Vibrations in the Environment - Remedial Actions at a New Compressor Foundation

Field Investigation and Redesign by FEM-Calculations

by

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Abstract

After installation of an additional 4 MW reciprocating compressor at an underground gas storage in Denmark very disagreeable vibrations occurred in the administration building nearby and in the private home of a neighbour, a bit more far away. Comprehensive field measurements were carried out in order to detect the mechanism of the vibration transmission. The results of the investigation revealed a resonance mode shape of the complete compressor foundation (rocking mode at approx. 13 Hz). The foundation was mainly excited by the free mass forces and moments of the compressor at the 2nd order of the operating speed. After discussion of the results the operator decided to reduce the vibrations at the source. Hence, the complete compressor foundation was built up in a FEM-model including the soil-structure-interaction. Challenging was that any measure at the foundation was restricted by the space available within the existing compressor hall. With the model the effect of a horizontal extension by a concrete slab at each side of the original concrete block was investigated. This article also deals with the particularities of FEM regarding the infinite extent of the soil.

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1 Introduction

The Stenlille underground natural gas storage is located in Seeland, Denmark and operated by a Danish energy utility. Originally, the storage was projected to supply peak loads and on the other hand to balance the lack between gas production and demand in summer and winter. Today, the facility is a more commercial storage and the gas is owned by the customers. Depending on their requests – forced by the situation on the gas market – the gas has to be stored or withdrawn as fast as possible.

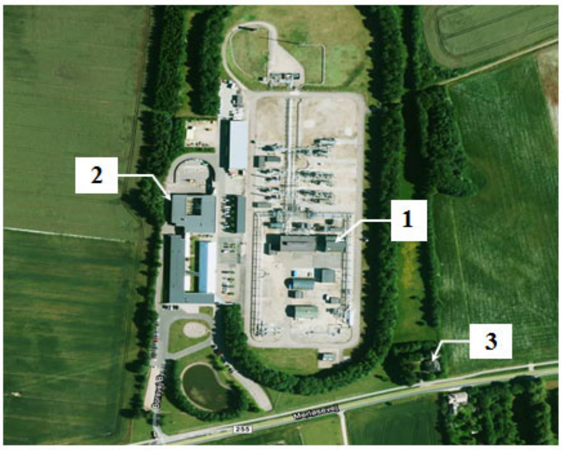


Figure 1: Aerial photo of the gas storage facility with building for engineering services and administration; 1: Machine hall for compressor K-24, 2: Administration offices, 3: Residential building.

The natural gas is stored in a groundwater reservoir (aquifer) at a depth of 1,500 m. The aquifer below Stenlille offers a capacity of approx. 2 · 109 m³ at a pressure of 150 bar.

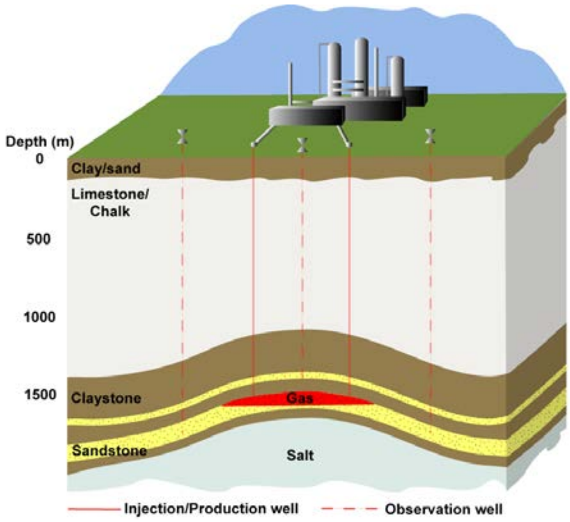


Figure 2: Geological configuration of the underground gas storage.

Up to the year 2007 three reciprocating compressor units produced a volume flow of approx. 100,000 Sm³/h. For doubling the capacity a new compressor was projected by the operating company and set into operation in July 2009. The new compressor was designed as 1-stage, 2-crank, flat-type case, running with constant speed at 375 1/min (6.25 Hz rotational frequency), power consumption: 4 MW. The volume flow is controlled by stepped suction valve unloaders.

In summer 2009 the mean line pressure of the suction piping was higher than expected and the new compressor K-24 could store 20 % more gas as predicted. However, several members of the staff in the administration building complained about vibrating desks, computer screens etc. when the new compressor was running. Hence, the vibrations could be traced back to compressor K-24. Thus, the question arose, whether the vibration level at the compressor foundation was harmful for the machine itself.

First measurements were conducted by the Danish engineering company, who had supported the energy utility in this project so far. It turned out that the vibrations were dominated by the frequency of 12.5 Hz, i.e. the double rotational frequency (6.25 Hz) of compressor K-24. The compressor manufacturer stated that the measured vibration level at the machine foundation was not harmful for long-term operation of the compressor.

However, in summer 2010 the neighbour outside the storage facility – distance 160 m from the K-24 compressor foundation - complained about vibration inside the house, see figure 1, position no. 3. For example, the central-heating boiler was making an annoying noise that was strongly inconvenient for sleep during the night.

The operating company took seriously the disturbances for the staff and the neighbour due to the compressor operation. At that time, it should be clarified, whether there was a mistake in the basic design of the compressor installation causing the vibration problem. Therefore, as a next step a detailed root cause analysis was performed.

2 Root cause analysis

2.1 Operational vibration measurements

For the design of mitigation measures to improve the vibration situation the picture that could be drawn from the first measurements was unsatisfactory. In particular, it was not clear if the compressor was running at a speed that excites a natural frequency of the complete compressor foundation, i.e. the concrete block with the machine set on the top.

A rough estimation of the lower natural frequencies of the foundation embedded in the soil turned out that a resonance at 12.5 Hz, i.e. twice the rotational frequency, could not be excluded.

Thus, in order to detect the vibration behaviour in detail, extensive measurements during operation of the compressor were performed on site. Figure 3 shows the compressor K-24 inside the hall. The essential measuring positions at the concrete foundation are depicted in figure 4. During operation of the compressor the maximum vibration velocities arose at positions v02 and v05 in z-direction. These positions were located on the foundation area for the (vertical) supports of the compressor cylinders, see figure 5.

Figure 3: Compressor K-24 in the machine hall.

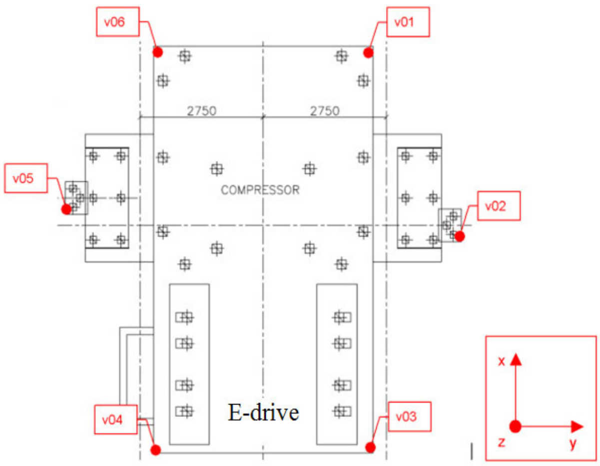


Figure 4: Denomination and location of the main measuring positions at the compressor foundation.

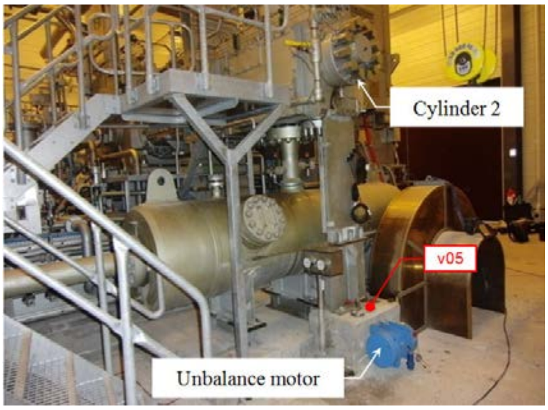


Figure 5: Support of cylinder 2, mounted unbalance motor (blue) at the foundation.

During the first 3 minutes after run up of the compressor (from approx. 18:00 h, see figure 6) the load, i. e. the volume flow, was increased stepwise by means of suction valve unloaders. The vibration level at the foundation (v05z) achieved a maximum of approx. 2.7 mm/s RMS at 100 % load, figure 6. In comparison to other compressors at similar installations this level is not unusually high. According to ISO 10816 – 8 [1] respectively EFRC guidelines [2] a vibration level up to 3 mm/s RMS is allowable for long-term operation of the compressor. Hence, this result mainly implied that regarding the dynamic behaviour a fundamental deficiency of the compressor foundation was not existent.

Nevertheless, on the floor slab in the office (see figure 1, no. 2, air-line distance approx. 150 m) and in the residential building outside of the facility area (see figure 1, no. 3, distance approx. 160 m) the vibration level achieved not more than approx. 0.05 mm/s RMS. This level is even below the defined sensitive threshold of 0.1 mm/s RMS. Anyhow, annoying secondary effects for the staff and the residents appeared like for example vibrating computer screens, noise emission at the heating system like "buzzing / growling" etc.

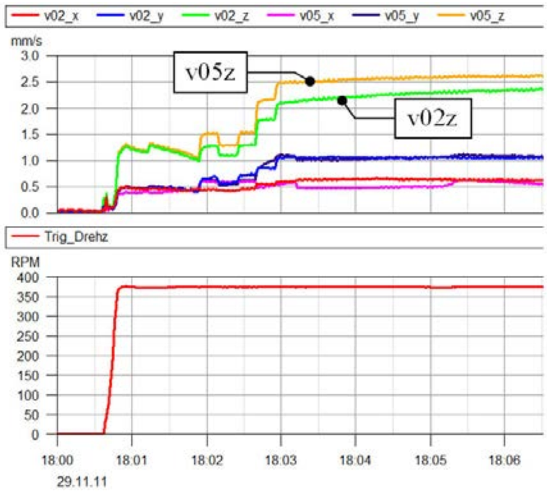


Figure 6: Top: Measured vibration velocity as RMS-values at the machine foundation during start-up of the compressor, below: compressor rotational speed.

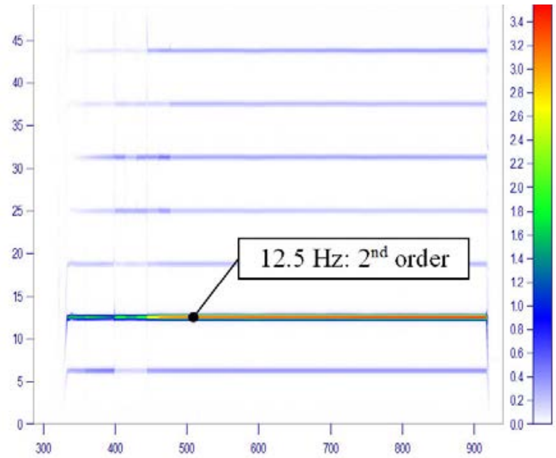


Figure 7: Time-frequency-spectrum of the vibration at the measuring position v05z during start-up of the compressor, cf. figure 6.

The time-frequency-spectrum in figure 7, which corresponds to the run up of the compressor in figure 6, reveals that the 12.5 Hz frequency was the dominating component of the foundation vibration for all load cases.

Regarding the phase shift relationship between the measured signals at different positions of the foundation it turned out that the foundation was rocking around the x-axis (rocking mode). The vibration mode shape of the complete compressor foundation (compressor, e-drive, concrete foundation) is depicted in figure 8.

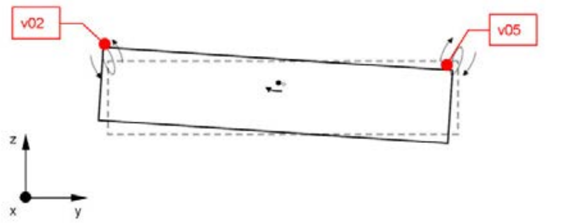


Figure 8: Vibration mode shape of the foundation with compressor, in the sketch there is only the block foundation depicted, „rocking“ with 12.5 Hz.

2.2 Excitation with unbalance motor

Since the compressor is running at a constant speed with 375 rpm, the resonance frequencies of the foundation cannot be determined by the results of the operational vibration measurements. Hence, an unbalance exciter (e-drive) with variable speed (controlled by a frequency converter) was used for the excitation of the foundation. The unbalance exciter was mounted with anchor bolts directly at the concrete foundation. Figure 5 shows the position of the exciter below the cylinder no. 2. With the known quantity of the exciting force the measured response of the foundation can be used to determine the transfer functions as shown exemplarily in figure 9. The transfer functions show obviously the resonance amplification at the frequency range around 13 Hz.

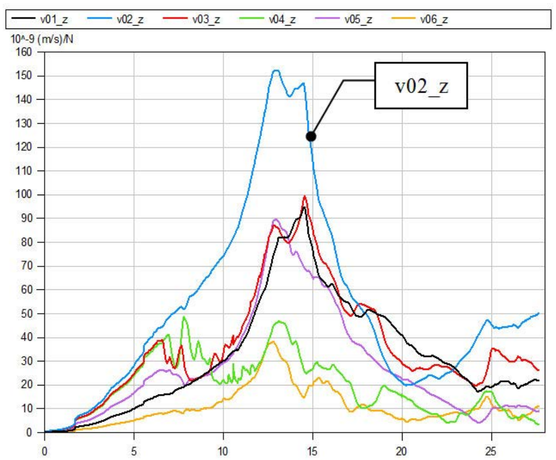


Figure 9: Transfer function (frequency response) at different measuring positions (ratio: vibration velocity in z-direction / exciting force), excitation by unbalance motor up to 28 Hz.

These results revealed that the 2nd order of the compressor speed at 12.5 Hz, i. e. two times of the rotational frequency (6.25 Hz), lay actually close to the “rocking mode” resonance of the foundation.

2.3 Possible mitigation measures

Although in this case the main goal was the reduction of the vibration level in the environment of the compressor and not the reduction of the foundation vibration itself, possible solutions had the focus initially on measures at the foundation itself. With regard to the results of the field measurements the detuning of the resonance frequency of the rocking mode, i. e. the ratio between exciting and natural frequency, can be considered as favourable solution. In the following some essential approaches for achieving this aim are presented:

- M1 Decreasing (M1.a) or increasing (M1.b) the natural frequency (rocking mode shape) of the complete machine foundation (concrete block including compressor and drive).
- M2 Decreasing or increasing the excitation frequency, i. e. change of the (constant) compressor speed.
- M3 Reduction of the resonance vibration at foundation by means of tuned additional oscillating masses (vibration absorber) mounted at the foundation.
- M4 Decreasing or increasing the (1st) natural frequency of the concrete floor slab in the office.
- M5 Reduction of the resonance vibration at floor slab in the office by means of tuned additional oscillating masses (vibration absorber) mounted below the floor slab.
- M6 Reduction of the vibration transmission in the soil by means of underground construction measures, for example diaphragm walls etc.

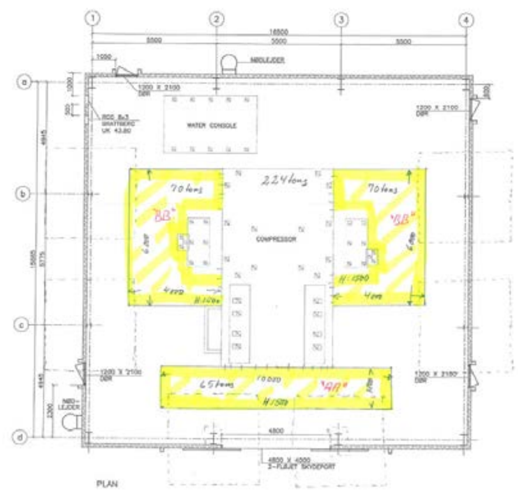


Figure 10: First draft for the extension (yellow) of the compressor foundation.

It is obvious that passive measures in the office (M4 or M5) do not have any impact on the situation at the residential building. After discussion with the operator it was decided to pursue the approach M1.b: shifting upwards the natural frequency of the machine foundation.

With regard to the discovered rocking mode shape the first idea for the redesign of the foundation was a horizontal extension of the concrete block. But the available space for this measure was quite restricted. Figure 10 shows the first design of the foundation extension with two "wings" on the left and the right side of the existing concrete block and an additional stripe in front of the e-drive.

3 Computations for redesign of the foundation

3.1 Modelling and adjustment

The goal of the structural dynamic calculations was an estimation whether the redesign of the foundation with the new horizontal extensions achieves a sufficient reduction of the vibration level in the administration building as well as in the neighbouring residential building.

At first, a FEM-model was built up for the reciprocating compressor with the e-drive and the concrete foundation embedded in the soil for the original situation as examined during the field measurements. With utilisation of the symmetry characteristics, which arise from the rocking mode of the foundation, and in consideration of the mainly concentric propagation of the soil vibrations from the source, an initial model with a quite rough meshing was generated, see figure 11. For this model the soil was considered as homogenous for the complete model extent.

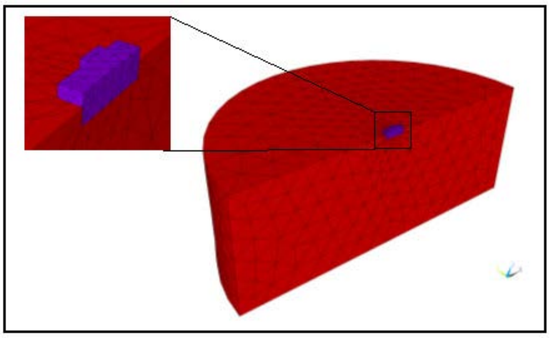
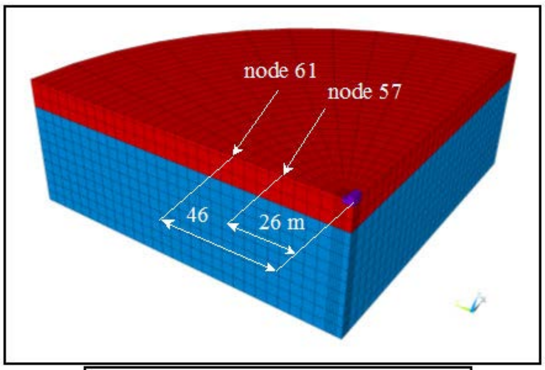


Figure 11: First FEM-model of the compressor foundation (purple) with soil bedding (red), radius: 150 m, depth: 54 m.

At this point it has to be remarked that FEM-modelling of infinite structures – in this case: the soil – leads by implication to artificial mode shapes of the model. The model dimensions and the parameters have to be chosen properly that the artefacts are minimized and do not overlap the frequency range of interest.

For excitation of the model the dynamic load reactions of the compressor were used as documented by the compressor manufacturer. The results of the first calculations did not show the rocking movement of the foundation. Further calculations revealed that for the appearance of this shape of movement an unbalanced inertia moment around the (crank) shaft axis was necessary, which was not indicated yet. It turned out that the reaction forces due to the inertia forces at the cross-head guides were mainly responsible for the sought load on the foundation and subsequently for the excitation of the rocking movement.



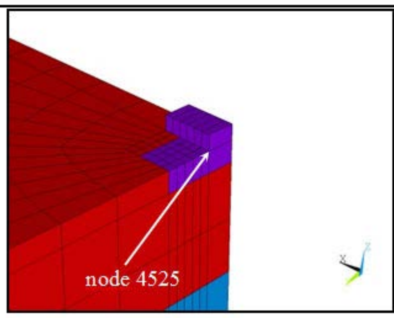


Figure 12: Tuned FEM-model of the compressor foundation with 2-layer soil model.

With this knowledge, i. e. the completed model, a first assessment of the planned foundation retrofit could be carried out. The results for the original design of the foundation were compared to the results of the retrofitted foundation. The results show that a reduction of the vibration level can be expected of at least 50 % at the foundation itself. However, the natural frequency of the rocking mode shape was shifted not more than 3 Hz upwards.

Further results of extended calculations revealed that the quite slim concrete stripe at the position in front of the e-drive had only a weak effect on improving the situation. Hence, this part of the retrofit was abandoned.

3.2 Optimisation of the foundation extension

In the next step, for improving the validity of the model – for areas far from the compressor (> approx. 25 m) - a structured (mapped) and finer mesh was generated for the soil. Meanwhile, the soil properties had been determined more in detail. The results were used to build a layered model of the soil with two layers. Additionally, further properties of symmetry were used which finally led to a "quarter pie" model, see figure 12.

The improved modelling of the soil succeeded in a better adaptation of the computed rocking mode frequency to the measured result. Nevertheless, with the available soil parameters the computed rocking mode frequency (approx. 20 Hz) was still above the measured frequency on site. At this time an improving of the model was not pursued furthermore. Thus, the assessment of design measures at the foundation was (mainly) carried out by comparing the results of the models for the state with and without the extension.

The results with the improved modelling showed now for the extended foundation that a reduction down to 30 % (in relation to the original situation) could be achieved. In the far field (administration and residential building) the model showed a reduction of about 50 %. In figures 13 and 14 the results are exemplarily presented for selected node positions as depicted in figure 12 (note: different scales are used in the charts).

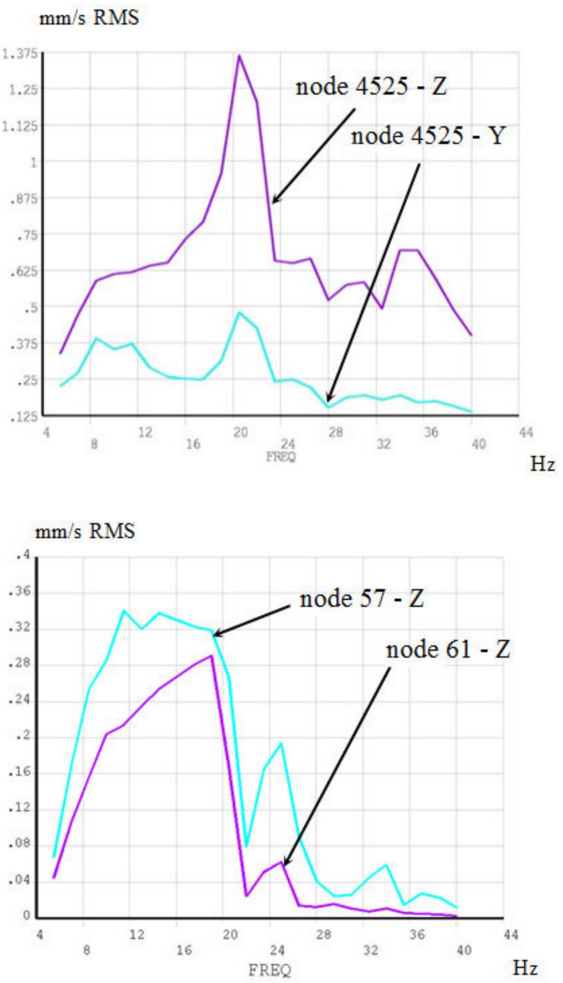


Figure 13: Frequency response of vibration velocity, foundation in original state, top: at the foundation, below: in the surrounding, see figure 12 for positions of nodes.

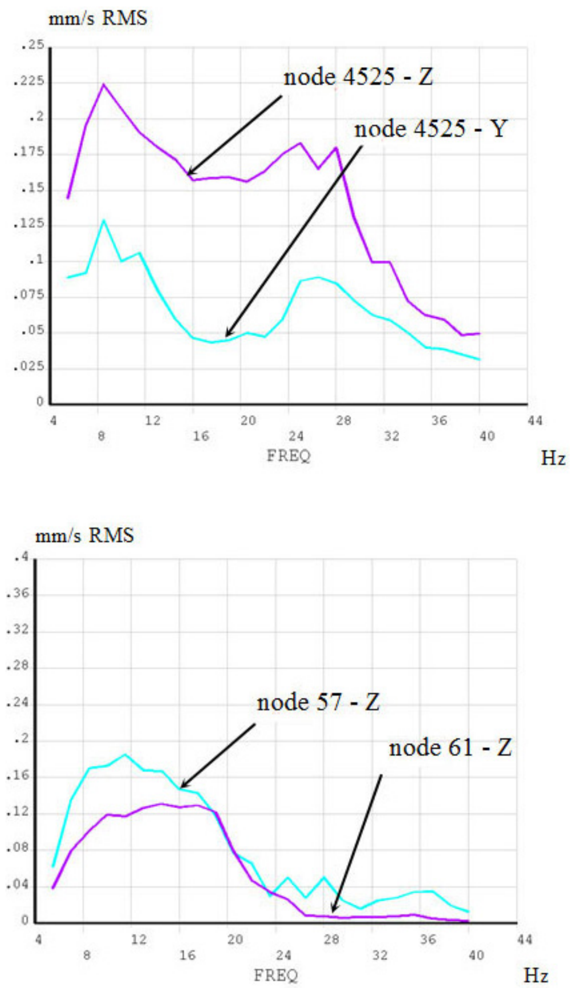


Figure 14: Frequency response of vibration velocity, foundation with extension, top: at the foundation, below: in the surrounding, see figure 12 for positions of nodes.

But the results for the "wings"-extension still showed a natural frequency for the "rocking" of the foundation which was not more than 2 – 3 Hz above that of the original foundation. Hence, the expected new "rocking" frequency was still close to the 2nd order excitation of the compressor. Therefore, in order to shift this frequency up, the effect of additional piles supporting the foundation "wings" was investigated in the next step. As an initial design 4 piles were placed below each wing, altogether 8 piles, see figure 15. The pile length was set to 14 m since they should penetrate sufficiently the stiffer lower layer. The pile diameter was set to 0.5 m.

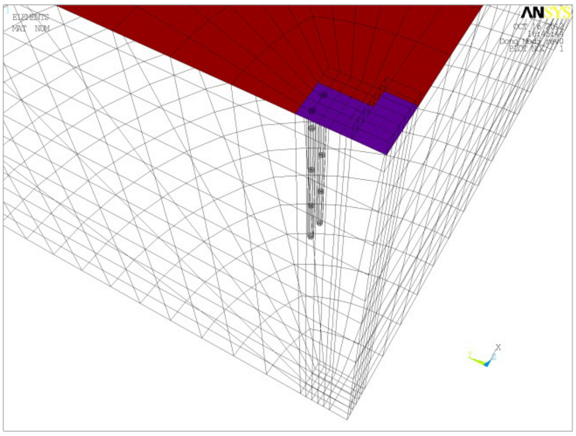


Figure 15: FEM-model for the foundation with extension and additionally 4 x 2 concrete piles below the foundation extension.

The results with the additional pile foundation revealed that this measure can shift the rocking mode frequency at least 6 Hz up compared to the original situation, see figure 16. Using 16 piles instead of 8 could shift up the frequency additionally 3 Hz.

After discussion with the operator and the supporting civil engineering experts the final design for the extension of the foundation was configured with overall 12 piles, 6 piles below each slab, see figure 17.

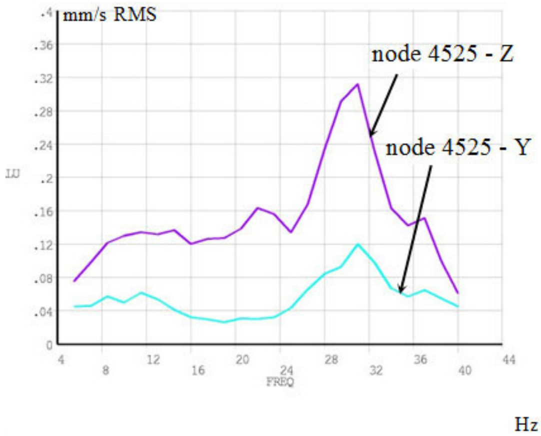


Figure 16: Frequency response of vibration velocity, foundation with extension and 8 piles, see figure 12 for positions of nodes.

In order to ensure the function of the extended foundation, it was absolutely necessary to accomplish as high stiffness as possible at the connection to the existing concrete block, although the dynamic load reactions are quite low at the interfaces. In the same way the connection between the concrete slabs (of the extension) and the pile heads had to be executed.

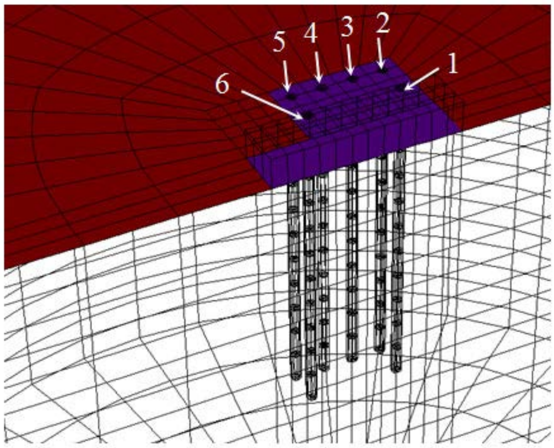


Figure 17: FEM-model with numeration of piles for the final design of the foundation extension with 2 x 6 concrete piles.

4 Realisation of retrofit

Between November 2012 and end of March 2013 the civil engineering of the retrofit was planned and executed, see figure 18. For the construction of the piles with on site mixed concrete it was necessary to ditch the ground around the compressor foundation inside the existing hall. Afterwards, the bore holes for the piles were drilled with a depth of 14 m, in which the baskets for reinforcement were put in.

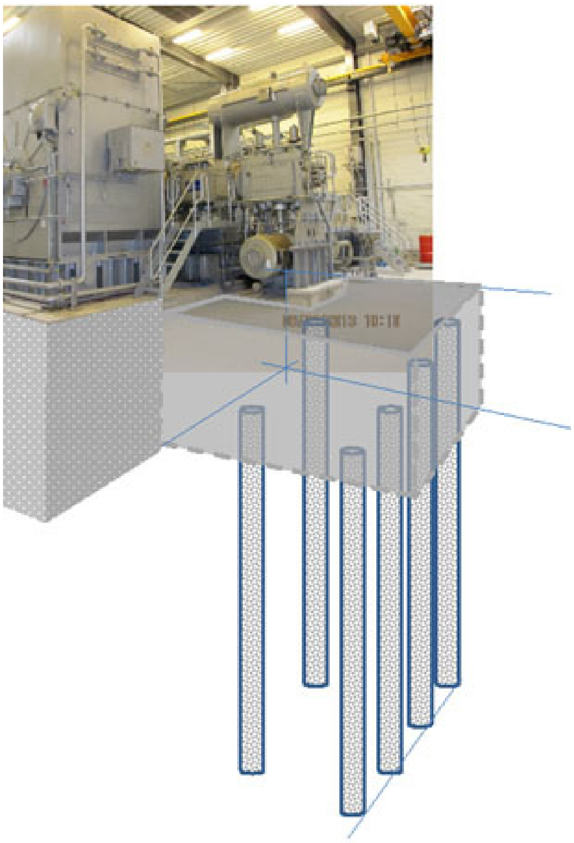


Figure 18: Sketch of the planned foundation extension in the machine hall.

Figure 19: View on one side of the foundation after completion of the concrete piles.

Figure 20: Reinforcement of the foundation extension.

Figure 19 shows the ends of the core wiring of the baskets which protrude from the pile heads for the monolithic connection with the extended slab ("wing"), see also figure 20.

5 Check measurements after retrofit

After recommissioning of the compressor in April 2013 the actual vibration situation was checked by measurements on site again at 100 % load. The results showed that the vibration level at the foundation was decreased to approx. 10 % compared to situation before the retrofit – from 2.7 mm/s RMS to 0.3 mm/s RMS. As predicted by the computations the diminution of the vibration level depended on the direction of the vibration. The vibration level in x-direction was reduced only down to approx. 40 % - 50 % compared to the original state, see figure 21.

In the office of the administration building a reduction of at least 50 % in any direction was achieved, although the natural frequency (13 Hz) of the floor slab was not modified. In vertical direction the vibration level lies at 44 % of the level before the retrofit, see figure 22.

Slightly different is the picture at the residential building. Here, the highest reduction was achieved – as intended – in horizontal x-direction, see figure 23. The vibrations generated by the compressor K-24 could be reduced to approx. 30 % of the level without the extension of the foundation. In the vertical direction the vibrations were very low already before the retrofit.

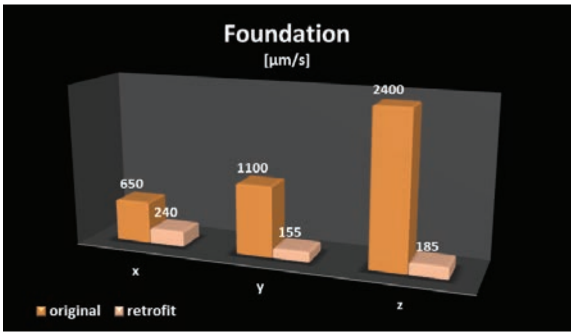


Figure 21: Comparison of vibration velocity level at the foundation (position v02) before and after retrofit.

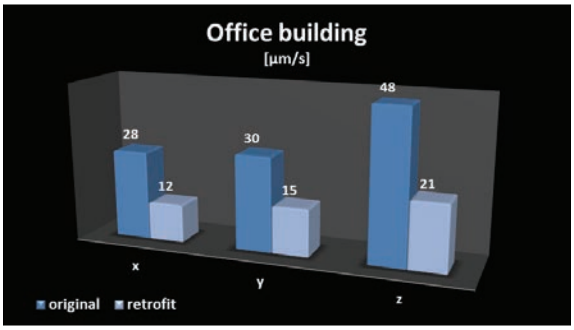


Figure 22: Comparison of vibration velocity level in the office building before and after retrofit.

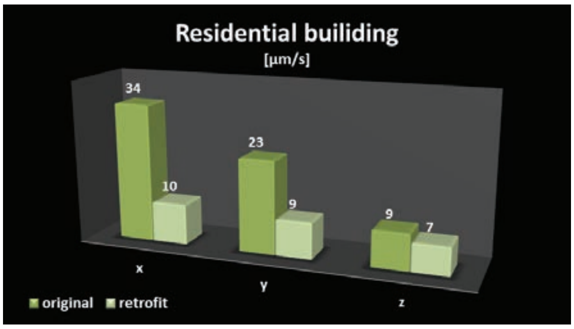


Figure 23: Comparison of vibration velocity level in the residential building before and after retrofit.

6 Conclusion

After recommissioning of a new reciprocating compressor at the Stenlille underground storage in Denmark inconveniently high vibrations arose in the administration building inside the facility and in a residential building close to the facility.

A comprehensive metrological investigation during operation of the compressor revealed that no exceeding vibrations occurred at the foundation itself. Nevertheless, the rocking mode resonance of the complete installation at approx. 13 Hz was excited by 2nd order of the compressor (12.5 Hz).

As a first step - due to the results of the measurements - an extension of the foundation was designed in order to improve the vibration situation in the neighbouring buildings. Finite-element calculations including the soil-structure interaction showed that additionally a pile foundation below the extended concrete slabs was necessary.

After the retrofit of the foundation a metrological check of the actual situation during operation of compressor K-24 was performed. The results could prove a successful reduction of the vibration level in the offices and in the neighbouring residential building, which give no reason for complaints anymore.

The presented case study in this paper shows that for the foundation design of reciprocating compressor installations possible vibration emissions in the environment, like neighbouring buildings close or far from the compressor, should be taken into account. At least it should be checked by calculations whether the lower resonance frequencies of the foundation might be close to the main excitation frequencies due to the free inertia forces and moments of the compressor. Even if the arising resonance vibrations are not harmful for the compressor, the vibration emission in the environment could be too strong.

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