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Flexible culverts in sloping terrain: Numerical simulation of soil loading effects

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ABSTRACT

This paper investigates the performance of flexible culverts – often referred to as soil–steel composite bridges (SSCB) – when constructed in sloping topography. A number of 2D finite element models were created to simulate three case studies compromising two pipe arches and one high profile arch. The models were generated to investigate the effect of different surface slopes for different depths of soil cover. The aim was to understand and perceive the change of sectional forces in the structure with respect to slope increase under different soil covers. In addition, the effect of structure presence in the soil was also investigated in terms of soil stability. The results enable to realize the susceptibility of such structures to low heights of soil cover when built in sloping environment, which is seen in the incremental change in displacements and sectional forces, specially the bending moments. It is also found that the geometrical aspects of the profile shapes have more pronounced effect on their performance when introducing steeper slopes. The safety factor of soil stability is found to decrease when introducing such structures in the soil.

1. Introduction

The research development of flexible buried structures is believed to have started as early as 1913 in Iowa State College by Marston, Spengler and others [1]. Later and in the 1960s, the concept of ring compression theory was introduced by White and Layer [2]. The Ontario Highway Bridge design code (OHBDC) was first introduced in 1979 which included a section for the design of flexible buried culverts [3]. Similarly, the American Iron and Steel Institute (AISI) and the AASHTO have their own design procedure regulating the design of flexible culverts. A soil–steel composite bridge (SSCB) can be defined as a structure comprised of corrugated structural steel plates and engineered soil, designed and constructed to induce a beneficial interaction between the two materials serving its ultimate purpose as a bridge or a culvert [1] (see Fig. 1).

In Europe, a research report was published in 1970 by Klöppel and Glock covering the load carrying behaviour of flexible earth embedded pipes under different soil covers [4]. The development and the use of finite element analyses in the 1970s and 1980s changed the nature of culvert assessment since they permitted consideration of the geometrical and material details of the burial condition as well as the construction process, and earth and vehicle loads [5]. This has allowed more research prospects in understanding the composite interaction which was utilized in the soil culvert interaction (SCI) design method [6]. SSCB were first introduced in Sweden in the mid-1950s, the design was performed in a simplified manner using diagrams and so-called standard drawings, and thereafter a design method was first presented in 2000 and further developed by Pettersson and Sundquist [7,8].

Traditional concrete structures are perhaps the first conventional choice when deciding to build tunnels, canopies or similar structures in a hillside. For instance, in countries like Norway and Switzerland, there exist design guidelines covering the design and the load actions involved when building concrete structures in hillsides serving as avalanche protections for roads [9–11]. Given the status of SSCB being in many cases competitive to traditional concrete structures in normal conditions having horizontal or near horizontal ground surface [1,12], it is of an interest to explore the feasibility of SSCB as an economical alternative to traditional solutions in sloping terrain environment (see Fig. 2). Nevertheless, there have been some uses of relatively small SSCB in Norway, where a few cases were built in hillside locations and have proven to perform successfully [13].

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Fig. 1. A typical corrugated flexible culvert under the E6 road at Saltkällan, Sweden.

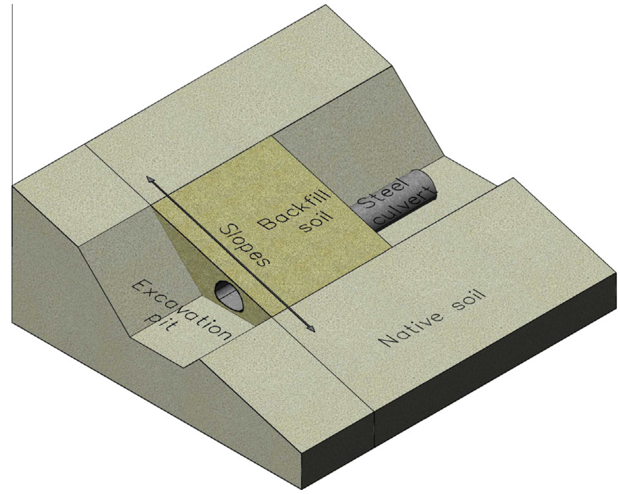

Fig. 3. Sketch showing the slope direction with respect to installed structure.

Fig. 2. Corrugated flexible culvert for a ski slope in Åre, Sweden.

1.1. Pettersson–Sundquist design method

The Pettersson–Sundquist design method, often called the Swedish design method (SDM) is based on several theoretical and empirical models which are compared and calibrated to full scale tests [7]. Upon design, external surface loads are converted into equivalent line loads using Boussinesq's load distribution theory. The design requirements imply verifying stresses in the pipe or arch for serviceability conditions (SLS) together with a set of ultimate limit state (ULS) verifications inclusive of formation of plastic hinge at crown, buckling capacity, and bolted connection, together with fatigue capacity, whereas these proofs can be performed according to relevant Eurocode. This design method is already in use in many countries in Europe especially in the Nordic region [14–16].

In conjunction to this study, the SDM is only applicable for a maximum longitudinal road surface slope of 10% (compare Fig. 3), thus the validity of the method for steeper slopes needs to be explored and investigated. In lieu of a special design, similar limitations do exist in AASHTO [17]. In the other hand, Norwegian documents do endorse the use of the method as for avalanche protection in a hillside environment provided that the maximum 10% slope is extended to at least three times the span from the steel pipe/arch edge [14]. This condition may in some cases increase the construction costs to undesirable limits, making the choice of SSCB in such cases less competitive to other conventional alternatives on the market.

1.2. Scope and limitations

This study is part of a series of investigations aiming to provide knowledge about the behaviour and feasibility of SSCB in sloping terrain. This paper aims primarily to focus on predicting the behaviour of these structures due to soil loading only under different cover heights and for various surface slopes. Therefore, external loads and other loads such as live loads are not part of this study level, as the authors intend to have separate studies covering these topics. The reason behind this is to be able to foresee and understand the different factors affecting the performance when introducing slopes to the structures, which practically reflected in the design and construction stages as well. Deliberately, this concept is in harmony with the design approach of SDM, where load effects are calculated for soil and live loads separately.

The structural behaviour of the corrugated steel wall is the main focus of this study, where sectional forces and deformations are explored and analysed for different numerical case studies. Moreover, the stability of soil around the structure will be also investigated.

The main idea of this study is to perceive the performance of SSCB when introducing different slopes to different cases of real structures. Having this in mind, this investigation is primarily based on numerical simulations in predicting the performance of SSCB using a finite element program called PLAXIS 2D. Although, this study does not attempt to compare numerical simulation results with design methods, the principle of the asymmetrical soil loading effect is illustrated in a limited calculation comparison using one design method. In overall, different design methods have different approaches for verifications, whereas this study should be read as first step guidelines of perceiving the various factors and the general behaviour of SSCB when built in sloping environment.

2. Case studies

When studying SSCB, it is of great importance to investigate the performance of different types of profile shapes. The importance lies in that the structural performance can differ considerably based on the different geometrical aspects for each profile. The