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Protection of ancient Viking ships from vibrations caused by groundwork

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ABSTRACT

A new Viking Age Museum is planned in Oslo, Norway. The museum will be built very near to the existing Viking Ship Museum. The ground conditions mainly consist of soft clay, and it is a concern that vibration from the groundwork will be transmitted to the existing building and cause damages to the collection. The museum objects are three Viking ships and many other smaller objects. Most of the objects are very fragile. This paper describes the work that has been done to set vibration limits, which will give reasonable protection of the museum objects, measurements of vibration transmission from the ground to the museum floors and the museum objects, and calculations of vibration exposure from groundwork. The measurements and calculations show that a prerequisite for vibration limits not to be exceeded are that some of the objects will have to be vibration isolated, and that construction methods are chosen that provide low vibration values.

Keywords: Vibrations, groundwork, fragile artefacts
I-INCE Classification of Subject Number: 40, 76

1. INTRODUCTION

A new Viking Age Museum is planned at the site of the current Viking Ship Museum in Oslo. The museum displays one the world's largest collections of artefacts from the Viking era. This includes three ships Oseberg, Gokstad and Tune dating back to the 800-900s, excavated in the period 1867-1904. In addition to the ships, several smaller items were found during the excavations. This includes textiles, jewelleries, wood carved animal heads, a cart and three sleighs from the Oseberg find.

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For preservation the smaller wooden objects were alumtreated, a technique that has proved to make the items very fragile over time. The ships, however, were only airdried and their materials are far more robust. Material tests on smaller wood samples from the Oseberg ship show that it's Young's modulus is about 60% of that of new oak (4). Common for the ships and most of the objects is the use of nails and pins together with glue and filler for reconstruction. This results in several weak and brittle connections with unknown mechanical properties. The Oseberg ship and Gustafson's sleigh are shown in Figure 1.

Figure 1 The Oseberg ships and Gustafson's sleigh (Museum of Cultural History, University of Oslo, CC BY-SA 4.0)

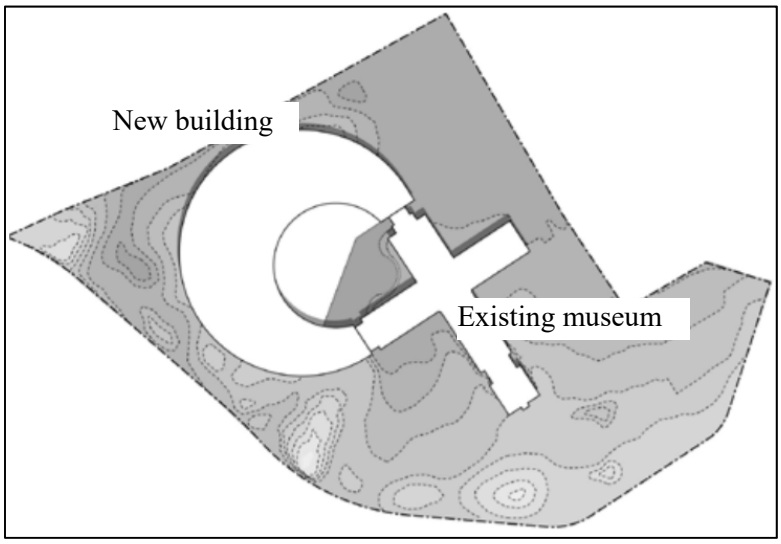

Figure 2 New building connecting to existing museum (Statsbygg)

The existing museum consists of four wings built in the period 1917-1957 with one wing for each boat (Oseberg, Tune and Gokstad) and a separate wing for the smaller artefacts (Fourth wing). The new building forms a quadrant connecting to the end of two of the existing wings, see Figure 2. The main motivation for the new building is a need for better climate control, maintenance facilities, safeguarding the collection, and better presentation of the objects to the visitors.

The site has typical ground conditions for the Oslo area, with a 0-30 m layer of soft clay covering the bedrock. Pillars, pile foundations and concrete walls on bedrock form the foundations for the existing building. Currently, the exhibition is situated at ground floor and a basement below the exhibition is used for storage and offices.

Vibrations due to construction work at the site is one of the main risks. To reduce the risk of vibration induced damages to the collection extensive work has been conducted to establish vibration limits, to estimate vibration values from planned groundwork, and to find suitable groundwork methods which give vibration values below the limit values.

2. ESTABLISHMENT OF VIBRATION LIMITS

When determining the vibration limits, both risk of damage due to fatigue and damage caused by single events must be addressed. Damage can be caused by high loads over one or a limited amount of cycles, or by lower loads over longer time. This principle is shown in Figure 3. The fatigue limit is the highest load the material can be exposed to for an unlimited amount of load cycles without causing damage. This also applies to the ships and artefacts at the museum. Preferably, the vibration limit should be set so that groundwork does not exceed the fatigue limit.

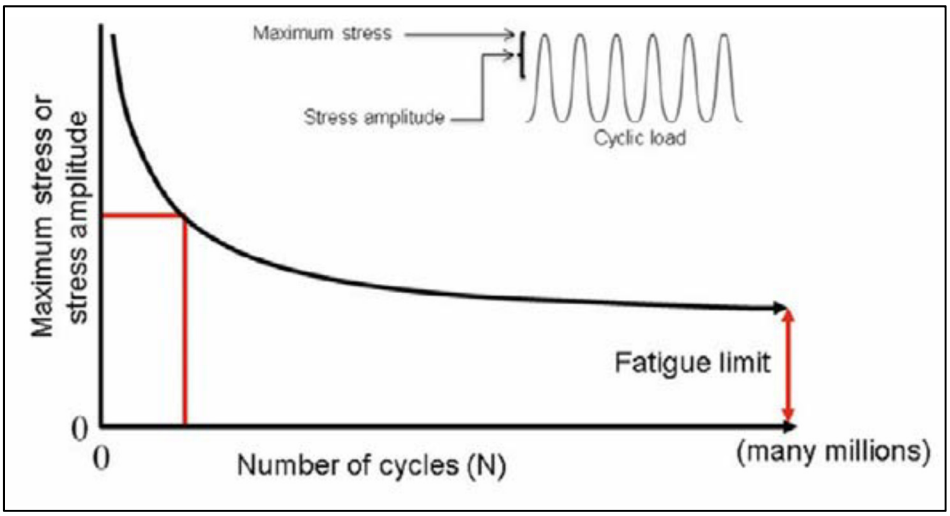

Figure 3 Material damage as function of load and number of load cycles (1)

The ships' and artefacts' complex structures and unknown mechanical properties makes it impossible to find exactly at what levels vibration loading will cause damage. Presuming the vibrations in the museum as it is today is lower than the fatigue limit, the basis for setting the vibration limit for groundwork is that it should not give higher vibrations at the artefacts than what they are exposed to already.

Having set the vibration limits for groundwork, appropriate groundwork methods satisfying the vibration limits need to be chosen. In order to do this, expected vibration values caused by different methods must first be found.

2.1. VIBRATION LIMIT PARAMETER

When conducting groundwork, the contractors will have to ensure that the vibration levels in the museum do not exceed the limits given. Thus, the limits must be given in a way that is easy to monitor and the contractors must have experience using the chosen parameter.

Peak velocity levels, v_{peak}, are widely used in vibration monitoring during blasting and construction work and is easy to monitor with real time alarms if given levels are exceeded. v_{peak} has also been used when setting vibration limits at other museums housing fragile items. Examples of vibration limits in other museums are given in Table 1 (1,2,3).

Table 1 Vibration limits in other museums (1 ,2,3).

Situation	Type of work	Vibration limit, v_{peak}
Art museums in Amsterdam	Construction work	2 mm/s
National museums of Liverpool		Warning: 2,5 mm/s Stop: 3 mm/s
The Modern Wing, Chicago		2,5 mm/s
Saint Louis Art Museum		3 mm/s
Sullivan Ach. Chicago	Piledriving	5 mm/s
Taff Museum of Art, Ohio	Construction of Metro culvert outside	3 mm/s
Mesopotamian Relief, Oriental Institute Museum, Chicago	Construction work	1,5 mm/s Extremely fragile reliefs

When monitoring vibrations to prevent building damage it is customary to measure at the building's foundations. In the case of safeguarding the artefacts in the museum it is more relevant to monitor the vibration levels at the objects of concern. However, monitoring vibrations at the actual items during the whole period of groundwork is not possible. Thus, the vibration limits have been set to apply to vibrations measured on the floors in the museum.

2.2. VIBRATION MEASUREMENTS FROM NORMAL ACTIVITY

To quantify the vibration levels caused by visitors and normal work and maintenance at the museum, floor vibrations near to the objects have been monitored over a period 20 months. Based on the measurement results, the expected number of events per year giving floor vibration levels over a given value is given in Table 2. The table also states the highest measured vibration levels for each wing.

Table 2 Expected number for events per year giving floor vibration levels over a given value

v_{peak}	Oseberg wing	Gokstad wing	Tune wing	Fourth wing
> 0.30 mm/s	-	-	-	1704
> 0.50 mm/s	-	2338	1510	333
> 0.75 mm/s	-	821	352	48
> 1.00 mm/s	761	334	91	13
> 2.00 mm/s	133	9	3	-
> 3.00 mm/s	31	-	-	-
> 4.00 mm/s	20	-	-	-
Highest measured	6,8 mm/s	2,6 mm/s	2,9 mm/s	2,0 mm/s

When establishing the vibration limits both frequency content and duration of the events is important. Higher frequencies and longer durations lead to a higher number of load cycles. Most of the measured events at the museum have a duration of about 2 seconds, and the main contribution to the vibration level is in the frequency region of 10-40 Hz. Mobility measurement of the floors and measured operational deflection shapes (ODS) for some of the artefacts, show that the dominating resonance frequencies lay in the same frequency region. Therefore, both the floors and these artefacts will have a higher response to the input vibrations in this frequency range.

Measured vibration spectra from normal groundwork operations show that there is a spread in frequency content depending on the type of operation. Most of the operations do however fall within the frequency region of 10-40 Hz. Some examples are presented in chapter 3. For groundwork most of the vibration generating operations give transient vibrations and can be compared to the events given in Table 2. In the case of more continuous vibrations a lower limit must be set to account for an increase in the number of load cycles.

2.3. VIBRATION MITIGATION MEASURES

Although the groundwork at the site should not give an increase in the vibration loading, the limits must be set so that it is possible to conduct the necessary construction work to build the new museum. Setting too strict limits can lead to large increases in the building costs, or even make the construction impossible. Thus, it is a trade-off between acceptable damage-risk for the artefacts and reasonable restrictions regarding the groundwork.

Possible mitigation measures making it possible to allow higher vibration levels, such as vibration isolation or relocation, were also considered when setting the vibration limits. Different mitigation measures to reduce the vibrations in the exhibition areas were assessed, as shown in Table 3. Unfortunately, most of them were found unsuitable.

Table 3 Assessed vibration mitigation measures

Mitigation	**Comments**
Temporary vertical columns between ground floor and basement.	Not suitable: Stiffens the floors but gives more efficient vibration transfer from the ground.
Struts between ground floor and foundations.	Not suitable: Stiffens the floors but requires extensive work and limitations for the use of the basement area.
Tuned mass dampers for the exhibition floors.	Not suitable: Can possibly give good results for stationary sources but gives little reduction of transients.
Vibration isolating the artefacts using stiff frames supported on isolators	Suitable: Can possibly give good results for both stationary and transient vibrations. Requires detailed design and high precision production.
Improving the artefacts' existing support structures	Suitable: Measured operational deflection shapes (ODS) for some of the artefacts show room for improvement giving less response to dynamic loading.

2.4. VIBRATION LIMITS

The vibration limits chosen should give a minimal risk of having to reduce the allowed vibration level during the construction work. However, they may be raised if the monitoring during the period of groundwork shows that the limits are stricter than

necessary. Table 4 shows the selected vibration limits for the three wings housing Viking ships. The Fourth wing will be emptied before groundwork starts. Note that the limits given in the table require both vibration isolation and improvements of the support structure for some of the artefacts.

Table 4 Vibration limits for the three wings housing Viking ships

Wing	Vibration limit, V_{peak}
Oseberg	5 mm/s
Tune	3 mm/s
Gokstad	3 mm/s

3. ESTIMATION OF VIBRATIONS FROM GROUNDWORK

Vibration values on floors caused by construction activities were predicted using a three-step methodology. The methodology is summarized in Figure 5, and described below.

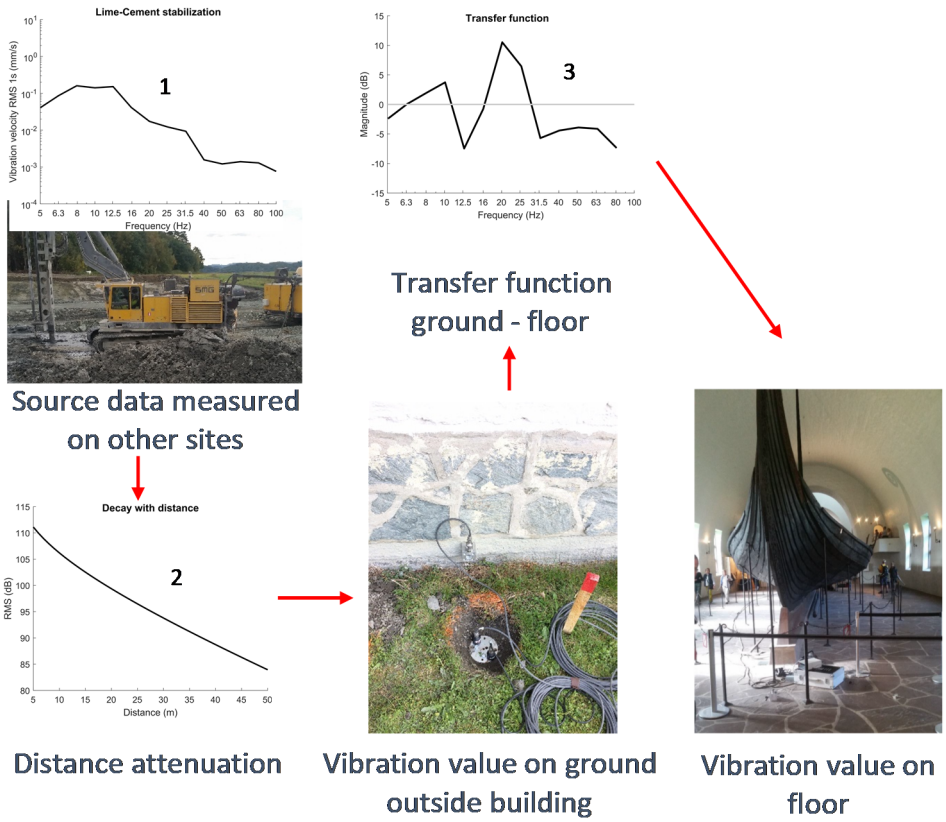

Figure 4 Methodology used to estimate vibrations from construction activities on floor in the museum.

1) <u>Source values (top left Figure 4):</u>
   Source values for different types of construction work were established using previously measured vibration values from groundwork activities on similar ground conditions. Both peak values and RMS 1s values in 1/3 octave bands were considered.

Figure 5 shows some examples of frequency content for different vibration sources. Note that the measurements in Figure 5 were performed at different distances. Hence, the vibration levels cannot be compared directly.

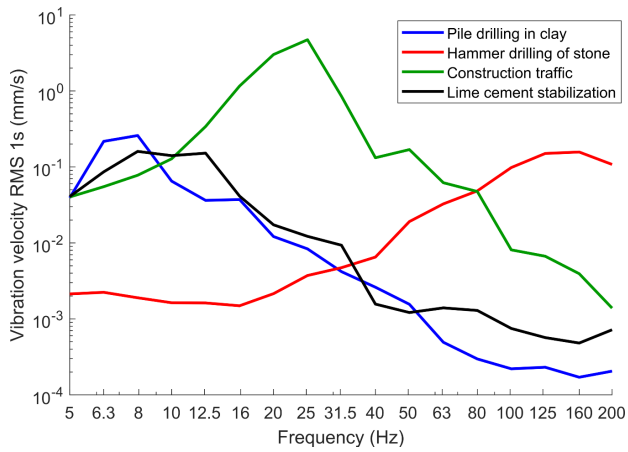

Figure 5 Example of frequency content of vibrations from different groundwork methods.

2) <u>Distance reduction (bottom left of Figure 4):</u>
The source levels were measured at a fixed distance close to the source. When determining the vibration levels at the Viking Ship Museum, they had to be converted to vibration values in relevant distances. The conversions were performed using the following equation:

$$L_{vx_2} = L_{vx_1} + C_j \cdot (x_2 - x_1) + 20 \cdot \log\left(\left(\frac{x_1}{x_2}\right)^{\frac{1}{2}}\right) \qquad \text{Equation 1}$$

Where:

$L_{vx_i} = Vibration\ level\ in\ x\ meter\ distance\ from\ source\ in\ dB = 20 \cdot log\left(\frac{v}{10^{-6}}\right)$

$C_j = damping\ in \frac{1}{3} - octave\ bands$

The damping in 1/3 octave bands was determined from measurements on the ground outside the Vikingship museum, using a 50 kg drop weight and a geophone array in different positions around the museum.

3) <u>Transfer function from outdoor to indoor (middle part of Figure 4):</u>
Most of the source measurements were performed on the ground outdoor. To be able to compare the estimated vibration values with the chosen limit values, the outdoor values were recalculated to vibration values on the floors inside the building.

Since different buildings amplify vibrations differently, site specific characteristics need to be used in these calculations. For that reason, measurements of transfer functions from ground outside to floors inside were performed at the Viking Ship Museum's site. The transfer functions were

determined using three excitation sources with different frequency content: A 50 kg drop weight, giving a broad band excitation; a lorry driving over a 1” wooden board, giving a low frequency excitation (simulating construction traffic), and a mobile drilling rig, giving high frequency excitation (simulating rock excavation). The measured transfer functions varied between the different source and receiver positions. As a conservative approach, the envelopes of all measured transfer functions for each museum wing were used in the calculations of vibration values on the floors inside. However, during the data analysis, it became evident that the transfer functions were different for excitations at larger 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 for each museum wing, one used for construction activities less than 10 meters from the building, and one for activities at distances more than 10 meters.

Figure 6 shows an example of a measured transfer function from ground outside to floor in museum, using the 50 kg drop weight in 8 m distance from the foundation of the museum. 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, manage to propagate upwards from ground to the floors in the building.

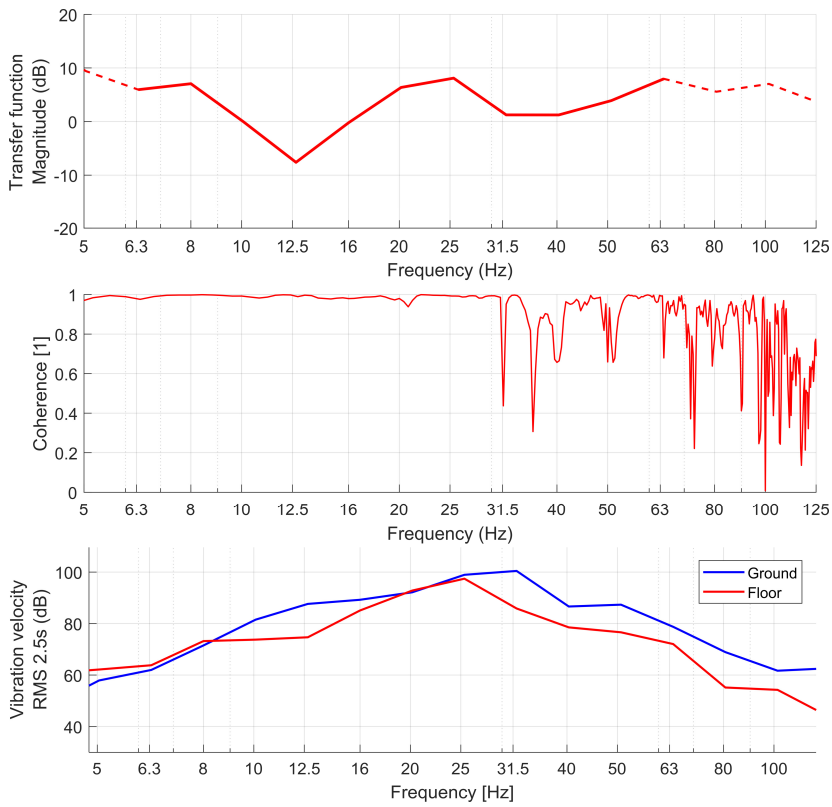

Figure 6 Top: Transfer function from ground outside to floor. Middle: Coherence between measurements on ground and on floor. Bottom: Measured vibration velocity on ground close to the building foundation and on floor.

3.1. COMPARISON WITH LIMIT VALUES

Table 5 shows examples of estimated vibration values from different construction activities. Estimated vibration values that are above the limit value for the affected museum wing are shown with red background colour in the table, while values below the limit value are shown with green background colour. Restrictions will be imposed on construction activities for which the calculations show exceedances, and alternative methods and/or mitigation measures, e.g. pavement of construction roads, will be considered.

Table 5. Estimated vibration values on floors in museum from different construction activities.

Activity	Distance to most exposed wing (m)	Vibration velocity (mm/s)
Lime cement stabilization	2	3
Jet stabilization	23	1
Construction traffic on unpaved road	10	5
Hammer drilling of stone	4	3
Sheet piling, vibro	20	5
Sheet piling, silent piler	20	1
Excavation	10	> 5
Vibro compaction	5	> 5
Pile drilling	12	< 3

4. CONCLUSIONS

Based on measured vibrations in the existing museum, vibration limits for groundwork at the site were set to v_{peak} = 3-5 mm/s. This is in accordance with known limits set at other museums. These limits do however require mitigation measures for some of the artefacts. This includes vibration isolation and/or improvements of the artefact's support structure.

Estimated floor vibration levels based on measured source levels and site-specific properties show that some relevant types of groundwork results in vibration levels exceeding the limits set. This requires restrictions or alternative methods for some construction activities.

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