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Containment and attenuating layers: An affordable strategy that preserves soil and water from landfill pollution

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ABSTRACT

The performance of a widely distributed natural clay to attenuate contaminants released from an old landfill was investigated. The objective is to evaluate its potential use as a barrier for waste containment systems. Core samples of the natural clay were collected below the landfill and their parameters distribution with depth was determined. Partition coefficients, retardation factors and percentage values of pollutants concentrations, revealed a rapid decrease of contaminants with depth. The background values of the pollutants were below the maximum limits for drinking and irrigation water and with no need of reactors, collectors, aeration or recirculation systems. Impermeable waste capping is discouraged in order to decrease leachate toxicity, decomposition time and conservative species, and in order to avoid high-reducing conditions that would mobilize redox-sensitive contaminants. A review on leachate-composition evolution and on natural-attenuation processes was undertaken to understand the interactions leachate-substratum, which is essential to properly estimate the leachate transport and implement the attenuation strategy. This strategy complements the traditional containment one regarding (1) the susceptibility of engineering liners to fail, (2) the inevitable diffusion of contaminants through them, (3) the remaining high number of old landfills before the requirements of liner systems and (4) the low-cost and feasibility for developing countries.

1. Introduction

Human activity inevitably involves a large and increasing amount of refuse, specifically municipal waste (MW). The European Union (EU) annually generates > 520 kg of waste per capita (approx. 572 000 olympic pools) which increases around 2% each year (EEA, 2010). The increase of MW generation is linked to the population growth and, to a greater extend, to the Genuine Progress Indicator; the economic growth indicator that incorporates environmental and social factors (Fig. S1, in the supplementary material, S). In the United States, as in the rest of major countries (Canada, Germany, France, Japan, United Kingdom...), waste is mainly handled in landfills (55%) rather than burned (12.5%), recycled or composted (32.5%) (EPA, 2010). This is especially accentuated in developing countries, where the landfilling supposes almost the only way of waste disposal.

Landfills generate and emit leachates; i.e., a toxic liquid that contains pollutants and is produced by percolation of aqueous substances through the deposited wastes. To avoid the leachate affecting surrounding lands, underlying aquifers or nearby rivers and, therefore, protect biodiversity and human health, two approaches exist: the containment strategy and the attenuation strategy. The containment strategy is based on the complete isolation of the waste by means of (1) bottom and top sealing liners, (2) collection systems of the pollutants emissions and (3) an everlasting-aftercare monitoring. The attenuation strategy considers that (i) a proper underlying natural substratum and (ii) the landfill itself, act as a biochemical reactor in which *natural attenuation processes* (dilution, dispersion, biodegradation, redox, precipitation, sorption, exchange reactions) take place, reducing and eliminating the contamination (Allen, 2001; Allen and Taylor, 2006). Although both strategies are meant to be applied jointly (c.f., multibarrier concept

Abbreviations: BOD, biological oxygen demand; CEC, cationic-exchange capacity; COD, chemical oxygen demand; δ, dry density; σ, electrical conductivity; Eh, redox potential; Ex_Cation, exchangeable cation; K_d, partition/distribution coefficient; MW, municipal waste; LMMOAs, low-molecular-mass organic acids; pe, the negative logarithmic value of the activity of the free electrons (e); *R*, retardation factor; Sol_ion, soluble ion; S, Supplementary material; $S^{BET}(N_2)$, specific-surface area; WSIC, water-soluble inorganic carbon; WSOC, water-soluble organic carbon; XRD, X-ray diffraction.

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in Europe), more effort has traditionally been devoted to the containment one because the attenuation strategy cannot be applied to all areas (e.g., karst limestone) and estimating the substratum behaviour to ensure that it performs properly as, what is called, an *attenuating layer*, is complex. Despite this, the containment strategy should not be the only approach.

First, under containment conditions, the waste itself remains a pollution source and, if something fails, the pollutants will be released: it is the so-called time-bomb effect. Engineering liners are likely to fail in a few years (Buss et al., 1995; Eid, 2011; Lee and Jones-Lee, 2009; Rowe and Sangam, 2002; Surmann et al., 1995), whereas the site remains dangerous for decades after this (EPA, 2007; Ritzkowski et al., 2006). In this event, the underlying natural substratum is the last chance to deal with the pollution. Second, diffusion of contaminants in leachate inevitably takes place through the compacted clay and engineering liners (Potter and Yong, 1993; Rowe, 1994). This transport is negligible relative to advective velocities but can result in significant long term contaminant flux in intact and non-fractured liners (Wiedemeier et al., 1998). From a sustainable perspective, we must act on that issue as we are liable for not leaving the present waste problems for the future generations (Brundtland Report, 1987). Third, the large majority of the existing landfills are old and abandoned dumps from before the imposition of installing composite-liner systems (150000–500000 in Europe were estimated by Hogland et al. (2011)). In these cases, landfills are not governed by the containment strategy and predicting the long-term behaviour of the interaction leachate-substratum is the only manner to know where it would be necessary to implement security measures to prevent and control landfill pollution. And finally, the attenuation strategy is independent from engineering or composite liners (expensive and complex structures), involving low installation, operation, maintenance and after-closure economical costs. This is critical for developing countries, due to their financial, technical, institutional and social constraints. The reluctance to believe that the attenuation strategy is safe, rendering water protection against pollution, is still strong. This locates to a second position what would be a more cost-effective plan. The cost to construct the engineered barriers, restore them after failure and remediate leachate-contaminated groundwater is vast. However, this could be mitigated by selecting an appropriate site that presents an attenuating layer, which would also reduce the environmental risk.

For these reasons, it is needed and expected that landfill policies will increasingly take into consideration the attenuation strategy. Despite this, there is a lack of studies that examine if a substratum can be used as an attenuating layer for safe disposal of wastes, as discussed in Cuevas et al. (2012). The current work is an advance over the few prior studies on soil samples at landfills because, as detailed in Table S1 together with other references reported below, those studies (1) are from samples surrounding the landfill area instead of underlying the layer of waste or (2) analysed a lower number of samples and parameters or/and (3) do not examine the variations with depth (Frascari et al., 2004; Goodall and Quigley, 1977; King et al., 1993; Koutsopoulou et al., 2010; Lake and Rowe, 2005; Marzougui and Ben Mammou, 2006; Munro et al., 1997; Xie et al., 2009; Zhan et al., 2014). This makes that the presented work can be applied to a broader range of contexts.

The objective of the present study is to identify if a common natural substratum can act as an attenuating layer and ensure enough protection against landfill pollutants. For that, we have assessed the performance of a widely distributed substratum underlying a no-lined landfill of 14 years old and we have considered that it would ensure enough protection for the environment and human health if the landfill pollutants were within the international authorized limits for drinking- and irrigation-water use. This work also provides information about the behaviour, interaction and effect of the released leachate pollutants on the underlying substratum. Finally, the natural attenuation processes that determine the capacity of a natural substratum as an attenuating layer of leachate pollutants are discussed.

2. Materials and methods

2.1. Materials

Attention was paid to the selection of the landfill substratum that would be analysed. It should be naturally underlying an old-MW landfill without barriers or collection systems. Additionally, the substratum should be a widely distributed and common natural material, with expected desirable characteristics for lessening the pollution of leachate. The selected substratum was chosen by its significant proportion of sodium smectite. Smectite is a 2:1 clay mineral with shrink-swell capacity and with elevated specific surface, ions-exchange capacity and charge (Geological Society of London, 2006). These properties are responsible for the high interaction of smectites with solutes by means of sorption, precipitation or cationic-exchange reactions; all of them natural attenuation processes (Czurda, 2006). Accordingly, monomineral rocks composed of smectite (bentonites) have been in common use as landfill liners (Hoeks et al., 1987) and have shown to improve the retention of landfill leachate pollutants in arkose sandstone (Ruiz et al., 2012).

The selected landfill was 14 years old and from South of Spain (Andalucía), with a Mediterranean climate. The landfill had an area of 30 ha and received 474500 t year^{-1} of MW. Three boreholes were drilled through 6–15 m of landfill waste to recover between 0.8 and 2.4 m-long of the underlying substratum in continuous vertical cores (Fig. 1). The cores were divided into 22 samples of different thicknesses and at different depths (Table S2), which were homogenized, preserved dark and refrigerated (4 °C) until their analyses. To facilitate the data interpretation, the cores are denoted as B and the samples as S followed by a consecutive number (B1, B2, B3 and S1, S2...). The liner material was composed of clayey sands: poorly graded sand-clay mixtures which typically developed during the erosion and accumulation of coarse detrital materials in fault troughs or low areas adjacent to granite massifs, during the Miocene period in Spanish tertiary basins.

2.2. Methods

The parameters of concern during the material characterization and the study of the leachate infiltration through it, were: percentage-based mineralogy, cationic-exchange capacity (CEC), external specific-surface area ($S^{BET}(N_2)$), dry density (δ), percentage-moisture content (H_2O (%)), pH, redox potential (Eh), electrical conductivity (σ), water-soluble species (organic and

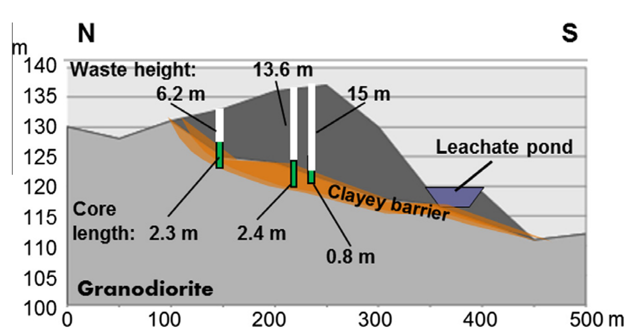

Fig. 1. Cross section of the landfill. Location and length depth of the boreholes (waste height plus core length).