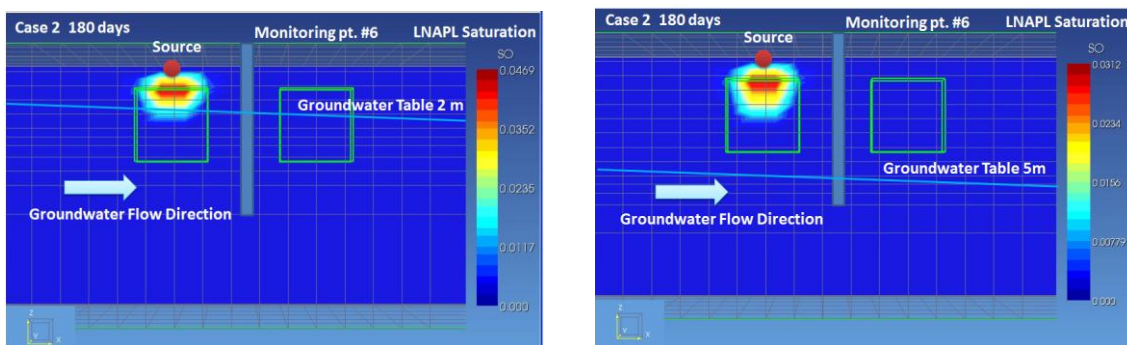


Figure 4. LNAPL saturation on day 180 in case 2

If k_h of backfill material increases 0.01 cm/s which is required by the regulation, it is possible that the benzene concentration in groundwater sampled from monitoring well #6 might reach 0.05 mg/L within 25 days and 45 days, for groundwater table of 2 m and 3 m, respectively. Although VOC vapour migration is driven by diffusion and not affected by k_h , the increased area of floating LNAPL will shorten the time for VOC vapour to migrate so that it also becomes more effective.

If the permeability is reduced to 1/10, the time for VOC vapour to reach 500 ppmV increases to 140, 160, and 230 days, respectively. Since the VOC vapour migration is driven by diffusion, it is likely that if the monitoring well is 1.5 m away from the leakage, the time for VOC vapour to reach 500 ppmV could be about 20 days.

The location of the leakage plays a significant role on the migration of LNAPL and its vapour. It can be seen in Figure 5 that for LNAPL leaks from above the tank (Case 1), the liquid will find its way to flow around and then downward along the side of the tank. Regardless of the depth of groundwater table,

vapour concentration in monitoring well #5 adjacent to the leakage will reach 500 ppmV within 30 days for sand backfill with a permeability of $2.5 \times 10^{-11} \text{ m}^2$ (Table 3). However, since the LNAPL accumulates on top of the tank, it is difficult for groundwater monitoring to detect the leakage even at high groundwater table condition. For case 3 where the leakage locates at the refilling port, the pattern of VOC vapour migration and dissolved VOC plume is similar to case 1. VOC vapour and groundwater monitoring by monitoring point #1 should be effective to detect the leakage within reasonable time even though the monitoring well is not at the downstream of the leakage.

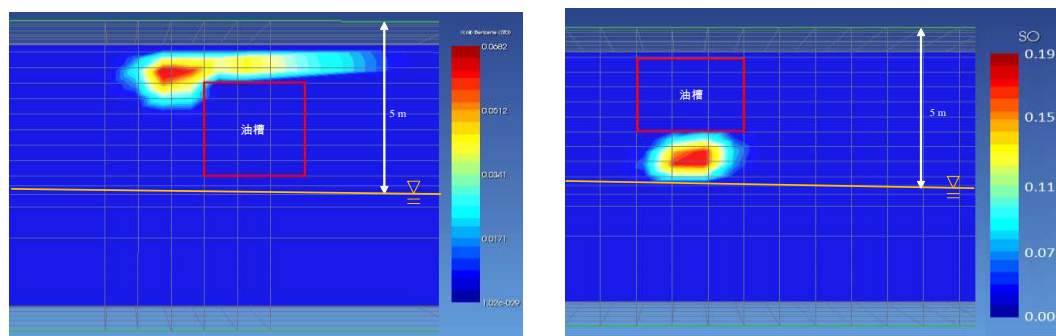
Table 3: Time to reach VOC vapour and benzene concentration limit in monitoring wells

		Monitoring location #1				Monitoring location #4			
Case	Ground water Table (m)	Time for soil vapour to reach 500 ppmV (day)		Time for benzene concentration to reach 0.05 mg/L (day)		Time for soil vapour to reach 500 ppmV (day)		Time for benzene concentration to reach 0.05 mg/L (day)	
		$K (\text{m}^2) 2.5 \times 10^{-12}$	$K (\text{m}^2) 2.5 \times 10^{-11}$	$K (\text{m}^2) 2.5 \times 10^{-12}$	$K (\text{m}^2) 2.5 \times 10^{-11}$	$K (\text{m}^2) 2.5 \times 10^{-12}$	$K (\text{m}^2) 2.5 \times 10^{-11}$	$K (\text{m}^2) 2.5 \times 10^{-12}$	$K (\text{m}^2) 2.5 \times 10^{-11}$
Case1	2	-	-	-	-	310	76	-	-
	3	-	-	-	-	-	100	-	-
	5	-	-	-	-	-	93	-	-
Case2	2	-	130	-	-	120	45	-	-
	3	-	205	-	-	180	80	-	-
	5	-	-	-	-	178	80	-	-
Case3	2	110	35	146	98	-	89	200	110
	3	110	40	-	180	-	120	-	350
	5	160	47	-	365	-	180	-	-
Case4	2, 3	-	-	-	-	-	-	-	-
	5	-	-	-	-	-	-	-	90
		Monitoring location #5				Monitoring location #6			
Location of Leak	Ground water Table (m)	Time for soil vapour to reach 500 ppmV (day)		Time for benzene concentration to reach 0.05 mg/L (day)		Time for soil vapour to reach 500 ppmV (day)		Time for benzene concentration to reach 0.05 mg/L (day)	
		$K (\text{m}^2) 2.5 \times 10^{-12}$	$K (\text{m}^2) 2.5 \times 10^{-11}$	$K (\text{m}^2) 2.5 \times 10^{-12}$	$K (\text{m}^2) 2.5 \times 10^{-11}$	$K (\text{m}^2) 2.5 \times 10^{-12}$	$K (\text{m}^2) 2.5 \times 10^{-11}$	$K (\text{m}^2) 2.5 \times 10^{-12}$	$K (\text{m}^2) 2.5 \times 10^{-11}$
Case1	2	46	23	-	-	300	80	-	-
	3	60	28	-	-	-	103	-	-
	5	70	33	-	-	-	130	-	-
Case2	2	1	1	102	85	140	45	140	102
	3	1	1	238	117	160	50	-	180
	5	1	1	-	-	230	61	-	-
Case3	2	-	185	300	118	-	200	-	120
	3	-	200	-	-	-	320	-	-
	5	-	-	-	-	-	-	-	-
Case4	2	-	-	-	-	-	-	-	-
	3	-	-	89	63	300	80	-	-
	5	-	-	200	90	-	103	-	-
		Monitoring location #7				Monitoring location #10			
Location of Leak	Ground water Table (m)	Time for soil vapour to reach 500 ppmV (day)		Time for benzene concentration to reach 0.05 mg/L (day)		Time for soil vapour to reach 500 ppmV (day)		Time for benzene concentration to reach 0.05 mg/L (day)	
		$K (\text{m}^2) 2.5 \times 10^{-12}$	$K (\text{m}^2) 2.5 \times 10^{-11}$	$K (\text{m}^2) 2.5 \times 10^{-12}$	$K (\text{m}^2) 2.5 \times 10^{-11}$	$K (\text{m}^2) 2.5 \times 10^{-12}$	$K (\text{m}^2) 2.5 \times 10^{-11}$	$K (\text{m}^2) 2.5 \times 10^{-12}$	$K (\text{m}^2) 2.5 \times 10^{-11}$
Case1	2	-	160	-	220	255	50	-	190
	3	-	190	-	-	260	63	-	310
	5	-	-	-	-	258	73	-	-
Case2	2	-	120	180	105	-	80	330	120
	3	-	165	-	350	-	100	-	210
	5	-	-	-	-	-	160	-	-
Case3	2, 3, 5	-	-	-	-	-	-	-	-
Case4	2, 3	-	-	-	-	-	-	-	-
	5	-	-	-	101	-	-	107	60

"-": Vapour concentration or benzene concentration lower than regulation limits

For case 4 where LNAPL leaks from the bottom of the tank, it is difficult for soil vapour monitoring to detect leakage even when the groundwater table is 5 m deep. Since the effective length of soil gas

wells are about 2.5 m long, the vapour takes 80 days to reach 500 ppmV in monitoring well #6. On the other hand, groundwater sample taken from monitoring well #5 will reach 0.05 mg/L in 63 days. When the groundwater table is 5 m deep, since more LNAPL is free to migrate downward the vapour accumulation in monitoring wells takes even longer and groundwater monitoring is more effective.



(a) Case 1 vapour distribution (GWT 5 m) (b) Case 4 LNAPL saturation (GWT 5 m)
Figure 5. Effect of leak location on LNAPL distribution pattern

4 CONCLUSION

Based on the results of the simulation and discussion, the following conclusions can be made:

1. Both soil vapour and groundwater monitoring are more effective when the groundwater table is higher. The concentration of VOC vapour increases faster when groundwater table is higher.
2. Both soil vapour and groundwater monitoring are more effective in backfill soil with higher permeability.
3. For leakage from the top or bottom of the tank where the path of vapour diffusion and LNAPL migration is obstructed, efficiency of both vapour monitoring and groundwater monitoring is reduced. More monitoring wells are required to ensure effective monitoring.
4. In general, the impact of the location of the leakage is more significant than the depths of groundwater table and permeability on the effectiveness of leakage monitoring. Increasing the number of monitoring wells is the best way to enhance effectiveness of monitoring.
5. TMVOC is a powerful and appropriate tool for simulating LNAPL multiphase transport, however, the selection of parameters is a difficult task. Modelling efficiency could also be improved.

5 ACKNOWLEDGEMENTS

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REFERENCES

- Mistry of Economy. (2010) Gasoline station statistics. <<http://www.moeaboe.gov.tw/>> (Dec. 31, 2011).
- Taiwan Environmental Protection Administration (TWEPA). (2011) "Codes on management and monitoring of underground storage tanks" (in Chinese) <<http://ivy5.epa.gov.tw/epalaw/index.aspx>> (Dec. 31, 2011)
- Taiwan Environmental Protection Administration (TWEPA). (2096a) "Stand procedure for soil vapour monitoring of underground storage tanks" (in Chinese) <<http://ivy5.epa.gov.tw/epalaw/index.aspx>> (Dec. 31, 2011)
- Taiwan Environmental Protection Administration (TWEPA). (2006) "Stand procedure for groundwater monitoring of underground storage tanks" (in Chinese) <<http://ivy5.epa.gov.tw/epalaw/index.aspx>> (Dec. 31, 2011)
- Weber, D. and F. Schwill. (1991) "Passive vapor monitoring of underground storage tanks for leak detection." *Environmental Monitoring and Assessment*, 16, 99-116
- Fagerlund, F. and A. Niemi. (2003) "Multi- constituent modeling of a gasoline spill using the T2VOC numerical simulator." Lawrence Berkeley National Laboratory Berkeley, California
- Zandin, H. and A. Niemi. (2006) "A modeling case study of napl transport in porous medium under the influence of variable water infiltration and geological heterogeneity." Department of Earth Sciences, Uppsala University, Sweden
- Kerarat, C. and S. Soralump. (2010) "Modeling of organic contaminant migration through soil cement barrier using TMVOC" The 17th Southeast Asian Geotechnical Conference, Thailand
- Noonan, D. C. and J. T. Curtis. (1990) "Groundwater Remediation and Petroleum: A guide for underground storage tanks." Lewis Publishers, Chelsea, MI.
- Charbeneau, R.J., Chiang, C.Y. (1995) "Estimation of free hydrocarbon recovery from dual-pump systems." *Ground Water* 33 (4), 627-634.

- Charbeneau, R.J. (2007) "LNAPL distribution and recovery model. distribution and recovery of petroleum hydrocarbon liquids in porous media vol. 1." API Publication 4760. API Publications, Washington, DC.
- Charbeneau, R.J., Beckett, G.D. (2007) "LNAPL distribution and recovery model. user and parameter selection guide, vol. 2." API Publication 4760. Publications, Washington, DC.
- Rasmusson, K., and M. Rasmusson. (2009) "NAPL spill modelling and simulation of pumping remediation." Master Thesis, Department of Earth Sciences, Air, Water and Landscape Science, Uppsala University, Villavägen 16, SE-752 36 Uppsala Sweden. ISSN 1401-5765