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CAUSES OF CRACKING OF CULVERTS ON FILLED SOIL AND THEIR PERFORMANCE AFTER REPAIR

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ABSTRACT: A box culvert and an underpass located approximately 3.5 km away from the West End of Jamuna Multipurpose Bridge (JMB) developed large cracks shortly after construction. Authors carried out an analytical investigation of the problem using finite element method to investigate reason for formation of these cracks and checked the consultants design report. This paper presents Finite Element analyses of these structures using three dimensional model that explains causes of cracking and shows the inadequacy of the two dimensional modelling done by the consultants. Focus is drawn on the design assumptions that are required for these structures. Comments on the repair methodology for such structures, when failed due to the improper design assumption is also made.

KEYWORDS: Culvert, underpass, crack, lateral earth pressure.

INTRODUCTION

Two box culverts W10 and W17 (traffic underpass) approximately 3.5 km away from the West End of JMB in contract 4 developed large cracks. The JMBA authority wanted to investigate the reason of these cracks and seek recommendations from BRTC (Bureau of Research Testing and Consultancy), Department of Civil Engineering, BUET. On April 17, 1998 authors visited the culvert sites and investigated the cracks. This paper reports the findings of the study conducted by the authors based on both field visit and the subsequent Finite Element study conducted regarding the culvert cracking.

Settlement of the soil is the most prominent contributing factor in producing the cracks. The problem is further complicated by the fact that soil settlement has at least four different components - elastic, inelastic, consolidation and creep components. However, to assess the adequacy of reinforcement design it is not always necessary to consider all these factors. The underpass and the culvert under study in this paper developed large cracks shortly after the construction. To investigate the causes of failure of the structures, FE analyses based on elastic material properties is conducted.

Design rationale adopted for the two structures

W10 and W17 designate the two structures the first one of which is a box culvert 4.4 m high and 38.8 m wide while the second one is 10.02

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m high and 35.0 m wide. W10 is a twin box culvert with a span parallel to traffic 10.59 m and W17 is a single box underpass with 5.7m span parallel to traffic. The following subsections describe the specifications, analyses and design of the two structures.

Design standard and software used for analysis

The design document (RPT-NEDECO-BCL, May 98) shows the loads used and assumptions made in the analyses of culvert W10 and underpass W17; these are:

Loading:	*According to BS 5400*
Materials:	
Compressive strength of concrete:	*35 MPa*
Steel yield strength:	*450 MPa.*
Design standard:	*BS 5400*
Software used:	*SAP90*

Stress developed in the direction perpendicular to traffic is ignored.

Data preparation method adopted for analysis using SAP90

Calculation of live load: Combination of HB and HA axle loads over the lanes that produce the maximum stress.

Calculation of pressure on top slab: These consisted of self-weight, weights of earth fill and live load.

Calculation of earth pressure on the side-walls: At rest earth pressure; surcharge due to fill and live load surcharge pressure considering the earth pressure theories.

Calculation of earth pressure on the base slab of the structure: Dividing the loads (self-weight, weights of earth fill and live load) by the area of base slab.

Finite element modelling using SAP90

Element orientation: Two-dimensional model in the direction of the traffic using frame elements.

Loading: As calculated using assumptions described above during data preparation and applied directly to the structure modelled. Fig 1 shows the FE model adopted in the actual analyses.

Results: Bending moments (sagging and hogging), axial force and shear for the elements.

Design: Steel required resisting the developed bending moment. Table-1 shows the reinforcements perpendicular to traffic together with tensile strength of reinforcing bars and concrete.

INVESTIGATION OF CRACKING

Site investigation

On April 17, 1998, authors visited the culvert sites and investigated the cracks. Figs. 2a and 2b shows the cracks of W17 (before repair) and W10 (after repair) respectively. It appeared that the cracks were due to the soil settlement caused by the dredge filled soil of the approach road embankment. To investigate the causes of the cracks without destruction of the culverts, necessity of numerical simulation of the structures was felt.

Table 1. Bars at the bottom slab of underpass W17 and culvert W10 (RPT-Nedeco-BCL, May 87)

Structure	Bars perpendicular to traffic		Total no of bars at bottom slab	Assumed tensile strength of reinforcing bars (MPa)	Assumed tensile strength concrete (MPa)
	top layer	bottom layer			
W17	T10-55-150	T10-53-150	78	600	3
W10	T10-57-150	T10-55-150	148	600	3

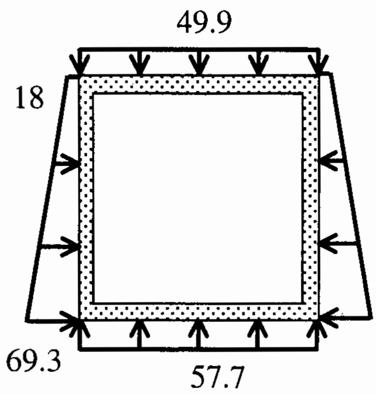

Fig 1. Two dimensional model adopted during analysis and design of W17 (Pressure values in MPa)

ANALYTICAL INVESTIGATION

Finite Element (FE) Modelling

The FE modelling consists of three components – the soil, the culvert and the interface between these two. The soil is modelled using common eight-noded brick elements, the culvert is modelled using four noded plate elements and the interface between soil and culvert is modelled using special interface "link" elements. The property of these interface elements is such that they are active only in compression and are incapable of transmitting tension. FE package STRAND6.1 (G+D Computing System Pty Ltd) has been used to carry out the analyses. Fig 3 shows the FE model adopted for checking the design of culvert W10. For the purpose of analyses it is essential to estimate the material properties of the components of the structure. Modulus of Elasticity of the soil was estimated using the SPT values from (RPT-Nedeco-BCL, May 87) and equations suggested by J.E. Bowles (1988). For both cases modulus of elasticity of concrete E_c = 2.10 x10^4 N/mm^2 and Poisson's ratio ν = 0.15 are assumed. Table-2 shows the data used for the culvert and the underpass in the FE model. In both cases the advantage of symmetry is utilised and only a half the structure is analysed with appropriate boundary conditions. The global axes of reference were set as follows – X axis is in the direction of traffic, Y axis is in the vertically upward direction and Z axis is in the lateral direction of the traffic. Table-3 shows the number of nodes elements and DOF's of the FE analyses.

Fig 2a. Cracks and separated reinforcements of underpass W17

Fig 2b. Repaired cracks of culvert W10

For both W17 and W10, the following boundary conditions are used:

- Vertical planes parallel to traffic (plane of symmetry) : Z movement restrained
- Vertical planes perpendicular to traffic: X movement restrained
- Bottom surface of the soil mass modelled: Y movement restrained
- Top and inclined surface of the soil mass: No restraint.

RESULTS OF FE ANALYSES

Underpass W17

Results of FE analysis show that the culvert is stressed highly at the bottom due to elastic settlement. Fig. 4 and 5 show the contours of vertical deformation and the principal stress for the culvert respectively.

Table 2. Data used for analyses of W17 and W10

Location of soil	Unit weight γ(N/mm³)	Modulus of Elasticity E_s (MPa)	Poisson's ratio ν	Depth/ height of soil (m)
Data used for analyses of W17				
Embankment	1.73×10^{-5}	41.0	0.35	7.35
Underlying soil-1	1.00×10^{-5}	15.0	0.35	1.00
Underlying soil-2	5.0×10^{-6}	5.0	0.35	5.00
Data used for analyses of W10				
Embankment	1.73×10^{-5}	40.5	0.35	9.61
Underlying soil	5.9×10^{-6}	8.5	0.35	6.00

Table 3. FE mesh details of the problems

Model	No. of solid elements	No. of shell elements	No. of interface elements	Total nodes	Degrees of freedoms
W10	800	108	105	1209	3144
W17	987	100	110	1437	4012

The vertical deflection of the soil at centreline of culvert section (section perpendicular to traffic) is 81.3mm and at the edge of the road is 69.8 mm giving a differential settlement of 11.5 mm. The peak tensile stress is 4.9 N/mm². It has been observed that the sum of horizontal forces on the nodes of the culvert bottom is 11,106 kN. Based on data presented in Table-2, the tensile load capacity of the reinforcement provided is 4,680 kN and the cracking load for concrete is 5,985 kN. Thus it is evident that lack of tensile resistance in the direction perpendicular to traffic caused the cracking of this culvert. Since it is a single box underpass the cracking pattern is similar to that of a normal beam subjected to uniformly distributed load i.e., bending cracks at the middle and diagonal shear cracks near the ends. A second analysis was made considering a fully open crack at the centre of the underpass as it occurred in reality, i.e. the culvert is completely divided into two separate equal parts. This analysis shows a peak tensile stress of 0.24 N/mm² which is much smaller than the cracking stress of concrete (see Fig. 6). This indicates that the possibility of developing further cracks is low.

Culvert W10

Results of FE analysis show that the culvert is stressed highly at the bottom due to the elastic settlement. Fig. 7 and 8 show the deformed shape of the culvert and the principal stress contour of the culvert respectively. The vertical deflection of the soil at centreline of culvert section (section perpendicular to traffic) is 78.3 mm and at the edge of the road is 74.4 mm giving a differential settlement of 3.9 mm. The peak tensile stress at the bottom slab is 5.63 N/mm^2. It has been observed that the sum of horizontal forces on the nodes of the culvert bottom is 22,086 kN.

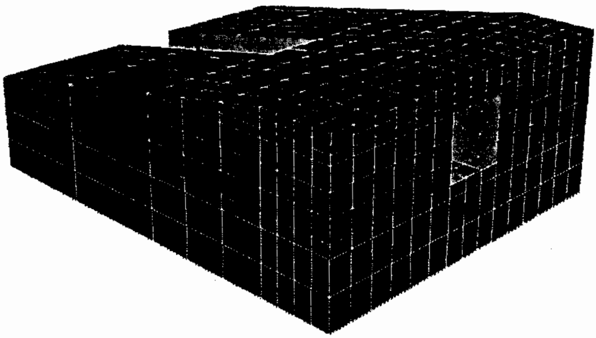

Fig 3 Finite Element model developed for W17

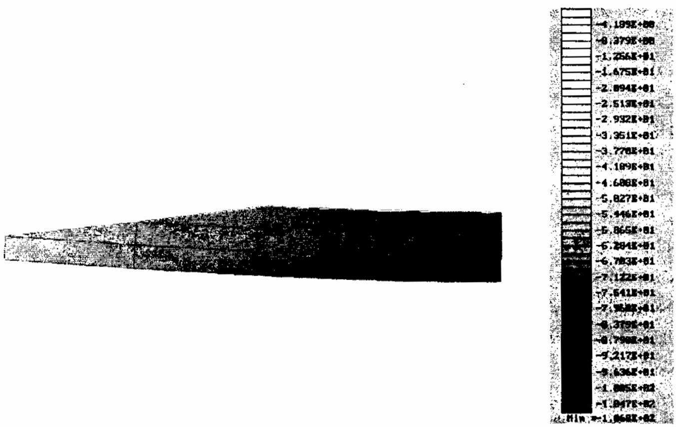

Fig 4. Contour of vertical deformation for W17

Based on data presented in Table-2, the tensile load carrying capacity of the reinforcement provided at bottom is 8,880 kN and the cracking load for concrete is 9,810 kN. Thus it is evident that lack of tensile resistance in the longitudinal direction (perpendicular to traffic) caused the cracking of this culvert. Presence of the R.C.C. vertical wall of this twin box culvert distributed the tensile force at the base to be distributed throughout the width of the culvert and thus distributed the cracks uniformly

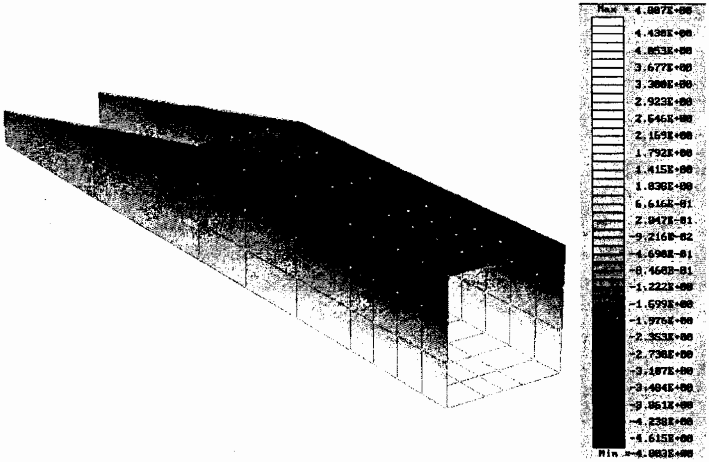

Fig 5. Contour of Principal stress W17

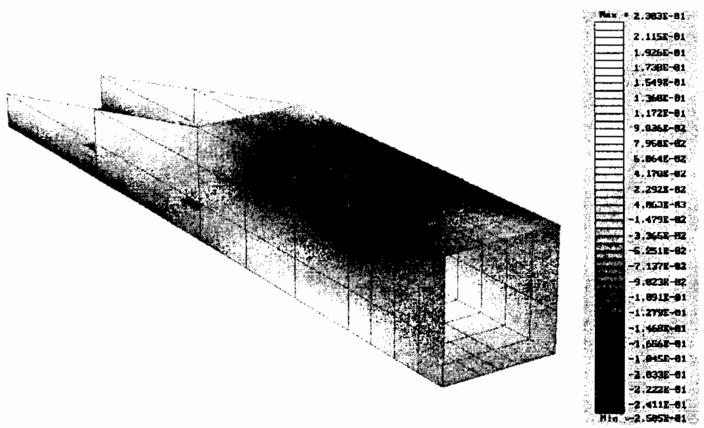

Fig 6. Contour of principal stress with full crack at the middle of W17

Conclusions from FE analyses

Although the FE analyses are based on elastic material properties, these confirm one thing that the reinforcement in the direction perpendicular to traffic was totally inadequate. The stresses produced by the elastic analyses are more than the capacity of the culverts. It is obvious that consideration of other kinds of soil settlements e.g. consolidation settlement will produce more severe results. It appears from the reinforcement detailing that the structures were designed to carry the load parallel to the direction of traffic only. The effect of settlement of soil which produces beam-bending like effect on the whole structure in the lateral direction (direction perpendicular to traffic) was not at all considered in the design.

Fig 7. Contour of vertical deformation for W10

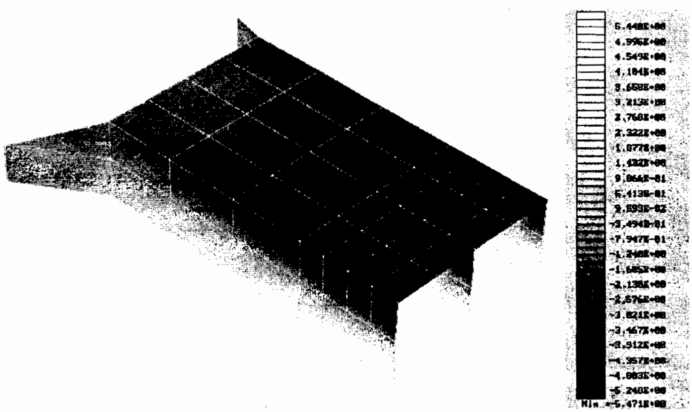

Fig 8. Contour of Principal stress W10

COMMENTS OF THE METHODOLOGY ADOPTED IN DESIGN

Calculation of reaction on top slab

Loading on the top slab can be considered to be satisfactory, as it is a direct load.

Calculation of earth pressure on the side walls

The structures are made on dredge filled sand and the earth fill for the embankment is about 10.667m for W10 and 7.80m for W17, the embankment is made of very stiff soil. Width of W10 is about 38.8m while width of W17 is 35.0m. It is clear from this structural configuration and soil stiffness that the soil will settle and the settlement profile would be like a parabola along the width of the structures (wing wall to wing wall) due to the overburden pressure of the embankment. This indicates that the use of traditional active earth pressure theories to compute the pressure on the structures is not suitable and this might lead to an incorrect loading on the structures. Fig.9 shows the pressure distribution of lateral earth pressure due to dead load only on W17 obtained from analysis conducted by the authors. This when compared with Fig 1, show clearly the difference between the assumed and the realistic pressure distribution which is consistent with arching theory (Terzaghi, 1947).

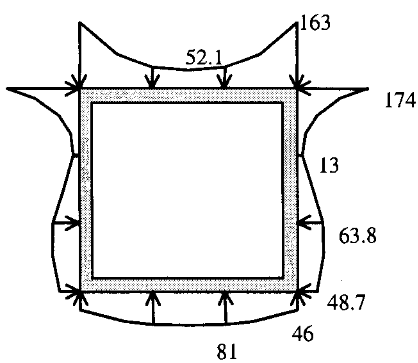

Fig.9 Distribution of lateral earth pressure due to dead load only on W17 (all values in Mpa)

Calculation of reaction on base slab

According to the soil condition and the configuration of the embankment, the deflection profile of the structure is of parabolic type. In such cases the reaction on the (wing wall to wing wall) base slab may not be uniform. The pressure distribution profile depends on many factors including the relative stiffness of the soil and the structure.Fig.10 shows the distribution of reaction pressure at the base slab of W17 obtained from the finite element analysis adopted. It is observed that the FEM analyses of used for designing produces approximately uniform reaction profile. Thus the assumption of uniform soil pressure in the perpendicular direction of traffic is acceptable as assumed in normal practice.

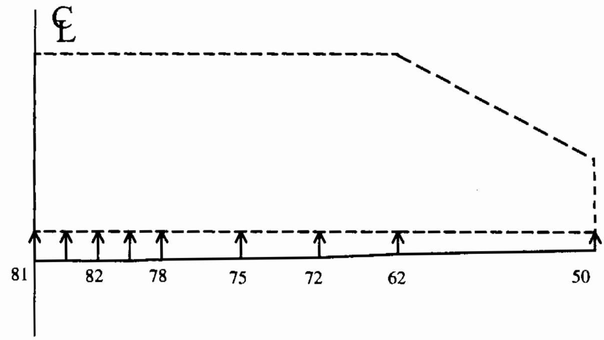

Fig.10. Longitudinal distribution of soil reaction at bottom slab of W17 (all values are in MPa)

Comments of the FE model adopted

Simulating a culvert failure using Finite Element method is a highly complex soil-structure interaction problem. Any reasonable FE modelling must consist of three components – the soil, the culvert and the interface between these two. The property of these interface elements should be such that they are active only in compression and are incapable of transmitting tension. Besides this the soil properties must be properly included in the model so that effect of the variation of the soil properties along vertical and horizontal directions can be considered. The FE model adopted in design by the consultants is very simple which does not consider any of the above mentioned important factors. The interaction between the soil and the structures is ignored and is simplified using earth pressure theories; tensile separation of the soil mass from the structures is not addressed. More importantly, no consideration was given to the stress developed in the direction perpendicular to the traffic, which is basically the cause of cracking of both structures. Analyses and design of was based on two dimensional plane stress conditions. Such analyses are acceptable for ordinary culvert structures whose length (dimension perpendicular to traffic) is not very large compared to the other dimensions of the box and where there is little or no overburden soil load on the top slab. The cases with both structures were different. The length of both structures was high as compared to the other dimensions of the box. The overlying soil load is also high and more importantly, it is not uniform over the length of the culverts. All these conditions invalidate the simple assumption of plane stress condition and necessitate an analysis and design procedure that considers the stress developed the direction perpendicular to traffic in addition to the stress developed in the direction of traffic.

Comments on the design of the structures

Results of FE analysis conducted by the authors show that the structures are highly stressed in the direction perpendicular to traffic at the bottom due to elastic settlement without considering the presence of live loading. The peak tensile stress was observed to be 4.9 MPa for W17. Similarly for culvert W10 the peak tensile stress (without considering live load) at the bottom slab is 5.63N/mm^2. Thus it is evident form these in conjunction with Table-1, that improper design in the direction perpendicular to traffic caused the cracking of underpass W17 and culvert W10.

Comments on crack repairing procedure

Crack repairing can be conducted by the method suggested by the designers (RPT-Nedeco-BCL, May 1987), this basically consists of cleaning the cracks and filling it up with epoxy. The structures have already been shown in Figs 2(a) and 2(b) that has gone through this process and is performing well for the last two years. Additionally, at the same time it is recommended that to ensure proper contact is established between the soil and the culvert bottom, holes can be drilled at few locations of the culvert bottom and then by concrete pressure grouting any void underneath the slab should be filled.

CONCLUSIONS

Analyses and design based on two dimensional plane stress conditions are acceptable for ordinary culvert structures whose length (dimension perpendicular to traffic) is not very large compared to the other dimensions of the box and where there is little or no overburden soil load on the top slab. When the dimension perpendicular to traffic is large compared to the dimension parallel to traffic and when there is soil over-burden pressure in addition to traffic load, the effect of settlement of soil, which produces beam bending like effect on the whole structure in the lateral direction (direction perpendicular to traffic), is to be considered in the design. Because of the high density of soil fill material, significant arching could develop in the lateral direction of the culverts that can create pressure in the head walls or wing walls and result in tension in the direction perpendicular to traffic. Unsuitable soil under box, wing-walls and apron should be excavated and removed, and replaced with granular sub base material compacted to 98% Proctor density in layers not exceeding 150 mm; to avoid the settlement problem that may arise in such structures. It is possible to repair and use these structures even after the failure (vertical and horizontal cracking along the wall and the base respectively and physical separation into one or more boxes) provided a proper investigation is made and adequate repair method is adopted like the two structures mentioned herein.

REFERENCES

Bowles, J.E. (1988) *Foundation Analysis and Design*, 4^{th} ed., McGraw Hill.

Design Report on Structures W10 & W17 under Contract-4, West Approach Road, May 1998, RPT-NEDECO-BCL, Ref.: PM/B10307/563/MJT/ALG Dated 7/5/98.

Report on causes of cracking of culvert W10 and underpass W17, contract 4, JMBP, June 1998. Bureau of Research Testing & Consultation (BRTC) Department of Civil Engineering, Bangladesh University of Engineering & Technology, Dhaka 1000, Bangladesh.

RPT-Nedeco-BCL, *Repairing of Crack Structures* (1987), Ref.: PM/B10078/ 519/ 356/ 456/ FCM, Dated 7/5/87. Drawing Nos. 4316A, 4301, 4336,4324A, 4326A, 4337A, 4323, 4325.

STRAND6.1 Finite Element Analysis System, G+D Computing System Pty Ltd, Suit 508, 3 Small Street, Ultimo, NSW 2007, Australia.

Terzaghi, K. (1947) *Theoretical Soil Mechanics*, John Wiley & Sons, Inc, NY.