BURIED FLEXIBLE STEEL STRUCTURES WITH WIRE MESH REINFORCEMENT FOR CUT PLATES

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Abstract

Buried flexible structures consist of corrugated metal plates bolted together to form rings that rely on the support of the surrounding soil envelope. When plates are cut on a slope or at a plane inclined to the vertical, their behaviour changes to a hybrid of a retaining wall and a buried flexible structure. For most applications, cut plate sections require additional reinforcement. Traditionally, this support is provided through concrete collars or longitudinal reinforcement. With the advancement of deep corrugated plate, traditional methods of support are not always feasible, or cost-effective. In this paper, a new method for supporting cut rings with wire mesh reinforcement is introduced. Wire mesh reinforcement provides an economical, easier to construct alternative that better controls cut ring deflection. In addition, wire mesh reinforcement increases the possible size of cut ring sections. Two case studies have been considered in the paper to study the proposed method.

Key words: Buried Flexible Structures, Corrugated Plate, Cut Rings, Skew Bevel, Welded Wire Mesh, Mechanically Stabilized Earth, MSE

1. INTRODUCTION

Buried flexible structures are commonly used for vehicular underpasses, river crossings, and wildlife crossings. The shape of buried flexible structures is often modified to meet site conditions. Cutting plates on a slope or at an inclination to the vertical is a common modification. Other advantages of cut rings include: reducing steel quantity through elimination of plates in the crown region, reducing footing loads, increasing the amount of natural light entering the structure, and improving site aesthetics.
Rings are cut either on the ends or in the middle of the structure. When structure ends are cut, bevels, skews, or skew bevels ends are created, as illustrated in Figure 1.0 (CHBDC, 2006).

**Skew end**

![Skew end diagram](image)

**Square bevel with roadway skew to transverse direction**

![Square bevel diagram](image)

**Skew bevel**

![Skew bevel diagram](image)

Figure 1.0. Different Type of End Cuts (CHBDC, 2006)

Structures with end cuts blend in and conform to the side slope of the road rather than extrude from the embankment, presenting a more aesthetically pleasing finish. Bevel and skew cuts are needed on some sites, particularly small sites with roadways skew to the stream crossings. Occasionally, a skew-bevel cut is the only option. The reduction of the top centre line with bevel cuts increases the amount of natural light entering the structure, which is a benefit for traffic and wildlife underpasses. Cuts in the middle of the structure are not as common as end cuts. Middle cuts can be used on twin highway overpasses. Removing the top of the structure brings more natural light into the structure.

Cut rings produce a structure that is a hybrid of a buried flexible structure and a retaining wall. Limited cut ring design information is available in the 2006 Canadian Highway Bridge Design Code (CHBDC) and the 2004 American Association of State Highway and Transportation Officials (AASHTO) LRFD. Traditionally, cut rings have been supported with concrete collars, longitudinal reinforcement, and deadman anchors. With the advancements of deep corrugated...
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2. ANALYSIS

Although forces applied to a cut ring structure are similar to forces applied to flexible buried structures with complete rings, a cut ring structure’s response is much different. When analysing cut rings structures, forces at each construction stage need to be determined. Typically forces acting on a cut ring structure are illustrated in Figure 2.0.

Figure 2.0. Typical Forces on Cut Ring Sections
2.1 Vertical Earth Load
Vertical earth load has a significant influence on the stress in the cut rings. When lever arm distance is large, bending stress in the structure can become substantial. The skew angle, \( \theta \), affects the overhang profile. The CHBDC (2006) restricts \( \theta \), as defined in Figure 1.0, to 40°.

2.2 Lateral Earth Pressure
Lateral earth pressure is a function of the soil characteristics between the structure and the failure plane, and the movement of the structure. Cut rings are backfilled using non-cohesive material with a minimum internal angle of friction of 35°. A typical active failure plane is inclined at an angle of 45° + \( \phi/2 \). A series of failure wedges are conducted to produce worst case conditions. Typically, the failure plane is:
1) Tangential to the structure
2) Located at the structure/footing connection

![Figure 2.1. Variation of Lateral Earth Pressure with Depth (Coduto, 2001)](image)

Lateral earth pressure is dependent upon structure movement. Movement away from the soil creates active pressure, while movement into the soil creates a much larger passive pressure. When vertical earth load is small, structure movement tends to be away from the soil. On the other hand, when vertical earth load is large, structure movement at the base tends to be into the soil and at the top of the structure, away from the soil. Lateral earth pressure coefficients are
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derived using a height deflection relationship found in Coduto (2001) as illustrated in Figure 2.2:

where: \( H \) is the wall height.

\[ \sigma_h' = \text{effective lateral pressure.} \]

\[ (\Delta H/H)_{\text{passive}} = 0.04H \text{ for loose sand.} \]

\[ (\Delta H/H)_{\text{active}} = 0.004H \text{ for loose sand.} \]

It is conservative to assume active pressure throughout the entire height. Friction between the structure and fill is conservatively ignored.

2.3 Compaction

Compaction force needs to be considered since backfill is placed and compacted in layers. A minimum lateral compaction surcharge of 12 kPa is applied in accordance with the CHBDC (2006). As shown in Figure 2.0, compaction force is applied until lateral earth pressure from the backfill is 12 kPa.

2.4 Live Load Vehicle

According to the CHBDC (2006), live load’s influence zone propagates through the soil at a 1.0 vertical to 0.875 horizontal distribution. Cut ring sections shall be designed for an equivalent height of fill surcharge where live load influence is applicable. The CHBDC (2006) uses an equivalent height of fill equal to 0.80 m.

2.5 Seismic

Seismic loading varies directly with vertical earth load. However, with cut rings, vertical earth load is small and live loads or compaction forces govern. Cut rings shall be designed for seismic forces if they are greater than live load or compaction forces.

2.6 Hydraulics

Hydraulic forces need to be considered when selecting the geometry and designing the cut rings. Hydraulics are of particular concern on structures with cut plates in the invert. Features such as concrete cut-off walls, act to prevent piping and help reduce and counteract uplift forces that my develop. Additional reinforcement or means to reduce hydraulic forces may be required.

3. DESIGN

Flexible buried structures with complete rings are at minimum statically indeterminate to the first degree, so formation of a plastic hinge is acceptable. On the other hand, cut ring sections are considered statically determinate and for-
mation of a plastic hinge is not permitted. As a result, maximum factored bending stress must be less than the factored elastic bending capacity. Bending moment is the governing design factor for cut ring sections and must be considered.

Traditional support methods for cut rings include reliance on the corrugations longitudinal strength, attaching longitudinal stiffeners, concrete collars, and deadman anchors.

When selecting the method to support cut rings, applied forces, cost, aesthetics, and accessibility of materials are considered. Concrete collars are recommended for structures located in areas where ice is common, to act as a fender protecting the end of the structure against ice and debris. Concrete collars may act as a secondary reinforcement in these situations.

**3.1 No Additional Reinforcement**

Corrugated plate’s bending resistance in the longitudinal direction is dependent on several factors including plate thickness, yield strength, and shape. When the skew angle $\theta$ is greater than $20^\circ$, reinforcement to resist the large earth pressure imbalance is required (CHBDC, 2006). Roads with a skew angle of $20^\circ$ or less may not require additional reinforcement, but consideration of loading, structure size, shape, and material strength is required. Table 3.0 shows a list of recommendations from the Australian/New Zealand buried structures code (AS/NZS, 1998). Recommendations are provided for end reinforcement need when span is less than 4.5 m. End reinforcement is recommended for structures with end cuts having spans greater than 4.5 m.

**Table 3.0. End Treatment Reinforcement Requirements (AS/NZS, 1998)**

<table>
<thead>
<tr>
<th>Skew in degrees $\pm \theta$</th>
<th>End Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vertical square cut end</td>
</tr>
<tr>
<td></td>
<td>1V:1H</td>
</tr>
<tr>
<td>&gt;35</td>
<td>Skew number not recommended</td>
</tr>
<tr>
<td>16-35</td>
<td>Yes</td>
</tr>
<tr>
<td>6-15</td>
<td>No</td>
</tr>
<tr>
<td>5</td>
<td>No</td>
</tr>
<tr>
<td>6-15</td>
<td>No</td>
</tr>
<tr>
<td>16-35</td>
<td>Yes</td>
</tr>
<tr>
<td>&gt;35</td>
<td>Skew number not recommended</td>
</tr>
</tbody>
</table>


3.2 Longitudinal Reinforcement

The structure is reinforced in the longitudinal direction by attaching angle or channel sections to the structure in this direction. Behaving similar to a cantilevered beam, required section capacity quickly increases with cut ring length. As such, longitudinal reinforcement is only a practical and cost-effective solution for small cut ring applications.

3.3 Concrete Collars

A concrete collar is a concrete beam cast against the top of the cut rings that forms a ring beam when applied to bevel ends. Concrete collars behave similar to longitudinal stiffeners in that they provide additional bending resistance to cut rings in the longitudinal direction.

The concrete collar needs to resist earth pressure from fill placed against cut rings. Cut ring sections are constructed by either bracing the cut rings and pouring the concrete after the structure has been backfilled, or by pouring the concrete collar prior to backfill. Cut rings may need bracing to support the wet concrete. Site conditions may eliminate the possibility of bracing cut rings.

Care needs to be taken when pouring a concrete collar prior to placement of backfill as buried flexible structures deflect when loaded. For instance, the CHBDC (2006) permits a maximum upward or downward crown deflection equal to 2% of the rise. Lateral movement is of particular concern for long cut ring sections. Quite often, cut ring movement in response to backfill pressure is significant enough to produce cracks and deformations in the concrete collar, as illustrated in Figure 3.0. Additional longitudinal reinforcement may be required to control deflection. Concrete collars are not recommended as a primary reinforcement means when anticipated deflection is large.
Collars are not economical on remote sites where concrete access is difficult. Concrete collars are difficult to pour in winter environments as additional heating methods is occasionally required to ensure proper curing. Size of the concrete collar is directly related to the magnitude of the cut ring section. Concrete collars are neither a practical or cost-effective solution for large cut ring regions.

3.4 Deadman Anchors

Deadman anchors resist lateral movement through connecting the cut ring sections to an anchor behind the failure plane. Deadman anchors need to be placed the greater of H/5 or 1.5 m behind the failure plane. Passive resistance develops on the structure side of the deadman anchor. Anticipated deflection to require adequate passive resistance varies and can be estimated using Figure 2.1. A reinforcement system for small and large cut ring sections can be designed using deadman anchors.

3.5 Wire Mesh Tiebacks

Numerous mechanically stabilized earth (MSE) walls are constructed with welded wire mesh. Wire mesh strengthens the soil and provides stability through frictional and passive resistance between the wire mesh reinforcement and the granular backfill. The new cut ring reinforcing system restricts lateral movement of the structure by attaching wire mesh to the cut rings. Wire mesh reinforcement is suitable system for supporting large and small cut ring sections.

Welded wire mesh is galvanized wire mesh reinforcement manufactured in accordance with ASTM A82-05a and A185-05a (2006). Welded wire mesh is referred to as inextensible reinforcement since little strain is needed to activate the steel. The mesh is manufactured by welding transverse wires perpendicular to longitudinal wires at a constant spacing. Longitudinal wires run parallel to the corrugation and transverse wires run across the corrugation (see Figure 3.1).

![Figure 3.1. Wire Mesh](image-url)
Diameter of the transverse wire must be at least 40% of the longitudinal wire to ensure a proper weld. Minimum and maximum spacing of transverse wires are 150 mm and 915 mm respectively. Longitudinal wires are typically spaced at 152 mm centre to centre.

Two failure modes exist for wire mesh: rupture and pullout. Rupture occurs when longitudinal wires are subjected to excess axial tension. Adequate cross-sectional area is required to resist rupture failure. Maximum tensile force in the mat is calculated using following formula found in AASHTO (2004):

\[ A = \frac{F}{\phi F_y} \]  

where: 
- \( A \) = cross sectional area of the wire.  
- \( F_y \) = Wire yield strength (typically 450 MPa).  
- \( \phi \) = Resistance factor.

Pullout failure occurs when the wire mesh mat pulls out of the soil. Pullout resistance is a function of the mesh-soil friction, and the passive resistance developed in front of the transverse wires. Only the portion of the mat behind the failure wedge can be relied upon for pullout resistance. AASHTO (2004) provides the following formula for calculating pullout resistance:

\[ L_e = \frac{T_{max}}{\phi \times F^* \times \alpha \times \sigma_v \times C \times Rc} \]  

where:  
- \( L_e \) = Length of reinforcement behind failure plane.  
- \( T_{max} \) = Applied factored load in reinforcement.  
- \( \sigma_v \) = Vertical mat spacing.  
- \( \phi \) = Resistance factor  
- \( F^* \) = Pullout friction factor  
- \( \alpha \) = Scale effect correction factor (1.0 for wire mesh)  
- \( C \) = Reinforcement surface area geometry factor (2.0 for wire mesh)  
- \( Rc \) = Reinforcement coverage ratio behind failure plane

A major benefit of wire mesh tiebacks is that mesh reinforcement anchors the structure and strengthens the soil, thereby reducing the load applied to the structure. If wire mesh is placed such that the maximum vertical spacing is 750 mm, the failure plane is reduced as shown in Figure 3.2 (AASHTO, 2004).
Mesh tiebacks are used to reduce bending stress during construction. Mats are connected to the structure at every outside crest providing continuous reinforcement as shown in Figure 3.3, and good deflection control.

Fill is first placed over the rear of the mat, as shown in Figure 3.4, to develop pullout resistance. During backfilling, the flexible cut rings move away from the backfill. A 20 mm (FHWA, 2001) maximum movement is required to
full activate pullout resistance. Therefore, cut rings supported by wire mesh reinforcement have a maximum horizontal deflection of 20 mm.

Comparing the backfilling time of a cut ring section with no wire mesh reinforcement to one with wire mesh reinforcement, the later will take 10% longer.

Pouring a concrete collar for aesthetic or design purposes requires less effort once the structure has been backfilled. Bracing is not required when cut rings are supported with wire mesh reinforcement, so forming and pouring the collar is easier. Post backfill deflection of cut rings is significantly reduced once the rings are surrounded with backfill. Since horizontal deflection is limited to 20 mm, significant concrete cracks will not form.

4. CASE STUDIES

4.1 Roddick Road, Ontario, Canada

The following case study demonstrates the need for a cost-effective reinforcement method for large cut ring sections.

A road overpass is required on a site in Markham, Ontario, Canada. Property restrictions are tight, and the only geometries that work are structures with large skew bevel ends. Skew angles are 39° on the east side and 27° on the west side. The magnitude of the cut rings is very large and reinforcement is required. The site is in a high profile location and an aesthetically pleasing structure is desirable. Providing an assembly system that gives the contractor a high degree of quality control of the cut rings during construction is desirable.
Traditional methods are first checked for a design solution. The use of longitudinal reinforcement or concrete collars is not practical in this application. There are two ways to construct a concrete collar. The first option is to pour the concrete collar and backfill once the concrete has properly cured. The second option is to brace the cut rings against backfill pressure, place and compact backfill, and cast the concrete collar once backfill is complete. With the first option, anticipated movement of flexible cut rings from backfill pressure is large enough to produce large cracks in the stiff concrete collar. Therefore, additional longitudinal reinforcement is required and a concrete collar can be used to provide secondary reinforcement with this construction sequence. The second option is not possible since a bracing system cannot be constructed as work in the stream is not permitted. The only reinforcing options are deadman anchors or wire mesh tiebacks. Wire mesh tiebacks provide more longitudinal reinforcement, reduce the applied force, and better control bevel movement caused by backfill pressure. Table 4.0 illustrates a comparison between deadman tiebacks and wire mesh tiebacks.

Field experience has shown that deadman anchors take approximately 10% longer to assemble than mesh tiebacks. Backfilling with deadman anchors or wire mesh reinforcement will respectively take 20% or 10% longer than backfilling with no reinforcement. The entire backfilling process takes ten days, and the step bevels represent 25% of the structure length. Deadman anchors and wire mesh reinforcement will add eight and four hours of labour respectively.

Effective design, economical material and construction cost, and reduced construction time are all positive reasons to use the wire mesh tieback system.
4.2 Trans-Canada Highway, New Brunswick, Canada

The following case study outlines a time and cost comparison between cut rings reinforced with a concrete collar or wire mesh reinforcement.

Deep corrugated structures with spans ranging from 8 m to 15 m are used on this project. All buried flexible structures have large step bevel ends. Large step-bevels are required on the wildlife underpasses to permit more natural light in the structure. Cut rings are of such a magnitude that reinforcement is required. Scheduling is tight on this project, so a cost effective solution that is quick to construct was sought. Longitudinal reinforcement is not a cost-effective solution. The Roddick Road case study demonstrated that wire mesh tiebacks are a better solution than deadman anchors, so a comparison between a concrete collar and wire mesh reinforcement was undertaken. Results are summarized in Table 4.1.

Forming the collar takes two days total (one day for each end of the structure). The concrete collar must be poured in three lifts. Each lift requires half a day of work, and occupies one day on the schedule. One day is required to strip the forms for a total of six days. Total hours for the concrete collar are 72.

Using wire mesh reinforcement, backfilling of the step bevel ends would conservatively take 10% longer. The entire backfilling process takes ten days, and the step bevels represent 25% of the structure length, so the mesh tieback system adds four hours of labour.

Concrete material costs $350/m$^3$ (CDN). Volume of concrete on one structure is 30 m$^3$. Total concrete material cost is $10,500 (CDN). Total material cost of the wire mats is $7,000.

Table 4.1. Trans-Canada Highway Reinforcement Comparison

<table>
<thead>
<tr>
<th>Category</th>
<th>Concrete Collar</th>
<th>Wire Mesh Tiebacks</th>
<th>Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Days in Schedule</td>
<td>6 days</td>
<td>0.5 day</td>
<td>5.5 days</td>
</tr>
<tr>
<td>Construction Time</td>
<td>72 hours</td>
<td>4 hours</td>
<td>68 hours</td>
</tr>
<tr>
<td>Material Cost (CDN)</td>
<td>$10,500</td>
<td>$7,000</td>
<td>$3,500</td>
</tr>
</tbody>
</table>
5. CONCLUSIONS

Cut rings on buried flexible structures are often both a required and cost effective solutions to a variety of applications. Cut rings destroy the ability of the ring to resist ring compression forces, and reinforcement is frequently required. The advancements of deep corrugated plate have resulted in a need for structures with large cut ring sections. Traditional reinforcement methods are not always suitable for these applications.

Reliance on the longitudinal stiffness of the corrugated plate is not recommended when the span is less than 4.5 m.

Attaching channel and angle sections to increase the longitudinal bending resistance are not practical or cost-effective for large applications.

Concrete collars can be poured prior to backfill, or after backfill if cut rings are braced during the backfilling process. When concrete collars are poured prior to backfill, deflection of the flexible cut rings shall be less then the amount that creates large cracks in the concrete. Concrete collars are not recommended as a primary means of reinforcement on large cut ring sections.

Deadman anchors may be used as a reinforcement method for large cut ring sections, but wire mesh reinforcement is a better option. A wire mesh system provides continuous longitudinal reinforcement, greater deflection control, and is easier to construct. In addition, the wire mesh system strengthens the backfill, thereby reducing the load applied to the structure.

Wire mesh reinforcement for cut rings is capable of effectively supporting a broad range of cut ring applications. The system adds little construction cost, is less labour intensive, and the material cost is economical. Wire mesh reinforcement is recommended for structures with large cut ring sections, and structures with cut rings on remote sites.

6. REFERENCES


Buried flexible steel structures with wire mesh reinforcement for cut plates


STALOWE KONSTRUKCJE Z BLACH FALISTYCH ZAGŁĘBIONE W GRUCIE ZE ZBROJENIEM OBSZARÓW ŚCIĘĆ KONSTRUKCJI NA ICH KOŃCACH

Streszczenie

Konstrukcje z blach falistych zakopane w ziemi składają się z blach falistych połączonych ze sobą za pomocą śrub, które utrzymują się w równowadze dzięki współpracy z otaczającym gruntem. W przypadku ścień konstrukcji do skarpy lub w skosie do dołu ich zachowanie zmienia się i jest hybrydowym połączeniem konstrukcji podanej i ściany oporowej. W większości zastosowań ścień elementy konstrukcji wymagają dodatkowego zbrojenia. Tradycyjnie tego typu wzmocnienia wykonywane są za pomocą wieńców żelbetowych lub uszytynień podłużnych. Wraz z rozwojem konstrukcji o głębokich falach zauważono, że tego typu wzmocnienia nie zawsze są skuteczne lub też efektywne kosztowo. Referat przedstawia nową metodę wspierania obciętych końców konstrukcji z zastosowaniem zbrojenia gruntu siatkami stalowymi. Ten sposób zbrojenia jest skuteczny i ekonomiczny oraz łatwiejszy do wykonania i lepiej kontroluje deformacje końców konstrukcji. W związku z tym pozwala on na wykonywanie dłuższych cięć w obszarze końców konstrukcji. Dla celów analizy zaproponowanej metody w referacie zaprezentowano dwa studia przypadków.

Słowa kluczowe: konstrukcje podatne zagłębione w gruncie, konstrukcje z blach falistych, ścieżki do skarpy i do osi, siatka stalowa, grunt zbrojony mechanicznie