Groundwater and Soil Vapour Containment Design at a Mercury-Contaminated Industrial Site

Gary R. Schmertmann[1], Ryan Huynh[2], James Stening[3]

[1]Associate, Golder Associates Pty Ltd, Sydney, NSW, Australia
[2]Senior Civil Engineer, Golder Associates Pty Ltd, Sydney, NSW, Australia
[3]Senior Environmental Technologist, Orica Australia Pty Ltd, Botany, NSW, Australia
Corresponding author's E-mail: gschmertmann@golder.com.au

Abstract

Operation of a chlorine manufacturing plant near Botany Bay, NSW, Australia resulted in mercury contamination in soil and groundwater. Site remediation included design and construction of an integrated groundwater and soil vapour containment system comprising a subsurface barrier wall up to 25 m deep, and a multi-layer cap designed to be compatible with ongoing site use as a paved hardstand for stockpiling operations. This paper presents a case history focusing on geoenvironmental engineering aspects of the design of the containment system. The paper presents the rationale for components of the design, including for the groundwater barrier wall: geometry, depth, hydraulic and vapour properties, construction method, and mix design. For the multi-layer cap design, topics covered include selection of material layers for vapour and infiltration control, design features for vapour monitoring and venting contingency, and landform shaping. Construction of the containment system occurred in 2015-2016, with the groundwater barrier wall formed using the cutter soil mixing method. The containment system notably provides combined groundwater and soil vapour management at a deep sand site with ongoing site use for industrial stockpile operations.

Keywords: design, containment, groundwater, vapour, mercury.

1. INTRODUCTION

A chlorine manufacturing plant using the chlor-alkali process was operated from 1944 to 2002 near Botany Bay, NSW, Australia (Figure 1). The operations resulted in mercury being present in soil, soil vapour, and groundwater. Site remediation has included construction of an integrated groundwater and soil vapour containment system comprising a subsurface barrier wall and a multi-layer cap.

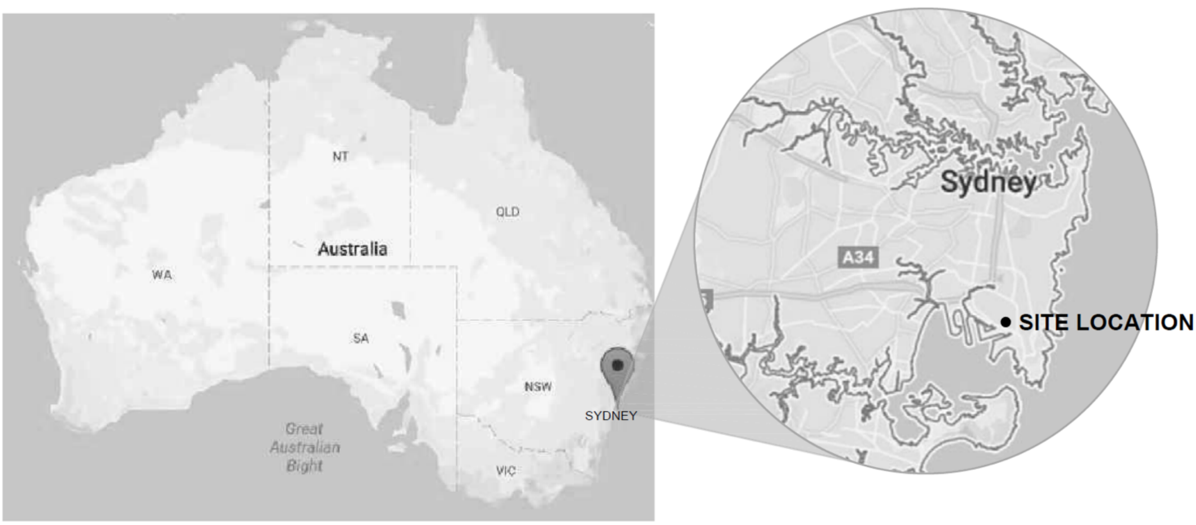

Figure 1. Site Location

The site is relatively flat with maximum grades of 2%. Subsurface conditions relevant to design and construction of the containment system are summarised below.

Subsurface Stratigraphy

- Dense, uniform medium sands underlie 0.5 to 4 m of surface fill and extend to a depth of approximately 18 to 24 m along the proposed barrier wall alignment. Peat horizons are generally present below the groundwater level within the sands. The sands comprise the Botany Sands strata. The permeability (i.e. saturated hydraulic conductivity) of the sands is approximately 10^{-4} m/s.
- Clayey alluvium or residual clay/weathered sandstone underlies the Botany Sands. These materials have permeability in the range of 10^{-7} m/s to 10^{-10} m/s.
- Mercury contamination in soil along the proposed barrier wall alignment ranged from <0.1 to 64 mg/kg with an average concentration less than 10 mg/kg.

Groundwater

- The depth to groundwater was approximately 6 m, with the depth at any one location observed to vary with time over an interval of up to 1 m.
- Groundwater flow is predominately within the Botany Sands in a south-westerly direction.
- Variable groundwater quality along the proposed barrier wall alignment: Total dissolved solids less than 1000 to over 120,000 mg/l, with the higher value reflecting a nearby industrial salt stockpile; sulphate concentrations near zero to 1800 mg/l; total mercury concentrations zero to 16 mg/l; and pH 4.2 to 8.6, with the lower values reflecting a nearby industrial acid leak.

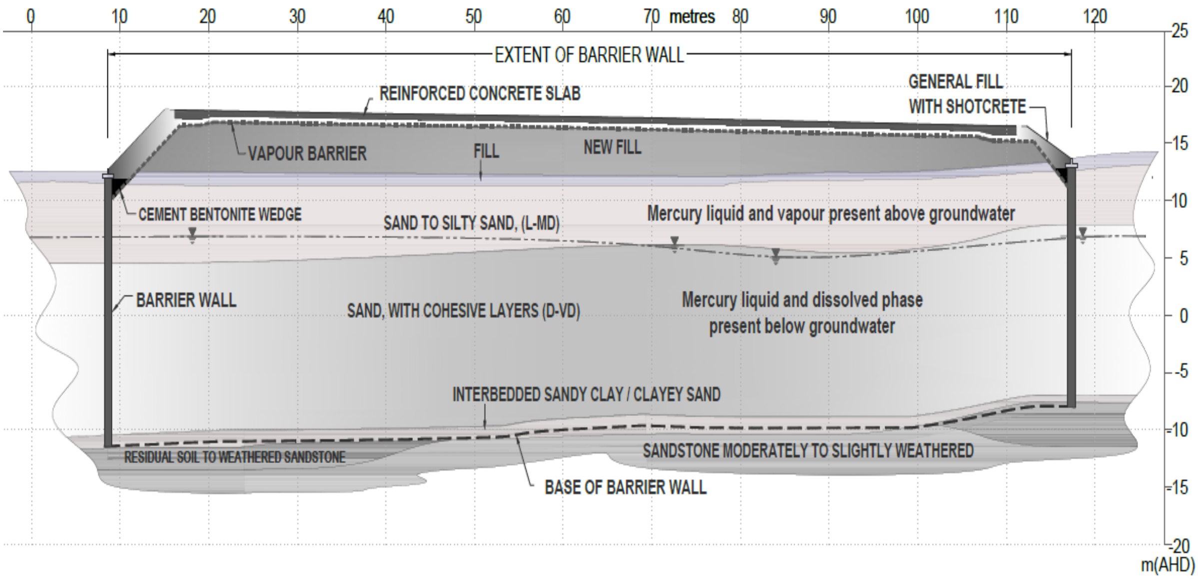

Figure 2. Site Conditions and Conceptual Design Cross-Section

The performance objectives of the containment system are summarised below.

Subsurface Barrier Wall: (i) restrict groundwater flow through the site; (ii) restrict lateral mercury vapour migration from the site; and (iii) long-term material compatibility in the subsurface environment.

Multi-Layer Cap: (i) restrict surface mercury vapour emission from the site; (ii) restrict surface water infiltration and manage storm water; (iii) prevent physical contact with contaminated soil; and (iv) cap surface to be used for industrial stockpile operations.

2. SUBSURFACE BARRIER WALL

Design features and processes for the subsurface barrier wall are summarised below.

Geometry - The design geometry of the barrier wall was established with the intent of encompassing the large majority of mercury contamination within the wall alignment to restrict migration in groundwater, as well as lateral vapour migration above the groundwater level. The barrier wall alignment reflected a closed square surrounding the former plant footprint, with total wall length of 400 m (Figure 3). The design thickness of the wall, 0.8 m, was selected to provide a robust thickness that was readily achievable with common construction methods. The design required the wall to extend downward from the cap, through the full depth of the Botany Sands strata, and to be keyed-in to the underlying lower permeability layers by at least 0.5 m (Figure 2): the depth of the wall therefore varied between 20 and 25 m. Cone penetration test soundings were conducted on 10 to 15 m centres to establish wall key-in depths and occurrence of peat layers immediately prior to construction.

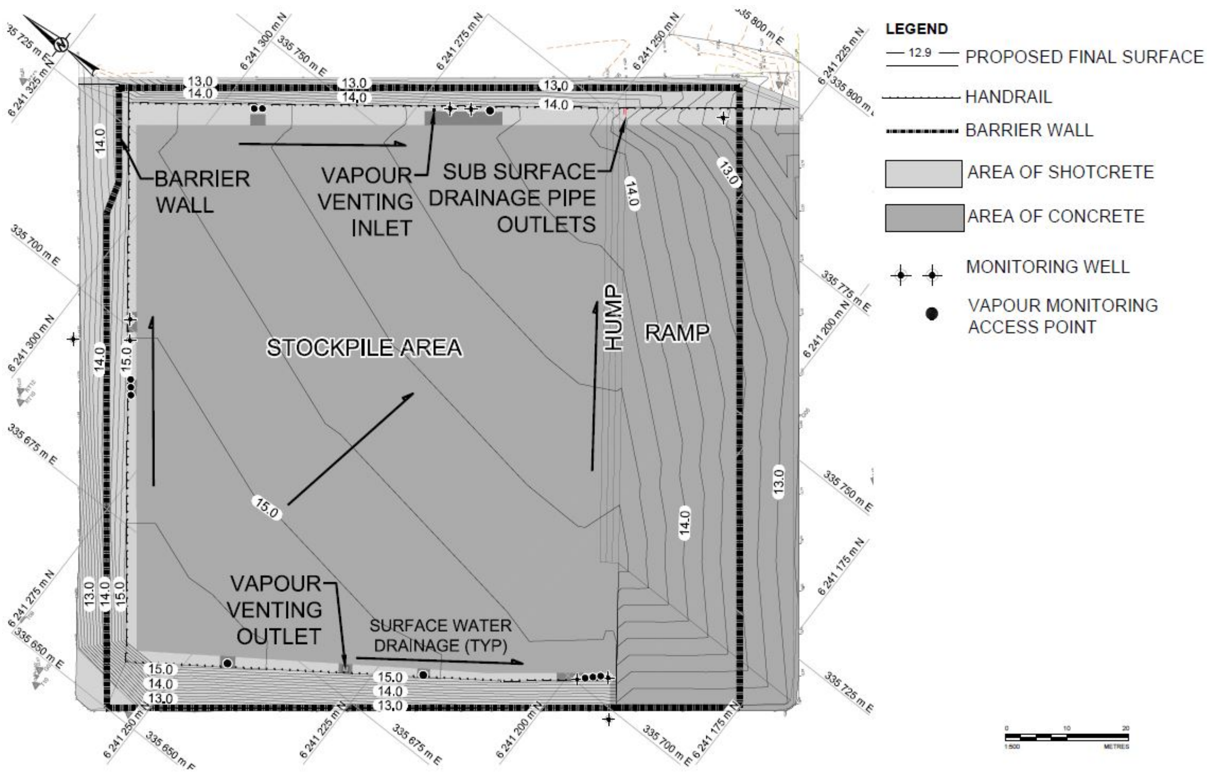

Figure 3. Site Design Plan

Wall Properties: Water Permeability - The design specified a maximum permeability to water (i.e., saturated hydraulic conductivity) of 10^{-8} m/s, applicable to the portion of the wall below groundwater. This was measured using distilled water as the permeant. Mix design for the wall material (see below) also included use of three sampled groundwaters from the site, with varying levels of chloride, sulphate, mercury and pH, as permeants for extended duration permeation testing to assess long-term chemical compatibility between the wall and site groundwater (i.e., wall durability).

Wall Properties: Vapour Permeability - The design specified a maximum permeability to gas/vapour of $1x10^{-8}$ m/s and a maximum vapour diffusivity of $5x10^{-7}$ m^2/s, applicable to the portion of the wall above the groundwater level. Both properties were measured using nitrogen as the permeating or diffusing gas. These vapour properties are sensitive to moisture content of the material and were first measured at 5% moisture content, after conditioning in a temperature and humidity controlled environmental chamber to simulate near-surface wall drying after construction. Subsequent vapour property measurements used a higher moisture content (>30%) based on a long-term moisture

equilibrium assessment performed subsequent to the original design period.
This assessment included measuring the soil water characteristic curve (SWCC) of the CSM wall material and comparing it to the SWCC of Botany Sand material. The assessment concluded that the wall material is likely to remain in a near-saturated condition as the material will tend to draw/retain moisture from the surrounding sand due to its smaller pores. However, because extreme weather influences cannot be ruled out in the near-surface environment, the upper 1.5 m of wall material was supplemented by the design of the connection between the wall and the multi-layer cap (see below).

Wall Properties: Strength – An unconfined compressive strength >2 MPa was specified for the upper portion of the wall to accommodate loading from future stockpiling operations, provide resistance to inadvertent wall disturbance in the future, and provide general resistance to cracking from desiccation and thermal stresses. The strength also allowed for excavation against the wall for the connection to the capping systems (see below). A strength of >1 MPa was required for the lower potions of the wall as a nominal quality control index for mixing uniformity and basic mix proportions.

Construction method - The cutter soil mixing (CSM) method was selected, wherein a soil-cement-bentonite structure is formed in-situ by controlled subsurface injection of bentonite slurry and cement grout and simultaneous mixing with existing soils, creating a temporarily liquefied mixture that permits the cutter device to be raised and lowered without getting trapped. Individual wall panels are formed by full-depth insertion and extraction of the cutter device, with the panels overlapped to form a continuous wall. A major factor in selection of the CSM method was that, being an in-situ method, there would be no excavation and surface exposure of mercury-contaminated soil. Another factor was the ability for mix design to include proportions of bentonite and cement to satisfy both water and vapour permeability design criteria. It was necessary to adjust the CSM construction procedure to accommodate actual site conditions (not described herein).

Mix Design – Design of the wall material mix comprised assessment of bentonite slurry and cement grout concentrations and subsurface mixing rates against the required wall properties. Major factors considered included in-situ soil composition and variability, groundwater chemistry and variability, and cement curing times. Materials used in the mix design tests included a marine grade type LH/SR cement and soil and groundwater sourced from the project site. The mix design resulted in target proportions of 25-50 kg bentonite and 200-250 kg cement per in-situ cubic metre of wall.

Bench-scale testing was used for the majority of the mix design. Limitations to the representativeness of bench-scale specimens include in-situ variability, particularly the effect of peat layers present at the site, the presence/absence of groundwater when mixing below/above groundwater, and the movement of water in and out of the wall panel during the injection, mixing, consolidation, and curing stages of CSM wall formation. These issues were considered through limited full-scale mix testing at another site where a CSM wall was under construction and through a requirement for trial CSM panels to be formed and assessed at the project site prior to commencing wall construction.

Performance Modelling - Hydrogeologic modeling to evaluate the barrier wall and multi-layer cap design indicated a reduction of 96% in the groundwater flow rate through the containment volume (steady-state). The modelling also predicted a two order of magnitude reduction in flow velocity within the containment volume and development of distinct differential groundwater levels across the wall thickness. Sensitivity checks with the model confirmed the importance of effective wall key-in and panel overlapping for reducing the volumetric flow rate.

Vapour modelling to evaluate the barrier wall and multi-layer cap design considered migration of mercury vapour from the unsaturated portion of the containment volume, with the source concentration (1.1×10^{-5} kg/m^3) reflecting vapour saturation at the average site temperature. The modelling considered advection and diffusion mechanisms through the CSM barrier wall and the geomembrane component of the cap, including through assumed flaws/defects in both materials. Advection, with primary driving force resulting from periods of low barometric pressure (typical pressure differential of 600 Pa), was calculated to be the dominant mechanism. The total predicted mercury mass flux from the containment volume was assessed against site exposure risks.

3. MULTI-LAYER CAP

Design features and processes for the multi-layer cap are summarised in this section. The following table presents the system components, listed from top to bottom, and their primary and secondary functions. The components are shown in Figure 4.

Table 1: Capping System Components

Component (listed from top to bottom)	**Objectives Addressed [1]**				**Primary Functions**	**Secondary Functions**
	VE	**WI**	**PC**	**FU**		
Surface Slab [reinforced concrete]	X	X	X	X	working surface for industrial stockpile; protect vapour barrier	surface water drainage
Protection and Drainage Layer [Drainage Sand]		X	X		drainage of water infiltrating through slab; layer includes a pipe network	protect vapour barrier during slab construction; vapour monitoring; slab foundation
Vapour Barrier [LLDPE Geomembrane]	X	X			barrier to vapour emission	water infiltration barrier
Bedding Layer [coated GCL]	X				suitable surface for deployment of vapour barrier	enhance vapour barrier function
Venting Layer [Geocomposite Drainage Net]	X				contingency for passive vapour venting; layer includes a pipe network	suitable surface for deployment of bedding layer

Note 1: VE=Vapour Emission; WI=Water Infiltration; PC=Physical Contact; FU=Future Site Use

Connection between cap and barrier wall – The connection was designed to provide continuity of vapour containment. The design included extending the vapour barrier and bedding layer components (i.e., LLDPE geomembrane and GCL) downward into a 1.5 m deep trench excavated against the completed barrier wall. After cleaning of the exposed wall surface and placement of the cap materials, the wedge-shaped trench would be filled with cement-bentonite.

The connection design also provided a supplementary vapour barrier for the upper 1.5 m of the barrier wall. As noted above, the vapour barrier function of the wall material is moisture-sensitive and diminished by drying/desiccation. Although the wall would be buffered from weather effects by the surface slab, wall capping tee, and soil layers (Figure 4), and also by adjacent road pavements, additional near-surface vapour migration resistance was considered prudent.

Venting and Monitoring Features – All venting and monitoring points for the containment system have been positioned on the edges of the capping system landform (Figure 4), outside the stockpile area, such that they can be safely accessed regardless of stockpile operations. The design provided:

- A venting layer to provide a contingency for passive venting from beneath the vapour barrier. The layer comprises a geocomposite drainage net with an air venting pipe network. The pipe network is configured with separate inlet and outlet pipe systems such that venting could be accomplished by a flushing mechanism in all areas of the cap. The design included details for penetration of the inlet/outlet pipes through the vapour barrier.

- groundwater wells (7) inside the barrier wall alignment. These wells could be monitored, along with corresponding wells outside the alignment, to assess the effect of the barrier wall on groundwater levels. The wells also provide a contingency capability to extract water from within the barrier wall. The design included details for penetration of the wells through the vapour barrier.

- vapour monitoring points (11) within the protection and drainage layer (i.e., positioned above the vapour barrier and below the surface slab). These monitoring points were constructed using stainless steel screens and were positioned near the top of the layer, to reduce the change of water saturation, and connected to access points along the slab perimeter with Teflon tubing.

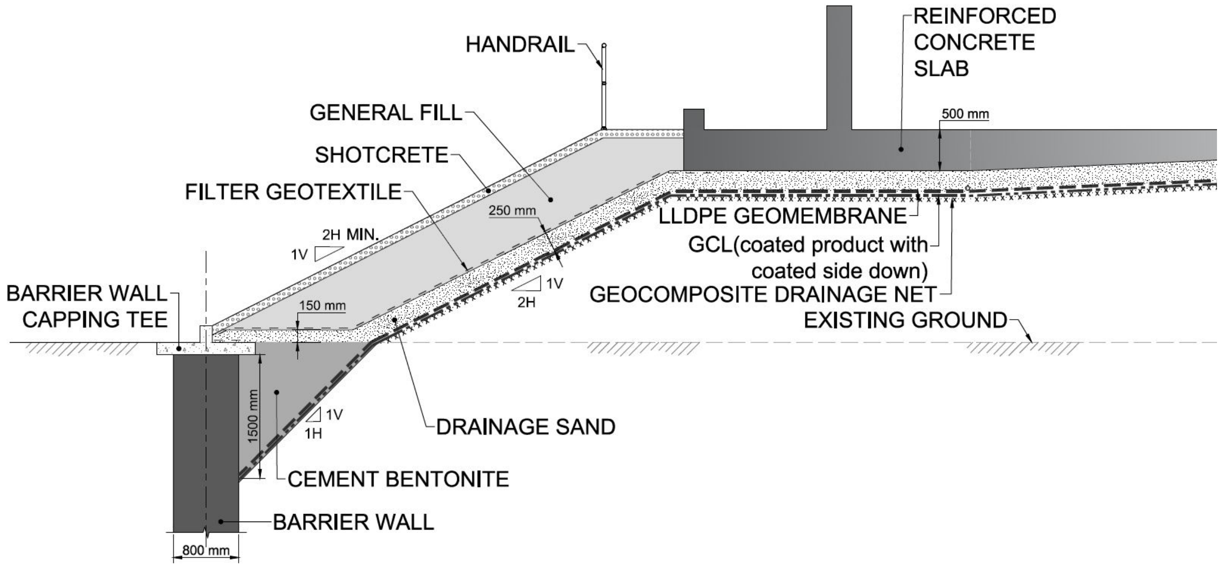

Figure 4. Multi-Layer Cap and Connection to Subsurface Barrier Wall

Landform – The remediation landform (Figure 3) was designed to provide suitable grades and levels for stockpile operations/access and for storm water drainage. The landform extended over the barrier wall alignment where possible to provide long-term protection for the wall. Due to its elevated shape the landform provided airspace that allowed for retention of contaminated spoil from the barrier wall and other construction activities within the site.

4. SUMMARY

Remediation of historical mercury contamination at the site included design and construction of an integrated groundwater and soil vapour containment system. The system comprises a subsurface barrier wall that is 400 m long and up to 25 m deep, integrated with a multi-layer cap over an area of 1 Ha, and accommodates ongoing site use for industrial stockpile operations. Geoenvironmental engineering aspects of the system design have been presented. Construction and performance aspects will be discussed in a subsequent paper.

ACKNOWLEDGMENTS

We acknowledge major contributors to the project design and assessment: Mr. Peter O'Dea and Mr. David Johnson of Orica Australia, Mr. Alan Lasse of A. D. Laase Hydrologic Consulting, Mr. Gavan Butterfield and Ms. Caroline Vernon of Golder Associates, Mr. Chris Jewell of C. M. Jewell & Associates, and Dr. Saman Zargarbashi of Arup.