Response to live loading of steel helical culverts with low cover

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Synopsis

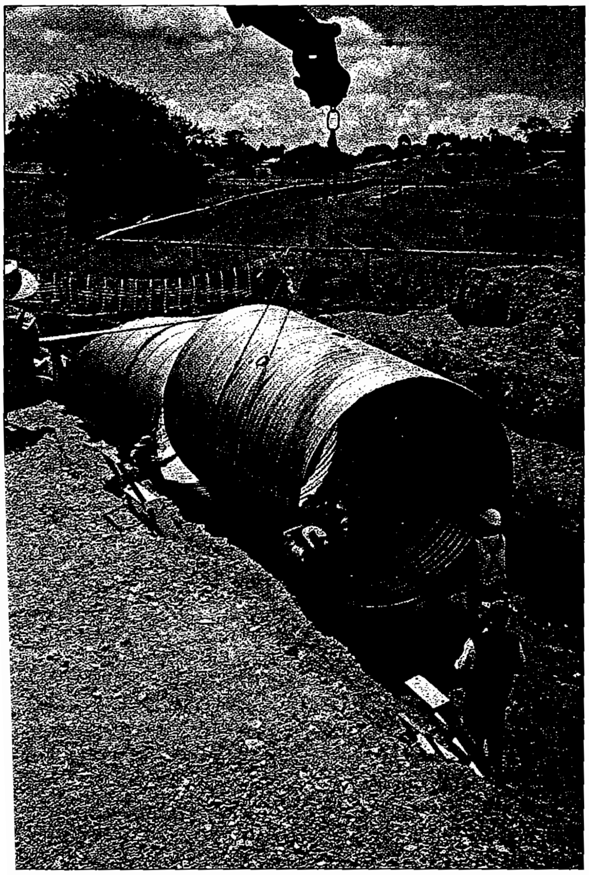
A research programme was initiated by the University of Queensland, Main Roads Queensland and Australian Standards committee CE/25 to investigate the adequacy of design provisions and performance of sinusoidal profile and ribbed profile steel helical culverts for a range of low covers (overburden fills). This paper reports on live load response of the culverts.

The paper examines the response of 3m diameter sinusoidal profile and ribbed profile culverts with 900mm of cover. Each culvert was instrumented with earth pressure transducers, displacement transducers and strain gauges.

The test program measured significant bending strains in association with hoop strains on the culverts. The paper examines the distribution of the hoop and bending effects about the circumference to reveal a more pronounced difference in response between the two culvert types. There are also major differences between the measured behaviour of the two culverts and the assumed ring compression model used in many design standards and guidelines, including current Australian and British documents.

Introduction

The paper describes the incremental live load response of a sinusoidal profile and a ribbed profile, 3m diameter steel culvert with 900mm of cover, subject to vehicular live loading. The limits of culverts conforming to AS1762 are maximum diameter of 3.6m and a minimum cover of 600mm. Whilst significant bending moment occurs during backfilling, this issue is not discussed in this paper.



ig 1. Installation of test culvert

Pressure and strains were measured at locations around the cross-section. Five displacement gauges measured change in diameter. The measured strain distribution was decomposed into hoop and bending components to develop an understanding of the response.

Background

Traditional design methods for circular steel culverts and pipes used in many codes worldwide are based on ring compression with no bending. This approach was derived from testing of about 130 culverts with diameters between 600mm and 1.5m at Utah University (Watkins and Moser, 1971, and American Iron and Steel Institute, 1994).

Abdel-Sayed, Bakht and Jaeger (1993) proposed a revised design method incorporating displacement and buckling at the crown of the culvert.

This current paper examines the hypothesis that under normal operating conditions, significant bending exists around the crown of a culvert in low cover installations.

Test site

The test site was located on a major road construction project utilising normal road construction crews thereby ensuring typical road construction practice was used in the installation of the culverts, Fig 1. The culverts were backfilled in 200mm layers. The difference in height of backfill on both sides of the culvert was limited to 300mm.

Test culverts

The test culverts reported in this paper were of 3m diameter with 125mm × 25mm sinusoidal profile (Fig 2) and ribbed T27 × 100 profile (Fig 3). Both culverts had a wall thickness of 1.6mm.

Instrumentation

Displacement transducers

Diametral deformation was measured using PSI-Tronix Model DT-15-420 displacement transducers with a maximum travel of 380mm. Typical error was 0.15%.

Pressure transducers

Geotechnical Systems Australia manufactured the earth pressure cells. The sensing diaphragm had a diameter of 170mm. A Druck PTX1400-2.5 bar pressure transmitter measured the hydraulic pressure within the cell directly by a micro-machined silicon pressure diaphragm. The manufacturer's stated error of the pressure transducers was 0.5%.

Strain gauges

Strain was measured using Micro-Measurements model

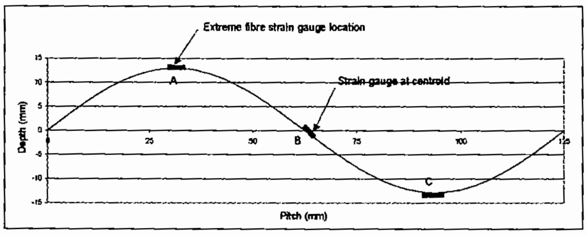


Fig 2. Profile of 125mm x 25mm sinusoidal profile culvert showing strain gauge locations

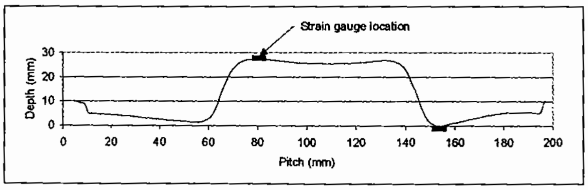


Fig 3. Profile of T27 × 100 ribbed profile culvert showing strain gauge locations

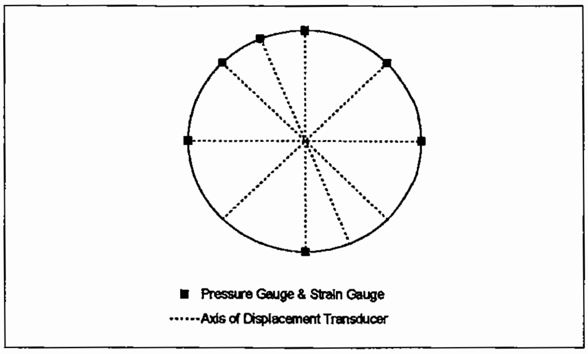


Fig 4. Transducer locations and displacement axes

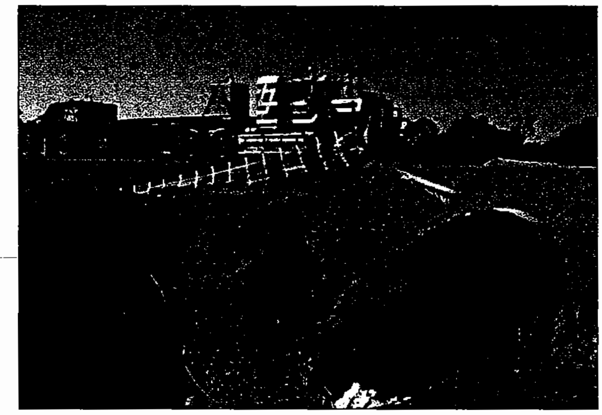


Fig 5. Test vehicle traversing culvert

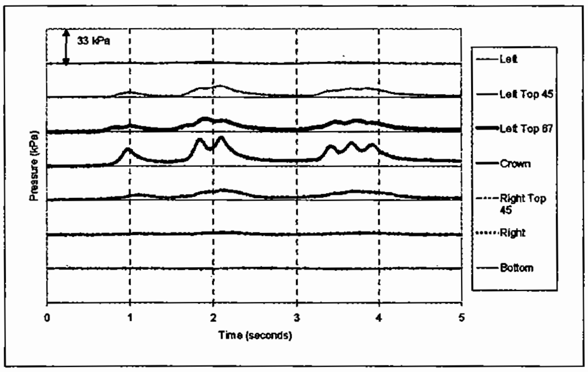


Fig 6. (left) Pressure plot for sinusoidal culvert Fig 7.(right) Peak pressure on sinusoidal culvert

CEA-06-125UN-350 precision strain gauges with an active length of 3.175mm and a nominal resistance of 350 Ohms.

The strain gauges were arranged into full Wheatstone strain bridges. Each bridge consisted of four gauges with two gauges measuring strain in the hoop direction and two gauges at 90° measuring Poisson effects. The use of the bridge magnified the strain by a factor of 2.6 (true strain at each location plus 0.3 times the true strain for the Poisson effect). The Wheatstone bridge configuration also provided temperature compensation. The manufacturer had a stated gauge error of 3%, but experience based on other testing suggests a real error closer to 1%.

Data acquisition system

Data were logged using the computer package Viewdac on an IBM compatible PC. Keithley Matrabyts DAS1800 data acquisition boards were used. Signal conditioning and filtering were undertaken using Dataforth industry standard 5B signal conditioning modules.

During the truck live load test runs, the response of the individual gauges was sampled at up to 500Hz with vehicle speeds up to 60km/h. For the reported test, individual channels were sampled at 200Hz. Sampling between individual channels was at 100kHz for each cycle of data acquisition.

Instrumentation cable and connections

Olex 2 twisted-pair shielded instrumentation cable connected the instruments to the data logger. The shielding limited noise in the cable and improved the quality of the signal. Gold plated contacts were used for connecting the instrumentation to the data logger.

Power supply

The power supply was normal mains power at 240V, 50Hz. A portable generator was not used because the noise in the power supply would have had a detrimental effect on the quality of the measured data.

Location of gauges

Each test culvert was instrumented for strain in the steel, earth pressure and deformation of the culvert.

The axes of the displacement transducers are shown on Fig 4, which also shows the location of the pressure transducers and strain bridges. At the gauge locations on the ribbed profile (Fig 4) strain bridges were installed on the extreme fibres as shown in Fig 3.

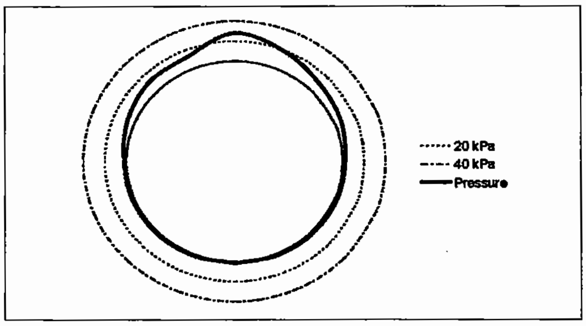
On the sinusoidal culvert, strain bridges were installed at the extreme fibres, positions A and C of Fig 2, at the crown and 67.5° above horizontal left. A single strain bridge at position B (Fig 2) was installed for all the other locations.

Test vehicle

The test vehicle was a legally loaded 38.83t six-axle semi-trailer travelling at 20km/h for the tests reported in this paper. The axle loads were:

- Single-steer axle 5.77t
- Dual-drive axles 16.55t
- Tri-axle trailer 16.51t

Axle spacing was 4.7m, 1.42m, 7.25m, 1.4m and 1.4m. Fig 5 shows the test vehicle traversing the test culvert.



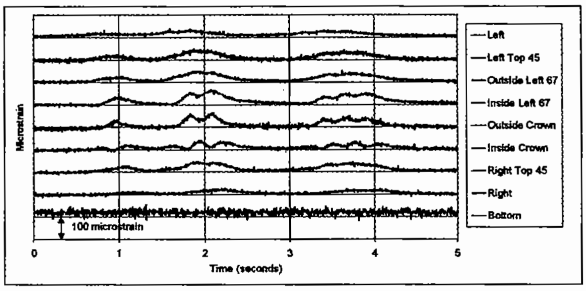


Fig 8. Strain in sinusoidal culvert

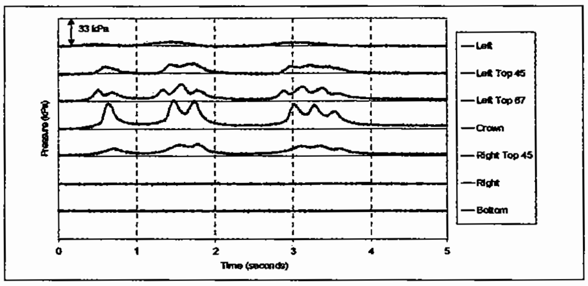


Fig 9. Pressure plot for ribbed culvert

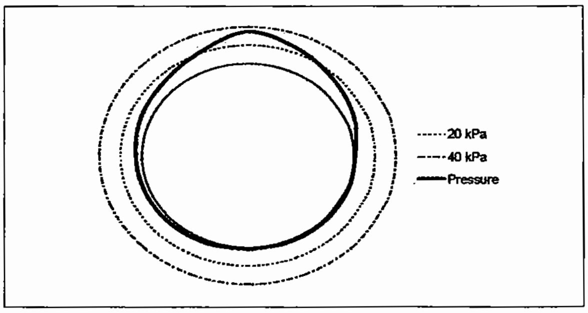


Fig 10. Peak pressure on ribbed culvert

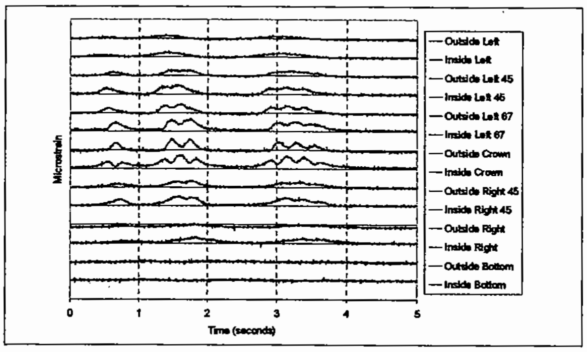


Fig 11. Strain in ribbed culvert

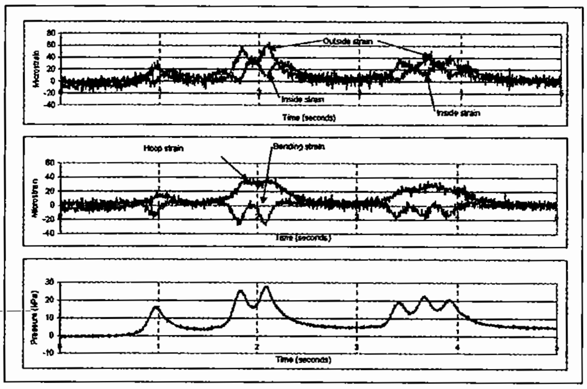


Fig 12. Strains and pressure at crown of sinusoidal profile culvert

Sinusoidal profile culvert test runs

Pressure

Fig 6 shows the distribution of pressure around the culvert for the passage of the test vehicle. The maximum pressure measured was 28kPa. The key features of the plot are:

- The pressure at the crown of the culvert has distinctive peaks as each axle passes over the gauge.
- The other gauges show an increase in pressure in response to the axle group rather than to individual axles.
- The largest pressure for a gauge was measured when the load was closest to the pressure transducer. This explains why all the peak pressures in Fig 6 occur at slightly different times.

The envelope of peak pressure is plotted in Fig 7. The live load pressure increment is most pronounced in the 90° arc extending 45° either side of the centreline.

Strain

Fig 8 shows the measured strain in all gauges. The gauges closest to the ground surface (crown of culvert and inside 67.5° left top) measured peaks corresponding to individual axles. The other gauges on the centroidal axis show the passage of axle groups. It is noted that the peak interior and exterior strains at the crown of the culvert are out of phase. At 67.5° left top, both interior and exterior strains are in phase. This effect can be explained in terms of the changing combinations of hoop and bending strain.

Deformation

No discernable diametral deformation was measured for the passage of the test vehicle on either type of culvert with 900mm of cover. However, in other tests with 300mm cover, significant elastic deformation was measured.

Ribbed profile culvert test runs

Pressure

Fig 9 shows the distribution of pressure for the passage of a test vehicle. At the crown and 67.5° left top, the pressure peak can be identified when each axle passes over the pressure gauge. At other deeper locations, each axle group can be identified.

The envelope of peak pressure is plotted in Fig 10. The response is similar to that of the sinusoidal profile with the pressure pronounced in a 90° arc extending 45° each side of the crown. The maximum pressure in Fig 10 is 35kPa.

Strain

The ribbed profile culvert has strain bridges located as detailed in Fig 3. Fig 11 shows the measured strains for the passage of the test vehicle. The inside and outside peak strains at the crown are out of phase. Individual axles can be identified at the crown and 67.5° left top. At the other gauge positions, only the axle group can be identified.

Discussion of hoop and bending effects in sinusoidal profile culvert

The strain data can be presented in a number of different formats including individual gauge strains, inferred hoop strain and strain associated with bending.

The measured extreme fibre strain can be decomposed to hoop strain and bending strain. For the symmetric sinusoidal profile, the hoop strain is the average of the extreme fibre strains, while the bending strain is half of the difference between these strains. For the ribbed profile, the neutral axis is not quite at mid-height of the profile, hence bending strain magnitude at extreme fibres differs marginally.

'The gauges closest to the ground surface (crown of culvert and inside 67.5° left top) measured peaks corresponding to individual axles.'

For the sinusoidal culvert, the strain at the crown and 67.5° left top was measured at both the extreme fibres (Fig 2). The difference between inside and outside strain in the sinusoidal culvert clearly exhibits the existence of bending action (Fig 12). A better understanding of the response is found decomposing the strain into hoop and bending components. Fig 12 also show the hoop and bending strains at the crown of the culvert and pressure at the crown. Maximum pressure coincides with each axle being located directly above the crown.

The main observations are:

- The hoop strain is relatively constant for the passage of each axle group.
- Peaks in bending strain coincide with the peaks in pressure when the individual axles are located over the crown of the culvert.
- The magnitude of bending strain is approximately 70% of the hoop strain. That is, the bending strain is over 40% of the total strain, a significant component of the total.

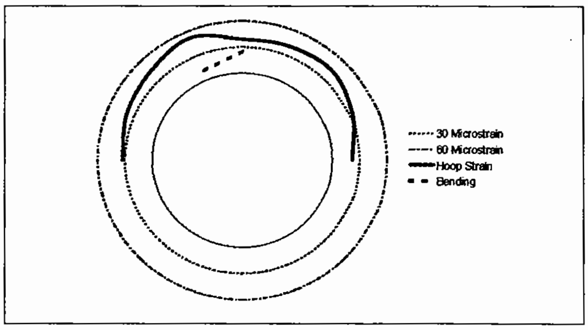


Fig 13. Envelopes of peak hoop strain and bending strain – sinusoidal profile

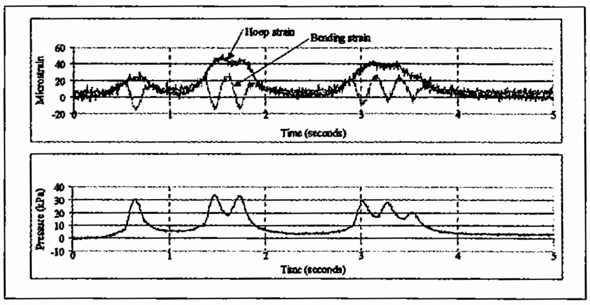


Fig 14. Strains and pressure at crown of ribbed profile culvert

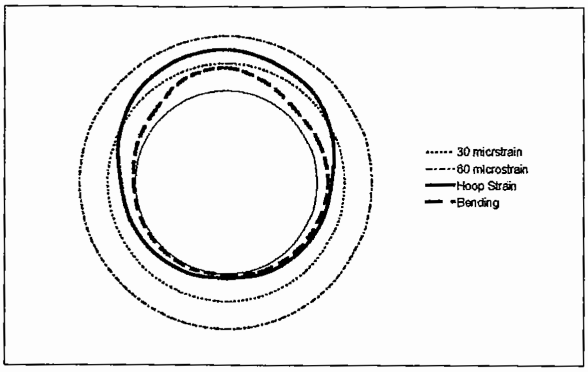


Fig 15. Envelope of peak strain – ribbed profile

Because the crown and 67.5° top left were the only positions on the sinusoidal culverts where extreme fibres strains were measured, these are the only locations where the strain can be decomposed into hoop and bending effects. At the other locations, only the hoop strain was measured.

Fig 13 plots the peak hoop and bending strains around the culvert. The peak hoop strain is reasonably uniform in the 180° arc extending 90° either side of vertical. The bending strain (Fig 13) and pressure (Fig 7) rapidly attenuate as the distance from the crown increases.

Discussion of hoop and bending effects in ribbed profile culvert

The hoop strain response at the crown of the ribbed profile culvert (Fig 14) is similar in shape to that of the sinusoidal culvert profile in that the strain is reasonably constant for the passage of each axle group.

The bending component is more prominent than for the sinusoidal profile culvert. The ribbed culvert initially has compression on the inside face, changing to tension on the inside face when the axle is over the gauge. The magnitude of the bending strain is just over half of the hoop strain when the axle is immediately over the gauge.

At 67.5° above the horizontal left, the bending strain is less than half of the hoop strain. The magnitude of the bending strain attenuates rapidly from the crown.

The hoop strain for each gauge location in the ribbed profile culvert is shown in Fig 15. All gauges in the top 135° arc centred on the crown show a fairly constant hoop strain for each axle group. The peak hoop strain is 44 microstrain at the crown. The distribution of bending strain around the culvert is also shown in Fig 15. The bending effect reduces rapidly as distance from the crown increases.

The maximum strain in Fig 15 occurs at the crown of the ribbed profile culvert compared to 67.5° left top above the horizontal for the sinusoidal culvert (Fig 13). Data from other tests show this not to be a consistent feature of response.

Comparison between sinusoidal and ribbed profile response

Pressure

The peak earth pressures for sinusoidal and ribbed profile culverts were similar at 28kPa and 35kPa respectively.

Strain

The peak hoop strain was 39 microstrain at the crown and 52 microstrain at 67.5° above the horizontal for the sinusoidal profile. The corresponding peak bending strains were 25 and 11 microstrain respectively.

The peak hoop strain in the ribbed profile was 44 microstrain at the crown and 43 microstrain at 67.5° above the horizontal left. The corresponding bending strains were 25 microstrain and 20 microstrain.

Table 1: Bending strain expressed as a percentage of total strain

Gauge location	Bending strain as percentage of total strain	
	Sinusoidal profile	Ribbed profile
Crown	40	36
Left top 67.5° above horizontal	17	32
45° above horizontal	–	21, 22

Bending strain is tabulated as a percentage of the total strain in Table 1.

The ribbed profile culvert has a more dominant bending effect at the crown than the sinusoidal profile. (Fig 12 and 14).

Current practice

Design procedures such as found in the *Design Manual for Roads and Bridges* (Highways Agency, *et al*, 2001), AS 1761 and AS 1762 are based on ring compression theory. This assumes a uniform pressure distribution around the culvert, uniform hoop force and no bending. The Highways Agency, *et al*, 2001 has additional requirements relating to buckling under situations of lower cover.

The measured test results show rapid attenuation of pressure with distance from the crown of the culvert. Additionally, a significant bending component has been measured in the upper quadrant of the culvert centred on the crown. These are the prominent aspects of response that are not reflected in design guidelines or codified methods.

The entire test program included a sinusoidal profile and ribbed profile culverts with diameters of 1500mm and 3000mm. Live load runs were undertaken with covers of 300mm and 600mm for the 1500mm diameter culverts and 600mm and 900mm cover for the 3000mm culverts. A total of 243 live load runs were undertaken. The two test results presented illustrate the similar measured response of all the live load tests.

Conclusions

The following conclusions are made:

- Both culvert profiles experienced hoop and bending effects due to the passage of the test vehicle. The bending effect is significant in the top quadrant of the culvert.
- The ribbed profile culvert experienced a larger bending effect than the sinusoidal profile culvert.
- The earth pressure due to live load attenuates rapidly from the crown.
- For low cover situations, the test results do not support the assumption of uniform pressure and ring compression without bending.
- This paper is based on one passage of a test vehicle for each culvert profile. Results from 243 live load tests lead to similar conclusions.
- Design codes and guidelines should be reviewed for low cover applications.

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