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Concrete arches and reinforced soil: a sustainable alternative structure for road bridges

Arches en béton et sol renforcé: une structure alternative durable aux ponts routiers

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ABSTRACT: Road bridges are necessary infrastructures for transportation. As such, they are subject to thorough scrutiny for their environmental, social, and economic impacts. An adequate substantiality assessment applied to bridge design must minimize the negative impacts of the structure on the surrounding environment. A concrete deck and piles, together with cantilever abutments, is a well-established and conventional bridge design option. An alternative solution is precast concrete arches, widely used in bridge and tunnel constructions, providing stable, long-lasting support even under heavy load conditions. Concrete arches can be constructed together with reinforced soil walls (RSW) solutions, for both embankment and abutment zones, which are considered cost-effective solutions with short construction periods, making them an attractive option for such structural and geotechnical engineering projects. The compound concrete arch and RSW structure results in a resilient, efficient, and cost-effective design. This study presents a simple approach for an environmental and economic assessment of two bridge designs: a classical solution with cantilever abutments and a concrete deck slab, and concrete arches with RSW on top. Based on the environmental impact, and associated costs, the precast arch bridges with RSW solution are judged to be the better alternative.

RÉSUMÉ: Les ponts routiers sont une infrastructure nécessaire au transport. À ce titre, ils font l'objet d'un examen minutieux quant à leurs impacts environnementaux, sociaux et économiques. Une évaluation adéquate du caractère substantiel appliquée à la conception du pont doit minimiser les impacts négatifs de la structure sur l'environnement environnant. Un tablier et des pieux en béton, ainsi que des culées en porte-à-faux, constituent une conception de pont bien établie. Une solution alternative consiste en des arches en béton préfabriqué, largement utilisées dans la construction de ponts et de tunnels, offrant un support stable et durable, même dans des conditions de charge lourde. Les arches en béton peuvent être construites avec des solutions de murs en sol renforcé (RSW), tant pour les zones de remblai que de culées, qui sont considérées comme des solutions rentables avec des périodes de construction courtes, ce qui en fait une option attrayante pour de tels projets d'ingénierie structurelle et géotechnique. L'arche en béton composée et la structure RSW donnent lieu à une conception résiliente, efficace et rentable. Cette étude présente une approche simple pour une évaluation environnementale et économique de deux modèles de pont: une solution classique avec des culées en porte-à-faux et une dalle de tablier en béton, et des arches en béton avec un RSW. Sur la base de l'impact environnemental et des coûts associés, les ponts en arc préfabriqués avec la solution RSW sont considérés comme la meilleure alternative.

Keywords: Geosynthetic reinforcement; precast arch bridges; reinforced soil walls; sustainability assessment.

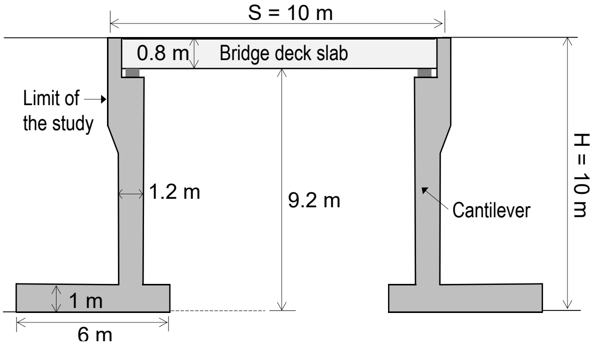
1 INTRODUCTION

Civil engineering works encompass a wide range of structures, including, but not limited to, buildings, pavements, bridges, foundations, and reinforced soil structures. The inclusion of sustainability criteria in the decision-making process of civil engineering design, including geotechnical engineering projects, is becoming prevalent (Aguado et al., 2012; MacAskill and Guthrie, 2013, Basu et al., 2014). Sustainability encompasses the fulfillment of three distinct sets of criteria regarding environmental, economic, and societal/functional aspects (Afnor Group, 2012; ISO, 2006). Bridges made of concrete arches with reinforced soil walls (RSW) are used for pedestrians, road, and rail traffics. The complexity of concrete arch and reinforced soil bridge systems resides in the proper assessment of soil-structure interaction, the impact of lateral soil pressure, and the boundary condition at the base of the bridge supports. This study presents a simplified and reduced approach and results to evaluate and compare the environmental and economic aspects of a sustainability assessment of two bridge designs composed of (i) cantilever abutments and concrete deck slab, and (ii) precast concrete arches and back-to-back reinforced soil wall embankment/abutment. The assessment of environmental factors is conducted utilizing a reduced Life Cycle Assessment (LCA) methodology (e.g., Damians et al., 2016). Ideally, a LCA should comprehensively evaluate all potential environmental implications associated with the construction process and materials employed in project activities.

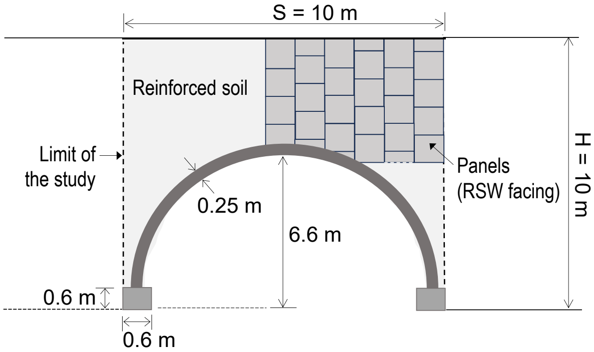
2 CASE STUDY AND METHODOLOGY

Figure 1 shows a schematic representation of the two types of road bridges included in this study. Dimensions were determined through conventional design methods. To properly evaluate the environmental impact across both alternative solutions, a Functional Unit (FU) must be defined. In this particular scenario, the comparative FU is defined as a bridge with a width of 12 meters and a span of 10 meters, designed to accommodate a two-lane civilian roadway with a distributed traffic surcharge load of 10 kPa, over a design life of 100 years. In this study, it is assumed that both alternatives are installed on a competent/stiff foundation and does not take into account the environmental and economic implications of site preparation and final grading (i.e., foundation preparation), as these impacts are expected to be comparable between the two types of structures. In the same way, the scope of this study is restricted to the bridge span S (see Figure 1). The analysis of the Cantilever+deck bridge does not take into account the material/filling located behind the cantilever abutments. Likewise, the Arch+RSW solution does not consider the RSW beyond the length S (see the limit of the study detailed zone in Figure 1). For the Arch+RSW bridge design, the back-to-back reinforced soil structure uses polymeric strap reinforcement and precast reinforced concrete panels.

The life-cycle stages encompass the entire process from the extraction of raw materials from the natural environment. Intermediate stages include material processing to create the necessary components, transportation of materials/components, installation work, etc.



(a) Geometry of Cantilever+deck.



(b) Geometry of Arch+RSW.

Figure 1. Schematic geometry for (a) Cantilever+deck and (b) Arch+RSW.

Table 1 shows the environmental inventory pertaining to the materials and construction-related activities included in the present investigation. The deck bridge and cantilever abutment alternative requires considerably more concrete and reinforcing steel (i.e., rebar) compared to the arch bridge segments and back-to-back RSW solution. The main structural component of the conventional bridge is the reinforced concrete, while that of the arch bridge is the reinforced soil (i.e., backfill and polymeric strap reinforcements).

Backfill material is assumed to be brought from a distance of 10 km. The cantilever+deck bridge includes on-site concrete pouring. The expected distance for the transportation of precast concrete panels and precast concrete arches from the manufacturing site was 10 km. In addition, the transportation distances for concrete mix trucks, steel rebar, and polymeric reinforcement straps were assumed to be 10 km because of consideration of the same distance/condition of transportation for all solutions.

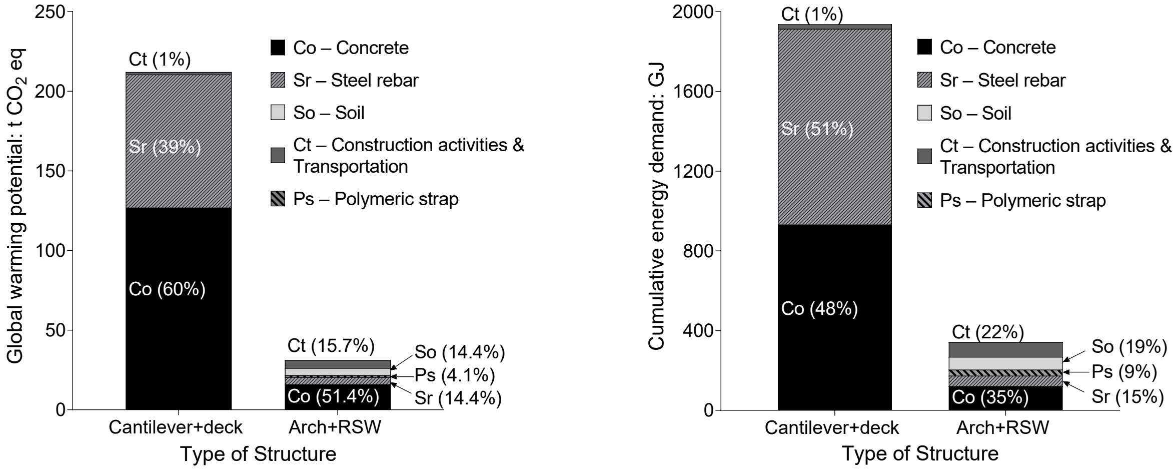
Life cycle assessments (LCA) were carried out using SimaPro v9.4.0.2 software (PRé Consultants B.V., 2010). Input values for material and energy usage were obtained using the Ecoinvent v3.8 database (Ecoinvent Centre, 2014) and ReCiPe 2016 method v1.1 (Huijbregts et al., 2017), all available within SimaPro. The economic analysis was conducted for both solutions using the ITeC BEDEC cost database. The environmental impact is assessed using only two midpoint indicators: the Global Warming Potential (GWP), which measures the impact of carbon dioxide equivalent (amount of CO_2 eq.) emissions on the atmosphere, and the Cumulative Energy Demand (CED), employed for the assessment of energy consumption (in Joules). Both environmental indicators are analyzed across the whole life cycle of the main involved materials, products, processes, and/or construction-related activities in both proposed bridge construction alternatives.

3 ENVIRONMENTAL AND ECONOMIC ASSESSMENT

Figure 2 shows the total GWP (2a) emissions and CED (2b) of both alternatives. As anticipated, the traditional solution (Cantilever+deck) results in the highest emissions of CO_2 eq. and energy consumption. GWP and CED values of the Arch+RSW structure were found to be about 85% and 82% lower than those of the Cantilever+deck design, respectively. This is explained by the high energy requirements in the production of steel and concrete, which serve as the main structural components of the conventional bridge case. Combined contributions of concrete and steel components are the most significant factors in the overall environmental impact of both cases, accounting for 58% and 37% of total CO_2 eq. and 46.2% and 45% of CED values, for the conventional and arch solutions, respectively. Compared to concrete and steel, construction activities and material transportation contribute a small portion of total CO_2 eq. and GJ values. Furthermore, according to the outcomes of the economic analysis, Arch+RSW solution led to about 47% reduction in construction costs with respect to the conventional bridge structure (Figure 3). In this solution, the RSW structure contributes most of the construction costs, at 56.7%, because more components need to be used for construction.

Table 1. Environmental inventory including materials, construction activities and transportation details.

Case	Category	Items	Unit	Value
Cantilever+deck	Structural material	Concrete	m^3	501.6
		Reinforcing steel (rebar)	t	39.3
	Construction	Pouring concrete	h	16.72
		Reinforcing (rebar) fixing	h	263.3
		Formwork installation	h	796
	Transportation	Concrete, reinforcing steel, etc.	km	10
Arch+RSW	Structural material	Concrete (footing)	m^3	8.4
		Precast arches	m^3	55.32
		Precast panels	m^2	100.2
		Polymeric strap	kg	288
	Construction	Reinforced backfill	m^3	601.2
		Panel installation	h	44.5
		Earth work (backfilling and compacting)	h	22.5
	Transportation	Concrete, precast arches/panels, reinfs., etc.	km	10
		Backfill material	km	10



(a) Total GWP for both bridges. *(b) Total CED for both bridges.*

Figure 2. Total (a) GWP, (b) CED of construction for both bridge solutions.

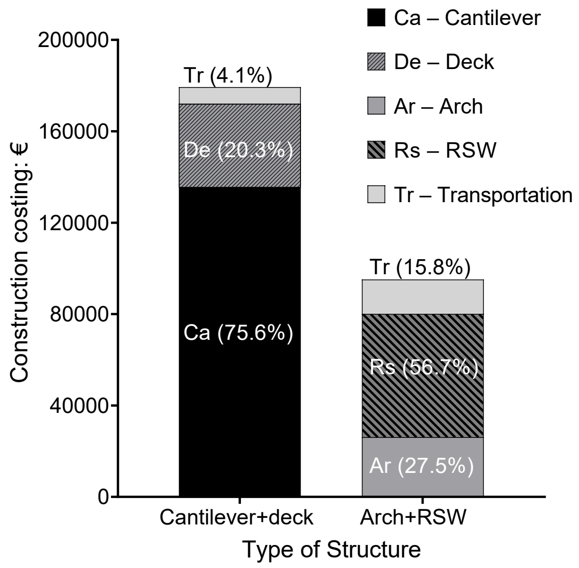


Figure 3. Construction costs for both bridge solutions.

4 CONCLUSIONS

A simplified life-cycle and economic assessment of Cantilever+deck and Arch+RSW bridge solutions that satisfy the same function were performed, and some results were presented. The primary findings of the comparison are as follows:

- Arch+RSW with reinforced soil structures showed reduced CO_2 eq. emissions and energy requirements compared to a conventional Cantilever+deck bridge design. Arch+RSW solutions resulted in reductions of about 85% and 82% for CO_2 eq. emissions and CED, respectively, with regards to the Cantilever+deck design approach.
- Reduced environmental indicators of the arch bridge alternative are attributed to the use of compacted soil and polymeric reinforcements as the primary structural elements, as opposed to concrete and steel in the conventional solution.
- Arch+RSW bridges can result in construction cost reductions of about 50%.

This study was limited to the environmental and economic impacts of two different bridge types: cantilever abutment with bridge deck slab and reinforced soil walls over precast arches. Forthcoming research requires a comprehensive study of full sustainability assessment including environmental, economic, and societal/functional/ technical aspects through multi-criteria analysis and different stakeholder scenarios. Furthermore, it is recommended to expand the scope of this study to encompass various types of bridges, including different dimensions and technologies.

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