Continuous monitoring of the High Coast Suspension Bridge
Measurement period: February to December 2010

IGNACIO GONZALEZ      RAID KAROUMI
Continuous monitoring of the High Coast Suspension Bridge

Measurement period: February to December 2010

**Commissioning body:** Staffan Gilliusson
Trafikverket (the Swedish Transport Administration)

**Monitoring project leader:** Raid Karoumi (KTH)

**Report written by:** Ignacio Gonzalez (KTH)

**Report reviewed by:** Raid Karoumi (KTH)

**Installation and maintenance of monitoring system:** Stefan Trillkott and Claes Kullberg (KTH)
1 The Bridge

The High Coast Bridge is a suspension bridge with a main span of 1210 m, a total length of 1867 m and a pylon height of 180 m (see figure 1). The bridge is only 70 meters shorter than the Golden Gate Bridge in San Francisco. The High Coast Bridge carries the main route E4 over the Ångerman River about 500 km north of Stockholm. The bridge is a vital link to northern Sweden. It was constructed between 1993 and 1997 and was officially opened on December 1st, 1997. The stiffening girder is a multiple-cell steel box-girder and is continuously suspended without any direct vertical supports at the pylons. The girder rests on sliding bearing at both ends, with a sliding surface of PTFE/Teflon. To decrease the horizontal movement due to vehicles breaking or accelerating on the bridge, each end of the girder is connected to the abutment via 2 viscous dampers.

2 Background and Aim

Inspections have shown that the main bridge bearings have been seriously affected by wear. The Teflon sheet of the bearings has been to a great extent peeled off in flakes (see figure 6). It was suspected that the actual vertical loads acting on the bearings are much larger than those theoretically calculated. As this was believed to be the cause to the problem, a monitoring program was initiated in 2005 by the former Swedish road administration (Vägverket), now Swedish Transport Administration (Trafikverket). The main aim of the program was to measure the loads in the first hangers as well as to monitor the vertical loads acting on the bearings.

3 The Instrumentation and Calibration

To monitor the vertical loads from traffic and permanent loads, the stiffening cross beam at the northern end was instrumented in 2005 with strain transducers and was calibrated. Thus, the cross beam was simply converted into two load cells; one over each bearing. At each bearing, eight strain gauges were welded on the stiffening steel plates of the cross beam giving one Wheatstone bridge. The strain gauges (type HBM 1-LS31-6/350) were connected to an amplifier (type HBM-MC3) and then to a data acquisition system (type HBM Spider-8). The data acquisition equipment can be seen in figure 2.

In order to calibrate the strain-transducers the bridge deck was lifted at the northern end until it separated from the bearings. For this, six hydraulic jacks were used. The pressure exerted by them was recorded so that the actual dead load affecting the bearing could be measured. Thus the output of the strain-transducer becomes known at 2 different load conditions (zero load and dead load). This together with the assumption of a linear behavior allows for a direct translation of the measured signal (in Amperes) to load (in Newtons). Five lifting were carried out, to obtain a more accurate estimation of the actual dead load. The cross beam is very stiff and it was therefore important to perform the lifting evenly at both bearings. To control the lifting process, one displacement transducer (type LVDT WA10 from HBM) was temporarily mounted at each bearing to measure changes in the distance between the bearing and the bottom of the cross beam. In
Karoumi et al. (2006), the instrumentation and calibration are more deeply described and monitoring results from October 2005 until May 2006 are presented.

Since 2010, the monitoring project was expanded to also include:
- a camera for traffic monitoring (see figure 3)
- two accelerometers (see figure 4) installed on the two first hangers close to the instrumented bearing (the two rightmost hangers in figure 1)
- a displacement sensor to monitor the longitudinal movement of the girder (see figure 5)
- a thermocouple registering the temperature at the soffit of the girder.

The calibration from 2005 resulted in the estimated bearing forces, due to the dead load, of 2.3 MN in the western bearing and 2.1 MN in the eastern bearing (both at the northern abutment).

Since that first calibration, the Teflon layer of the bearing had to be replaced due to the wear sustained. The new Teflon layer was somewhat thicker than the original. This moved the girder slightly up a bit, causing an increase in the forces acting on the bearings while reducing the load in the hangers close to the abutment.

After the replacement of the Teflon layer and the installation of the additional sensors in 2010, a second calibration involving live load (one moving truck) was carried out. Here, a 3-axle truck (see figure 7) of known weight 25.7 tons was driven over the bridge lanes at different speeds to be able to estimate the effects of the speed and to study whether the calibration factors found from the 2005 test could still be valid. It was found that the calibration factors from the 2010 test differed significantly (approx 17%) from those of the initial 2005 test. Throughout this report the calibration results from 2005 are used.

Figures 8 and 9 show the force acting on the west and east bearings respectively as the calibration truck was driven at different speeds and on different lanes. It can be observed that little dynamic effect was found, since the force registered remained the same for different speeds. The normal traffic was not closed during the calibration procedure, so some loads other than the calibration truck can also be seen in the signals.

### 4 Data acquisition

The signals from all the sensors, except the camera, are sampled at 100 Hz and saved in files composed of 30 minutes of measurements. Using a special software (a Matlab based code) developed by the first author, The collected 30 minute files are preliminary analyzed in the personal computer deployed in the bridge (see figure 2). To keep track of the long term variation as well as the overall statistics of the different physical quantities measured, the maximum, minimum and average of each channel are also stored in a special file for every 30 minute period. If there are interesting features in a particular 30 minute file (e.g. high load or large horizontal displacement, exceeding a triggering value) the file is stored permanently, otherwise only the maximum, minimum and average for each channel are stored. Only pictures corresponding to the instants of high loading are stored permanently.
Figure 1: View of the northern end of the bridge.

Figure 2: The data acquisition system.

Figure 3: Traffic Camera from Axis (www.axis.com).

Figure 4: Accelerometer mounted on a hanger. (Si-Flex accelerometer developed by Colibrys http://www.colibrys.com/e/page/184/).
Figure 5: Extensometer connecting the girder to the abutment.

Figure 6: Teflon flakes observed on the sliding bearings.

Figure 7: Truck utilized for the live load calibration in 2010.
Figure 8: Results from 2010 calibration tests with the truck shown in figure 7. South-going calibration loading of the west bearing. As can be observed, the normal traffic was not stopped during the measurements, so vehicles other than the test truck appear in the signal (second red peak at 110 seconds). One of the test loading had to be discarded because other simultaneous truck loads rendered it impossible to interpret.

Figure 9: Results from 2010 calibration tests with the truck shown in figure 7. South-going calibration loading of the east bearing. As expected only the loading in Lane 2 (closest to the center) had an observable effect on the east bearing. The rest of the peaks are due to vehicles other than the test truck.
5 Longitudinal Displacement Monitoring

The Teflon layer in the bearings at the abutment have sustained a large amount of damage in the form of peeling (see figure 6). Large flakes have been observed to come off the Teflon layer. This was an unexpected kind of damage so additional sensors were installed in 2010 to monitor the longitudinal dynamic displacements of the bridge girder. The initial suspicion was that the peeling of the Teflon was caused by large and very sudden (dynamic) longitudinal displacements due to the live load. Thus the monitoring system was configured to save all the registered dynamic readings only in the case of a live load in excess of 78 tons, to study the effects these loads had on the longitudinal displacement of the girder. Also the maximum and minimum values registered by each sensor every 30 minutes were stored, independently of the level of loading. From the 30-min max and min values the daily cycle of thermal expansion and contraction can be clearly seen. For the first month (from the 17th of March to the 21st of April 2010) of monitoring the traffic, the highest load was registered to 1500 kN, or 153 ton, caused by a convoy of heavy loaded trucks as captured by the traffic camera. The maximum girder displacement associated with this load was found to be 9 mm (figures 10 and 11).

However, in 5 occasions during the first monitoring period the max-to-min variation in the bearing displacement (taken at intervals of 30 min) exceeded 40 mm (figures 12 and 13). None of these events could be associated with an even moderately high load. What is more; all the events were registered between, 09:30 and 11:30. This suggested that this large variation could be due to thermal expansion of the bridge caused by the sun directly shining on the structure. Given the regular time-pattern at which these events occurred it was considered unlikely that they could be caused by breaking forces.

Further, in all 5 occasions, these large displacements only showed in one of the 30-minutes measurements, and always as the bridge was in thermal expansion and crossing the level of about 810 mm, as can be seen in figure 12. This could indicate a malfunctioning of the sensor at that level.

Initially the monitoring system only saved the complete dynamic readings in the case of a very high live load. Thus, the signals corresponding to these unusually large longitudinal displacements were not stored. Only the information regarding the maximum and minimum of the 30 minutes measurement in which they were registered remained available.

The monitoring system was duly modified in order to save, not only the 30-minutes measurements involving high live loads but also those files that registered large longitudinal displacements. This allowed for these signals to be studied more in detail.

During the second period of monitoring the actual time-signal, sampled with 100 Hz, were saved when either the load or the horizontal displacement exceeded given triggering value. By closer study of the large displacement registered it could be observed that the variation was very sudden, starting at normal displacement levels to increase rapidly and the go back to the normal levels often within a fraction of a second. Figure 18 shows on the most dramatic cases where the measured displacement fluctuates several times, with maximum amplitude of over 400 mm. An event of such magnitude would be registered in the accelerometers, which did not occur. This indicates that it is due to some problem with disturbance in the signal/sensor.
Smaller, very quick perturbations occurring in fractions of a second also appeared with relative frequency, sometimes even several times in a 30-minute measurement. Their amplitude varied from less than a millimeter continuously up to the aforementioned 400 millimeters. It was unclear if this lesser perturbations were, as the larger ones, just an artifact or if they corresponded to a physical rapid displacement of the bridge. In figure 13 two instances of these peaks in the displacement signal are shown. Their shape and duration is similar, but their amplitude differs greatly.

Figure 10: Sequence of pictures taken from the monitoring camera. The convoy caused the largest force at the north-west bearing during the first period of monitoring.

Figure 11: Reaction force (blue, left Y-axis) and longitudinal displacement (green, right Y-axis) for the 30-minutes measurement registering the highest live load measured during the first period of monitoring (the convoy is shown in figure 10).
Figure 12: Max (red) and Min (blue) values of the longitudinal girder displacement taken every 30 minutes and its difference (green, in a different Y-axis). The top five values of the difference are encircled and with the date and time of their occurrence marked.

Figure 13: Two different peaks in the longitudinal displacement registered in different 30-minutes measurements. Both are very similar in shape and duration, but their amplitude varies.
6 Traffic Monitoring

The High Coast Bridge is a 4 lane bridge. For the dynamic calibration described in section 3 it could be observed that the truck load on the north going lanes (at the east side) had little or no effect on the load acting on the west bearing and vice-versa. Nonetheless truck load on the central, south-going lane have a large effect on the bearing force, about 70% of the effect the loads in the outer, south-going lane have. Thus even if a high load is registered it can be very difficult to decide from the registered signal if it was due to one single, overloaded truck or to 2 or more trucks crossing at the same time side by side.

Another conclusion drawn from the controlled speed dynamic calibration was that the influence line of the bearing force is unexpectedly long. The load coming from the traffic should, theoretically, be carried exclusively by the cable system and not affect the bearing force as soon as the truck is some few meter in the side-span. But the truck load in the calibration still affected the bearing force 20 seconds after it had entered the bridge at 70 km/h meaning that the influence line is non-zero for at least the first 380 m. Thus even if a convoy of trucks is spaced, the effects on the bearing force of different trucks are difficult to separate.

Overloaded trucks were suspected to pass the High Coast Bridge, but in order to be absolutely certain, a camera\(^1\) monitoring the traffic was installed (see figure 3). By studying the signal recorded and the images from the monitoring camera the events of a load higher than the triggering value can be classified into three different causes: (1) Multiple vehicles that together exceed the triggering value, (2) Single vehicle with a static load below the triggering value, but exceed the triggering value due to dynamic effects (see figure 16) and (3) single vehicle with static load exceeding the triggering value (see figure 17). With the aid of the camera some of the load registered that exceeded the triggering value could be associated with single overloaded trucks, as shown in figure 14 and 15. As seen, even if the most obvious dynamic effects are removed the remaining load still exceeds 80 ton. It is very unlikely that the truck could be carrying 80 tons of timber. A far more reasonable explanation is that some dynamic effects that are harder to separate are present in the signal. In any case, we can conclude that very large live loads (static a dynamic) exist and are affecting the bearings.

\(^1\) Camera from Axis, [www.axis.com](http://www.axis.com)
Figure 14: Timber truck whose static weight was found to exceed the allowed 60 tons. The signal of the strain transducers is reproduced in figure 15.

Figure 15: Measured force at the bearing for a single timber loaded truck exceeding considerably the maximum allowed gross weight. Even if the largest peak could be regarded as dynamic effect the maximum static loading still is 30% above the limit.
During the monitoring period two special transports were registered, the 19th and 20th of May 2010. Both were registered by the monitoring system and their weight was found to be approximately 94 ton, identically for both, far beyond the allowed 60 ton limit (see figure 17). Special transports like this constitute excellent material for validating the monitoring system’s triggering value.

In the following, the worst loading cases registered during the monitoring period from February 2010 to December 2010 are presented. The results are also summarized in Figure 17: Special transport registered on the 19th of May, weighting in excess of 80 ton. The safeguard car can be seen behind the truck. A similar transport was also registered the day after.

During the monitoring period two special transports were registered, the 19th and 20th of May 2010. Both were registered by the monitoring system and their weight was found to be approximately 94 ton, identically for both, far beyond the allowed 60 ton limit (see figure 17). Special transports like this constitute excellent material for validating the monitoring system and can be used for testing the reliability of the discrimination criteria implemented in the monitoring system.

In the following, the worst loading cases registered during the monitoring period from February 2010 to December 2010 are presented. The results are also summarized in

Figure 16: Measured force at bearing for a typical truck which static load does not exceed 60 ton (red), but the contribution of dynamic due to impact forces surpasses the monitoring system’s triggering value (green).
tables 1 and 2, and shown in figure 18 and 19. These figures show the max/min of every 30-minutes file.

In figures 20 to 23 the 30 min measurement files that showed the largest horizontal displacement are plotted. It was observed that the sudden and large displacements were always produced when a relatively heavy truck was at more or less the center of the bridge. Trucks going in the north and south direction produced this effect. No perturbations where observed in the accelerometers placed at the cables or in the forces at the bearings. It was considered unlikely that the bridge could displace a distances of about 1 meter in a matter of seconds, without any effects in the accelerometers or strain transducers. Therefore this type of peaks in the horizontal displacement was considered as an abnormality/disturbance in the sensor. Figures 24 and 25 show close-ups of the two largest displacement peaks. From them it can be seen that they in fact do not correspond to any real displacement in the structure. For comparison purposes the 30-minutes displacement measurements in the absence of such peaks are also presented in figures 26 and 27. From them it can be observed that thermal stresses build up while the temperature changes rapidly and the sliding bearing is locked by friction. When a truck crosses the bridge the friction is overcome and the displacement jumps into a next level, giving the displacement curve a staircase appearance, with jumps in the displacement up to 5 mm. This phenomenon could contribute to the wear observed in the bearings.

Figure 28 to 31 shows the four largest bearing forces registered during the monitoring period. They were also considered to be peaks caused by possible electrical disturbances (in the case of the two largest) or dynamic impacts.

Figures 32 to 35 show the four largest bearing forces when such peaks were absent, indicating the 4 largest static loadings. In all cases they are clearly caused by multiple heavy vehicles crossing the bridge in rapid succession a few seconds from each other.

Figures 36 to 43 show the 30-minute signals which include the four largest registered bearing forces. At first, these were believed to be caused by single loading events. But thanks to the installed camera and to the ability of the monitoring system to save the pictures taken during moments of high loading, it can be observed that only one of them truly correspond to a single vehicle. In this case it’s a special transport weighting in excess of 110 ton.

<table>
<thead>
<tr>
<th>Time and date</th>
<th>Figures</th>
<th>Maximum displacement [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>18-Sep-2010 07:02</td>
<td>Figure 20</td>
<td>1465</td>
</tr>
<tr>
<td>17-Jun-2010 15:25</td>
<td>Figure 21</td>
<td>465</td>
</tr>
<tr>
<td>10-Jun-2010 13:45</td>
<td>Figures 22 and 24</td>
<td>438</td>
</tr>
<tr>
<td>12-Aug-2010 08:48</td>
<td>Figures 23 and 25</td>
<td>425</td>
</tr>
</tbody>
</table>

Table 1: Maximum registered longitudinal girder displacements (all are considered to be caused by disturbance in the signal/sensor).
<table>
<thead>
<tr>
<th>Time and date</th>
<th>Figures</th>
<th>Maximum load [ton]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total Maximum (static + dynamic)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25-Jun-2010 18:51</td>
<td>Figure 28</td>
<td>1306 (due to electrical disturbance!)</td>
</tr>
<tr>
<td>06-Jun-2010 21:56</td>
<td>Figure 29</td>
<td>784 (due to electrical disturbance!)</td>
</tr>
<tr>
<td>11-Oct-2010 14:53</td>
<td>Figure 30</td>
<td>194</td>
</tr>
<tr>
<td>21-Oct-2010 09:58</td>
<td>Figure 31</td>
<td>172</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Maximum static (multiple vehicle and single vehicle events)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>31-Mar-2010 16:01</td>
<td>Figure 32</td>
<td>149</td>
</tr>
<tr>
<td>12-Jul-2010 14:56</td>
<td>Figure 33</td>
<td>143</td>
</tr>
<tr>
<td>28-Jun-2010 11:02</td>
<td>Figure 34</td>
<td>138</td>
</tr>
<tr>
<td>02-Sep-2010 06:47</td>
<td>Figure 35</td>
<td>133</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12-Feb-2010 18:31</td>
<td>Figures 36 and 37</td>
<td>132</td>
</tr>
<tr>
<td>01-May-2010 22:30</td>
<td>Figures 38 and 39</td>
<td>129</td>
</tr>
<tr>
<td>22-Jun-2010 15:29</td>
<td>Figures 40 and 41</td>
<td>126</td>
</tr>
<tr>
<td>16-Oct-2010 21:39</td>
<td>Figures 42 and 43</td>
<td>122</td>
</tr>
</tbody>
</table>

Table 2: Maximum registered bearing forces.

![Graph showing displacement over time](image)

Figure 18: Maximum longitudinal displacement taken every 30 minutes.
Figure 19: Max and Min values for bearing forces, taken every 30 minutes throughout the monitoring period. Upper plot: west bearing, Lower plot: east bearing.
Figure 20: Largest longitudinal displacement registered, most likely caused by electric disturbance.

Figure 21: Second largest longitudinal displacement registered, most likely caused by electric disturbance.
Figure 22: Third largest longitudinal displacement.

Figure 23: Fourth largest longitudinal displacement.
Figure 24: Close-up on the third largest longitudinal displacement.

Figure 25: Close-up on the fourth largest longitudinal displacement.
Figure 26: Typical example of 30-minutes file showing girder displacement and force on bearing.

Figure 27: Typical example of 30-minutes file showing girder displacement and force on bearing.
Figure 28: Largest bearing force registered, most likely caused by electrical disturbance.

Figure 29: Second largest bearing force registered, most likely caused by electrical disturbance.
Figure 30: Third largest bearing force registered.

Figure 31: Fourth largest bearing force registered.
Figure 32: Largest static bearing force registered.

Figure 33: Second largest static bearing force registered.
Figure 34: Third largest static bearing force registered.

Figure 35: Fourth largest static bearing force registered.
Figure 36: Fifth largest static bearing force registered, due single loading event (see figure 37).

Figure 37: Traffic corresponding to largest bearing force shown in figure 36.
Figure 38: Sixth largest static bearing force registered (see figure 39).

Figure 39: Traffic corresponding to largest bearing force shown in figure 38.
Figure 40: Seventh largest static bearing force registered, due single loading event (see figure 41).

Figure 41: Traffic corresponding to largest bearing force shown in figure 40.
Figure 42: Eight largest static bearing force registered (see figure 43).

Figure 43: Traffic corresponding to largest bearing force shown in figure 42.
7 Cable frequency Monitoring

The forces in the hangers that suspend the bridge girder to the two main cables are an important parameter to monitor. A simple way of evaluating the real tension force in a hanger is by measuring the eigenfrequencies of the hanger, which are a function of the hanger’s axial stiffness, the axial force and the boundary conditions. The axial stiffness is usually well-known, and the boundary conditions together with the axial force can be derived from the measurements. Any damage in the main cables or other hangers will affect the tension in the instrumented hangers, and will be seen in the measurements as changes in the eigenfrequencies of the hangers.

In order to use the eigenfrequencies of the hangers as a parameter for damage detection it is necessary to understand the behavior of the hangers, i.e. the range of possible eigenfrequency values and there dependency on ambient effects such as temperature.

The accelerometers are located on hanger 81 and hanger 82 (west-side hangers) at one 10th of the height of the hanger, at the point where the 5th eigenmode should have the largest displacement for a theoretical string, without bending stiffness. Therefore the 5th eigenfrequency is the most easily detectable frequency from the recorded acceleration signals. In the case of hangers 81 and 82, this eigenfrequency was found to be at 14.95 and 24.56 Hz respectively. The 5th eigenfrequency against the temperature are presented in figure 44.

From the data collected it can be inferred that the first eigenfrequency of hanger 81 varies with the temperature at a rate -0.00125 Hz per °C (-0.0086 Hz per °C for the 5th frequency, see figure 45). This translates into a variation in the force of 0.56 kN per °C. For hanger 82 the variation was found to be -0.0014 Hz per °C (-0.008 Hz per °C for the 5th frequency) or, equivalently, 0.64 kN per °C.

From the results, the influence of temperature is readily visible as well as the spread in the frequencies, even for a given temperature, due to probably the different load configurations that affect the axial force in the hangers.

During the first monitoring period the frequencies of the instrumented hangers were not directly monitored, but they were extracted from the acceleration data, i.e. from the permanently stored 30-minutes acceleration files.

It is noticed that from measurements carried out in 2005 (Sundquist et al., 2005) the first eigenfrequency of hanger 81, on the east-side, was found to be 3.1 Hz. This is considerably higher than the 2.8 Hz (see figure 45) currently registered in the monitoring system installed on the corresponding west-side hanger. The registered frequency indicates a hanger force of 607 kN to compare with the force which was obtained in 2005 on the east-side hanger which is about 708 and 742 kN. No such difference can be directly observed in the first eigenfrequency of hanger 82. Lower forces in the west-side hangers were expected, since the forces in the west bearing are higher than those of the east bearing, indicating that a lesser part of the force is transferred to the main cable.

The changes in the eigenfrequencies, and thus in the normal forces, due to temperature are relatively small. A temperature difference of 40 °C will introduce a change slightly above 1% in the normal forces. It could also be observed that the bearing forces (see figure 19) corresponding to no live load are very consistent throughout the year, so that the way the cable and the girder interact does not change so much with temperature.
Figure 44: The fifth eigenfrequency of the hangers 81 and 82. It can be observed that
the spread in hanger 82 is not completely stochastic but seems to define two clearly
differentiated bands around 24.6 and 25.7 Hz. The reason for this is yet unknown.

Figure 45: The first eigenfrequency of hanger 81. The temperature dependency is
clearly visible. Beside a few outliers the spread of the frequencies for a given
temperature is relatively low. Encircled are the frequency peaks above a threshold
value.
Figure 46: Spectrum from a typical acceleration signal recorded at hanger 82. The peak corresponding to the 5th eigenfrequency is highlighted.
8 Conclusions

This report has presented results from monitoring of traffic loads, longitudinal girder displacements and hanger forces for the period February-December 2010. Based on the collected and analyzed data, the following conclusions are made:

8.1 General Conclusions

- The monitoring system worked satisfactorily. The data gathering, the developed monitoring and analysis algorithms, and the camera worked together seamlessly.
- The utilized data logger software (Catman) stopped quite often. This required manual restarts every few days and a constant watchful eye. The reason for this is believed to be the relatively low performance of the computer placed in the bridge.
- The high quality of the signals has enabled the evaluation of the gross weight of vehicles passing over the instrumented bearings. This rather simple instrumentation has in other words converted this bridge into a scale for weighing all passing traffic, a so-called Bridge Weigh-in-Motion system (B-WIM).
- Short-duration peaks in the bearing force signals could be observed. The largest of them are clearly electric disturbances, since they do not appear when the truck is directly on the bearing and their magnitude is unrealistically high.
- The longitudinal displacement signal also presents high peaks. Given their magnitude and shape it was ruled out that they could correspond to a physical displacement of the bridge girder. They occurred more often than the peaks in the bearing force signal and no relation between these two abnormalities could be observed.
- Smaller displacement peaks of just a few millimeters were found to occur relatively often. It is unclear if this are produce by the same kind of disturbances that produces the large ones or if they correspond to a physical displacement of the bridge. See figure 13.
- Large peaks in the longitudinal displacement signal where found to occur fairly often, more or less once a week, while peaks in the bearing force occurred very seldom.

8.2 Conclusions on the results

- During the measurement period relatively large loads from traffic were registered on the bearings. The total loads acting on the bearings are still much less than the total design load according to the Swedish bridge design code, see also the previous report by Karoumi et al. (2006).
• Some of the high loads registered on the bearings are caused by single vehicle events (overloading, e.g. trucks with a gross weight larger than 100 ton have been measured).

• The maximum static live load registered on the west-side bearing was 149 ton.

• Higher dead and live loads are measured on the west-side bearing than on the east-side bearing.

• Some high peaks occur when the bearing is directly loaded and could be attributed to dynamic effects. It is unclear why some trucks cause this kind of peaks while others do not. The high dynamic effects registered from passing trucks (dynamic factor $\geq 200\%$) can be caused by the misalignment at bridge expansion joints.

• The maximum longitudinal displacement that could be connected with traffic load was 10 mm. The bridge girder moves away from the abutment and back to its original position in about 40 seconds.

• No significant changes could be observed in the bearing forces and in the hanger forces due to the yearly temperature fluctuations.

• The maximum displacement registered in a 10 minutes file due to temperature was 20 mm.

• In periods of rapid temperature change the thermal expansion is incapable of overcoming the friction at the bearing. As a result stresses build up and are released when a vehicle passes the bridge. This could be a possible cause of the wear observed in the bearings.

Finally, it’s concluded that this monitoring project and the results from the signal analysis have increased our understanding of the loads acting on the bearings, the traffic events and the type of traffic passing over the bridge as well as the dynamic displacements of the bridge girder. Unfortunately, we can still not definitely point out the main cause to the severe wear of the Teflon layer of the bearings. We can thus not rule out the hypothesis that this is caused by the high loads and dynamic effects acting on the bearings in combination with the longitudinal movements of the bridge girder on the bearings.

9 Acknowledgement

The funding for this project is provided by Trafikverket (the Swedish Transport Administration) and is gratefully acknowledged. The authors of this report would also like to thank the KTH laboratory technicians Claes Kullberg and Stefan Trillkott for their excellent installation, calibration and maintenance work of the monitoring system. Last but not least, without the camera provided from Axis Communications, the identification of the multi-vehicle events would not have been possible.
10 References
