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A Proposed Lined Efficient Monitoring System for Landfill Gas Migration - A Comparative Study on Mid Auchencarroch's Experimental Emissions and Computational Flux Data for Environmental Protection

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Abstract : A risk assessment computational base for the proper monitoring of landfill gas migration control is presented, avoiding any associated risks next to landfill boundaries. A quantitative spatial analysis is presented for landfill gas advection velocity's variations, based on the field data of Mid Auchencarroch experimental landfill project. In this paper, are investigated the spatial dynamic thresholds of landfill migration quantities with the aid of comparative computational flux data. The presented results are useful for the proper efficiently lined and maintained biogas monitoring control system in order to avoid any associated environmental impacts protecting flora, fauna, anthropogenic properties and public health.

Key words : risk analysis; solid waste management; landfill gas; environmental impact assessment; numerical modeling; spatial analysis; lining methods; public health.

Introduction

Nowadays, innovative monitoring systems and synthesizing information are necessary not only for the environmental protection of our planet but also for the sustainable development of our community (Cairns, 2006, 2007; Vlavianos, 1991). Waste management is the discipline that is concerned with resources once society no longer requires them. It is necessary to manage the waste in an sustainable way by minimizing the environmental impacts related to waste. Solid waste disposal starts to be problem when the amount and the environmental impacts of such disposal arise and become an environmental public health hazard. Then the improvement of the management solid waste systems on a monitoring and spatial diagnosis base is necessary (Koliopoulos *et al.* 2007c; Kollias, 2004; Skordilis, 2001; Tchobanoglous *et al.* 1993).

Although the operation of efficient waste management and control systems is semantic, the environmental awareness campaigns should be organized to the public information. Therefore, in such cases there will be a public support to the installation of any necessary monitoring systems and efficient eco-designs for the sustainable development of our society.

Risk assessment tools are necessary not only to protect building properties and environmental sustainable projects but also to set up efficient monitoring control systems. Spatial numerical diagnostic tools, and

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accurate, rapid in execution lining methods of technical manufactures should take place for the maintenance and control of particular monitoring systems, developing associated databases, solving effectively associated engineering problems and protecting public health (Koliopoulos, 2000; Koliopoulos *et al.* 2007c; Brimicombe, 2003; Chivers and Sleightholme, 2005).

This paper presents the installation and proper lining of a monitoring network based on the results of a numerical risk assessment model, taking into account Mid Auchencarroch's experimental landfill field data. This paper also analyzes an environmental impact assessment base of landfill gas (LFG) migration to environmental resources and anthropogenic properties, like farms, agro-tourism's activities, agricultural or veterinary regional units that are commonly located next to landfill boundaries. The Mid Auchencarroch experimental landfill was a UK Environment Agency (EA) and industry-funded research facility (Koliopoulos, 2000; Koliopoulos and Fleming, 2002; Koliopoulos and Koliopoulus, 2007a,b).

The use of controlled anaerobic batch bioreactors keeps waste mass temperature at low levels and so minimizes the risks associated with LFG migration, like gas explosions, fires and others (Derby Evening Telegraph, 1986; DOE, 1989, 1995; Koliopoulos, 2000). Any uncontrolled dumps have to close so as to avoid any threats to the public (Canter, 1996; Davis and Cornwell 1998; Elliott *et al.* 2001; Friis and Sellers 2004; Lawrence, 2003).

Gases found in landfills include methane (CH_4), carbon dioxide (CO_2), carbon monoxide (CO), hydrogen (H_2), hydrogen sulfide (H_2S), nitrogen (N_2), oxygen (O_2) and trace gases. The anaerobic phase is the main phase, occupying the greater part of the life of the landfill. This phase is more significant in terms of methane gas formation. Methane production in landfills can be optimized by temperature control (Koliopoulos and Koliopoulou, 2007a).

For the efficient monitoring and control of landfill emissions' migration should be taken into account the geological properties and the topography next to landfill boundaries collecting all the necessary data for proper risk analysis and lining of monitoring control systems (Koliopoulos, 2000).

Material and Methods

This paper analyzes the modeling of landfill gas migration thresholds in time and the proper lining of monitoring boreholes based on field data of Mid Auchencarroch (MACH) experimental landfill project. MACH site is located next to Alexandria area, between the Loch Lomond and Kilpatrick hills outside from Glasgow city, in Scotland. It has been constructed in order to assess a number of techniques that promote sustainable landfill design. MACH experimental landfill, is an Environment Agency, DTI and industry funded research facility. MACH experimental batch anaerobic landfill bioreactor has been capped since November 1995. The experimental variables are waste pretreatment, wet biomass pulverization, leachate recirculation and co-disposal with inert material. The experimental landfill Mid Auchencarroch is a field scale facility which is consisted of four cells each of nominal volume 4,200 m^3. MACH experimental project examines techniques so as to enhance the waste degradation, pollutant removal processes and control of landfill emissions (Koliopoulos, 2000; Koliopoulos and Kolipoulou, 2007a,b).

The MACH experimental landfill project has presented a number of waste management techniques that accelerate waste biodegradation and heat generation, minimizing the associated environmental impacts of landfill emissions (Koliopoulos and Koliopoulou, 2007a,b). The wet-flushing sequential batch bioreactor landfill model is seen as the method of achieving the goal of sustainable development avoiding any long term biogas or leachate hazardous thresholds.

Experimental results - Potential landfill gas concentration thresholds

For MACH the higher temperature in the waste mass is taken at the landfill mid-depth. A multi comprehensive robust spatial dynamic risk management numerical model for the simulation of biogas risk (SIMGASRISK), has been presented in the literature, which simulates the particular landfill biodegration stages; calculates the produced biogas emissions and provides the grades of landfill gas migrated risk quantities (Koliopoulos, 2000; Koliopoulos *et al.* 2007). Comparing the MACH's experimental field data and the numerical results, it was clear that the particular SIMGASRISK's numerical modules operate efficiently, giving satisfactory results (Koliopoulos *et al.* 2007). The output results could be saved in data files, which can be easily manipulated by the user, applying them in several types of digital spatial databases for further comprehensive spatial system dynamic analysis, taking any associated hazards' confrontation works in time, based on any particular topographical characteristics (Koliopoulos, 2000; Brimicombe, 2003).

The experimental field data from Mid Auchencarroch batch experimental bioreactor show that waste biodegradation has been achieved in a short time, minimizing any long term associated landfill emissions' risks to natural resources or to anthropogenic properties (Koliopoulos and Koliopoulos, 2007a,b). Any uncontrolled dumps or landfills with high putrescible waste fractions should close to prevent plant asphyxiation, landscape degradation, flora and fauna degradation, gas explosions, landfill fires and other associated impacts next to anthropogenic properties.

Based on the biomass's peak temperature and production, can be calculated the landfill gas migration by advection velocity, with discussion of associated risks and environmental impacts. A numerical modeling fast solution scheme of heat transfer in porous media could be realized for the lateral temperature regime in one meter clay width next to landfill boundaries, assessing probable gas migration spatial flows (Koliopoulos and Koliopoulou, 2007b). The governing equation of this phenomenon in four dimensions, 3-D in space and 1-D in time, is described by the partial differential equation (1), which is presented below:

$$\frac{\partial U(x,y,z,t)}{\partial t} - \beta \frac{\partial^2 U(x,y,z,t)}{\partial x^2} - \beta \frac{\partial^2 U(x,y,z,t)}{\partial y^2} - \beta \frac{\partial^2 U(x,y,z,t)}{\partial z^2} = \alpha \qquad \text{.........} \ (1)$$

where

$\beta = k/\rho C_\upsilon$

k	thermal conductivity (kcal/day m ^{o}C)
ρ	density (kg/m^3)
Cu	heat capacity (kcal/kg ^{o}C)
U	temperature in spatial (x,y,z) location in clay material (^{o}C)
t	time (day)
x, y, z	spatial location in x, y, z axis (m)
α	heat generation source term from landfill mass material (kcal/m^3 day)

The numerical solution of the above governing equation gives higher temperature inclination in the middle of the examining clay barrier, taking into account the temperature boundaries conditions next to the landfill mass in one meter width of a homogenous clay barrier and as height the landfill depth (Koliopoulos and Koliopoulou, 2007b).

Taking into account the particular chemical and physical properties of the surrounded landfill ecosystem, the calculation of the biogas migration advection velocity adjacent to landfill boundary can be calculated and magnitudes' ranges of it in relation to peak biogas production gas pressure and geotechnical porous media properties (Koliopoulos and Koliopoulos, 2007b; Brewiz and Rothfuchs, 2000). At each examining landfill site, based on its topographical, geometrical elements, an effective influence vertical area zone should be taken into account for the batch bioreactor cells' biogas flux migration bearing in mind particular spatial conditions and waste material properties (i.e. cracks, dynamic loads, effective heights and lengths along biogas migration pathways). Therefore, a high risk for gas explosions and damage to properties under unfavorable conditions exists at sites with high biogas production, low waste density and respective landfill gas pressure.

Monitoring boreholes should be located next to landfill boundaries to allow measurement of landfill emissions and proper remedial action. In this way, buildings, other anthropogenic properties and surrounding landscapes will be protected. The uses of dynamic models, like SIMGASRISK one, are necessary not only to model, analyze and to maintain the biomass biodegradation of efficient bioreactor designs but also to diagnose particular produced landfill emissions and properly monitor, control them.

However, another risk analysis stage is to determine the proper locations for the lining of an efficient monitoring control system for biogas emissions' adjacent to landfill boundaries. Several efficient lining methods and maintenance certification methods of manufactures can be realized bearing in mind particular topographies, structural properties and landfill boundary locations (Kaparis, 1993; Koliopoulos *et al.* 2007c). The problem is transferred to the right location of the migrated landfill gases' monitoring boreholes so as to line properly any necessary confrontation works and to take the right measures with good timing next to landfill boundaries.

During the lining of landfill boundaries should be taken into account the surrounded existing areas of ecosystems, land uses and other anthropogenic activities which are taking place there. The latter anthropogenic properties should be protected by an efficient lined monitoring control system of landfill gas migration and probable biogas pumbing system. This could be achieved as a result of an additional computational risk assessment spatial analysis, which is analyzed below.

The associated risk assessment's spatial analysis could provide the right solution to the examining problem analyzing the particular factors and parameters which affect on it. Hence the thresholds of migrated landfill gas could be calculated by the solution of the diffusion-advection biogas's flux in a porous medium problem, which is described by the following equation (2).

$$R\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} - V\frac{\partial C}{\partial x} \quad \text{......... (2)}$$

where,

- *C* gas concentration by volume
- *x* the distance along the migration pathway (m)
- *t* is time (s)
- *D* the diffusion coefficient (m^2/s)
- *V* velocity (m/s)
- R the retardation factor

The analytical solution of equation (2) could be given by the following presented formula (3) (Van Genuchten *et al.* 1982):

$$\frac{C}{C_o} = \frac{1}{2}\operatorname{erfc}\left[\frac{Rx - vt}{2\sqrt{DRt}}\right] + \frac{1}{2}\left[\frac{vx}{D}\right]\operatorname{erfc}\left[\frac{Rx + vt}{2\sqrt{DRt}}\right] \quad \text{......... (3)}$$

where

- *Co* equals to 1
- *erfc* complimentary error function
- *R* the retardation factor, equals to 1 for the case of LFG interacting with the ground
- *V* velocity (m/s)
- *D* gas diffusion coefficient (m^2/s)
- *t* time (s)

Moreover, according to the literature and field data measurements (Williams *et al.* 1999) an estimation is made for the calculation of lateral distance of biogas migration and probable explosions next to landfill boundaries as it is presented in Table 1, assuming that the threshold of 0.1 biogas concentration by volume will take place in t years since gas was migrated from landfill boundaries and taking constant the values of the advection velocity and diffusion coefficient. Some times due to the anisotropic complex nature of the geological strata adjacent to landfill boundaries there are cases that are difficult to be monitored by gas probes the threshold of 0.1 biogas concentration by volume. Hence, in such latter cases it is preferable for safety reasons to investigate firstly the calculated threshold of 0.5 biogas concentration by volume, as in many real relative cases the respective measured real threshold value is more than the half magnitude of the respective calculated one. Afterwards, the next step is to line a dense monitoring network for further biogas migration control, setting up primary and secondary risk assessment distances of lateral biogas migration, as it is presented below in Table 1, taking into account several scenarios of particular landfill properties and adjacent ground spatial conditions, which are applied to the above presented equations. The variation of the advection velocity, which is presented in Table 1, is based on MACH experimental site emissions and on the respective numerical SIMGASRISK modules' operation (Koliopoulos and Koliopoulou, 2007 b).

The retardation factor R describes the interaction of ground with biogas and according to the bibliography, the retardation factor R equals to 1, in the case of landfill gas flow in the soil porous media (Williams *et al.* 1999). However, the biogas diffusion coefficient D in the porous medium is related to the porosity Φ of the porous medium and to the gas diffusion of the biogas in air $Do = 1.7\ 10^{-5}$ (m^2/s), by the following equation (4) (Williams *et al.* 1999):

$$\frac{D}{D_o} = \Phi^{1.33} \qquad \text{......... (4)}$$

Hence, according to the above, solving the diffusion - advection differential equation it yields the investigated risk assessment distances. A monitoring control system of probable biogas migration should take place along and across the above calculated threshold distances in Table 1. The proper lining of an efficient and economic monitoring control

Table 1 : Computational risk assessment results of the lateral landfill gas flux adjacent to landfill boundary

Advection velocity (m/s)	Time (years)	Porous medium's Φ porosity	Gas diffusion coefficient (m2/s)	Distance (m) for the lining of the primary monitoring network	Distance (m) for the lining of the secondary monitoring network
3 E -7	6	0.4	0.5 E -5	58	112
1 E -7	6	0.4	0.5 E -5	28	80
1.5 E -7	6	0.4	0.5 E -5	36	86
1.5 E -7	6	0.3	0.3 E -5	33	75
1 E -7	10	0.1	0.8 E -6	31	59
2 E -7	4	0.2	0.2 E -5	29	54
3 E -7	3	0.4	0.5 E -5	31	54

system under stable conditions is discussed below in the next section of this paper.

Discussion

LFG migration can be recognized by the adverse impacts on vegetation quality that is developed on the top soil cover next to the boundaries of a landfill. The emission of LFG can exclude oxygen from the root zone of vegetation and thus lead to vegetation damage, provoking a non proper vegetated area with several sequential environmental impacts to flora, fauna, human food chain and public health. The principal hazard of concern with LFG emissions is the potential for explosion of methane. The lower explosive limit for methane is about 5%; methane in concentrations above about 5% in air is explosive. There have been numerous case studies reported of bad odours, explosions next to landfill boundaries with human injuries and loss of anthropogenic properties. There have also been numerous examples of underground migration of LFG to nearby properties and sufficient accumulation of LFG in buildings to become an explosive mixture, which could be set off by a spark (Derby Evening Telegraph, 1986; DOE, 1989, 1995). In such cases several spatial investigations and environmental impact assessments should take place for the proper lining of the particular confrontation works to the associated hazards (Canter, 1996; Davis and Cornwell 1998; Friis and Sellers 2004; Elliott *et al.* 2001).

However, based on the computational results of Table 1 is clear that the spatial threshold of 5% methane by volume is mainly dependent on porosity, gas diffusion coefficient and the magnitude of the advection velocity. The latter computational scenarios in Table 1 are indicative for the examining data and they should be verified by the particular in-situ measurements and in collaboration with the Local Authorities.

The lining of a dense monitoring system in space and frequent samples of landfill emissions in time should take place next to landfill boundaries. An initial investigation grid of boreholes should be installed at 5-10 m along adjacent to landfill boundary and on the particular distanced threshold locations should be installed monitoring gas probes at 10-20 m across distances respectively. According to Table 1, for both risk assessment distances (the primary and secondary one) an initial investigation mesh of 10-20 m by 10-20 m should be installed, taking into account the insitu geotechnical and topographical properties next to landfill boundaries. A proper biogas suction pumping network supported by renewable resources should operate, when it is necessary, in order to adverse gas migration.

Table 2 : Actions which should be taken for the confrontation of associated environmental impacts and risks by landfill's emissions

- Odors – Dumping & Landfill Gas – for Aesthetics, Public Health protection move any surrounded affected land uses to other safe areas;
- Migration of Methane, Carbon Dioxide and V.O.C's – for Public Health, Explosions, Toxicity to Plants, Landscape degradation, Loss of Building Properties do not operate any agricultural, veterinary or other anthropogenic activities along the risk distances adjacent to landfill boundary;
- Environmental Impact's minimization - develop and operate boreholes, pumping network at the monitoring zone next to landfill boundaries;
- Landfill Fires – Gas Explosions – for Aesthetics and Public Health protection, develop and operate a proper lined fire brigade system according to landfill topography.

The above presented risk assessment's spatial analysis and proper lining monitoring control system should take place for the avoidance of LFG explosions or any associated risks. Proper quantification of LFG risks so as to take the right timing should be realized by the development and use of efficient dynamic numerical modules like it was presented above. Several actions which should be taken in time so as to avoid any associated risks and environmental impacts are presented in Table 2.

The problems of explosive conditions, which are developed by methane emissions from landfill sites should be avoided by the proper operation of LFG collection pump systems. The operation of biogas pumps is necessary for the avoidance of gas migrations and explosions in particular cases (i.e. landfill slope stability collapse; foundations' settlements or deformation; failure of clay barriers at landfill boundaries due to several accidents flood, storm, earthquake, fire etc.). Pumps' operational costs could be minimized by the consumption of electricity from renewable resources (i.e. photovoltaic units and wind or hydrodynamic generators) instead of oil unsustainable fuel's generator consumption.

More field data, case studies and spatial computational risk assessment models are necessary so that optimize landfill design's monitoring and maintenance principles. This will cause control of pollutants protecting the ecosystems, public health and exploitation of emissions for regional development. The installation of a monitoring network next to landfill boundaries according to the guidelines, which were presented above, will be useful so as to: control better landfill's life cycle design and migrated pollutants' behaviour in time on a given topography; communicate with the responsible Local Authorities; take the right spatial risk management actions in time; collect necessary data for efficient lining of proper reclamation works; proper maintenance design in time, safe control, right confrontation and efficient bioremediation of landfill emissions.

Conclusion

The comprehensive simulation numerical models, as it was described in this paper should be used as proper spatial diagnostic tools, which have been validated and they are robust, based on field measurements of experimental sites like Mid Auchencarroch one and on relative literature sources.

Moreover, the development of sustainable sequential batch bioreactors and simulation numerical models of biomass biodegradation are useful not only to make accurate estimations of biomass emissions but also to diagnose current sites or any proposed planning scenarios. MACH's monitoring experimental data and its waste biodegradation simulation show that batch anaerobic bioreactor design is sustainable and its sustainable principles should be applied at any landfill site so as to be stabilized in short time avoiding any long term spatial associated risks and hazards.

According the above, there will be an effective protection of any surrounded ecosystems on a given landfill site topogrpahy so as to minimize any probable associated risks by the relative sources of pollution. The MACH wet-flushing bioreactor landfill project is seen as the method of achieving the goal of sustainability, minimizing the risks of landfill fires and associated environmental impacts, such as loss of flora-fauna resources, buildings, architectural values or other anthropogenic properties. The development and use of proper efficient spatial useful numerical models is necessary in order to solve particular environmental problems like to give solutions to emerging lining methods; locate proper fire protection equipments; and design, develop and use proper confrontation and reclamation technologies for environmental protection.

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References

Bockreis A. and Steinberg I. (2005): Influence of mechanical-biological waste pre-treatment methods on the gas formation in landfills, *Waste Management Journal*, **25**, 337-343.

Brewitz W. and Rothfuchs T. (2000): In-situ testing of underground barrier systems in view of pa-relevant parameters, In proceedings of Euradwaste 1999 conference, Edited by C. Davies,European Comission Pubs., Directorate-General for Research, 282-296.

Brimicombe A. (2003): GIS, Environmental Modelling and Engineering, Taylor & Francis Publs, London, U.K.

Cairns J. (2006): Sustainability and the Global Commons, *Asian J. Exp. Sci*., 20(2), 217-224.

Cairns J. (2007): Preparing to Monitor for Sustainable Use of the Planet, *Asian J. Exp. Sci*., 21(2), 179-190.

Canter L. (1996): Environmental Impact Assessment, McGraw-Hill, New York, USA.

Chivers I. and Sleightholme J. (2005): Introduction to programming with Fortran: with coverage of Fortran 90, 95, 2003 and 77. Springer Publications.

Davis M. and Cornwell D. (1998): Introduction to environmental engineering. McGraw Hill Publications.

Derby Evening Telegraph (1986): Destroyed Bungalow at Loscoe, Derbyshire, UK Newspaper.

DOE. (1989): Waste Management Paper No 27, Landfill Gas, HMSO, London, UK.

DOE. (1995): A guide to risk assessment and risk management for environmental protection, HMSO, London, UK.

Elliott P., Briggs D., Morris S., Hoogh C., Hurt C., Jensen T.K., Maitland I., Richardson S., Wakefield J. and Jarup L. (2001): Risk of adverse birth outcomes in populations living near landfill sites, *BMJ*, **323**, 363-368.

Friis R.H. and Sellers T.A. (2004): Epidemiology for Public Health Practice, Jones and Bartlett Publishers.

Kaparis S. (1993): Special Subjects of Topography, Greek Ministry of Education Pubs., Athens, Greece.

Koliopoulos T. (2000): Numerical Modelling of Landfill Gas and Associated Risk Assessment, Ph.D. Thesis, Dept. of Civil Engineering, Univ. of Strathclyde, Glasgow, U.K.

Koliopoulos T. and Fleming G. (2002): Modelling of Landfill Gas Production of Treated and Untreated Waste - Mid Auchencarroch, In Proceedings of I.S.W.A Congress 2002: vol. 2, pp. 1019-1028, (Ed. G.Kocasoy, T.Atabarut, I.Nuhoglu), Istanbul, Turkey.

Koliopoulos T. and Koliopoulou G. (2007a): Evaluating Biomass Temperature vs Biodegradation for Environmental Impact Minimization: Mid Auchencarroch Experimental Landfill, *Asian J. Exp. Sci*., **21(1)**, 43-53.

Koliopoulos T.C. and Koliopoulou G. (2007b): Risk Analysis of Landfill Gas Emissions: A Report on Mid Auchencarroch Project, *Asian Journal Exp. Sci*., **21(2)**, 215-226.

Koliopoulos T. C., Koliopoulou G. and Axinte C. (2007): The use of efficient lining methods combined with numerical models for optimum project management of manufactures, *M.O.C.M Journal*, Volume II, Number 13, pp. 379-384.

Kollias P. (2004): Solid Wastes, Lichnos Publications, Athens, Greece.

Lawrence D. (2003): Environmental Impact Assessment, John Wiley & Sons, New Jersey, USA.

Skordilis A. (2001): Waste Disposal Technologies for Non-Hazardous wastes, ION publications, Athens, Greece.

Tchobanoglous G., Theisen H. and Vigil, S. (1993): Integrated Solid Waste Management, McGraw-Hill Book Company, New York, USA.

Van Genuchten M.T.H. and Alves W.J. (1982): Analytical solutions to the one dimensional convective-dispersive solute transport equation. U.S Department of Agriculture, Agricultural Research Service, Technical Bulletin No. 1661.

Vlavianos-Arvanitis A. (1991): Biopolitics the Bio-Environment, B.I.O. Publications.

Williams G.M., Ward R.S. and Noy, D.J. (1999): Dynamics of landfill gas in unconsolidated sands, ISWA, *Waste Management and Research Journal*, **17(5)**, 327-342.