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A Study on Structural Stability and Suitability of Corrugated Long Span Soil-Steel Bridges

K.B.K. Shanaka
CSEC, Sri Lanka
Email: kbkshanaka@gmail.com

C.S. Lewangamage & M.T.R. Jayasinghe
Department of Civil Engineering, University of Moratuwa, Sri Lanka

ABSTRACT: Corrugated Soil-Steel bridges have been used as drainage structures and underpasses in the ongoing Southern Highway project. Because the Soil-Steel bridges are novel to Sri Lankan context and the catastrophic bridge failure at Poddala, 2009 led to a controversy about the suitability and the stability of Soil-Steel bridges.
The structure safety against crushing failure of the corrugated steel arch was determined using finite element methods. Furthermore, even though the Soil-Steel bridges failed mainly due to the buckling of the corrugated plates and AISI guidelines, which had been used to design bridges in Sri Lanka, doesn't cooperate versatile design procedure for the buckling failure. Therefore, the structural stability against crushing and buckling failure of the existing bridges (Long Span Type) with respect to the different fill heights were determined using finite element analysis.

Keywords: Soil-steel bridges, Finite Element Modelling

1. INTRODUCTION

Corrugated Soil-Steel Structures, consisting of a combination of shells of corrugated steel plates and surrounded with well compacted backfill soil, have been used in Sri Lanka for the first time in the Southern Highway Project as underpasses and drainage structures. The main reason this type of bridge was selected is that they are considered to be more economical and have much shorter construction periods compared to traditional bridges.
However, the technical knowledge about accurate analysis procedures, design guidelines, possible failure mechanisms and durability studies is yet to be developed. Furthermore, the applicability of these structures to Sri Lankan conditions is yet to be analyzed.
In 2009, the catastrophic failure of an HPA 74N type bridge led to controversy about the structural stability and the suitability of the structures to Sri Lankan conditions. Therefore it was imperative to develop a reliable analysis method for the complex mechanics of behaviour of Soil Steel Bridge Structures.

Figure 1HPA 74 Bridge Type

Figure 2 HPA 60 Bridge Type

Figure 3 HES 87 Bridge Type

2. LITERATURE REVIEW

2.1 Structural Design Philosophy

The design of corrugated steel pipe has mainly based on the semi empirical Marston-Spangler Method and the Ring Compression Theory. But it has further developed to more sophisticated methods which recognize compressive failure by crushing or buckling instability. There are several codes in practice to design Soil-Steel bridges, such as

- AASHTO Method
- AISI Method
- CHBDC Method

The AISI method and AASHTO methods have been used for Southern Highway Bridges. But CHBDC method provides a more up to date approach to the determination of thrust and buckling resistance, and is based on ultimate strength principles rather than working stress or service load design. The structural design mainly base on the crushing and buckling of the corrugated steel structure and failure of seams.

3. METHODOLOGY

A literature survey was carried out in order to find the researches have already been done about this particular area. The design and construction of the soil-steel bridge are thoroughly studied in order compare the finite element results and design guideline's results. The following design guidelines are usually being used by the designers.

3.1 Data Collection

The material properties such as elastic modulus, Poisson ratio and density of steel, concrete, soils and asphalt were found from the design guidelines and from the borehole tests. The structural details of the structure were obtained by referring to the structural drawings. The fill heights were taken from the contractor and verified by field visits. The section properties of the corrugated steel arch was obtained by the ASTM A 796/A 796M [3]

Table 1 Material Properties

Material	Density	Elastic Modulus	Poisson Ratio
	(kNm^{-3})	($kNmm^{-2}$)	
Engineering Backfill	19	0.15	0.2
Compacted Soil	17	0.02	0.2
Asphalt	22	2	0.2
Concrete	24	25	0.3
Steel	77	200	0.3

3.2 Development of Finite Element Model

HPA 74 and HPA 60 long span bridge types were modelled. The highway HA and HB live loads and dead loads were applied. In ANSYS and SAP2000 finite element packages, shell elements are used to model the ring wall and the corrugated steel arch. The corrugation was modelled by idealizing a rectangular section with equivalent membrane and bending thickness. In order to model the shell element in ANSYS [8], SHELL 43 and SHELL 63, which can model both membrane and bending effects, are used. The ordinary back fill, engineering back fill (well compacted ABC), foundation and truss beams were modelled by using solid elements. In ANSYS 8 node SOLID 45 [8] solid element is used for modelling straight regions. 20 nodes SOLID 95 element was used to model the curved solid boundary adjacent to the steel arch. PLAXIS software is used to simulate the bridge failure at Poddala, Galle.

3.3 Method of Computation and Analysis

Linear elastic material constitutes models and Mohr Coulomb Material models were used to model the soil phase of the structure. Linear Elastic analysis was carried out using ANSYS and SAP2000 finite element software packages and the Mohr Coulomb

Material Model is used in the PLAXIS software. The analysis was carried out for different allowable thicknesses of soil covers and obtained the axial forces and bending moments of the corrugated steel shell. PLAXIS software is based on the plain strain idealization. In order to carry out three dimensional analysis SAP2000 and ANSYS software were used. ANSYS, PLAXIS and SAP 2000 results were used to compare the Ring Compression method.

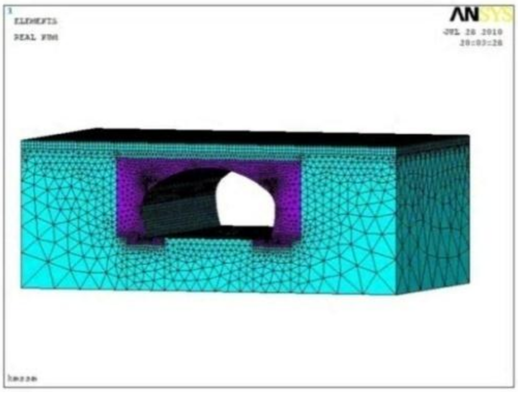


Figure 4 Meshed ANSYS Model

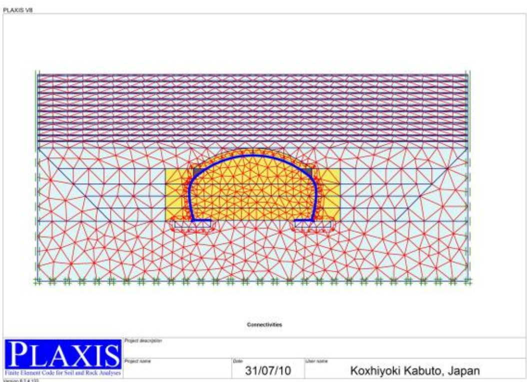


Figure 5 Meshed PLAXIS Modelling

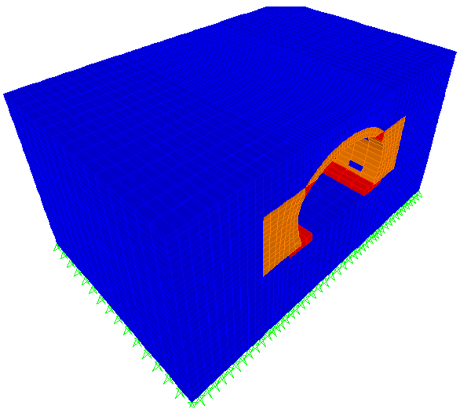


Figure 6 SAP2000 Computer Model

3.4 Buckling Failure Analysis

The Soil-Steel bridges failure mainly due to the buckling of the corrugated plates. But AASHTO (American Association for Highway and Transportation Official) and AISI (American Institute of Steel and Iron) guidelines, which had been used to design bridges, doesn't cooperate versatile design procedure for the buckling. The structures hasn't design for buckling failure but the resistance to buckling has been improved by introducing special structural features such as transverse stiffener and longitudinal stiffener. But the amount of improvement due to installation of stiffeners is not explicitly defined in the design guidelines. The Canadian Highway Bridge Design Code (CHBDC) is support fluent buckling analysis. The buckling stresses and the ultimate stresses of the structure for different fill heights of FE analysis were compared and structural stability against buckling was determined.

The buckling capacity of each type of long span soil steel bridges for different fill heights, were calculated using CHBDC. The buckling capacity of the top arch and bottom arch was separately calculated. The buckling stress and the ultimate stresses of defined maximum and minimum fill heights were compared to evaluate the buckling resistance of the steel structure.

4.0 RESULTS AND DISCUSSION

4.1 Comparison of Finite Element Result with AASHTO and AISI Methods

The axial compression of soil-steel bridges (long span) was calculated according to the AASHTO section 12. The load calculation was carried for both live and dead loads according to the design guidelines.

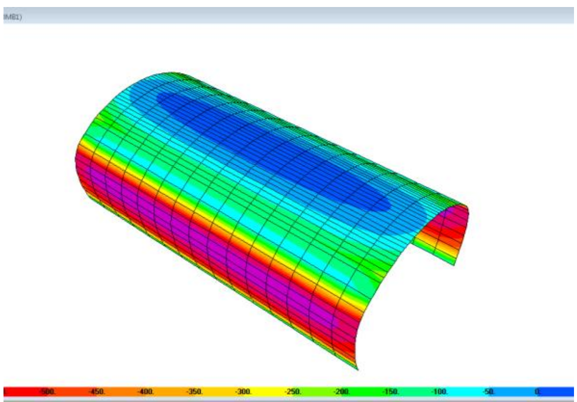


Figure 7 Axial Forces on Steel Arch, SAP2000

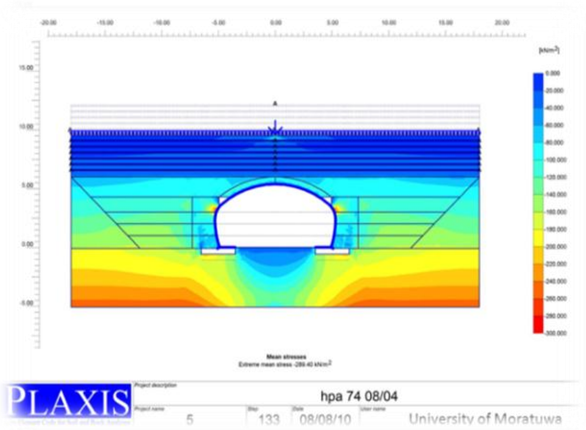
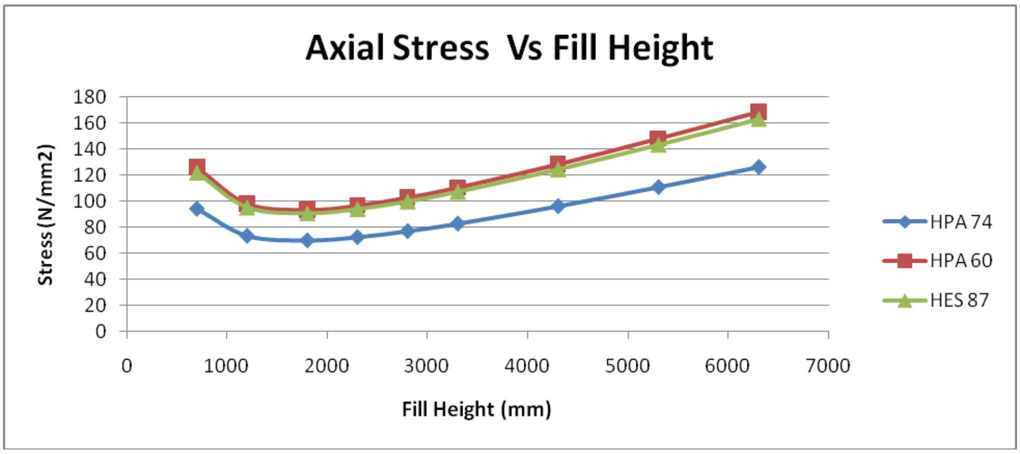
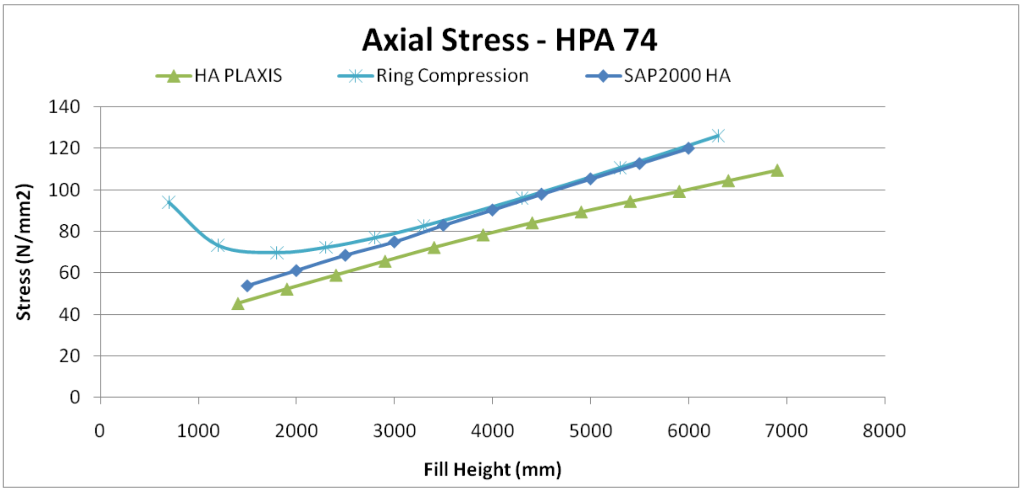


Figure 8 Soil Stresses, PLAXIS

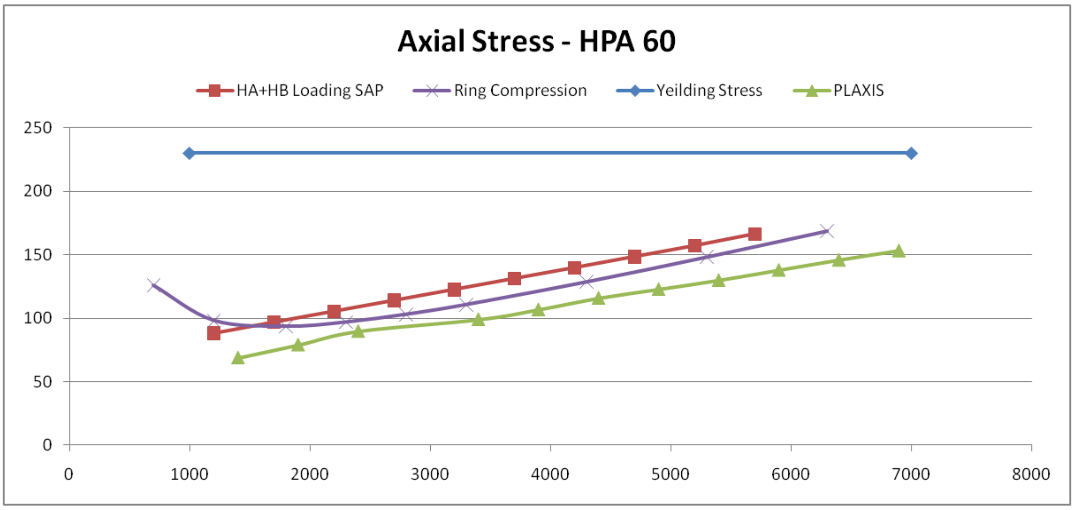
Ring Compression theory has a parabolic relationship between axial force and depth of cover. According to FEM the axial force and depth of cover have a linear relationship. The ring compression results and FEM results are not compatible for lower depth of covers. For higher depth of covers FEM and Ring theory approximately has linear relationship. According to FEM, the internal stresses of the steel arch for maximum and minimum fill heights are below than the yielding stress (230 N/mm2). [Graph 1, 2, 3 & 4]



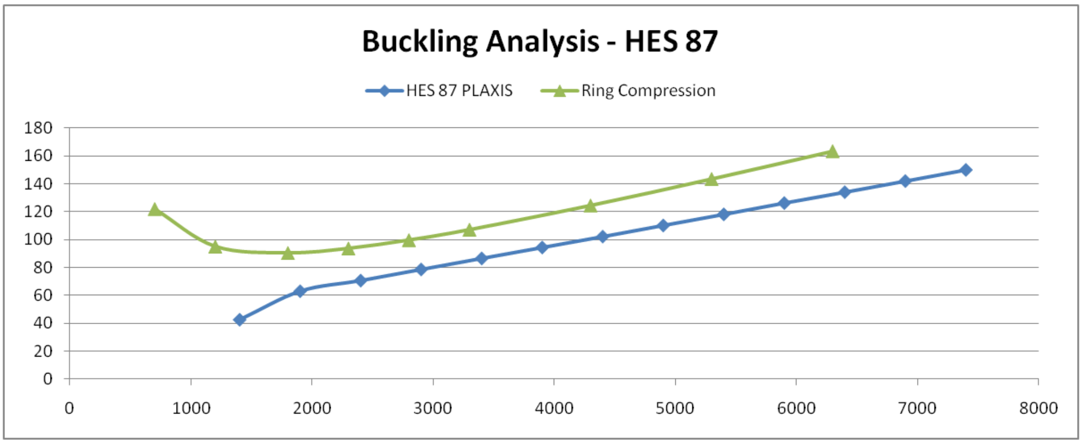
Graph 1 Axial Stresses of Steel Structure According to Ring Compression Theory



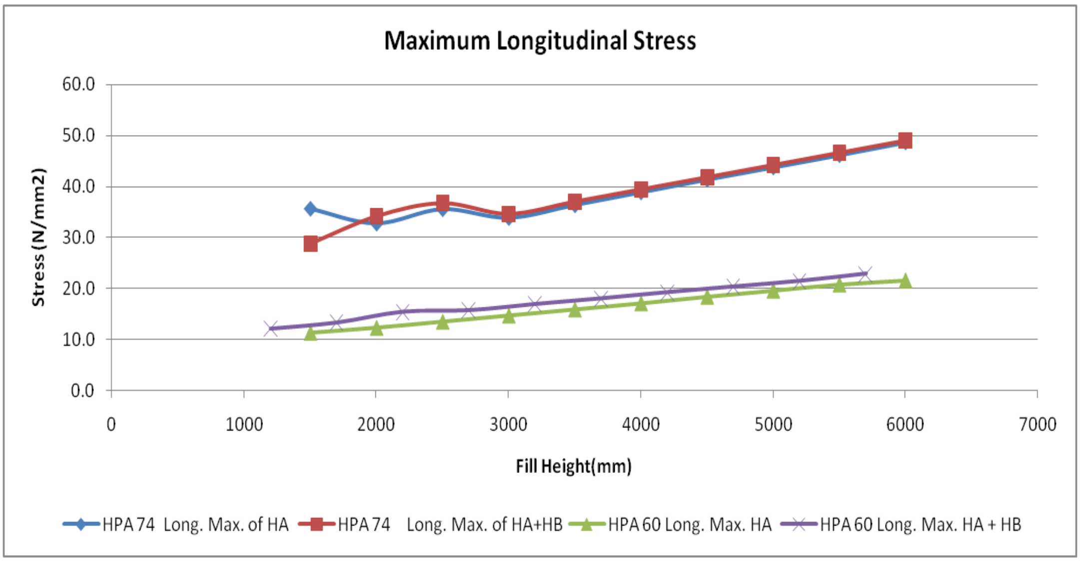
Graph 2 FEM and Ring Compression Comparison, HPA 74



Graph 3 FEM and Ring Compression Comparison, HPA 60



Graph 4 FEM and Ring Compression Comparison, HES 87



Graph 5 Longitudinal Stress due to HA and HA/HB Load Combinations

Ring Compression used two-dimensional idealization and the plane strain idealization has been used. So that no HA/HB load combinations as mention in BS 5400:Part2:1978 haven't considered. Though the stiffness of longitudinal direction is much less than the transverse direction due to the corrugation pattern, the stresses in the longitudinal direction haven't considered in the AASHTO and AISI methods. Graph 5 shows the stresses along the longitudinal direction for HA and HA/HB load combinations.

There is no significant stress difference in between HA and HA/HB load combination. The stresses in longitudinal direction are negligible relative to the crushing stress of the steel (230 Nmm^{-2}).

4.2 Buckling Failure Analysis

The longitudinal stiffeners have been used in the southern highway bridges. Using finite element method, soil-steel bridge was modelled with and without thrust beam and the axial compression of top arch for identical load combinations was evaluated. Figure 9 show the results of above analysis.

According to the FEM results, the thrust beam has drastically reduced the axial forces at the top arch. It implies that the buckling resistance of the top arch has increased by longitudinal stiffener by reducing the axial force at the thrust beam location.

But when we consider the entire structure, from FE analysis we can observe that a maximum axial force occurs at bottom arch instead of top arch. In AASHTO method only consider about the buckling of the top arch. It doesn't consider about the axial forces and the failure of the bottom arch due to crushing and buckling.

4.3 CHBDC Buckling Analysis

According to the CHBDC method, the buckling stresses for the soil steel bridges are below than the crushing strength of the steel plates. The buckling resistance of the corrugated steel plate is increased with the fill height. The fill will increase the stiffness of the surround soil at both bottom and top arch. The stiffness of the soil increases the resistance to buckling.

Furthermore, it can be seen that bottom arch having higher buckling resistance relative to the top arch. This is because bottom arch fill depth is greater than the top arch fill depth. So that soil adjacent to bottom arch restrain the buckling more than the top arch soil. Also the buckling stress becomes constant after a particular fill height.

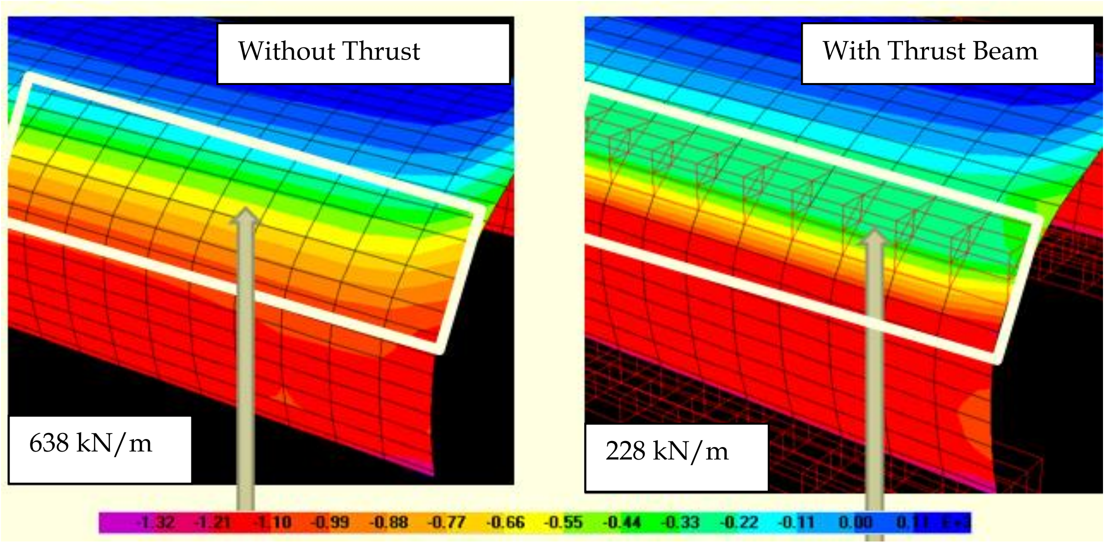
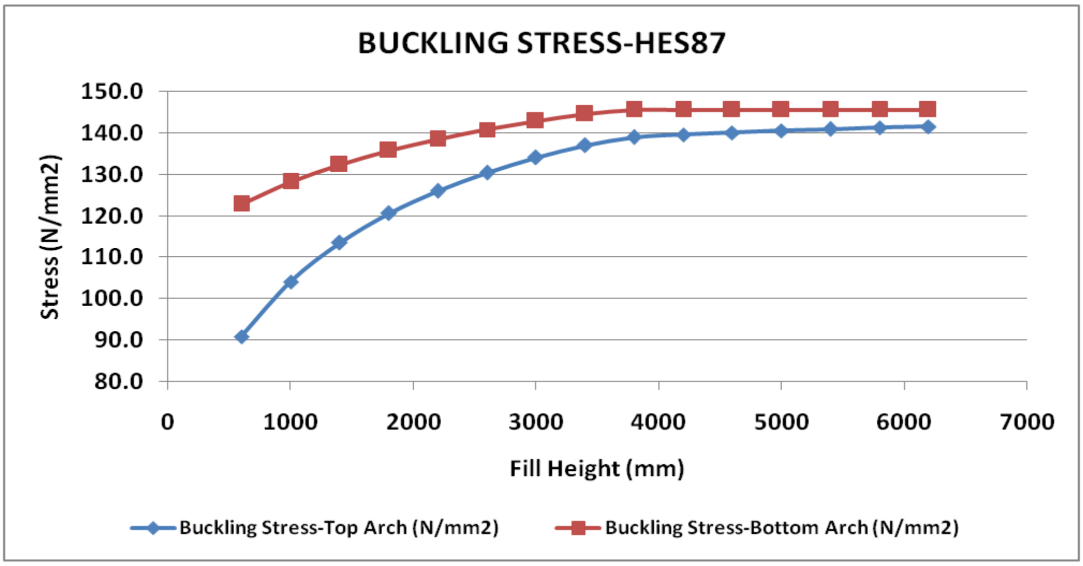
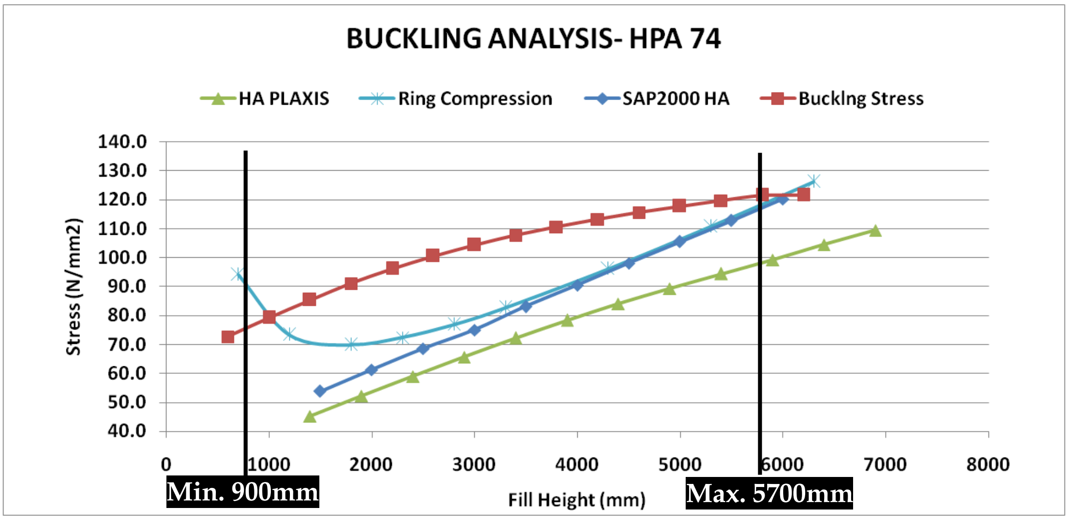


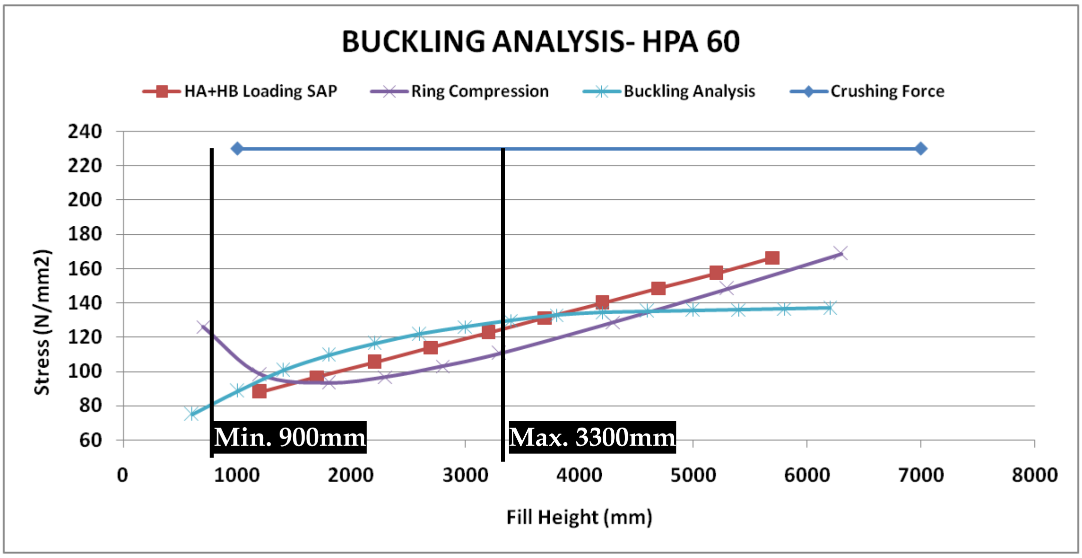
Figure 9 Axial Compression of Steel Structure with and without Thrust Beam



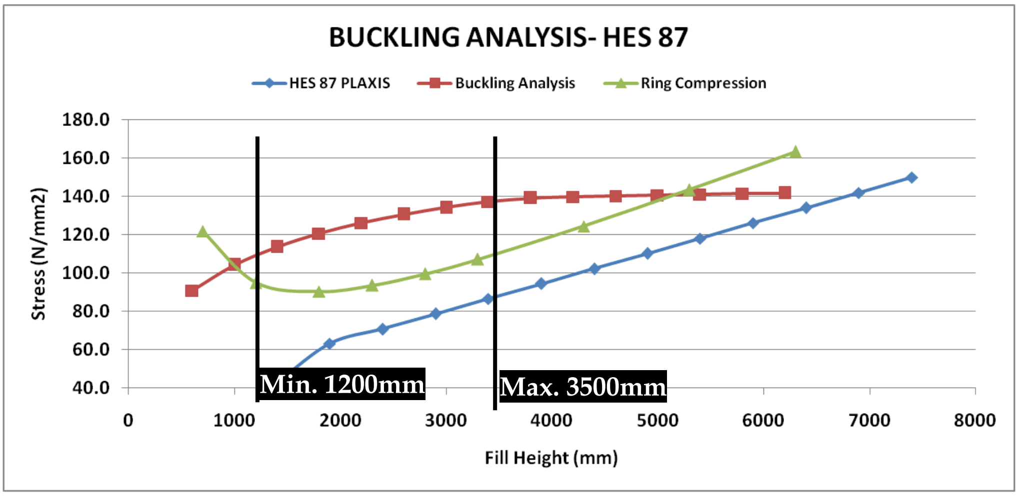
Graph 6 Buckling Failure Stress According to CHBDC, HES 87



Graph 7 Buckling Analysis for HPA 74 Top Arch



Graph 8 Buckling Failure Stress According to CHBDC, HES 87



Graph 9 Buckling Analysis for HES 87 Top Arch

The buckling stress of the structure for top arch was compared with the ultimate axial stresses given by the FEM for maximum and minimum fill height range. The result of Ring Compression Theory for HPA 60 bridge type, for fill depth less than 1400 mm, is greater than the buckling failure stress. But FEM result satisfies the buckling criteria for that fill height range.

5.0 CONCLUSIONS

The Ring Compression theory and FE results were compatible for higher depth of fill heights but it doesn't compatible for the lower depths. According to the finite element analysis it is found that the ultimate stresses of the steel structure for maximum and minimum heights are smaller than the crushing strength of the steel. (230 N/mm^2)
The stresses in longitudinal direction are negligible relative to the yielding stress of the steel. Plain strain idealization can be used since the stresses due to asymmetric loading due to load combinations, are insignificant
AASHTO requirements for buckling design of soil-steel bridges are not explicit enough, and thus require interpretations. CHBDC (2006) accommodate versatile buckling analysis for soil-steel bridges. The buckling resistance of the structure improves with the depth of soil fill. The structures with small fill heights are more vulnerable to buckling failure. Ultimate stresses of HPA 74, HPA 60 and HES 87 structures according to FEM satisfy the buckling failure conditions. [Graph 7, 8 and 9]

6.0 REFERENCES

[1] BS 5400: *Steel, concrete and composite bridges, Part 2: Specification for loads*, British Standard Institute, London, 1978
[2] PLAXIS *modelling manuals*
[3] ASTM A 796/A 796M : *Standard practice for structural design of corrugated steel pipe, pipe-arches, and arches for storm and sanitary sewer and other buried applications*,
[4] Method Statement : *Installation of Metal Underpass Structures*, Kumagai Gumi Co.,Ltd.
[5] Goerge Abdel-Sayed, Baidar Bakht, Leslie G. Jaeger. n.d. "*Soil-Steel Bridges, Design and Construction*". Structural Design Philosophy. New York : MacGraw Hill, Inc, n.d, ch 4, pp. 80-81.
[6] *Steel Drainage and Highway construction products*, Corrugated Steel Pipe Institute, Canada, 2002,ch 6, pp. 203-308
[7] AASHTO Section 12, *Standard Specification for highway Bridges*, American Association of State Highway and Transportation Officials, Washington, USA, n.d
[8] Theory Reference for the ANSYS Workbench Product, (2007), ANSYS, Inc., USA, Version 11.0.

[9] Paul J. Fanning ,Thomas E. Bothby, "*Three-dimensional modelling and full scale testing stone arch bridges*", 2001

[10] *Hand Book of Steel Drainage and Highway Construction Products*, American Iron and Steel Institute, USA, n.d, ch 4