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Stress Reduction in Flexible Culverts Due to Overlays of Geofabric

Diminution des contraintes dans les conduits souterrains souples grace à un recouvrement de géotextile

Increasing number of flexible metal culverts of different geometries and shapes are being used successfully to bridge across streams and canals. These flexible metal culverts derive a considerable portion of their load carrying capacity through interaction with the surrounding backfill. By including layers of geofabric, the effectiveness of these backfill materials can be improved and the stresses in the culvert can be reduced. This paper reports the results of finite element analyses of a box culvert to provide a quantitative assessment of the reduction in stresses due to the inclusion of geofabrics. The nonlinear and stress-dependent stress-strain behavior of the backfill and the actual sequence of construction operations are taken into consideration in the analyses. The bending moments, axial forces, and deflections in the structure with and without the use of the geofabric are compared for the performance of the structure under the weight of backfill and traffic loads.

De plus en plus de ponceaux métalliques fléxibles de différentes formes et géometries remplacent avec succès des structures plus rigides. Ces ponceaux métalliques flexibles obtiennent une grande partie de leur capacité partante de l'interaction avec le remblai avoisinnant. L'inclusion de couches de geotextiles augmente l'efficacité du remblai et reduit les contraintes induites dans le ponceau. Cet article présente les résultats d'analyses d'éléments finis d'un ponceau fermé et une évaluation quantitative de la réduction des contraintes due à l'inclusion de geotextiles dans le remblai. La relation contrainte-dèformation (non-lineáire et dépendante des contraintes) et les étapes de constructions sont utiliseés dans les analyses. Les moments de flexion, forces axiales et déformations du systéme soumis avec charges de remblai et de circulation automobile sont comparés pour les cas avec et sans géotextiles.

INTRODUCTION

Geofabrics are being used successfully for many engineering applications and the details are given in (1, 2, 3, 13, 14, 17, 18, 19, 20). Soil reinforcement is one of the more common applications of geofabrics. There have been extensive research on the behavior of soil-geofabric reinforcement and the extent to which the geofabric-soil interaction will improve the load carrying capacity of the soil is well understood. Although there have been a tremendous increase in the use of flexible metal culverts in highway bridge projects, no attempt has been made up to date to study the desirable effects of overlays of geofabric placed in the backfill used around and over the culvert. These corrugated culverts derive a considerable portion of their stiffness and load-carrying capacity through interaction with the surrounding backfill. Therefore the quality of the backfill used around and over the structure will determine the performance of these culverts under backfill and live loads. By using several layers of geofabric, embedded in the surrounding backfill, the effective modulus of the backfill can be increased by a substantial amount and the stresses induced in the culvert can be reduced. If the stresses in the culvert can be reduced by an appreciable amount, much thinner culvert structural sections can be employed and a greater economy in use of corrugated flexible metal culverts can be achieved. Because of the complex nature of the soil-structure-geofabric interaction, design of these structures thus requires a method of analysis which is capable of taking this interaction into account, so that the loads in the structure due to both backfill and traffic may be determined. In this paper, the finite element method of analysis is used to study the effects of the presence of geofabric on the loads carried by the culvert. Several series of analyses were performed to provide a quantitative assessment of the reduction in stresses in the culvert structure for varying properties of fabric and loading conditions. The increases in the factor of safety, against development of plastic hinges in the culvert section, due to the use of geofabric were calculated using the bending moments and the axial forces determined from the finite element analyses. The deflections of the structure with and without the use of the geofabric were also calculated as part of this study.

GEOMETRY AND FINITE ELEMENT MESH

A cross-section through the backfill and the aluminum box culvert used in this study is shown in Fig. 1, and the finite element mesh used for the analyses is shown in Fig. 2. The culvert was modeled by linearly elastic beam elements and the geofabric was included in the analyses using a series of linearly elastic bar elements with no compressive strength. The backfill was modeled by two-dimensional isoparametric elements. A no-slip condition was simulated at the interfaces between the culvert and the backfill and between the geofabric and the backfill.

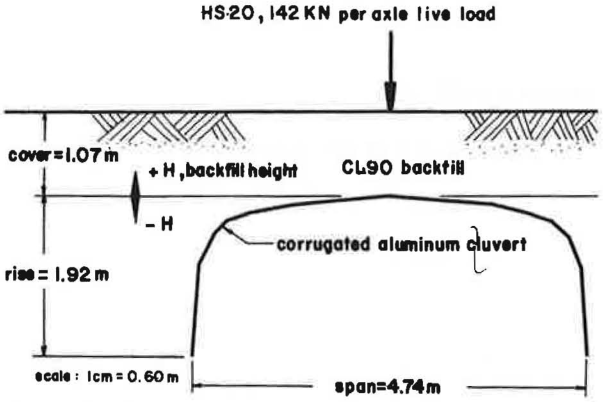

Figure 1. Cross-Section of Box Culvert.

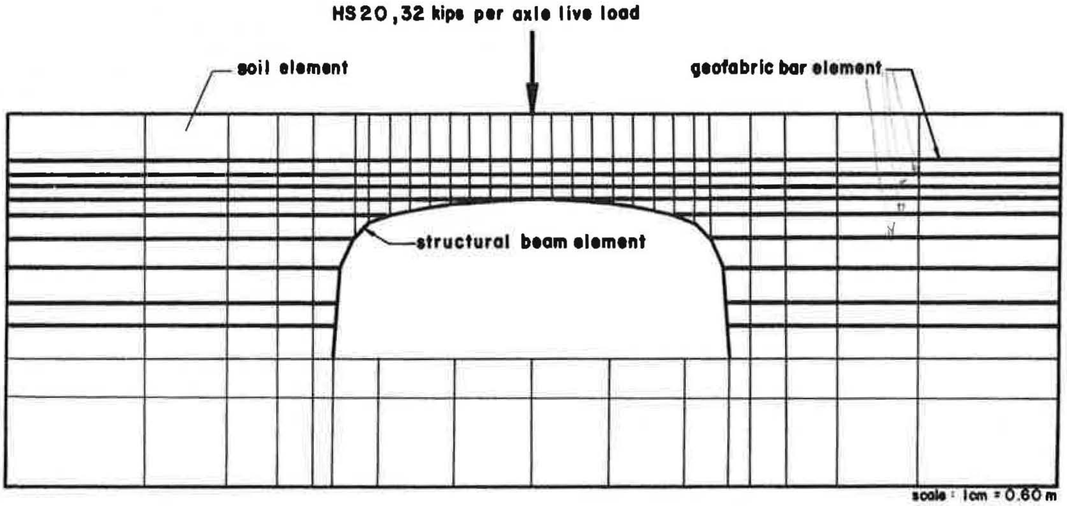

Figure 2. Finite Element Mesh

ANALYSIS PROCEDURE

The interactions between the flexible metal culvert, the surrounding backfill, and the overlays of geofabric were studied using the finite element analysis procedures. The finite element method has been successfully applied to culvert structures including many box culverts of the type chosen for the present study (5, 6, 8, 9, 10, 11, 12, 15). The analyses described in this paper were performed using a hyperbolic stress-strain relationship for the backfill material. This relationship, which is described in detail in (4, 7), model the nonlinear stress dependent stress-strain behavior of soils incrementally, by varying the values of Young's modulus and bulk modulus in each element according to the previously calculated stresses. The analyses herein were performed incrementally, simulating the field construction operations. The backfill was placed around and over the structure one layer at a time, followed by one overlay of geofabric at a time as shown in Fig. 2. The analyses were performed with and without the placement of overlays of geofabric and an AASHTO HS-20 live load was simulated subsequent to the completion of construction.

MATERIAL PROPERTIES

The properties of the low plastic clay backfill employed in the analyses are listed in Table 1. These properties correspond to clay compacted to 90% of the maximum dry density as determined by the Standard AASHTO compaction test. The properties of the aluminum structural plate and the structural plate with angle stiffners used respectively in the side section, haunch and crown sections of the culvert are listed in Table 2. The properties of the geofabric used in the analyses are summarized in Table 3.

REPRESENTATION OF TRAFFIC LOADS

Two-dimensional analyses of the type discussed in this paper, represent a slice of unit thickness through the culvert and the backfill. In these analyses it is assumed that the slice analyzed is representative of any section along the length of the structure, and that

Table 1. Properties of Backfill Material used in Finite Element Analyses

Property	Values Used
Unit weight, γ (kN/m^3)	1.8
Cohesion, C (kN/m^2)	2.9
Modulus Number, k	90
Modulus Exponent, n	0.45
Bulk Modulus Number, k_b	80
Bulk Modulus Exponent, m	0.2
Failure Ratio, R_f	0.7
Angle of Internal Friction, ϕ (degrees)	30

Table 2. Properties of Culvert Sections used in Finite Element Analyses

Property	Values used for Side Section	Values used for Haunch Section	Values used for Crown Section
Cross Sectional Area (m^2/m)	0.0558	0.0100	0.0091
Moment of Inertia (m^4/m)	0.0239×10^{-4}	0.1448×10^{-4}	0.1646×10^{-4}
Plastic Moment M_p (kNm/m)	16.5	57.4	61.9
Plastic Axial Force P_p (kN/m)	858.2	2023.0	1757.4
Young's Modulus (kPa)	70,355,520		

Table 3. Properties of Geofabric used in Finite Element Analyses

Property	Values Used
Cross Sectional Area (m^2/m)	0.0030
Young's Modulus (kPa)	4800 to 4800000

loads are continuous along the length of the structure. Therefore, to perform two-dimensional analyses of live load effects, it is necessary to represent the actual traffic load by an equivalent line loading which is continuous along the length of the structure. Therefore, for the chosen HS-20 AASHTO permit load vehicle configuration and wheel loads, it was necessary to determine the equivalent line loading which produces the same peak vertical stress at the crown of the structure using an elastic theory of stress distributions. As shown in Fig. 3 and Table 4, the magnitudes of these equivalent line loads decrease as the depth of soil cover over the crown increases, due to the spreading of the vehicle loads along the axis of the structure.

Table 4. Equivalent Line Loads for HS-20 142.4 kN Single Axle Permit Load

Depth of Cover (meter)	Equivalent Line Load (kN/m)
0.5	75.0
1.0	48.8
1.5	37.5
2	32.5
3	27.7
4	21.5
5	18.4
7	14.2
9	11.3

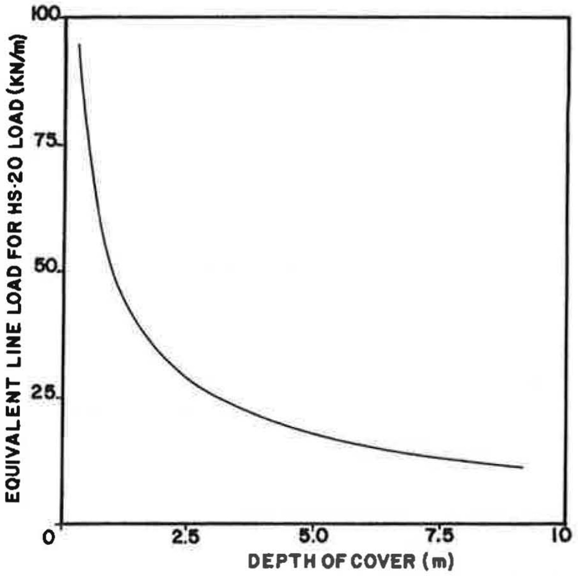

Figure 3. Variation of Line Load With Cover Depth

BENDING MOMENTS

The magnitudes and distributions of bending moments in the box culvert were determined with and without the overlays of geofabric under both backfill and traffic loads as shown in Figs. 4 and 5. The modulus-area (EA) of the fabric used in the analyses was varied through several orders of magnitude and the variations of maximum crown and haunch bending moments with EA are shown in Fig. 6. The bending moments determined with the fabric of EA = 14600 kN/m are listed in Table 5 with those obtained without the fabric. The reductions in bending moment due to the use of geofabric are in the range of 11 to 24%.

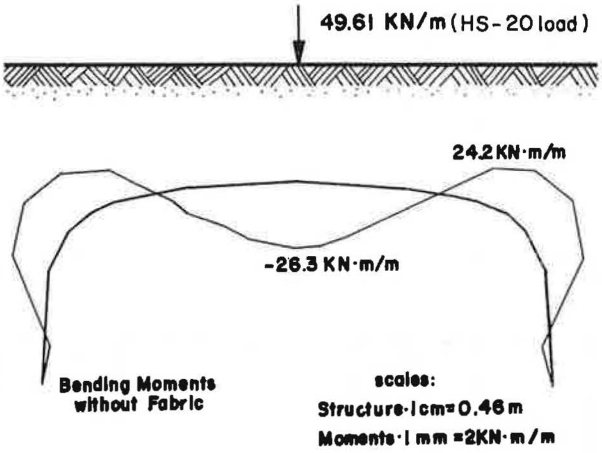

Figure 4. Bending Moment Distribution.

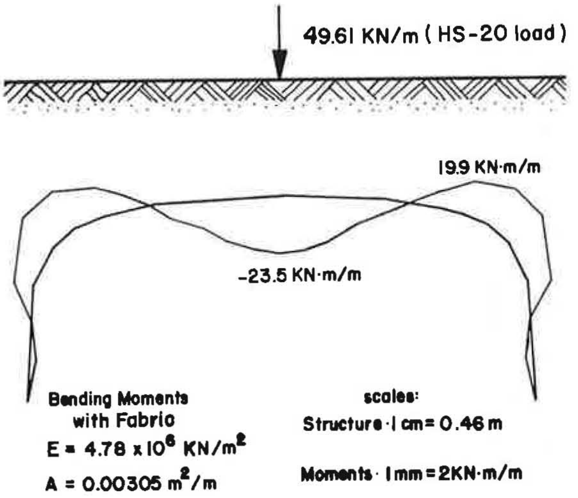

Figure 5. Bending Moment Distribution

Table 5. Bending Moments

Location	Moments Due to Backfill only (kNm/m)		Moments Due to Backfill & Live Load (kNm/m)	
	w/o Fabric	w/Fabric	w/o Fabric	w/Fabric
Crown	12.8 (100%)	9.7 (76%)	26.3 (100%)	23.5 (89%)
Haunch	13.8 (100%)	10.6 (77%)	24.2 (100%)	19.9 (82%)

AXIAL FORCES

The distributions of axial force calculated for the geofabric with EA = 14600 kn/m under backfill and traffic loads are shown in Fig. 7 with those calculated without the fabric. The variations of maximum crown and haunch axial forces with EA of the fabric are shown in Fig. 7. Although the axial forces increased with the use of geofabric, these were sufficiently small in all cases, that they had a negligible influence on the factor of safety with respect to development of a plastic hing (Fp). The increases in axial force due to the use of geofabric with an EA = 14600 kn/m, are listed in Table 6. These increases are in the range of 13 to 83%.

Table 6. Axial Forces

Location	Axial Forces Due to Backfill only (kN/m)		Axial Forces Due to Backfill & Live Load (kN/m)	
	w/o Fabric	w/Fabric	w/o Fabric	w/Fabric
Crown	46.7 (100%)	57.0 (122%)	46.0 (100%)	84.6 (183%)
Haunch	65.4 (100%)	73.8 (113%)	94.6 (100%)	114.1 (121%)

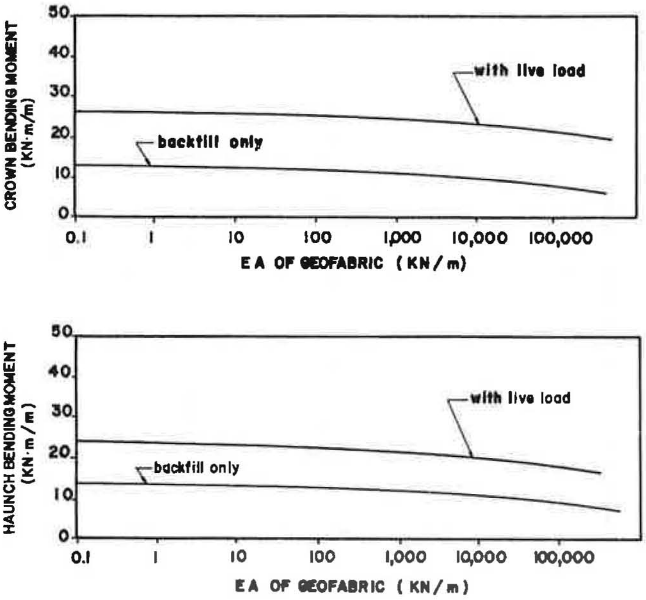

Figure 6. Variation of Bending Moment with Fabric Properties.

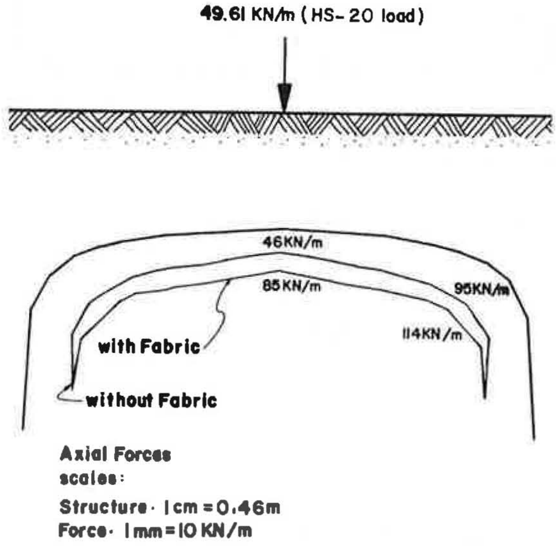

Figure 7. Axial Force Distribution.

FACTORS OF SAFETY

The factor of safety (F_p) against development of a plastic hinge may be calculated using the following equation, which considers the effects of both bending moments and axial forces in the culvert:

$$F_p = 0.5\frac{P_p}{P}\left\{\sqrt{\left(\frac{M}{M_p}\right)^2 \left(\frac{P_p}{P}\right)^2 + 4} - \left(\frac{M}{M_p}\frac{P_p}{P}\right)\right\} \quad (1)$$

in which P = axial force (kn/m)
P_p = plastic axial capacity (kN/m)

M = bending moment (kNm/m)
M_p = plastic moment capacity (kNm/m).

Using the bending moments and the axial forces listed in Tables 5 and 6, values of F_p were calculated for the crown and haunch sections of the culvert. These values are listed in Table 7 for the geofabric with an EA of 14600 kN/m. The increases in factor of safety due to the use of geofabric are in the range of 11 to 20%.

Table 7. Factors of Safety Against Formation of Plastic Hinges

	For Backfill Loads		For Backfill and Live Loads	
Location	w/o Fabric	w/Fabric	w/o Fabric	w/Fabric
Crown	4.69	5.98	2.34	2.59
Haunch	4.01	4.99	2.34	2.81

CROWN DEFLECTIONS

Crown deflections due to backfilling are shown in Fig. 9 for both with and without geofabric. The calculated deflections for backfilling and live loads are listed in Table 8. The reductions in crown deflection due to the use of geofabric are in the range of 26 to 31%.

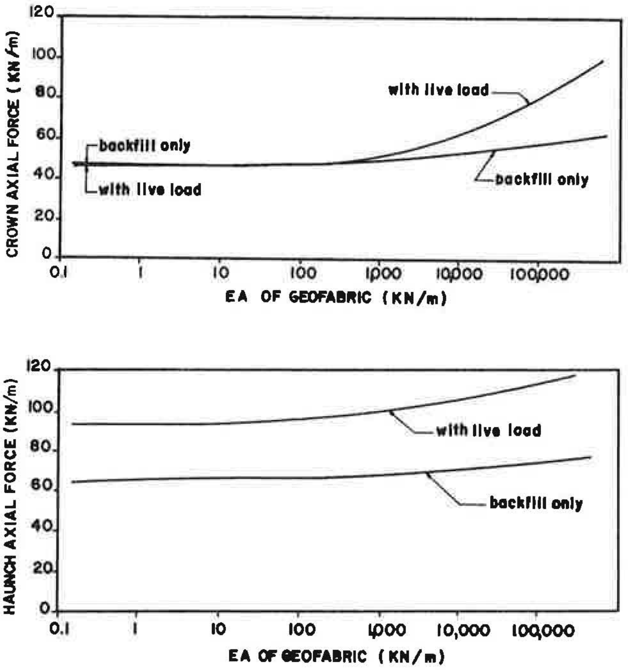

Figure 8. Variation of Axial Force with Fabric Properties

Table 8. Summary of Crown Deflections

	Deflections Due to Backfilling	Deflections Due to Backfilling and Live Loads
Without Fabric	14.5 mm (100%)	26.9 mm (100%)
With Fabric	10.0 (69%)	20.0 mm (74%)

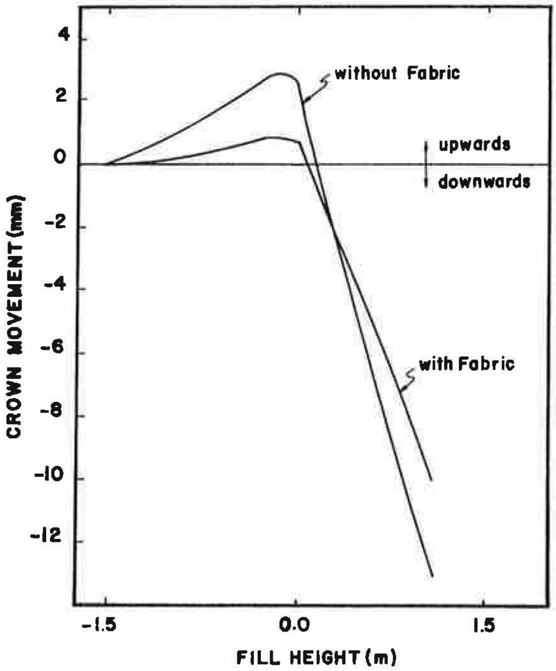

Figure 9. Crown Deflections During Backfilling.

CONCULSIONS

This study of the behavior of an aluminum corrugated box culvert under backfill and live loads clearly indicates the potential use of overlays of geofabric to increase the factors of safety and reduce the crown deflections. The factors of safety against development of plastic hinges increased by about 25% and the crown deflections decreased by about 30% for the cases analyzed in this study. This shows that the box culvert can successfully perform with thinner structural sections when geofabric overlays are used. This flexible culvert-soil-geofabric interactive design would lead to a greater economy in the use of flexible metal culverts for bridges.

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Sonderfall (nicht ausgeführt ?)
Reklame für Kaiser Aluminium?

Erinnert an NÖT