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DOCUMENTED FIELD EXPERIENCE OF MEASUREMENTS ON ASCC STRUCTURES

Summary. The main goal of this work is complete a thorough review and evaluation of the state of the art in design and construction of reinforced concrete and steel Arch-Shaped Cut-and-Cover (**ASCC**) constructions, investigate **ASCC** behaviour trough full-scale laboratory and field tests and extensive computer modelling of these structures. This paper is focused on documented field monitoring experience on full-scale **ASCC** structures built throughout the world.

ASCC constructions pertain to the special group of underground structures constructed at shallow depth and they are increasingly used in road and railway projects as an alternative solution to bridges and culverts. The construction period is short and the structures have both technical and economical advantages. The most frequently used types of ASCC constructions in practice are thin walled soil-steel structures (e.g. Linear-Plate, Multi-Plate, Bridge-Plate, Super-Span, Box-culverts, etc.) and structures with a subtle reinforced precast concrete lining (e.g. BEBO arch-bridge systems, MATIERE precast arch system, etc.).

To obtain better understanding of ASCC structure behaviour under different loads and within different geological conditions it is necessary to test and monitor these structures. Several full-scale comprehensive tests have been performed in the field to validate the long term performance and load bearing capacity of these structures. Within the paper some of these full-scale field tests and measurements are briefly described. Number of the field measurements were carried out within the Czech Republic as well, namely, the Hvížďalka transport tunnel and TOM2 constructions. Unfortunately, all available data obtained from the measurements performed in the Czech Republic were focused on concrete ASCC constructions. Due to the lack of results obtained from field investigations on steel ASCC structures in the Czech Republic it is necessary to use results from abroad.

UDOKUMENTOWANE DOŚWIADCZENIE TERENOWE W DZIEDZINIE POMIARÓW BUDOWLI ASCC

Streszczenie. Głównym celem niniejszej pracy jest sporządzenie gruntownego przeglądu i oceny aktualnego stanu wiedzy w dziedzinie projektowania i budowy żelbetowych i stalowych konstrukcji ASCC, zbadanie zachowania ASCC w badaniach laboratoryjnych i terenowych na obiektach normalnej wielkości oraz intensywne komputerowe modelowanie tych budowli. Artykuł ten jest poświęcony udokumentowanemu doświadczeniu terenowemu

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w zakresie monitorowania budowli ASCC normalnej wielkości budowanych na całym świecie.

Konstrukcje ASCC należą do specjalnej grupy budowli podziemnych budowanych na niewielkich głębokościach i są one coraz częściej stosowane w przedsięwzięciach drogowych i kolejowych jako alternatywne rozwiązanie w stosunku do mostów i przepustów. Okres budowy jest krótki,a budowle mają zalety zarówno techniczne,jak i ekonomiczne. Najczęściej używanymi typami konstrukcji ASCC są w praktyce cienkościenne budowle ziemno-stalowe (np. liniowo-płytowe, wielopłytowe, mostowo-płytowe, superprzęsło, , przepusty skrzynkowe itp.) oraz budowle o lekko zbrojonych prefabrykowanych wykładzinach betonowych (np. systemy mostów łukowych BEBO, system prefabrykatów łukowych MATERIE itp.).

Aby osiągnąć lepsze zrozumienie zachowania budowli ASCC pod różnymi obciążeniami oraz w różnych warunkach geologicznych trzeba te budowle przebadać i monitorować. Przeprowadzono liczne badania polowe tych budowli normalnej wielkości w celu potwierdzenia ich długookresowych osiągów oraz nośności. W artykule tym opisano pokrótce niektóre spośród tych badań polowych obiektów normalnej wielkości oraz pomiary. Pewna liczba tych pomiarów in situ została wykonana również w Republice Czech, mianowicie w tunelu transportowym Hvížďalka oraz konstrukcjach TOM2. Niestety, wszystkie dane uzyskane z pomiarów przeprowadzonych w Czechach dotyczyły betonowych konstrukcji ASCC. Z powodu braku badań polowych stalowych budowli ASCC w Republice Czech trzeba wykorzystać wyniki zagraniczne.

1. Introduction

The style and organisation of life today produces an increasing enforcement on engineers to transform the landscape into villages, towns and cities together with a comprehensive infrastructure linking them. Whilst fulfilling these needs, many difficulties are met that have subsequently to be solved. One of these difficulties is, for example, how to cross long line roads and motorways. Of course, there are many ways of solving this kind of problem. One of them is, as is presented in this work, to build an Arch-Shaped Cut-and-Cover (ASCC) construction. Flexible and rigid ASCC constructions with a large span, ranging from 3m to occasionally more than 15m, are often a practical structure for short to intermediate span crossings, especially on local road systems. The use of these structures is increasing; however, the available design and construction specifications have not been updated for many years, and modification is needed to reflect current design theory and current construction practices as well as to take advantage of increased computational power for analysis.

ASCC constructions pertain to the special group of underground structures constructed at shallow depth and they are increasingly used in road and railway projects as an alternative solution to bridges and culverts. The construction period is short and the structures have both technical and economical advantages. The most frequently used types of ASCC constructions in practice are thin walled soil-steel structures (e.g. Linear-Plate, Multi-Plate, Bridge-Plate, Super-Span, Box-culverts, etc.) and structures with a subtle reinforced precast concrete lining (e.g. BEBO arch-bridge systems, MATIERE precast arch system, etc.).

To obtain better understanding of ASCC structure behaviour under different loads and within different geological conditions it is necessary to test and monitor these structures. Several full-scale comprehensive tests have been performed in the field to validate the long term performance and load bearing capacity of these structures. Within the paper some of these full-scale field tests and measurements are briefly described. Number of the field measurements were carried out within the Czech Republic as well, namely, the Hvižďalka transport tunnel and TOM2 constructions. Unfortunately, all available data obtained from the measurements performed in the Czech Republic were focused on concrete ASCC constructions. Due to the lack of results obtained from field investigations on steel ASCC structures in the Czech Republic it is necessary to use results from abroad.

2. Documented field experience

2.1. Field measurement of transport tunnel Hvižďalka

A comprehensive investigation of reinforced concrete traffic tunnel Hvižďalka have been carried out in a project sponsored by the company so-called Českomoravský cement a.s. since 1995. The massive reinforced concrete arch structure with the wall thickness of 850 mm approximately and total length of 224m was built as access tunnel to limestone mine face. The cross-sectional dimensions subjected to testing structure, 7.7m span and 6.8m rise, are shown in Fig. 1. The measured tunnel with the wall thickness of 0.85m is not subtle construction at all. However, the tunnel design took into account the final thickness of 60m overlay mined out rock at the crown of the tunnel arch. The load pertains to cover of 60m makes the lining relatively flexible. The objectives of observation measurements performed on covered Hvížďalka tunnel were to monitor deformations of massive tunnel lining during backfilling procedure and also to compare obtained results with design parameters.

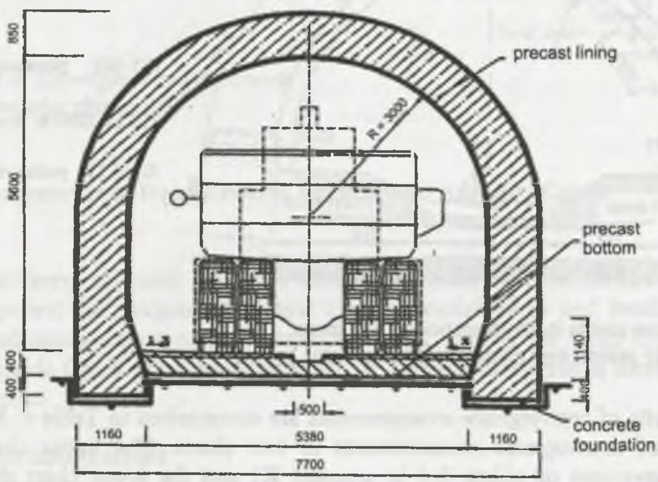


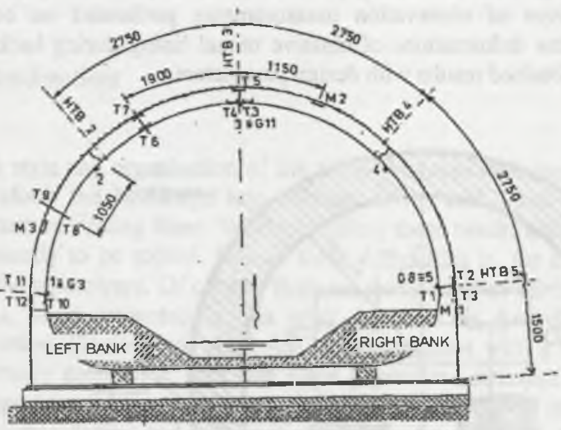
Fig. 1. Geometry of covered access tunnel Hvížďalka
Rys. 1. Geometria krytego tunelu dojazdowego Hvížďalka

Geodetical measurement determined relationship between deformation of subsoil, the construction and the lining itself. Convergence measurement determined absolute magnitude of conversion of distinctions of installed convergence points. These measurements were executed by using special adapted tapes and/or special laser rangefinders. The movement of the construction was carried out by means of five points based on the tunnel lining in six representative sections.

2.2. Field measurement of TOM2

Two reinforced precast concrete arch tunnels so-called TOM2 were built as a cut-and-cover structures on the road II/180 between the towns Zbůh and Nýřany, which belongs to the main project of the highway from Plzeň (Czech Republic) to Nürnberg (Germany). These structures TOM2 were first constructed examples of this type of cut-and-cover construction in the Czech Republic in 1996. Because of that one of these two constructions has been chosen for detailed investigation. The TOM 2 tunnel has a single tube profile with the cross-section at area of $38m^2$, 55m length and 4.6m thick overlay of soil at the crown of the arch. TOM 2 is an ASCC precast concrete structure, which is composed of arch-shaped segments in longitudinal direction. The individual arch-shaped segments consist of four reinforced precast elements with the wall thickness of 300mm in cross direction.

Strains, displacements of the arch and earth pressure around the construction in the various phases of backfilling were measured at certain characteristic points of the loading process. The placing of measuring sensors throughout the construction cross-section is shown Fig. 2.



Key to Fig. 2:

1-5: places for convergent measurement

T1-T5: places with string tensiometers on reinforcement

M1-M3: **pressure gauges**

HBT1-HBT5: hydraulic pressure cells

G1-G11: points of geodetical measurement

Fig. 2. Measure points in cross-section of a segment
Rys. 2. Punkty pomiarowe na przekroju segmentu

The results of convergence measurements are summarised in Table 1. Fig. 3 presents the evaluation of convergence measurements in two charts. The upper chart represents the absolute conversion of points 2-4 in segment Kl and the lower chart shows the absolute distance conversion of points 1-5 in segment Kl. The measurements of the distance conversion are carried out commensurate with the height of backfill. The horizontal axes represent the height of the backfill in metres and the vertical axes the distance conversion in millimetres.

Table 1
The distance conventions of points 1~5 and 2~4
in [mm]

collimation line	convergence measurement
1~5 = G3~G8	25,9 mm
2~4	18,65 mm

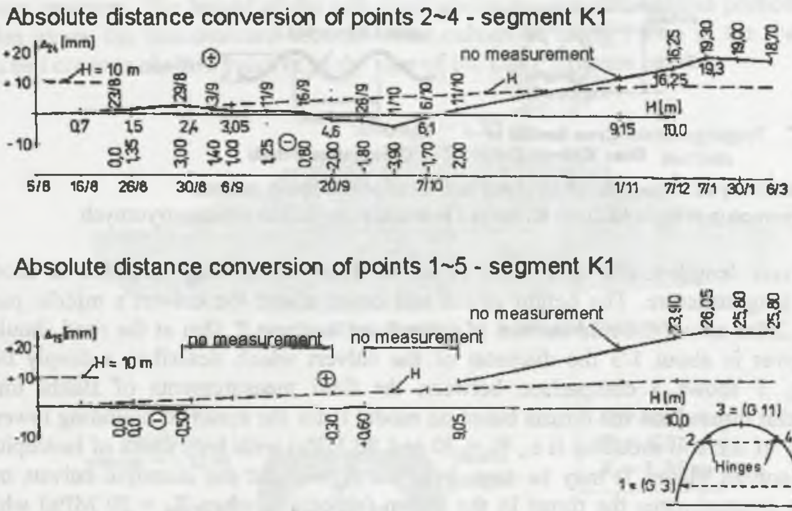


Fig. 3. Evaluation of convergence measurements
Rys. 3. Ocena pomiarów zbieżności

2.3. Field measurements of Deux Rivieres circular and Adelaide Creek

A group of different soil-steel structures were tested under the effect of heavy truck loads in 1981 and reported the predicted structural circumferential thrust and bending moments. Two of the tested constructions exist in Ontario, Canada; namely the Deux Rivieres circular culvert and Adelaide Creek elliptical culvert. In the following paragraphs these two culverts are briefly described.

Deux Rivieres circular culvert

The Deux Rivieres culvert selected for field testing is circular in cross-section and is constructed from corrugated steel plates with length of 31m and 7.7m in diameter. The corrugation was 250 x 50mm and the wall thickness t = 5.45mm. The mid cross-section of the tested culvert was instrumented by strain gauges to measure strains at different locations along the cross-section. Fig. 4 shows the geometry of the Deux Rivieres culvert and also the locations of the strain gauges on the instrumented section.

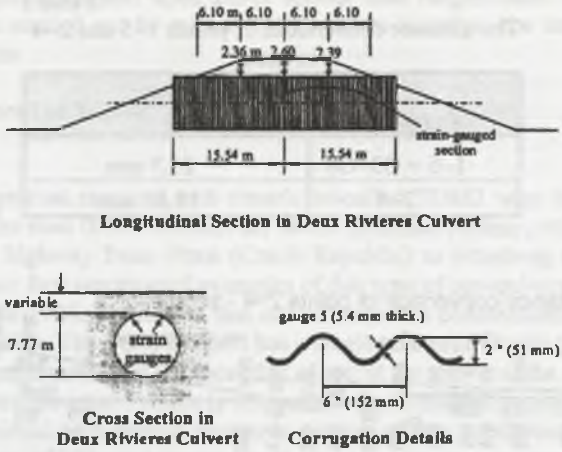


Fig. 4. Geometry of Deux Rivieres culvert and locations of strain gauges
Rys. 4. Geometria przepustu Deux Rivieres i położenie czujników tensometrycznych

The culvert length-to-diameter ratio is about four which may describe a short to moderately long structure. The height of the soil cover above the culvert's middle portion varies from 2.6m above the mid section of the culvert to about 2.38m at the road shoulders. This soil cover is about 1/3 the diameter of the culvert which describes a deeply buried culvert. Fig. 5 shows a comparison between the field measurements of Bakht for the circumferential thrusts and the thrusts based on model II for the assumed bounding lower and upper values of the soil modulus (i.e., E_s = 30 and 80 MPa) with both cases of isotropic and orthotropic culvert plates. It may be seen from the figure that the isotropic culvert model significantly overestimates the thrust in the crown (especially when E_s = 30 MPa) while it moderately overestimates the thrust at the culvert shoulders. On the other hand, and for both E_s = 30 and 80 MPa, the orthotropic culvert model slightly underestimates the thrust at the crown and slightly overestimates it at the shoulders (i.e., at location of maximum thrust).

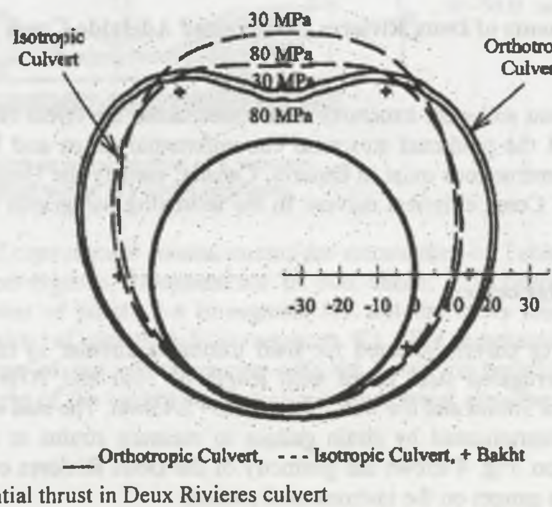


Fig. 5. Circumferential thrust in Deux Rivieres culvert
Rys. 5. Parcie obwodowe w przepuście Deux Rivieres

Adelaide Creek elliptical culvert

The cross-section of the Adelaide culvert is elliptical with dimensions of 7.24m wide and 4.08m high. The Adelaide culvert is 25m long and is composed of four circular corrugated steel segments with different radii of curvature. The corrugation was 250 x 50mm and the wall thickness t = 4.67mm. A cross-section, slightly offset of the middle, was instrumented and the strains were measured at different locations along the cross-section. Fig. 6 shows the geometry of the Adelaide culvert and the location of the instrumented section. To define the length-to-diameter ratio for the Adelaide culvert, the average of the top and bottom radii (5.49m) is used and the ratio is found to be 4.6, which describes a short to moderately long culvert structure. The height of the soil cover above the culvert's middle portion varies from 1.35m above the instrumented section of the culvert to about 1.09m at the road shoulders. This soil cover is shallow relative to the case of the Deux Rivieres culvert.

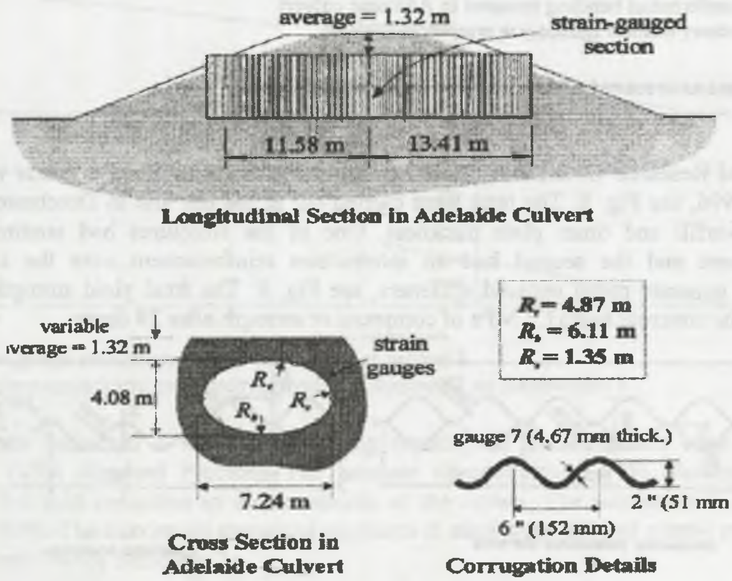


Fig. 6. Geometry of Adelaide culvert and locations of strain gauges
Rys. 6. Geometria przepustu Adelajda i położenie czujników tensometrycznych

Fig. 7 shows a comparison between Bakht's measurements of the circumferential bending moments and the ones based on the FE analysis. It may be seen from the figure that a reasonable match between Bakht's results and the FE results has been observed for the case of orthotropic culvert and Es = 30 MPa except at the crown and the right shoulder where huge differences are observed. This may be due to the sensitivity of the circumferential bending moments to the value of the soil modulus and the non-linear behaviour of the soil-culvert structure. Therefore, the accurate assessment of the circumferential bending moments in the culvert may need a more complex non-linear analysis.

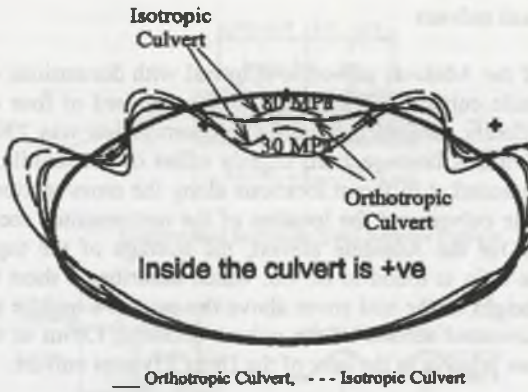


Fig. 7. Circumferential bending moment in Adelaine culvert
Rys. 7. Obwodowy moment zginający w przepuście Adelajda

2.4. Field measurement of Dorchester Box culvert

National Research Council of Canada sponsored tests on two box culverts with 12,09m spans in 1996, see Fig. 8. The tests were carried out at the test site in Dorchester N.B. with 300mm overfill and 6mm plate thickness. One of the structures had continuous crown reinforcement and the second had an intermittent reinforcement over the crown using composite concrete metal encased stiffeners, see Fig. 9. The steel yield strength was 348.5 MPa and the concrete had 31.7 MPa of compressive strength after 28 days.

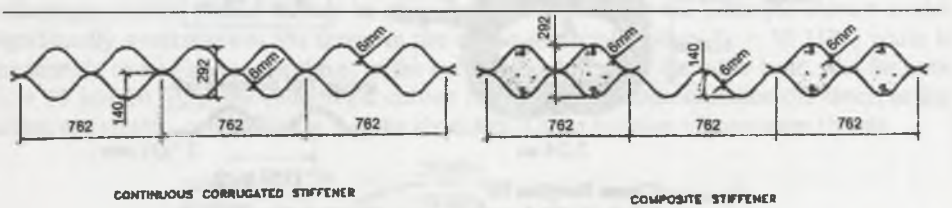


Fig. 8. Continuous corrugated stiffeners and composite stiffener (EC rib)
Rys. 8. Ciągłe faliste elementy usztywniające i złożony element usztywniający (żebro EC)

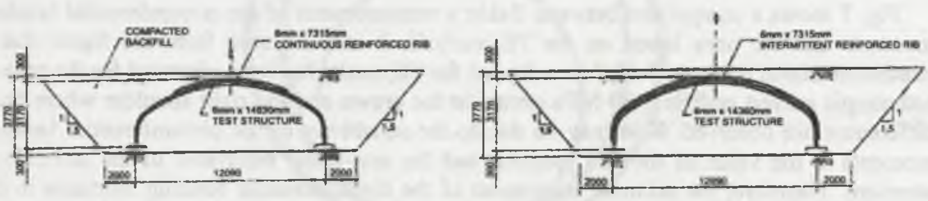


Fig. 9. Cross-section of testing structures
Rys. 9. Przekrój budowli testowych

The tests were performed for two densities of backfill 85% and 95% Standard Proctor. The backfill conformed to A-1 based on North American specs – it is sand and gravel mixture. The load truck corresponded to CL 625 kN truck with three axles and max axle load of 127.5 kN. Strains and deflections were measured to evaluate the response of the structures to static loads positioned at six locations on the test surface. The Structure 1 had 28 strain gauges in eleven stations and five displacements transducers. The testing Structure 2 had 36 strain gauges set in eleven stations and five displacement transducers. Fig. 10 shows the strain gauge measurements for Structure 2 at Station 6 for both 85% and 95% backfill conditions. As can be seen, the strain measurements are not located on one line; however, they indicate considerable coupling between the arch and stiffener. the graphs also show that the magnitude of slippage is higher for 85% compaction than for 95% compaction, as expected, since the moments are higher for 85% compaction case.

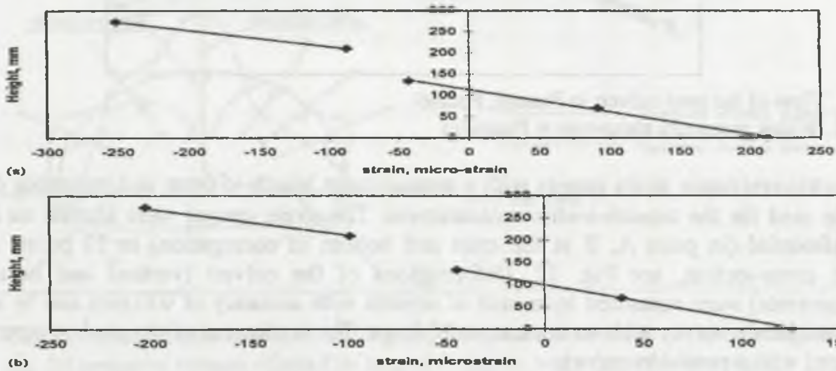


Fig. 10. Strain gauge measurements for Structure 2 at Station 6
Rys. 10. Pomiary czujnikami tensometrycznymi dla Budowli 2 na Stanowisku 6

The results indicated a very good bearing capacity of the structures even with low compaction (85% standard Proctor). The increase of compaction 95% Standard Proctor resulted in 3-4 fold reduction in displacements of the crown. The maximum moment was reduced by 50%. The maximum measured moments in steel were 17% of plastic moment for Structure 1 and 7% for Structure 2.

2.5. Field measurement of Poznan culvert

Field measurements on a steel culvert used for replacement of a severely corroded concrete railway bridge in Poznań (Poland) were carried out, see Fig. 11. The steel culvert is a pipe arch with a span of 8.9m, a height of 7.76m and a soil cover of 1.8m. The corrugated steel was 7mm thick and the corrugation was 150 x 50mm. The steel complies with the Swedish Standard SS-EN 10025 and is marked as Fe 3600 B FN. The culvert was backfilled with sand-gravel mix with uniformity of granulation U=5 (according to Polish Standard) not exceeding the grain size of 45mm. The compaction degree for the subsoil was around 98% Proctor Standard and was 98% Proctor Standard for 2m around the structure. In higher layers, 100% Proctor Standard was used. The top 100mm of the subsoil directly beneath the bottom plates was loose sand.

Fig. 11. View of the steel culvert in Poznań, Poland
Rys. 11. Widok przepustu stalowego w Poznaniu

Electric-resistance strain gauges with a measurement length of 6mm and resistance of 120 Ω were used for the tension-metric measurement. The strain gauges were located on inside circumferential (in pairs A, B at the crest and bottom of corrugation) in 10 points at the middle cross-section, see Fig. 12. Deformations of the culvert (vertical and horizontal displacements) were measured by means of sensors with accuracy of 0.01mm and by means of trigonometric survey with an accuracy of 0.1mm. The settlement of the steel structure was measured with a precision survey.

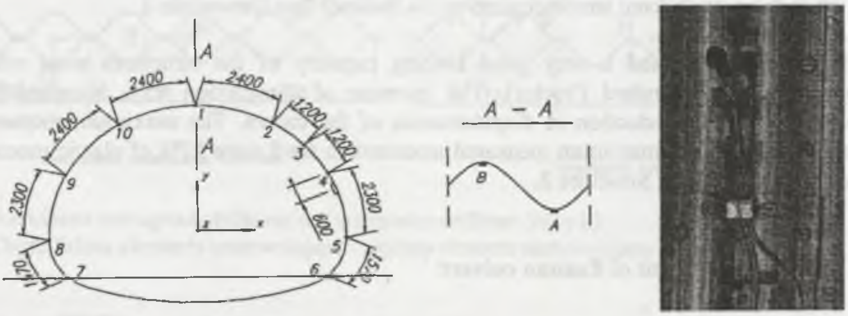


Fig. 12. Location of stain gauges on corrugated steel plates
Rys. 12. Położenie czujników tensometrycznych na falistych płytach stalowych

During backfilling, the deformation of the culvert and strains in steel plates were measured. All deformation data were stored on the deformation control sheet. Based on the measurements, the horizontal and vertical deformations were calculated. The maximum vertical deformation was 150mm upward and it declined to 120mm upward after total backfilling of the structure. The measurements of the strains of the steel plates indicated the increase of stresses during backfilling; however, the increase was not equal. It appeared that the highest stresses occurred at the crown of the structure and reached the value of 221.5 MPa (affected by bending moments). At the remaining points the stresses did not exceed 150 MPa. The stresses during backfilling procedure are presented in Fig. 13.

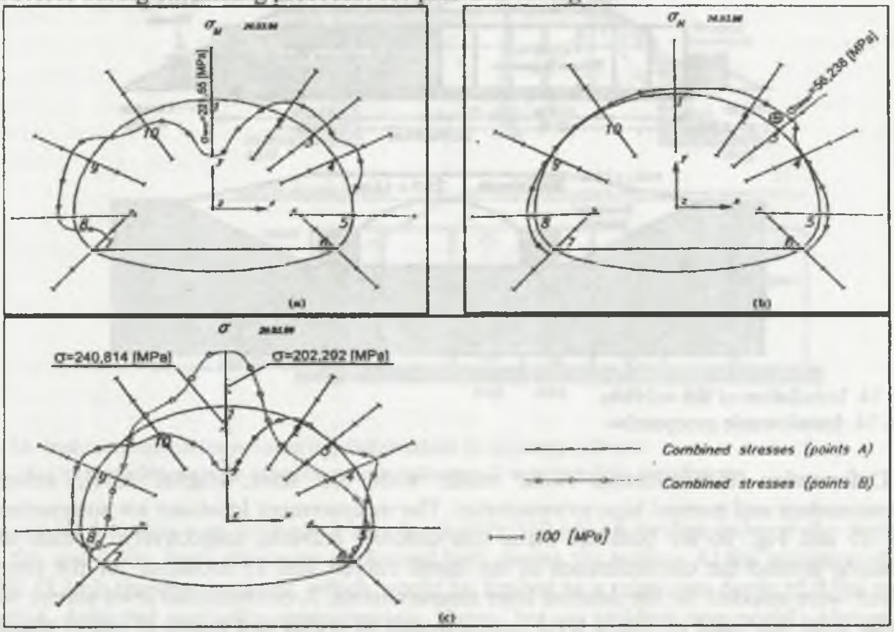


Fig. 13. Stresses in steel plates during backfilling: (a) measured stresses effected by bending moment σ_M, (b) measured stresses effected by normal forces σ_N, and (c) combined stresses

Rys. 13. Naprężenie w płytach stalowych w czasie zasypywania: (a) mierzone naprężenie pod wpływem momentu zginającego σ_M, (b) mierzone naprężenia pod wpływem sił normalnych σ_N, oraz (c) naprężenia łączone

2.6. Field measurement of the concrete and steel culverts, Massachusetts

Two full-scale field tests were conducted at the University of Massachusetts at Amherst (UMass) within the framework of the National Cooperative Highway Program to investigate the structural behaviour of large-span culverts under shallow fills. The test investigated the culvert response to forces resulting from erection, placement and compaction of backfill as well as from live load. During field measurements culvert behaviour, soil behaviour, culvert-soil interaction during backfilling and live loading were monitored. The culverts were installed end to end in a single trench, see Fig. 14. The span and rise of both test culverts were approximately 9.3 and 3.6m, respectively. The concrete culvert was precast and delivered to the site in 1.8m segments. The metal culvert was assembled on site from corrugated structural plates. Two sets of tests were carries out. The first installation used a well-graded, clean sand backfill compacted to 92% Proctor Standard. The second test used the same backfill but without compaction. In this second test, the material achieved about 85% Proctor Standard density.

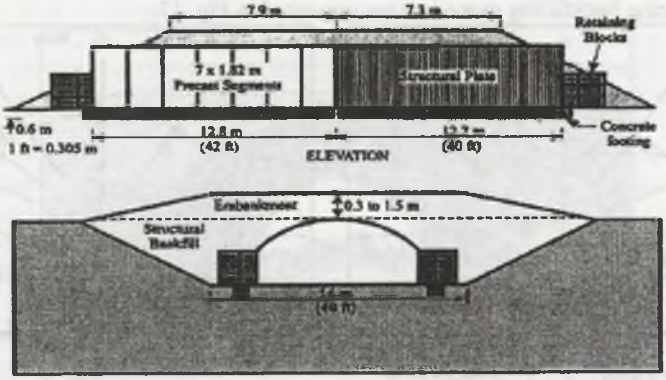


Fig. 14. Installation of the culverts
Rys. 14. Instalowanie przepustów

Deformation measurements were made with the laser, digital level, structural extensometers and manual tape extensometer. The measurement locations are summarised in Fig. 15 and Fig. 16 for both the metal and concrete culverts, respectively. A total of 26 locations around the circumference of the metal culvert and 23 locations for the concrete culvert were selected for the detailed laser measurements. A conventional level survey with a digital level was used to obtain level measurements of crown and points of radius change at two stations along the top of each culvert. Structural extensometers were used to measure relative horizontal movement between points of radius change at two stations along the length of each culvert.

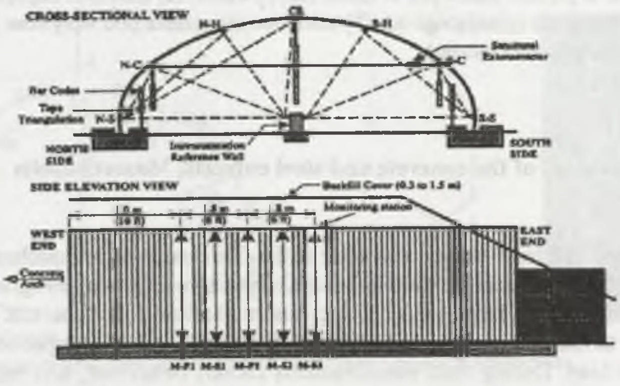


Fig. 15. Instrumentation for monitoring deformation in metal culvert
Rys. 15. Oprzyrządowanie do monitorowania deformacji w przepuście metalowym

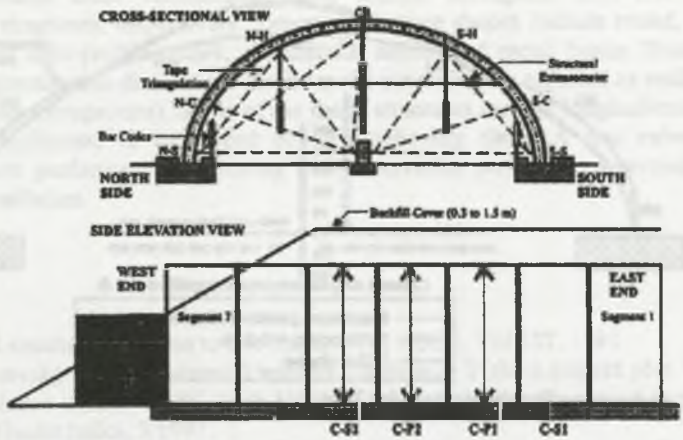


Fig. 16. Instrumentation for monitoring deformation in concrete culvert
Rys. 16. Oprzyrządowanie do monitorowania deformacji w przepuście metalowym

Live-load testing was conducted by a truck with 310 kN on tandem axles at the depth of 0.9, 0.6 and 0.3m. Both structures performed well during the testing. At the minimum depth of fill (0.3m), the metal culvert, which would be limited to a minimum depth of 0.9m under practice, deflected vertically approximately 50mm, but no yielding was noted. Also at the minimum depth of fill, the reinforced concrete arch culvert deflected about 1.5mm and cracks on the underside of the crown opened to a width of about 0.01mm, the service stress limit. Those cracks closed when the live load was removed. During backfilling, the crown of the concrete culvert moved upward about 1.5mm in both tests as the backfill was raised to the top of the structure and then return close to the original position after backfill was placed over the top of the culvert. In the case of metal culvert, the top moved upward about 72mm in Test 1 with compaction and 53mm in Test 2 without compaction. Deformed metal culvert shapes due to backfill operations are shown in Fig. 17 for both tests as measured with the laser device. This figure shows the maximum peaking of the structure at 0.3m of soil cover and the final shape after backfilling.

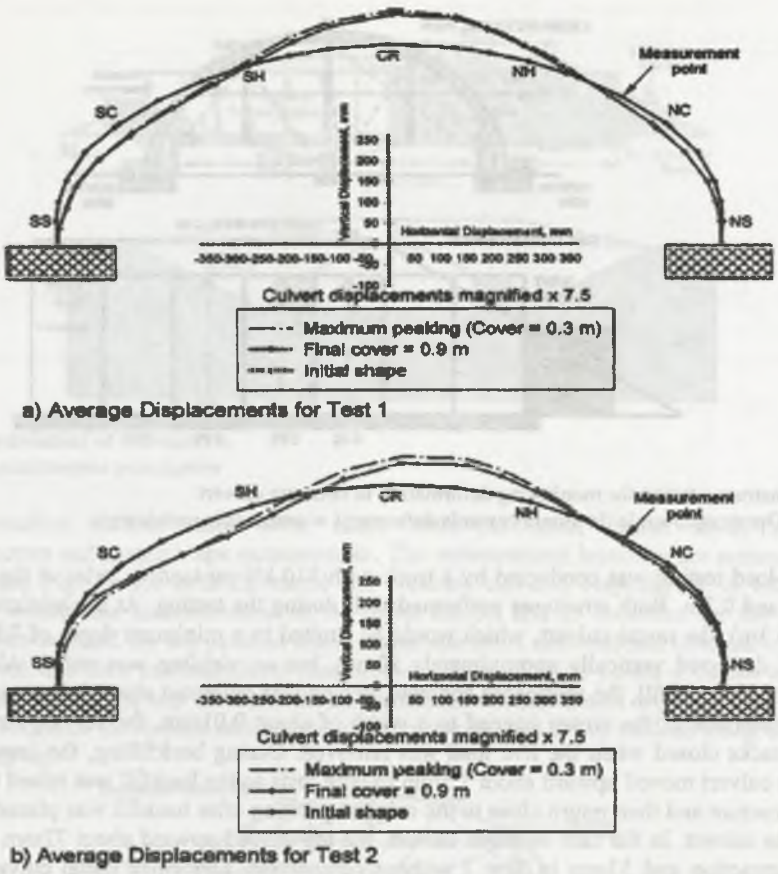


Fig. 17. Deformed metal culvert shapes after backfilling
Rys. 17. Zdeformowane kształty przepustu metalowego po zasypaniu

3. Conclusions

Documented installation cases for both corrugated metal and reinforced concrete long-span ASCC structures were identified and briefly described above. Most cases had construction deflection measurements as a minimum. Some cases included pipe wall strain measurements and soil stress, strain and deformation measurements. Laboratory test results on soil properties are also available for some cases. Soil tests conducted varied, including standard and/or modified Proctor, relative density, soil classification, CBR tests, one dimensional (1D) compression tests and triaxial compression tests. Many of the case studies served as research projects to advance the state of the art and have been evaluated by numerical models.

The instrumented cases summarised above include corrugated steel and reinforced concrete ASCC structures, respectively. Reported structure shapes include round, horizontal ellipses, low- and high-profile arches, semicircular arches and metal boxes. Standard plate thicknesses and corrugation dimensions for the metal structures are reported as well as special corrugations (deep corrugations). Some of the metal structures include longitudinal stiffeners, transverse ribs stiffeners, or reinforced concrete relieving slabs. A few culvert studies included long-term performance monitoring with observation periods from several month up to years after installation.

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