Urban Development and Land Contaminants Migration – A Case Study of Huntsman Chemical Plant in Melbourne

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Abstract: Land contaminant migration in urban areas increases the risk of land contamination presenting to the community and government. The migration of contaminants from former industrial sites can expand the adverse impact ranging from human well-being to environmental health. However, the current land use policies are primarily focusing on fixed limits of sites with contaminant risks rather than the increased range of pollution from diffusing contamination. The risk of land contaminant migration is yet to be better understood, particularly in former industrial districts. This paper investigates the natural and urban factors that impact the spatial migration of land contaminants. It is based on the analysis of the historical soil contamination data and recent soil sampling data across Brooklyn, a highly-industrialized suburb in Melbourne’s inner west. It then evaluates the factors that may have profound influences on land contaminants migration and predicts the trend of the migration and spreading range. It is hoped that this research will help planners to make the most appropriate land use decision when considering soil contaminants risks in urban development.

Keywords: Land contaminant migration; urban development; brownfield development

1 Introduction

The State of Victoria Department of Environment, Land, Water and Planning (2016) states that the projected total population of Victoria in 2051 will be 10,086,500, which is nearly the double of its figure in 2011. This dramatic increase indicates a need for more housing across the state. The number of total household is projected to be 4,094,200 in 2051. Therefore, a large amount of land will be used for residential development in the future in Victoria. As the capital city of Victoria, Melbourne has a massive supply of industrial land near its CBD that has been earmarked for new housing and commercial development. When reforming these industrial used zones to more sensitive used zones, site contamination is a historical issue that needs to be emphatically considered by planners when making urban development decisions (KMH Environmental, 2013).

Australian Standards (2005) defines contaminated site as a site where assessment indicates hazardous substances occur at concentrations which pose, or are likely to pose, an immediate or long-term hazard to human health or the environment. About the site assessment, Australian Standards (2005) state that in preliminary site investigation, soil contamination data should be collected by identifying the possible distribution of contamination by relating site history to existing conditions and redistribution of contaminants across the site. ASC NEPM (2013) mentions the mobility of contaminants within contaminated site, and suggests the potential for off-site environmental impacts should be considered in the development of the conceptual site model. However, there is still not enough research for modelling the migration of contaminants through subsurface movement and erosion of contaminated soils.

There have been some studies discussing how land contamination relates to urban planning issues (e.g. Rodrigues et al., 2009, Beaufoy, 2010, USEPA, 2014, Davies et al., 2015, Luo et al., 2009). However, there have been fewer studies addressing off-site soil contaminants issue in relation to urban
This paper will discuss the preliminary findings of land contamination study focused on the soil contaminants migration. It provides a deeper discussion about how to predict and trace the off-site land contaminants and how to improve the current brownfield redevelopment planning policies. Section 1 provides an overview of the land contaminants migration problems in Australia and the potential hazards for public health when urban planners remediate the contaminated sites without considering the contaminants migration. Section 2 points out the factors that will influence the scope of soil contaminant migration. Section 3 provides a contaminant migration model based on the preliminary soil contamination data from an environmental audit report of a former industrial site in Brooklyn, within the Brimbank local government area in Melbourne. This section will discover a new method for studying the soil contaminant migration issue by building models to recognize the most influential factor in contamination migration process and predict the migration directions around the polluted source. A test of the model is also conducted in this section. The Results shows the most influential factor of the migration of soil contaminants is the convection of the soil solute, and a predicted trend calculated by the equation of pollutants migration within or beyond the site boundaries. The discussion explores some of the deficiencies of the model and gives advice on the future brownfield redevelopment planning based on the model. The study highlights that the migration of land contaminants may be neglected when formulating urban planning policy for urban brownfield development and that a more specific study and cost-efficient prediction of contamination migration is needed to safeguard public health in future urban planning.

2 Urban land contaminants migration in Australia

In Australia, the migration of broad range of soil contaminants has been affecting urban environments. Australia has numerous industries (such as Mining and extractive industries, engine works and Land fill sites) which could cause soil pollution (ASC NEPM, 2013). The contaminants from these industrial activities will impact varyingly between different cities because of various migration ways in different land use field (ANZECC, 1992). According to the guidelines and policies in Australia, industrial sites are subject to site assessments using a conceptual site model, and the sites will be remediated thoroughly before redevelopment. The migration of contaminants has been considered in building the conceptual site model, especially the leachable contaminants in Schedule B1 of National Environment Protection (Assessment of site contamination) Measure 1999 (ASC NEPM). In Schedule B3 of ASP NEPM (2013), the leachable contaminants are addressed and the document mentions that contaminants in soil can transfer to surrounding areas by leaching into groundwater. However, the guidelines do not provide methods about how to deal with the situation of contaminants migration in soil, nor do they provide enough methods for tracing and predicting the migrating path of soil contaminations. As a result, the remediation plan used for brownfield redevelopment may be inaccurate thus pose negative effects on public health and environmental safety.

The migration of soil contaminants should be the focus point in Australian urban soil contaminants and urban planning studying fields. The soil contaminant is defined as a substance that can migrate into soil and affect the normal function of soil (ANZECC, 1999). ASP NEPM (2013) categorises soil contaminants mainly into Metals, Halides, Non-metals and Organics. All kinds of contaminants in soil have mobility, so the high levels concentration of contaminants in industrial sites may affect the surrounding areas through accumulative concentrations of the off-site contaminants (Finegan, 1996). It is therefore necessary to effectively recognize the total area of the contaminated land when developing
zones around these industrial sites for sensitive use (such as residential or educational use).

2.1 Previous study
The factors that can influence the migration of soil contaminants in the previous study can be summarised as the convection of soil solute, soil dispersion and soil attribute. Kanmani and Gandhimathi (2013) explored the concentration of soil contaminants by collecting soil samples around the municipal solid waste, and they concluded that precipitation of one area can affect the migration of contaminants. They also mentioned that the heavy metals (Pb, Cu, Mn and Cd) might contaminate the groundwater system by migrating through the soil strata continuously through the convection of soil solute. Grifoll and Cohen (1996) mentions that soil erosion can affect the migration of soil, thus influence the movement of soil contaminants. David and Paloma (2009) indicates that some soil contaminants from polluted sites can adsorb on the surface of soil particles and migrate with the soil. Li et al. (2001) studied the heavy metal contents both in urban parks and street dust, and they found that the physical characteristics (e.g. larger grain size) of contaminants and the groundwater flow speed were probably the factors that affected the mobility of these metals on ground surface. Hu et al. (2013) concluded that anthropogenic activities, such as land use type and traffic have impacts on the certain heavy metal contaminants redistribution in surface soil. The study about the leachability of soil contaminants are discussed in section below, Maskall et al. (1995) states that heavy metals’ vertical migration ability appears to be increased at lower soil pH for the site with same parent material.

3 Soil investigation survey

3.1 Study area
Lying approximately 10km from the Melbourne’s central business district, Brooklyn is a highly-industrialized suburb, in Melbourne’s inner west. A chemical manufacturing plant located at 454-460 Somerville Road in this suburb was once operated by Huntsman Chemical Company of Australia Pty Ltd (HCCA). This plant occupied approximately 36.5 hectares in size, and the site area is bounded by commercial/industrial properties to the north, Somerville Road to the south, Market Road to the west and a regional railway corridor to the east (Fig. 1).

Fig.1 Huntsman chemical plant site map (Source: Open Street map, 2017)
The site is located in an industrial zone, and itself has a long history of industrial use. The site was constructed in 1940 during World War II for chemical manufacturing for various chemical products, including pharmaceuticals, plastics, resins, phenols, styrene and styrene derivatives (e.g. polystyrene and polyester resins). Site operations are reported to have ceased in 2010. The chlorination of phenols and associated processes that took place within the site resulted in the generation of solids (e.g. flakes and dust) which may have the potential to migrate or be actively transported and disposed of to land and water.

Based on the historical land use of various parts of the site, it has always been divided into a total of 25 investigation zones for the purpose of managing site investigations.

3.2 Surrounding Land Use

According to the Brimbank City Council Planning Scheme, the site is zoned as Industrial 1 Zone (INZ1) (Fig.2). The historical land uses within the area surrounding the site are to have included stock grazing, quarrying and commercial/industrial uses (PB, 2012).

3.3 Site Features

Most of the former aboveground infrastructure has been demolished since the closure of Huntsman chemical plant. The main site features relevant to the soil contaminants include (Fig.3): landfill in north-west portion of the site (Area 1), dioxins-impacted soil stockpile (Area 2) and former East quarry (Area 3).

The potential sources of soil contamination have been considered primarily in the site investigation survey. Besides the on-site sources that are closely related to the previous on-site historical industrial activities, the site has several potential off-site sources, including the former surrounding landfills, which could also influence the movement of contaminants due to historical dewatering activities, current or past industrial site near the site and the railway line to the east. According to the site history, site inspection and sampling, contaminates include: metals (antimony, arsenic, boron, chromium,
chromium, copper, lead, manganese, mercury, molybdenum, nickel, selenium, tin and zinc) and Non-metals.

4 Methods

4.1 Contaminants migration model
To recognize the most influential factor of contaminant migration, a mathematical model is considered the most economical method to simulate the migration of soil contaminants. This paper focuses on the migration of soil contaminants in a post-industrial site. In this scenario, the total amount of contaminants of the site is stable and no more new contaminants will be adding in, while the migration of the contaminants that reserved in the soil will be focused. It is practical to build the simulation model under this situation.

According to the previous study, the migration process of soil contaminants occurs in the process of soil substance convection, soil dispersion and adsorption. Based on the migration theories put forward by Thomas Graham and Adolf Eugen Fick (Mason and Evans, 1969), with the principles of energy and mass conservation, a mathematical model is build up to simulate the migration of soil contaminants in both saturation and unsaturated soil:

\[ C_d - C_c - C_s = C_a \]  \hspace{1cm} \text{Equation (1)}

Where:
- \( C_d \) is the dispersion of soil contaminants (see Equation 2 for details);
- \( C_c \) is the convection of soil contaminants (see Equation 3 for details);
- \( C_s \) is the adsorption or degradation of soil contaminants (see Equation 4 for details);
- \( C_a \) is the accumulation of soil contaminants in the area which is off the pollutant source (see
In Equation (1), $C_d$ is the soil contamination migration caused by concentration difference of contaminants, and it fit Fick’s diffusion law (Fick, 1855). It can be calculated as

$$C_d = \frac{\partial}{\partial X_i} \left[ \theta D_{ij} \frac{\partial C}{\partial X_j} \right]$$  \hspace{1cm} \text{Equation (2)}

Where:
- $X_i$ and $X_j$ are Cartesian coordinates;
- $\theta$ is volumetric soil water content;
- $D_{ij}$ is diffusion coefficient.

In Equation (1), $C_c$ is the soil contamination migration that caused by the flow of groundwater, and it can be described with Darcy’s Law (Darcy, 1856). It can be calculated as

$$C_c = \frac{\partial}{\partial X_i} (C v_i)$$  \hspace{1cm} \text{Equation (3)}

Where:
- $v_i$ is Darcy velocity towards $X_i$ direction.

$C_s$ is the contaminates that are adsorbed by soil or degraded by soil microbial community, and it calculated as

$$C_s = \theta \lambda C R_d$$  \hspace{1cm} \text{Equation (4)}

Where:
- $\lambda$ is a coefficient for bio-degradation or radioactive decay.
- $R_d$ is a constant relate to adsorption.

Finally, $C_a$ the accumulation of soil contaminants in the area which is off the pollutant source, which can be calculated as

$$C_a = R_d \frac{\partial (\theta C)}{\partial t}$$  \hspace{1cm} \text{Equation (5)}

Where:
- $t$ is time.

Thus, the equation can be written as below.

$$\frac{\partial}{\partial X_i} \left[ \theta D_{ij} \frac{\partial C}{\partial X_j} \right] - \frac{\partial}{\partial X_i} (C v_i) - \theta \lambda C R_d = R_d \frac{\partial (\theta C)}{\partial t}$$  \hspace{1cm} \text{Equation (6)}

Based on the assumption of a saturated soil environment, the equation can be simplified as:

$$D_x \frac{\partial C}{\partial x^2} + D_y \frac{\partial C}{\partial y^2} + D_z \frac{\partial C}{\partial z^2} - v \frac{\partial C}{\partial x} - \lambda C R_d = R_d \frac{\partial C}{\partial t}$$  \hspace{1cm} \text{Equation (7)}

Where:
- $D_x, D_y$ and $D_z$ are diffusion coefficients in X, Y, Z directions respectively.
- $v$ is the velocity of groundwater flow.
- $C$ is the concentration of contaminants in soil.

To analysis which factor among convection, diffusion, dispersion and adsorption is the most influential one, we assume that the pollution source is stable, and the concentration of contaminants in the area
that beyond the pollution source boundary is 0.

4.2 Establish coordinate
Assume the study area is a three-dimensional cubic with 1m in length. The coordinate of the contaminant source is: (0, 0, 0). We assume that the groundwater flow direction is along x-axis. To understand the spatial and temporal distribution of soil contaminants, 6 analysis points has been set to assess the migration: \( P_1 (0.05, 0, 0) \), \( P_2 (0.05, 0.05, 0) \), \( P_3 (0.05, 0, 0.2) \), \( P_4 (0.5, 0, 0) \), \( P_5 (0.5, 0.2, 0) \), and \( P_6 (0.5, 0, 0.2) \).

4.3 Site Investigation survey
A site investigation survey has been conducted for Huntsman chemical plant. The investigation survey is conducted by reviewing the site assessment works conducted by Parsons Brinckerhoff Australia Ltd (PB) from 2006 and the current environmental audit report completed in July 2014. The types of the soil, contaminants and basic site soil situation have been reported in the document, which can help provide basic information and support data for the equation calculation. Besides, the environmental audit report of the plant recorded the contaminants concentration situation from over 400 in-site and 16 off-site soil sampling locations during 2008-2012 (PB, 2010), which can be used as an examination for the mathematical model proposed earlier.

4.4 Calculation
By solving the equation, we can find out the relationship between concentration of contaminants and time. For example, we can use \( C_t \) as the concentration of contaminants in a particular time. In that case, \( C_0 \) means the primary concentration of contaminants. To simulate the real contaminated process of Huntsman Chemical plant site, we assume that the contamination source will release the contaminants at a constant concentration for 10min at first, and then it will stop. The contaminants reserved in the soil will continue migrating.

The data used in the equation is based on Huntsman chemical plants soil environment. We assumed that the soil environment is saturated, and the data is listed below (Table 1).

<table>
<thead>
<tr>
<th>Model Parameter</th>
<th>Data</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary stable contaminants concentration (( C_0 ))</td>
<td>100 mol/m³</td>
<td>Assumption</td>
</tr>
<tr>
<td>Degradation coefficient (( \lambda ))</td>
<td>0.68 g/ml</td>
<td>PB, 2010; Ogram et al, 1985</td>
</tr>
<tr>
<td>Sorption coefficients (( R_d ))</td>
<td>1.53 g/ml</td>
<td>PB, 2010; Ogram et al, 1985</td>
</tr>
<tr>
<td>Diffusion coefficient in x and y direction (( D_x, D_y ))</td>
<td>12 cm²/min</td>
<td>Assuming as spatial isotropy</td>
</tr>
<tr>
<td>Diffusion coefficient in z direction (( D_z ))</td>
<td>8 cm²/min</td>
<td>Assuming as spatial isotropy</td>
</tr>
<tr>
<td>Average velocity of groundwater (( v ))</td>
<td>4 cm/min</td>
<td>Assumption</td>
</tr>
</tbody>
</table>

4.5 Application
After understanding the most influential factor of the migration by the mathematical modelling, urban planners can figure out the approximate land range of contaminants migration and make better planning decision when redeveloping the polluted site. The site, Huntsman Chemical Plant, is used as an example for the application of the mathematical model. The migration of Benzene, a chemical contaminant, is going to be predicted. The coefficients are same with the ones mentioned in last session, and the predict period (T) is from the plant closure date (2010) till 2014. The original site
contamination data is provided by Environmental Risk Sciences Pty Limited (2013).

5 Results

5.1 The most influential factor
The preliminary results from this study have identified that the solute convection in soil is the most influential factor in soil contaminants migration phenomenon. The results are presented by Figures 4 and 5 below.

Fig.4 Contaminants distribution map after emission in 250s

Fig.5 Concentration variation of analytical points after emission
According to fig. 4 and fig. 5, key findings from this study are as follow:

a) The concentration of contaminants between $P_1$ and $P_4$, which have same coordinates on Y and Z-axis, differs greatly. That phenomenon is mainly caused by the velocity of groundwater, since the groundwater is assumed to flow along X-axis. This can be described as the contaminants migration caused by convection of the soil solute, because the water flow through the pore of the soil with soil contaminants, and leave the pollutants along its flow paths.

b) The concentration of contaminants symmetrically distributed on both sides of X-axis after contaminants emission, and the concentration is lower when the analyse point is further from pollutant source in all directions.

c) The concentrations of contaminants of $P_1$, $P_2$ and $P_3$ are high at the beginning, but they decreased sharply as time goes on. Besides the convection of soil solute reason, the adsorption and degradation parameters are the reasons to concentration decrease as well. The adsorption process will slow down the migration velocity of contaminants, while the degradation process will decrease the total amount of contaminates.

d) The concentrations of contaminants of $P_4$, $P_5$ and $P_6$ increased at the first 100s, and then they decreased slightly after 500s. This phenomenon also shows the retardance of the adsorption and degradation process to migration of soil contaminants.

e) The appearance of peak value of the concentration of contaminants has been delayed by adsorption and degradation processes, and the peak value has been reduced for the same reason. These two processes should be emphasized when controlling the migration process of soil contaminants.

5.2 Application

By understanding that the convection of soil solute is the main cause of the contaminants migration, the study analyses the groundwater flow of the Huntsman Chemical Plant and predicts the migration range of a soil contaminant, Benzene, on site (Figs 6 and 7). The prediction of migration of Benzene does not totally match with the data that has been collected from field soil sampling, that may due to the inaccurate coefficient, or other unrecorded anthropogenic activities happened on site.

From Fig 7, the model predicts that large amount of Benzene migrates outside the site boundary through the groundwater flow path in 2 years by using MATLAB for solving equation and geographic information system (GIS) for classifying. The result shows the fact that when redeveloping the site land use, urban planners should be careful about the land use of the surrounding areas.

6 Discussions

6.1 Limitation of the study and future work

Soil contaminants migration is a complicated subject, and the study requires high quality data about the soil properties and is expected to consider all the factors that could influence the migration of soil contaminants. The high dependence on precisely measured data makes the model hard to popularize in some parts of Australia, where the data about the soil environment is insufficient. Besides, some unrecorded anthropogenic activities happened on site may change the contaminants migration trend, and these activities cannot be predicted by the model, which may contribute to errors and increase discrepancy.
Fig. 6 Groundwater flow and Stable contamination source map (Source: PB, 2012)

Fig. 7 The migration range of Benzene on site surface (Source: PB, 2012)
This study simplifies the real soil situation by making several assumptions and building an ideal soil environment when calculating the migration range of the contaminants. Although this prediction model can predict the migration of contaminants cost-efficiently in a macroscopic level, the precision of this study is still hard to compete with the field sampling collected data. This may cause a low applicability in practice.

In the future study of redeveloping brownfield, the migration of soil contaminants is an issue that should not be neglected. Mathematical models as a cost-efficient method to predict the migration issue deserves to be developed vigorously. Future efforts should be put on to link the method of predicting the range of off-site contaminants with planning practice. It would be desirable for urban planners to plan the most suitable land use type for the post-industrial areas by understanding the real polluted range of the site.

6.2 Future urban brownfield development

The developing of brownfield in Australia needs a more cost-effective way to conduct the site assessment other than the field sampling collection, and the method mentioned in this paper have the possibility to achieve that goal. In the future, this method can be used by urban planners to conduct a preliminary soil assessment when they are trying to redevelop the former industrial zones into a more sensitively used zone. Besides, if this method is used in the conceptual site modelling process proposed in the official guidelines, it could be easier for planners and engineers to define the actual contaminated site boundaries. By analysing the potential polluted zone, a more logical urban land use plan might be designed, for example, land use types with better contaminants degradation ability can be planned in the predicted polluted range, while the other land use types can be planned out of the predicted range.

7 Conclusions

In this study, we analysed the influential factors that could affect the migration of contamination on and off site. We established a model that successfully calculates the spreading range of soil contaminants by considering the convection, adsorption and degradation process happened in soil. We conclude that the convection of soil solute, which highly relate to the site groundwater velocity, is the most influential factor that causes the migration of contaminants. We also found that the absorption and degradation happened underground can gradually decrease the concentration of contaminants. We hope that in future brownfield redevelopment planning, the model can be used as a cost-efficient method to estimate pollution areas and help urban planners to make decisions when considering the future land use type of the contaminated sites.

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