Sustainability of Vertical Barriers for Environmental Containment

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Abstract. Vertical barriers have long been used to control groundwater flow and subsurface contaminant migration from contaminated land sites. Commonly employed vertical barrier types available to owners and designers including those constructed using slurry trenching techniques such as soil-bentonite (SB), and cement-bentonite with slag (slag-CB), in situ soil mixed walls (SMW), as well as driven barriers such as sheet piles. The selection of the appropriate vertical barrier technique depended upon site geology, cost, and regulatory requirements with no consideration of the global environmental impact of the type of vertical barrier chosen in terms of sustainable engineering. In this paper, the sustainability of four commonly deployed vertical barrier techniques is discussed. Using the case study method, the paper evaluates a previously completed project where an SB slurry wall was constructed. Evaluations are described for an environmental sustainability assessment (based on the materials, fuels and equipment used; transport distances for personnel travel and materials/equipment transport), an economic sustainability assessment (based on the direct and indirect costs) and a social sustainability assessment (based on a survey to stakeholders/professionals/experts). The paper closes findings, conclusions and recommendations regarding the sustainability of vertical barriers.

Keywords: Vertical barrier, sustainability, soil-bentonite, slag-cement bentonite, soil mixing, sheet piles

1 Introduction

The United States Congress has declared sustainability as national policy committing "to create and maintain conditions under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic and other requirements of present and future generations" (The National Environmental Policy Act of 1969). For environmental remediation projects, sustainability is an important consideration in the selection of remediation approaches or even comparison of sub-approaches, e.g. vertical barrier walls. This paper provides a summary of a comparison of the sustainability of four common vertical barrier installation methods in terms of their relative environmental, economic, and social sustainability. Although this study is limited in scope, especially due to the relatively small size of the case study project, the methods presented may be used to assess the sustainability of larger vertical barriers or vertical barriers vs. alternate remediation methods.

2 Vertical Barriers

The four cutoff wall installation (i.e. vertical barrier) methods that were chosen for evaluation in this paper are commonly used techniques for slowing the flow of groundwater or the migration of subsurface contaminants. A planned companion paper will address other available installation methods and sub-variations of these methods.

2.1 Method 1: Soil-Bentonite Slurry Trenches

The terms slurry trench and slurry cutoff wall are widely recognized to refer to the installation of non-structural walls using long, continuous slurry supported excavations (Evans 1993). The slurry trench installation method refers to construction practices that utilize an engineered fluid, generally consisting of some mixture of clay and water, to hold open the sidewalls of an excavation, thereby permitting the excavation of deep and narrow trenches without the need for other conventional excavation support systems. Slurry trench cutoff walls have been employed at thousands of sites across the United States and internationally in a variety of applications, including at waste sites to contain contaminated groundwater, at "clean" sites to dewater excavations, and at dams, levees, and similar structures to improve stability. Most slurry trenches are excavated with excavators which can be modified to dig up to 30 m deep and deeper depths are possible with clamshell excavators.

In the installation of soil-bentonite (SB) slurry trench cutoff walls, the trench is excavated under slurry followed by a distinct backfilling step wherein the slurry is displaced by a mixture of soil and slurry. This is sometimes referred to as a two-step or two-stage slurry trench installation. SB cutoff walls are the most common type of non-structural slurry trench. These walls were sporadically used in the United States between the 1940s and 1970s after which their use became commonplace. Thousands of these walls have been constructed for a number of purposes.

SB backfill may be blended using a variety of equipment, but the most common and convenient method is to mix batches of backfill alongside the slurry trench using small excavators and/or dozers. The resultant mix looks like wet concrete (i.e. low to moderate slump) and is normally placed in the trench with an excavator. The mixture is placed in a semi-fluid state which allows it to flow into the trench and displace the trench slurry. Once the backfill operation is complete, the SB backfill consolidates slightly, ultimately behaving like a soft clayey soil. The most important property of the SB backfill is low permeability. Typically, SB backfill has a permeability in the range of 10^{-6} to 10^{-8} cm/sec. Environmental projects often require a permeability less than $1x10^{-7}$ cm/sec, but a levee or dewatering project may require a permeability less than $1x10^{-6}$ cm/sec. Either value is achievable with the right mix of materials. SB backfill has low strength and will remain soft (in the range of 0 to 15 kPa) for the life of the barrier, but this is nearly always sufficient to maintain a vertical cut through the wall for subsequent installation of utilities and other light structures. The most important variables in a SB mix design are bentonite content and grain size distribution. In general, SB backfill performs well when exposed to pure phase contaminants or impacted groundwater due largely to the fact that most of the matrix is composed of inert soil particles (Ruffing et al. 2018).

2.2 Method 2: Self-Hardening Slurry Trenches, e.g. Cement-Bentonite or Slag-Cement-Bentonite

Cement-Bentonite (CB) slurry trenches represent a smaller and more specialized type of slurry trench installation method used in the US since the early 1970s. In Europe and many other international locales, CB walls are the more common barrier wall choice. In this method, the wall is excavated through a slurry that typically consists of water, bentonite, cement, and granulated ground blast furnace slag cement. The trench slurry hardens in place, normally overnight. The hardened CB slurry serves as the final barrier wall. CB installations do not require a separate backfilling operation, and it's for this reason that this technique is sometimes referred to as one-step or one-phase slurry trench construction.

CB walls are excavated using hydraulic excavators and/or clamshell excavation equipment, the same equipment used for other slurry trench installations. At the slurry plant, cement, or some other setting agent, is added to the bentonite slurry. The viscosity of the mixed slurry is designed to be in the fluid range during the excavation process. The slurry is then pumped from the mix plant to the excavation. Once the excavation is completed to full depth, the bottom is cleaned, and the process moves on. The slurry stays in the trench and is allowed to set. Typical CB slurry will attain a butter-like consistency overnight and a clay-like consistency after fully hardening.

The properties of interest for most CB slurry walls are strength and permeability. CB slurry has relatively high water content, and because of this, there are more water-filled voids than in a SB backfill. Despite the higher void ratio, typical permeability values that are similar to SB backfills, generally less than $1x10^{-7}$ cm/sec after a month of curing. Without the addition of slag, permeability values are one to two orders of magnitude higher. CB can take months to fully harden, and long-term tests have shown CB permeability gradually decreases (improves) over long timescales, measured in years. CB material generally attains 75% of its ultimate strength after 28 - 56 days of curing and close to 100% after 90 days of curing. The addition of blast furnace slag typically results in a higher strength, lower permeability material, but it takes much longer to achieve the final properties with properties shown to improve out to 6 months and beyond (Opdyke and Evans 2005). Chemical compatibility is also an important factor when designing containment systems for impacted groundwater. CB is particularly well-suited to resisting certain oils and petroleum products, and thus, it is often preferred on sites with heavily contaminated groundwater.

2.3 Method 3: Soil Mixed Walls

The term soil mixing loosely refers to any construction approach used to mix soils with or without a reagent additive. In the fields of geotechnical and environmental construction, the term often refers to methods of soil mixing performed *in situ* for the addition of a cementitious reagent, most commonly Portland cement. The concept for soil mixing originated in the US, but much of the early technological development took place in Europe and Japan until the technology was reintroduced into the US market in the 1980's. There are many equipment configurations and processes that can be used for the successful completion of soil mixing, but the goal is almost always the efficient creation of a soil-reagent mixture with improved properties relative to the soils alone. Independent of the approach, soil mixing equipment typically includes some sort of cutting component (an auger or wheel), mixing paddles, and grout ports through which a fluid grout is pumped through a hollow shaft and out the grout ports. The fluid (which usually contains additives) acts as an aid to drilling and is mixed into the soil column creating the soil-reagent mixture. The term deep soil mixing (DSM) often refers to the use of multi-auger soil mixing rigs that can be used to install linear elements, e.g. cutoff walls. DSM auger configurations are specific to each contractor, but typically include 3 or 4 relatively small (~ 1 m) diameter augers spaced evenly apart. Another method of soil mixing for the installation of linear elements is chain trenching (Evans and Garbin 2009). This type of soil mixing is completed using essentially a large chainsaw mounted on a tracked chassis.

Soil mixing is often a preferred cutoff wall installation method on highly contaminated sites due to the limited handling of the contaminated soils, the high strengths (350 to 1400 kPa unconfined compressive strength UCS) and low permeability (~$5x10^{-7}$ cm/s) values that are achievable, and because the method is less susceptible to variations in surface topography and soil consistency.

2.4 Method 4: Sheet Pile Walls

Sheet pile in the context of vertical barriers generally refers to methods of driving, vibrating, or placing interlocked individual components of “sheet” material into the ground for the purpose of constructing a barrier. In most cases, the “sheet” material used is steel, but HDPE and vinyl can be used as well. The individual sheet piles often have a “Z” or “W” shaped cross-section in order to give the sheet pile enough rigidity to withstand the driving forces. Various interlock configurations are available, but all are designed to promote continuity between the individual components for the construction of a continuous barrier. Sheet pile barriers are regularly used in temporary applications in which the sheet piles can be retrieved at the end of the project for reuse elsewhere or in applications where the wall is expected to withstand substantial stresses, e.g. seawalls. Conventional sheet piling installations are generally limited to 40’ unless sheet piles are welded together to install deeper walls. Steel is the sheet pile material of choice for the case study sustainability evaluation.

3 Case Study

A SB cutoff wall having a length of 200 m, a width of 0.8 m and an average depth of 7 m was constructed on a site near the Bucknell University campus during the summer of 2016 as part of an NSF funded research project. The subsurface stratigraphy as determined prior to construction is depicted on Fig. 1. The original design included stripping of topsoil, and backfill made of the excavated silty sands, sands and gravels and underlying clays. These inferred subsurface conditions are assumed the same for each of the four alternative vertical barrier methods assessed for this sustainability assessment case study.

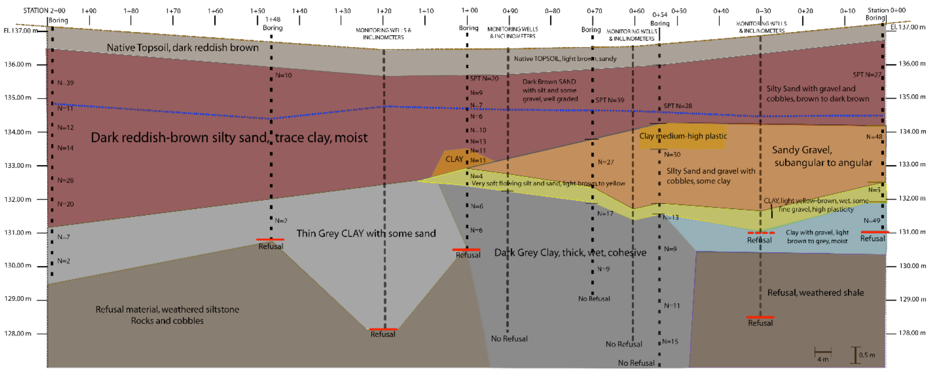

Fig. 1. Subsurface profile along the cutoff wall alignment based upon preconstruction investigations

3.1 Sustainability Assessment

In this study, sustainability assessment of the four vertical barrier alternatives (soil-bentonite wall (SB), cement-bentonite wall with slag (CB), in situ soil mixed wall (SM), and sheet pile wall (SP)) was performed using the triple bottom line sustainability framework (Reddy and Adams, 2015; Reddy et al., 2018; Reddy and Kumar, 2019). It consists of environmental sustainability assessment, economic sustainability assessment, and social sustainability assessment.

Environmental Analysis. The schematic in Fig. 2 shows the primary work phases for each barrier wall type and the inputs and outputs assessed for each in terms of environmental sustainability. The life cycle assessment (LCA) was conducted in SimaPro v8.5.2 software using the inventory data for each of the life cycle stages involved in each of vertical barrier methods (Pré, 2018; ISO, 2006). The scope of the LCA was limited to the construction stage only so the use and maintenance and end-of-life stages were not included. The functional unit used for the LCA was a 200 m long, 7 m deep and 0.3 m wide vertical barrier, i.e. the entire case study wall, including the specific geographic location.

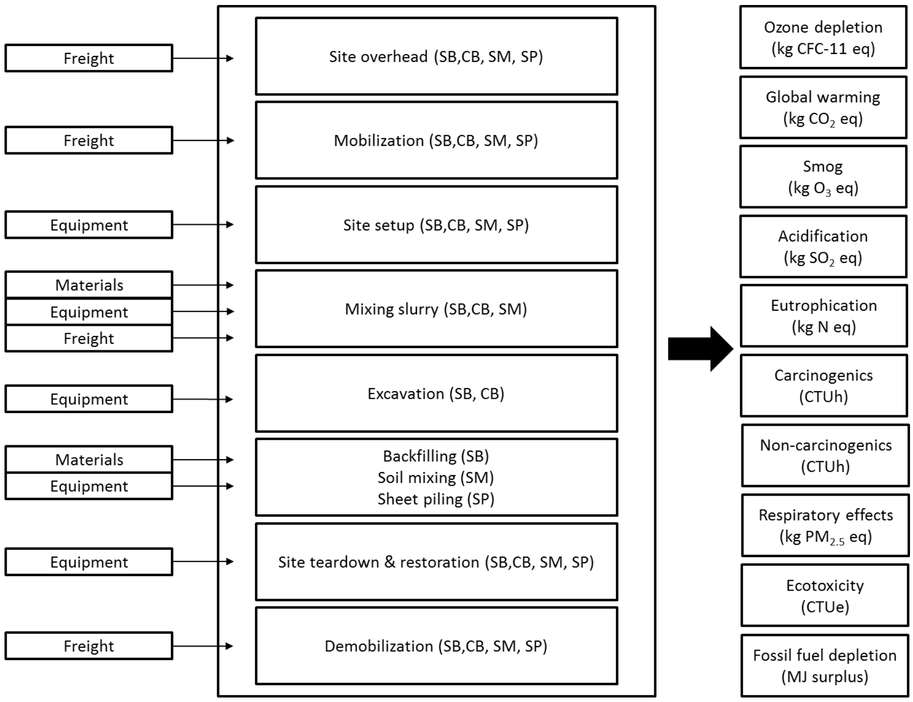

Fig. 2. Phases of construction, system boundary, inputs and outputs for life cycle assessment

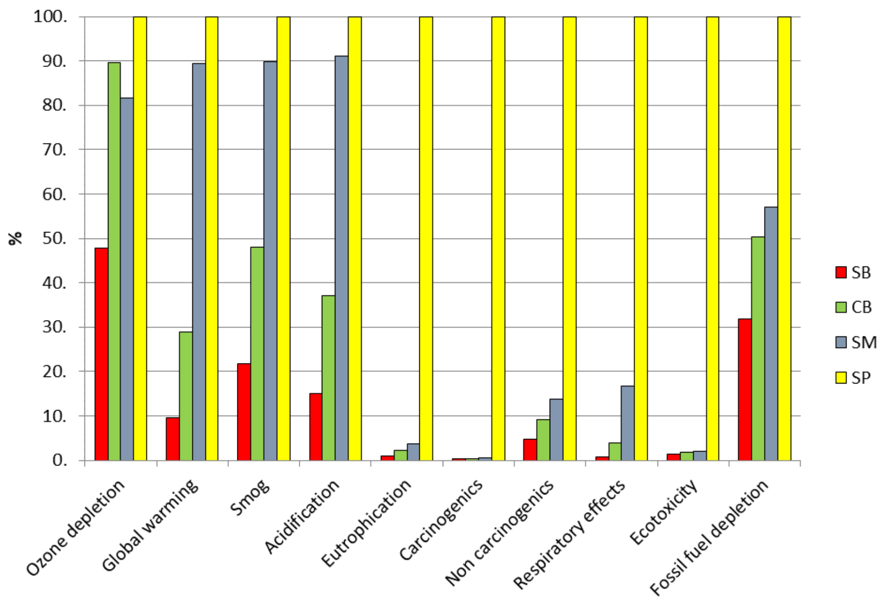

Fig. 3. Environmental impacts of the four vertical barrier systems across the midpoint impact categories of TRACI 2.1 LCIA method.

The Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) version 2.1 US-Canadian 2008 life cycle impact assessment (LCIA) method (Bare, 2002) was used for the environmental impact assessment. Using these methods, Fig. 3 shows the environmental impacts from the LCA of the four vertical barrier systems across all the impact categories of TRACI v2.1 LCIA method. Fig. 4 shows the results of the LCA with the freight distances limited to ten miles to determine if the reduction in freight distances influenced the results.

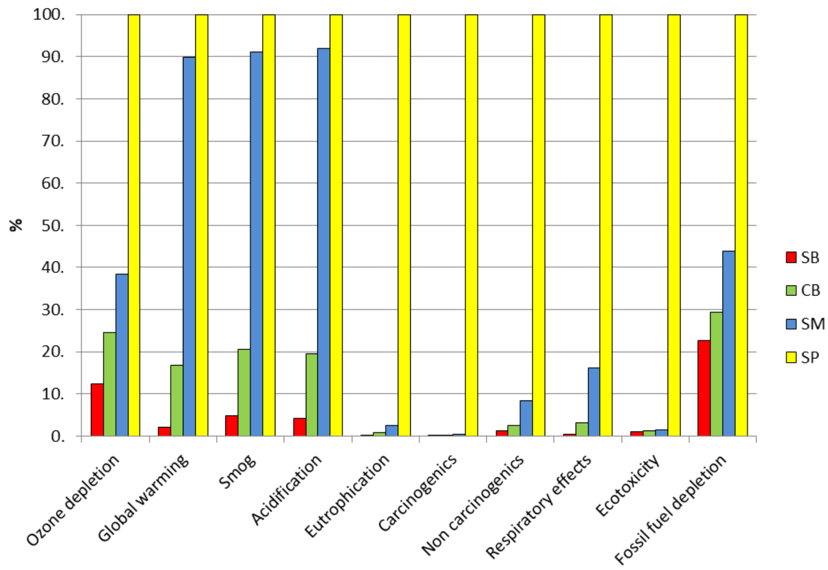

Fig. 4. Environmental impacts of the four vertical barrier systems across the midpoint impact categories of TRACI 2.1 LCIA method with freight distances limited to ten miles

Economic Analysis. Fig. 5 shows the direct and indirect costs associated with each of the four vertical barrier types. The direct cost accounted for the costs of freight/transport, labor, materials and equipment/machinery used in the construction of the vertical barrier system. The indirect costs were based on the carbon emissions during the design and implementation and were calculated using the social cost of carbon (SCC) established by United States Environmental Protection Agency (USEPA 2017).

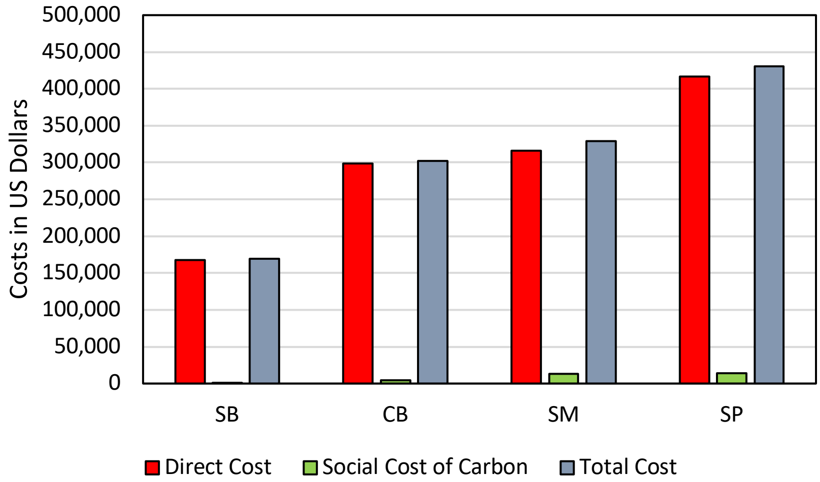

Fig. 5. The direct, social cost of carbon and total costs of the four vertical barrier systems

Social Analysis. Social sustainability is a subjective field which makes it difficult to quantify the social impacts of any activity. However, a few approaches, such as Social Sustainability Evaluation Matrix (SSEM), have been developed to quantify the social impacts of an activity (Reddy et al. 2014). In this study, the functional and social impacts of each vertical barrier option were assessed by conducting an online survey among professionals familiar with these barrier systems. Questions for the survey were structured to provide indicators of the social impact of each of the vertical barrier options on aspects at the functional, individual, community, economic and environmental levels.

The survey results were analyzed and scores ranging from 1-4 (1 represents the best, preferred, or most positive impact case and 4 represents the worst, least preferred, or least positive impact case) were assigned to each indicator under each category. The survey was performed using a Google survey with the indicators as shown in Table 1. Respondents included mainly contractors, designers, researchers and students with various years of experience in the field of vertical barriers. In total, 20 responses were received among which 12 were from contractors/designers/researchers with more than 10 years of experience, 3 were from contractors/designers with 5-10 years of experience, 3 were from contractors/designers with 1-5 years of experience and 2 were from students/researchers with less than one year of experience. The total score obtained for each barrier alternative under each category is also summarized in Table 1.

The sustainability index was calculated for each alternative following the Spanish Integrated Value Model for Sustainability Assessment (MIVES) methodology as explained in Reddy et al. (2018). The MIVES methodology assists with normalizing the scores obtained from the survey in the range of 0 to 1 which makes the comparison more transparent. The larger the number, the greater the sustainability. Table 2 shows the sustainability index values obtained by the barriers under each category and this information, along with overall social sustainability index, is also presented graphically in Fig. 6.

Table 1. Social sustainability assessment of the barriers based on the relative preference of the respondents

Category	Indicator description	Scores based on the survey			
		SB	CB	SM	SP
Functional Indicators	Relative preference of barrier type (by industry)	12	27	28	40
	Relative level of research and development involved for barrier type	24	27	29	32
	Relative ease of design (e.g. specialty designs)	18	30	34	25
	Relative ease of construction (e.g. equipment, skilled labor, no. of labors, specialty construction technique)	20	34	35	24
	Relative duration of construction	16	23	36	31
	Relative ease of maintenance and repair	21	29	27	34
	Relative flexibility to change design during construction for changed site conditions	21	22	28	36
Socio-Individual (workers, residents)	Relative level of noise pollution	19	19	30	46
	Relative exposure to dust and contaminants (if applicable)	35	34	25	17
	Relative risk of accidents (safety during construction)	20	22	24	41
	Relative opportunities for skill development	26	20	20	31
Socio-Community	Relative employment opportunities for locals	27	29	35	27
	Relative traffic congestion during construction	26	27	29	26
	Relative involvement of community organizations in the project	32	33	30	26
	Relative improvement in quality of life	22	25	27	29
Socio-Economical	Relative use of local materials	27	30	26	36
	Relative impact of the project on the local economic growth	28	31	28	32
	Relative impact on property value increase	32	32	29	25
	Relative potential for beneficial land use	32	27	22	24
Socio-Environmental	Relative impact on surrounding local water resources	19	22	23	24
	Relative air emissions (air pollutants, GHG) during construction	26	23	24	29
	Relative impact on land and agriculture	30	24	22	21
	Relative use of renewable resources	30	32	30	34
	Total Score	989	1055	1087	1151

Note: Lowest score = most preferred/best, highest score = least preferred/worst

Table 2. Social sustainability index for the alternative vertical barriers

Category	SB	CB	SM	SP
Functional	0.12	0.08	0.05	0.04
Socio-individual	0.15	0.15	0.14	0.09
Socio-community	0.12	0.10	0.08	0.11
Socio-economic	0.09	0.10	0.13	0.09
Socio-environmental	0.12	0.11	0.14	0.11

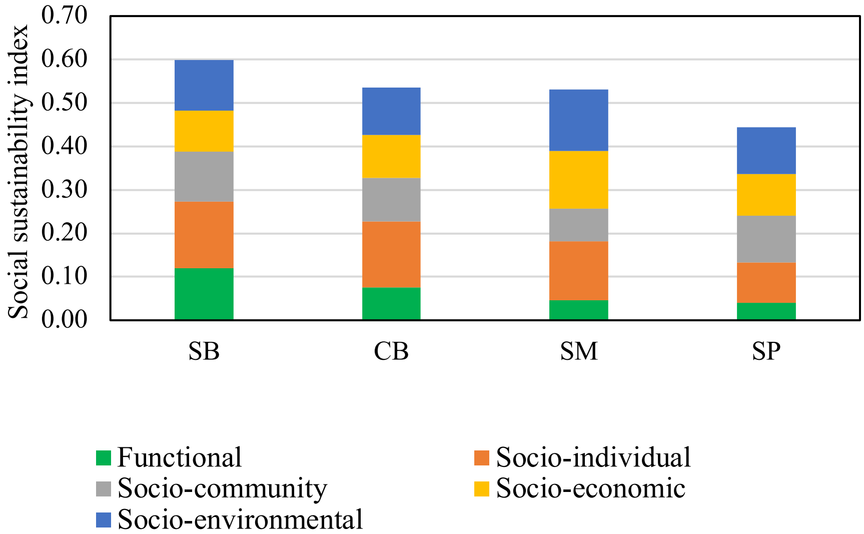

Fig. 6. Comparison of social sustainability of alternative vertical barriers

Discussions. A review of **Fig. 3** indicates that the SB and the SP vertical barrier systems have the least and the highest negative environmental impacts, respectively, across their life cycle (from raw materials acquisition to end of construction). The high negative environmental impacts of the SP wall mainly derived from the manufacture of the steel that was used, fuel used by the equipment to drive the piles, and the impacts from transportation of the materials and equipment to the site. In the CB and SM cases, most of the environmental impacts were due to the manufacture of the Portland cement, the transportation of the materials and equipment to the site, and the use of fuel for the equipment for mixing the slurry. The conclusions drawn from **Fig. 3** do not change with a review of the information in **Fig. 4** which shows the environmental impacts from the transport distance limited analysis as there is no significant difference in the outcome compared to the actual case. Thus, the SB wall can be regarded as the most environmentally sustainable vertical barrier system evaluated for the case study project.

In **Fig. 5**, the magnitude of the indirect cost is not as high as the direct cost because the carbon emissions across the life cycle of the case study barrier were limited due to the small size of the project. Based on the direct and indirect costs, the SB and SP cases were the most economical and least economical options, respectively. Even if the indirect costs are not considered, the SB option is still the most cost-effective option among the four alternatives.

As shown in **Table 2**, the SB wall obtained the highest social sustainability index values under most of the categories except for socio-economic and socio-environmental, which means the SB vertical barrier is the most socially preferred choice. As shown in **Fig. 6**, the SB wall also received the highest total social sustainability index meaning it is the most preferred choice socially. Since social sustainability is subjective to relative preference of stakeholders, this conclusion could vary with an increased the number of respondents.

4 Conclusions and Future Study

The sustainability assessment performed for this paper was limited in size and scope and the conclusions are relevant only in the context of the inherent biases for the case study project. However, the general conclusion that the SB barrier wall type is the most sustainable method amongst the four methods evaluated makes sense in the context of the simplicity of this method in terms of relative offsite material consumption and onsite material reuse.

For future sustainability assessments of vertical barriers, the economic sustainability analysis could include other indirect costs, e.g. the cost of other emissions, or a cost benefit analysis could also be performed for a thorough investigation of the economic sustainability of the different barrier systems. In that case, the indirect costs would sometimes far exceed the direct costs. However, in this study the indirect costs are limited to the SCC only. SCC is essentially an estimate of the monetized damages associated with an incremental increase in carbon emissions in a given year. The SCC integrates different climatic processes, economic growth, and interacts between the climate and the global economy to reflect the climatic impacts in terms of economic damages/costs. Although this does not account for all the economic and social issues associated with a vertical barrier, it does help in evaluating the broader long-term consequences of the different vertical barrier systems and thereby on the decision making of the most appropriate vertical barrier system to be used. A multi-criteria decision analysis could also be performed to integrate environmental, economic and social impacts and derive overall sustainability index.

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