

The new museum of the Viking Age – Assessment of vibration from groundworks to avoid damage to artefacts



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ABSTRACT

Construction activities such as blasting, pile driving, compaction, excavations, and construction traffic can cause damage to neighbouring buildings and structures. The situation is even more critical when the nearby buildings are museums with fragile collections. This case study presents vibration assessment work performed in connection with the planning of the construction activities for the planned Museum of the Viking Age on Bygdøy, outside of Oslo, Norway. The planned museum will be built as an extension of the existing Viking Ship Museum, where one of the world's foremost collections of artefacts from the Viking age is displayed. Although the existing museum will be closed during the construction period, objects that are considered too large or too fragile to be temporarily relocated will remain in the museum. Therefore, one of the main challenges during the construction of the new museum is to ensure that vibrations from the ground- and construction work do not damage the fragile objects in the existing museum. Strict vibration limits have been set based on the daily vibration values during normal operation of the museum. The vibration limits are given both as vibration peak limits and as vibration root mean square (RMS). Early calculations showed that especially the RMS limits will be difficult to meet. A "vibration budget" was established, which provides a systematic overview of the vibrations from different construction activities with the expected total time at different RMS levels and with the associated dominating frequency. Based on the results, the most critical construction activities are identified, and effects of mitigation measures are estimated. In addition, the results can form a basis for adjustments of the RMS limits for activities that are expected to last for only a short time. As the main vibration mitigation measure, a screen made of jet-grout columns is planned in the ground between the existing museum and the main construction area. FE-calculations show that the screen may reduce the vibration values by up to 80%. However, since not all activities are affected by the screen, the effect on the vibration budget is somewhat lower.

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1. Introduction

The effect of vibrations on objects of art and cultural heritage is a continued source of concern for museums [1]. Vibrations from construction work have been in focus in several projects with similar challenges as the Museum of the Viking Age. In [2] strategies for vibration monitoring and mitigation during the renovation of the Metropolitan Museum of Art are described. Among other things, vibration measurements were performed during testing of relevant construction equipment on site. Ref. [1] describes shaker table tests to determine allowable vibration limits in connection with the renovation of the Naturalis Biodiversity Center in Leiden

in the Netherlands. In Ref. [3] work performed in the connection with renovation of the Art Institute of Chicago and The Saint Louis Art Museum is described and a general methodology for vibration control during museum construction projects is presented. The methodology involves use of preconstruction testing of vibration response and field trials at the site. In Ref. [4] an integral approach is presented, which was adopted during the renovation of the Central Library in Liverpool, UK. The approach involved extensive risk analysis, continuous monitoring, and close cooperation with the contractor. Ref. [5] describes a preventive monitoring model, which was applied in connection with construction of a railway tunnel close to historic churches in Stockholm. The conclusion of the study was that visual inspection was crucial for protection of the artworks and that the concept of vibration standards relying on fixed numbers of critical vibration levels is questionable.

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Ref. [6] presents estimates of damage levels based on observed damage to a small number of objects during a construction project at the British Museum. As a comprehensive program of vibration measurements was carried out during the project, it was possible to link the damage to the actual vibration levels.

This paper presents vibration assessment work performed in connection with planning of construction activities for the New Museum of the Viking Age on Bygdøy, outside of Oslo, Norway. The planned museum will be built as an extension of the existing Viking Ship Museum, which displays one of the world's foremost collections of artefacts from the Viking Age. Although the existing museum will be closed during the construction period, objects that are considered too large or too fragile to be temporarily relocated will remain in the museum. Therefore, one of the main challenges during the construction of the new museum is to ensure that vibrations from the ground- and construction work do not damage the fragile objects in the existing museum. In the planning of the Museum of the Viking Age a risk assessment approach is undertaken to evaluate whether the vibration induced by the foreseen construction activities may cause damage to the collection. In the early planning phase, a workshop was organised involving stakeholders in the project. In the workshop the likelihood for exceeding the vibration limits and the consequences of exceedances were assessed, the most critical construction activities were identified and the need for mitigation measures was assessed [7]. Later in the planning phase a "vibration budget" was established, which provides a systematic overview of the vibrations from different construction activities with the expected total time at different vibration levels and with the associated dominating frequency. The vibration budget, which is the focus of this paper, forms a useful basis for assessing the risk for vibration induced object damage based on the vibration limits. It also works as a priority list for vibration reducing mitigation – sources dominating the budget should be prioritized. The vibration budget also provides an opportunity to investigate the total effect of various vibration-reducing measures, considering both the potential for vibration reduction and the possible addition to the vibration load from the construction of the mitigation measure, e.g. a vibration screen in ground.

2. The Viking Ship museum and the collection

The collection in the Viking Ship Museum includes three ships, Oseberg, Gokstad and Tune, and several smaller objects such as textiles, jewellery and three sledges. The Oseberg ship and the Gustafson's sledge are shown in Fig. 1.



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

The collection, which dates to the 800–900s, was excavated in the period 1867–1904. After excavation, several of the smaller wooden objects, including the sledges, were alum-treated for preservation, which has made them very fragile over time. The ships were airdried, and the strength of their materials is more intact. Common for most of the objects is that nails, pins, glue and filler were used during the reconstruction resulting in weak and brittle connections with unknown mechanical properties [7]. The ships and sledges will remain in the museum during the construction period.

The existing Viking Ship Museum building was built between 1917 and 1956 and consists of four wings (Oseberg, Gokstad, Tune and Fjerde). The Tune, Gokstad, and Oseberg wings, completed 1926–1932, contain the three viking ships, whilst the fourth wing (Fjerde), which was completed in 1956, contains the smaller objects such as the sledges. Fig. 2 shows the existing museum with its four wings and the planned Museum of the Viking Age as an extension.

3. Vibration limit values and monitoring

In Norway, limit values for vibrations from construction activities are usually set as peak vibration velocity measured in the vertical direction on walls close to the building foundation according to the method in NS 8141:2001 [8]. The guideline limit values are calculated from a basis value and a set of factors which takes into consideration the ground conditions, building category, type of foundation, building material, distance from the building and type of vibration source. The guideline limit values are frequency independent but some of the factors indirectly takes the frequency content of the vibrations into account, i.e. the ground condition factor and the distance factor. With the ground conditions, the type of building and the activities planned at the new Museum of the Viking Age, a typical limit value to avoid damage to the existing museum would be about 5 mm/s. In a normal construction project, this would have been considered a strict limit value. For the planned Museum of the Viking Age, however, it is assumed that stricter limit values will be required to protect the fragile collection.

Damage to objects can be caused both by short events with one or few vibration cycles with high levels, and by many vibration cycles with lower levels. If the vibration levels are below the fatigue limit, the object can be exposed to millions of cycles without damage. According to [9], limit values for vibrations for cultural heritage is therefore not just a question of vibration levels, but also



Fig. 2. The planned Museum of the Viking Age including the existing Viking Ship Museum with its four wings (AART Architects).

requires knowledge of the relationship between cyclic stress levels and the duration (number of cycles) of the vibration loading which can cause damage. However, the tolerance of the objects in the Viking Ship Museum to vibrations are not known and although there has been an increase in research on the effect of vibrations in museums [4], there is a lack of published damage levels for museum objects to gain experience from. Since the history of the objects is unique, being buried and waterlogged for a thousand years and then alum-preserved (sledges) and exposed to fluctuating indoor climate for a hundred years, it is also not possible to find similar materials to perform tests on.

Work to come up with recommendations on vibration limit values that will apply during the construction is carried out in a separate project, the Safeguarding of objects (SGO) project, which aims to minimize the risk of object damage. Taking both the short-term and long-term damage potential into account, the SGO project has suggested using two vibration limits, a peak vibration limit for short time incidents, and a root mean square vibration limit (RMS) for more sustained vibrations. The RMS limit value is recommended to be set as RMS1s, which is the running average with an integration time of 1 s. The RMS limit value is also intended to address risk for resonant response in the structure and objects that requires some time to build up. The RMS1s limit value will therefore be combined with a requirement that the limit value must be exceeded for several consecutive seconds to be regarded an exceedance.

As a premise for the project, the museum has stated that climate impact, static and dynamic loads, and dust deposition during normal museum operations are considered baseline and should be used as the starting point for acceptable risk and acceptance criteria in the building phase. As a first approach, the vibration limits were therefore set based on baseline vibration measurements. The idea was that the vibration exposure due to construction work should not exceed the daily exposure in the museum. The baseline data is mainly vibrations from visitors walking in the museum and consists of both long-term measurements of peak floor velocities with corresponding dominating frequencies, and measured vibration time histories on the floors and at the objects during shorter time periods. The vibration limits depend on the vibration signal's dominating frequency, which is determined as the frequency of the

peak in the frequency spectrum established from the discrete Fourier Transform according to the procedure described in Annex D of DIN 4150-3 [10].

The vibration limits are set as limit values on the objects. However, for the contractor's planning and vibration assessment work, the vibration limits are also converted to limit values on floors. The reason for the conversion is to avoid uncertainties in the vibration transmission from floor to objects affecting the vibration assessments, and because contractors in Norway have experience with vibration limits set as velocity limit values measured on buildings according to NS 8141:2001. To reduce the vibration exposure during the construction period, the objects will be placed on vibration isolated skids. The vibration reduction of the skids has so far only been estimated. However, transfer functions from floor to object will be determined on site before the construction work starts, when the objects are installed on the skids. The estimated vibration reduction of the skids is taken into consideration in the conversion of the limit values on objects to limit values on floor. The suggested limit values on floors varies from about 1 mm/s to 7 mm/s for v_{peak} , and from about 1 $\mu\text{m/s}$ to about 0.1 mm/s for v_{RMS1s} , depending on dominating frequency and location in the museum. The suggested limit values on floors in the Gokstad wing based on baseline measurements are shown in Fig. 3.

The suggested peak limit values are similar to limit values that have been used in other comparable projects, e.g. the renovation of the Metropolitan Museum of Art in New York, where alert limits of between 1 and 3 mm/s were set [2], the renovation of the Naturalis Biodiversity Center in Leiden the Netherlands where it was recommended that vibrations in floors should not exceed 1.5–2 mm/s [1], the renovation of the Art Institute of Chicago and The Saint Louis Art Museum where the limit value in the vicinity of artwork was set to about 3 mm/s below 10 Hz and about 13 mm/s above 30 Hz [3], and the major renovation of the Central Library in Liverpool, UK, where a limit value of 3 mm/s was adopted. As a comparison it may be mentioned that the measured acceleration damage levels in connection with the building project at the British Museum were between $a_{\text{peak}} = 0.2\text{--}0.6\text{ g}$ [6], which corresponds to about $v_{\text{peak}} = 15\text{--}45\text{ mm/s}$ assuming a dominant frequency of 20 Hz, [3]. Limit values for RMS have to our knowledge not been used in other comparable projects. However, the importance of

fatigue is discussed in the literature, e.g. in [9 and 3], showing that long time exposure is a concern.

Early calculations of expected floor vibration levels showed that while it probably will be possible to meet the suggested v_{peak} limits, a construction completion which meets the much stricter v_{RMS1s} limits was unlikely to be feasible. Thus, new limit values for v_{RMS1s} are under preparation. The vibration budget may provide valuable information for this work on the expected durations of vibrations with different RMS levels and dominating frequencies during the construction period.

During the construction period, vibrations on objects and floors will be continuously monitored and both peak and RMS values will be checked against the limit values and alert thresholds. Exceeding the alert thresholds, which are set lower than the limit values, will trigger alert messages and various actions will be implemented. If the limit values are exceeded, the construction work will in principle be stopped and further work will be determined in close collaboration between the contractor and the conservators. The measurement system will also be used to gather experience along the way and as a basis for adjusting the construction implementation if it proves necessary.

4. Description of the site and planned ground work

The ground conditions at the site consists of soft marine clay on top of bedrock. The depth to bedrock varies across the site but is at most about 30 m below the ground surface. The clay is normally consolidated with an undrained shear strength ranging from about 20 kPa at the top to about 50 kPa at 20 m depth, i.e. a shear strength trend vs depth corresponding to 0.3 times the effective in-situ stress. The clay's natural water content was determined to be about 35–45 % and its plasticity index about 10–20 %. The clay is partly classified as a quick clay, i.e. a considerable decrease in shear strength upon disturbance and remoulding.

Based on in-situ seismic refraction tests and multichannel analysis of surface waves (MASW) measurements, the shear wave velocity of the clay was evaluated to about 100–150 m/s at the top increasing to about 250–300 m/s at the bottom of the clay. The shear wave velocity in the bedrock was evaluated to about 400–600 m/s, i.e. relatively low compared to other types of rock, see Fig. 4. The described ground conditions are unfavourable in terms of vibrations and can potentially lead to high vibration values and vibration transmission over long distances.

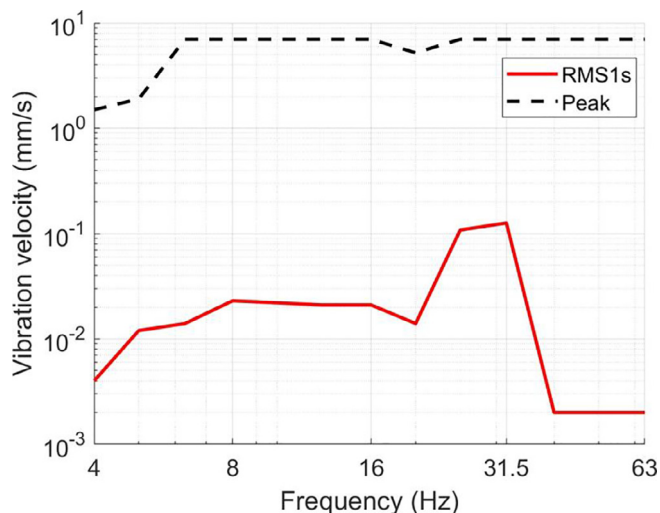


Fig. 3. Limit values on floors in Gokstad wing based on baseline measurements.

4.1. Planned ground work

The planned museum building will consist of one to two base-ment levels, with excavation down to about 6 m beneath the orig-inal ground level. The clay is to be stabilised with dry deep mixing using lime cement to secure excavatable masses. This stabilisation is performed using a 600–800 mm diameter mixing tool which inject a binder of lime and cement with a medium-pressure air flow whilst mechanically mixing the binder and natural clay [11]. The cement and lime will result in a strength increase and improved workability for both excavation and for construction equipment traffic. In addition, steel sheet pile walls will be used to enable vertical excavation. The sheet pile walls will be pushed, possibly vibrated if the drivability is poor, down to bedrock and secured with anchors.

The new museum building foundation will be constructed on drilled steel core piles. This is chosen to minimise vibrations during construction as drilled piles generate less vibrations than driven piles. A part of the fourth wing will be underpinned using jet grout columns, which also will act as a supporting structure for the adja-cent excavation. Jet grout columns will also be used in a vibration screen in the ground between the main construction area and the Gokstad wing. Jet grout columns are created by high-pressure injection of a cement slurry into the clay, forming high strength columns of 1.5–1.8 m in diameter [12]. The jet column strength is estimated to be around 2 to 4 MPa, i.e. considerably higher than the natural clay.

Adjacent to the Gokstad wing, rock excavation is needed. The rock will be fractured by a hydraulic system using predrilled bore-holes, and thereafter excavated with excavators.

4.2. Foundation of the existing museum building

The Tune, Gokstad, and Oseberg wings in the existing museum are built with spread foundations on bedrock or on concrete piers founded on the bedrock. Beneath the fourth wing the thickness of the clay deposit increases up to about 8–12 m and this part of the museum's foundation is on pre-casted concrete piles that were dri-ven down to bedrock. The piers and concrete piles support the building structure, whilst the museum floor foundation is a con-crete slab directly on the ground.

5. Methodology - the vibration budget approach

The strict vibration limits for v_{RMS1s} , based on a concern for fati-gue, point to a need for more knowledge about the total vibration dose during the construction period and not just information about expected vibration peak values. The vibration budget can make a valuable contribution in this context. The vibration budget is based on vibration measurement data and a detailed construction plan. The measurement data are collected from vibration measurements on the museum site and on other construction sites with similar ground conditions. The detailed construction plan is prepared based on construction site phase plans. In the detailed construction plan, each planned activity is assigned an estimated effective vibra-tion time, which is distributed over relevant distances from the existing museum. The methodology used in the vibration budget is illustrated in Fig. 5. Measured v_{RMS1s} on the ground outdoors are first converted to relevant distances. Thereafter, the v_{RMS1s} on the ground outdoors are converted to v_{RMS1s} indoors on the floors.

5.1. Vibration source data

Considering that vibration damage may not only be caused by the highest vibration values, but also by many vibration cycles at

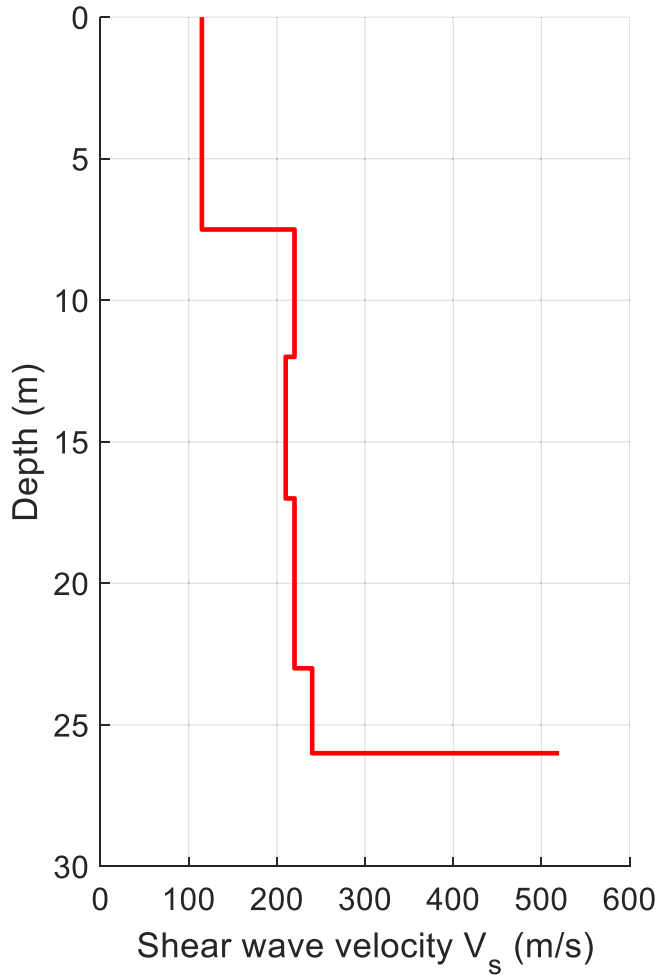


Fig. 4. Typical shear wave profile determined by MASW measurements at the site.

lower levels, a statistical approach based on percentiles is adopted. The percentiles are determined based on measured vibrations over longer periods of time. Time periods representative of various construction activities are selected from the measurement data and divided into 1-second intervals. v_{peak} and v_{RMS1s} are then determined for each 1-second interval in the selected time periods and percentiles for 1-second intervals are calculated. The percentiles are the vibration values that a given percentage of the vibration values in all the 1-second intervals are lower than or equal to. Percentiles are determined for both v_{peak} and v_{RMS1s} (total value and in 1/3-octave bands). The percentiles for 1/3-octave bands are determined separately for each 1/3-octave band and the results are corrected so that the sum over the 1/3-octave bands for each percentile is equal to the percentile for the total v_{RMS1s} . The further calculations are based on percentiles for v_{RMS1s} in 1/3-octave bands in the frequency range from 5 Hz – 400 Hz and the calculations are performed for the 10-, 20-, 30-, 40-, 50-, 60-, 70-, 80-, 90-, 95-, 98-, and 99th percentiles.

An example is given in Fig. 6, which shows percentiles for v_{peak} and v_{RMS1s} calculated from a 1600-second-long measurement period of vibrations from lime cement stabilization performed at a construction site in Oslo with similar ground conditions.

5.2. Distance attenuation

Vibrations are reduced with the distance from the source. The reduction is different for different frequencies and therefore both

the frequency and amplitude of the vibrations will be affected by where on the building site the work is carried out. Conversion from measuring distance to the relevant distances, according to the detailed construction plan, is performed for the percentiles of v_{RMS1s} in 1/3-octave bands using Eq. (1) from [13]:

$$\frac{v_1}{v_0} = \left(\frac{R_1}{R_0}\right)^{-n} e^{-\alpha(R_1-R_0)} \quad (1)$$

where:

v = is the vibration amplitude at distance R from source

$n = 0.5$ for surface waves.

α = attenuation factor.

The attenuation coefficient is not a material-independent constant but varies with the vibration frequency and wave propagation velocity, as well as with the ground properties at the site, e.g. distance to bedrock and soil layering. Site specific attenuation coefficients have been developed based on measurements at the museum site. This is further described in section 6.3.

5.3. Transfer function from outdoor on ground to indoor on floors

All measurement data used in this study are from measurements made on the ground outdoors and are converted to indoor values on the floors, using transfer functions, before they are used in the assessment. The transfer functions can be estimated as the frequency response functions (FRF), determined from measurements according to Eq. (2) from [14].

In Eq. (2), the influence of random noise is reduced by averaging. However, the influence of unrelated stationary indoor vibration sources will not be removed and may lead to an overestimation of the vibration transfer from outdoor to indoor. The coherence determined according to Eq. (3) provides a measure of the extent to which indoor vibration in floors are caused by outdoor vibrations and may be used to select usable data. A coherence equal to one implies that the indoor floor vibrations originate fully from the measured outdoor vibration and a coherence close to zero that the indoor floor vibrations are caused by other unrelated sources. In this study a criterion of coherence higher than 0.5 in 1/3-octave bands are used for selection of usable data.

Site specific transfer functions were developed based on measurements at the museum site using Eq. (2) and Eq. (3). This is further described in section 6.4.

$$\hat{H}(f) = \frac{\hat{S}_{yx}(f)}{\hat{S}_{xx}(f)} \quad (2)$$

$$\hat{\gamma}_{xy}^2(f) = \frac{|\hat{S}_{yx}(f)|^2}{\hat{S}_{xx}(f)\hat{S}_{yy}(f)} \quad (3)$$

where

$\hat{H}(f)$ is the average frequency response function from outdoor vibration on ground to indoor vibration in floors.

$\hat{\gamma}_{xy}^2(f)$ is the coherence between outdoor vibration on ground and indoor vibration in floors.

$\hat{S}_{yx}(f)$ is average of the cross spectral density between outdoor vibration on ground and indoor vibration in floors from several measurements.

$\hat{S}_{xx}(f)$ is the average of auto spectral density of the outdoor vibration on ground from several measurements.

$\hat{S}_{yy}(f)$ is the average of auto spectral density of the indoor vibration in floors from several measurements.

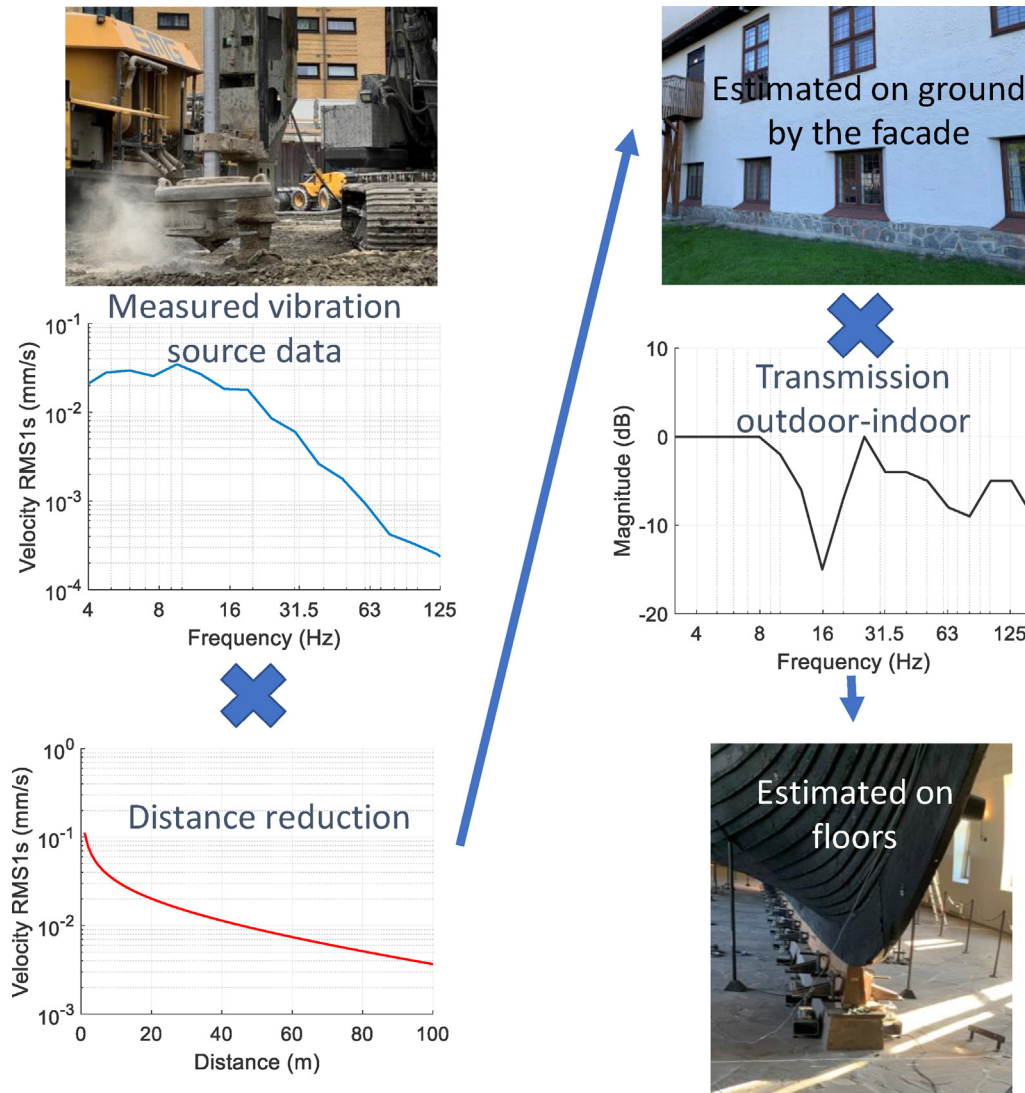


Fig. 5. Methodology – Estimation of vibration values, v_{RMS1s} , on floor in building from measurements on construction equipment at the museum site and other construction sites.

5.4. Calculation of total time with different RMS levels

The vibration budget is an accounting of the total time with different vibration values, v_{RMS1s} , during the construction period. Indoor percentiles for different construction activities are first converted to seconds per hour and thereafter to total time using rough estimates of how much of the time different construction activities will take place at different distances and the total effective vibration time for each activity. This information is obtained from the detailed construction plan. The calculation of seconds per hour is described by Eq. (4).

$$N_{i,j,k} = \frac{P_k - P_{k-1}}{100} \cdot 3600 \cdot t_{i,j} \quad (4)$$

where:

$N_{i,j,k}$ = Seconds per hour with a vibration value between v_k and v_{k-1} from construction activity A_i at distance d_j .

P_k = Percentile k for construction activity.

$t_{i,j}$ = Estimated part of time for construction activity A_i at distance d_j .

As an example of the procedure, the calculation for lime cement stabilization 18 m from the museum is shown in Fig. 7. The per-

centiles are the vibration values that a given percentage of all observed vibration values are lower than or equal to. In this example v_{RMS1s} is lower than or equal to 0.08 mm/s 95 % of the time (95-percentile) and lower than or equal to 0.07 mm/s 90 % of the time (90-percentile). Hence, 5 % of the time, the vibrations are between 0.07 and 0.08 mm/s. Lime cement stabilization 18 m from the museum will take place about 1.6 % of the total time for lime cement stabilization. The seconds per hour with v_{RMS1s} between 0.07 and 0.08 mm/s from lime cement stabilization 18 m from the museum will then be: $(95-90)/100 \cdot 3600 \cdot 0.016 = 2.9$ s. The frequency spectra show that the dominating frequency for the 90- and 95-percentile is 10 Hz.

Thereafter, the contributions from all calculation distances and percentiles for a selected construction activity are added to get the average seconds per hour with different v_{RMS1s} for that construction activity. To be able to sum and to compare contributions from different construction activities and distances, the results are first sorted into $v_{RMS,1s}$ groups with fixed intervals. In this study the results are sorted into 22 vibration groups with a maximum value of $v_{RMS1s} = 0.5$ mm/s and an interval width of 5 % of the maximum value, i.e. 0.025 mm/s. However, in the three lowest vibration groups interval widths of 1.25 % and 2.5 % of the maximum value

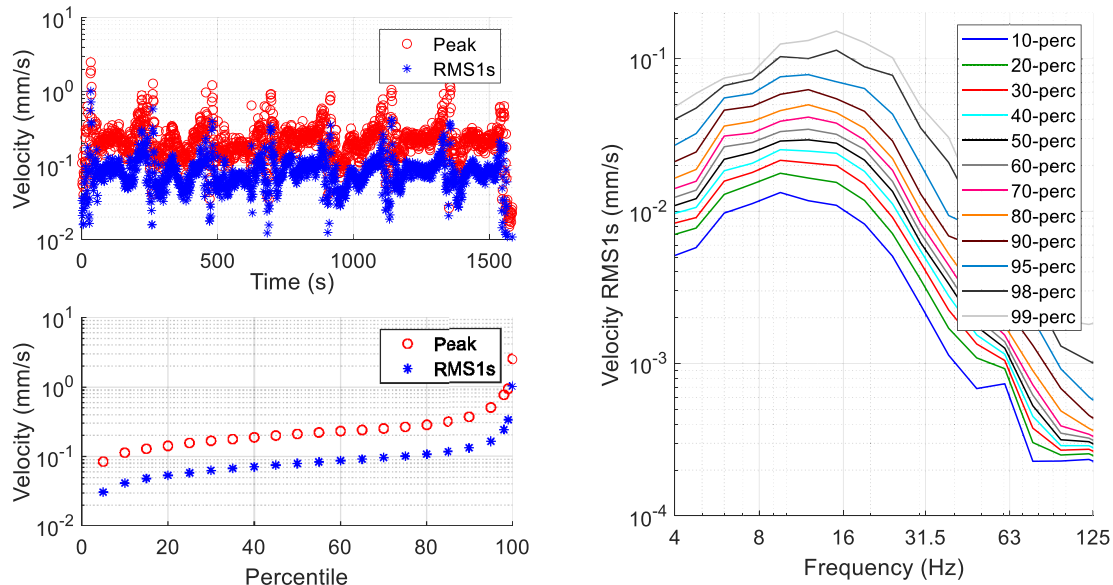


Fig. 6. Left upper panel: v_{peak} and v_{RMS1s} for each second in the selected 1600-second period with vibration measurement on lime cement stabilization (measured at 12 m distance). Left lower panel: Percentiles for v_{peak} and v_{RMS1s} . Right: Percentiles for v_{RMS1s} in 1/3-octave bands.

are used to obtain a better resolution and facilitate comparison with the strict limit values. An average frequency is also calculated for each vibration group. Finally, the total time (in seconds) with vibration values in the different vibration groups for each activity is calculated by multiplying the average seconds per hour by the estimated total vibration time (in hours) for each activity according to the detailed construction plan.

Fig. 8 shows as an example the average seconds per hour with corresponding frequency in the different vibration groups from lime cement stabilization 15–90 m from the museum.

6. Input data to the calculations

While typical vibration peak values from different construction activities can be found in the literature, e.g. in [15 and 16] there is little or no information available about typical RMS vibration values and especially not in the form of percentiles which were used

as input data to the vibration budget. Preconstruction field tests with different types of construction equipment were therefore performed at the museum site together with the contractor. In the planning phase of the project, field measurements of vibration transmission and distance attenuation were carried out at the museum site using artificial sources, i.e. a drop weights and a geotechnical drill rig. However, the preconstruction field tests at the museum site with relevant construction equipment provides a better basis to determine distance attenuation and vibration transmission during the construction. The collected measurement data were therefore used both as vibration source data in the calculations and to determine site specific distance attenuation and transfer functions from outdoor on ground to indoor on floors.

6.1. Tested equipment

Since the ground conditions affect the vibration values, the most reliable source data are obtained from measurements at the relevant location. However, the advantages of on-site tests must be weighed against the disadvantages in terms of risk to the collection, given that the collection has not yet been placed on vibration isolated skids. Therefore, construction equipment that were considered safe to use, were tested on the museum site. The selection criteria were that the equipment could be stopped quickly if the limit values were exceeded and that it could be transported into the area by ordinary trucks on rubber tyres, since the access road is narrow and at a short distance from the existing museum. An example of such equipment is an excavator with a hydraulic breaker, see Fig. 9 left. Vibration source data for other machines, e.g. large drill rigs and jet-grouting rigs, were determined from measurements on other construction sites with similar ground conditions, see Fig. 9 right. Table 1 shows measured construction equipment and the working conditions during the measurements.

The choice of measuring distance must be made with care, as measurements near the source may be affected by near-field phenomena and thus sensitive to small changes in distance [17]. Measurements far from the source, on the other hand, are heavily affected by the ground conditions at the site, which is especially important for source data based on measurements on other construction sites. Measurements used for source characterization in

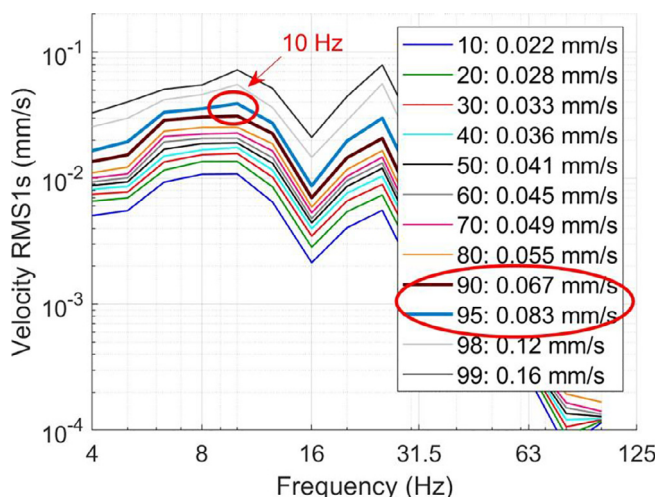


Fig. 7. Example of calculation of seconds per hour with $v_{RMS,1s}$ between 0.067 and 0.083 mm/s for lime cement stabilization of clay at 18 m distance from the museum. Note the effect on spectra of transmission from outdoors on ground, Fig. 6, to indoors in floor (Fig. 7).

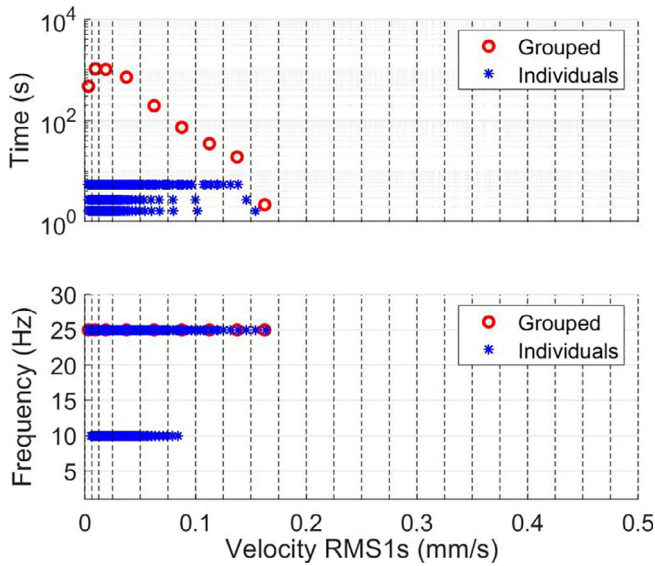


Fig. 8. Upper panel: Average seconds per hour in the different vibration groups for lime cement stabilization. The blue markings show individual contributions (one blue marking per calculation distance and percentile), while the red ones show grouped results (the sum of all blue markings in each vibration group). Bottom: Frequency for the individual contributions (blue markings) and for grouped results (red marking - average of the blue ones). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Tested construction equipment.

Type of equipment	Working conditions	Test site
Sheet pile installation with vibro hammer	Low, normal and high frequency on hammer	Viking Ship Museum
Tipping of crushed rock, laying and compaction with plate vibrator	Normal	
Excavation of hard top layer	Normal	
Excavation of soil and backfilling.	Normal	
Excavation of rock with hydraulic rock breaker	Normal	
Demolition of building foundation using hydraulic rock breaker	Normal	
Moving large excavator on belts	Slow, normal and high speed	
Construction traffic on paved road	Normal	
Construction traffic on gravel road	Normal	Other construction sites with similar ground conditions
Lime cement stabilization	Normal	
Jet column grouting	Normal	
Drilling of steel tube casing for steel core pile installation	Normal	

this study were performed at about 10–15 m distance from the vibration source, and are believed to be a good compromise between the two considerations.

6.2. Instrumentation and data analysis

The location of the sensors and the construction equipment are shown in Fig. 10. The outdoor measurements on the ground were performed with PCB393B12 seismic accelerometers with a sensitivity of 10 V/g and 3D SM-PE-6/B 4.5 Hz geophones with a sensitivity of 28.8 V/m/s. The outdoor sensors were mounted on metal

plates, which were firmly connected to the ground by spikes on the underside of the metal plates. The indoor measurements were performed with PCB356B18 triaxial accelerometers with a sensitivity of 1 V/g. The indoor sensors were located on the floors near the support of the ships and the showcases with the sledges.

Measurement data in the form of time series were collected with a sampling frequency of 1000 Hz for the geophones and 1024 Hz for the accelerometers. The collected time series from all sensors were analysed in MatLab.

6.3. Distance attenuation

The method used to determine frequency dependent attenuation coefficients for the museum site was as follows:

- Representative time segments from the measurements of the various construction activities were selected. Depending on the type of source, the segments were 20-second to 5-minutes long (longer time segments were used for more continuous sources and shorter time segments for transient sources).
- FFT was performed on each segment using a 3 s analysis period and 50 % overlap, resulting in a number of frequency spectra per selected time segment. Power spectral densities (PSD) were determined from the frequency spectra by averaging the squared spectral magnitudes (variance spectra). The average PSD was then calculated from the PSDs of all 3 s time periods and the 1/3-octave band values were determined from the average PSD.

- For each 1/3-octave band, the 1/3-octave band values for all sensors on the ground were plotted against the distance from source to sensor and a curve as described by Eq. (1) was fitted to the data using the least squares method. An example is shown in Fig. 11.

- The final damping coefficients to be used in the calculations of the vibration budget were determined from all curve fittings that satisfied a given requirement for the mean squared error (MSE). In this study, curve fittings satisfying MSE < 15 dB were used.

The attenuation coefficients used in the calculations of the vibration budget are tabulated in Table 2.

According to [13], the attenuation factor relates to frequency and material loss factor as.

$$\alpha = \frac{-2\pi Df}{V} \tag{5}$$

where:

- f = frequency.
- V = is the propagation speed for the wave type in question.
- D = The loss-related distance attenuation factor.

The reduction of the attenuation coefficient with frequency in the frequency range from 5 to 16 Hz in Table 2 is not in accordance with what could be expected from Eq. (5). However, as described in [13], Eq. (5) represents an oversimplification compared to real cases where surface waves may become dispersive and wave propagation wavelength-dependent. In addition, other wave types can appear along layer interfaces and be guided within layers.

6.4. Transfer functions from outdoors on the ground to indoors on the floors

Vibration transfer functions from outdoors on the ground to indoors on the floors were estimated from frequency response functions (Eq. (2)) determined from vibration measured outdoors close to the façade in the vertical direction and indoors on the floors in vertical and horizontal direction, in the measurement position with highest value. Fig. 12 shows the frequency response functions for the different sources and the “design” transfer functions which were used in the vibration budget for all sources except sheet piling and rock excavation. Only 1/3-octave bands



Fig. 9. Left: Excavator with hydraulic rock breaker tested at the museum site. To the left is the gable of the Gokstad wing and to the right the Oseberg wing. Right: Lime cement stabilization rig measured at site with similar ground conditions. The seismic accelerometer mounted on metal plate is seen in the front.

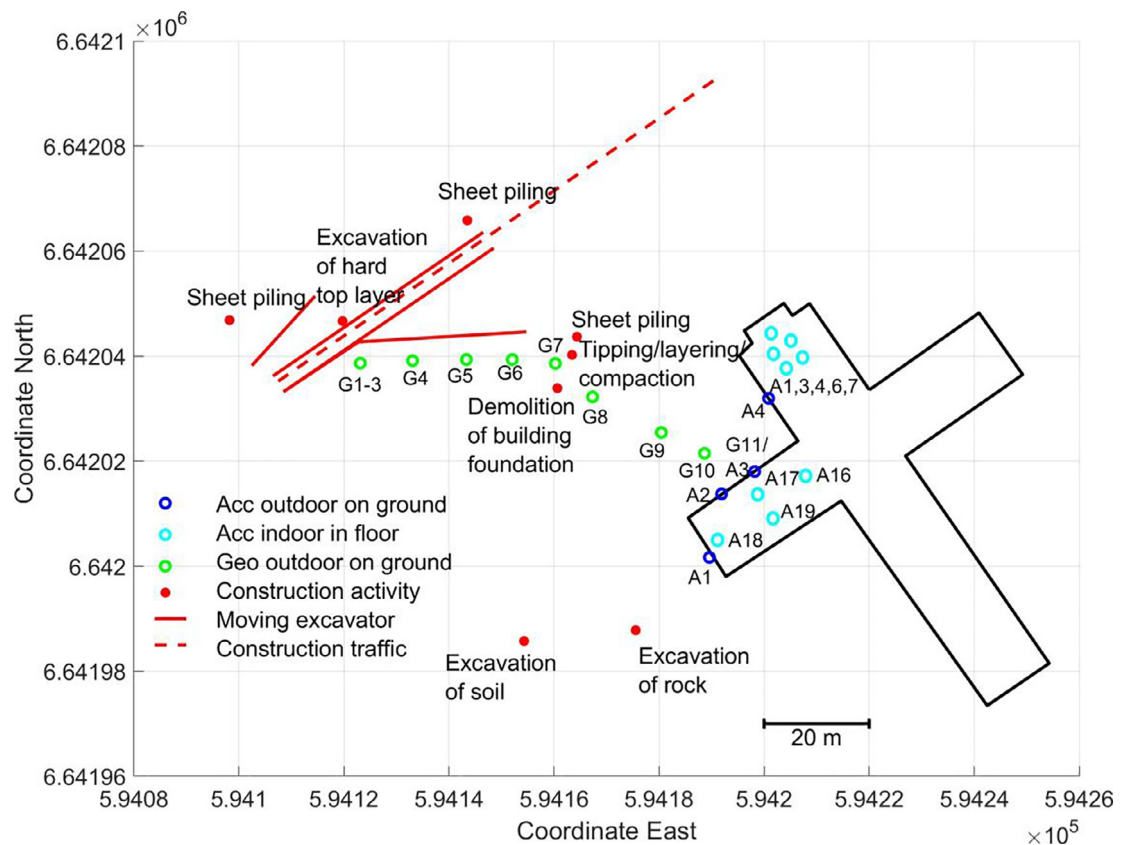


Fig. 10. Measurements at the museum site. Location of construction equipment and vibration sensors outdoors and indoors (“A#” are accelerometers) and “G#” are geophones (G1-3 is a triaxial geophone where G3 is the vertical direction). Coordinate system EU89, UTM-zone 32.

Table 2
Attenuation coefficient, α , used in the vibration budget.

Frequency (Hz)	5	6.3	8	10	12.5	16	20	25	31.5	40	50	≥ 63
Attenuation coefficient	0.2	0.2	0.3	0.3	0.2	0.1	0.1	0.1	0.1	0.1	0.3	0.3

where the FRFs have a coherence (Eq. (3)) higher than 0.5 are shown in the figure and were used in the estimation of the transfer functions.

As can be seen from the figures the frequency response functions for different vibration sources and locations vary. The vibration budget uses estimated transfer functions based on the envelope of all measured construction equipment. Sheet pile installation with vibratory hammer and rock excavation with a hydraulic breaker are assessed separately, since the results for these sinusoidal sources are clearly different than for the other more transient sources. As expected, the transfer function is higher in the horizontal than in the vertical direction in the low frequency region below about 8 Hz where the fundamental frequencies for movement of the whole building are expected to be located, [18]. The transfer function in the vertical direction has a peak in 1/3 octave band with a mid-frequency of the 25 Hz. Calculations and shaker measurements indicate that there are several floor resonances in this frequency region.

7. Evaluated mitigation measures

As the main vibration mitigation measure, a screen made of jet-grout columns in ground is planned between the existing museum and the main construction area. The screen will have an effect on vibrations from all construction activities that are in the shielded sector behind the screen. However, activities such as construction traffic to and from the site and rock excavation will not be affected by the screen.

The effect of the screen was evaluated by dynamic FE-calculations performed in the frequency domain using the finite element software package COMSOL Multiphysics [19]. A three-dimensional (3D) model was used to correctly describe the vibration attenuation with distance and to avoid problems with oscillating vibration amplitude that often occur in

two-dimensional models, [20]. The model describes a typical cross section in the direction from the construction area to the museum (the museum building is not included in the model). The third dimension is modelled as a thin slice (two-meter thick) to limit the computational effort. Due to symmetry, only half of this slice is modelled. The model is equipped with specially designed absorbing boundary domains (PML), which allow vibrational energy to dissipate out of the area of interest and prevent the waves from being reflected from the outer boundaries of the model [21].

The model is excited with a vertical dynamic unit force density (1000 N/m²) over an area of 0.04 m², representing a point load. The excitation frequencies are the mid-frequencies in the 1/3-octave frequency bands from 4 Hz to 20 Hz. The ground conditions and measurement results from the building site indicate that the calculated frequencies represent the most important frequency range. The element types are quadratic (second order) Lagrange elements with a maximum element size dependent on the frequency to maintain good resolution, i.e. approximately 8 elements (or 16 evaluation points) per wave length for a shear wave with a wave velocity of 95 m/s. Vibration waves with higher wave velocities (shear waves with higher wave velocity and compressional waves) are hence described with more elements. At 20 Hz the model size is 1.23 million DOF. An isotropic structural loss factor of 0.1 has been used in the models for clay and jet grout columns, which gives a good match between calculated distance attenuation in a model without screen and the measured distance attenuation at the site.

Table 3 shows the input data to the calculation in the form of material properties. Input data are determined from geotechnical site investigations and seismic measurements performed at the site. Fig. 13 shows as an example the calculated v_{RMS1s} in the ground when the FE-model is excited with a 10 Hz dynamic unit force 30 m from the Gokstad wing. The FE-calculations indicates that the screen may reduce vibration values transferred to the building with 70–80 % for construction activities performed within the shielded area.

Other measures to reduce vibrations could for example be:

- Speed restriction for construction traffic leaving and entering the construction area.
- Paving of construction roads and frequent cleaning and maintenance to maintain a smooth road surface free from clay deposits.
- Restrictions on certain activities and equipment in the shortest distances from the museum, e.g. tipping of soil from trucks and heavy rigs and excavators on belts.

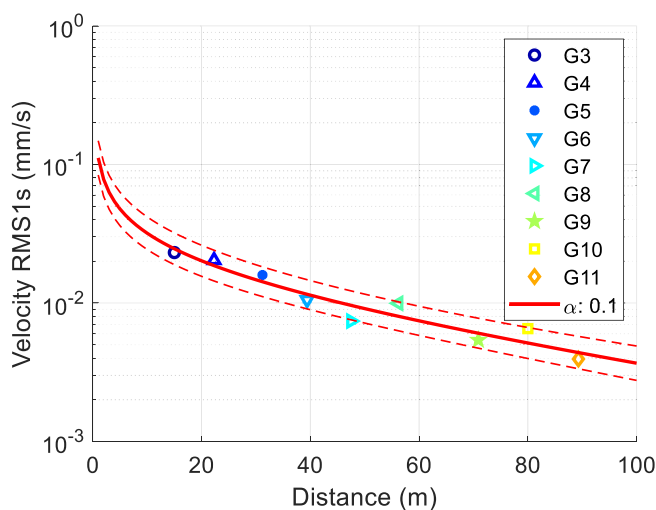


Fig. 11. Example of attenuation coefficient at 16 Hz determined by curve fitting measured vibrations from the movement of belt excavator (the red line on the far left of the Fig. 10) using nine sensors positions on the ground. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Material properties.

Material	Youngs modul E_{max} (MPa)	Poissons-tall ν	Density ρ (kg/m ³)	Loss factor η_s
Clay top layer	69	0.485	1750	0.1
Clay lower layer	252	0.485	1750	0.1
Bedrock	36E3	0.25	2700	0.02
Jet grout columns	6E3	0.2	2100	0.1

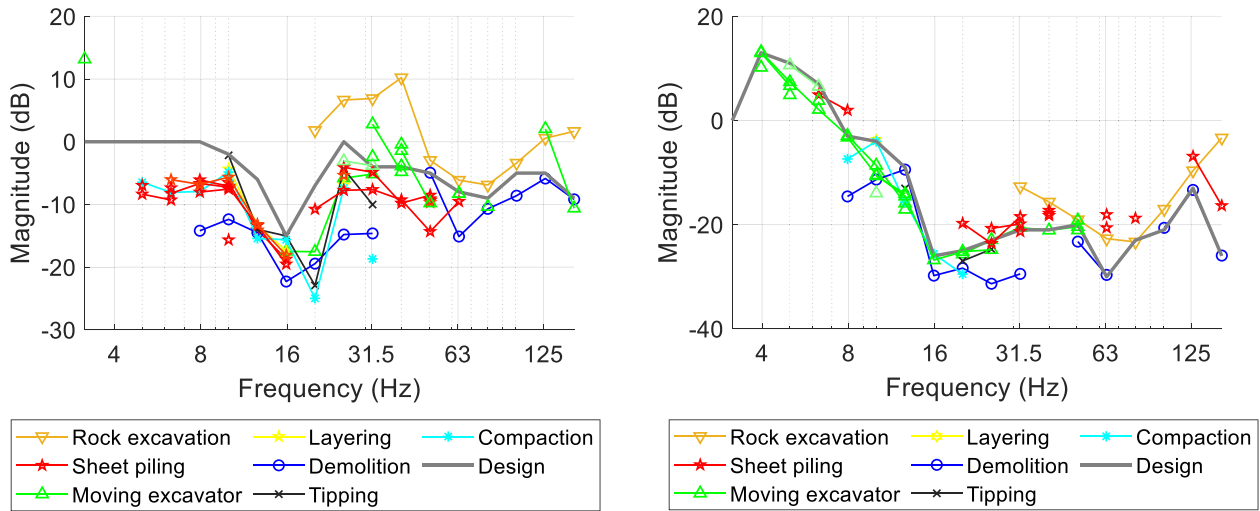


Fig. 12. Vibration transfer functions from outdoor on ground to indoor on floors from measurements at the museum site. The “design” transfer function is used in the vibration budget for all sources except sheet piling and rock excavation. Left: outdoor vertical to indoor vertical direction. Right: outdoor vertical to indoor horizontal direction.

- Alternative more low-vibrating equipment and procedures, e.g. sheet pile installation with equipment using hydraulic pressure in addition to vibratory hammer and rock excavation using drilling and wire sawing instead of hydraulic rock breaker.
- Postpone certain construction activities until the collection has been moved to its future location in the new museum.

In addition, it is an overriding goal to establish a workplace culture where the safety of the collection and consideration for vibrations are paramount. The safety of the collection will be a topic at intake courses for personnel and at progress meetings etc. in the same way as HSE and Quality Assurance. Procedure and order in groundwork will be assessed regarding object safety in addition to the usual construction considerations. Close collaboration is also planned between the contractor and the museum conservators during the construction work.

8. Results

The resulting vibration budget for the Gokstad wing is shown in Fig. 14 together with the limit values for v_{RMS1s} based on baseline. The limit values are exceeded a large portion of the total time, i.e. 19 %. The figure also indicates that activities such as excavation and sheet piling give a large contribution to the total time the limit values are exceeded, while activities such as drilling and lime-cement stabilization are of less concern. Fig. 14 right shows the vibration budget for the situation with a jet-grout screen in ground. The FE-calculation described in section 7 indicates that the vibration screen will give about 70–80 % reduction of the vibration values from shielded activities. However, the vibration budget shows that with the screen, the portion of time that the limit values are exceeded is only reduced from 19 % to 15 %. This is partly because activities such as construction traffic to the site and rock

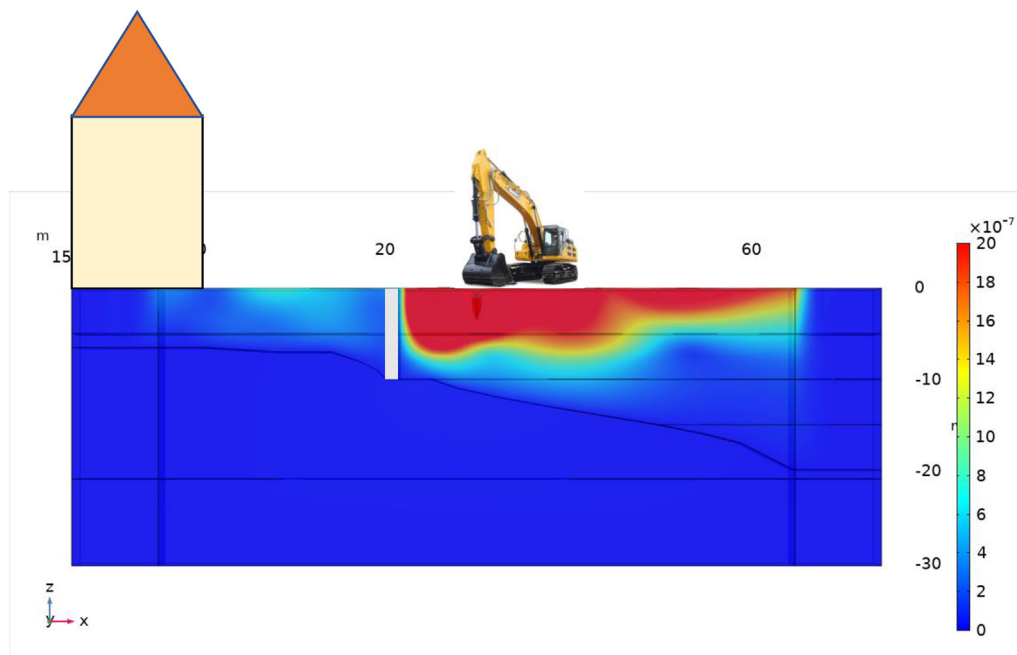


Fig. 13. Calculated v_{RMS1s} (m/s) in ground when the FE-model is exciting with a dynamic unit force 30 m from the Gokstad wing (where the excavator is in the figure).

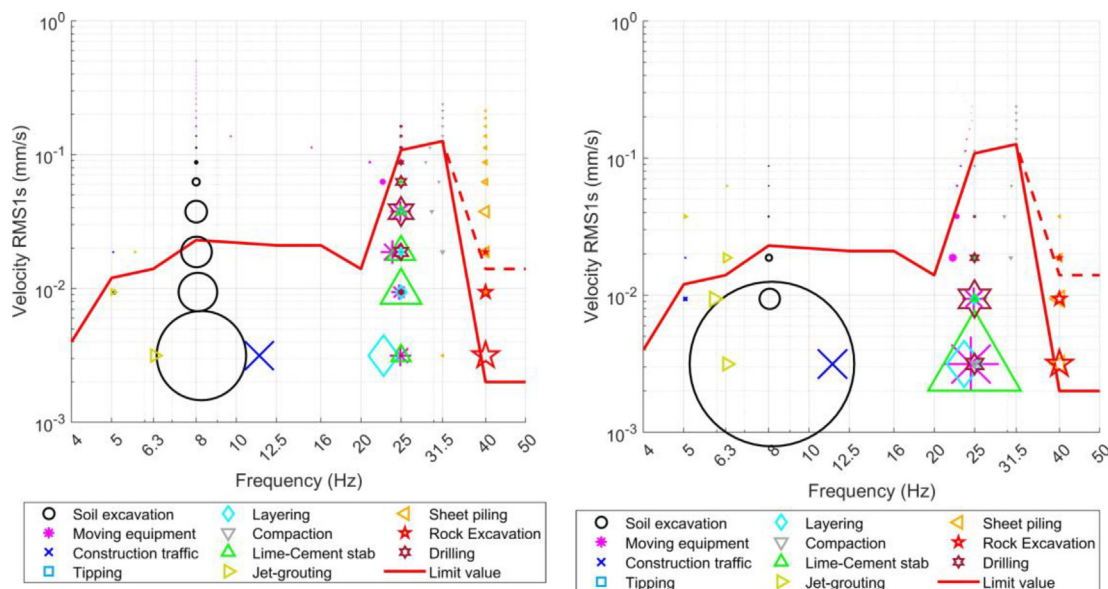


Fig. 14. Calculated v_{RMS1s} vs dominating frequency in the Gokstad wing plotted together with the v_{RMS1s} limit values based on baseline. The center position of the symbols marks the frequency and vibration velocity, while the sizes of the markers are relative and reflect the total time with the current frequency and vibration velocity. Left: without mitigation measures. Right: with jet-grout column screen in ground.

excavation are not affected by the screen. Nevertheless, the main reason is the extremely strict limit values from 40 Hz and upwards where activities such as sheet piling have their dominating frequency. If the limit values from 40 Hz and upwards are set equal to the limit value at 20 Hz (dotted line in the figures), the vibration budget shows that the screen reduces the portion of time that the limit values for v_{RMS1s} are exceeded from 12 % to 5 %. New limit values for v_{RMS1s} are under preparation and are expected to be adjusted upwards, especially for the higher frequencies.

9. Conclusions

A comprehensive methodology, the “vibration budget”, for assessing vibrations from the construction period based on statistically processed measurement data in percentiles is described. The method provides an opportunity to assess not only the peak vibration values, but the total vibration load during the construction period as a basis for an evaluation of risk of vibration damages. In the vibration budget, the total time with different vibration levels from the various construction activities are estimated. Based on the results, the most critical construction activities can be identified, and effects of different mitigation measures can be estimated.

For the planned Museum of the Viking Age project, a concern is that vibrations from the construction work of the new extension can cause damage to the fragile collection in the existing museum and strict limit values based on baseline measurements were therefore set. The vibration budget is used to identify the activities that contribute most to the total vibration load and to assess the effects of planned mitigating measures.

The planned main mitigation measure is a screen made of jet-grout columns in the ground between the existing museum and the main construction area. Dynamic FE-calculations show that the screen may reduce vibrations from the shielded area with up to 70–80 %. However, the vibration budget shows that even with the screen the strict limit values for v_{RMS1s} are expected to be exceeded a significant portion of the time. This is partly because some activities are not shielded, but mainly because the v_{RMS1s} limit values are extremely strict from 40 Hz and upwards, where

activities such as sheet piling have their dominating frequency. Therefore, it is unlikely that construction work which meets the v_{RMS1s} limits based on baseline measurements will be feasible. New limit values for v_{RMS1s} are therefore under preparation. The vibration budget may provide valuable information for this work on the expected durations of vibrations with different RMS levels and dominating frequencies during the construction period.

In addition to the vibration screen other mitigation measures are evaluated and it is an overriding goal to establish a workplace culture where the safety of the collection and consideration for vibrations are paramount. There will be a close collaboration between the contractor and the museums conservators, and measurement data will be used actively as a basis for adjusting the construction implementation if it proves necessary.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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