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DEVELOPMENT OF DESIGN TOOLS FOR SOIL STEEL COMPOSITE BRIDGES

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Abstract

This paper describes some of the research background needed for the development of the Swedish design method for Soil Steel Composite Bridges. The research work was undertaken at the Department of Civil and Architectural Engineering, division of Structural Engineering and Bridges, at KTH Royal Institute of Technology in Stockholm, Sweden. With spans growing larger and heights of cover smaller, the aim was to develop a design method that could be used in everyday design work. The design method, based on several full-scale tests, is today a code requirement in Sweden and Finland and is in use in several other countries in Europe. This paper describes some of the background to the design method, but also on-going research and planned future developments.

Key words: Soil-steel flexible culvert, soil-steel composite bridge, design, design method, handbook, full-scale tests, large span, low height of cover

1. INTRODUCTION

1.1. The Soil Steel Composite Bridge

Corrugated flexible steel pipes are often used in road and highway construction. By dividing the pipe into several curved plates and bolting those together at the construction site the problem of transporting larger structures could be overcome and the concept of multi-plate structures was born. This new concept, first introduced in the 1930's, made larger spans possible and today structures with spans over 20 m are being built.

Larger span flexible pipes or culverts, as they are often referred to, have been used not only for water passages through road embankments but also frequently as bridges to carry roads or railways. In many instances roads or railways are also carried through the culvert itself, an example of this is shown in (Fig. 1) which shows two corrugated flexible culverts used as a railway bridge in Poznan, Poland.

Fig. 1: Two corrugated flexible culverts beside each other used to carry a two track railway line over a road and a foot-path in Poznan, Poland.

The advantages of this type of structure are quite obvious. Normally, because only simple methods of construction are needed, the time of installation is short. The weight of the steel structure itself is low and since it is possible to pile up curved corrugated steel plates in low stacks, transportation is simple. Once they arrive at the installation site the plates are bolted together.

Corrugated flexible culverts have in many cases proved to be economical alternatives to conventional concrete culverts and bridges. Also the bearing capacity of older culvert structures has been debatable because of continuously increasing live loads. Therefore the interest in such structures has increased and the need arose for a design method capable of handling larger spans and low heights of cover, the latter being a consequence of the flexible culverts being used as bridges.

It is a well-known fact that culverts with larger spans and lower heights of cover are becoming more common worldwide. It is also well known, in many cases, that the cover height must be kept small. This is essential for a large span culvert to be able to compete with other types of bridges. With increasing spans and new culvert profiles, the need for a design method capable of predicting the structural behaviour becomes more pronounced. It is also important that a design method let the designer make a choice when it comes to the quality of the materials used in the structure (i.e. the steel plate material <u>and</u> the soil). Larger spans and smaller heights of cover have turned the culvert structure into a bridge structure competing with other bridge types built of concrete, steel and timber. Naming this bridge type the Soil Steel Composite Bridge therefore seemed natural.

1.2. Design method developed in Sweden

Realizing that this development may lead to the development of a “new” bridge type, the Swedish Road Administration started a project at the KTH Royal Institute of Technology to study design methods for soil steel flexible culverts.

Over the years different design methods have been developed and incorporated in international bridge codes. However, design methods have been simplified and therefore conservative. One of the interesting design methods that have been studied in more detail is the so-called Soil Culvert Interaction (SCI) method developed by Duncan [1, 2]. This method has qualities that make it suitable for bridge design.

An important reason for the development of the Soil Culvert Interaction (SCI) method presented above was to be able to determine minimum required heights of cover. The question of whether a culvert installation is regarded as being under high or shallow cover has always been a point of discussion. Different ways of determining what should be regarded as high or low height of cover have been proposed. Also, different rules of what should be regarded as the minimum height of cover have been evolving over the years. However, it is the opinion of the authors that there are no such limits. Therefore, in the design method, using the SCI-method as a starting point, no requirements for minimum or maximum fill heights etc. are included. The loads that should be applied together with the available soil and corrugated steel plates will determine what height of cover is required.

As described above the SCI-method allows the designer to calculate section forces (normal forces and bending moments) for a variety of culvert profiles. In the Swedish design method the SCI-method is supplemented with a general live load model, buckling theories and formulas for calculating a design soil modulus. In this way the design method allows the designer to analyze 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.

Culverts are available in several different shapes, normally called culvert profiles. In the original SCI-method six different profiles were covered. These are the circular profile, the vertical ellipse, the pipe-arch, the single radius arch, the double radius arch and the horizontal ellipse. Since the box culvert profile is very efficient in certain situations this profile has been included in the Swedish design method as well. All in all seven culvert profiles are therefore covered by the design method. Other types of profiles than those listed above may occur. However, it is believed that the profiles presented above are representative of most culvert profiles available on the market.

Even though several full scale and laboratory tests have been performed around the world, the effect of different heights of cover on live load effects and the ultimate capacity has not been tested in many instances. It has been well known that the capacity of culvert structures is high but it has been unclear what the limit of the capacity is. Several full scale tests performed in Sweden were used to verify the design method.

The main conclusion from the full scale testing and theoretical studies is that the performance of flexible culverts is such that a rational design method for everyday use can take important aspects of the structure into account. Earlier guidelines for the allowed height of cover are too conservative, this being based on both Swedish full scale tests as well as international testing having cover to span ratios below 0.06. The design method makes it possible to design culverts with large spans and low heights of cover, although the availability of appropriate metal plates, soil materials etc. set a natural limit to what is possible.

The design method has been implemented in a design handbook, Pettersson & Sundquist [3]. The design method has been in use since the year 2000 when the first edition of the design handbook was presented. See also Pettersson [4].

2. DESIGN METHOD BACKGROUND

2.1. Height of cover

For calculation purposes a definition of what is meant with height of cover, h_c, is needed. In situations with a large height of cover, an exact definition may seem unnecessary. However, in low height of cover situations, a small change in the height of cover may be critical for the load bearing capacity and therefore an exact definition is necessary. In the design method, the height of cover is defined as the distance between the top of the corrugation and the road surface. It is important to note that this distance should be taken as the net distance i.e. after the vertical deflection of the culvert crown caused by the backfilling soil load. Again, a small change in the height of cover may be critical to the load bearing capacity and therefore this “net” definition is necessary.

In the full scale test Enköping presented below, the importance of a “net” height of cover was clear, studying the test results from the first test series where the effect of a reduced height of cover was tested. Using the same test vehicle the increase in the crown bending moment was approximately 75% when reducing the cover-to-span ratio, h_c/D, from 15 % to 12.5 %. Like the Enköping tests, the Järpås tests (presented in this paper as well) also show that in low height of cover situations the live load has a significant effect on the thrust and the bending moments in the culvert wall.

It has been discussed among designers and researchers when the cover height should be regarded as low (or small). In the literature a low height of cover situation has for example been discussed in terms of percentage of the span of the structure and this is often a good way of defining whether the structure is a low height of cover structure or not. However, the size of the live load is also important and the best way is of course when the design method itself is capable of determining what situation is at hand, meaning that the design method is valid for the whole range of cover to span ratios.

2.2. Structural soil

The soil that surrounds the culvert is very important for the load carrying capacity of the soil steel composite structure. It is well known that frictional soils are suited for the use in bridge and culvert applications. Therefore, in the design method, frictional soil in the structural soil envelope is assumed. To be able to calculate the bending moments as well as the critical buckling stress of the culvert wall an appropriate value of the soil modulus is needed. Klöppel & Glock [5] recommended the use of a constrained soil modulus de-noted S_v. The constrained soil modulus was recalculated using Poisson's number to a Young's modulus in turn being recalculated to a spring stiffness using the radius of the culvert wall. Values of the constrained soil modulus of 20 to 60 MPa were recommended depending on the soil types ranging from sandy to gravelly soils respectively. Duncan [2] recommends values of the tangent (secant) soil modulus based on tri-axial tests with values in the interval 3 – 12 MPa. Recommended soil tangent moduli in the Canadian Highway Bridge Design Code, CHBDC, are dependent on the soil type and degree of compaction in the interval 6 – 24 MPa.

2.3. Soil modulus and flexibility number

In the SCI-method developed by Duncan [1, 2] a representative modulus of the soil stiffness is important in order to correctly calculate bending moments in the conduit wall. Duncan suggested that the relative stiffness between the pipe and the surrounding soil, the so-called flexibility number be used as the basis for bending moment calculations. The soil modulus should be a tangent modulus of the soil at a stress state representative for the soil steel structure in order for the designer to perform calculations where the structure may be regarded as linear elastic and where load effects, as a consequence, from different loads may be added.

In the finite element calculations performed by Duncan a non-linear soil modulus was used. The soil model input data was based on tri-axial test data from numerous soils. By choosing the modulus number and the soil modulus exponent in a conservative way compared to the test data Duncan was able to simplify the choice of the soil modulus for well defined groups of both frictional and cohesion-frictional soils.

Since the soil is an important part of the soil steel load carrying system and the different soils have different properties it is of course of interest to be able to estimate or preferably calculate the soil modulus, given certain basic data for the soil are available. Examples of such data are first of all the soil gradation and the degree of compaction. In a very thorough investigation of the one-axial constrained compression modulus Andréasson [6] found that relative density, particle shape and size and gradation are important for the stiffness of a frictional soil. The investigation performed by Andréasson was limited to first-time loading of the different soils and as such a conservative measure of the stiffness (or compressibility) of the soil which will, by subsequent loading, be stiffer. Using statistical methods, Andréasson was able to formulate expressions describing the compression modulus as a function of frictional soil relative density and gradation.

2.4. Arching

Arching is a phenomenon that is often referred to in connection with flexible culverts. In short, arching describes the way the load is transferred to the flexible culvert and is important both in low height of cover situations as well as when the height of cover is large. The weight of the soil directly above the culvert is taken as a starting point. In the ring compression theory developed by White and Layer this load was assumed to be carried by the culvert by ring compression forces.

Measurements in full scale tests have shown that the compression force in some cases is smaller than calculated using the ring compression theory, and in other cases larger. In the former case positive arching is at hand and in the latter negative. It has been found that in low height of cover situations arching is normally negative. This is explained by Duncan by the relatively high vertical stiffness of the culvert in relation to the surrounding soil. This effect is included in the so-called SCI-method described above. On the other hand, in high fill situations arching is normally becoming positive and the culvert is only exposed to a part of the weight exerted by the overburden soil load. In several laboratory and full scale tests this load pattern has been shown and experimentally verified. Vaslestad [7] proposed a method to calculate the normal force from the soil load in high height of cover situations taking arching into consideration. This approach has been incorporated in the design method. In this way the design method takes both negative and positive arching into account.

Measurements of live load arching were performed by Temporal et al. [8] by placing soil pressure cells horizontally approximately at the crown level. The soil pressure readings clearly showed that the measured vertical soil pressure is lower over the crown compared with “free-field” measurements at the side of the culvert structure. The same arching effect was recorded in the full-scale test *Enköping*, compare below. Soil pressure under live load was measured at different heights of cover. The increase in the vertical soil pressure at low heights of cover is an indication of the fact that live load arching is reduced. Arching effects are not possible to the same extent as in the Newport culvert tests reported by Temporal. The backfilling soil in the two tests is quite different; in the Enköping test uniformly graded sand was used compared to well-graded gravel in the Newport test. This is an important reason for the requirement for the soil type in the cover soil layers in the design method.

2.5. Backfilling and compaction effects

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 stated requirements, is critical for a successful result. The interaction between the pipe and the surrounding soil is the key factor for high bearing capacity of flexible pipes buried in soil. A design method must properly model this interaction both for the low height of cover situations and in the large cover height situations. In the low height of cover situations the interaction between the soil and the pipe will have a significant effect on the size of the bending moments in the conduit wall. In the large cover height situations the so-called arching will have a significant effect on the size of the thrust. When developing the design method it has been of great importance to include a way to take advantage of the quality of the surrounding soil. This is important since the soil is not only acting as a load but at the same time as a major load carrying structural element and the quality of the soil has a big influence on the bearing capacity of the structure.

Placing of the soil close to the conduit is done in thin layers which should be well compacted. It is crucial that backfilling is done in a symmetrical manner, meaning that the backfilling level should be almost the same at both sides of the conduit. A backfilling procedure not conforming to the two basic requirements that the backfilling level should be at the same level and that the soil is well compacted, may lead to uneven deformations and even failure of the culvert. Equally important is to keep heavy equipment away from the culvert during backfilling.

The backfilling of the conduit may, for theoretical purposes, be divided into two separate phases. The first phase is when backfilling up to the level of the crown and the second phase corresponds to a backfilling level from the level of the crown up to the finished backfilling level.

The influence of the backfilling up to the level of the crown may in turn be divided into two separate parts. The first part is the placing of the soil, which leads to horizontal soil pressures against the conduit wall. The second part is the compaction of each layer of the backfill. This effect has been studied by Duncan by comparing FEM-calculations with full scale tests Duncan and Jeyapalan [9]. It was concluded that the SCI-method did not fully consider the compaction effects. The SCI original equation for this phase has therefore been adjusted in the design method to better reflect the compaction of the soil by introducing the compaction factor f_3 which is proposed to be a function of the ratio

$$\frac{H}{D}\ .$$

2.6. Movements of the culvert wall during backfilling

Backfilling against a flexible structure like a culvert of course has to be done with great care. Backfilling in an unsymmetrical way may lead to a collapse of the structure because of the large bending moments that are introduced. This means that backfilling has to be done in a symmetrical fashion in order not to overload the structure

Backfilling against the culvert is done by placing the soil in thin layers, often as thin as 0.2 to 0.3 m. These layers are compacted with special compaction equipment to achieve the required degree of compaction. Close to the culvert light compaction equipment should be used in order not to cause damage to the culvert. Using heavy compaction equipment close to the culvert during the backfilling process may cause serious damage to the culvert. However, at a distance from the culvert, heavier (and faster) equipment may be used.

If the backfilling is done symmetrically, the culvert will be compressed (for closed profiles the span will be reduced) and the crown will move upwards, causing the so called peaking. The movement of the crown will be at its maximum when the backfilling level is at the crown level. After this, the culvert crown will start moving downwards. When the downward movement of the crown starts, the culvert, at the springlines, will move towards the soil. If the soil is well compacted, the downward movement of the crown is well restricted.

Once the backfilling level is above the crown level the culvert is locked in its position and it cannot move, other than what is allowed by the stiffness of the soil. At the final position the bending moments are what could be called locked-in bending moments.

In some instances the structure being backfilled is too flexible to carry the imposed loads. This may be the result of bad backfilling practice and can be avoided by checking the dimensions of the culvert throughout the backfilling process. It may also be a part of the design and the internal forces in the culvert wall is then controlled by special measures during backfilling, like placing soil on the culvert crown. The design method may be used to check whether the structure is prone to overstress by the backfilling loads and if special measures have to be in place.

Sometimes a backfilling load that is unsymmetrical may be advantageous. It can be used to achieve a symmetrical final bending moment situation in situations where the soil itself has a certain, relatively large, slope across the culvert axis. By leading the backfilling process by one or two layers on the side of the culvert that will be the lower side in the final structure the bending moments that are created by the soil load from the higher side may be balanced by the backfilling process.

2.7. Live loads

Many proposals for the representation of the live load for use in the design of flexible culverts have been made over the years. Concentrated live loads on the road surface will spread through the soil fill and affect the culvert with a pressure that is dependent on the ratio of horizontal to vertical spread. Dependent on the slope of the load spread the pressure will of course be affected and so will the corresponding sectional forces in the culvert wall.

Spreading the concentrated loads through the soil fill will result in a vertical pressure on the level of the crown. This vertical pressure is, in the ring compression method, comparable to the pressure exerted by the soil column above the culvert and the thrust is easily calculated according to the ring compression fundamental equation for the normal force.

The principle above has been adopted in many international codes as a straight forward way of representing live loads. However, the method has been shown, by comparison with full scale tests to yield conservative normal forces in many cases. However, the method is simple and straight forward and is therefore attractive in every day design work.

Spreading concentrated loads by the Boussinesq equation for loads acting on a semi-infinite elastic half-space is a method that is used in many other design situations. Even if the soil is affected by the culvert and in this way cannot be treated like a semi-infinite half-space, the method is still attractive because of its simplicity. Comparing to more simple methods of spreading live load the Boussinesq equation is comparable to a load spread by 4:3 approximately through the soil fill.

The Boussinesq equation can be used for several loads acting on the surface of the elastic body. Looking at a certain point at a certain depth the vertical pressure can be calculated as a sum of the pressure exerted by the respective concentrated loads.

Adding the effect from several concentrated loads the point having the maximum vertical pressure can be identified. Using this pressure an equivalent line load can be back-calculated in order to be used in a plane strain analysis. The method is therefore used in the design method for the determination of an equivalent line load to be used in design calculations.

In this way the equivalent line load will be represented by a concentrated load in the plane strain analysis. It may be argued that at low heights of cover the vertical pressure will be large under a certain concentrated load and that other loads will contribute with small vertical pressures only. However, the pressure in the point under consideration will be large and it can be easily realized that multiplying this pressure with the radius of the culvert a normal force according to the ring compression principle will be derived. Other loads, the same size or smaller, will exert a pressure on the culvert as well, but it is clear that they will not increase the normal force in the culvert if not placed immediately adjacent to the first load. It is at the same time clear that this way of representing the live load will be conservative for bending moment analysis.

2.8. Live load deflections

Culvert deflections under live load are normally very small in soil steel flexible culverts even at low heights of cover. Measurements of maximum deformation under live load for some full-scale tests are summarized in the below table:

Measured maximum deformation under live load for some full scale tests compared to culvert span

Test reference	**Span**	h_c / D	δ_{max}, D/δ_{max}
Enköping test culvert	6,10 m	0,148	1,9 mm, 3210
Flener and Karoumi [10], “Skivarpsån” single radius arch	11,1 m	0,16	0,6 mm, 17500
Flener et al. [11], Järpås I, box culvert without reinforcing plates (structure 1)	8,08 m	0,056	12 mm, 670
Flener et al. [11], Järpås II, box culvert without reinforcing plates (structure 1)	14,25	0,032	12 mm, 1289

Deformations in the above tests were recorded under live load consisting of a fully loaded three-axle 30 ton truck, except for the “Skivarpsån” test culvert where a 78 ton 4 axle locomotive was used (railway bridge). As can be seen from the table above, the deformations are very small compared to the conduit span. Calculation of live load deflection has therefore not been included in the design method.

2.9. Braking loads

Many researchers and designers have discussed the effect of braking loads. In addition, only a few tests with braking load have been reported in literature, two of these being Temporal et al. [8] (road traffic load) and Flener and Karoumi [10] (railway load). In both reports, the conclusion is that the effect of a braking load is small or non-existent. Braking load can therefore be disregarded in flexible culvert design and are not included in the design method.

2.10. Local failure of the soil cover

The Enköping full scale test showed that there is a risk for a local soil failure at very small cover depths. This fact has lead to the conclusion that the requirements for the soil in the cover must address this possible mode of failure using higher quality soils in the road structure also above the culvert.

The loading device used in the Enköping tests to simulate live load wheel loads is conservative in this respect, in some cases even penetrating the soil cover. Of course this should not have been the case using ordinary wheel loads. The tests reported by Temporal et al. [8] and the Järpås test reported by Flener et al. [11] shows that using soil types normally found in road structures local failures of the soil cover do not occur even at extremely low heights of cover (less than 0,5 m).

Theoretical analyses, together with laboratory and full scale testing, of soil failure in culvert structures having a shallow cover were performed by Hafez [12]. Hafez studied the influence of the following four parameters on the stability of the soil cover under loads from live load:

- Height of cover
- Size of the conduit
- Shape of the conduit
- Eccentricity of the load

The live load consisted of single axle loads as well as multi axle loading. The results were presented as the load causing failure related to a 140 kN axle. The soil used in the calculations had a weight density of 18.4 kN/m^3 and an angle of internal friction of 45 degrees. The results presented in the report indicates that a circular conduit with a span of 7.62 m and a height of cover of 1.20 m

$$h_c/D = \frac{1}{6}$$

loaded with a single centrally placed axle should fail in a soil failure at a load level of approximately 2.4 times the 140 kN axle i.e. approximately 335 kN. By reducing the height of cover to 0.60 m the soil failure axle load is reduced to approximately 110 kN. Moving the axle eccentrically, again having a height of cover of 1.20 m, the soil failure load is reduced to approximately 230 kN.

These results could be compared to the Enköping full scale tests. In the final failure load test the culvert failed in a soil failure under a single axle load placed eccentrically close to the most critical position according to Hafez. The measured failure load was 432 kN at a cover to span ratio of 1/8. The measured angle of internal friction was 30 degrees only. With a centrally placed axle the culvert wall failed under a high normal force and bending moment (not soil failure) at an axle load of 524 kN (at the same height of cover and degree of compaction).

The angle of internal friction and the height of cover both have big influence on the soil failure load. Full scale testing show that soil failure loads will be very high and are not regarded as being a probable mode of failure.

2.11. Added effects from soil and live load

As in all of bridge design the load effect of soil and live load cases on the culvert have to be combined in a certain manner to be used in the different capacity described below.

Since the load effect of the soil load as well as the live load is divided into several parts the combination of the sectional forces has to be done accordingly. It is perfectly possible to arrive at a maximum normal force and a bending moment belonging to this maximum normal force. Of course, it is also possible to arrive at maximum (or minimum) bending moment and a normal force belonging to this moment.

The live load induces both positive and negative moments during a passage of the culvert. This principle applies irrespectively of the size or type of the culvert, compare for example Flener et al. [11]. This implies that there is a need to know not only the positive bending moment induced by the live load but the negative part as well.

2.12. Flatter profiles parametric study

The influence of flatter culvert profiles (i.e. two radius profiles and box culvert profiles) on the sectional forces is included in the design method. The sectional forces design expressions have been developed using a parametric study with different culvert profiles having the same span.

In the original SCI-method Duncan proposed a bending moment coefficient that is independent of the type of culvert profile. Different culvert profiles were used in the finite element calculations but the effect of for example a flatter type of culvert was not evaluated. This is valid for both soil and live load bending moments.

By comparing calculated moments using the original SCI-method with measured moments for box culverts it can be concluded that the shape of the profile is important for the resulting bending moments. Again, this is valid for both soil and live load moments. The difference is evident when comparing backfilling moments for the Skivarpsån railway culvert, Flener and Karoumi [10] and Järpås I test culvert, Flener et al. [11]. In spite of the same relative height of cover, for the two culverts the bending moments at finished backfilling for the Skivarpsån culvert stay on the negative side, while for the Järpås I box culvert the bending moments change sign and a positive crown moment is created at finished backfilling.

This effect is interesting since the original SCI-method includes circular as well as horizontal ellipse culvert profiles. Theoretically this means that the method's "built-in" factor of safety is larger for circular profiles. To be able to predict the bending moments in flatter profiles a relation between the top and side radii has been introduced in the design method. If the relation between the top and side radii is equal to one, the parameter can be used in the equations for the bending moments without affecting the results. However, with a relation between the two radii ≠1 the factor will affect the resulting bending moments.

$$\left(\frac{R_t}{R_h}\right)^{\alpha}$$

The size of the influence from this factor is dependent on the value of the exponent α. To determine what size should be used a parametric study has been performed comparing the original SCI-method with finite element analysis and full scale test data for flatter types of culvert profiles such as the two radius arch and the box culvert. In this parametric study it was decided to use a traditional arch, with one radius only, a two radius arch and a box culvert all with the same span, culvert wall stiffness and backfill soil. The calculations were performed using the CandeCAD finite element software.

The first part of the parametric study included analyses of the normal force in the three profiles described above. As discussed in previous sections the main load bearing in a flexible culvert is through ring compression forces. It is interesting to note that this is the case for flatter profiles as well. The normal forces from the soil load changes with type of profile but the principle of ring compression is still valid. The change in normal force is more related to the fact that the soil volume above the culvert is smaller and therefore the soil weight is also smaller when the culvert profile is flatter.

Live load calculations were also performed and included in the parametric study. The load used in the calculations was an equivalent line load corresponding to an axle load of 221 kN. The line load was placed at the centreline of the structure and was moved in 0.90 m steps outwards from the centreline. The pattern from the soil load calculations with somewhat lower normal forces in the flatter profiles is repeated for the live load.

For bending moments it is obvious from the flatter shape of the two radius arch and the box culvert that they will be exposed to larger moments from both soil and live load than will the arch structure. This fact has to be reflected in the design equations for the bending moments.

The shape factor as described above is used both in the design method bending moment equations for soil and live load respectively. The exponent value of 0.75 has been chosen to get a reasonable agreement between the parametric study calculated bending moments during the backfilling cover phase.

For live loads, again the original SCI-method is not capable of predicting bending moments. As for the soil load it is proposed to use the relation between the top and side radii to account for the higher bending moments in the flatter types of profiles. Using an exponent of 0.25 for live load give a reasonable agreement with the parametric study results.

For details comparing the design method modified for flatter profiles, with full-scale test results, compare Pettersson [4].

2.13. Full scale tests

Six extensive full scale tests were performed in Sweden. Two of these have been performed over several years including several test series. The test culverts were named after the places where they were built (Nyköping, Enköping, Skivarpsån, Järpås I, Järpås II and Märsta). Three of these tests were performed on culverts built for testing purposes only (Enköping and Järpås I and II). This has lead to the possibility not only to use “operational” load levels but also to load the culverts to failure. Using a culvert built for testing purposes also opens the possibility for extensive testing.

The full scale test culverts, (with pipe-arch, arch and box culvert shapes) have been loaded with both road and railroad loads, static and dynamic loads, locomotive breaking loads, live loads at different heights of cover and also with different degrees of compaction. For the box culverts, tests have been performed both with and without stiffening plates.

The six full scale tests have therefore, to a high degree, increased the knowledge in the behavior of flexible soil steel culverts. This knowledge is crucial when a design method is developed especially when it comes to the ultimate capacity of the culvert at very low heights of cover.

In the table below important data for the tests are given. For detailed test results test reports are available at the department of Structural Engineering and Bridges at KTH.

Test culvert	Type of culvert	Culvert span	Type of measurements
Nyköping	Pipe arch	6,40 m	Steel strains, deflections and soil pressures during backfilling and live load
Enköping	Pipe arch	6,10 m	Steel strains, deflections and soil pressures during backfilling and live load. SLS live loads at varying height of cover. Effects of different road embankments. Loading to failure at different compaction levels.
Skivarpsån	Arch	11,1 m	Railroad bridge. Steel strains and deflections under backfilling and static and moving train load. Dynamic amplification using varying train speeds. Effects of braking train. Ballast acceleration levels.
Järpås I and II	Box culverts	8,1 and 14,3 m respectively	Steel strains and deflections during backfilling and live load. SLS live loads at varying height of cover. Effect of strengthening plates. Loading to failure.
Märsta	Vertical ellipse	3,75 m	Steel strains, deflections and accelerations under railway load at high speeds. Ballast accelerations.

2.14. Stability of the culvert wall

The strength analysis of the soil steel structure has to consider the culvert wall as a compression member supported by the surrounding soil mass. When the height of cover is reduced the support the soil offers decreases, and at the same time the live load bending moments introduced in the culvert wall increases.

Buckling of the culvert wall which occurs at stress levels below the yield stress is normally referred to as elastic buckling while inelastic buckling occurs after the culvert wall at some location(s) undergoes yielding. It is of course possible that the soil restrains the culvert from buckling and the culvert wall will fail by crushing (yielding). With values of the soil support in between the elastic case and the fully plastic case there will be a transition zone which in buckling curves normally is expressed with a smooth transition between the two cases.

Earlier expressions for the buckling stress of the culvert wall assumed a constant radial pressure around the conduit. For low heights of cover this is not true. Luscher [13] used a model with a soil ring with the thickness surrounding the conduit to study this special case. Luscher showed that the relation between the radius of the conduit and the thickness of the soil ring will affect the modulus of soil reaction according to the expression:

$$\eta_s = \left(1 - \left(\frac{R}{R+h_c}\right)^2\right)$$

The investigation by Klöppel & Glock [5] focused on the upper portion of the culvert since it was believed that, because of reduced soil support, this is the most critical section. Klöppel and Glock modelled the upper part of the conduit as a radially soil supported arch which was also elastically supported at the supports. The work presented by Klöppel and Glock concluded that the support offered by the soil at the sides of the culvert will result in tangential movements of the culvert top section. The support from the soil at the sides of the culvert may be represented by tangential springs. It is realized that using springs at the supports the buckling stress of the culvert wall will be reduced.

Based on the investigations in Abdel-Sayed [14] the reduction in the buckling normal force from a small height of cover and the tangential movements at the supports can be written according to the following expression:

$$N_{cr,el} = \frac{3 \cdot \sqrt{\dfrac{E_s \cdot (EI)_s}{R_t}}}{\left(1,22 + 1,95\left(\dfrac{(EI)_s}{\eta_s \cdot E_s \cdot R_t^3}\right)^{0,25}\right)^2 \dfrac{1}{\sqrt{\eta_s}}}$$

Abdel-Sayed also introduced a reduction factor for low height of cover situations. This factor was introduced for relative heights of cover less than 0.5. At this relative height of cover the reduction factor = 1. For smaller relative heights of cover the reduction factor, which is denoted ξ, was proposed to follow the following expression:

$$\xi = \sqrt{\frac{h_c}{R}} \leq 1,0$$

It is interesting to note that in the above expression the height of cover to culvert radius is introduced as a reduction factor. The effect of live load on the road surface is of course taken into account in design by the increase in culvert wall normal stress, but the effect of the bending moments introduced by the live load is not considered other than by this reduction factor.

If the Duncan [2] proposal for a safety factor against the formation of a plastic hinge is taken as a starting point, and at the same time noting that the top portion of the culvert under live load will act as a transversally loaded strut in compression, the failure criteria of the culvert may be written as an expression for the interaction between the normal force and the bending moment. Using an expression for the interaction between the normal force and the bending moment can, for simplicity, be compared to replacing the low height of cover factor, i.e. putting $\xi = 1$.

2.15. Capacity checks

The important part of a culvert design when the capacity check is performed could be divided into several parts. In the design method it is assumed that a partial safety philosophy is used. The capacity of the culvert should consequently be checked in the ultimate limit state (ULS) and the serviceability limit state (SLS). It should be noted that checks concerning fatigue are regarded as being part of the ultimate limit state checks.

Full scale tests performed on large span culverts show that even under extremely low height of cover situations deflections under live load are very small and as such do not pose a serviceability limit state problem. Therefore, in the design method, calculation of live load deflections is not deemed necessary. On the other hand in cases with a low height of cover the influence of the live load on the sectional forces 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. It is therefore important to take the deflection of the conduit during construction into account when performing culvert capacity checks.

In the design method buckling is considered for normal force capacity. To account for low height of cover and a reduced support from the soil, the interaction of 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.

Very often in culvert design the structure will experience the biggest load effects during construction. Using the design method this stage can be checked as well. Starting from the critical situation when the backfilling level has reached the level of the crown the capacity of the culvert can be checked. The design method allows the designer to model all types of live load, of course including construction vehicles.

Corrugations available on the market are normally given such dimensions and plate thicknesses that local buckling will not pose a problem. However, in recent years larger corrugations have been developed where local buckling may be of interest. Therefore, a method to check the corrugated section for local buckling is introduced using the result from an investigation performed by Cary [15].

The conduit corrugated steel plate capacity to withstand repeated loads should be checked. This is true especially in low height of cover situations when the load effect of the live load is large. The fatigue capacity of the steel plates should therefore be checked.

Bolted connections should be designed in such a way that the prevailing normal forces and bending moments can be transferred. As far as bolted connections are concerned it is vital that, for every adjacent crest/trough of the corrugation, at least two bolts must be used and that their positions are chosen in order for the bending moment to be transferred. The capacity check of the bolted connections is then divided into several checks, the first being the shear capacity of the bolts including bearing failure of the plates. Secondly, a capacity check of the bolted connections includes a case of combined shear and tension. Thirdly, the check of the bolted connections includes a check of the fatigue capacity.

As discussed above the soil radial pressure against the steel plates depends on the radius of the respective plate. The radial pressure is inversely proportional to the radius of the plate. For example, in corner plates of pipe arch culverts the radial pressure may be relatively high. By limiting the relation between the top radius and the corner radius the radial pressure is kept at acceptable levels. However, in cases with low capacity soil below the culvert, separate checks of the soil bearing capacity may be performed.

In the serviceability limit state it is important that the yield stress of the culvert wall is not exceeded under repeated live loading. In the design method it is therefore suggested that the stress in the conduit wall is less than the yield stress under serviceability limit state loads. The design normal force and bending moment are calculated as the sum of normal force and the bending moment calculated for soil and live load.

For culverts with arch or box culvert profiles on foundation slabs the design of these slabs follows standard procedures for such slabs according to applicable standards. Normally the culvert profile is connected to the slab by means of a moment free connection. The force from the culvert acting on the slab is then the normal force. Consideration should be taken of the inclination of the plates at the connection point to the slab. With the normal design forces in both ultimate as well as serviceability limit state known both ULS and SLS checks of the foundation slabs may be performed.

2.16. Reinforcement plates

A culvert is normally designed with a constant wall cross section. However, in some cases the capacity of the culvert wall is not high enough and the use of so-called reinforcement plates is necessary. Reinforcement plates are corrugated plates bolted to the culvert profile where it is found necessary. Reinforcement plates therefore may be continuous or intermittent. In the case with continuous reinforcement plates the design the culvert may be treated as having a constant wall cross section. However, when determining the wall cross section properties, the slip between the plates bolted together must be taken into account.

However, in some cases, strengthening of the culvert wall by adding corrugated plates intermittent on the outside of the culvert barrel may be an alternative to achieve the necessary capacity of the culvert. An example of how strengthening plates may be placed on a box culvert profile is shown in (Fig. 2).

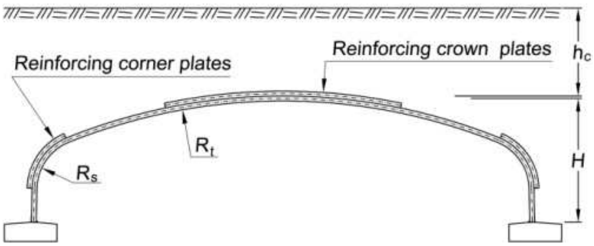

Fig. 2: Box culvert cross section with strengthening plates

In the case of intermittent plates, the calculation of section forces starts with the unreinforced culvert profile. 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 in comparison to 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 is high enough on its own. 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. The calculation could be done simply by applying a vertical concentrated load to the naked culvert profile without and with the reinforcing plates respectively. By comparing the vertical deflection of the crown for the two culvert profiles, the stiffness for the reinforced culvert profile can be determined and a new stiffness number can be calculated. With a stiffness number for the reinforced culvert the calculations can now be reiterated. The process is iterative. Once the moment bearing capacity of the reinforcing plates is found to be high enough and the length of the reinforcement plates have been determined the culvert profile is checked in the same way as a culvert without reinforcement plates using the section parameters for the reinforced section. However, since the normal force is carried mainly through the barrel itself it is proposed to use the cross section area for the barrel only when calculating the ultimate normal force, neglecting the effect of the reinforcement plates. On the other hand the reinforcing plates will naturally have an effect on the critical normal force. These calculations of the culvert capacity may show that further reinforcement is necessary. It should also be noted that the slippage between the two plates in a reinforced section has to be taken into account when determining the section parameters. The section parameters therefore have to be determined by testing.

2.17. Eurocode design

The design method was originally developed for use together with Swedish design codes. However, with the introduction of the Eurocode it was necessary to adapt the method. A section in the design handbook, Pettersson and Sundquist [3], therefore deals with the adaptation of the design method to the principles of the Eurocode.

3. ON-GOING AND FUTURE RESEARCH

3.1. Load classification methods

The Swedish Design method for soil steel composite bridges gives the possibility for a design engineer to design a culvert in the same way as a bridge. Closely connected to this is of course load classification of older Soil Steel Composite Bridges. A load classification method has been developed at KTH and is in use by the Swedish Transport Administration. On-going research is aimed at special cases, for example culverts having very small cover-to-span ratios.

3.2. Fatigue design

The deep insight in the behavior of this type of structure has of course lead to new questions being raised, one of these being the fatigue capacity of the bolted connections. Normally not a problem, fatigue capacity can be the governing criteria at very low height of cover situations using heavy loading. A project, including laboratory testing of fatigue capacity is therefore ongoing at KTH Royal Institute of Technology. The results from this project will be incorporated in the design handbook as soon as they are available.

3.3. High speed train design

Another very interesting ongoing project at KTH is the study of the behavior of flexible culverts used as bridges in high speed railways. In the continuation of the Skivarpsån test and Märsta tests, studying both dynamic amplification factors and ballast acceleration levels, theoretical studies are on-going aiming at developing design recommendations to be incorporated in the design handbook.

3.4. Light weight backfilling materials

Being light, soil steel composite bridges are advantageous in situations with poor native soil conditions. The backfill soil surrounding the culvert and the approach embankments may therefore be the designing factor from a geotechnical perspective. Lightweight backfilling material is therefore of a great interest for the use in the backfilling. KTH is therefore planning a study of the requirements for such materials.

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Streszczenie

Praca opisuje częściowo podstawy badań przeprowadzonych w opracowania szwedzkiej metodologii projektowania mostów gruntowo-stalowych. Badania zostały przeprowadzone na Wydziale Inżynierii Lądowej i Wodnej i Architektury w katedrze Inżynierii Budowlanej i Techniki w Królewskim Instytucie Techniki KTH w Sztokholmie w Szwecji. Ponieważ zwiększają się rozpiętości, a wysokości naziomu maleją, celem pracy było opracowanie metody projektowej, którą można stosować w codziennej pracy projektowej. Metoda projektowa, oparta o kilka prób w pełnej skali, stanowi dzisiaj część wymogów przepisów projektowych w Szwecji oraz Finlandii i jest również stosowana w innych krajach europejskich. Praca opisuje część badań, które pozwoliły opracować tę metodę, a także badania prowadzone obecnie i planowane.

Słowa kluczowe: gruntowo-stalowy przepust podatny, most gruntowo-stalowy, projektowanie, metoda projektowa, podręcznik, testy w pełnej skali, duża rozpiętość, niski naziom