SOIL-STRUCTURE INTERACTION IN BURIED RIGID CULVERTS

INTERACTIONS SOLS-STRUCTURES DANS DES BUSES ENTERRÉES

S. SERAJ, A. RAHMAN

Bangladesh University of Engineering & Technology, Dhaka (Bangladesh)

The paper considers the interaction between rigid circular culverts and their surrounding soil. The finite element method has been employed. Detailed investigations have been performed to study the fundamental behaviour of rigid culverts under different cover depth, thickness, installation and bedding conditions.

Cette étude est basée sur l'interaction entre les buses et leur environnement. La méthode des éléments finis a été utilisée. Des études dans le détail ont été faites pour évaluer le comportement de fond des buses sous des couvertures et des épaisseurs différentes ainsi que leurs conditions d'installation et de remblayage.

INTRODUCTION

Moderate to large diameter rigid conduits are frequently used as buried culverts for the drainage of water across road and other embankments. The culvert, being a structure buried in the ground, interacts with the surrounding soil. The soil contributes to the performance of the culvert in two ways. The earth fill above the culvert helps distribute the surface loads more evenly on the culvert and even reduce their intensity. Moreover, the culvert, being confined in the soil mass, is in a state of triaxial loading, thus gaining a considerable structural advantage. Due to the deformation and rigid body movement of the rigid culvert, stress redistribution takes place in the culvert-soil system. Thus the behaviour of a rigid culvert buried in a soil mass poses a complex problem and must be addressed by applying the principles of soil-structure interaction. There is a general lack of knowledge regarding the real behaviour of buried rigid culverts under different installation and bedding conditions. It is the purpose of this paper to attempt to bridge this gap in understanding the behaviour of rigid culverts.

ANALYTICAL REPRESENTATION OF THE INTERACTION PROBLEM

The finite element method can be used successfully for the two dimensional analysis of buried culverts. The real challenge, however, is to construct analytical models that behave something like the real world; while at the same time, striking a balance between rigorous mechanics and engineering simplicity. Three types of elements have been used in the computer program developed to study the interaction of buried rigid culverts with soil. Line element with circular arc, Livesley(1975),having three degrees of freedom(horizontal and vertical displacement and a rotation) at each node,was used to represent the circular culvert.Eight noded isoparametric quadrilateral element with two degrees of freedom(horizontal and vertical displacement) at each node was used to represent the soil and the bedding. Thin layer interface element,Desai et al(1984),was used to represent the culvert-soil interface. Spline functions have been used to represent the non-linear material properties of the soil.The tensile strength of the soil is negligible which results in tensile failures within the soil mass and at boundaries.This introduces a further non-linearity in the problem which has been tackled by a dynamic configuration and stiffness regeneration scheme,Rahman(1978),Seraj(1986).Incremental method of analysis has been adopted in this study for accommodating the non-linear behaviour of soil.

LOADS ON STRUCTURES AND MATERIAL PROPERTIES

In the two dimensional plane strain analysis of the culvert-soil system,only a slice of unit thickness through the culvert,bedding and the soil is considered.The vertical load comprises the dead weight of the culvert,the soil and the bedding and the live loads due to highway or railway traffic.The unit weight of concrete used in the culvert and bedding was 23.563 kN/m^3.The unit weight of the original soil and the embankment backfill were 18.849 kN/m^3 and 14.136 kN/m^3 respectively. In calculating live loads AASHTO MS18 loads have been used.To simulate the worst loading condition the 72 kN wheel load has been placed on the embankment just above the crown of the culvert.For all the analyses in this paper the culvert material was assumed to behave linear elastically having a modulus of elasticity E and Poisson's ratio ν equal to 2.068 x 10^7 kN/m^2 and 0.2 respectively. Concrete cradle bedding had a value of E equal to 1.773 x 10^7 kN/m^2 and ν equal to 0.20. The soil properties were obtained from two sets of octahedral shear stress and octahedral shear strain curves. The set of curves shown in Fig. 1 were used to represent embankment fill. The curves used in this study to represent original soil were 50% steeper than the curves shown in Fig. 1.

ANALYSES SCHEME

For all the analyses presented in this paper the internal diameter of the culvert has been kept constant at 1.524 m.Two types of installation conditions have been considered.Fig.2 shows both positive projecting

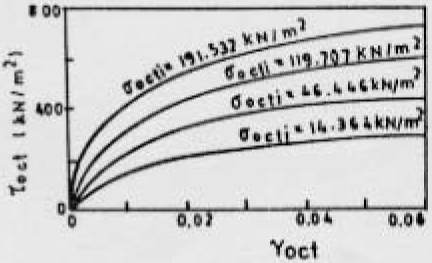

Fig.1.τ_{oct} -γ_{oct} curves of fill

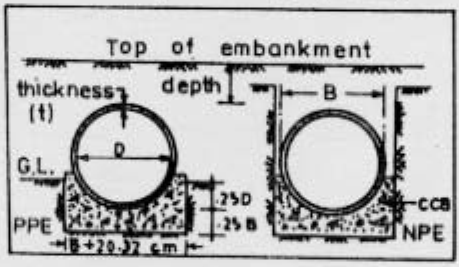

Fig.2 Installation conditions and size of bedding

embankment(PPE) and negative projecting embankment(NPE) installation condition.In some of the analyses a concrete cradle bedding(CCB),Fig.2 has been provided below the invert of the culvert.In this study the culvert thickness has been varied from 76.2 mm to 152.4 mm.The cover depth above crown has been considered to be a variable and has a minimum and maximum value of 1.524 m and 7.62 m respectively.

EFFECT OF INSTALLATION CONDITIONS AND DEPTH OF COVER ABOVE CROWN

To study the effect of installation conditions on the performance of buried rigid culverts,the depth of cover above crown over a 76.2 mm thick,1.524 m diameter concrete culvert was varied from 1.524 m to 7.62 m.This series of analyses were performed for both PPE and NPE installation conditions. No special bedding was provided under the invert of the culvert.

The maximum moment and maximum axial stress occurred in the culvert at crown and springline respectively.In Fig.3 moment at crown and axial stress at springline are plotted against depth of cover for both the installation conditions. It has been observed that there is an optimum depth of cover at which moments at different sections of the culvert are less than those for the same culvert with other depths of cover. The axial stress,on the other hand,is found to be increasing steadily with an increasing depth of cover. However, concrete is strong in compression, and the axial stresses at various sections of the culvert for all the depth of cover considered remained well within the allowable compressive stress of the culvert.On the other hand,concrete is very weak in tension,and consequently it is the moment that governs the design of the culvert section.As such adoption of moment as the design criterion is logical. Based on this criterion,for the culvert under consideration,optimum depth has been found to lie between 5.5 m and 6.5 m for both the installation conditions.

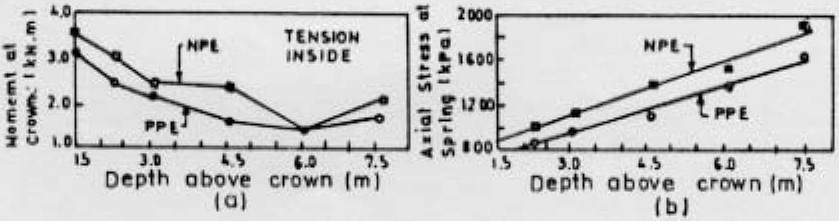

Fig.3 Variation of(a) moment at crown and (b) axial stress at springline with depth of cover for PPE and NPE installation condition

Stresses in structural members develop due to the combined effect of live and dead loads.As the depth of cover increases, effect of dead load increases due to increasing soil pressure.On the other hand,live loads are distributed over a larger area when depth of cover is increased. As such effect of live load decreases with an increasing depth of cover. Combination of varying contributions from dead load and live load is considered to be responsible for yielding an optimum depth of cover at which design stresses are minimum.

It has also been observed from the results obtained that under NPE installation condition, a culvert is subjected to greater amount of stresses and deflections. The ratio of these values to those under PPE installation condition increases with increasing depth cover above crown upto the optimum depth.

In PPE condition, backfill soil is uniform on both sides of the culvert, Fig.4(a). As such live load applied on the surface directly above the crown can dissipate freely over a large area of the soil mass. On the other hand, in NPE condition soil in the exterior prisms is more dense than the soil in the interior prism, Fig.4(b). This non uniformity of the soil results in the formation of weak shear planes as shown in Fig.4(b). This weak shear plane hinders effective transfer of load from the interior prism to the exterior prism. Thus in NPE, the portion of live load transmitted to the culvert is greater than that in PPE condition. In Fig.5, the difference between nodal vertical stresses in the soil in NPE and PPE conditions is plotted at various nodes along the vertical centre line of the culvert-soil system. It is observed from this figure that the difference of vertical nodal stress between NPE and PPE condition is positive at all the points. Therefore, soil directly above and below the culvert is stressed to a higher degree in NPE condition. Greater load is thus transmitted to the culvert under NPE condition. This explains the higher stresses and deformations in culverts installed in NPE condition. With the increase in cover depth, the rate of decrease of the effect of live load is less pronounced in NPE condition due to the presence of weak shear planes mentioned earlier. The ratio of the stress values of NPE and PPE condition is, therefore, increased.

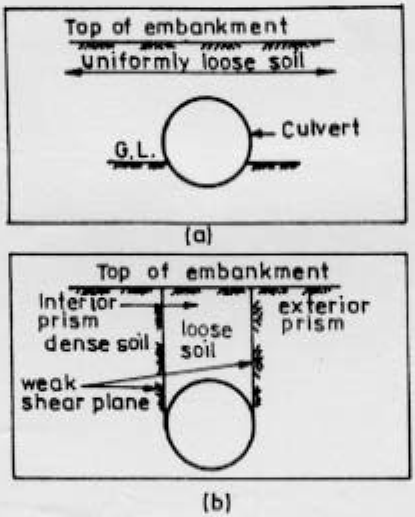

Fig.4 Types of soil in (a) PPE and (b) NPE installation condition

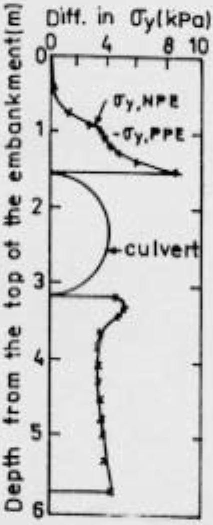

Fig.5 Relative increase in nodal vertical stress in soil with depth due to a change in installation condition

EFFECT OF BEDDING CONDITIONS

In order to investigate the effect of bedding conditions on the performance of buried rigid culverts,two types of bedding conditions viz.concrete cradle bedding and no bedding have been studied. The culvert was installed in PPE condition and the depth of cover was varied from 1.524 m to 4.572 m.Analysing the results of the above study it has been observed that a CCB under the invert of the culvert reduces the moments at crown and springline.At the same time moment at invert is almost eliminated. In Fig.6, total deflection at crown and change in vertical diameter of the culvert are plotted against increasing cover depth. By comparing the curves considering no bedding and concrete cradle bedding cases, it is observed that although the total deflection at crown is increased by 10%-17% due to the provision of a bedding,the change in the vertical diameter is reduced to 44%-53% of the diameter change under no bedding condition at various cover depths. This indicates that a bedding reduces deformations and thus moments in the rigid culvert.

A bedding gives firm support over the lower 120° sector of the culvert. The vertical component of the forces acting on the culvert is transmitted to the bedding. This results in an almost uniform shear stress in the invert region which ultimately yields very small values of bending moments at the invert.

In fig.7, vertical nodal stress is plotted along the vertical centre line of the culvert-soil system. Both no bedding and concrete cradle bedding cases of a 1.524 m diameter,76.2 mm thick rigid culvert under PPE condition have been considered.

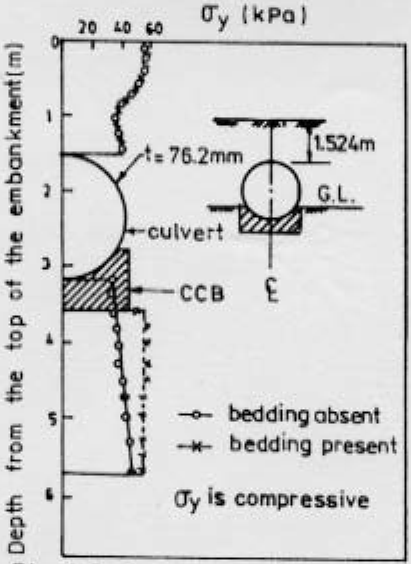

Fig.6 Influence of bedding conditions on (a) total deflection at crown (b) change in vertical diameter with cover depth

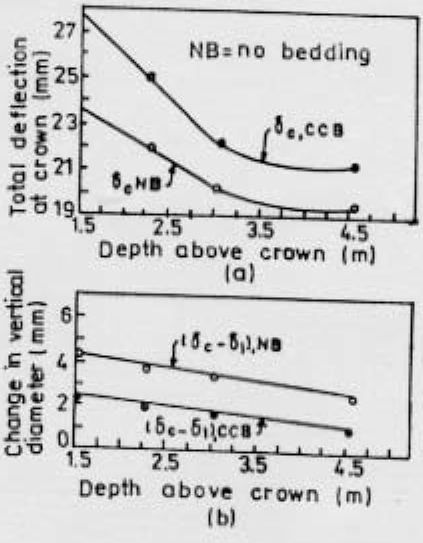

Fig.7 Variation of vertical stress in soil with depth in the centre line nodes under different bedding conditions

Critical analysis of Fig.7 shows that nodal stresses remain more or less unaltered above the crown of the culvert due to the inclusion of the CCB.However,the stresses are greatly increased beneath the bedding and the value of the nodal stress adjacent to the bottom of the bedding is found to be about 57% higher than the corresponding nodal stress under no bedding condition.This phenomenon can be explained by considering that the stiffness of the bedding material is very high in comparison to the adjoining soil. Thus the bedding attracts a greater amount of load of the structure-soil system.As such soil below the bedding is subjected to greater amount of stresses. At the same time due to the higher share of load,the bedding and the culvert as an integral body undergoes greater amount of rigid body movement. That is why the crown of the culvert shows greater amount of deflection when bedding is provided. The net amount of diameter change in the vertical direction is,however,significantly reduced as CCB adds to the overall stiffness of the structure.

EFFECT OF CULVERT THICKNESS AND INSTALLATION CONDITIONS

To ascertain the effect of change in the thickness of the rigid culvert, thickness of a 1.524 m diameter culvert was varied from 76.2 mm to 152.4 mm under both PPE and NPE installation conditions. Bedding was not provided and the depth of cover was kept constant at 1.524 m.

It has been observed that with the increase in the culvert thickness, moments and forces in the culvert increase.The rate of increase in the magnitude of these forces is less in case of NPE than in PPE condition. Total deflection at crown does not vary significantly with the variation of the culvert thickness. The change in vertical diameter, however,due to the change in thickness is significant. This change for a 152.4 mm thick culvert has been found to be only 37.60% of the change in vertical diameter of a 101.6 mm thick culvert.

With the increase in the thickness of the culvert, the relative stiffness of the culvert with respect to the adjoining soil is increased. Greater amount of stress is,therefore,shared by the culvert material.The soil in the exterior prism of the culvert-soil system is more flexible in the case of PPE condition than in the case of NPE condition. The relative change in the stiffness of the culvert with respect to soil is, therefore, less in the case of NPE condition in comparison to PPE condition. This is considered to be the reason why the stresses in the culvert under NPE condition increases at a rate lower than that under PPE condition with the increase in the culvert thickness. The phenomenon regarding deflection can be explained by considering that the total deflection at the crown is due mostly to the rigid body movement of the culvert in the soil, which is somewhat independent of the culvert stiffness. On the other hand,the change in the vertical diameter of the culvert is influenced significantly by the structural stiffness of the culvert, which is higher for the thicker culvert.

STRESSES IN SOIL

The contour lines of the vertical stresses in a culvert-soil system are shown in Fig.8. In the case under consideration, the culvert is 76.2 mm thick and has a diameter of 1.524 m. It is installed in PPE condition and bedding is not provided.

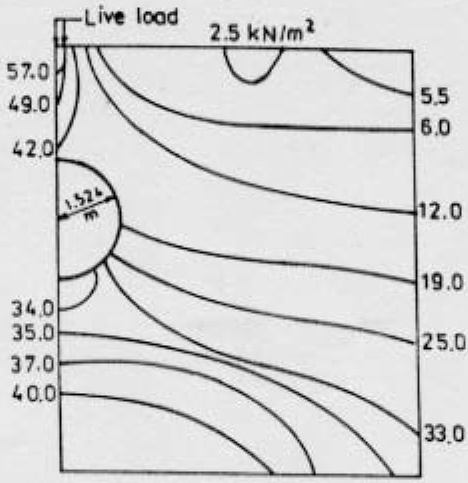

Fig.8 Loci of equal vertical stresses

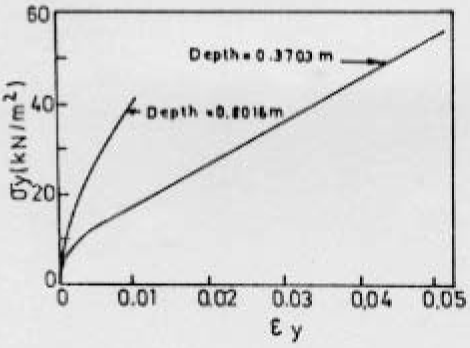

Fig.9 Stress-strain curves at two locations in the centre line of the culvert-soil system

A distinct colum of high stresses is observed directly under the loading points. This high stress value is reduced by about 26% at a point just above the crown. The values of vertical stresses reduce very rapidly at points away from the loaded region. Soil under the bottom of the culvert suffers a higher stress in comparison to soil at the same elevation away from the culvert.

The stress strain curves at two nodes along the line of symmetry of the same system are shown in Fig.9. The soil near the top of the embankment is found to be highly strained in comparison to the soil at a greater depth but at the same stress level. This is because soil elements become stiffer with the increase in depth having a higher value of confining stress. This also points out clearly that contributions of soil at greater depths to the settlement of the structure are smaller. The argument is further substantiated by comparing the variations of stress and strain with depth under the same location of the culvert-soil system as shown in Fig.7 and Fig. 10 respectively. The steep gradient of strain distribution along depth demonstrates that contributions of soil at greater depths to the deformation of structure diminish rapidly. This leads to the useful information that a large extent of soil need not be included in the analysis of rigid culverts buried in soil. The finding confirms that of Nazneen(1986) who investigated the interaction of building structures with soil.

It becomes apparent from the variation of stress with depth as shown in Fig.7 that the reduction in soil stresses with depth is only barely noticeable near the surface and is absent at higher depths. Even near the surface the gradient of soil stress variation is far from the steep gradient of a Boussinesq type variation with a stress ordinate asymptotic to the upper soil boundary. The reason for this may be attributed to the stiffness of the buried culvert and its bedding not accounted for in the Boussinesq solution.

CONCLUSIONS

There is an optimum depth of cover above crown at which design moment is the smallest. This optimum depth is independent of the installation conditions of the culvert. A culvert is subjected to greater amount of stresses and deformations under negative projecting embankment installation condition. Concrete cradle bedding contributes to the reduction of design moments and deformations of a rigid culvert. The share of load carried by the culvert is increased due to an increase in its thickness. Thicker culverts are also subjected to smaller deformations. A large extent of soil need not be included in the analysis of buried rigid culverts. Maximum vertical soil pressure is found to occur directly above and under the culvert and it reduces rapidly at points away from the culvert. The variation of vertical soil pressure with depth is less pronounced than a Boussinesq type distribution.

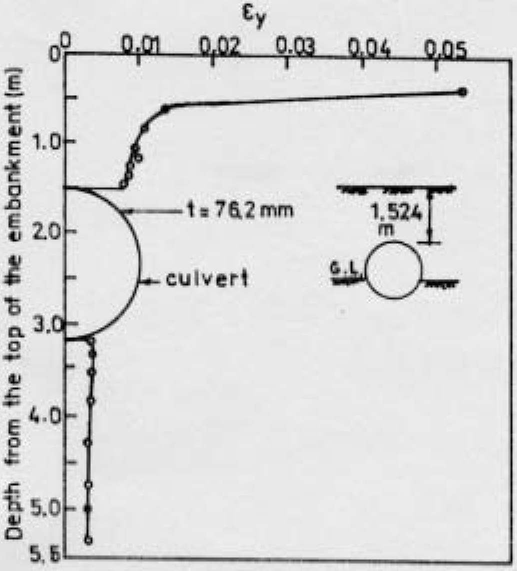

Fig.10 Variation of nodal strain in soil with depth

REFERENCES

Desai,C.S.,Zaman,M.M., Lightner,J.G. and Siriwardane ,H.J.,"Thin-Layer Elements for Interfaces and Joints",International Journal for Numerical and Analytical Methods in Geomechanics, Vol.8,1984.

Livesley,R.K.,"Matrix Methods of Structural Analysis",Pergamon Press, 2nd Edition,1975.

Nazneen,S.,"Structure-Soil Interaction in Framed Buildings with Orthotropic Wall Infills",M.Sc.Engg. Thesis,Bangladesh University of Engineering and Technology,Dhaka,1986.

Rahman. M.A.,"Interaction between Foundations and Structures",Ph.D. Thesis, The University of Aston in Birmingham,1978.

Seraj.S.M.,"Structure-Soil Interaction in Buried Rigid Culverts", M.Sc. Engg. Thesis,Bangladesh University of Engineering and Technology, Dhaka,1986.