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Risk assessment of vibrations caused by groundworks

Risque associé aux vibrations causées par travaux de terrassement

J. Langford
NGI, Oslo, Norway

K. Norén-Cosgriff, S. Lacasse
NGI, Oslo, Norway

T. Sørgjerd
Statsbygg, Oslo, Norway

A. Brekke
Brekke & Strand, Oslo, Norway

G. Koelsch
Multiconsult, Oslo, Norway

ABSTRACT: A new Viking museum is planned in Oslo, Norway. The museum will be built adjacent to the existing Viking ship museum, which hosts three Viking ships and artifacts from the ninth-century. The ground conditions consist of normally consolidated clay, with depths to bedrock varying from 0 -30 m. One of the main challenges for the project is to limit groundworks and construction-induced vibrations to ensure that the artifacts presently the museum are not damaged.

The allowable vibration limits were set at very low levels. Potential vibration levels caused by different construction activities, and their uncertainties, were predicted, based on field measurements at the site and using NGI's database on vibrations from earlier projects.

A risk assessment approach was undertaken to semi-quantitatively assess the risk whether or not the vibration induced by the foreseen construction activities will cause damage to the Viking ships. To assess the risk, a workshop involving stakeholders in the project evaluated the likelihood for exceeding the preset vibration limits and the consequences associated with exceeding the vibration limits. Based on the results, the most critical construction activities were identified and the need for mitigation measures were assessed.

It was concluded that construction traffic, excavation and vibro-compaction were the activities causing largest risk. The stakeholder consensus approach was helpful and successful for identifying the need for mitigation efforts already at an early stage of the project.

RÉSUMÉ: Un nouveau musée des bateaux Viking est planifié à Oslo, Norvège. L'extension sera construite adjacente au présent musée.. On y trouve trois bateaux Viking et nombre d'artefacts du 9è siècle. Les sol de foundation est de l'argile normalement consolidée d'une épaisseur 0 -30 m sur un substrat rocheux. L'un des défis principaux du projet est de limiter les vibrations causées par les travaux de terrassement et de construction qui pourraient endommager les bateaux et artefacts dans le musée actuel.

Les vibrations permissibles ont d'abord été définies comme valuers très basses. Les vibrations causées par les différentes activités de terrassement et construction, de même que leurs incertitudes, ont été estimées, utilisant une base de données du NGI et les données d'expérience venant de projets antérieurs.

Une analyse de risque semi-quantitative a alors été initiée pour estimer si les vibrations endommageraient les bateaux Viking. Une atelier de travail a été organisé, avec des participants de toutes les parties prenantes. Les probabilités de dépassement des limites de vibrations et les conséquences de ces vibrations sur les artefacts ont été estimées. Sur la base des discussions, les activités de terasssement et construction le plus critiques et les mesures potentielles d'atténuation ont été identifiées.

Il a été conclu que les traffic de construction, les travaux de fouilles et le vibro-compactage étaient les activités causant les risques les plus élevés. L'approche consensus fut très utile et permit d'identifier les mesures d'atténuation nécessaires dès le début du project.

Keywords: Risk assessment; construction vibrations; goundworks

1 INTRODUCTION

A new Viking museum is planned on the Bygdøy peninsula, outside of Oslo in Norway. The new museum will be build as an extention of the existing Vikingship museum, where one of the largest collection of artifacts in the world dating from the Viking age is displayed. The collection consists of the three ships Oseberg, Tune and Gokstad and objects found on these ships (Figure 1). The ships dating back to the 800-900s were discovered and excavated between 1867 and 1904. The existing museum was buildt in the period 1917 to 1957.

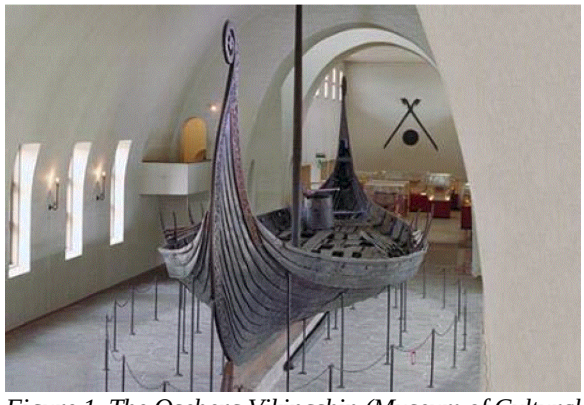


Figure 1. The Oseberg Vikingship (Museum of Cultural History, University of Oslo,CC BY-SA 4.0).

The collection is very fragile and has been suffering from being diplayed in a building with poor control of the indoor climate. In fact, the main reason for planning the new museum is to optimize indoor temperature and humidity, as well as reduce the deterioration due to cleaning dust from the ships.

The most fragile objects in the museum are the smaller wooden artifacts which have been alum-treated. Figures 2 and 3 show the Gustafson sleigh which has been remounted from small pieces of wood using glue, filler, nails and pins.



Figure 2. The Gustafson sleigh (Museum of Cultural History, University of Oslo,CC BY-SA 4.0).

One of the main challenges for the project is to limit construction-induced vibrations to ensure that the artifacts in the existing museum are not damaged.

This paper presents a risk assessment undertaken during early planning, to identify risk scenarios and to plan mitigating measures for the geotechnical work early in the project.

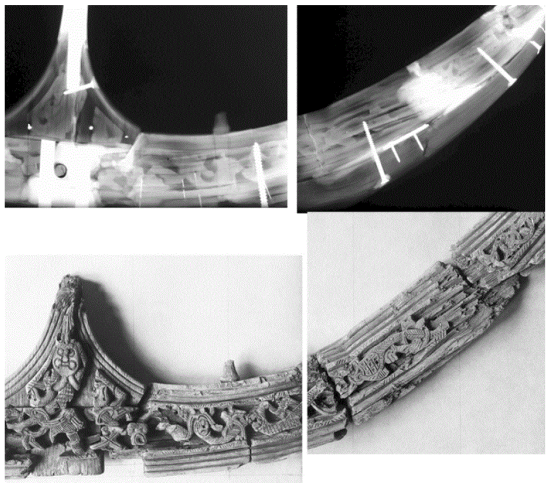


Figure 3. X-ray of part of sleigh showing glue, fill, screws and pin (Museum of Cultural History, CC BY-SA 4.0).

2 THE NEW VIKING MUSEUM

2.1 Site conditions

The ground conditions at the site is typical for Oslo. The site is covered with close to normally consolidated soft clay deposited after the last ice age. The depth to bedrock is 0-30 m. The clay is quick with water content w_n ranging from 35-45%, plasticity index I_p ranging from 10-20% and an undrained shear strength corresponding to $0.3\sigma'_{v0}$, where σ'_{v0} is the *in situ* effective over-burden stress.

2.2 The existing museum and its extension

The new museum is planned as a circular building which will be attached to the north and west wings of the existing museum (Figure 4).

The existing museum has wings named after the three Viking ships, Osberg, Tune and Gokstad, which are displayed in each of the wings (Figure 4). The fourth wing will not contain sensitive artifacts during construction and was therefore not considered in the risk assessment.



Figure 4. The new Viking Age Museum including existing museum and three main wings (AART Architects).

2.3 Planned geotechnical work

The new museum will be built with one to two basement levels, with excavation down to 6 m beneath the ground level. The excavation is planned to be performed unsupported, using stabilisation with lime cement columns. The excavation will also require excavation of bedrock over a smaller area. Blasting is not possible due to restriction on vibrations.

The new museum will be founded on steel core piles. This pile type is chosen since pile driving is not possible due to restriction on vibrations. The steel core piles are installed by drilling an outer casing into bedrock. Inside the casing, a steel core pile will be cast in place. The pile type was choosen due to restrictions on vibrations.

There will possibly be a need for foundation improvement of one of the existing museum wings. This is planned by underpinning, using jet-columns.

The following construction and groundworks activities are planned as listed below, in the order of execution:

1. Construction traffic
2. Installation of lime-cement columns
3. Jet-stabilisation
4. Installation of sheet pile wall (silent piler)
5. Excavation lime sement stabilised soil

6. Excavation inside atrium
7. Excavation of rock (shiseling or wire-cutting)
8. Drilling for piles
9. Groundworks for water and waste water system
10. Backfill and vibro-compaction

3 VIBRATIONS

3.1 Allowable vibration thresholds

Due to limited information about which vibration loads the artifacts have been exposed to up until now and how much they can sustain without being damaged, a precautionary principle was applied when setting the thresholds: the construction process shall not cause any additional vibration loads on the artifacts. Hence, the vibration limits were based on measured levels of vibrations on the floors in the current museum during normal opening hours.

The resulting vibration limits were therefore set to very low values compared to what is usually done on construction projects. Vibration isolation are planned for the Gokstad ship and for the sledges in the Tune wing during the groundwork, see Figure 2 and 4. These mitigation measures then allowed the limit values to be set to somewhat higher values. However, they are still very strict.

To ensure full control of the exposure to vibration, the limits were set on the floor in the existing building, and not on the building foundation as usually is the case for construction-induced vibrations. The limit values on the floors in the museum were between v_{peak} = 3 - 5 mm/s. These limit values apply to frequencies between 1 Hz and 80 Hz. These limit vibration values were given as "stop limits", i.e. the construction work will be stopped if the limits are exceeded.

3.2 Estimated vibrations from groundworks

Potential vibration levels caused by different construction activities were predicted using NGI's database with measurements from earlier projects. Since the measurements for the cases in the database were in general not performed within the distances similar to those planned for at the Viking Ship Museum, the vibration values were converted to vibration values within the relevant distances for the museum. The conversions were done with the following equation:

$$L_{vx2} = L_{vx1} + C_j \cdot (x_2 - x_1) + 20 \cdot \log\left(\left(\frac{x_1}{x_2}\right)^{\frac{1}{2}}\right)$$

where:

L_{vx} = vibration level in x meter distance from source in $dB=20 \cdot log(v/10^{-6})$

C_j = damping in 1/3-octave bands determined from measurements on the ground outside the Vikingship museum

The measurements in the database were mostly performed on the ground close to different vibration sources. To compare the estimated vibration values with the allowable threshold values, the vibration values were recalculated to vibrations on the floors inside the museum.

With respect to vibration amplification from ground to floor, all buildings have different characteristics. Site-specific characteristics need to be used. Measurements of transfer functions from outside ground to floors inside were therfore performed at the Vikingship museum's site.

The distance attenuation and transfer functions were measured using a 50 kg drop weight, and lorry passing a wooden board (Figure 5).

Simultaneous measurements of vibrations were performed in several positions on the floors in the museum's four wings, and outside on the ground. The distance attenuation and the transfer functions from ground outdoors to the floors in the museum's four wings were determined from the measured difference in vibration velocity in

the various measurement positions. An example of results is shown in Figure 6.

As illustrated by Figure 6, the coherence is excellent in the low frequency area, but decreases for the higher frequencies. This is as expected since the higher frequencies attenuate more rapidly with distance, and to less extent, propagate upwards from ground to the floors in the building.



Figure 5. Excitation from a lorry passing a wooden board (left) and a 50 kg drop weight (right)

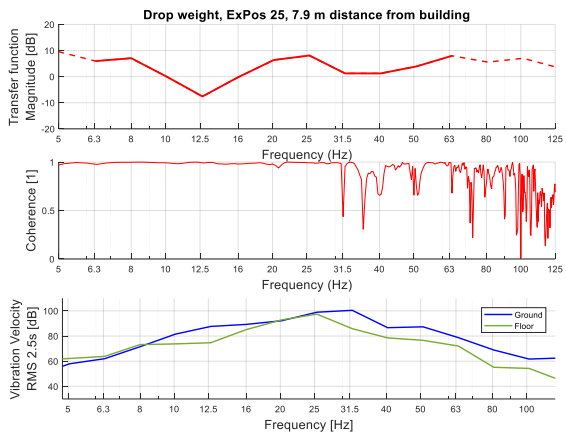


Figure 6. Example of measurement results. Top: Transfer function from ground outside to floor in the Tune Wing. Middle: Coherence between measurements on ground and on floor. Bottom: Measured vibration velocity on ground close to the building foundation and on floor.

During the data analysis, it became evident that the transfer functions were different for excitations at larger longer distances from the building compared to excitations close to the building. Excitation at longer distances seemed to set up vibrations in the floors more efficiently. Therefore, two sets of transfer functions were adopted, one to be used for construction activities less than 10 meters from the building, and one for activities more than 10 meters from the building.

The methodology used to estimate vibrations from construction activities on the ground floor in the museum is summarized in Figure 7. Examples of the calculations are shown in Table 1. Estimated vibration values (vibration velocities) above the limit values are shown with red background colour in the table, while values below the limit value are shown with green background colour.

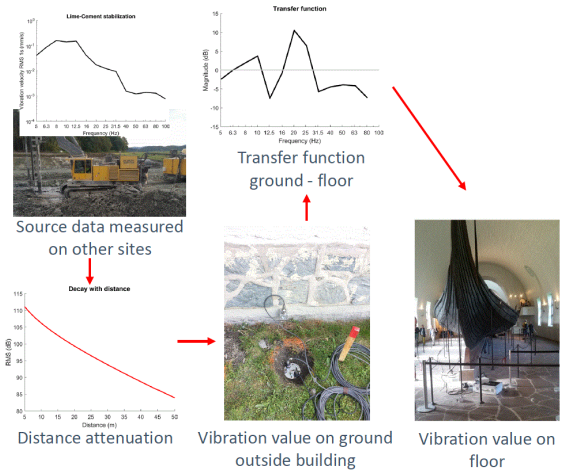


Figure 7. Methodology to estimate vibrations from construction activities on floor in the museum.

Table 1. Estimated vibration values on floors in museum caused by different construction activities.

No	Activity	Min. distance to exposed wing (m)	Vibration velocity (mm/s)
1	Construction traffic on unpaved road	10	5
2	Lime cement stabilization	2	3
3	Jet stabilization	23	1
4	Sheet piling, vibro	20	5
4	Sheet piling, silent piler	20	1
5	Excavation	10	> 5
7	Rock excavation	4	3
8	Pile drilling	12	< 3

9	Vibro compaction	5	> 5

4 RISK ASSESSMENT AND MANAGEMENT

In ISO 31000, risk is defined as the effect of uncertainty on objectives. In the project, the objective was to build an new museum with as low risk as possible or, preferable, no risk of damage to the Viking ships and other museum artifacts. A risk assessment was undertaken to identify and evaluate the risk for damage on the museum collection caused by vibrations from the planned construction activities.

The assessment was undertaken in a workshop format based on the ISO 31000/NS-EN 5815 framework, with participants from the project stakeholders: Statsbygg (client), Hjellnes Consult/Multiconsult (main consultant), Brekke & Strand (expert on vibrations, main consultant for the safety project), NCC (contractor with expertise related to methods, equipment and execution) and NGI (expert on vibrations, geotechnical consultant). No representative from the museum participated.The aim of the workshop was to identify risk-scenarios, uncertainties and evaluate the risk, and to aid the decision process for choosing construction methods and mitigating measures, where needed.

The workshop resulted in a qualitative risk matrix of likelihood of damage vs. consequence class, using an adapted tool developed by Vangelsten et al. (2016).

The workshop covered the first four steps in the following risk assessment process:

1. Establishing context: critereas for risk acceptance, qualitative descriptions of likelihood and consequence classes
2. Risk identification: Review of planned construction activies.
3. Semi quantitative risk analysis:
   - How likely is the occurrence?
   - What are the consequences?
4. Risk evaluation: Is the risk acceptable?
5. Risk mitigation: Where risk is high, what measures can be taken to reduce the risk?

The last step will be covered in the next project phase.

4.1 Likelihood and consequence class

The first step at the workshop was to define likelihood classes and consequence classes for the assessment. After thorough discussions, the workshop participants agreed to define the likelihood and consequence classes qualitatively. Five classes were defined for both the likelihood and consequence. The likelihood was assessed with five classes from "very unlikely that the event occurs" to "the event occurs" (Table 2). The consequence was assessed with five classes from "harmless" (no damage) to "catastrophic" damage (Table 3).

Table 2.Verbal description of likelihood classes.

Probability class	Qualitative description
1	Event occurs
2	Likely that event occurs
3	As likely as not
4	Event will likely not occur
5	Very unlikely that event occurs

Table 3. Verbal description of consequence classes.

Consequence class	Qualitative description	Description in NS5815
1	No damage	Harmles
2	Reparable damage	May cause harm
3	Critical damage	Critical
4	Very critical damage	Very critical
5	Catastrophic damage	Catastrophic

4.2 Risk acceptance

The workshop participants discussed the acceptance levels for the project and came to a consensus on the risk matrix shown in Figure 8.

The matrix agreed on has a strong risk aversion, due to the requirement on low to no risk related to damage on the museum objects.

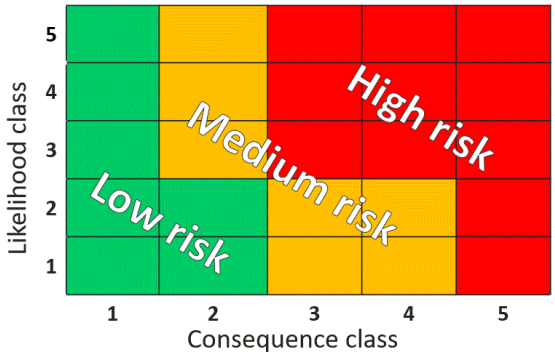


Figure 8. Consensus on risk levels in the risk matrix.

4.3 Discussion and results – risk matrix

For all planned construction activities, the expected vibrations were estimated. The likelihood of the construction vibration exceeding the vibration limits were discussed in the workshop. For each activity, the three museum wings were given a likelihood class for exceedance of the vibration limits. Similarily, for each activity, the three museum wings were given a consequence class for possible damage due to exceedance of the vibration limits.

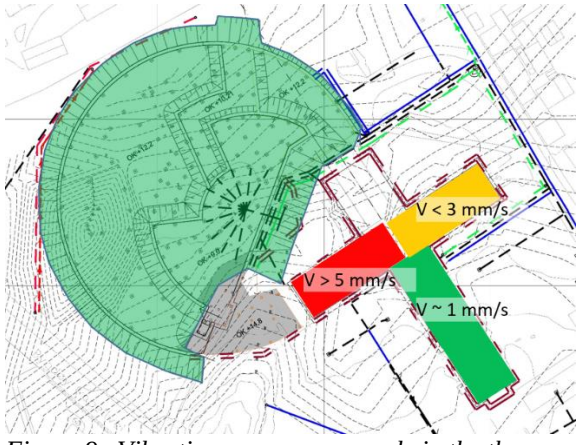


Figure 9. Vibration response example in the three existing museum wings, from Activity no 5: excavation of lime-cement stabilized soil (pale green area).

Figure 9 gives an example of the calculated vibration levels on the three museum wings (v_{peak} =1-5 mm/s), caused by excavation for the new building. The colour illustrate the magnitude of the calculated vibrations: green – below limit, yellow- close to limit, red-over limit values.

The risk matrix in Figure 10 summarizes the assessment of the likelihood class and consequence class for the three museum wings and all construction activities. In the risk matrix, cells have a symbold composed of numbers and letters (*n:m-S*). The first number in the each cell corresponds to the construction activity (list in paragraph 2.3); the second number identifies the museum wing (1=Oseberg, 2=Gokstad, 3=Tune). Lastly, the letter S identifies the consequence class S, which is damage to ships or artifacts (Norwegian: ***S**kade*). Othe consequences will be assessed in the next project phase, such as financial, time for construction and effects on surroundings.

Several of the planned construction activities represent a high risk of exceedance of the vibration limits and potentially causing damage to the Viking ships and artifacts.

Especially Activity 1. (Construction traffic), Activities 5. and 6. (Excavation), Activity 9. (Groundworks for water and waste water system) and Activity 10. (Backfill and vibro-compaction) will have to be further evaluated and risk reducing measures need to be undertaken.

5 CONCLUSION AND FURTHER WORK

The workshop based risk assessment was successful in:

- Identifying risk scenarios in a systematic manner
- Evaluating the level of risk associated with different groundworks and construction activities
- Identifying the activities that need to be further investigated and where mitigating measures need to be planned for.

In addition, the assessment was useful for enhanced communication amongst the stake-holder and will aid "risk-informed" (ISO 2394:2015) decision making process in the future.

The risk assessment will be revisited and revised during the next project phase to take into account possible new design conditions, such as revised vibration limits. In the meantime, additional data will be collected to fill in information gaps. Lastly, the assessment will also be updated with respect to vibration reducing measures. Representatives for the museum will participate in the revision of the risk matrix.

To ensure that all aspects are vibration and construction aspects will be understood and followed through all the way from ground breaking to building construction, the contractor will also be involved in the risk assessment, to help with their planning and execution of the work.

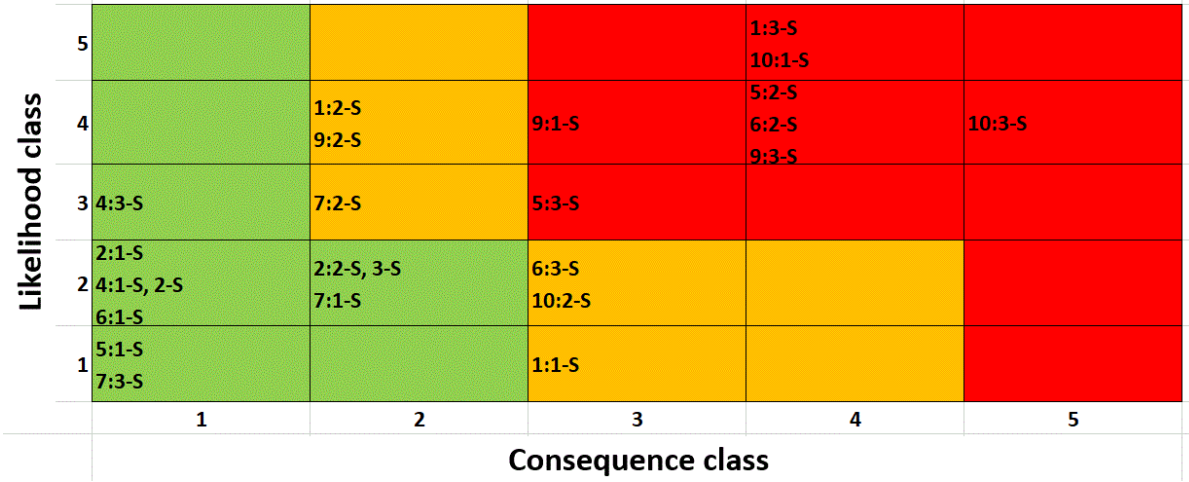


Figure 10. Risk matrix after workshop consensus, with each cell giving n:m-S, where n is the construction activity number m the museum wing (1=Oseberg, 2=Tune, 3=Gokstad) and S is the damage consequence.

6 ACKNOWLEDGMENTS

The Museum of Cultural History/The University of Oslo are acknowledged for providing photos of the museum artifacts. NGI also thank the workshop participants for their contribution to the risk assessment.

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