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Design of Soil Steel Composite Bridges

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ABSTRACT: Soil-steel composite bridges are considered competitive structures being an economical alternative to similar span concrete bridges. This frequently stimulates practitioners to push their design limits and expand the different areas of application including their performance in sloping terrain. This also implies that most design methods are continuously being developed to address new market challenges and at the same time to seek for better design and construction. This paper compiles the recent research efforts to advance the knowledge on the structural performance of soil-steel composite bridges (SSCB).

KEYWORDS: Soil Steel Composite Bridges (SSCB), Finite Element Modelling, PLAXIS 2D

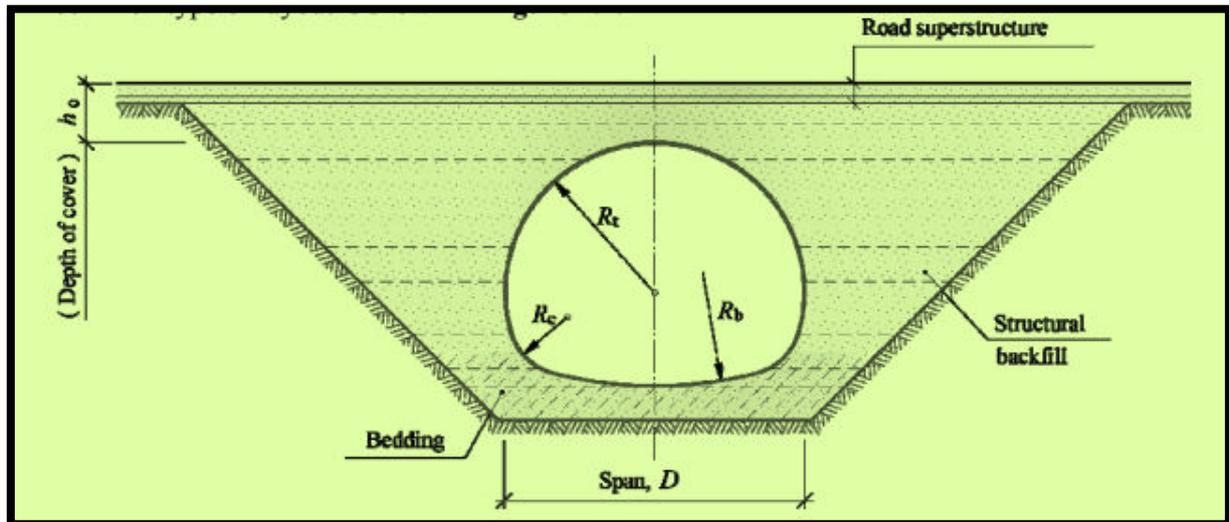
I. INTRODUCTION

The Soil Steel Composite Bridges (SSCB) are structures that are being used more often nowadays all around the world because those structures can be erected in an easier and faster way than for example a concrete bridge and are much cheaper than other structures that could carry the same functions. Soil steel bridge is a structure based on corrugated steel plates bolted together creating a pipe embedded in well compacted engineering soil surrounding the structure. Those flexible steel shell structures began to be used in bridge design at the end of the nineteenth century. Initially, such bridge structures were constructed as riveted pipes with circular cross-section and a relatively short span. The second generation of that type of structures had a span in the range of 8 to 16 m. Their development was ensued in Canada around 1960. It was encouraged by a better understanding of principles of interaction of soil and steel shell. In that period, an intensive research in these structures resulted in the development of a number of analytical methods for determining the distribution of internal forces and stresses structure.

This manual presents analysis models and methods for the design of soil steel composite bridges. Both new and existing structures can be analyzed using this manual. An example of this type of structure is flexible culverts made up of corrugated steel sheets in composite action with the surrounding soil. The analysis methods presented was originally based on the Swedish standard for steel structures BSK 99 and was applied for the Swedish bridge standards ATB Bro 94 and ATB Rörbroar. This manual has now been adapted to Eurocode and the Swedish Bridge Standard TRVK Bro 11 and recommendations TRVR Bro 11 and can be applied for other standards by adjusting the partial coefficients in the standard at hand and the soil and other parameters for local conditions. The manual can also be used for other structures than what could be considered “bridges” and thus following the general standards for buildings. The design methodology is however the same. The design theory where the soil acts both as load and as a stabilizing media makes this simplification possible. The design method examples presented are based on Swedish standards for i.e. plate profiles, bolts and tolerances. The standards and tradition might be different in other countries. The relevant regulatory authority in the country at hand, might thus issue complementary rules, i.e. partial coefficients, for using this manual.

Throughout this report, the term culvert is used to describe a bridge which consists of a pipe or an arch usually made of corrugated metal plates which, together with the surrounding compacted soil, form a structure capable of carrying a load. This type of structure is often referred to as a multiple structure since the pipe profile is created by bolting curved and straight metal plates together. In some cases, the pipe is made of helically corrugated sheet metal. An essential requirement is that the sheets are sealed together so that there is a complete static interaction between the segments or metal sheets of which the structure is built. This manual can in principle also be used for other types of flexible tubular

structures whose load-bearing capacity is achieved by interaction with the surrounding compacted soil. An example of a common type of layout is shown in Figure 1.1.



(Figure 1.1 Typical layout of a pipe arch culvert of corrugated sheet metal. Careful compaction of the soil around the culvert is important in order to achieve the desired interaction between the pipe and the soil.)

A culvert is often a cost-effective solution in many situations where a small waterway, road or railway is required to pass under a road or railway. In these cases, the culvert has the form of a “cut and cover” tunnel. There is no well-defined distinction between what is regarded as a tunnel and what is regarded as a culvert, but, it should be possible, from a strength point of view, to use this manual for the structural design of long tunnels built in the same manner as culverts. The manual is designed so that a large number of parameters that are significant in the design of culverts can be taken into consideration. Although the manual is primarily directed towards culverts made of corrugated steel sheet metal, it should be possible to use the design methods proposed for other structures, provided they consist of flexible pipe-like structures stabilised by surrounding soil.

II. CALCULATION AND DESIGN METHODS

The forces and moments described in this manual, are calculated using the principles given in the so-called SCI-method, Duncan (1977), Duncan (1978), Duncan (1979), with certain modifications regarding load distribution, soil modulus, depth of cover, and flatter culvert profiles. It is suggested that the load-bearing capacity should be verified following the general principles applied to structures according to the partial safety factor method. The suggested total design method has been verified by comparison with the results of full-scale tests performed and reported by Pettersson&Persson (1984), Temporal et al (1985), Beben&Manko (2002), Pettersson (2007), Flener (2009) and Pettersson&Wadi (2013). These tests have included loading to failure, and it has been shown that the safety factor against the development of a plastic hinge is high in the original SCI-method.

The following modifications have been introduced in the SCI-method:

- The design normal force has been reduced when the cover depth is large, following the principles given in Vaslestad (1990).
- The load-bearing capacity has been reduced taking into account second-order theory.
- Methods to calculate the soil modulus has been included based on Andréasson (1973).
- Box culvert profiles are included The calculation methods used in this manual have been developed by Lars Pettersson and are based on two different theories
- the so-called SCI-method (Soil Culvert Interaction) presented in Duncan (1978) and Duncan (1979), and
- the theory described in Klöppel& Glock (1970).

In order to create a theory that incorporates different pipe designs, different soils, different loads etc., the above theories have been complemented with currently used geotechnical analysis methods. The design methods were originally adapted to conform to the manual on steel structures published by the Swedish National Board of Housing, Building and Planning (Boverket), first BSK 99 (1999) and then BSK 07 (2007). The calculation models presented by Duncan and by Klöppel& Glock have been compared and calibrated by the results of full-scale tests, among which can be mentioned a pipe-arch profile in Newport, Wales 1984, Temporal et al (1985), a pipe-arch profile in Enköping, Sweden 1987 - 1991, Pettersson (2007), a box culvert over the Gimån river, Sweden 2002, Beben&Manko (2002), an arch profile (railway bridge) over the Skivarpsån river in Sweden 2003 – 2005, Flener (2003), Flener (2004), Flener (2005), and two box culvert profiles in Järpås, Sweden 2005 - 2006, Flener (2006) and Flener (2007). The results from the tests at the Skivarpsån Bridge and at the Järpås bridges are also presented in the PhD thesis Flener (2009).

Since an efficient interaction between the soil and the structure is crucial for the load-bearing capacity of the culvert, the entire structure, including the structural backfill, must be designed and built with the same care as a structure built entirely of steel or concrete. In addition to acting as a bridge, a culvert may often form part of a road or an embankment. This means that the requirements which apply for these structures must also be met by the part that forms the culvert.

Durability and lifetime:

In this manual the design model presupposes that the thickness of the culvert wall, whether this is made of steel or of some other material, remains intact throughout its lifetime. According to general principles, this requirement can be met using three principles:

- The pipe is given an extra thickness to provide for possible corrosion or abrasion, so that the effective structural thickness throughout its lifetime is at least that required according to these design rules.
- The pipe is given corrosion protection in the form of galvanising and/or protective painting so that its thickness throughout its lifetime is at least that required according to these design rules.
- The culvert pipe is inspected, maintained and repaired so that its thickness during its lifetime is at least that required according to these design rules. It is also necessary to check the soil surrounding the pipe to ensure that it remains intact and can fulfil its purpose to provide the required support to the pipe throughout the culvert's lifetime.

Preliminary design of culverts:

Culverts should be planned with the same degree of care as other structures and according to the rules and regulations laid down by the authority in question.

Geotechnical investigations:

Geotechnical investigations shall be carried out according to the principles that apply for the road, track or their equivalent in which the structure is to be included. Often the part of the track or road surrounding the culvert is heavier than the part containing the culvert. Therefore, the requirements regarding settlements etc. are no more stringent than those for the road or track in general. Culverts of steel are flexible structures and small settlement differences (angular changes of less than 1:50 in the pipes longitudinal direction) can normally be accepted, at least as far as the culvert's load-bearing capacity is concerned.

In addition to the geotechnical investigations required for the track or road in general, the structural backfill and the bedding material must be checked to ensure their suitability for achieving the necessary density, degree of compaction and stiffness. In order for the more exact method to be applicable, it is assumed that the properties of the soil are checked with regard to:

- a) particle size grading,
- b) maximum dry density, and
- c) achieved dry density.

Construction methods:

In many cases the erection and final construction of soil-steel composite bridges is a fast and cost-effective process. Figure 2.1 shows an example of the finalized erection of the steel part of the bridge just before starting the backfilling process.



(Figure 2.1 The finalized erection of the steel part of a SuperCor horizontal ellipse bridge)

In contrast to many other types of bridges where the soil surrounding e.g. abutments solely contributes in the form of a load, the load-bearing capacity of a culvert relies on an effective interaction between the pipe and the soil. Careful workmanship, where excavation, backfilling and compaction conform to the stated requirements, is critical for a successful result. The principles for the construction are indicated in this manual and in the regulations issued by the relevant national or local authorities.

Aesthetical design of soil steel composite bridges:

The vault form of the most used culverts is of many considered to be aesthetical pleasing. By completing the steel structure by well designed details, nice looking bridges can be achieved. Figure 2.2 shows an example of a nice design of an overpass for animals and Figure 2.3 shows a small bridge, where the glacis is covered by stones in concrete.



(Figure 2.2 By completing the steel structure with well-designed details, nice looking bridges can be achieved. This bridge is one of the largest SSCB in Europe having a 20 m span.)



(Figure 2.3 A nicely worked out glacis covering the slopes of a pipe-arch bridge.)

General calculation principles:

When designing a culvert, it is assumed that the culvert has a uniform section over a long distance in the pipe's longitudinal direction. Further, the calculation model assumes that it is possible to consider a strip with a length of one metre subjected to loading forces acting perpendicularly to the axis of the pipe. If the culvert changes section in any part, then each section must be checked. This also applies if the depth of cover or backfilling material varies along the culvert. When subjected to a traffic load, the upper part of the culvert profile (roughly speaking, the region between the quarter-points, see Figure 1.2) can be considered separately. This "toparch" has elastic supports whose characteristics are defined by the amount of lateral support that can be provided by the soil surrounding the pipe. The arch is also continuously elastically supported with the aid of the mass of soil lying above the arch. The most important calculation is directed to the treatment of this top-arch, as it is mainly this area that is affected by the traffic load. In the upper part of the pipe profile (the top arch), the normal force can from a calculation point of view, be considered constant, while the bending moment due to the traffic load is such that the negative value is roughly half the positive value. Culverts where the surrounding backfill consists entirely, or in part, of light-weight filling material are not directly covered by this manual. In those cases where such culverts need to be designed it is first necessary to establish the characteristics of the surrounding fill, in terms of its tangent modulus¹⁰ and density, in order to determine a stiffness parameter.

Bending moments:

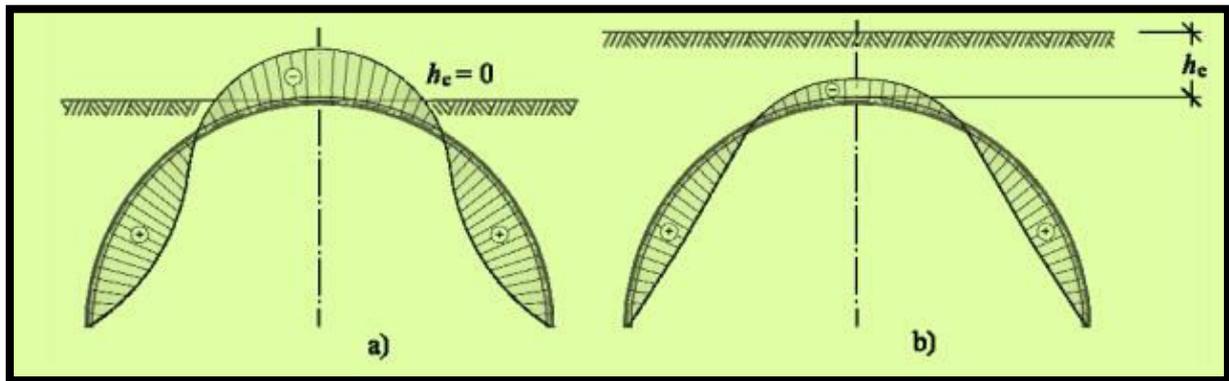
The bending moment in the wall of the pipe depends on the relationship between the stiffness of the soil and the stiffness of the pipe.

The moments which arise in a culvert are built up in three different stages:

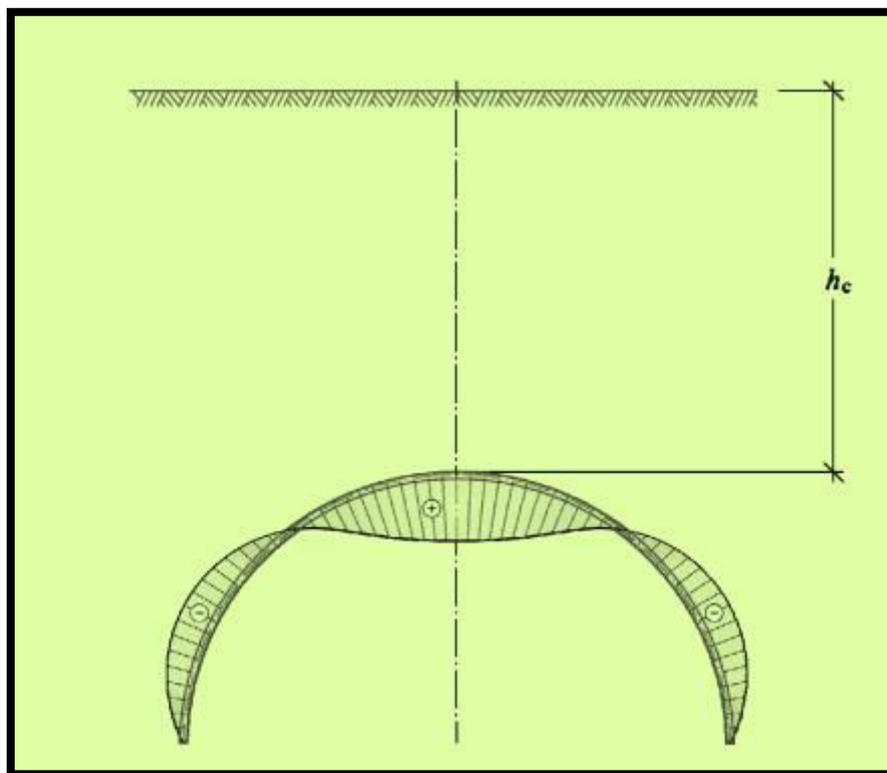
1. Firstly, a moment distribution is created by the lateral pressure which arises before any filling material is placed on top of the culvert, as shown in Figure 4.4 a)
2. When the culvert is later covered, i.e. material is packed above the level of the crown, the moment will change, as shown in Figure 4.4 b) and Figure 4.5.
3. Traffic and other loads will subsequently give rise to other moment distributions, as indicated in Figure 4.8 a) and Figure 4.8 b).

Bending moments due to the surrounding soil:

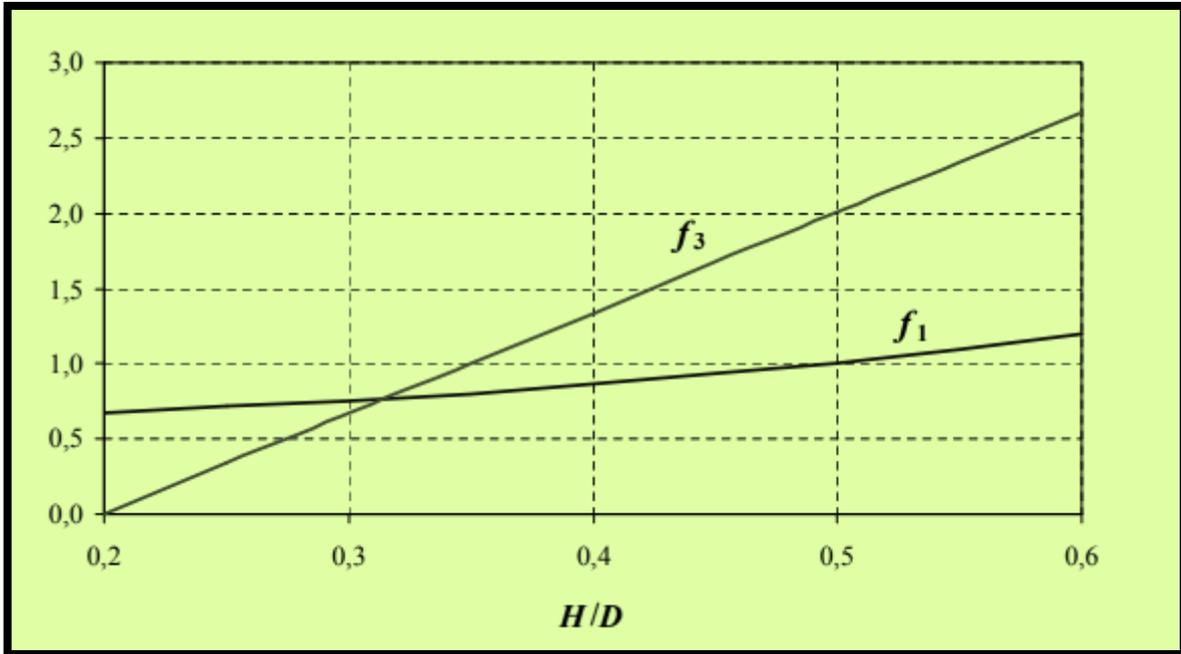
The equation is based on the observation that when the backfill is compacted around the flexible structure, the structure is pressed inwards at the sides and a negative moment is created at the crown. This reaches a maximum when the level of filling reaches the level of the crown. When the work of filling is continued above the level of the crown, the structure is pressed down and the negative moment is reduced. These processes are shown schematically in Figure 4.4. If the height of the cover is large, as is shown in Figure 4.5, the moment in the crown can change sign and become a positive moment.



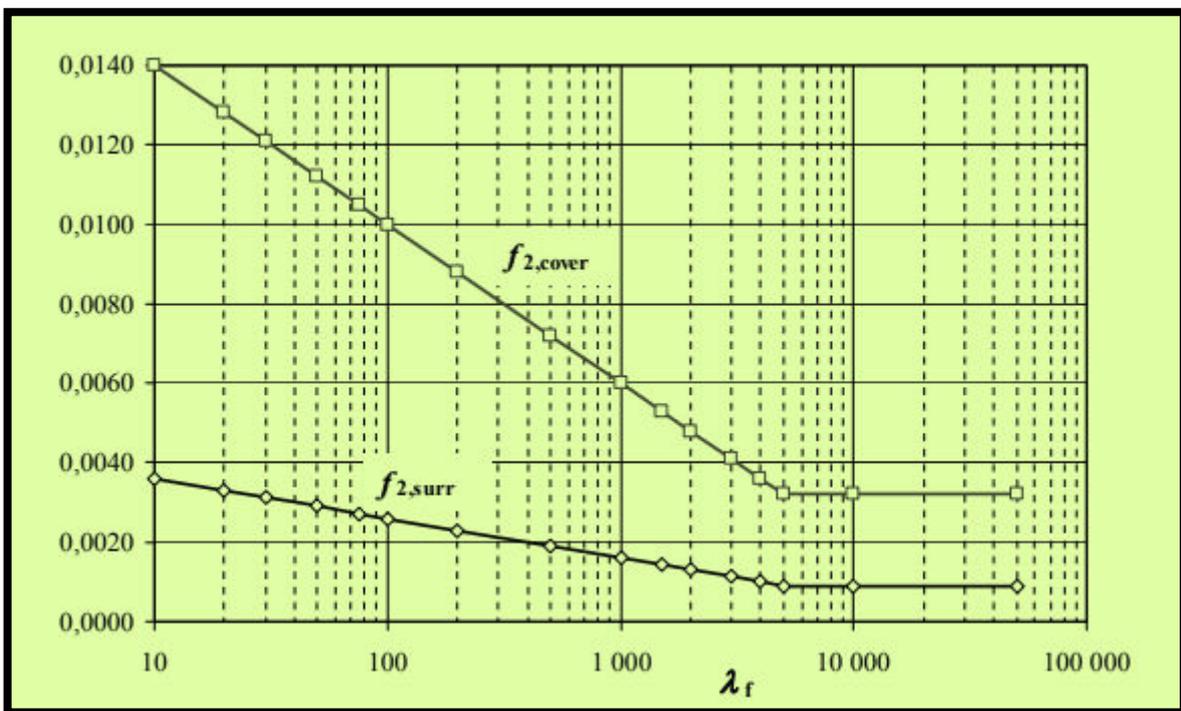
(Figure 4.4 A schematic representation of the distribution of moments in a culvert during backfilling. a) the moment distribution when the backfilling has reached the level of the crown and when the negative moment has reached its maximum value. b) the absolute value of the moment in the crown decreases as the cover over the crown filling increases.)



(Figure 4.5 With a large depth of covering fill, the moment in the crown may change sign, so that a positive moment is experienced in this region. Note that the figure is schematic both in respect of moment signs and sizes.)

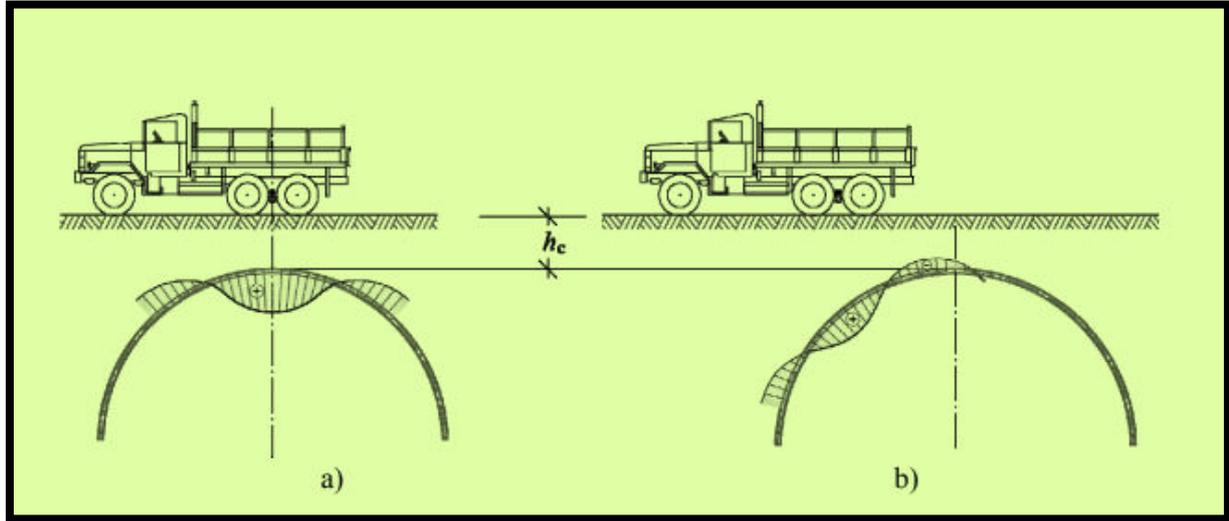


(Figure 4.6 The functions f1 and f3 as functions of the ratio of the height H to the span D.)



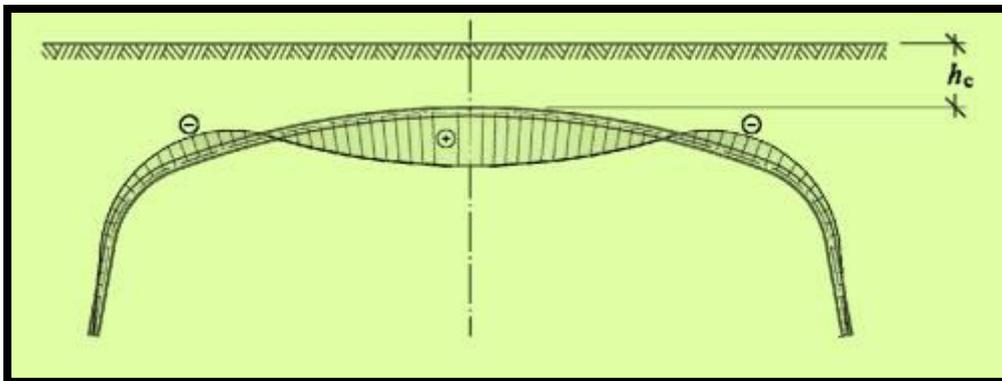
(Figure 4.7 The function f2 plotted as a function of the flexibility number λ_f .)

Bending moments due to traffic load:



(Figure 4.8 A schematic description of the moment distribution a) when the design load is above the crown, and b) when the load is positioned in such a way that the largest moment is at the sides of the culvert profile.)

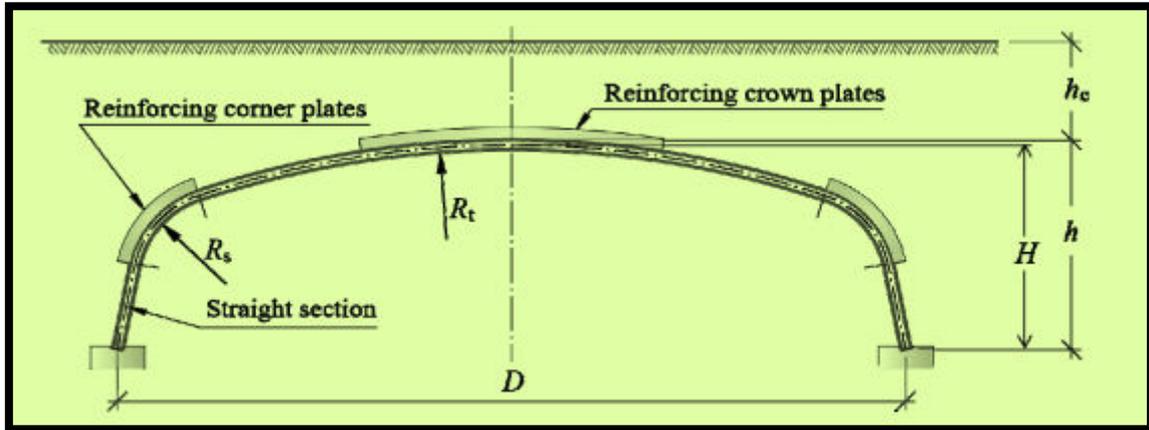
In the case of a culvert with a horizontal elliptical shape or a box culvert, the moment distribution corresponding to the condition in Figure 4.8 a) is approximately as indicated in Figure 4.9.



(Figure 4.9 The moment distribution in a horizontal ellipse or box culvert under the traffic load which gives the largest moment. Note that the figure is schematic.)

Distribution of moments in a culvert with varying cross-section:

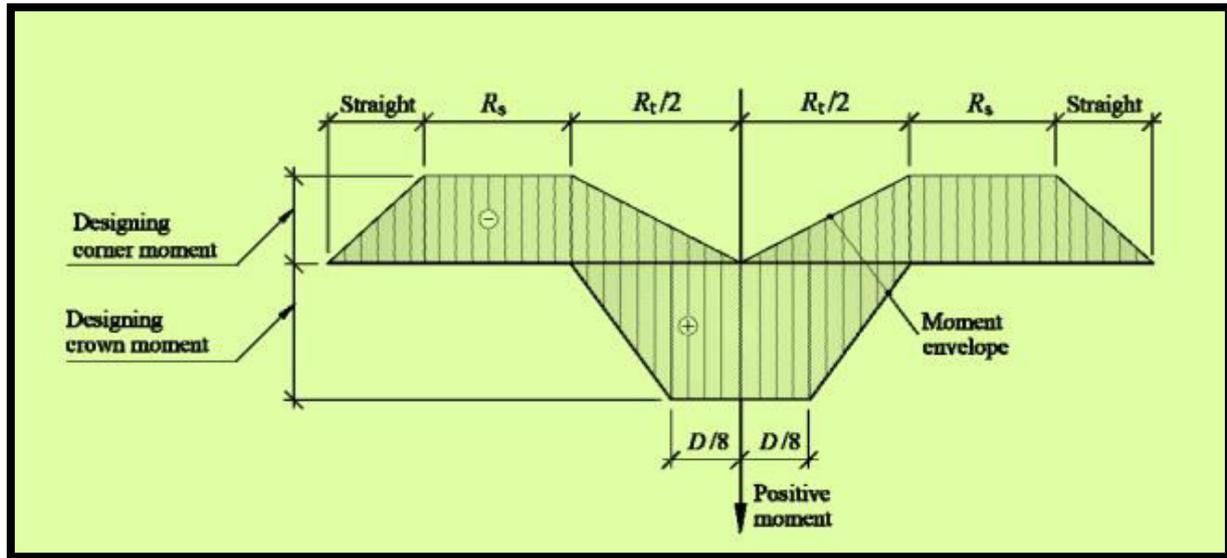
A culvert is usually designed with a constant cross-section and, as indicated above, this means that it is only necessary to calculate the moment-bearing capacity in the crown where the stresses due to bending are largest. In some cases, however, it can be more economical to use reinforcing plates to increase the load-bearing capacity in the most exposed regions, as shown in Figure 4.13. The necessary dimensions of these reinforcing plates are calculated according to the principles indicated in Figure 4.14, which shows schematically the moment distributions for both soil and traffic loads.



(Figure 4.13 It can in some cases be appropriate to reinforce the cross-section with reinforcing plates.)

The design corner moment, as indicated in Figure 4.14, is the combined moment due to soil and traffic loads according to the principle:

Dimensioning corner moment = $\frac{2}{3}$ of the crown moment due to soil load $(4.z) + \frac{1}{3}$ of the crown moment due to traffic load.



(Figure 4.14 The principles for the determination of the moment distribution in box culverts and, where appropriate, in horizontal elliptical culverts)

Reinforcement plates are corrugated plates bolted to the culvert profile where it is found necessary. Reinforcement plates may be continuous or intermittent. In the case with continuous plates the design is straight forward using the section parameters for the two plates bolted together. In the case with intermittent plates, for example as shown in Figure 4.13, the calculation of section forces starts with the un-reinforced culvert profile (often referred to as the “barrel”). If reinforcement is deemed necessary a preliminary amount of reinforcement plates is determined by adding plates until the bending capacity of the composite section is high enough comparing the bending capacity with the design bending moment. Both haunch area as well as the crown area should be checked. The length of the plates is determined by extending the plates until the section is found where the capacity of the basic culvert profile (barrel) is high enough on its own. The moment distribution is shown in Figure 4.14. After the amount and length of the reinforcement plates have been estimated the culvert profile is checked in the same way as a culvert without reinforcement plates using the section parameters for the composite section. If the length of the reinforcement plate in

the crown area is less than the length of the top radius plate the bending stiffness EI should be replaced with an equivalent bending stiffness for the composite section taking the length of the reinforcement plate relative to the crown plate length into account. With this preliminary layout and size of the strengthening plates the stiffness of the strengthened culvert profile should be determined in order to calculate section forces for the now stiffer culvert. This is done according to the principles above by calculating a new stiffness number for the culvert now stiffened by the reinforcing plates, compare Pettersson (2007).

III. CONCLUSION

Soil steel composite bridges (SSCBs) have become a competitive alternative to conventional/ types of short span bridges being comparatively feasible in its construction time and the total cost as well. The design of SSCBs is faced nowadays by many challenges requiring longer spans and even low heights of cover in some other cases. This would require having a robust and flexible design methods aiming to tackle these challenges together with the new technology in profile sections and material.

Suggestions for future research

Here are some suggestions for improving the FE-model and further research for the dynamic analysis of soil-steel composite bridges. Influence of assigning frictional behavior between the backfill and the culvert on the response of the bridge need to be investigated. The behavior of the ballast and the backfill around the culvert can be non-linear. Using nonlinear behavior with a specified tension cutoff can improve the behavior of the soil material. In order to model the wave propagation properly, coupled criteria between the mesh size and the time increment should be respected, and, need to be investigated deeper. Moreover, appropriate boundary conditions should be used to avoid the reflection of the waves. For this purpose, using of infinite elements for the boundaries can be examined. In order to better capture the acceleration in the ballast, a moving mass or a sprung mass model can be adopted instead of moving concentrated loads. Besides, the acceleration of the train itself is also of the interest for the high-speed train applications for further checking the comfort criteria. The influence of the culvert shape, span, culvert length, and height of the cover on the bridge response shall be investigated. Moreover, the influence of different parameters (soil Young's modulus, Poisson's ratio, density, and damping properties) on the natural frequencies of the structure and on the bridge responses due to the train passages with higher speeds need to be investigated. Finally, more full scale field measurements are needed to calibrate the FE-models.

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