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Research article

Comparative Life Cycle Assessment of possible methods for the treatment of contaminated soil at an environmentally degraded site

Alenka Mauko Pranjić [a], Primož Oprčkal [a], Ana Mladenovič [a], Peter Zapušek [b], Marjan Urleb [b], Janez Turk [a, *]

[a] Slovenian National Building and Civil Engineering Institute, Dimičeva ulica 12, 1000 Ljubljana, Slovenia
[b] Stonex d.o.o., Cesta Leona Dobrotinjška 18, 3230 Šentjur, Slovenia

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ABSTRACT

This study reports on the assessment of the environmental sustainability of different management practices for an environmentally degraded site in Slovenia: the Old Zinc-Works in the town of Celje. Life Cycle Assessments (LCAs) were applied in order to evaluate possible trade-offs by comparing a proposed in situ remediation scenario with two other reclamation scenarios (scenario 2: incineration, metal extraction, underground disposal and reclamation of the site by refilling it with replacement material, and scenario 3: underground disposal and reclamation of the site by refilling it with replacement material) and with a no-action scenario. The results of the comparisons performed show that in the case of the in situ remediation scenario, the consumption of resources is smaller by a factor of 51 compared to that in the second scenario and by a factor of 7 compared to that in the third scenario. The impacts on human health and ecosystem quality are approximately 30 and 3.5 times less in the first scenario than in the second and third scenarios, respectively. Compared to the impact of the no-action scenario, the impact on human health of the in situ soil remediation scenario is approximately 6 times less, whereas its impact on the ecosystem is approximately 4 times less. The results confirmed that the in situ soil remediation scenario is the most sustainable practice from an environmental point of view. Its main advantage lies in the achieved conservation of natural resources. Despite the recovery of valuable metals (Zn, Pb, Cu, and Ni) from the bottom ash, the second scenario is significantly more environmentally burdensome compared to both the first and third scenarios. This outcome is due to the significantly high impacts related to the consumption of fuels needed to support the incineration of low-calorific contaminated soil and to electricity consumption. The present study demonstrates that the results of LCA studies, in addition to technological, economic and social indicators, yield important information about the sustainability of different management practices and therefore should be an important part of decision-making when approaching the reclamation of environmentally degraded sites.

1. Introduction

Soil contamination due to industrial and mining activities is a global problem. Soils are the major sink for potentially toxic elements (PTE) and some organic chemicals that are released into the environment by anthropogenic activities; this fact is of particular concern since, due to their long persistence, these contaminants do not undergo microbial or chemical degradation (Wuana and Okieimen, 2011; Science Communication Unit, 2013). Thus, through different exposure pathways (skin contact and absorption, inhalation, and the direct ingestion of contaminated water or food), they present significant risks for the health of humans and of all living beings (Wuana and Okieimen, 2011; Panagos et al., 2013).

In Europe, the number of potentially contaminated sites is approximately 1,470,000 (Panagos et al., 2013). Over the last 30 years, approximately 80,000 such sites have been reclaimed (Witters et al., 2012). To bring contaminated industrial sites back to beneficial use, the contaminated soil need to be remediated in situ or ex situ, or the sites need to be subjected to some other kind of reclamation activity such as the removal of the contaminated soil

* Corresponding author.
E-mail addresses: alenka.mauko@zag.si (A. Mauko Pranjić), primoz.oprckal@zag.si (P. Oprčkal), ana.mladenovic@zag.si (A. Mladenovič), peter@stonex.si (P. Zapušek), m.u@stonex.si (M. Urleb), janez.turk@zag.si (J. Turk).

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and its replacement by virgin material or inert fill material obtained from secondary sources. According to data supplied by the European Environment Agency (2014a), excavation and disposal is the prevailing treatment practice in numerous European countries. However, according to Dermont et al. (2008), in the USA, the most commonly applied techniques for the remediation of sites contaminated with PTE are immobilization, soil washing, and phytoremediation. The selection of a suitable technique is of the utmost importance for successful remediation. It requires preliminary inspection and characterization of the site based on an adequate level of knowledge about possible remediation methods. The selection of the technique to be used should be based, on the one hand, on technological, economic and social criteria, but on the other hand, the environmental aspect needs to be considered (Capobianco et al., 2017). For example, the use of heavy equipment during site reclamation can be responsible for the production of significant amounts of greenhouse gases and other emissions, which can have an important impact on the environment. For site reclamation activities to be sustainable, the environmental impact should not exceed the benefits of such activities (Harbottle et al., 2007; Morais and Delerue-Matos, 2010; Cappuyns and Kessen, 2012). Life Cycle Assessment (LCA) can be used to quantify the impacts related to a certain reclamation activity, as well as to evaluate environmental trade-offs between different treatment options for contaminated soils. For this reason, LCA is considered a powerful tool that can be used to support environmental decision-making (European Environment Agency, 2014b, 2016).

The main goal of the LCA study described here was to evaluate trade-offs by comparing the in situ remediation scenario with the other two reclamation scenarios, which included landfilling of the hazardous waste (i.e., the contaminated soil or its residues after incineration), and with a no-action scenario. Some other possible in situ soil remediation methods, such as soil washing and phytoremediation, were not discussed in this study. The reason for this was because the characteristics and capabilities of these other possible remediation procedures were found to be unsuitable and inadequate for the efficient treatment of contaminated soil from the Old Zinc-Works site.

2. Materials and methods

2.1. Case study and description of the considered scenarios

This study refers to the reclamation activities that were performed at the Old Zinc-Works site in the town of Celje (in eastern Slovenia). At this site the industry started in 1874 with a zinc ore smelter and was later expanded to the production of zinc and lead oxides and chemicals. All industrial activities ceased in this area in 1990. However, they left behind a degraded site covering a total area of 17 ha. Due to the low environmental standards that were in force at the time of production, the industrial wastes, which included mainly metallurgical slags, ashes, tailings from zinc ore processing, tar from coke ovens, and various chemicals, were disposed of at site itself or mixed with the parent soil (Grilc, 2013).

In 2009, approximately 15,300 m^3 of contaminated soil was excavated at the degraded site during earthworks (the construction of a new sewerage system). The excavated soil was temporarily deposited in a number of piles located on the site itself. Chemical analysis of the soil showed that the total concentrations of As, Cd, Cu, Ni, Pb, Zn and PAHs exceeded the critical limit values according to the current Slovenian legislation (Official Gazette of RS, No. 68/1996). High water-soluble concentrations of Cd, Pb, Zn, and SO_4^{2-} were determined such that according to the national landfilling legislation (Official Gazette of RS, No. 36/2016), the soil was classified as hazardous waste (see Table S1 of the Supplementary Material). Different alternatives with regard to the Old Zinc-Works site reclamation and the management of excavated contaminated soils were considered. Finally, it was decided to remediate the soil using an immobilization process. In this way, the contaminated soil was processed in situ in order to obtain an inert geotechnical composite, which was used for reclamation of the site (Mladenovič et al., 2015a).

2.1.1. The first scenario (in situ soil remediation)

During this first scenario, the excavated soil was sieved by a mobile screener to a gradation of less than 16 mm. The remaining larger pieces of solid material, which mainly consisted of slag, were crushed by a mobile crusher in order to obtain grains smaller than 16 mm. A temporary depot was constructed on site from horizontal layers of the prepared material, according to geotechnical principles. This material was then moved from the depot by means of an excavator, in such a way that it scooped up the prepared material perpendicular to the layers. In this way, the greatest possible homogeneity of the contaminated soil was achieved. Paper ash, which was used as an additive and obtained from the incineration of deinking sludge, was transported to the remediation site from the paper mill at VIPAP VIDEM KRŠKO company. The soil and the additive were mixed together in a dry mass ratio of 3:1 in the mobile mixing plant, followed by adding water in order to reach an optimal water content (22 ± 2 wt %); this content was determined by using the Proctor compaction test (SIST EN 13286-2:2005). The produced composite was spread over the excavation area in layers, each having a thickness of 30 cm. These layers were separately compacted by means of a heavy roller up to 98% of the reference dry density as determined by the Proctor test. The procedure was repeated until a fill had been constructed (average thickness of approximately 3 m), in which the contaminants were immobilized by means of physical and chemical mechanisms. Finally, a layer of waste rock was spread on top of the fill to a thickness of 0.9 m using a bulldozer, in order to ensure sufficient resistance of the composite to freezing/thawing conditions. A heavy roller was then used to compact this layer. A water aerosol was used during the whole process in order to reduce the dust emissions. The distances between the excavation/installation site, the temporary depot, and the location of the remediation process were negligible. This condition meant that the remediation process was performed completely in situ.

2.1.2. The second scenario (incineration, underground disposal and refilling with replacement material)

In this hypothetical scenario, excavated contaminated soil was assumed to be removed from the site. To restore the site, the excavated pit needed refilling. Waste rock, which is a side product of stone quarrying, was assumed to be used as the fill material. The contaminated soil, which was excavated from the site, was assumed to be loaded onto a train, transported and thermally treated at a hazardous waste incineration plant in order to reduce the volume and mass of waste. Moreover, by incineration of waste containing significant amounts of metallic contaminants, partial recovery of valuable resources from incineration residues, i.e., metal-rich bottom ash, was assumed to be achieved. Incineration also yielded another benefit in the decomposition of the PAHs present in the contaminated soil (decomposition takes place at temperatures above 900 °C; Turk et al., 2014). Bottom ash still containing hazardous substances had to be disposed of in a landfill area for hazardous waste. The same was assumed for the other solid residues left after incineration (the unprocessed fly ash and filter cake), which were also classified as hazardous waste, considering their total content of metals and their potential leachability.