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INSTRUMENTATION AND MONITORING OF LARGE-SPAN CULVERT BUILT UNDER A RAILWAY IN FINLAND[1]

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Large span soil-steel culverts are rarely used in Finland as vehicular underpasses. The large span and low soil cover height together with high traffic loads place high demands on the construction of culvert backfills. Traffic-induced stress changes and the fatigue resistance of the plates play a major role in the endurance of a culvert. According to design calculations, the most critical section of the culvert is the crown. For this reason, the focus of this project is on the assessment of the structural behaviour and performance of the crown area under the influence of traffic load. The structural performance of the culvert was verified by monitoring stress changes and deformations under live railway traffic, which proved the suitability of the multi-plated culvert built under a railway.

Key words: Instrumentation, culvert, railway, live loads, monitoring

1. INTRODUCTION

In Finland, soil-steel composite bridges or culverts are typically used as pedestrian underpasses and as routes for water flow through embankments. The use of soil-steel composite bridges in larger scale as vehicular underpasses is rare so there is only slight experience of large culverts built under railway in Finland.

The aim of the project described in this paper is to gain knowledge of the technical performance of large span steel culverts built under a railway. The research is done by instrumenting the bridge under consideration and by measuring and analysing the actions of the bridge under live railway traffic. The main focus is on structural behaviour of the bridge. Particularly the traffic load effects and stress ranges and fatigue on culvert plates together with deformations due to traffic load are of particular interest.

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A full scale test was arranged to measure the traffic load effects and stress ranges on culvert plates, in Hanko-Karjaa rail section on which the large span culvert was built. A more detailed article about monitoring and analysis of the results is published in the Structural Engineering International Journal [2].

2. DESCRIPTION OF THE BRIDGE AND INSTRUMENTATION

General

The instrumented culvert is located on mixed traffic track section between Hanko and Karjaa. The allowed maximum axle weight on the track is 25 tonnes. The current traffic volume of the section is 2.3 million gross tonnes/year.

The bridge is drop-shaped pipe arch whose theoretical internal height is 6 865 mm and maximum span length 7 755 mm. The plate cross section is type MP200x55 (A2) with plate thickness 7.0 mm presented in Fig 2.

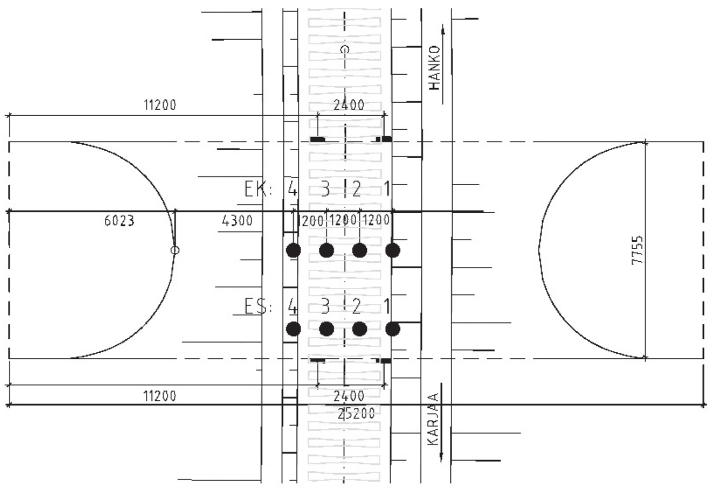

Fig. 1a). A plane view and cross section of culvert and location of monitoring points

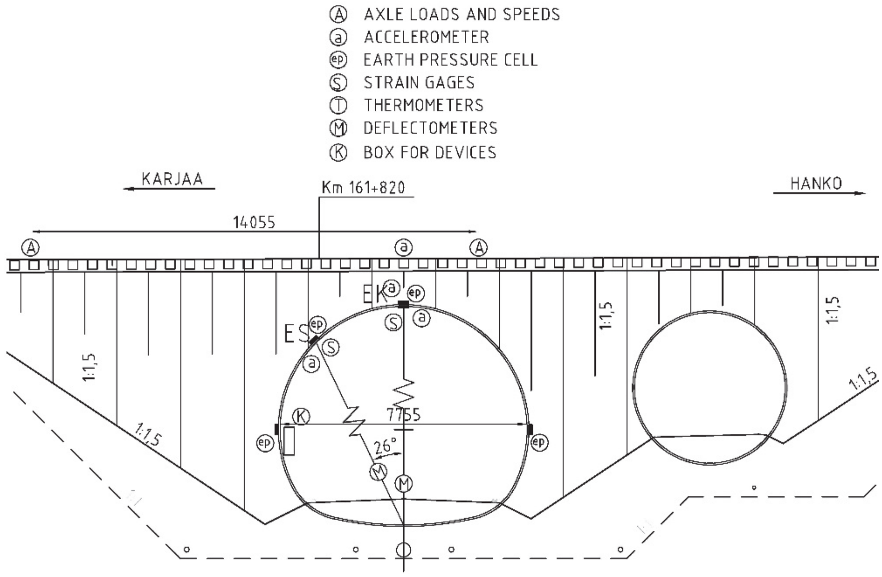

Fig. 1b). Side view of bridge location and monitoring points [2]

The soil used in bridge backfill is aggregate with particle size 0-63 mm and 21 kN/m^3 dry density. The degree of compaction is 95% modified proctor. The thickness of fill on the crown of the bridge is 1 400 mm, measured from outer surface of top plate to the bottom of the lower rail foot. The value of 1 400 mm is also the allowed minimum for soil cover on a steel culvert built under the railway [1].

Instrumentation

To assess the structural behaviour of culvert plates the instrumentation devices were assembled at four points directly on top of the arch, see Fig 1. Another four points are located on the culvert shoulder. The two middle points are located 600 mm from the track centreline. The distance between the points is 1 200 mm. Each of the instrumented points consists of strain gauges attached on the surface with the glue specified for this purpose, displacement gauge and accelerometer, all installed on the inner surface of the culvert plate. Earth pressures were monitored with earth pressure cells installed at each monitoring point on the outer surface of the plate.

The strain gauges are installed on the sides of rail web to measure the static axle loads. The axle load was determined based on the shear force occurring at the rail web calibrated by static weight of known axles crossing the bridge, e.g. those of a locomotive. This method is accurate enough to determine the order of axle loads and to distinguish between loaded and unloaded freight trains.

The rate of data recording was 1 sample/minute during construction and 2 000 samples/second or (Hz) during monitoring subject to the influence of railway traffic. Monitoring was carried out at three different periods. The first period started when the construction was completed and the track opened to railway traffic on May 2013. The other two periods were in February 2014 and May 2014.

3. INSTRUMENTATION DEVICES

Strain gauges

Strain gauges (two pcs) are installed on each ridge and valley of the plate cross section on the inner surface of the culvert, at the monitoring point. The type of the strain gauge is 90° bi-axial rosette with which strains are recorded in two perpendicular directions, circumferential and longitudinal. The stresses were calculated according to equation 1. A plane stress state is assumed on the section surfaces. Also the direction of strain gauge is assumed to be the same as the principal stress direction.

According to Hooke's law, the relation between stress and strain in plane stress state is:

$$\varepsilon_x = \frac{1}{E}(\sigma_x - \nu\sigma_y) \qquad (1)$$

The equation above is applied to calculate the stress ranges on each direction from the corresponding monitored strains. In equation 1 the directions *x* and *y* refer to perpendicular directions in surface plane of the culvert plate monitoring point. E and ν are Young's modulus (210 GPa) and Poisson's ratio (0.3) for steel.

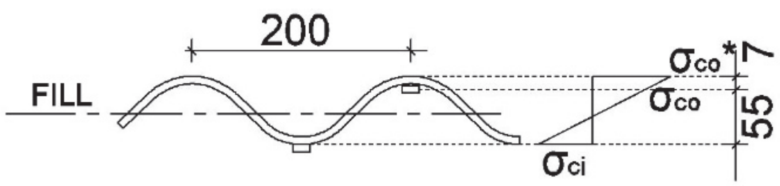

Fig. 2. Cross section of the culvert plate and stress distribution and locations of strain gauges. [2]

For accessibility and durability reasons, all of the strain gauges were installed on the inner surface of the culvert. Therefore, the circumferential stress σ_{co}* on the outer surface needs to be extrapolated according to figure 2 and equation 2.

$$\sigma_{co}* = \frac{62}{55} \cdot (\sigma_{co} - \sigma_{ci}) + \sigma_{ci} \qquad (2)$$

Displacement monitoring

Displacement gauges were installed inside the culvert on the floor. The measurements of displacement were carried out with steel wire fixed at monitoring point at the upper end and on the springs connected on the floor at the lower end. The change of deflection of the spring at the lower end of the steel wire was measured.

4. MONITORING RESULTS AND ANALYSIS

Field measurements were performed under the influence of live railway traffic. The traffic during the monitoring periods consisted of freight trains and commuter trains. Only the effects of freight trains were considered because commuter trains have only a minor effect on the bridge plates.

The zero level was set to correspond to an unloaded bridge, since traffic-induced effects were under consideration.

Deformations due to traffic load

The order of maximum deformation during monitoring was about 1 mm when the heaviest allowed axles on the track section (observed) crossed the influence length. The difference between monitoring points at the top centreline of the culvert can be noticed. The deformations of the outermost plates on top, EK1 and EK4, are about 60-70 % in comparison to deformations of plates EK2 and EK3, which are located directly below the track.

Traffic induced stress ranges

Plate stresses change as train axles are passing across the bridge. When the bogie arrives at the influence length, a compressive normal force together with the bending moment arises in plates. The positive bending moment reaches its maximum when the axle is located directly on top of the culvert.

In this culvert a one-third of the traffic induced stress range, occurring at the crown, is due to the bending moment and two-thirds are due to the normal compressive force. This means that the stress effect of the observed bending moment is minor in comparison to the normal force and the sum of stress ranges due to these two effects are mainly negative.

The basic pattern of the shape of the traffic induced stress at the monitoring point in the top plate is presented in Fig 3. The shape of the stress pattern depends on the axle and bogie geometry, the axle loads and the distance between adjacent axles and bogies. The distance between bogies is longer in Fig 3b in comparison to the case presented in Fig. 3a. The positive bending moment arises when the axle is located directly above the culvert centreline. When the bogies are located on both sides of the culvert the bending moment is negative. The dominating effect of the normal force causes the smoothness of curve σ_{CO}* which also falls deeper in the compressive direction in Fig. 3

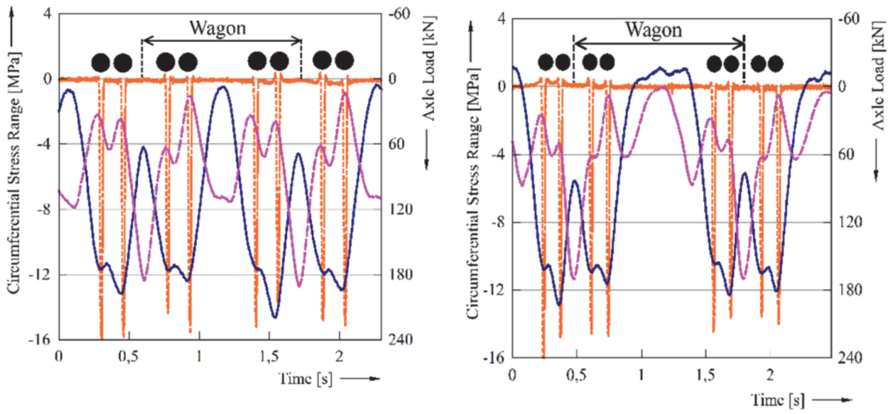

Fig. 3. Typical stress range patterns on the top plate as a group of bogies crosses the bridge. a) Bogie pairs closer together and b) Bogie pairs further apart. [2]

Fatigue

The recorded stress histories of freight trains were analysed with rainflow algorithm. Only loaded freight trains were taken into account and the number and total gross tonnes of the observed loaded trains are presented in Table 1.

Table 1. The number of observed freight trains during different monitoring periods

Monitoring period	Number of observed freight trains	Total gross tonnes of observed freight trains [t]	Average total number of stress ranges / top plate ($\Delta\sigma > 3$ MPa)
I	33	48 600	9347 (922)
II	8	9 500	1393 (3)
III	20	28 300	3458 (646)

The frequency histograms of stress ranges at the monitoring points are compiled by dividing stress ranges in 2 MPa wide bins. For example, the '4 MPa' bin contains stress ranges from 3 MPa to 5 MPa. The smallest stress ranges $\Delta\sigma < 3$ MPa are neglected to make the diagrams easier to analyze. The total number of recorded stress ranges varied between 3 000 and 14 000 depending on the plate. The majority of stress ranges fall in bin of 2 MPa and are thus neglected. The percentages of bins presented in charts in Fig. 4 are calculated by neglecting the bin of 2 MPa.

The monitoring period II took place in wintertime which means that the backfill around the culvert was frozen. In monitoring period II the sample of 8 trains contained only 10 stress ranges falling into the lowest bin "4 MPa"

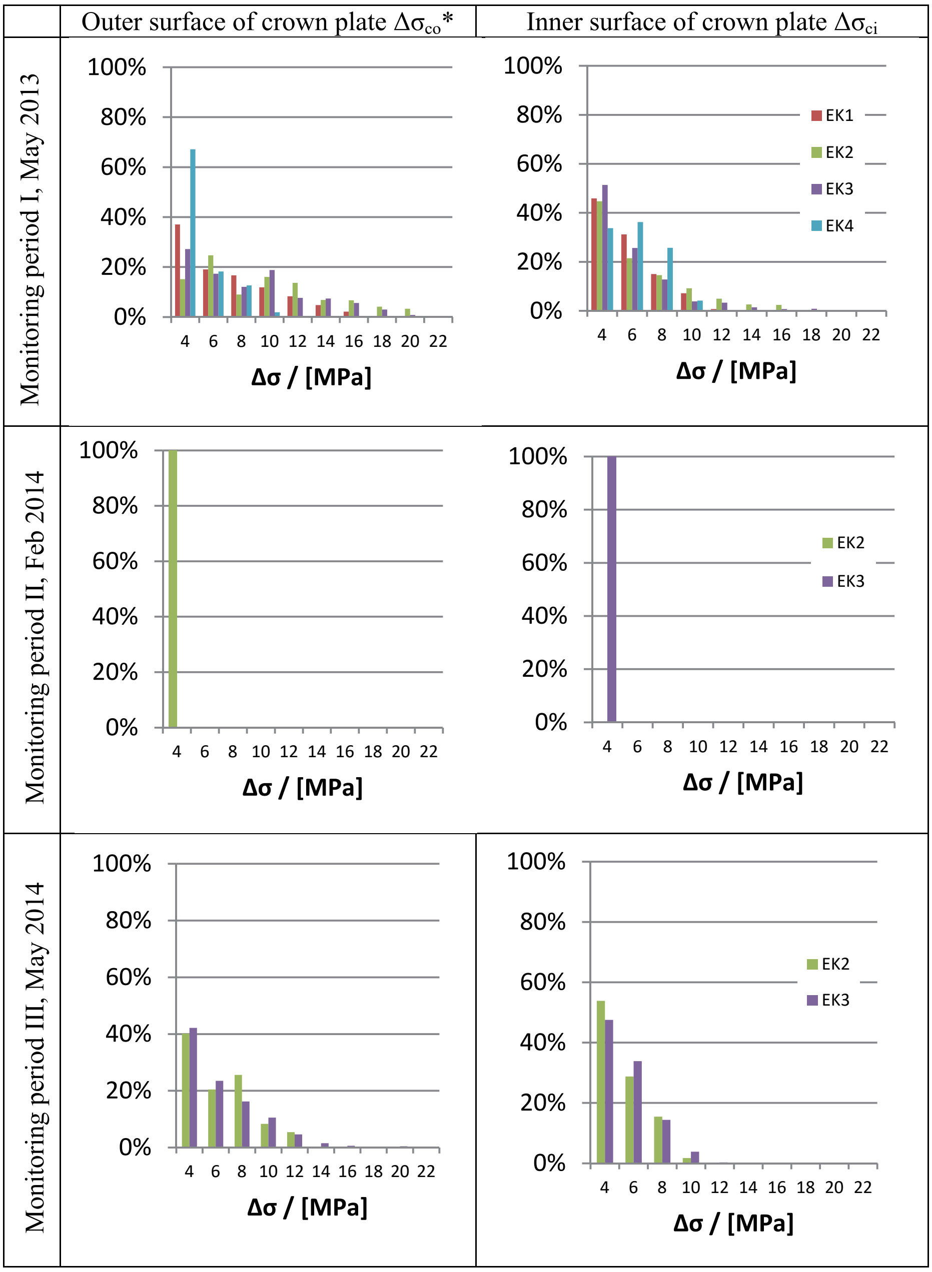

Fig. 4. The proportions of circumferential stress ranges on surfaces of crown plates observed during monitoring periods

The magnitude of longitudinal stress ranges was minor.The maximum observed longitudinal stress range on centermost plates EK2 and EK3 was about 6 MPa while maximum circumferential stress of 14 MPa was observed.

According to EN-1993-1-9, Table 8.1, the fatigue class of corrugated plate with one-sided connection with pre-loaded high-strength bolts is 90 MPa. The design calculations for fatigue of the plates are performed according to this class.

The observed stress ranges were small in samples in all the monitoring periods and exceedance of cut-off limit $\Delta\sigma_L$ (=36.4 MPa) was not observed. The stress ranges below $\Delta\sigma_L$ do not contribute to the cumulative damage. In wintertime with backfill frozen, the stresses caused by railway traffic are minor.

5. CONCLUSIONS

During the monitoring periods, the observed traffic-induced stress ranges were considerably lower than expected according to design calculations. The exceedance of cut-off limit was not observed during the monitoring periods, which means that the cumulative damage due to fatigue is not present in the current structure.

The frozen backfill causes the backfill around the culvert bond with culvert plates and acts as a load bearing arc, which leads to the change in the behaviour of culvert plates. Only minor tensile stresses arise in culvert plates due to traffic load when the backfill is frozen.

The observed low stress ranges together with the low values of vertical deformation during the monitoring periods indicate good structural performance of the culvert. FE-modelling conducted in project [2] showed that the change in the structural behaviour of the culvert as the backfill stiffness varies. The increase of vertical deformation and bending moment is observed by means of FE-model with lower backfill stiffness moduli.

Acknowledgements

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The contribution of the research project is first published in the Structural Engineering International Journal, see ref. [2]

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