ARCHIWUM INSTYTUTU INŻYNIERII LĄDOWEJ
Nr 23 ARCHIVES OF INSTITUTE OF CIVIL ENGINEERING 2017

BURIED FLEXIBLE STEEL STRUCTURES. KEY PROBLEMS OF DESIGN CODE STUDY[1]

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Currently in Europe there is no uniform design code for buried flexible steel structures. In different EU countries there are different regulations concerning design methods, construction and control of such structures. This paper is an attempt at presenting the problems that need to be solved in order to prepare an uniform European Code. The thematic range of the proposed code is also outlined. The idea is based on the author's own studies on buried flexible steel structures and design methods and codes from other countries, such as: AASTO, CHBDC, ZTV and TRVK Bro 11. Concluding remarks contain a proposal of a committee consisting of several sub-committees that needs to be appointed in order to solve particular issues. This paper should be considered as a starting point for further discussion – it is not intended to be a "closed" proposal.

Key words: buried structures, codes, ULS, SLS

1. INTRODUCTION

1.1. Reasons for the initiative of creating a uniform code

Buried structures are specific as their load-bearing capacity depends not only on the structure (the culvert), but also on the surrounding soil (the backfill). The main structure, which is surrounded by engineered soil can be made of different materials: stone, brick, concrete, metal or plastic. Buried structures made of stone or brick have been well known for a long time. Subsequently, concrete was introduced as a structural material. Metal plates have been used since the beginning of the 20th century. Although culvert materials may be different, the key point of the design of such structures is to estimate the load-bearing capacity of the backfill. In stone or concrete structures the backfill was treated only as a means of transferring the load to the structure and it was not considered in the calculations. This approach changed significantly with the emergence of flexible steel culverts – mostly corrugated. At the beginning the load-bearing capacity of

[1] DOI 10.21008/j.1897-4007.2017.23.01

such structures was estimated intuitively and based mainly on construction and maintenance experiences. Then a theoretical base for designing was formed, but it still relied on practical experience. Only the emergence of finite element methods made it possible to apply more analytical methods of design. However, they require access to software and also an appropriate description of boundary conditions (e.g. culvert – backfill contact layer) and soil parameters.

Experience from research and experiments proved the significant impact of the construction method on the ULS and SLS.

1.2. Proposed thematic range of the code

Structures capable of carrying only constructional loads will be understood as "buried structures" (loads occurring during the construction stage of the culvert itself and placing the backfill – the weight of soil, people and equipment). Live load can be carried only with the assistance of engineered soil (the backfill).

The subject of this design, construction and maintenance study will be flexible structures only (plates made of steel or plastic). It is stated that the culvert is made of corrugated plates, however flat plates are not excluded.

Another division criterion may be stiffness of the structure as a whole (culvert and backfill). However, I am fully convinced that it should only be an auxiliary criterion – during the design code study we should be guided only by the culvert material type and stiffness.

For the code concerning concrete, stone or brick buried structures a separate sub-committee should be appointed.

The code should consist of five main issues:
- material requirements,
- culvert structure formation,
- design method,
- construction stage,
- maintenance.

It is proposed not to include issues concerning the production process. Topics concerning hydraulic calculations should also be excluded.

1.3. Division of buried structures covered by the code – division criteria

It is proposed to set forth the following basic division criteria:

a) depending on the profile type:
- circular pipe,
- ellipse,
- pipe-arch,
- arch consisting of plates with a single radius or more different radii,
- box culvert;

b) depending on the corrugation:

- shallow corrugation (MultiPlate type),
- deep corrugations (SuperCor type),
- deeper corrugations (UltraCor type);

c) depending on the foundation type:
- “closed” profiles placed on bedding,
- “open” profiles on special foundations;

d) depending on the span:
- short spans (up to 4m),
- medium spans (up to 15m),
- big spans (over 15m).

1.4. Main issues to be addressed in the new code

The main issues to be addressed in the new code are:

a) material requirements:
- requirements for engineered soil and the effect of the backfill on ULS and SLS, minimum cover depth,
- requirements for steel (or aluminum) used in culvert production, requirements for bolts;

b) geometrical requirements:
- admissible profiles,
- maximum spans for different structure types (pipe profiles, box profiles, etc.),
- corrugation parameters,
- steel plate thickness,
- shape and location of holes for bolts,
- geometry of different structure types ;

c) durability issues:
- types of corrosion threats (exposure classes),
- aggressive environmental conditions,
- protection against corrosion,
- protection against stray voltage;

d) design procedure:
- method of ULS and SLS calculation,
- partial safety factors in ULS and SLS,
- dead load calculation (including the bridging effect)
- live load calculation (models that consider the rules of existing Eurocodes, models for fatigue design),
- structures under high-speed railways,
- dynamic amplification factor,
- calculation of normal force in the plate – caused by dead and live load,

- calculation of bolted connections,
- local buckling,
- global buckling,
- soil load-bearing capacity (over and at the sides of the structure), bedding load-bearing capacity for “closed” profiles,
- fatigue effects;

e) construction stage:
- methods of construction,
- shape control (before and after backfilling),
- connections control,
- backfilling process (soil compacting methods),
- loads occurring during construction;

f) maintenance:
- maintenance procedures,
- criteria for estimating the culvert’s technical condition,
- renovation,
- repair and rehabilitation.

2. LOAD EFFECTS

2.1. Dead loads

Internal force calculations should take into consideration:
- the arching effect (it is required to set forth rules for the bridging effect calculation; the effect of structure stiffness and soil type and compaction on the bridging effect),
- soil pressure without live loads on the surface (even or sloping terrain),
- residual stresses as “dead load” (pipe profiles, including profiles with plastic deformation – elliptical, pipe-arch profiles).

2.2. Live loads

Models for live loads are required for:
- road traffic actions (without concentrated load; concentrated load only for a local analysis),
- rail traffic actions – different models for low speed (<160km/h) and high-speed (>160km/h) railways,
- special vehicles (e.g. industrial and army transport),
- fatigue analysis (especially for structures under high-speed railways),
- loads occurring during the construction stage (general rules to be adjusted each time for particular equipment used on site),
- -seismic loads.

Calculation and application of the dynamic amplification factor should be also stated in the code. It is suggested to use dynamic factors according to the existing Eurocodes. Certain new rules for dynamic loads on high-speed railways need to be defined. The method of dynamic factor calculation should depend on the cover depth and surface stiffness.

A procedure for calculating internal forces in the buried structure (effected by live loads) should be stated (method of defining the converted load – as a load directly causing the internal forces – rules of distribution of the load applied on the surface or an alternative model dependent only on the cover depth and type). Surface stiffness should be included in the calculations (especially in the calculation of soil pressure effected by live load).

3. MATERIALS AND PRODUCTS

The code should be limited only to certain material requirements for the plates (steel, aluminum), bolts and the engineered soil. In case of concrete, reinforcing and structural steel (other than that used for the plates), the code should make references to specific Eurocodes.

3.1. Material requirements

Basic requirements for structural materials should be given for:

- steel (aluminum) for plates (yield strength, tensile strength, ductility, resilience),
- class of bolts for connections,
- plastic,
- backfill (density, elastic modulus, graining non-uniformity coefficient, grading curve, frost resistance),
- soil,
- light aggregate.

3.2. Products for buried structures

General characteristics of products for buried structures should be defined with regard to:

- plate thickness,
- corrugation geometry,
- structure geometry,
- bolt geometry.

4. DESIGN METHODS

4.1 Introduction

According to general rules of analysis, buried flexible steel structures should be checked in ULS and SLS, including the durability aspects. Therefore the code should define ULS and SLS for buried flexible steel structures and set forth criteria for reaching the limit states.

Partial safety factors should be used in the code according to Eurocode 1990. Therefore it is necessary to determine:

- partial load factors γ,
- combinations of actions,
- combinational factors Ψ.

Partial safety factors should differ depending on the structure type and the stage of checks (construction stage, operation stage). The design methods are appropriate only for certain types of structures – limit parameters of structures for a proper application of the formulas need to be stated in the code (especially parameters concerning structure stiffness).

4.2. Internal forces

Internal forces calculation is allowed using:

- analytical methods,
- numerical methods,
- research and experiments results.

Elastic analysis should be used for internal forces calculation. In the case of analytical methods, equations for normal forces and bending moments should be given in the code. In the case of structures with large deformations, second order theory analysis should be applied.

4.3. Ultimate limit states (ULS)

The structure load-bearing capacity can be calculated in an elastic or non-elastic analysis. The structure load-bearing capacity during the construction stage can be checked using an elastic analysis only. A non-elastic analysis is admissible only at the operation stage when global buckling is prevented. In a non-elastic analysis interactional equations need to be applied. The stress limit state must always be checked. Time-dependent changes need to be considered in the soil (changes caused by loads and humidity) as they affect internal force values.

Load-bearing capacity needs to be checked separately at the construction stage and at the operation stage. The checks should address load-bearing capacity of the soil and the culvert, both at the construction and operation stage.

Checks are required for:

- yielding in the wall and plastic hinge mechanisms,
- local buckling of the culvert,
- global buckling of the structure,
- strength of the bolted connections (bending, shear, tension),
- fatigue capacity.

In the case of complex states of stress, interactional formulas should be applied; for the culvert – only the interaction of normal force and bending moment (without shear); shear should be included for bolted connections.

Fatigue capacity check should be done only for bolted connections and haunches of box culverts. It is recommended to use the damage equivalent stress range method (Palmgren – Miner Rule is not recommended). Therefore it is necessary to define a method of calculating the equivalent stress range for the culvert and for bolted connections.

The limit state of the soil needs to be checked:

- below the structure (only in the case of "closed" profiles; for "classical" foundations the code can make a reference to existing Eurocodes),
- in the structure surroundings (at the sides and above).

4.4. Serviceability limit states (SLS)

Checks are required for:

- deformations,
- stresses,
- oscillation (normal and forced mode, acceleration, amplitude) – checks only for structures under high-speed railways.

The code should determine methods of checking these limit states and set limit values for them. The SLS (except oscillation) should be checked at the construction and operation stage. Geometry changes must also be checked for time-dependent causes.

4.5. Durability

The code should contain certain rules concerning structure durability. Therefore durability classes should be introduced with the criteria for division to certain classes. Requirements for particular classes have to be described, as well as the rules for providing durability and methods of protection against corrosion.

5. STRUCTURE GEOMETRY REQUIREMENTS

The new code should introduce requirements concerning structure parameters and determine a construction method suitable for the code's content. If a certain structure does not meet the code's guidelines, it can still be used as long it is supported with proper research. Below there is a list of parameters concerning structure geometry that need to be determined.

Steel culvert geometry:
- minimal curvatures,
- requirements for cut ends,
- stiffening ribs.

Connection with the foundation:
- foundation geometry,
- rules of anchorage.

Bolted connections:
- shape of bolt holes,
- hole dimensions,
- rules for hole location and spacing between the holes (minimum and maximum distances),
- bolt forces.

Backfill geometry:
- dimension of the area that has to be made of engineered soil,
- required compaction index in each area,
- minimal cover depth,
- minimal distance between two adjacent structures,
- rules of using plates for reducing loads,
- special requirements, e.g. areas of higher requirements.

Requirements for cut ends and embankment slopes:
- cut end type,
- method of slope strengthening (reinforced soil, stones, etc.).

Drainage:
- protection against water (admissible types of insulation, protection of bolts holes, contact layer between the structure and the foundation),
- evacuation of water from the structure (in the case of two or more adjacent structures),
- backfill drainage.

Equipment elements:
- lighting,
- protection against mechanical damage by vehicles,
- items related to environment protection issues.

6. CONSTRUCTION. INSTALLATION CONDITIONS

Admissible construction methods should be stated in the code together with requirements concerning control during the construction stage (required range of measurements to be done depending on the construction method):

- geometry control after installation (admissible engineering fit),
- bolted connections control,
- checks of protection against corrosion.

Characteristics of installation conditions:

- bedding preparation and control ("closed" profiles, structures of foundation made of corrugated plates); preparation and control of concrete foundations,
- general backfilling rules (compaction methods, depth of single layer of soil for compaction, compaction control),
- structure geometry control during backfilling (methods, admissible engineering fits),
- structure geometry control after backfilling (methods, admissible engineering fits),
- final checks, including tests under static and dynamic load (requirements for the range of tests, ways to perform the tests, results evaluation criteria).

7. STRUCTURE DURABILITY. MAINTENANCE

The code should contain information and introduce rules on:

- threats for the structure (corrosion, abrasion, mechanical damage),
- damage classification (damage scale and threats resulting from them), description of limit values of damage resulting only in durability decrease and influencing operating safety (load-bearing capacity),
- rules of protection against corrosion and mechanical damage.

The code should also describe basic maintenance procedures of buried flexible structures:

- requirements and range of inspections,
- methods for damage diagnosis,
- repair of the anti-corrosion layer,
- repair of mechanical damages (e.g. after car accidents),
- maintenance and repair of slopes of embankments,
- repair of equipment elements.

The code should also describe basic repair procedures of buried flexible structures – general rules:

- anti-corrosion layer damage,
- mechanical damage,
- culvert deformation.

8. PROPOSED SUB-COMMITTEES

It is suggested to appoint several sub-committees for the study of the following issues for the purpose of developing the buried flexible structures code:

- material matters (culvert and backfill),
- structural matters –profile geometry, foundation, backfill geometry, equipment,
- loads (dead and live load, load combinations, partial safety factors, combinational factors, special loads), load influence of the structure, structures in untypical conditions (seismic areas, permafrost areas),
- methods of analysis (analytical methods, numerical methods, research based methods), ULS and SLS (methods of description and criteria),
- durability (environmental threats classification: soil, water, atmosphere); anti-corrosion protection and protection against mechanical damage,
- methods of construction, control during the construction stage, final checks,
- structure maintenance, damage classification, methods of rehabilitation.

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