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DEVELOPMENT OF THE SWEDISH HANDBOOK FOR BURIED FLEXIBLE CULVERTS

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Abstract

The development of the Swedish handbook on design of buried metal flexible culverts started in 1983 with the Swedish National Road Administration highlighting the need for a design method capable of handling larger spans and small heights of cover. A research project was started at the Royal Institute of Technology in Stockholm and a first full-scale test on a 6,1 m pipe arch culvert having a 1,0 m height of cover was performed. At the same time theoretical studies of different international design methods was started. A second full scale test was performed on a 6,0 m span pipearch culvert varying the height of cover. The design handbook was presented in 2000. Based on the Soil Culvert Interaction-method developed by Duncan the design method allow the designer to calculate both thrust and bending moments in a large variety of culvert profiles and taking different soil conditions into consideration. Both road and railroad live load can be used. Several full scale tests have been performed including the so-called BoxCulvert. A revised handbook has been presented in 2006 including the BoxCulvert extended method. The Swedish bridge codes, both for road and railroad bridges, require the use of the handbook method in the design of buried metal flexible culverts.

Key words: Flexible culvert, full scale tests, height of cover, ultimate load, design handbook, thrust, bending moment, live load, railroad, BoxCulvert

1. INTRODUCTION

Corrugated flexible steel culverts having larger spans are being used around the world. Often, also a low height of cover is necessary. To increase the free room other pipe profiles than the circular type are being used. Durability has been improved with surface treatment specifications defined in bridge codes and therefore life span is today fully comparable with other bridge types. Todays corrugated flexible culverts compete with ordinary concrete, steel and timber bridges. Interesting in this context is that larger spans, lower height of cover and new types of culvert profiles call for design methods being developed.

Over the years different design methods have been developed and incorporated in international bridge codes. However, the design models have been simplified and therefore conservative. Since 1983 the design of flexible culverts embedded by soil has been studied in greater detail in Sweden. The requirement has been to develop a rational design method for every-day use but at the same time able to handle large spans and low height of cover.

It's well known that the flexible culvert bearing capacity is mainly dependent on the surrounding soil. Therefore, with larger spans being more common, a design model must be able to model the quality of the soil more precisely. Developing the Swedish design model this has been one of the main goals and equations have been given to make it possible for the designer to calculate a design soil modulus. With a long series of full scale tests with spans ranging from 6 to 14 m to support the design model the Swedish design method make it possible to design structures in excess of 20 m.

2. DESIGN METHOD

2.1 General

The design model is based on the so called Soil Culvert Interaction method (SCI-method) originally developed by Duncan. The SCI-method allows the designer to calculate section forces (thrust and bending moments) for a variety of culvert profiles. The SCI-method is supplemented with buckling theories developed by Klöppel & Glock. Together with basic formulas for the calculation of a design soil modulus the design model allows the designer to analyse the effect of using different steel plate strength and stiffness as well as different soil particle size distribution and relative compaction on the bearing capacity of the soil culvert structure.

The design method is based on the so called flexibility number defined as

$$\lambda_f = \frac{E_s D^3}{EI} \tag{2.1.1}$$

were E_s is the soil modulus, D and EI are the culvert span and culvert wall bending stiffness respectively. The flexibility number represents the relative stiffness between the soil and culvert profile and is a major parameter in the design of a flexible culvert embedded in soil.

As in all soil culvert installations an effective compaction with the backfill soil placed and compacted in layers is crucial for the ultimate capacity of the structure. In the design model the designer may choose a soil particle size distribution and relative compaction appropriate for the structure at hand. In the handbook three different soils commonly used in Swedish bridge and culvert installations are defined. The design method will, for a given live load and a given soil material (denisty, particle size distribution and relative compaction), result in a design steel plate stiffness and strength.

Variations in cover height are of great interest when it comes to low cover heights in combination with live loads. Therefore, variations in cover height are taken care of by calculating a crown rise that will result in a net cover height used in the calculations.

The required minimum height of cover is dependent on the load that has to be carried. However, even if the design method will indicate a minimum cover needed for a particular load, the requirements for an adequate compaction of the soil above the culvert may very well prevail. Also, failure of the soil under heavy live load must also be avoided. Therefore, in the design handbook a soil cover of min 0,5 m is indicated, this in turn being based on full scale tests having a soil cover of 0,45 m only.

For simplicity the handbook indicates equations for calculating section parameters for commonly used corrugations.

2.2 Culvert profiles

In the original SCI-method six different culvert profiles are included. These are the single radius arch, the double radius arch, the horizontal ellipse, the vertical ellipse, the circular profile and the pipe arch.

All the profiles mentioned above are commonly used. However, in recent years the so called box culvert has been introduced, compare figure 1. The difference between the horizontal ellipse and the box culvert is mainly the smaller haunch or side radius used in the box culvert.

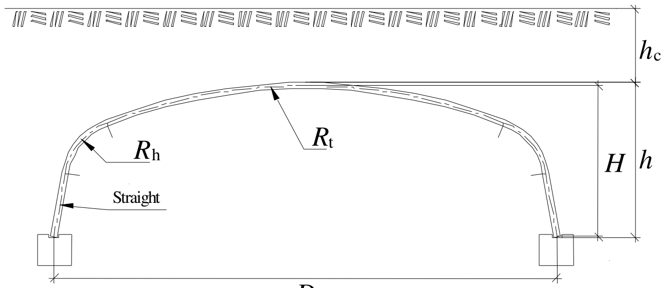

Figure 1. Box culvert profile

Since the box culvert profile is very effective in certain situations necessary adjustments have been made to the design model to include the box culvert as well. All in all seven culvert profiles are therefore covered by the design model.

2.3 Limitations

An important goal developing the design method has been to reduce the number of method limitations to a minimum. However, there are some important limitations that have to be observed, the first one being the seven accepted culvert profiles as indicated above.

Secondly the method is only valid when using frictional soils within a defined backfill envelope.

Thirdly, since the structure that is dealt with in the design method is what is called flexible it is natural to define the flexibility limits within which the method is valid. The starting point in this context has been the limits within the original SCI-method calculations were performed. The main limitation in the design method is therefore the upper and lower limits for the flexibility number i.e the relative stiffness between the culvert itself and the surrounding soil. The following limitations prevail:

$$10^2 < \lambda_f < 10^5 \tag{2.3.1}$$

Another important limitation is the minimum cover height of 0,5 m which is introduced partly for soil compaction purposes and partly to guarantee a minimum thickness of the road structure above the culvert.

For normal roads and railways the longitudinal slope is normally not a problem for the culvert design. In order to clarify that the design model is developed with a horizontal or close to horisontal soil top surface in mind a limit for the longitudinal slope of the road above the culvert of 10% has been introduced.

2.4 Soil and soil load

It is well known that soil material behaviour is non-linear and that the modulus of the soil is dependent on the stress level. To be able to develop a rational design method it is necessary to define a stress situation in the soil in which section forces in the culvert wall can be accurately predicted. Duncan suggested the stress at the depth (h_c+H/2) to be used in the calculation of the soil tangent modulus. Using a soil modulus based on this suggestion calculated sectional forces agree well with full scale test results.

The flexible corrugated steel culvert is highly dependent on the interaction with the surrounding soil. Further, changing the quality of the soil will change the performance of the structure and its load bearing capacity. Being able to change the soil parameters (particle size distribution and degree of compaction) in the design is therefore of great importance.

In Duncans original work the soil tangent modulus used in the design is based on conservative values for the soil modulus number and the soil stress exponent. The values are based on a large number of tri-axial test on soils used in different road and dam projects. However, measured values differ a lot with soil quality and since the soil modulus values are conservative the effect of using different soils is limited.

In the work by Andréasson the effect of the particle size distribution and the relative compaction on the frictional soil stiffness was studied. Using a large number of tests Andréasson was able to conclude that the dominating factors for the soil stiffness are the particle size distribution and the relative compaction. Other factors also influence the stiffness but to a lesser degree. The large number of tests allowed Andréasson to develop expressions for the calculation of the soil stiffness. This basic knowledge of the soil behaviour is used in the Swedish handbook to calculate a characteristic soil modulus to be used in the design. Partial safety factors for bridge safety class (1,1 or 1,2 depending on structure span) and soil material safety of 1,3 are used to develop a design modulus.

The design handbook allow the designer to choose the quality of the backfilling soil. To ease the use of the handbook parameters of some typical soilmaterials used for backfilling against bridges in Sweden are indicated.

Bending moments from soil load are calculated using an equation dividing the backfilling into two phases. The first phase is when the backfilling level is at the level of the crown and the second phase corresponds to the finished backfilling level.

The equation appreciate the fact that during backfilling the pipe will be compressed and accordingly the crown will deflect upwards. When the backfilling level reaches the crown the upward deflection will be at it’s maximum. When the backfilling level passes the crown level the crown will start to move downwards. The equation is based on Duncans suggestions in the SCI-method. However, when comparing the SCI-method with full scale test measurements calculated bending moments are normally small. This is believed to be the result of compaction effects being underestimated. The SCI original equation for this phase has therefore been adjusted to better reflect the compaction of the soil.

The design model takes both negative and positive arching into account. For low heights of cover the SCI-method include negative arching for soil load thrust. For larger heights of cover, when positive arching is at hand equations developed by Vaslestad have been incorporated in the design model.

2.5 Live load

The live load three dimensional problem is translated into a two-dimensional design problem using the Boussinesq theories for loads acting on a elastic half space for live load distribution through the soil above the culvert. The three dimensional live load is in this way translated into an equivalent line load the same way as proposed by Duncan.

However, full scale testing show that bending moments from live load are smaller than predicted by the SCI-method. In addition, the variation in calculated bending moments due to a variation in cover height differ from measured values. It was found that by using the basic formulas for the soil tri-axial tangent modulus and assume an at-rest soil stress situation the size and the variation of measured bending moments from live load with a change in the cover height could be better predicted.

2.6 Section forces

The normal force or thrust is relatively independent of the culvert stiffness. However, parametric studies indicate lower thrust in flatter profiles, which is implemented in the design method using the the double corner radius of horizontal ellipses and box culverts instead of the culvert span for the protion of the soil load below the crown level.

Parametric studies have shown that the change in thrust depending on culvert profile is small using the same span. This is true both for soil load and live load. However, bending moments differ a great deal depending on culvert profile. Therefore, again based on parametric studies in addition to comparisons with full scale test results, factors for this change in culvert profile are introduced to basic formulas in the SCI-method. It was found that bending moments were depending on the relation between the top radius and the haunch/side radius. By introducing the expression

$$\left({R_t}/{R_h} \right)^{\alpha} \tag{2.1.1}$$

were α is an exponent with different values depending on load type (soil or live load) bending moments can be accurately predicted.

2.7 Culvert capacity

The ultimate capacity of the soil-corrugated steel plate system is highly dependent on the relative compaction of the soil. Full scale testing show that an increase in the relative compaction of 1% will at least increase the ultimate capacity of the structure with 5%. Full scale testing also show that the factor of safety against formation of a plastic hinge proposed by Duncan will generate a very high safety against failure.

In the design model buckling is considered for normal force capacity. Here theories developed by Klöppel & Glock are implemented. To account for low height of cover and a reduced support from the soil, an interaction formula is introduced were the combined effect of thrust and bending moments is considered rather than introducing a reduction in the critical normal force depending on the height of the soil cover.

3. SUMMARY

Research and development within the area of soil steel flexible culverts have been intense in Sweden over more than 20 years. Several full scale tests have been performed to form the base for and verify the Swedish bridge code design method which was presented in the year 2000 in the form of a design handbook. The design method is based on two major contributions in the field of flexible culverts, namely the SCI-method developed by Duncan and the buckling theories developed by Klöppel & Glock. In addition, the soil stiffness analysis performed by Andréasson has been implemented in the design method.

The design method allows the designer to choose a backfilling frictional soil material in terms of particle size distribution and relative compaction. To simplify the design, formulas for the calculation of section parameters for the corrugated wall are given including effects of local buckling and cross corrugation where applicable.

In cases with a low height of cover the influence of the live load is relatively large. Since the upward deflection of the crown during backfilling decreases the height of cover the design method takes this into account, using a reduced height of cover.

Both negative and positive soil arching is included in the design method. In cases with a low height of cover the negative arching normally found in full scale tests and FEM-calculations is taken into account. In cases with a large height of cover the positive effect on thrust and moments is likewise taken into account using a method proposed by Vaslestad.

The live load is transformed into an equivalent line load using the Boussinesq formulas for a load acting on an elastic halfspace in the same way that was originally proposed by Duncan for the SCI-method.

Using the equivalent line load thrust and bending moments from live load are calculated and added to the effect of the soil load to form design section forces. To allow for the newly introduced so called BoxCulvert profile the formulas for bending moments originally proposed by Duncan in the SCI-method are adjusted by introducing a factor taking the relation between the top and haunch radii into account.

The culvert is checked in both the ultimate and serviceability states. A fatigue design check is also included in the design method.

The capacity of the corrugated wall is checked using an interaction formula taking the critical buckling normal force of the wall into account. For the top portion of the culvert profile the outward movement of the culvert into the soil is allowed for when calculating the critical force. For other parts of the profile this type of movement is neglected.

4. REFERENCES

Andréasson L., (1973): *Compressibility of cohesionless soils. A laboratory investigation*. Byggforskningen, Sweden, Report R36:1973.

Cary R. L., (1987): *Inelastic Buckling Stability of Corrugations*, TRR 1087.

Duncan J. M., (1979): Behavior and Design of Long-Span Metal Culverts, *Journal of the Geotechnical Eng. Div.,* Mars 1979.

Duncan, J. M., (1978): Soil-Culvert Interaction Method for Design of Metal Culverts, *Transportation Research Record 678* (Tolerable Movement of Bridge Foundations, Sand Drains, K-Test, Slopes, and Culverts), Transportation Research Board, National Academy of Sciences, Washington D.C., USA, 1978.

Duncan, J. M., (1977): Behaviour and Design of Long-Span Metal Culvert Structures, *ASCE Convention Soil-Structure Interaction for Shallow Foundations and Buried Structures*, San Francisco, USA, October 1977.

Klöppel K., Glock D., (1970): Theoretische und experimentelle Untersuchungen zu den Traglastproblemen biegeweicher, in die Erde eingebetteter Rohre, Heft 10, *Veröffentlichung des Institutes für Statik und Stahlbau der Technischen Hochschule Darmstadt*, Darmstadt 1970.

Pettersson L., (2007), *Full Scale Tests and Structural Evaluation of Soil Steel Flexible Culverts with low Height of Cover, KTH, 2007*

Pettersson L., Sundquist H., (2000), *Design of soil steel pipe bridges*, Technical report 58, Dept of bridge and structural engineering, KTH, 2000.

Pettersson L., (1998a): *Load classification of soil steel pipe bridges*, Technical Report 1998:17, Dept. of bridge and structural engineering, KTH, Stockholm.

Pettersson L., (1998b): Full Scale Live Load Tests on a Corrugated Steel Culvert, *IABSE Colloquium Tunnel Structures*, 1998.

Vaslestad J., (1989): *Long-term Behavior of Flexible Large Span Culverts*, Transportation Research Record 1231, Transport Research Board, National Research Council, Washington DC, pp. 14-24.

Vaslestad J., (1990): *Soil Structure Interaction of Buried Culverts*, Doctor of Engineering thesis 1990:7. Norwegian Institute of Technology, Trondheim.

POWSTANIE SZWEDZKIEJ METODY DO WYMIAROWANIA KONSTRUKCJI Z BLACH FALISTYCH

Streszczenie

Stworzenie szwedzkiego podręcznika do projektowania konstrukcji podatnych z blach falistych została zapoczątkowane w 1983 przez Szwedzką Administrację Drogową , która zwróciła uwagę na konieczność stosowanie większych rozpiętości konstrukcji przykrytych niskim naziomem. Badania rozpoczął Królewski Instytut Technologii ze Sztokholmu. Pierwszym zbadanym obiektem była konstrukcja o kształcie kroplistym o rozpiętości 6,1 m przykryta naziomem o miąższości 1,0 m. W tym samym czasie rozpoczęto studia teoretyczne nad istniejącymi metodami z zagranicy. Drugie badania w skali naturalnej wykonano na obiekcie o kształcie kroplistym przykrytej naziomem o zmiennej miąższości. W 2000 roku zaprezentowano podręcznik do projektownia. Metoda projektowania bazuje nametodzie współpracy gruntu z przepustem opracowanej przez Duncana. Pozwala ona na uwzględnienie sił normalnych i momentów zginających w różnorodnych profilach konstrukcji z uwzględnieniem różnych gruntów. Obciążenia mogą pochodzić od ruchu kołowego i kolejowego. Na podstawie kolejnych pełnowymiarowych badań konstrukcji o kształcie skrzynkowym (Box Culvert) w 2006 roku zaprezentowano udoskonaloną wersję podręcznika uwzględniająco wymiarowanie konstrukcji o kształcie skrzynkowym. Szwedzkie normy mostowe nakładają obowiązek stosowanie niniejszej metody przy wymiarowaniu konstrukcji z blach falistych.

Słowa kluczowe: przepust podatny, badania w skali naturalnej,naziom, obciążenia zmienne,obciążenia graniczne,podręcznik, konstrukcja skrzynkowa,linia kolejowa, dorgi kołowe, siła normalna, moment zginający