Observed soil displacements above rigid culverts

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ABSTRACT
Centrifuge model tests were performed to observe soil displacements above twin rigid circular culverts. Positive projecting as well as induced trench culvert configurations were investigated. The experimental work utilized digital photography, particle image velocimetry (PIV), and close-range photogrammetry to track the deformations associated with positive and negative arching for induced trench and positive projecting construction. The data on soil deformations from twin culverts are compared with the data for a single culvert to investigate the effect of interactions of twin culverts on the deformation pattern. The configuration of compressible zones above twin culverts was varied to study the influence of this variable on the deformation behavior. The effect of friction mobilized along the boundaries of the centrifuge strong box on the deformation pattern is also discussed. The results indicate that the observed deformation patterns are significantly different than those typically assumed in simplified design procedures.

RÉSUMÉ
Une centrifugeuse fut utilisée pour observer les déplacements au dessus d'un double ponceau circulaire rigide. Des configurations à projections positives ainsi qu'avec des tranchées induites furent étudiées. Les déformations associées à l`effet d'arche positive et négative pour ceux-ci furent évaluées à l'aide de photographie numérique, la vélocimétrie par images de particules, et la photogrammétrie. Les données obtenues des essaient pour les ponceaux doubles furent comparées avec ceux d'un ponceau simple afin d'évaluer l'effet d'interactions entre les ponceaux. De plus, la configuration de la zone compressible au-dessus des ponceaux doubles fut aussi variée afin d'étudier son effet sur le déplacement. Le frottement entre le sol et les murs de la centrifugeuse et son effet sur le déplacement du sol est aussi discuté. Les résultats indiquent que les modèles de déplacements se différencient selon l'emplacement d'un ponceau simple ou double.

1 INTRODUCTION

In some instances twin culverts are designed and constructed under high embankments. The current design methods used in Canada (CSA 2006, AASHTO 2007) provide guidelines and recommendations only for single culverts under positive projecting and trench installations. For twin culvert installations, designs based on the Marston-Spangler Theory (Spangler and Handy, 1973) developed for single culverts are used for positive projecting as well as induced trench conditions. The theory is based on the assumed direction of the mobilized shear forces and relative deformations above twin culverts as illustrated in Figure 1. For positive projecting installations, the shear forces due to differential settlements act downwards resulting in negative soil arching while in the case of induced trench installations, the differential settlements lead to positive soil arching. Using the simple deformation model shown in Figure 1, earth pressures are calculated on the buried culvert accounting for positive or negative arching.

A review of the literature indicates that research pertaining to twin culvert behavior under high embankments is somewhat limited. As a consequence a research program has been undertaken at the University of New Brunswick to study soil structure interaction of twin culverts for positive projecting and induced trench installations (Bourque, 2002; McAffee, 2005; and McGuigan 2010). The aim of the research was to study the effect of spacing between the pipes, height of embankment, and geometry of the compressible layers within induced trench installations on the soil-structure interaction of twin culverts.

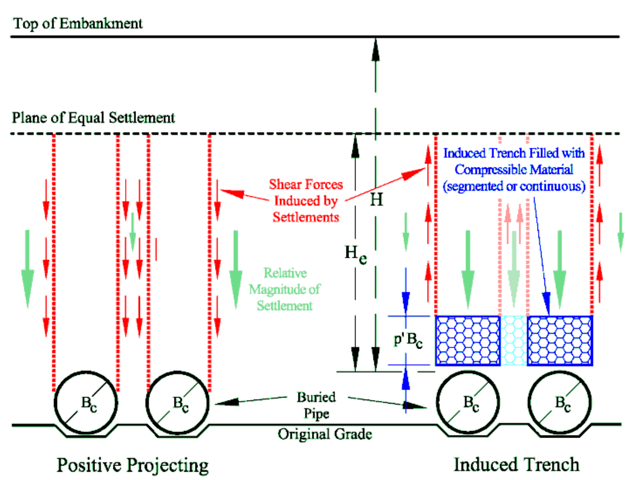

Figure 1: Mobilized shear forces and relative deformations for both positive projecting and induced trench installations

In this paper, results of centrifuge tests performed on single and twin model culverts are presented where soil deformations around and above the culverts were measured to study the internal kinematics associated with the positive projecting and induced trench twin culverts. Particle image velocimetry (PIV) and close-range photogrammetry techniques were used to study soil deformations (White, 2002; Take, 2003; White et al. 2003). Geo PiV (White et al. 2003) software was used to track the soil deformations during the centrifuge model testing.

2 CENTRIFUGE MODELS

Centrifuge tests were performed in the UNB Geotechnical Centrifuge Facility which consists of a medium sized beam-type centrifuge capable of accelerating a 100 kg payload to 200g. The centrifuge has a maximum effective radius of 1.6 m.

Circular dowels made from solid hardwood were used to model the rigid circular culverts. The dowels were 24.5 mm in diameter and founded on a 27 mm thick silica sand layer. The silica sand used to represent the soil medium was placed by air pluviation to achieve a total density of 1.5 g/cm^3, corresponding to a relative density of 69%. The height of silica sand above the crown of the model culverts was maintained at 183.5 mm in all the tests performed. To simulate induced trench installation, expanded polystyrene (EPS) was used as the compressible material above culverts. For single culvert tests, the EPS was 24.5 mm wide and 18.4 mm thick and was located 6 mm directly above the crown of the model culvert. In twin culvert tests, two configurations of compressible zones were studied. In one test, two individual compressible zones 18.4 mm thick with a width of 24.5 mm were placed at a distance of 6 mm above each culvert. The spacing between the culverts was 24.5 mm (i.e., one diameter). In the second test, a continuous compressible zone which was 18.4 mm thick and 73.5 mm wide was placed 6 mm above the crown of the model culverts. For the positive projecting twin culvert model test, the spacing between the culverts was maintained at 24.5 mm with the thickness of silica sand below the invert and above the crown of the culvert being similar to the single culvert tests. All tests were performed at 50g to simulate prototype culverts of 1.225 m diameter under 9.2 m of soil cover.

A Canon Powershot A70 digital camera was mounted approximately 30 cm from the transparent face of the strong box. The field of view of the camera was oriented to take advantage of the plane of symmetry of the problem (Figures 2 and 3). The field of view captured by the camera was 156 mm x 208 mm in size. Using the maximum resolution for the camera of 3.2 million pixels, the level of detail recorded was 0.10156 mm / pixel. Assuming that the combined system precision of the GeoPiV Software is at least 1/10th of a pixel (White el al., 2003) the precision of soil movements which can be detected are estimated to be 0.01 mm at model scale which corresponds to 0.5 mm at the prototype scale (tested at 50g).

Figure 2: Typical digital image captured during testing (twin culvert layout with an induced trench using a segmented compressible layer).

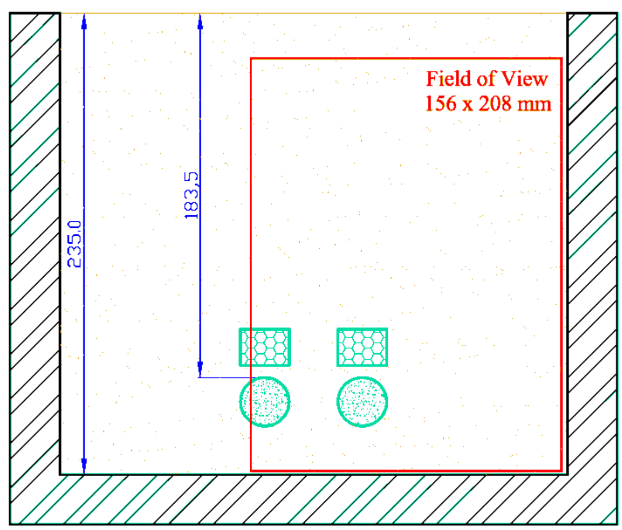

Figure 3: Field of view utilizing the plane of symmetry for taking digital images (all dimensions in millimeters)

Further details on the control points used for photogrammetry, the location of these control points, lighting system used, blending of color silica sand with light color silica sand to enhance digital imaging are reported in McAffee et. al. (2006) and McAffee (2005).

In each centrifuge test, digital photographs were taken at the start of the test and then at every 5g level as the gravity forces on the model were increased to the 50g level. With this approach, incremental displacement vectors were obtained in small steps which resulted in a higher level of accuracy in determining the incremental displacement vectors thereby providing more accurate estimates of soil deformation at 50g.

3 RESULTS

The internal soil deformations above and below the model culverts were first investigated for a single culvert both with and without a zone of compressible material. These results were presented in McAffee et al. 2006 but are summarized in this paper to facilitate comparison with the data obtained from the twin culvert experiments. Figures 4 and 5 show the final vertical settlements above a single culvert layout measured at 50g as contour plots for both configurations.

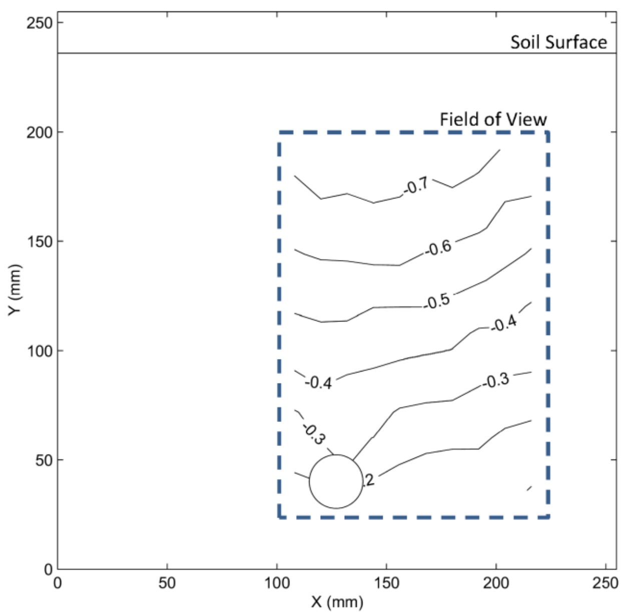

Figure 4: Vertical deformation observed with digital image testing for a single culvert installed in the positive projecting position

The final vertical settlements for the positive projecting model culvert varied from 0.3 mm immediately above the crown of the culvert to a maximum of 0.8 mm at the surface directly above the culvert. In comparison, for the induced trench configuration, the final total vertical settlement near the crown is 13% greater than that measured for the positive projecting culvert installation. At the elevation corresponding to the top of the compressible layer directly above the culvert, approximately 60% more vertical settlement was measured when compared to the positive projecting culvert. The results confirm that significantly more settlements occur within the area above the culvert with the induced trench installation but the zone of greater settlement is not confined within just the vertical soil prism above the culverts. Thus, the data from measured soil deformations demonstrates that the soil prism model assumed in the Marston-Spangler theory is too simplistic and any soil arching analysis based on the model is going to be approximate only.

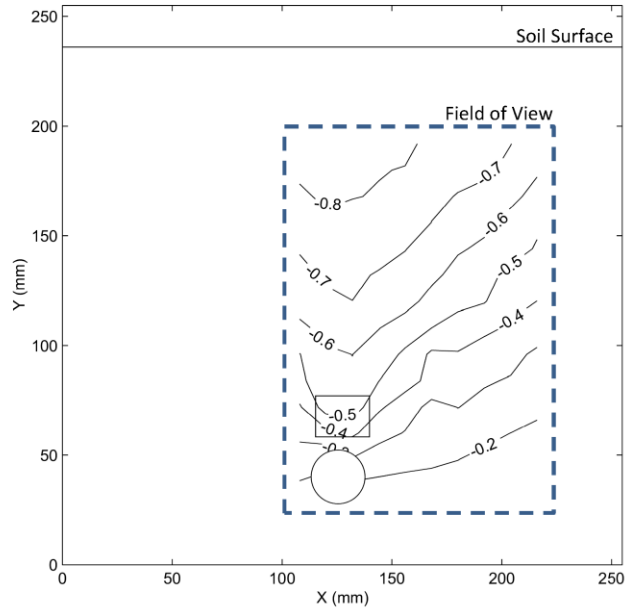

Figure 5: Vertical deformation observed with digital image testing for a single culvert installed in an induced trench configuration

The soil deformation data for twin culverts are presented in Figures 6, 7 and 8. A comparison of Figure 6 with Figure 4 indicates that the soil deformation patterns above a single culvert installation are different than those for twin culverts due to the interaction between two culverts. The final vertical settlements above the crown of the twin culverts are 6% larger than those for a single culvert. For a single culvert the slope of settlement contours are inclined at approximately 25 degrees to the horizontal. In comparison, the slope of the settlement contours for twin culverts in positive projecting installations are more steeply inclined at between 40 and 45 degrees to the horizontal. The maximum vertical settlement at the ground surface for the twin culvert layout is noted to be about 12% smaller than that for a single culvert. The observed differences in deformation patterns between the single and twin culverts are for a clear spacing of one diameter between culverts and should not be extrapolated for other spacing between twin culverts.

The effect of incorporating two individual compressible zones above the twin culverts on the measured soil deformations is presented in Figure 7. As can be expected, the vertical settlements at the top of compressible layer were significantly greater (64%) than those for positive projecting twin culverts at comparable elevations. The slope of the settlement contours above the compressible zones is also much steeper (50 degrees to 55 degrees) when compared to the positive projecting twin culvert layout. The data on soil deformations between compressible zones indicates that the assumption of two vertical prisms associated with each compressible zone extending up to the line of equal settlement is too simplistic. The complex soil deformation pattern also suggests that the earth pressures on the inside surfaces of the culverts (sides of the culverts that face each other) are likely to be noticeably different than those exerted on the outside surfaces.

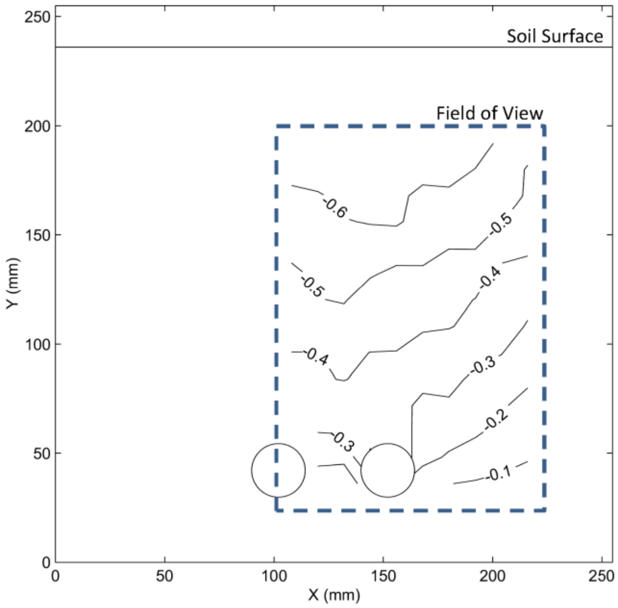

Figure 6: Vertical deformation observed with digital image testing for a twin culvert layout installed in the positive projecting position.

The soil deformations for a continuous compressible layer spanning both culverts are presented in Figure 8. A comparison of the data from Figure 8 to the data from Figure 7 indicates that due to the continuous nature of the compressible layer a composite soil prism slides down differentially with respect to the outer soil. The data indicate that the ground surface settlements for a continuous compressible layer will be 20% greater than the corresponding settlements resulting from the use of two individual compressible zones. However, once again the data clearly demonstrates that an assumption of a simple vertical soil prism above the entire compressible zone spanning both culverts may be too simplistic.

Finally, the data from all the tests performed indicate that the friction between the sand and side wall boundaries of the strong box affects soil deformations in the vicinity of these boundaries. The results from the positive projecting tests in particular show that the settlements along the edge of the models are reduced due to the frictional effects along the sides of the aluminum centrifuge strong box.

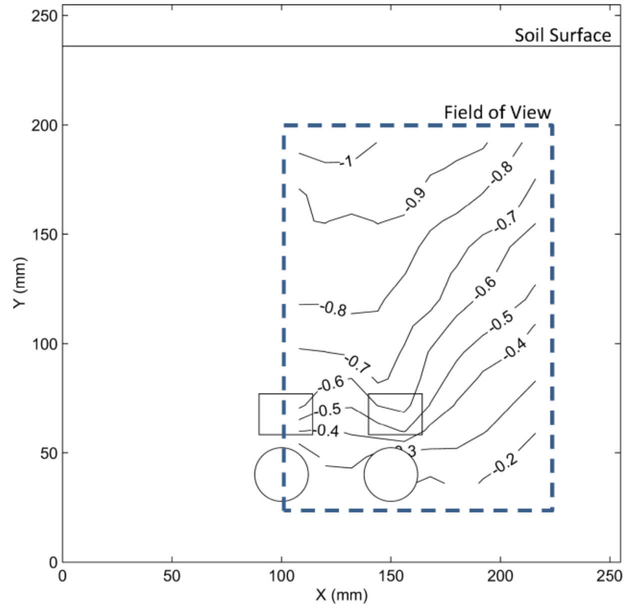

Figure 7: Vertical deformation observed with digital image testing for a twin culvert layout installed in an induced trench configuration (segmented compressible layer).

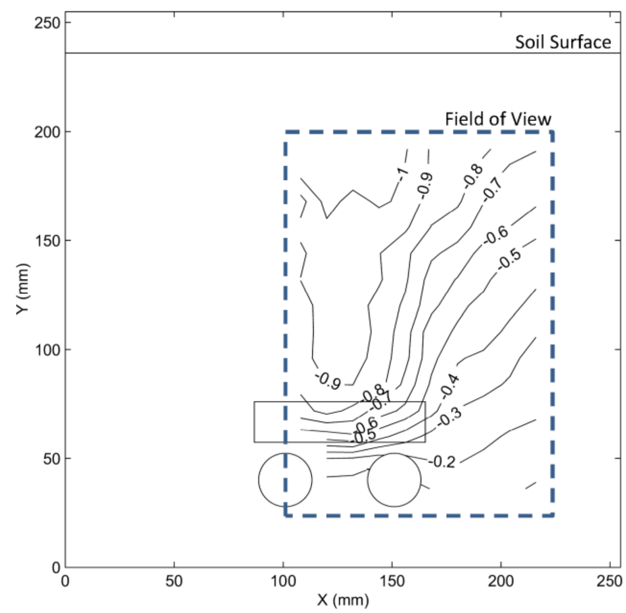

Figure 8: Vertical deformation observed with digital image testing for a twin culvert layout installed in an induced trench configuration (one continuous compressible layer).

4 CONCLUSIONS

The design methods for twin culverts based on the Marston-Spangler theory make the simplified assumption that only a vertical column of soil over the individual culverts settles inducing negative soil arching. In the case of an induced trench twin culvert installation with two individual compressible zones above the culverts, once again an assumption of two vertical columns of soil prisms settling differentially are made to evaluate negative arching. For the case of a continuous compressible zone spanning both culverts an assumption of a single vertical soil prism directly above the compressible zone is made.

The data of soil deformations above and around the twin culverts reported in this paper demonstrates that the vertical soil prism assumptions utilized in the Marston-Spangler theory are too simplistic. The data also indicates that significant settlements within the soil mass outside the vertical prism of soil immediately above the twin culverts occur for induced trench installations. In view of the findings of this research, the use of the Marston-Spangler theory for design of twin culverts should be used with caution. The paper also demonstrates that digital photography, particle image velocimetry (PIV) and close-range photogrammetry can be effectively used to monitor soil deformations in centrifuge tests performed on model sized culverts.

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