Summary

This document describes Structural Health Monitoring as an innovative solution for the bridge structures maintenance, with special attention to the cable-stayed bridges.

Monitoring should be understood as a process of structural supervision and observation of the bridge. This treatment is necessary to prosecute full control over the structure. It is ensured by constant or periodical inflow of the information about structural condition of the appointed building system.

Especially, it covers the problem of quantitative deployment of the stay-force measuring devices and proceeds benefits from its employment.

Main idea is to mature methods of measurements and their influence on the cost of the whole enterprise, basing on the real example.

Two, state-of –the-art, solutions have been proposed:

- Direct measurement of the forces by means of elasto-magnetic sensors,
- Indirect measurement of the forces by means of accelerometers.

Technical backgrounds of the solutions are elaborated, as well as its pros and cons. Deliberation is proceeded on the base of: New planned Cable-Stayed Bridge along the ring road of Wroclaw, over Odra River, Poland. Real prices of the devices and related services are implemented in order to authenticate considerations.

Main idea is to convict authorities and people involved in designing process, that complete Structural Health Monitoring is the initial investment that brings financial profits during service live of the bridge.
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1. INTRODUCTION

1.1 description of the cable-stayed idea

Figure 1.

Idea of well known in our present stay systems is very old and remember antique times. Centuries before people started erecting cable-stayed bridges, method of sustaining beams by means of cables had been well known by ancient Egyptians, to construct sail systems of their boats. After many years this idea has found its application in bridge engineering. First European sources that describe cable-stayed bridges are dated on the year A.D. 1617. In this papers author, Faustus Verantius, portrayed cable stayed bridge, equipped with chain-stays.

In the nineteenth century, several suspension bridges were successfully erected. Additional inclined cables were used in order to ensure appropriate stiffness of the whole structure and provide stability against wind loads. Fast development of so called: “modern cable-stayed bridges” began in the second half of the twentieth century and bases on the new technologies of pre-stressed cables.

Parallel fast growth in the calculation facilities introduced by the use of computers resulted in appropriate and cost-effective possibilities of cable-stayed bridges designing.

Except economical and technical reasons, cable-stayed bridges provide unique view and are composed as distinguishable element of the surrounding environment.

Since these times, development of advanced materials and more efficient methods of erection, contrived width employment of cable-stayed idea in order to span long distances. Basic elements of cable-stayed bridges are:

- supports,
- towers,
- main girder,
- stay system.
1.1 Configuration of stay systems

We can distinguish four, the most common methods of stay systems arrangement:

**Mono:**

Figure 2.

**Harp:**

Figure 3.

**Fan:**

Figure 4.

**Star:**

Figure 5.

Presented constitutions are only basic propositions. On the world have been designed and erected another, not ‘off the shelf’ solutions.
1.2 Profitability of the C-S idea implementation

In case of the expensive public investments, economical aspects play the most important role. However, in recent times aesthetics is also taken into account to fulfill expectations of the investors. Cable-stayed bridges are characterized by interesting architectural profile, that is why continuously there is a rise in their employment.

Graph above, presents dependence of the cost on the span length. As we can observe, when the span length L exceed 180m, cable-stayed bridges become economically profitable. Mainly it is because of the slender girder and limitation of the supports. Elimination of the support number (in case of the bridge over the river), results in avoidance of interference in the natural environment of the river.
1.4 Examples of C-S idea employment

- **Brooklyn Bridge, milestone in the bridge engineering – suspension bridge, USA**

![Figure 7. (Old view, year 1890)](image1)

**Description of the structure:**

The Brooklyn bridge was designed by German-born Roebling and completed in the year 1883, New York USA. Having total length of 1059.9 m and a main span of 486.5 m represents milestone in the bridge construction.

![Figure 8. (Present view)](image2)
• First cable-stayed bridge of the modern era: Stromsund bridge, Sweden

Figure 9

Description of the structure:

The Stromsund bridge in Sweden, opened to traffic in 1956, is generally considered as the first cable-stayed bridge of the modern era. It is a three span structure with the main span length: 182,6 m and total length: 332 m. Complexed deck (steel and concrete) is suspended by means of diagonal cables from 2 pylons.

• Normandie Bridge, France

Figure 10
Description of the structure:

The bridge was designed by Michel Virlogeux. Construction process began in 1988 and lasted 7 years. The bridge was opened on January 20, 1995. At that time the bridge was both the longest cable-stayed bridge in the world, and had the record for the longest distance between piers for any cable-stayed bridge. It was more than 250 m longer between piers than the previous record. This record was lost in 1999 to the Tatara Bridge in Japan. The cable-stayed design was chosen because it was both cheaper and more resistant to high winds than a suspension bridge.
• World record in C-S span length, Sutong Bridge, China

The Sutong Bridge is a cable stayed bridge that spans the Yangtze River in People's Republic of China between Nantong and Changshu in the upstream from Shanghai, that is currently under construction. It is currently due to open in the early 2008. With a span of 1,088 metres, it will become cable stayed bridge with the longest main span in the world. Two towers of bridge are 306 metres high and thus second tallest in the world. Overall the bridge length will be 8,206 metres. Construction began in June 2003 and bridge was linked up in June 2007.
2. OBJECTIVES

Stay system is the most significant and sophisticated part of the C-S bridge structure.

Its main idea, pre-stressing, implementation of the additional force to the cables requires control and supervision. This paper covers study of the location, type and number of the force measuring devices in stay system, taking into account Life Cycle Cost (LCC).

Deliberations are conducted on the example of planned C-S bridge in Wroclaw over Odra river.
3. STRUCTURAL HEALTH MONITORING (SHM) - Overview

3.1 Major assumptions

Aim

Main aim of the monitoring idea is to understand mechanism of the structure and early-warning before the damage-risk. Thanks for this treatment it is easier to avoid serious technical drawbacks and eventual financial losses brought by reparation and closure of the bridge.

Effect

Monitoring system is an investment that brings comfort of maintenance for the bridge-authorities and it is a good method of receiving information about actual condition of the structure. It can be defined as an innovative approach to the engineering that ensures proper functioning and longer service life of the structures, thanks for immediate reactions on the detected abnormalities.
Major tasks are:

- Health monitoring and damage detection,
- Monitoring of weather factors (e.g. temperature, wind-velocity; direction; angle of attack, sun radiation, humidity, precipitation),
- Monitoring of traffic load,
- Monitoring of seismic activities,
- Monitoring of dynamic behavior (acceleration, dumping, frequency of vibration),
- Monitoring of mechanical parameters (force, strain, stress),
- Monitoring of displacements and deviations.

**Structural Health Monitoring should be divided on two sub-groups:**

3.2. Periodical bridge monitoring system

In this method we can predict the lifetime bridge performance on the base of particular measurements.

For this process it is recommended to use advanced mathematical tools, like: Markov process, Bayesian theory, Monte Carlo method or quite new approach, genetic probabilistic methods.

3.3. Permanent bridge monitoring system

This type will be accurately elaborated in this essay with special attention to the force measurements in stays

Fundamental principle of this method is constant process of structural observation and obtaining of structural data in real time.
3.4. Step by step of the long term structural health monitoring

1. **Data sampling** – by means of deployed on the structure sensors and measuring devices.

![Elastomagnetic force sensor](image16)

![Accelerometer](image17)

Figure 16. Elastomagnetic force sensor.  
Figure 17. Accelerometer

2. **Data gathering** – by means of installed on the bridge, center of data acquisition.

![Data acquisition center](image18)

![Data acquisition center](image19)

Figure 18, 19. Data acquisition center.

3. **Data compilation**- by means of special software.

![Data compilation-equipment](image20)

![Data compilation-equipment](image21)

Figure 20, 21. Data compilation-equipment
4. **Output- data after treatment, displayed as charts, histograms, tables etc. (Optionally on the web-site).**

Figure 22, 23. Data output- presented on the web-site

3.5. Loads on cables of cable-stayed bridges

3.5.1. Wind

Stay as a single element of a bridge structure, shows the highest susceptibility towards wind induced phenomena. Wind is the most significant load component and can exceed 50% of the total transverse load on the bridge structure. Individual cable is susceptible to the wind effects, due to the low bending stiffness, implemented high prestressing force, cable length and orientation to the wind. Stay, under wind load can be considered as a body subjected to a flow.

Let is consider fixed-rigid cylinder, of infinite length, immersed in a smooth wind-flow.

Figure 24
• $\beta$ – angle of cartesian system rotation, in order of alignment of the system with the wind direction,
• $U$ – mean wind velocity,
• $B$ – cable diameter.

**Aerodynamic forces:**

• $F_d(t)$ – drag force,
• $F_l(t)$ – lift force,
• $M(t)$ – moment component, acting on the elastic centre of the body.

**Wind induced phenomena on the bridge structure, overview**

3.5.1.1. Galloping, whole structure

It occurs on a slender elements with rectangular sections and sometimes on stays covered by ice. Induces the vibrations transversal to the wind direction. Characterized by oscillations transversal to the wind direction. Galloping effect is similar to vortex-shedding, however this phenomenon is quite different. Galloping produces high amplitudes of vibration, even 10 times as body dimension, in for all wind speeds above critical value. This phenomenon, first time, was reported on the lines of ice-coated power line cables.

3.5.1.2. Rain-Wind induced vibrations, stay system

Observed on the skewed stays as well as on the vertical hangers of the suspension and arch bridges. During the rain, water settle on the cable surface and is flowing down, creating 1 or 2 regular streams. Wind induced movement of the cable provoke alternating changes of the stream position. As the result, effective change of the, cable cross-section-dynamical parameters occurs. Intensity of vibrations depends on the natural damping of the body.
Important fact is that this phenomenon occurs in the low range of the wind velocities and can provoke damage, mainly as the result of excessive amplitudes of vibration and and related local fatigue occurrences. In some case vibrations, provoked by Rain-Wind induced phenomenon can be transmitted to the deck and disturb in the normal exploitation of the bridge. In recent years this phenomenon has been studied and described on the example of the “Erasm Bridge” in Rotterdam, Netherlands.

Possible arrangements of the streams on the cable surface and related implications:

**Vibration along the wind direction:**

![Diagram of vibration along the wind direction](image)

As visible on the drawing (25), in case of the symmetrical streams position, vibrations direction is in concurrence with a wind. Alternating changes of the streams position, provoke intensification of the vibration amplitude along the wind direction. Wind blows in the plane of cable’s tilt.
Vibration in transversal direction to the wind.

In the event of 2 asymmetrical streams position, cable vibrates in the transversal direction to the wind. Streams are positioned on the windward cable part. Related vibrations are activated by asymmetrical movement of the streams. Wind blows in the plane of cable’s tilt.

Wind blows transversally to the plane of cable’s tilt. Single stream occur on the lee part of the stay. Effect of lifting connected with the wind direction, results in the in diagonal movement.
3.5.1.3. Buffeting

Main effect of this phenomena, are the vibrations corresponding to the wind direction. Main activator are turbulences that are characterized as differential wind speed. Occurrence of the bending and torsioning vibrations is possible. Response of the structure on buffeting, is dependent on intensity of turbulences, shape of the element and natural frequencies.

3.5.1.4. Flatter (bending with torsioning), deck

It is one of the most dangerous phenomena. It occurs when the natural frequencies of bending and torsioning vibrations are close to each other or interfere. To avoid these situation compulsory condition should be fulfilled:

\[
\frac{f_t}{f_b} \leq 1.5
\]

\(f_t\) - frequency of torsioning vibrations,
\(f_b\) - frequency of bending vibrations.

3.5.1.5. Vortex shedding, whole structure

These components are associated with the vortex shedding that occurs on the surface of the cylinder and should be understood as an alternating flow of the vortices, that activate the movement of the body.

Figure 28 (Vortex Shedding)
Values of the aerelastic forces are determined from the balance between inertial and viscous forces around the cylinder that is quantified by the Reynolds number Re:

\[
Re = \frac{U \cdot B}{v}
\]

Re – Reynolds number,
U – Wind velocity,
B – Body dimension,
v – kinematic viscosity [0.150 cm²/s, 20°C]

Depending on its value, shape of the flow is changing, activating movements of the body.

This phenomenon occurs already in the low wind velocities. Shedding frequency is characterized by the Strouhal number \(St\):

\[
f_v = \frac{U \cdot St}{B}
\]

\(f_v\) – shedding frequency of the vortices,
U – Wind velocity,
St – Strouhal number,
B – Body diameter (cross-section).

Figure 29 (Van Karmann Vortex trail, 30 \(\leq\) Re \(\leq\) 5000)
3.6. Traffic loads

Obviously, important component that induce internal forces in stay system. Especially important in case of footbridges, where frequency of the steps has a prominent influence on the structural behavior.

3.7. Temperature

Sun radiation and atmospheric temperature generate differential areas of temperature in the structure elements. It induce additional axial forces, depending on the gradient of temperature.

In this case very important is choice ducts color. In the areas of the high sun radiation, recommended is using of the ducts in bright colours.

3.8. Force measurements, using accelerometers

Figure 30 (Accelerometer installed on the external surface of stay)

Accelerometer is a device that main purpose is to measure acceleration and vibration of the body. The idea is, that accelerometer deployed on the structure, measure its own motion. Further we treat accelerometer and body as one system, then dynamical characteristics of appointed structure can be obtained.
Rough dynamical analysis of stays
In this method we base on the so called “vibrating chord theory”.
Assumptions:

- Negligible flexural stiffness of the cable,
- There is no relative displacement between fixing points of the stay,
- The transverse in plane deflections of symmetrical modes do not generate any additional tensioning in cable.

Basic value that describes dynamical behavior of stay is ‘frequency of vertical vibrations’.
Rough estimation of ‘stay dynamical behavior’ can be researched in two levels.
(first eigenfrequency)

1. Without taking into account stay-sag:
Frequency can be assigned from the below formula:

\[ f_{c1} = \frac{1}{2L_c} \sqrt{\frac{S}{m_c}} \]

\( f_{c1} \) – frequency of stay vertical vibrations [Hz],
\( L_c \) – Length of stay [m],
\( S \) – Axial force in stay [N],
\( m_c \) – Weight of stay on the length unit [kg/m].

Going further, it is easy to assign desired force in stay:

\[ S = (f_{c1} \cdot 2L_c)^2 m_c \]

\( f_{c1} \) – value can assigned, using accelerometer
Taking into account stay-sag:

Frequency can be assigned from the below formula:

\[ f_{cl} = \frac{1}{2L_c} \sqrt{\frac{S}{m_c} + \frac{E_c \cdot A_c \cdot f_z^2}{2m_c \cdot L_c^2}} \]

- \( E_c \) – Modulus of elasticity of the strands-material [GPa],
- \( A_c \) – Area of stay bearing-section [m²],
- \( f_z \) – Sag arrow [m].

After reform we obtain the desired force:

\[ S = m_c \cdot \left( f_{cl} \cdot 2L_c \right)^2 - \frac{E_c \cdot A_c \cdot f_z^2}{2m_c \cdot L_c^2} \]

It is recommended to use second method in case of longer stays, when sag has a prominent influence on the behavior of cable.

**Problem of the external positioning of accelerometers**

As mentioned above, stay consists of the set of strands (bars) covered by pipe. Method of deploying accelerometers on the external surface is reasonable because of unfailure of corrosion protection. Furthermore it is easy to replace it on another cable in case when we do not dispose enough quantity of accelerometers, equal with the number of stays.

![Figure 31 (Positioning of the accelerometers on stays (Vasco da Gamma bridge, Portugal))](image)
Examples:

- Binzhou Yellow River Highway Bridge, People’s Republic of China

![Binzhou Yellow River Highway Bridge](image1)

**Figure 32**

**Description:** 38 accelerometers used for the force and vibration measurements.

- Siekierkowski Bridge, Poland

![Siekierkowski Bridge](image2)

**Figure 33**

**Description:** Accelerometers used for the force and vibration measurements.
3.9. Force measurements, using elasto-magnetic sensors (EM)

Main purpose of this method is constant, non-contact measurement of the stress in prestressed steel elements.

**Magnetic analysis**

Steel belongs to the family of ferromagnetic materials. It means, that it is susceptible on the interferences of magnetic field. Ferromagnetic materials have specific internal structure, that let them, in special circumstances, to induce ambient magnetic field. Function that describe behavior of ferromagnetic materials, in the magnetic field, is a hysteresis loop. It describes relationship: magnetic induction $B$ [T] - magnetic field intensity $H$ $[A/m]$.

![Figure 34 (Elasto-magnetic sensor)](image)

![Figure 35. Hysteresis loop](image)
(1)- Characteristic of primal magnetization,
(2)- Characteristic of demagnetization,
(3)- Full hysteresis loop,

\( B_S \) - Magnetic saturation,
\( H_S \) - Intensity saturation,
\( B_R \) - Remanent flux density or Remanence,
\( H_C \) - Coertion intensity.

Shape of hysteresis depends on the kind of material. We can distinguish two types of ferromagnetic materials: hard (maintain their magnetization after withdrawal of external magnetic field) and soft (forfeit their magnetization after withdrawal of external magnetic field)

Measurement idea

Figure 36  Elasto-magnetic sensor deployed on the anchor
Mechanical stress-tension, compression, pull, torsion, bend etc, causes the hysteresis loop, of ferromagnetic material, to change its shape.

\[ \Delta B(F) = \mu \cdot \Delta H \]

- \( \mu \) - Permeability of material [H/m]

Permeability is a function of temperature and magnetization, refers to the mechanical stress.

Magneetoelastic method is based on the theory, that magnetic field in steel is dependent on the stress level. It means that permeability of steel changes with the fluctuation of stress.
Measurement process

Figure 39 (Measured element, over-girdered by coil)

\( \sigma \) – Mechanical stress [Pa],
\( T \) – Temperature [K],
\( S_F \) – Sectional area [m²],
\( F \) – Axial force [N].

As mentioned above, measuring process is based on the magnetization of researched material.

Step by step:

- Coil (1), as a part of sensor, is responsible for magnetization of material through activation of magnetic field,
- Magnetized material gives a response in form of its own magnetic field,
- This effect is scanned by coil (2),
- Appropriate transducer and software convert magnetic field to mechanical stress or force,
- Data treatment, to the desired form – numbers, tables, plots.
Sensors deployment

Sensors are installed over the strands during process of stay-system erection. It is reasonable to know the force variation in particular stay, during stressing process of another.

Figure 40 (Construction stage-installed sensors.)

Quantity of devices, necessary for measurements of the force level on the one stay, depends on the method of 'stay system stressing'.

This measurement method is highly recommended for isotension method of stay stressing. Because of the same force-value, applied to every strand, deployment of sensors on every line is not a precondition.

Figure 41 (Magnetoelastic sensors installed on particular strands)
We base on the compulsory condition that the force-value difference, between particular strands can not exceed +/- 2.5% of the designed force. Thanks for this assumption, it is permitted to estimate the force in whole stay structure. In recent years this method is the state-of-the-art technology

Examples:

- Tabor Bridge, Czech Republic

![Tabor Bridge, Czech Republic](image1.jpg)

Figure 42

**Description**: EM sensors used for the force measurements.

- C-S Bridge in Plock, Poland

![C-S Bridge in Plock, Poland](image2.jpg)

Figure 43
Description: EM sensors used for the force measurements.

Figure 44 (Control cabinet in the pylon of the Bridge in Plock)
4. STRUCTURAL HEALTH MONITORING (SHM) AND LIFE CYCLE COST (LCC)

Main purpose of this essay is trial to convince bridge managers and owners about necessity of the structural supervision of the structures. Neglect may effect in serious criminal consequences for the authorities, because of the people perish.

With respect to monetary consequences, bridges are structures that ensure connection for the transport-roads and permit over passing of the existing obstacles. Every bridge should be understood as a particular element of the system, called “network”. Damage of the one component contrive breakdown of the whole system and brings financial looses for the bridge owners and occupants.

It should be assumed that main duty of every structure: Geometrical invariability always withstand many phenomena and situations, such as: chemical attack from de-icing salts, environmental stressors (wind, earthquakes, temperature, water), traffic (for the existing structures, higher than previously designed) may degrade the long-term performance of the structures, its damage or collapse.

Fast reaction on detected irregularities is the best way to avoid serious consequences. Permanent control by means of inspection is the best solution for the problem avoidance. However, impossible is to locate inspectors on the bridge for the on-time measurements and supervision. That is why proposed and recommended is Structural Health Monitoring, specially designed system of devices and software that brings possibility of the structural control without constant human engagement.

Special alarm procedures let to keep hand on pulse in case of problem, remote control. In the next chapter, presented will be “joint venture” of SHM and LCC. Deliberated problem is, employment of the force measuring devices.

On the base of Author’s assumptions, equation of SHM profitability will be acquired.
Life Cycle Cost with respect to lifetime performance is considered to be the most widely used factor for the optimum design of new structures [Frangopol and Messervey, 2006].
5. SHM APPLICATION, CABLE-STAYED BRIDGE IN WROCLAW

Figure 45 (Visualization of the bridge)

5.1 Description of the bridge structure

Presented structure is a cable stayed bridge along the ring road of Wroclaw in Poland. It consists from the main cable stayed bridge and two approach estacades.

Whole cost of investment estimated on approx. 450 mln. PLN (approx. 125 mln. EUR). Estimated cost of the cable-stayed structure: 220 mln. PLN (approx. 60 mln. EUR).

5.1.1 Main structure – cable-stayed bridge

- 4 spans, (256+256meters),
- 2 symmetrical spans in cable stayed part,
- 160 stays in total,
- one pylon, height: h=122.00 meters,
- 4 planes of stays,
- 2 parallel concrete girders.
5.1.2 Approach estacades

Left side estacade

- 11 spans, (40+2x52+56+6x60+50 m.)
Right side estacade

- 9 spans, (50+7x60+50 m.)

Figure 49

5.1.3 Bridge location

Figure 50
- Estimated daily traffic: 14000 cars.

New C-S bridge over Odra river will be second Wroclaw’s bridge in this technology, parallel to already existing “Milenijny bridge”. Both structures state as a great symbols of the city.

Figure 51 (“Milenijny bridge” in Wroclaw)

Let is consider 2 proposals of the “stay-force measuring devices” arrangement. First, 2 positions, method that use accelerometers as a measuring devices has been proposed.

5.2 Proposal No.1, Measurements of the forces on particular stays
### Sensor Logos and Quantity

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Logo</th>
<th>Quantity</th>
</tr>
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<tbody>
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<td>Wind speed and direction</td>
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<td>Precipitation</td>
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<tr>
<td>Humidity</td>
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<td>Inclinometers</td>
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<td>Displacement</td>
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<tr>
<td>Accelerometers for the force and vibration of the cables</td>
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### Item Logos and Quantity

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<tr>
<td>Data acquisition center</td>
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<tr>
<td>Additional equipment</td>
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</tr>
</tbody>
</table>

**Total price: 600000 EUR**

Whole system: Share in whole investment (C-S bridge): \[ \frac{600000EUR}{60000000EUR} \cdot 100\% = 1\% \]

24 force measuring devices.

Assumption: Price/unit: 1500 EUR

Force measuring devices: \[ \frac{36000}{60000000EUR} \cdot 100\% = 0,06\% \]
5.3 Proposal No.2, Measurements of the forces on every second stay-row.

Figure 53

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
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<td>Wind speed and direction</td>
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<td>Humidity</td>
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<td>Air temperature</td>
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<td>Solar radiation</td>
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<td>Accelerometers for deck and pylon</td>
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<tr>
<td>Video cameras</td>
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<tr>
<td>Deformation sensors</td>
<td>14</td>
</tr>
<tr>
<td>Inclinometers</td>
<td>10</td>
</tr>
<tr>
<td>Displacement</td>
<td>4</td>
</tr>
<tr>
<td>Pylon GPS</td>
<td>1</td>
</tr>
<tr>
<td>Accelerometers for the force and vibration measurements of the cables</td>
<td>80</td>
</tr>
<tr>
<td>Item</td>
<td>Quantity</td>
</tr>
<tr>
<td>------------------------------------------------</td>
<td>----------</td>
</tr>
<tr>
<td>Power supply</td>
<td>1</td>
</tr>
<tr>
<td>UMTS unit for data transmission to the CoHA</td>
<td>1</td>
</tr>
<tr>
<td>Data acquisition center</td>
<td>1</td>
</tr>
<tr>
<td>Additional equipment</td>
<td>-</td>
</tr>
</tbody>
</table>

Total netto price: 700000 EUR

Share in whole investment (C-S bridge): \( \frac{700000 \text{EUR}}{60000000 \text{EUR}} \cdot 100\% = 1,16\% \)

80 force measuring devices.

Assumption: Price/unit: 1500 EUR

Force measuring devices: \( \frac{120000}{6000000 \text{EUR}} \cdot 100\% = 0,2\% \)

Both prices include:

- Elements of the system,
- Transport (incoterm),
- Installation,
- Calibration,
- Training for the bridge management team,
- Service hotline.

5.4 Accelerometers, comparison

**Proposal No.1**

In this solution, 24 accelerometers were proposed to measure the forces in whole stay system.

It means that necessary is displacement of the devices on another stays in order to measure its behavior. It requires additional financial resources. Additionally, this number of devices, exactly shows that it is not possible to call this type of monitoring control as: permanent.
Let us assume: 2 Qualified Engineers for the sensors displacement works.

Flight: 1000 EUR,
Hotel: 200 EUR/day,
Engineer fee: 300 EUR/day for one Engineer,
Working days: 5
Total cost: 6000 EUR for one visit.

Let us assume that it is reasonable to measure force in every stay in half year intervals.
It means that every year we spend additionally 12000 EUR for these operations.
Let us take into account important fact, that every position changes are associated with damages of the devices and roughly we can estimate that we will have to add 1 new device per year, that will increase the price to approx. 14000 EUR.

Approximated additional cost/year: 14000 EUR

Proposal No.2

In this solution, 80 accelerometers were proposed to measure the forces in whole stay system. We base on the assumption: that adjacent (not monitored) stays have direct influence on the measured, and on the base of its behavior we can estimate condition of the whole system.
Displacement of devices is also recommended, but in longer intervals, let us assume 2 years.

The idea of the monitoring system is to avoid serious damages by immediate reactions on detected abnormalities. Going further, also in this arrangement we have not got full control over the structure, because we will receive information about damage of the “not monitored” stays, by “sudden” changes of the “monitored” stays behavior.
Let is assume: 2 Qualified Engineers for the sensors displacement works.

Flight: 1000 EUR,
Hotel: 200 EUR/day,
Engineer fee: 300 EUR/day for one Engineer,
Working days: 14
Total cost: 8000EUR for one visit.
Additionally let is assume that we will loose on device, during displacement operation.
Total cost: 10000 EUR

**Approximated additional cost/year: 5000 EUR**

Let is consider 2 proposals of the stay-force measuring devices arrangement
For these 2 positions, method that use elasto-magnetic sensors has been proposed.
In these point we will be considering only force measuring devices.

5.5 EM sensors, Proposal No.1

(Full remote control over the bridge structure, quantity of sensors is equal with Number of stays).

![Figure 54](image)

In this scheme, total quantity of devices is equal with the number of stays-160 units.

160 force measuring devices.
Assumption:

Price/unit:
- Sensor with 3m long connection cable: 36 EUR/unit,
- waterproof box: 110 EUR/unit,
- temperature sensor: 25 EUR/unit,
- Total/stay: 171 EUR

Additional costs:
- Software: 5000 EUR,
- Site engineer: 400EUR/day,
- Above price includes: Engineer working hours, hotel, transport.

Note: installation and calibration time: 7 weeks
- Elements of the system,
- Transport (incoterm),
- Installation,
- Calibration,
- Training for the bridge management team,
- Service hotline.

\[
\text{Force measuring devices: } \frac{49000}{60000000}\% = 0.082\%
\]

5.6 EM sensors, Proposal No.2

(Measurements of the forces on every second stay-row)

![Figure 55](image)

In this scheme, total quantity of devices is equal 80 units
Assumption:

Price/unit:
- Sensor with 3m long connection cable: 36 EUR/unit,
- waterproof box: 110 EUR/unit,
- temperature sensor: 25 EUR/unit,
- **Total/stay: 171 EUR**

Additional costs:

- Software: 5000 EUR,
- Site engineer: 400 EUR/day,
- Above price includes: Engineer working hours, hotel, flight.

Note: installation time: 5 weeks

- Elements of the system,
- Transport (incoterm),
- Installation,
- Calibration,
- Training for the bridge management team,
- Service hotline.

**Total price: 33000 EUR**

Force measuring devices: \[
\frac{33000}{60000000 \text{EUR}} \times 100\% = 0.055\%
\]

5.7 EM sensors, comparison

Proposal No.1

In this solution, 160 E-M sensors were proposed to measure the forces in whole stay system.

We base on the assumption, that adjacent (not monitored) stays have direct influence on the measured stays, and on the base of its behavior we can estimate condition of the whole system.

Displacement of devices is also recommended, but only in case of failure, let is assume 5 years as a review time.
Let is assume: 2 Qualified Engineers for the sensors service works.

Flight: 1000 EUR,  
Hotel: 200 EUR/day,  
Engineer fee: 300 EUR/day for one Engineer,  
Working days: 14

Total cost: 8000EUR for one visit.

Additionally let is assume: loose of 10 devices per service event,  
Special equipment for the operation on the anchor

Total cost: 10500 EUR

**Total cost/year, including equipment and maintenance: 2500 EUR/year**

**Proposal No.2**

In this solution, 80 E-M sensors were proposed to measure the forces in whole stay system.

We base on the assumption: that adjacent (not monitored) stays have direct influence on the measured stays, and on the base of its behavior we can estimate condition of the whole system.  
Displacement of devices is also recommended, but in longer intervals, let is assume 2 years.

Let is assume: 2 Qualified Engineers for the sensors service and displacement works.

Flight: 1000 EUR,  
Hotel: 200 EUR/day,  
Engineer fee: 300 EUR/day for one Engineer,  
Working days: 10

Total cost: 6000 EUR for one visit.
Additionally let is assume: loose of 5 devices per service event,
Special equipment for the operation on the anchor

Total cost: 7000 EUR

**Approximated additional cost/year: 3500 EUR**

5.8 Consideration of the possible traffic disturbances.

Let is assume that failure of more than one stay is the reason for the traffic closure on the bridge.

Possible emergencies
- Drop of the force,
- Damage of the anchor provoked by fatigue,
- Cracks on the anchor blocks,
- Fatigue of the stay bending zone,

By the control of the stay-force, using SHM, we can predict these mechanical breakdowns.
Immediate reaction on the detected uncertainties ensure avoidance of these problems.

Let is consider the situation, that the failure of the more than 1 stay, will enforce us to the bridge closure.
Looses calculations:

Closure Duration:
- Time of delivery for materials: 3 weeks,
- Reparation: Dependent on the elaborated option,
- Total: 25 days.

a) Gasoline looses:
Assumptions:
- Daily traffic: approx. 14000 cars/24hours
- Bypass length: 14 km.
- Average fuel expenditure: 8 liters /100 km
- Gasoline price: approx. 1.25 EUR/liter

Cost of the bridge closure/24 h: \( C_{\text{closure24}} = \frac{14000 \cdot 8 \cdot 14 \cdot 1.25}{100} = 19600 \text{EUR} \)
b) Labor looses (traffic jams)

Assumptions:

- Proposed bypass is goes threw highly congested streets, let is assume daily traffic with the number of cars: 7000/24hours.
- Without any disturbances, travel by the marked route takes: 30 minutes. Let assume that bridge closure will affect in traffic jams that would increase travel time to 1 hour.
- Let is assume average rate/hour in Poland (on the base of approx. average monthly salary: 800 EUR gross) on 5 EUR gross, approx. 3.5 EUR.

On the base of above assumptions, let is calculate looses for the labor force, brought by the bridge closure.

\[
C_{labor/24} = \left(7000\right) \cdot \frac{3.5}{2} + 14000 \cdot 3.5 = 61250EUR
\]

<table>
<thead>
<tr>
<th>Position</th>
<th>Name</th>
<th>No of days</th>
<th>Price/position</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gasoline looses</td>
<td>25</td>
<td>490,000,00 €</td>
</tr>
</tbody>
</table>

Note: 18 working days

c) Cost of reparation:

Option No.1

Let is assume that 2 anchors failed and displacement is necessary:

- Cost of material:

<table>
<thead>
<tr>
<th>Position</th>
<th>Product</th>
<th>Quantity</th>
<th>Price/unit</th>
<th>Price/position</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Stay anchor</td>
<td>2</td>
<td>15,000,00 €</td>
<td>30,000,00 €</td>
</tr>
</tbody>
</table>
Cost of manpower:

Let is assume: 2 Qualified Engineers for the anchor displacement works.

Flight: 1000 EUR,
Hotel: 100 EUR/day,
Engineer fee: 500 EUR/ Engineer/day,
Working days: 4

<table>
<thead>
<tr>
<th>Position</th>
<th>Name</th>
<th>No.</th>
<th>Price/position</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 Engineer</td>
<td>2</td>
<td>5 800,00 €</td>
</tr>
</tbody>
</table>

Additional equipment:

<table>
<thead>
<tr>
<th>Position</th>
<th>Name</th>
<th>No.</th>
<th>Price/position</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Additional equipment</td>
<td>-</td>
<td>7 000,00 €</td>
</tr>
</tbody>
</table>

Miscellaneous losses (Traffic control): 1000 EUR/24

Total losses of the bridge closure:

<table>
<thead>
<tr>
<th>Total cost/21 days bridge closure, service included</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

Let is assume that during service live of the bridge, approx. 120 years, we can expect similar situation to repeat about 6 times. That gives total amount: 9,961,811,80EUR/service life.

TOTAL:
9,961,811,80 EUR/service life
83,015,00 EUR/year

Option No.2

Let is assume that 2 stays in the anchor zone failure and displacement of 2 sets (one set: 2 anchors+strands+HDPE pipe) is necessary:
• Gasoline looses:

<table>
<thead>
<tr>
<th>Position</th>
<th>Name</th>
<th>No of days</th>
<th>Price/position</th>
</tr>
</thead>
<tbody>
<tr>
<td>[-]</td>
<td>[-]</td>
<td>[-]</td>
<td>[EUR]</td>
</tr>
<tr>
<td>3</td>
<td>Gasoline looses</td>
<td>28</td>
<td>548 800,00 €</td>
</tr>
</tbody>
</table>

• Labor looses:

<table>
<thead>
<tr>
<th>Position</th>
<th>Name</th>
<th>No of days</th>
<th>Price/position</th>
</tr>
</thead>
<tbody>
<tr>
<td>[-]</td>
<td>[-]</td>
<td>[-]</td>
<td>[EUR]</td>
</tr>
<tr>
<td>3</td>
<td>Labor looses</td>
<td>18</td>
<td>1 225 000,00 €</td>
</tr>
</tbody>
</table>

Note: 18 working days

• Cost of material:

<table>
<thead>
<tr>
<th>Position</th>
<th>Product</th>
<th>Quantity</th>
<th>Price/unit/kg/m</th>
<th>Price/position</th>
</tr>
</thead>
<tbody>
<tr>
<td>[-]</td>
<td>[-]</td>
<td>[-]</td>
<td>[EUR]</td>
<td>[EUR]</td>
</tr>
<tr>
<td>1</td>
<td>Stay anchor</td>
<td>4</td>
<td>15 000,00 €</td>
<td>60 000,00 €</td>
</tr>
<tr>
<td>2</td>
<td>Strands</td>
<td>40 000</td>
<td>1,4 €</td>
<td>56 000,00 €</td>
</tr>
<tr>
<td>3</td>
<td>HDPE pipe</td>
<td>540</td>
<td>35 €</td>
<td>18 900,00 €</td>
</tr>
</tbody>
</table>

Total [EUR]: 134 900,00 €

• Cost of manpower:

Let is assume: 4 Qualified Engineers for the reparation works.

Flight: 2000 EUR,
Hotel: 100 EUR/day,
Engineer fee: 500 EUR/Engineer/day,
Working days: 7

<table>
<thead>
<tr>
<th>Position</th>
<th>Name</th>
<th>No.</th>
<th>Price/position</th>
</tr>
</thead>
<tbody>
<tr>
<td>[-]</td>
<td>[-]</td>
<td>[-]</td>
<td>[EUR]</td>
</tr>
<tr>
<td>2</td>
<td>Engineer</td>
<td>4</td>
<td>18 800,00 €</td>
</tr>
</tbody>
</table>

• Additional equipment:

<table>
<thead>
<tr>
<th>Position</th>
<th>Name</th>
<th>No.</th>
<th>Price/position</th>
</tr>
</thead>
<tbody>
<tr>
<td>[-]</td>
<td>[-]</td>
<td>[-]</td>
<td>[EUR]</td>
</tr>
<tr>
<td>3</td>
<td>Additional equipment</td>
<td>-</td>
<td>7 000,00 €</td>
</tr>
</tbody>
</table>
Miscellaneous looses (Traffic control): 1000 EUR/24 h

**Total looses of the bridge closure:**

<table>
<thead>
<tr>
<th>Position</th>
<th>Service</th>
<th>Quantity</th>
<th>Price/position</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,2,3</td>
<td>Stay anchor displacement</td>
<td>[-]</td>
<td>1 962 500.00 €</td>
</tr>
</tbody>
</table>

Let is assume that during service live of the bridge, approx. 120 years, we can expect similar situation to repeat 4 times. That gives total amount: **7.850.000 EUR/service life.**

**TOTAL:**

*7.850.000,00 EUR/service life*

*65.417,00 EUR/year*

5.9 Monitoring during bridge erection

Let is estimate cost of the design on 1% of the whole investment. For this bridge, it is about:

\[ Cp = 1\% \cdot 60.000.000EUR = 600.000EUR \]

In this case it is hard to estimate possible drawbacks, because construction has not already started. That is why possible profits related to this position will not be considered.

Designer takes responsibility for the supervision during erection stage. Main Contractor, on the base of tender, nominates Sub-contractors for different types of works.

In case of cable-stayed bridge it is necessary to employ specialized company that can supply, install and calibrate stay system.

**Force measurements during construction stage, main advantages:**

- Permanent control of the stays for stay by stay method application,

This treatment ensures control of the stresses in particular stages of erection.

It helps to maintain project assumptions and to avoid situation of the stay over-lifting.
- On-time control of the project calculations

This treatment is especially comfortable for the supplier of the stay system. It ensures permanent control of works and gives arguments against Designer in situation of inconsistencies.

5.10 “SHM profitability” equation, elasto-magnetic sensors

Option No.1

Proposition of the “SHM profitability” equation:

On the base of the proposition: E-M sensors, monitoring devices deployed on every particular stay

a. Without monitoring:

\[ C_{et} = C_t + C_{pm} + C_f \]

- \( C_{et} \) - Expected total cost,
- \( C_t \) - Cost of design and construction,
- \( C_{pm} \) - Cost of routine maintenance,
- \( C_f \) - Cost of failure and repair,

\[ C_{et} = 60.000.000EUR + 12.000.000EUR + 9.961.811,8 = 81.961.811EUR \]

b. Monitoring included

As a possible mistake of the measurements, let is consider not fulfillment of the EN condition that force in particular strands should not exceed in total 5% of the assumed in project.
Let us consider the longest stay.

**Designed force: 7028.53 kN**

**Number of strands: 55**

**Force/strand: 127.8 kN**

---

**Figure 57**

**Figure 58**
Stay Area: 8250 mm$^2$

Normal stress: $\sigma_i = \frac{7028530N}{8250mm^2} = 851.9 \frac{N}{mm^2}$

As stated in the specifications for the elasto-magnetic sensors, resolution of the measurements is assumed as $1 \frac{N}{mm^2}$ (Jarosevic, 2008), that form 0.12% of the total stress, which is much less than mentioned +/-2.5%.

Security Factor for stay system, as stated in EN: $\gamma = 0.45$

Because of that, in normal conditions, it is impossible to overload stay with a break effect.

It is possible only, in abnormal circumstances, especially during erection stage. Perchance failure may occur in the anchor zone, as mentioned before.

Despite implementation of the monitoring, we assume that there is a possibility of failure.

Let is assume, that:

- Wedge failure provokes that EN condition would not be fulfilled in 2 anchors, two times during service live and their replacement would be necessary.

$$C_{et} = C_i + C_{pm} + C_m + 0.33 \cdot C_f$$

$C_{et}$ - Expected total cost,

$C_i$ - Cost of design and construction,

$C_{pm}$ - Cost of routine maintenance,

$C_m$ - Cost of monitoring system, maintenance included,

$C_f$ - Cost of failure and repair,

$$C_{et} = 60,000.000EUR + 12,000.000EUR + 301,000EUR + (0.33 \cdot 9,961,811.8) = 75,588.398EUR$$

**c. Benefits**

$$B = C_{et} - C_{et}^m$$

$B$ - Benefits,

$$B = 81,961.811EUR - 75,588.398EUR = 6,373.413EUR$$

**Roughly estimated benefit as a result of SHM application: 6,373.413EUR**
Option No.2

Proposition of the “SHM profitability” equation:

On the base of the proposition: E-M sensors, monitoring devices deployed on every particular stay

d. Without monitoring:

\[ C_{et} = C_t + C_{pm} + C_{f2} \]

- \( C_{et} \) - Expected total cost,
- \( C_t \) - Cost of design and construction,
- \( C_{pm} \) - Cost of routine maintenance,
- \( C_{f2} \) - Cost of failure and repair,

\[ C_{et} = 60.000.000EUR + 12.000.000EUR + 7.850.000 = 79.850.000EUR \]

e. Monitoring included

\[ C_{et}^m = C_t + C_{pm} + C_m + 0.33 \cdot C_{f1} \]

- \( C_{et}^m \) - Expected total cost,
- \( C_t \) - Cost of design and construction,
- \( C_{pm} \) - Cost of routine maintenance,
- \( C_m \) - Cost of monitoring system, maintenance included,

\[ C_{et}^m = 60.000.000EUR + 12.000.000EUR + 301.000EUR + (0.33 \cdot 7.850.000) = 74.891.500EUR \]

f. Benefits

\[ B = C_{et} - C_{et}^m \]

- \( B \) - Benefits,

\[ B = 79.850.000EUR - 74.891.500EUR = 4.958.500EUR \]

Roughly estimated benefit as a result of SHM application: \( 4.958.500EUR \)
5.11 “SHM profitability” equation, accelerometers

Option No.1

Proposition of the “SHM profitability” equation:

On the base of the proposition: accelerometers deployed on every second stay

a. Without monitoring:

\[ C_{et} = C_r + C_{pm} + C_l \]

- \( C_{et} \) - Expected total cost,
- \( C_r \) - Cost of design and construction,
- \( C_{pm} \) - Cost of routine maintenance,
- \( C_l \) - Cost of failure and repair,

\[ C_{et} = 60.000.000EUR + 12.000.000EUR + 9.961.811,8 = 81.961.811EUR \]

b. Monitoring included

Despite implementation of the monitoring, we assume that there is a possibility of failure. Let is assume, that:

- Wedge failure provoked that EN condition would not be fulfilled in 2 anchors, two times during service live and their replacement would be necessary.

\[ C^m_{et} = C_r + C_{pm} + C_m + 0.33 \cdot C_l \]

- \( C^m_{et} \) - Expected total cost,
- \( C_r \) - Cost of design and construction,
- \( C_{pm} \) - Cost of routine maintenance,
- \( C_m \) - Cost of monitoring system, maintenance included,
- \( C_l \) - Cost of failure and repair,

\[ C^m_{et} = 60.000.000EUR + 12.000.000EUR + 720.000EUR + (0.33 \cdot 9.961.811,8) = 76.007.398EUR \]
c. Benefits

\[ B = C_{et} - C_{et}^m \]

- Benefits,

\[ B = 81.961.811EUR - 76.007.398EUR = 5.954.413EUR \]

Roughly estimated benefit as a result of SHM application: 5.954.413EUR

Option No.2

Proposition of the “SHM profitability” equation:

On the base of the proposition: E-M sensors, monitoring devices deployed on every particular stay

a. Without monitoring:

\[ C_{et} = C_t + C_{pm} + C_{f2} \]

- Expected total cost,

- Cost of design and construction,

- Cost of routine maintenance,

\[ C_{et} = 60.000.000EUR + 12.000.000EUR + 7.850.000 = 79.850.000EUR \]

b. Monitoring included

\[ C_{et}^m = C_t + C_{pm} + C_m + 0.33 \cdot C_{f2} \]

- Expected total cost,

- Cost of design and construction,

- Cost of routine maintenance,

- Cost of monitoring system, maintenance included,

\[ C_{et}^m = 60.000.000EUR + 12.000.000EUR + 720.000EUR + (0.33 \cdot 7.850.000) = 75.310.500EUR \]
c. Benefits

\[ B = C_{ct} - C_{cm} \]

\( B \) - Benefits,
\[ B = 79,850,000\,EUR - 75,310,500\,EUR = 4,539,500\,EUR \]

Roughly estimated benefit as a result of SHM application: 4,539,500EUR
6. CONCLUSIONS

Theory of 2 rooms, 1 monitored:

Very rich man, well known as a mean person, decided to locate his whole estate in specially built house. He did not want to listen specialists in the field of security and he decided to deploy cameras only in the intermediate room, he said: ´´Why do I have to pay for something that do not gives me any additional comfort, I have got thick walls and iron doors to my treasure-house, it is good enough´´

![Figure 59](image)

He lived in this fabulous confidence till one sunny day, when he entered his beloved chamber and realized that something is new and something is missed. New was big hole in the wall and missed was his gold that he was gathering for so many years. Cameras in the next room did not help.

![Figure 60](image)
Because of this sad incident, he had to leave his beautiful house and he lost his friends.
Now he works as a specialist for hazard avoidance and he always advises maximum possible safety measures. He promised to himself: “I will never do anything again, without full control over”.

Basing on the calculations and assumptions, initial implementation of Structural Health Monitoring brings profits, numbers shows exactly, that expectations are fulfilled.

In the opinion of author, it is more reasonable to use elasto-magnetic sensors for the force measurements, pros:

- Lower price,
- Accuracy, under 1 MPA (Jarosevic, 2008)
- Not exposed to the external aggressive environment,
- Avoidance of anti-vandalistic actions.

This is money that is visible and can be used in order to improve another parts of the structure.

In case of accelerometers:

In the opinion of author, employment of these devices is a great solution for periodical monitoring.

Commonly slogan: Accelerometers are profitable because can be used for the force and vibration measurements as well. It is not truth from the economical point of view, because accelerometers for the force measurement have to measure its motion only in 1 dimension, whereas measurements of vibration should be conducted in 3 dimensions, using so called 3D accelerometers, that are more expensive.

Cons:

- Expensive,
- Accuracy, 1% (VCE, 2008),
- As an external devices, exposed to vandalistic and negative environmental factors,
- Enormous quantities of cables for devices connection in one system, 
  (possibility of avoidance in case of wireless network)

Summarizing: In the opinion of author, the best solution is deployment of elasto-magnetic sensors on every stay and purchase of the one accelerometer for periodical measurements of vibration amplitudes and damping.
7. LITERATURE

- Caetano E: “Cable Vibration in Cable-Stayed bridges”, IABSE, Zurich, 2007
- Biliszczuk J: „Podwieszony most przez Wisle w Plocku”, DWE, Wroclaw, 2007
8. SOURCES OF FIGURES

Joint work under redaction of Jan Biliszczuk: „Podwieszony most przez Wisłę w Plocku”,

Figure 1: Author
Figure 2: Author
Figure 3: Author
Figure 4: Author
Figure 5: Author
Figure 6: Author
Figure 7: Wikipedia
Figure 8: Wikipedia
Figure 9: Wikipedia
Figure 10: Wikipedia
Figure 11: Wikipedia
Figure 12: Wikipedia
Figure 13: Wikipedia
Figure 14: Wikipedia
Figure 15: mageba sa
Figure 16: Dywidag
Figure 17: VCE (Vienna Consulting Engineers)
  Joint work under redaction of Jan Biliszczuk: „Podwieszony most przez Wisłę w Plocku”,
Figure 18: Wikipedia
Figure 19: mageba sa
Figure 20: Futurtec
Figure 21: VCE (Vienna Consulting Engineers)
Figure 22: Futurtec
Figure 23: Futurtec
Figure 24: Author
Figure 25: Author
Figure 26: Author
Figure 27: Author
Figure 28: Author
Figure 29: Wikipedia
Figure 30 VCE (Vienna Consulting Engineers)
Figure 31 Wikipedia
Figure 32 VCE (Vienna Consulting Engineers)
Figure 33 VCE (Vienna Consulting Engineers)
Figure 34 Dynamag
Figure 35 Author
  Joint work under redaction of Jan Biliszczuk: „Podwieszony most przez Wisłę w
Figure 36 Płocku”,
Figure 37 Dynamag
Figure 38 Dynamag
Figure 39 Dynamag
Figure 40 Mekano4
Figure 41 Mekano4
Figure 42 Dynamag
Figure 43 Wikipedia
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Figure 44 Płocku”,
Figure 45 GDDKiA Poland
Figure 46 Tender drawing
Figure 47 Tender drawing
Figure 48 Tender drawing
Figure 49 Tender drawing
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Figure 52 Tender drawing
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Figure 56 Google Map
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