4th International FLAC Symposium on Numerical Modeling in Geomechanics – 2006 – Hart & Varona (eds.) Paper: 05-10

Structural plate steel underpasses during backfilling – how to minimize the bending moment

G. Pittino & J. Golser
University of Leoben, Chair of Geomechanics, Tunneling and Heavy Construction Engineering, Austria

ABSTRACT: Curved corrugated steel plates are field assembled into pipes, arches, underpasses and other shapes. The lateral bedding that is responsible for the load bearing capacity of the flexible, earth embedded steel pipe is provided only by way of backfilling with soil material. The earth pressure that develops by backfilling must be solely born at first by the small bending resistance of the pipe. The bending moments remain nearly "frozen" after backfilling up to the top. This paper deals with the soil-structure interaction. This is shown by means of numerical calculations with *FLAC* as to how the steel conduit should be backfilled so that the bending moments remain small.

1 INTRODUCTION

Soil-steel underpasses have been successfully used as an alternative to the conventional reinforced concrete and steel bridges in the USA for 100 years.

Corrugated steel products are available in a wide range of sizes and shapes for many applications. Round pipe is available in diameters of 0.15 m to nearly 16 m. Pipe-arches, long span structures, arches and box culverts are available in many combinations of rise and span up to 23 m. The corrugated steel plates are assembled into various shapes. A well situated, properly bedded, accurately assembled, and carefully backfilled galvanized structural plate corrugated steel pipe (SPCSP) will function properly and efficiently over its design life (CSPI 2002).

Figure 1 shows the corrugated profile. Corrugations are circular arcs connected by tangents and are described by way of pitch, depth and inside forming radius. The y-axis represents the circumferential direction and the x-axis the underpass longitudinal direction.

The lateral bedding that is responsible for the load bearing capacity of the flexible, earth embedded steel pipe is provided only by way of backfilling with soil material. The earth pressure developing by way of backfilling must be solely born at first by the relatively small bending resistance of the pipe-arch.

Two movements may occur during backfilling – "peaking" and "rolling". The pressure of the compacting sidefills causes peaking. Rolling is caused by unbalanced fill or greater compaction on one side. Size control cables and soil mound loading on the top are known to control the upward peaking of the SPCSP. The following analyses with *FLAC* (Itasca 2005) shall demonstrate that loading the top of the pipe-arch at a particular backfill depth reduces the bending moments during the entire construction sequence.

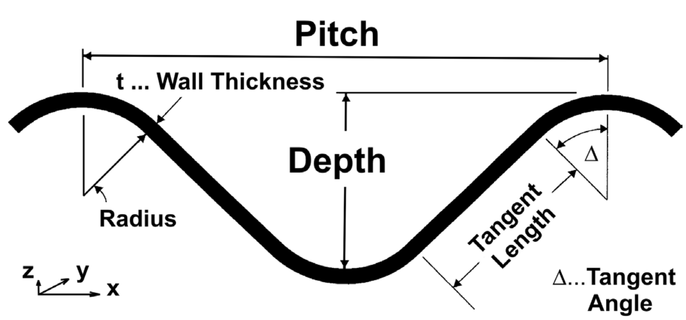

Figure 1. Corrugation profile of the structural plate.

2 NUMERICAL MODEL AND MATERIAL PROPERTIES

To analyze the backfilling of the SPCSP in layers, the grid must have continuous, horizontal, and equidistant layers. Forming the mesh to fit the shape of the SPCSP was necessary for grid generation. By means of Visual Basic within Excel (Microsoft) the coordinates of the SPCSP-nodes are calculated and stored in a file by specifying the centers and radii of the arches (Fig. 2). In *FLAC^{3D}* (Itasca 2002) the vertical distances of the nodes must be equal in order to simulate horizontal layers (backfilling) of same thickness.

The grid generation with *FLAC* is made easy. The shape of the SPCSP is defined in a fine grid with the command "generate table n". The mesh and geometry of the entire embedded structure (SPCSP on a prepared base) is shown in Figure 2. In *FLAC^3D^* the mesh is generated by a FISH procedure after reading the above-mentioned file (Fig. 3). The minimum height of the cover (HC) is one sixth of a span (CSPI 2002), therefore, 2.0 meters. To avoid the error message "bad geometry", the expected uplift of the pipe-arch should be smaller than the grid point distance (Fig. 4).

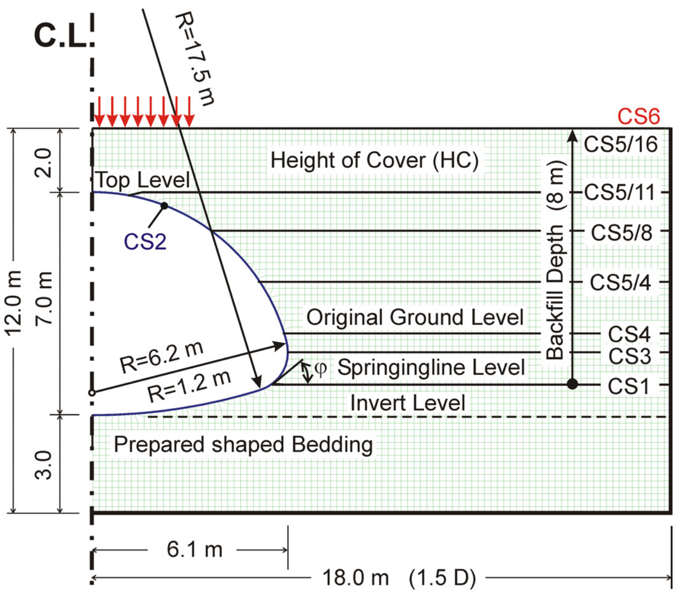

Figure 2. Half-symmetry *FLAC* model of the SPCSP as "beam structural elements" with the construction, backfilling and loading stages (CS).

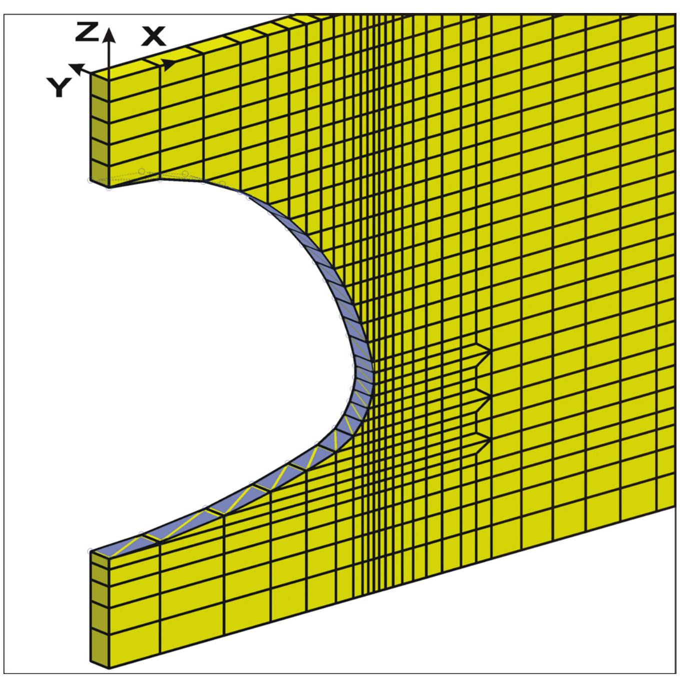

Figure 3. Half-symmetry *FLAC^3D^* model of the SPCSP as "shell structural elements" and the surrounding backfill soil.

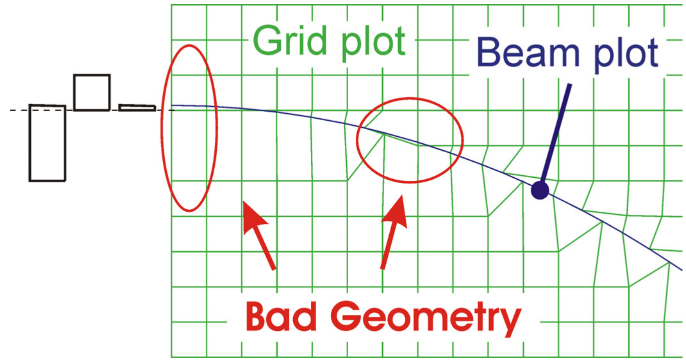

Figure 4. If the uplift of the pipe-arch exceeds the grid distance the grid generation causes the error message "bad geometry".

In *FLAC*, the SPCSP is modeled with the structural element "beam". The beam elements are assumed to behave as a linearly elastic material without an axial compressive failure limit, and without a specified maximum moment (plastic moment). The geometric and material properties assigned to the beam elements are shown in Table 1. The bedding and backfill material are described as elastoplastic by means of the Mohr-Coulomb criterion and parameters as shown in Table 2.

Table 1. Properties of the beam elements used in *FLAC*.

Property	Magnitude
Density (kg/m^3)	7850
Elastic modulus (GPa)	210
Poisson's ratio	0.3
Cross-sectional area (cm^2/m)	83
Second moment of area (cm^4/m)	325

Table 2. Geomechanical properties of the backfill material.

Property	Magnitude
Density (kg/m^3)	2000
Elastic modulus (MPa)	200 (50)
Poisson's ratio	0.4*
Friction angle (°)	35
Cohesion (MPa)	0

* Magnitude to model the compaction.

Displacements, bending moments and axial forces in the SPCSP are calculated for the following construction stages (CS) shown in Figures 2 & 5:

The first construction stage (CS1) is to prepare the shaped bedding. The bedding can be produced up to a slope corresponding to the friction angle φ. The bedding is flat or shaped. The upper 5 to 10 cm layer should be uncompacted so that the corrugations can seat in the bedding. The soil beside and below the corners of the pipe-arch must be of excellent quality, highly compacted, and thick enough to spread and accommodate the high reaction pressure that can develop at that precise location (CSPI 2002).

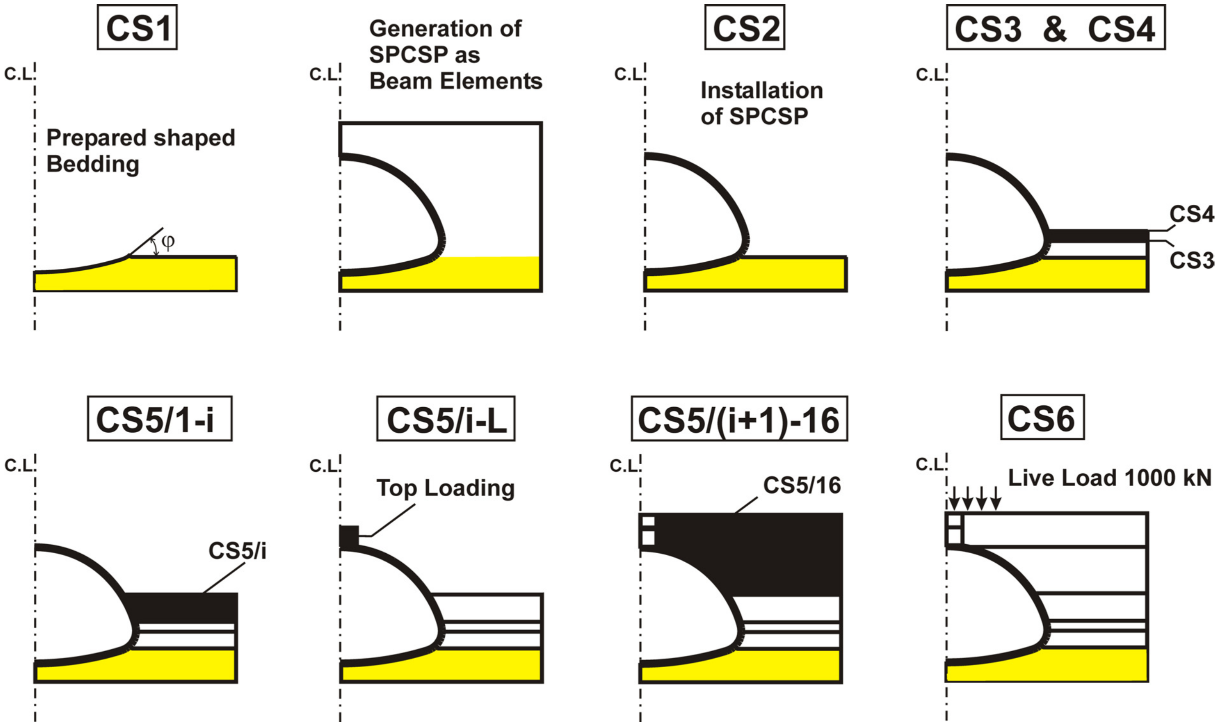

Figure 5. This modeling scheme describes, by way of single construction stages (CS), the construction sequence (C) for bedding, SPCSP-construction, sequential backfilling and loading (L).

In the second construction stage (CS2) the pipe-arch is installed. It is loaded only through its self weight.

With the third construction stage (CS3) the back-filling is modeled up to the springing line of the pipe-arch.

In the fourth construction stage (CS4) the backfill height goes up to the original ground level.

The fifth construction stage (CS5) models the filling placed in the layers with a 400 mm thickness. In CS5/i i means essentially the i^{th} layer in CS5. After CS5/i is run to equilibrium, the top of the pipe-arch is loaded (CS5/i-L). In CS5/11 the backfill depth reaches to the top of SPCSP. The pipe-arch is entirely embedded with the height of cover (HC) of 2.0 meters at CS5/16.

The sixth construction stage (CS6) consists of the live load. 1000 kN are applied on 6 m^2.

mean an uplift. The backfill depth starts from the prepared bedding surface as shown in Figure 2.

Table 3. Maximum displacements, axial forces and bending moments for various construction sequences (C) as well as construction stages (CS).

Constr. Sequence	Disp. mm	CS	Force kN/m	Moment kNm/m	CS
C-0	260 (240)	5/12	700	46 (45)	5/16
C-35	70 (35)	4/5	920	-19 (16)	5/5-L
C-357	85 (90)	5/5-L	980	-25 (-22)	5/5-L
C-4	150 (130)	5/12	860	28 (30)	5/16
C-4(20)	85 (65)	5/12	900	19 (20)	5/16
C-4(20)8	50 (35)	5/4-L	940	-15 (15)	5/4-L
C-46	50 (40)	5/9	917	14 (15)	5/6-L
C-468	40 (60)	5/6	960	-18 (-18)	5/6-L
C-57	65 (50)	5/9	910	-14 (15)	5/16

( ) Magnitudes for displacements and moments due to CS6.

3 RESULTS

The maximum displacements, axial forces and bending moments for 9 construction sequences are shown in Table 3. The construction stage that caused the maximum magnitude is indicated in column CS. In addition, the maximum displacement and the maximum bending moment are shown in the bracketed expressions due to construction stage CS6.

Figures 9-11 illustrate the influence lines that are dependent on the backfill depth for the top of the SPCSP. The displacements with a positive sign

The notation for the construction sequences is for example C-4(20)8. The numbers 4 and 8 indicate the construction stage CS5/4 and CS5/8. The top loading of 12 kN normally is used. The bracketed expression indicates another magnitude. At CS5/4 20 kN are applied and at CS5/8 12 kN.

Sign convention: All of the axial forces in the pipe-arch are compressive forces with a positive sign. The positive bending moment causes compression on the inner side of the pipe-arch and is drawn also on the inner side.

The analysis of the construction sequence C-0 is carried out without top loading. Figure 7 shows the displacement vectors and the bending moments around the pipe-arch for the construction stages CS5/16 and CS6. The maximum displacement is reached at CS5/12 with a magnitude of 260 mm. With that, the following general rule is not corresponded to. The deflection in any direction, that measures greater than 2% from the original shape, should not be allowed during backfill operation (CSPI 2002). Additionally, the withstanding bending moment of the pipe is lower than the maximum acting bending moment of 46 kNm/m. For comparison purposes: the plastic moment of the corrugated plate is 35 kNm/m.

In Figures 9-11 the red influence line increase during backfilling until the top of SPCSP is reached. Subsequently, the uplift and the bending moment remain nearly the same, except for the influence line for the axial force (Fig. 11). For the backfill beyond the top of the pipe-arch the axial force increases almost linearly. At CS5/16 the axial forces are about 350 kN/m for all the construction sequences. It increases to 950 kN/m due to CS6 (Fig. 12).

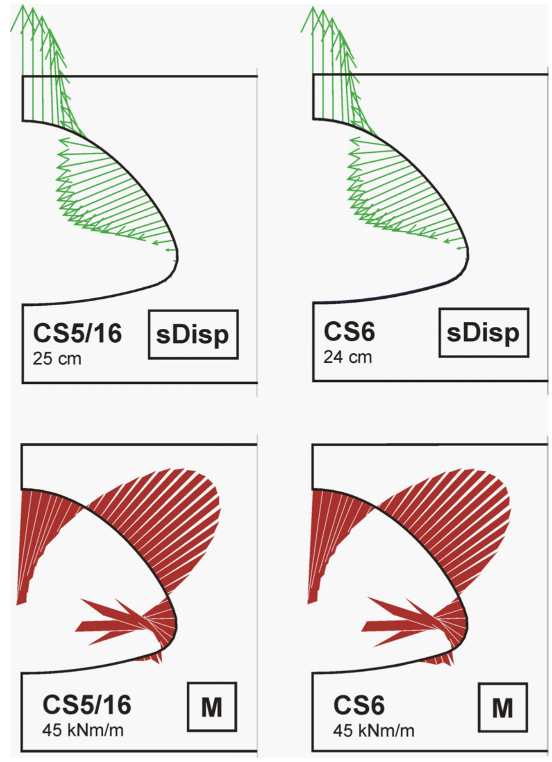

Figure 7. Displacement vectors and bending moments in SPCSP due to C-0.

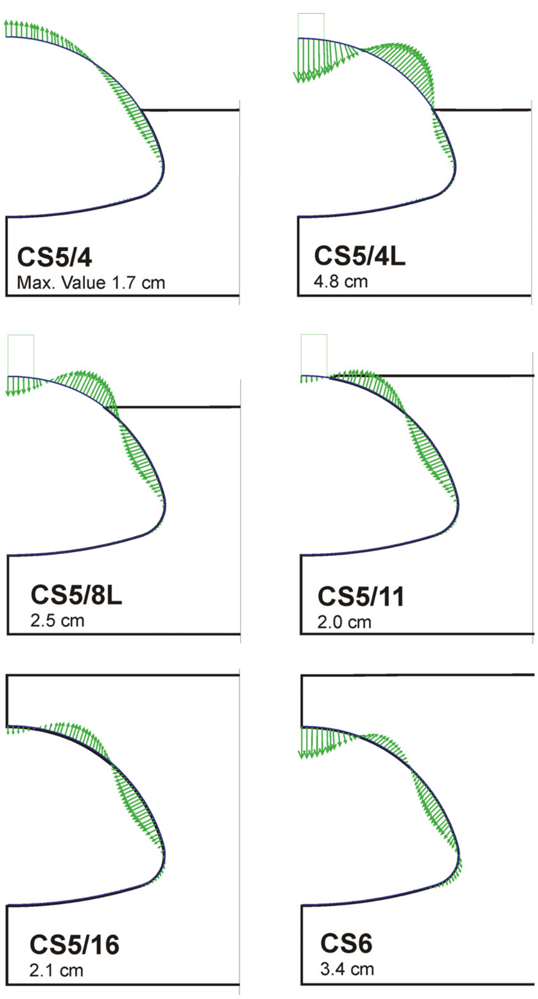

Figure 6. Displacement vectors of SPCSP due to C-4(20)8.

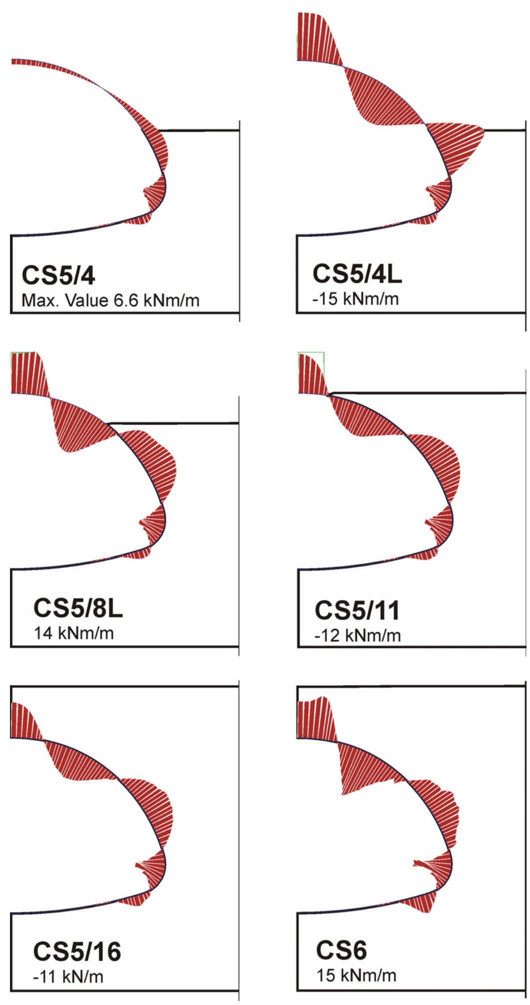

Figure 8. Bending moments in SPCSP due to C-4(20)8.

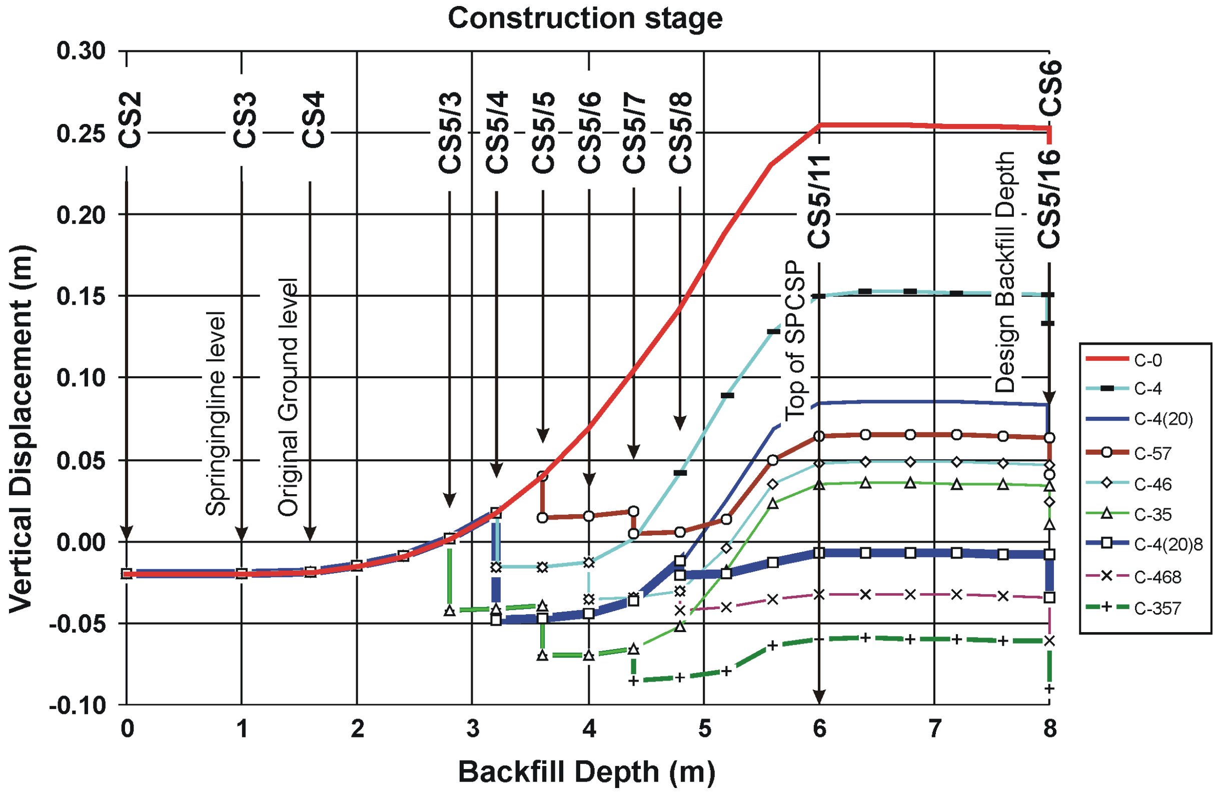

Figure 9. Vertical displacement versus the backfill depth for the top of SPCSP for several construction sequences.

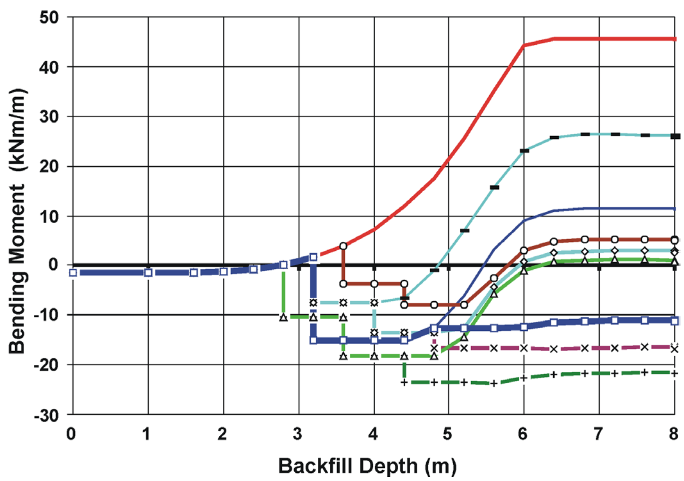

Figure 10. Moment versus backfill depth for the top of SPCSP.

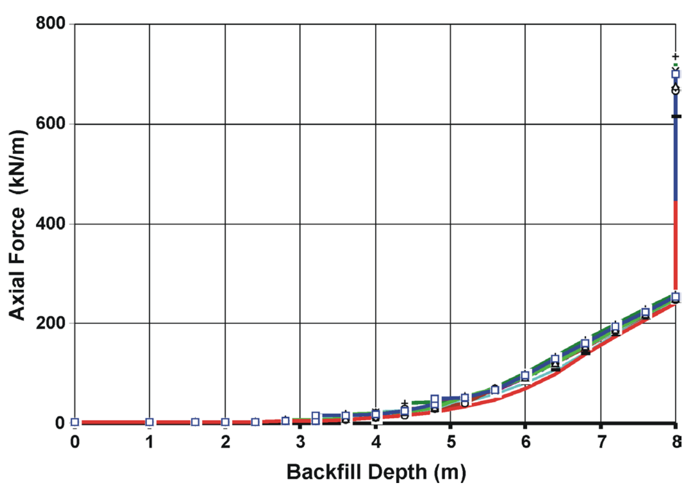

Figure 11. Axial force vs. backfill depth for the top of SPCSP.

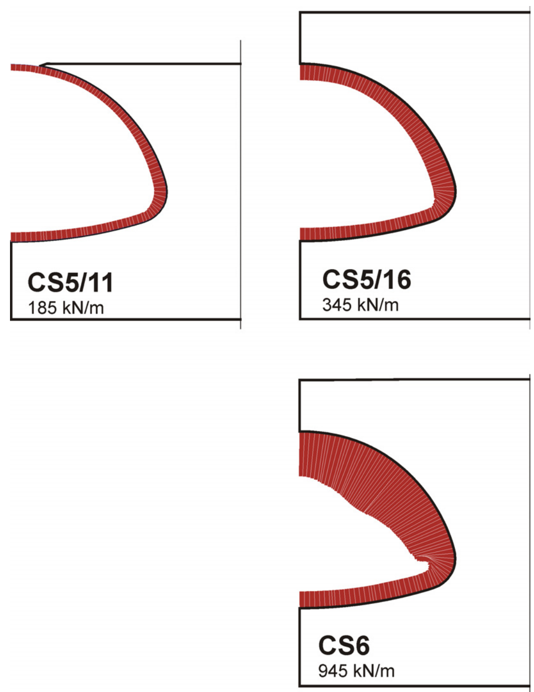

Figure 12. Axial force in SPCSP due to C-4(20)8.

To prevent large bending moments and large deformations the top of the pipe-arch is loaded with backfill material.

The construction sequence C-4(20)8 is described in the following. The top loading of 20 kN at CS5/4-L causes a top displacement of 65 mm. At this time the backfill depth is 3.2 m. If the backfill depth is 4.8 m, a load of 12 kN (CS5/8-L) causes only a deformation of 10 mm. After CS5/11 the blue displacement influence line is nearly constant on -10 mm (Fig. 10). At the first loading stage (CS5/4-L) the maximum bending moment increases from 7 kNm/m to 15 kNm/m, which is not exceeded any further (Table 3). With increase of the backfill depth to CS5/8 the maximum bending moment decreases to 13 kNm/m. At CS5/8-L the maximum moment is 14 kNm/m and decreases to 11 kNm/m at CS5/15. Due to the CS6 the maximum moment is 15 kNm/m as shown in Figure 8.

The construction sequences, C-35, C-46 and C-57, are different by the backfill depth at the top loading (Fig. 10). At CS5/11 the top displacements are 35, 50 and 65 mm (Fig. 10). The corresponding maximum deformations are, 70, 50 and 65 mm (Table 3) and the maximum bending moments, -19, 14 and -14 kNm/m.

4 STRUCTURAL PLATE AS AN ORTHOTROPIC PLATE USED IN *FLAC^{3D}*

To model the corrugated plate as an orthotropic plate, the nodes are predefined to where the principal directions of orthotropy fall into the circumferential direction and longitudinal direction. In this case the material-stiffness matrix can be expressed in terms of 4 independent elastic constants.

Figure 13 shows the flow chart and the equations for how to model the corrugated structural plate as an equivalent orthotropic plate. The width of a plate is measured in a direction perpendicular to the length of the structure around the periphery of the structure. Therefore, the y-axis represents the circumferential direction.

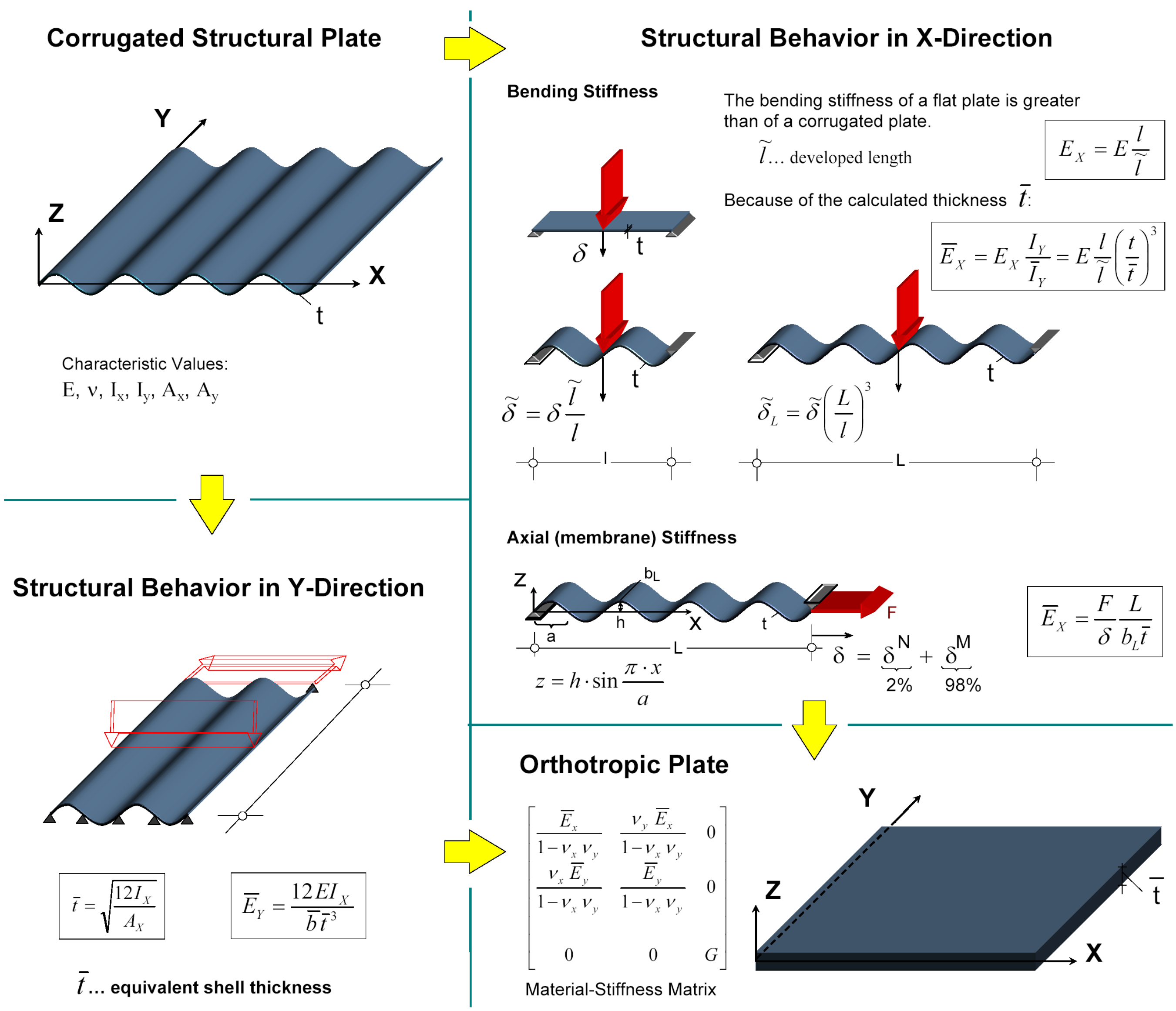

Figure 13. Flow chart for the modeling of the corrugated structural plate by means of an equivalent orthotropic plate.

The structural behavior in the y-direction must be the same for the corrugated structural plate and the orthotropic plate. Hence, for both plates, the bending stiffness EI_x and the normal stiffness EA_x must be equal. This yields to the equivalent shell thickness $\bar{t}$ and the equivalent elastic modulus $\bar{E}_y$.

Because of the equivalent shell thickness determined beforehand only the elastic modulus in the x-direction can be modified. Therefore, in the x-direction we have to decide whether the bending stiffness or the normal stiffness is significant.

If the bending stiffness is important, then we have to calculate the elastic modulus E_x by means of the developed width factor WF, the ratio of the flat plate width to the corrugated plate width after forming. For the corrugation profile 152 × 51 mm, the WF is 1.24. Because of the equivalent shell thickness, the modulus of elasticity must be reduced once again on $\bar{E}_x$. If the normal stiffness is important, we must calculate the modulus of elasticity $\bar{E}_x$ according to the equation in Figure 13. Large-scale tests should be carried out and compared with these numerical analyses.

5 CONCLUSIONS

Size control cables as well as soil mound loading on the top of the pipe-arch are known to control peaking. During backfilling the displacements and the bending moments around the pipe-arch may exceed the allowed magnitudes. The analyses with *FLAC* have shown that loading the top of the pipe at particular backfill depths reduces the bending moments during the entire construction sequence compared to the analyses without top loading of the pipe-arch.

The aim is a compromise between the theoretically optimized construction sequence and the practical site conditions.

The subject of future research should be to develop an automatism for optimization the top loading sequence dependent on the geometry of the pipe-arch, the geotechnical parameters of the backfill material and in combination with geogrid.

REFERENCES

Corrugated Steel Pipe Institute (CSPI) 2002. *Handbook of Steel Drainage and Highway Construction Products*. Ontario, Canada.

Itasca Consulting Group, Inc. 2005. *FLAC – Fast Lagrangian Analysis of Continua, Version 5.0 User's Manual*. Minneapolis: Itasca.

Itasca Consulting Group, Inc. 2002. *$FLAC^{3D}$ – Fast Lagrangian Analysis of Continua in 3 Dimensions, Version 2.1 User's Manual*. Minneapolis: Itasca.