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Life cycle assessment of a geosynthetic-reinforced soil bridge system – A case study

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ABSTRACT

Road infrastructures are a very important component of the world's total transportation network. Investment in its construction and maintenance is significant on a global scale. The paper presents some results from an environmental study of a geosynthetic-reinforced soil integrated bridge system. The Pavlovski potok stream in Slovenia was used as a demonstration case for this study. It is the first GRS bridge system with full-height rigid (FHR) facings in Europe. It was constructed at the end of 2014. The goal of these analyses was to compare two different types of bridges: the new GRS bridge system, which is comprised of a simple girder partially structurally integrated to FHR facings of GRS bridge abutments and a conventional reinforced concrete road bridge. The results of an environmental life cycle assessment (LCA) show that the GRS bridge system has a much lower environmental impact than an equivalent bridge conventionally built with reinforced concrete.

1. Introduction

Over the past two decades, some major developments have occurred in the field of the infrastructure management of deteriorating structures (Furuta et al., 2014). The purpose of infrastructure managing is to provide a more robust life-cycle management approach with a more accurate prediction of structural performance. The optimal conditions for life-cycle intervention require using the highest possible percentage of local natural material. Especially geotechnical engineering can significantly influence the sustainability of infrastructure development because of its early position in the construction process (Basu et al., 2014).

Life cycle assessment (LCA) has proven to be an effective method for quantifying and assessing the environmental impact of products or services throughout their whole life cycle, from cradle to grave (EN ISO 14040: 2006; EN ISO 14044: 2006). In recent years, research in the field of the LCA of civil engineering material has accelerated (Strauss et al., 2012; Dixon et al., 2017). Even though it has been widely used in different fields over the last decade, it was mainly used as a supporting tool. Its application, by means of a LCA environmental impact study for geosynthetic-reinforced soil integrated bridge systems (GRS-IBS), has not yet been published in publications.

Nowadays, and all over the world, the use of geosynthetic-reinforced soil (GRS) technology has become widely used in civil engineering infrastructure projects, such as embankments (King et al., 2017; Oliaei and Kouzegaran, 2017), retaining structures (Sadat et al., 2018), roads (Correia and Zornberg, 2018) and railway line structures (Satyal et al., 2018). Their advantages are in the achievable cost savings of the whole structure due to a simple and fast construction technique (Han et al., 2017), decreased construction time (Lenart et al., 2016) and good seismic resistance (Tatsuoka et al., 1997; Ghaderi et al., 2017; Helwany et al., 2017). It has been reported that the use of GRS technology in infrastructure projects has a low environmental impact (Damians et al., 2014; 2016). International agreements on reducing greenhouse gas emissions are based on country-specific action plans for mitigation and adaptation against climate change. The potential for geosynthetics to help achieve these targets has been identified (Heerten, 2012; Müller and Saathoff, 2015; Abu-Farsakh et al., 2016; Zastrow et al., 2017; Kumar and Das, 2018). Additional benefits on environmental impact can be achieved by combining geosynthetic material with various recycled materials as substitutes for high quality natural materials (Vaníček et al., 2017). Over the last two decades, a considerable number of studies have investigated the applicability of GRS technology on the construction of bridge support-structures (Tatsuoka et al., 1997; Adams et al., 2002; Wu et al., 2006; Nicks et al., 2016; Zheng and Fox, 2016; Ardah et al., 2017, Chang et al., 2017; Leshchinsky et al., 2017; Saghebfar et al., 2017; Iwamoto et al., 2015). In the case of a foundation in soft ground, there is a remarkable advantage in using GRS structures for the bridge abutments in comparison with concrete piles (Wu et al., 2006; Talebi et al., 2017). Bridge abutments with GRS structures have a lower cost and allow the entire structure to eliminate "bridge bumps", which are caused by differential

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settlement between the embankment and the traditional reinforced-concrete bridge abutments supported by piles (Helwany et al., 2003). The next advantage is in the use of natural aggregate from nearby quarries instead of concrete.

The design of a new bridge over the Pavlovski potok stream in the village of Žerovinci in the Municipality of Ormož in northeastern Slovenia (Lenart et al., 2016), which is presented in this paper, took into account the same considerations. From the beginning, the design of the bridge was limited by very short deadlines, requested by the investor, so that the bridge could be opened for traffic within two months - at the end of 2014 (this period included both the design and the construction of the bridge). Next, the geological situation was very inconvenient because of soft foundation soil, which encouraged the authors to propose integrating GRS on the bridge abutments. It would simultaneously support both the bridge beam and the approach road embankments. The solution combines two approaches for GRS integrated bridge system designs. One approach has been used in Japan (Tatsuoka et al., 2009) with full structural integration of a deck onto a pair of FHR facings. The other is being proposed by the FHWA (Adams et al., 2010) without full integration of the deck onto the GRS retaining walls. The solution analyzed in this paper is not the integral bridge in a rigorous sense. It is actually a bridge system that is comprised of a simple girder placed directly on the FHR facings of the GRS bridge abutments (Lenart et al., 2016). Thus, the deck is only partially structurally integrated to the FHR facings of the GRS abutments, forming the so-called GRS bridge system.

Although the stress and strain distribution in the deck and facing, as well as those in the GRS abutments, is highly dependent on the level of structural integration of the deck to the facing, the life cycle assessment method presented in this paper is not limited to a specific GRS bridge system. But it is also relevant for general GRS bridge systems that are comprised of GRS abutments: i.e. (a) GRS integral bridge system with a deck that is fully structurally integrated to the FHR facings of the GRS abutments; and (b) GRS bridge systems, which are comprised of a simple girder placed on the crest of GRS abutments, having either rigid or flexible facing and with partial or no structural integration.

In comparison with the traditional structure approach, the use of geosynthetic-based solutions generally results in a considerably smaller cumulative energy demand and smaller CO_2 emissions. Although analyses of several case studies on geosynthetic applications in pavements, retaining structures, and drainage systems (Stucki et al., 2011) have shown a smaller negative impact on the environment compared to traditional methods, no environmental performance analysis of a GRS bridge system has yet been reported in publications.

Until now, bridge life cycle analyses have already been used for several different structures. For example, it was used to evaluate and compare two different types of steel bridges. The difference was in the thickness of the bridge girder. These two bridges were compared according to CO_2 emissions and costs. The analysis included construction, use, and the replacement stage of the LCA. The results show that the minimized girder bridge resulted in both lower CO_2 emissions and lower total costs (Itoh et al., 2003).

Two comparisons of concrete bridge deck designs were made by Martin (2004), with regard to energy use and the emission of greenhouse gasses. A calculation of the whole life-cycle of the construction material was done that included raw materials, construction, demolition and the recycling phase. The calculation compared a steel-concrete composite deck and a concrete deck (including girders). The concrete alternative resulted in lower energy consumption and GHG emissions (defined as CO_2-equivalents), but the composite solution resulted in lower GHG emissions when recycled materials were used. In the second study, three types of concrete material for bridge decks were compared: lightweight, normal density and high-strength concrete (including girders). In the second case, for energy consumption, no significant difference was found for the three alternatives. In any case, it is known that high-strength concrete has a longer durability in comparison with other solutions and would suggest an alternative solution.

An environmental evaluation of the use of fibre-reinforced polymers (FRP) was done on two UK highway bridge-deck replacement applications. It was performed in order to compare the environmental impacts of two bridge deck replacement alternatives (Zhang, 2011), based on the calculation of carbon emissions. For the LCA analysis, the initial demolition, construction works, and future maintenance were taken into consideration. Within these boundary limits, three sources of CO_2 emissions were considered: the carbon of the materials, transportation and traffic disruption. The use of construction equipment, end-of-life demolition, and materials recovery were not considered. The life cycle design period was 120 years. The results showed that in the case of the entire service life of the bridge, the pre-stressed concrete option had a lower environmental impact than the FRP option. If we go into detail, it is obvious that emissions caused by the FRP are smaller in the construction stage. However, in the maintenance stage, FRP decks are less advantageous due to the higher amount of embodied carbon in the surfacing material.

A detailed comparative environmental life cycle assessment (LCA) of three bridges built in Norway was presented by Hammervold (Hammervold et al., 2013). This analysis included a wide range of bridge designs: a steel box girder bridge, a concrete box girder bridge and a timber arch bridge. The following were included in the calculations: material production, transportation, construction, operation maintenance, repair and the end of life stage. Traffic disruptions were excluded from the analysis. The three main impact categories were global warming potential (GWP), abiotic depletion potential (ADP), and acidification potential (AP). The results of the study showed that the materials for the main load-bearing systems (i.e. the bridge superstructure) and the abutments had a higher environmental impact because these parts needed large quantities of materials. A comparison of the three bridges showed that the concrete bridge performed best in the category of environmental impact, except in global warming, where the timber bridge proved better than the other two variants.

A life cycle assessment was also done for a steel arch railway bridge located in Spain, constructed with pre-stressed concrete decking (San Martin, 2011). The analysis included material production, construction, use, maintenance (repair and replacing) and the end of life stage. In the end of life scenario, it was assumed that 70% of the concrete and 90% of the steel would be recycled, except the wood, which was land-filled. The results show that the material production, which represents 64% of the total results, had the main environmental impact. The highest rate is for concrete and steel production, followed by timber production. This accounts for the large emissions of CO_2. Among the structure elements, the main contributing elements that had an impact on the environment are: the temporary structure, the substructure and the superstructure.

A comprehensive life cycle assessment of Norwegian bridges was performed on 14 bridges (Dequidt, 2012). The methodology was adapted to the needs of the case study, but the goal and scope was kept wide enough to enable comparisons between different bridge technologies. Input data were gathered from the client and subcontractors of the project. The input was assumed in cases where there was a lack of information. Output data (greenhouse gas emissions) were calculated by LCA software or directly collected from environmental reports.

The LCA methodology proposed by Lounis (Lounis and Daigle, 2010), for the sustainable design of highway bridges, was used to compare two bridge deck designs: a high performance concrete (HPC) bridge deck and a conventional concrete bridge deck. Calculations showed that the CO_2 emissions were almost three times less for the HPC than for the conventional concrete one. This was due to the production of cement. Concrete and timber bridges provide a lower environmental impact than steel or composite concrete-steel bridges. The greatest impact on the environment is with the material used for the production stage. But, due to future improvements in material design and a higher use of recycled materials, the environmental impact should be reduced.

Promptly evaluating the environmental loads of the various design