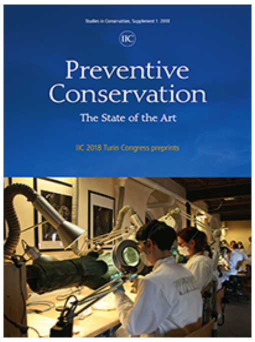

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A Model for Vibration Monitoring of Immovable Art in Churches: Reflections on Monitoring as a Tool for Preventive Conservation

Anna Henningsson

Disent AB, Stockholm, Sweden

ABSTRACT
During construction of a 6 km long railway tunnel close to historic churches in Stockholm, a preventive monitoring model was applied for ensembles of large-scale immovable ecclesiastical artworks. Construction work such as blasting and pile-driving took place during five years under or very close to these immovable works of art. In Sweden, risk assessment related to construction work is focused on risks associated with the building; meanwhile, there is no common approach for protecting the immovable historic works of art and architectural surfaces. This paper discusses how a preventive model for vibration monitoring on immovable artworks was developed and used as well as how the preventive purpose was perceived by different stakeholders during and after the tunnelling work. Experience from this project concludes that monitoring that includes uniform visual inspection becomes crucial for being able to protect the artworks. The concept of vibrations standards relying on fixed numbers of critical vibrations levels for mitigating the effects of vibration on immovable art can be questioned based on experiences from this project.

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Immovable artworks; vibrations; monitoring; condition survey; preventive conservation; tunnelling; altarpieces

Introduction

From 2007 to 2014, a 6 km long railway tunnel was constructed under the bedrock of Stockholm. Construction work, including blasting and pile-driving, took place under or very close to five historic churches in the city. In these churches, extensive ensembles of immovable artworks such as large-scale altarpieces (Figure 1), wall paintings, pulpits and sculptures of wood, stone, and stucco are present. In Sweden, risk assessment related to construction work is focused on risks associated with the building. As a consequence, risk mitigation activities are geared towards structural aspects of the building rather than protection of immovable historic works of art and architectural surfaces integrated into the building. In addition, the immovable artworks in churches in Sweden are sparsely investigated regarding how they were originally constructed and altered over time (Henningsson and Wei 2016, 64–65). These circumstances in combination with the limited research and experience with vibrations from construction work and its possible effects on immovable artworks led to the development of a *preventive model* customized for large-scale immovable works of art for the churches within this project.

This paper discusses how this model for vibration monitoring of churches' immovable artworks was developed and used. This will be followed by a discussion of the different project stakeholder's perception regarding the outcome of the model's preventive purpose and usage during the tunnelling work as well as today – after the tunnelling project has been completed.

The Stockholm City-Line project

The City-Line project included the construction of a main tunnel, several service tunnels, and new underground stations. The tunnelling techniques used were blasting in combination with pile-driving. In large infrastructure projects like this, potential risks refer only to structural damage to the building itself and serve to establish the responsibility for damage due to vibrations and groundwork. As a consequence, the overall building construction of the churches was examined by experts whose framework is defined by a standard[1] specific for buildings. The aim of this standard is to establish the responsibility for damage due to vibrations and groundwork. In addition, this standard is the basis for setting permissible vibration levels. *But how to capture and mitigate the risks due to vibrations for immovable works of art?* This standard does not include any approach that aims to *prevent* damage to the buildings' immovable works of art (RAÄ 2010, 1–19). There was no other specific framework defining how to conduct pre-inspections and monitoring of architectural integrated artefacts before any vibration related building work.

The developer of the train tunnel was the Swedish state through the governmental Swedish Transport Administration which also managed the project. The

CONTACT Anna Henningsson info@disent.se Disent AB, Eastmansvägen 29, Stockholm 113 61, Sweden

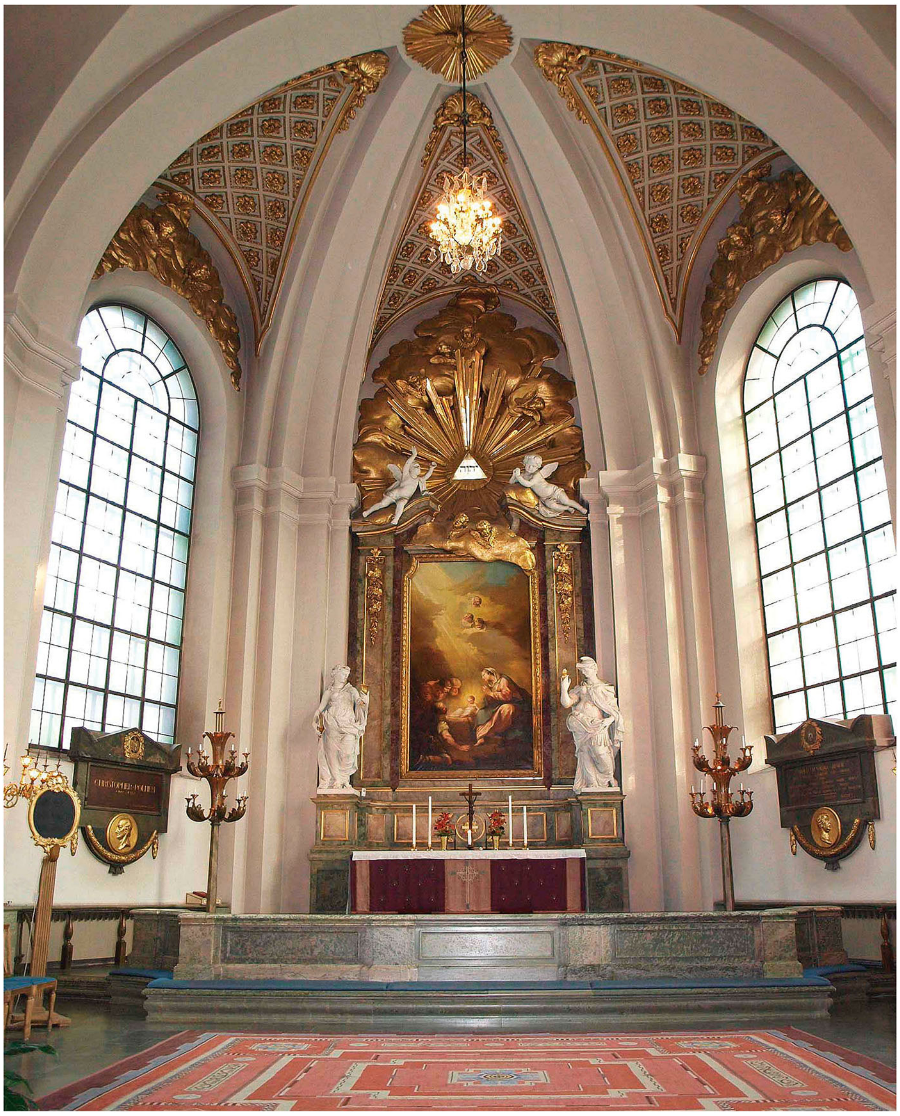

Figure 1. The altarpiece in Maria Magdalena Church, Stockholm. Photo: Anna Henningsson.

church buildings and artworks are the property of a non-governmental organization, the Church of Sweden. The Swedish government demanded that the tunnelling work should be undertaken such that it did not affect the historic buildings (Hultberg and Pamp 2011, 13). The churches are protected by the Swedish Heritage Conservation Act.[2] An inter-disciplinary expert group of blasting experts, building and tunnelling engineers, conservators, and art historians was set up for developing a working model for identifying, mitigating, and monitoring risks related to the immovable works of art.

Knowledge of the effects of vibration

In the field of cultural heritage, the effects of vibration on historic materials have been a recurrent topic for discussion (Henningsson and Wei 2016, 10–12). Despite this, there is limited knowledge addressing *when and how* different types of vibrations can affect the diversity of historical materials and their construction and condition (Wei, Krumperman, and Delissen 2011, 2). In 2007, as this project started, research on vibration and its impact on historic materials in artworks was very limited with a focus on risk due to high-velocity (mm/s) (RAÄ 2010, 1–19). Aspects related to the duration or direction of vibration was not a part of the discourse on vibration at this time (Henningsson and Wei 2016, 61–63). As a consequence, identification of risks related to vibration of immovable art was occasionally based on empirical and individual perceptions about possible effects on these objects. Additionally, these estimates were based on the response of a single material. That artworks set into architectural spaces involve the interaction of different materials reduces the practical application of a fixed definition of vibration levels.

Based on this background the City-Line project in Stockholm decided to develop a model for this tunnelling project (Figure 2) with the *aim of preventing* damage to the works of art through risk assessment and continuous monitoring of the actual response of the works of art to the tunnelling work.

Figure 2. Construction work close to one of the churches in Stockholm during the City-Line project. Photo: Ask Lenzig.

The City-Line model

Aim of the model

This model was divided into three phases: before, during, and after the construction work. The model's aim was, in a uniform and consistent way, to identify and mitigate risks related to the effects of vibration on these works of art in the different churches.

Before the construction work

This phase consisted of an *in situ* investigation of the materials that constitute the works of art. An understanding of the character of the structural bond of the artefact's original and altered parts or layers became central in this investigation. How the objects are *integrated* into the building structure as well as location relative to the sources of vibrations was of importance as it influenced how vibrations were being transferred into these immovable works of art. Furthermore, there was no information available about earlier conservation treatments and so records of conservation documentation and alterations had to be retrieved by observing the objects.

The reports, drawings, and photographs from these investigations were distributed to the stakeholders, providing insights about the objects' restoration history and current condition: defined as each object's *zero-position* – before the construction work. Included in this zero-position were measurements of the background levels of vibration in the buildings as well as on the sensitive objects. The measurement of background vibrations took place over a long period and resulted in data about which levels and cycles of vibration the objects were already exposed to. It was also a way to learn about the diversity of the object materials and their response to vibrations. Ultrasonic testing was conducted to determine the condition behind the visible surface of stucco objects, and cracks in wall paintings (Figure 3). Alteration in width of cracks was measured. All of the churches were heated and in use so vibration was not the only possible agent of deterioration affecting condition.[3] To be able to trace the specific impact of vibrations more selectively, the relative humidity and temperature were measured in some of the churches.

The initial investigation resulted in a set of preventive actions, which were undertaken before the construction work started. Preventive conservation is rarely conducted related to Swedish church art. Instead, maintenance is focused on active conservation treatments in order to secure the historic art for the future. Preventive thinking aiming to reduce risks and manage changes was new for the stakeholders. A distinction was made between *indirect* and *direct* preventive solutions. The following definitions were agreed:

Indirect preventive conservation consists of interventions that reduce the impact from the *surroundings* of the work of art in the buildings or its sites. The owners of these indirect solutions were blasting experts, tunnelling constructors, or the railway management board. These actions reduced the intensity of the vibrations or re-directed them away from the most sensitive object. Examples of this were modification of the pile-driving process, or using an electrically controlled blasting method.

Direct preventive conservation had a remedial character with direct action on the artefacts by a conservator, but unlike 'traditional' remedial conservation treatments, the direct preventive conservation in this context strived to be completely reversible and purely *temporary* – in place during the tunnelling

Figure 3. Ultrasonic measurement of cracks and cavities in architectural surfaces. Photo: Anna Henningsson.

work only. An example of a direct preventive solution within this project was the application of temporary facings over particular risk zones in stucco or plaster in the upper parts of altarpieces.

This distinction made it easier to communicate who was responsible for the preventive solutions and involved a broad set of different stakholders and experts within the project. A set of preventive solutions (indirect and direct) was prepared as part of a *preventive risk preparedness plan*, to be applied if needed. An example was a reversible supportive construction to dampen and interrupt the vibration transmittance from a wall in the building to a sensitive large-scale altarpiece.

During construction work

The objects defined to be at risk during the *in situ* investigation were monitored during the entire construction project. In these large-scale objects, monitoring areas were selected based on the risks identified. One larger scale altarpiece had 164 monitoring areas for regular inspection (Figure 4). Vibration data was continuously measured (at different heights on the art objects and the building structure) and correlated with daily or monthly *visual inspections* of the objects and their response. Works of art were monitored for possible changes in their surfaces, between structural parts, or in the zones where the works were integrated into the building.

Object monitoring was carried out in a uniform manner for ensuring traceability in observed changes in the artwork's materials. This meant, for example, that the lighting was always the same for each inspection (Figure 5). Digital images were used as a basis for the visual inspection. If a visual alteration was registered on an object, a comparison with the digital *zero-point images* was undertaken *in situ* – in front of the object – by someone other than the person who first detected the change. The monitoring resulted in monthly reports for the stakeholders. The report contained the interpreted and measured vibration levels, results from visual inspections, crack measurements, and deformation measurements within the building in relation to the position of the large-scale artworks.

Monitoring was also connected to the risk preparedness plan. If inspection and measurement indicated any tendency of alteration or signs of change in the materials, extra inspections were established and indirect preventive measurements to reduce the level or adjust the intensity of vibrations taken. The frequency of the visual inspections could also be increased if the agreed level of vibrations inadvertently exceeded the maximum level set. Then the construction work stopped until the cause of the exceeded level was investigated, and extra inspection of the objects had been undertaken.

After the construction work

When the construction work was completed, final inspections of each object took place. The drawings and the images gathered in the first stage were used as baselines representing the zero-position. The condition of the objects was examined for changes in, for example, surface condition, or wear in joints between supportive elements, or anchors between

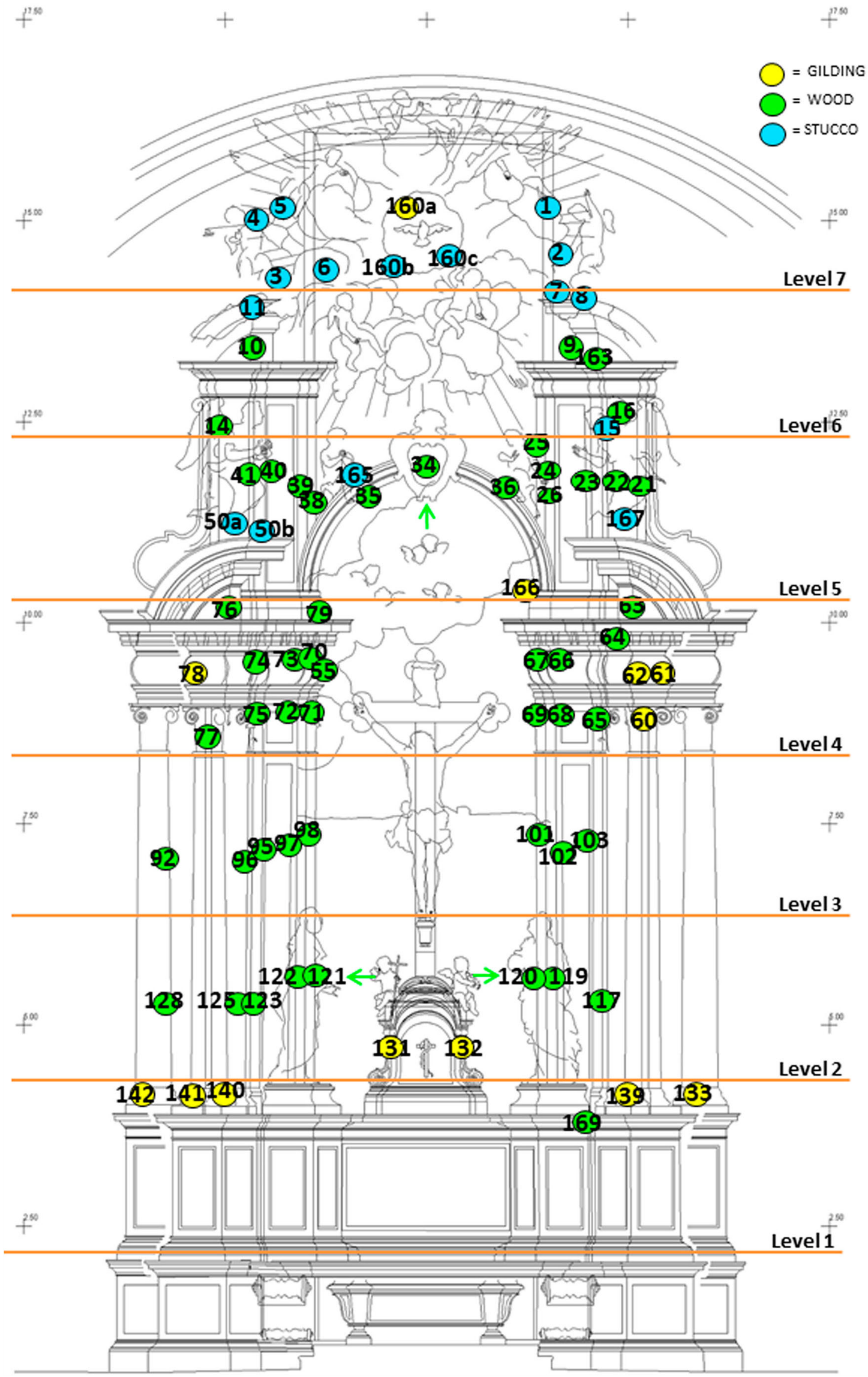

Figure 4. A freestanding 15 m altarpiece had 164 monitoring areas. Photogrammetric drawing: Fokus GmbH Leipzig.

Figure 5. Visual monitoring of a sensitive portion of an altarpiece. Photo: Anna Henningsson.

building and works of art. All measured vibration and deformation data over the years was evaluated in relation to the monthly and final visual inspections. The internal stability of stucco and plaster areas that were initially investigated with ultrasonic measurement was re-investigated and the data integrated into the final overall evaluation. It is important to bear in mind that alterations discovered during the project could be due to other environmental factors normally impacting the art, such as climate fluctuation, lighting, or visitors and users of the ecclesiastical buildings. The conclusion was that there were no changes in visual or measured conditions of the artworks in the churches related to vibrations during the period of the tunnel work.

Stakeholder reception of the model

The involved stakeholders were a diverse set of actors; cultural heritage experts, engineers, project managers, church congregations, and governmental authorities. In the beginning, there was anything but consensus regarding the approach to protect the churches and the art from the vibration effects. A recurring question was: *what if something were damaged*? And *could it be repaired*? Each stakeholder's view of damage and repair was different. The property owner the Church of Sweden stated that repair or conservation of the object was not accepted if it became damaged due to vibrations (even if repair would be financed by the developer). The cultural heritage experts noted that the value of a repaired object is not the same as an original artwork.

At the beginning of the project, almost no relevant experience from similar projects with trustworthy, critical, and realistic vibration levels for large-scale artworks similar to these could be found. There were phases in the project planning where the stakeholders just focused on determining a general allowable level of vibrations expressed as velocity in millimetres per second. It was impossible to predict the critical level of vibrations for this diversity of objects. This focus on a definitive allowable level of vibrations was not constructive for the project progress as it resulted in a locked negotiation between the stakeholders. One single vibration level is seldom 'safe' for a large-scale immovable artwork with a diverse set of materials interacting, integrated into a building. Instead, it was agreed on a set of vibration levels for the different objects (depending on each object's value and fragility of construction) to enable prediction, mitigation, and management of potential impacts within the project. This led to a pro-active preventive model of monitoring and risk preparedness becoming the solution that everyone could agree on (RAÄ 2015, 19).

Those most familiar with the preventive approach and integral monitoring were the stakeholders who had an engineering background. Meanwhile, the conservators considered it difficult to observe the art in a uniform and stringent way. Often a bias in observing what was seen and how it was interpreted occurred. When evaluating a crack, the conservators had difficulties determining if it was altered or not by observing it in a subjective way. This became apparent when similar areas were also inspected by non-conservators (building inspectors with an engineering background). What was seen on the objects were older repairs, dust, as well as stable deterioration phenomena such as cracks. In this context, I noted that my profession considered it difficult to observe only *whether* these irregularities had changed – due to impact from a single deterioration agent – due to vibration. The conservators tended to want to *take care of* a tentative change through active conservation rather than just observe if and how changes in the object might have occurred.

Active conservation would have resulted in new materials such as plaster and synthetic adhesives with other properties than the original materials being added on the art objects. In the project meetings with the engineers, critical conservation questions arose such as*: How do we know that conservation treatments do not cause more extensive long-term problems on the objects than the assumed effects from vibration? Or was it just a concern regarding the unknown effects of vibration? And were the objects really in a condition that needed active conservation intervention?*

These questions also raise thoughts regarding any long-term effects from future background vibration from the train traffic in the tunnel under the churches, versus the effects of using conservation products. Infrastructure projects and the limited knowledge of the effects of vibration should not be a justification for conservation treatments that otherwise would not have taken place. The consequences arising from conservation treatments undertaken in this context might be more extensive than the actual effects from vibrations.

Finally, a practical solution to reduce concerns regarding damage due to vibration was that some extra fragile areas were temporarily secured through reversible stabilization with cyclododecane, or by facing with cellulose ether. This also enabled the very crucial aspect that the artworks were preserved as *information sources*, i.e. unaffected by conservation products that otherwise might reduce the future research potential of these materials (Ballestrem 1978, 125–126).

This way of working within a defined model created communication at different levels. The regular inspection of the art on-site showed people working and visiting the churches that the works of art were cared for during the tunnel construction. The new facts about the art that were revealed through inspecting and photography added new value to the ecclesiastical cultural heritage in Stockholm. The diocese of Stockholm stated that this working model ought to be a standard for future projects (Gillsäter 2017, 180).

This is one side of the reception of the model employed here. Another view became apparent at the very end of the project when it was concluded that it went well – neither the art nor the building was not directly affected by vibrations that caused damage. The property owner did not fully agree that there was no new damage – even if it could not be established by visual observation using images or technical measurements.

It might be that the concept of pro-active prevention through management of change was not fully understood and valued by the property owner since preventive conservation in Sweden is not common for churches. The fact that the physical forces caused by vibration are *one of* the agents of deterioration that can cause changes was not fully taken into consideration by the owner and the cultural heritage stakeholders in the project. This reflection is based on the fact that two of the churches were totally renovated after the tunnelling work was completed.[4] The surface finish was renewed and conservation treatments were carried out by the property owner. With this, the potential to use the results of monitoring collected over years to observe potential cumulative aspects of change related to vibrations in the future disappeared. If the preventive approach of *management of change* would have been adapted and considered as a future potential for knowledge regarding long-term effects of vibration, this alternative approach to conservation ought to have been a topic for consideration before treatments were undertaken.

Furthermore, the new knowledge about the art and its response to vibration that were revealed by monitoring, and which could help in future care of the artefacts and similar projects, seems to have fallen into oblivion.

Conclusion

Management of change in architecturally integrated objects due to tunnelling and vibration is a new area for cultural heritage and conservation practitioners.

Experience shows that different stakeholders and professionals perceive value, risk, prevention, and the meaning of long-term management of change very differently. The frequently expressed wish to determine allowable vibration levels and the seeking for a standard that would provide 'safe numbers' in order to ensure that objects are not affected can be challenged. It is difficult to apply 'safe numbers' to the diversity of architectural integrated materials and constructions.

With this awareness, a monitoring approach that also includes visual inspection based on images interpreted in correlation with vibration data becomes crucial for sustainable and relevant management of changes now and in the future. Based on my experience from this and other similar projects, I would like to argue for a shift in the orientation from the concept of vibration standards relying on fixed numbers. The experience from this monitoring is that a high velocity expressed in mm/s does not necessarily have negative effects on sensitive artworks. Seen in this light a uniform case-by-case assessment, as this model practised, can be an efficient and meaningful focus for managing the impact of environmental influences on cultural heritage artefacts. This project has given insight into standards based on fixed allowable vibration levels needing to include a wider thinking on what 'safe numbers' really mean – beyond being an agreement.

Notes

1. Swedish standard SS 460 48 60.
2. Swedish Heritage Conservation Act 1988:950, Chapter 4, section 2: 'Church buildings and church sites shall be cared for and maintained in such a way that their cultural historic value is not diminished and their appearance and character are not debased'.
3. The 'ten agents of deterioration' are described at https://www.canada.ca/en/conservation-institute/services/agents-deterioration.html [Accessed 8 October 2017]
4. Restoration permissions with registration numbers 433-5696-2017 and 433-35489 in the archive of the County Administrative Board of Stockholm.

Disclosure Statement

No potential conflict of interest was reported by the author.

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