ADVANCED VIBRATION ISOLATION OF A MULTI-STOREY BUILDING USING TAILORED SOLUTIONS FOR DIFFERENT FOUNDATION SYSTEMS

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1 INTRODUCTION

Urban development near railway or subway lines presents significant challenges, particularly due to vibrations that can be transmitted through the ground and foundation structures into buildings. These vibrations can lead to both structural, vibrations and secondary airborne noise emissions, which can severely impact the comfort and usability of indoor spaces. Effective vibration isolation is therefore crucial for ensuring a comfortable and functional indoor environment in such settings.

This paper shows the project OPTINEO in Munich as a case study of a project specific and very individual approach based on the actual requirements coming from various measurement scenarios and modelling prognosis. The property is situated directly next to a subway tunnel and just a stone's throw away from a suburban railway line, making it a particularly challenging site for mitigating vibration impacts. To prevent load transfer to the subway tunnel, the building is partially supported on piles with the loads transmitted through a three-metre-thick floor slab. High resilient elastic polyurethane bearings are used to insulate the base plate from the pile heads, while a 100 mm thick polyurethane foam layer further reduces load transfer, ensuring effective isolation.

This study points out the legal situation and definition of prospected noise and vibration requirements, the measurement procedures, and the prediction methods used to specify the elastic solution. Additionally, it compares the measured results with the project requirements and provides detailed insights about the used elastic solution used.

Figure 1: OPTINEO Munich, © Nieto Sobejano Arquitectos, MadridBerlin

2 INTRODUCTION TO VIBRATION ISOLATION

Vibration emissions caused by rail or road sources can be transmitted through the ground into neighboring buildings via structure-borne noise, may resulting in disturbing vibrations or secondary airborne noise. A proven solution to this problem is the elastic vibration isolation of the building base. The mechanism functions like a mass-spring system, with the elastic mount acting as the spring element, in addition to the resilience of the subsoil. Key factors for determining the tuning frequency are the dynamic stiffness C_{EL} of the bearing and the building mass being supported. Additionally considered is the damping ratio of the bearing D_{EL} From this, a theoretical transfer function is derived, which describes the isolation effect of the solution. Prediction models also include transfer functions to estimate secondary airborne noise, allowing for comparisons with legal or project defined requirements. The elastic bearing described in this paper involves using a solution of foamed polyurethane used as a full-surface application, meaning the building base slab and basement outher walls are completely lined with mats ensuring not having any noise bridges. Other options for elastic isolations of buildings include point or strip bearings with polyurethane or rubber pads or spring boxes. Retrofitting solutions may include side wall decoupling or slot walls, but their effectiveness is generally considered limited.

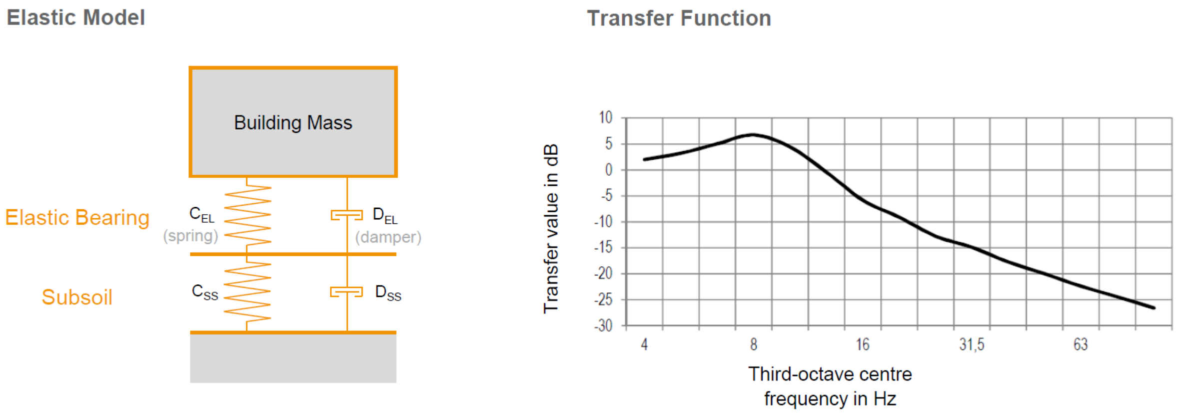

Figure 2: Building isolation elastic model (left, © Getzner Werkstoffe) and example transfer function[1] (right, © PMI Ingenieure)

3 CASE STUDY: THE OPTINEO PROJECT

3.1 Overview

The Werksviertel in Munich is a 39-hectare urban district near the Ostbahnhof. Developed since 2016 as part of a comprehensive redevelopment of the area, it was awarded the German Urban Planning Prize in 2023. Like many metropolitan areas worldwide, central areas near railway lines were historically used for industrial purposes. However, the value of these areas for mixed-use developments that combine residential, office, and commercial spaces is increasingly recognized, especially given the scarcity of such spaces in inner-city areas.

Special attention must be paid to vibration protection in these new developments, as demonstrated by the Optineo project, designed by Nieto Sobejano Arquitectos of Madrid/Berlin. Located not only close to the suburban railway tracks of Munich's Ostbahnhof but also adjacent to the U5 subway line tracks, the building required special engineering support to prevent disturbing vibrations from affecting the structure.

Typically, disruptive vibrations or secondary airborne noise within a building can occur when above-ground vibration sources are within a distance of 50 meters of the building structure. Consequently, the railway tracks passing 30 meters northwest of the site will potentially result in negative effects.

Even more critical are underground sources, where disturbance can occur within 25 meters besides the track. Given that the tunnels of Munich's U5 subway line directly adjoin the planned building in a northwest direction, adverse effects were highly likely, especially given that the project includes high-quality office spaces requiring particular quiet.

In such a situation, a dynamic assessment is recommended. This generally includes vibration measurements on site followed by predictive modelling of expected vibration mitigation into the building and an estimation of expected secondary airborne noise levels. For this project, PMI Ingenieure of Munich/Berlin conducted the assessment, including after measurements to verify the predicted values.

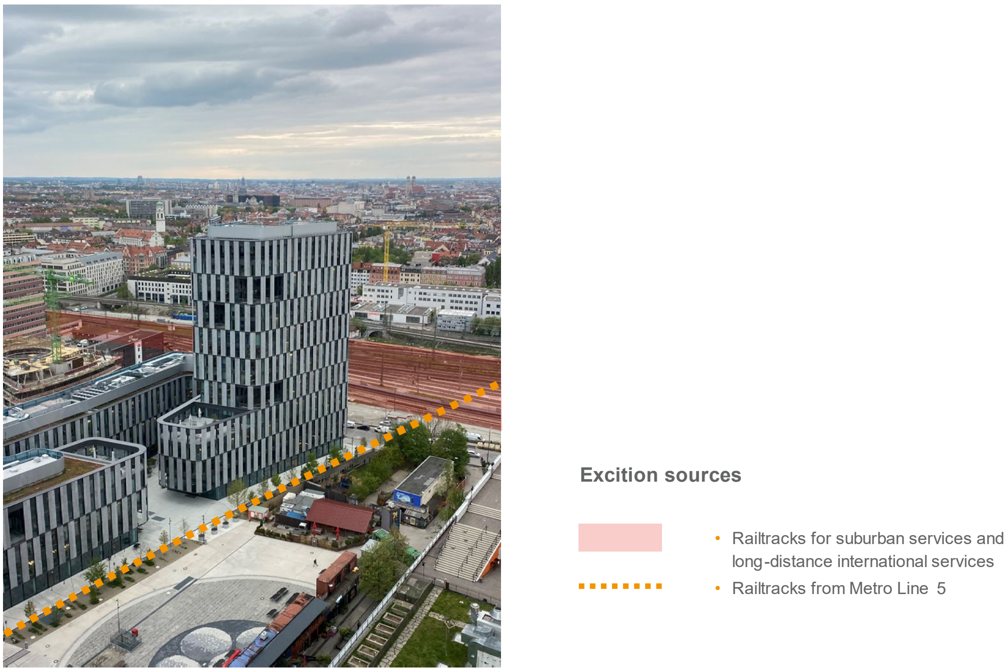

Figure 3: OPTINEO Munich project location with ground borne noise sources, © Getzner Werkstoffe

3.2 Legal Situation and Project Limits

The legal framework for limiting vibrations and secondary airborne noise induced by external sources such as rail traffic varies significantly worldwide. Not all regions have legally binding vibration and/or noise limits. Moreover, international and national standards use different indicators for measuring vibration levels. The most important international standard is ISO 2631, which uses RMS values (Root Mean Square) for evaluation. In contrast, the German DIN 4150-2 standard, which was applied in this project, uses KB values. The following project limits were defined:

- KB_{Fmax} (Maximum weighted vibration strength): ≤ 0.15
- KB_{FTr} (Mean vibration strength): ≤ 0.1

These values must be determined in all directions (x, y, z), with the ceiling showing the highest amplitudes being decisive.

For secondary airborne noise levels, no legally binding values are defined. Guideline values for Germany are provided by VDI 2719, the TA-Lärm, and DIN 4109. Based on these guidelines, the following project-specific limits were defined:

- $L_{AF,max}$ (A-weighted max. sound level, fast time weighting): ≤ 45 dB-A
- $L_{AF,m}$ (A-weighted avg. sound level, fast time weighting): ≤ 35 dB-A

These values must be fulfilled at all times.
Referring to the RIVAS Report², which provides a comprehensive overview of national and international measures for vibration control in buildings.

3.3 Measurement and Prognosis Modelling

To predict vibration and secondary airborne noise levels in the planned building, vibration measurements were conducted at various stages of the project. Initially, measurements were taken at different distances from the railway tracks on the ground surface. Transfer functions were then used to estimate the coupling effects of the building's foundation and the ceiling resonances. A separate transfer function estimated the expected secondary airborne noise within the rooms. These functions, refined through numerous projects and subsequent measurements, require ongoing verification throughout the project, as universally applicable values do not exist.

Measurements of vibration levels on surface and foundation level

Preliminary vibration measurements were carried out using accelerometers at fourteen points on the existing asphalt surface. Five of these points were positioned along the planned building line, parallel to the subway line, with the other measurement points each with distance of 8 meters from these like shown in the figure below. A total of 41 subway passes were recorded. The vibration levels reached up to L_v = 68 dB at the primary disturbing frequency of f_{Tn} = 63 Hz typical for subways. Due to the asphalt surface representing a very dense surface, uncertainties were expected, leading to the decision to conduct further measurements later in the project at the foundation level. Based on these initial measurements and subsequent simulations of induced vibrations and secondary airborne noise, an elastic building mounting was recommended to meet the defined limits.

Figure 4: Measurement points for initial evaluation of the situation, © PMI Ingenieure[1]

At a later project stage, additional measurements were executed in drill holes for more detailed specification. Four measurement points were selected in the areas with the highest values from the initial measurements. The levels were approximately 3 dB lower compared to the first measurements; however, a significantly broader frequency spectrum was observed. In addition to the main frequency at 63 Hz, special attention was given to the 100 Hz range, as it corresponds to the resonance frequency of the hollow floors. With the applied depth correction, the final levels were approximately 3 dB higher than the previous calculation. This confirmed the recommendation for a elastic building solution.

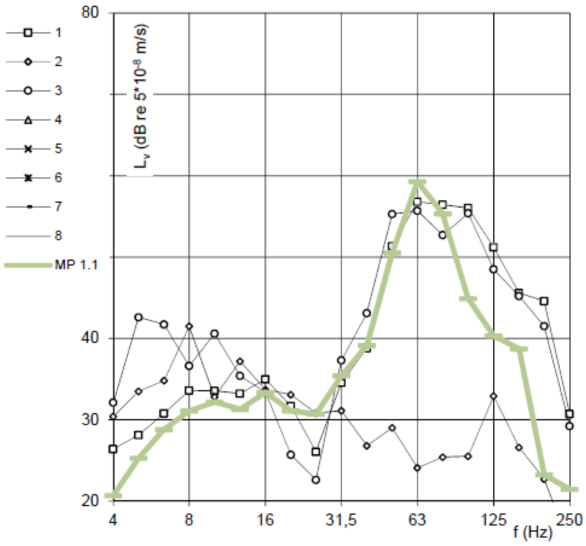

Figure 5: Excitation frequencies from drill hole measurements with typical highest values at 63 Hz, © PMI Ingenieure[1]

Furthermore, to refine expected vibration and noise levels for the modelling and to verify earlier measurement results, vibrations measurements on foundation eight points on foundation level were carried out.

When comparing these results with the initial and borehole measurements, a generally similar spectral distribution was observed, with the main natural frequency consistently at 63 Hz. However, the foundation-level measurements showed results approximately 7 dB higher than those from the borehole tests. Based on these findings, the elastic building isolation could be specified with its tuning frequency to fulfil the requirements.

Prediction modelling with and without elastic decoupling of basement

The prediction modelling was done by PMI using a custom-developed model with transfer functions. The calculations were based on theoretical approaches, incorporating empirically derived data processed according to statistical principles. The elastic bearings were included in the transfer function for vibration transmission to the foundation slab. For vibration transmission to the floor slabs, a natural frequency of 12.5 Hz was assumed, leading to a significant amplification. A hollow floor with a tuning frequency of 100 Hz was assumed for calculating vibration transmission up to the screed.

First, the vibration and secondary airborne noise levels without an elastic decoupling where modelled. The predicted vibration emissions, in terms of subjective perception, were just above the threshold of perception with $KB_{Ftm} \leq 0.11$ and therefore not critical. The emission protection according to DIN4150-2 was expected to be met with a high probability, with predicted $KB_{Ftr} \leq 0.04$. However, the predicted average maximum levels of structure-borne noise were about 5 dB above the emission guideline value of 45 dB-A. Consequently, an elastic mounting was recommended in specific areas to reduce the average levels below the emission guideline value.

Second, the vibration and secondary airborne noise levels with a specified elastic solution with 12.5 Hz tuning frequency was modelled. The predicted maximum values for subjective perception were then below the noticeable threshold of $KB_{Ftm} < 0.1$. The emission requirements according to DIN 4150-2 were also expected to be clearly below the limits. The average maximum noise levels were predicted to be $L_{AF,\ max,\ mittel} \leq 40$ dB-A. This ensures that the emission guideline value of 45 dB-A is met, achieving an improvement of approximately 10 dB.

3.4 Tailored Solutions implemented

Based on the prediction model and described requirements, the dynamic experts specified an elastic building isolation system with a theoretical tuning frequency of ≤ 12.5 Hz for a 38-meter-wide strip along the building's length parallel to the subway line. No elastic isolation was therefore needed for the remaining building areas facing away from the subway. Additionally, the side walls were specified to be elastically separated from the surrounding soil.

A full-surface elastic isolation using polyurethane mats was proposed. The calculated overall solution of floor mats and side mats resulted in a theoretical tuning frequency of 11.8 Hz for a total decoupled dynamic mass of 58,410 tons. The solution covered an area of 4,574 m² of base mats and 2,399 m² of side mats, each with a thickness of 25 mm.

Figure 6: Specified solution with elastic decoupling of partly areas, © PMI Ingenieure[1]

Foundation Level -3

For most of the slab foundation on Level -3, a full-surface solution using closed-cell polyurethane mats with a thickness of 25 mm was applied. The quasi-permanent loads from the structural assessment resulted in pressures ranging from approximately 0.050 N/mm² to 0.350 N/mm², requiring six different stiffness types of materials for optimal performance. The closed-cell structure is important to ensures full functionality, as this level is below groundwater level.

Foundation Level -3, Pile Foundation Area

A special situation came up in the northern part of the building, along the subway line. According to the structural assessment, it was not possible to transfer additional loads from the weight of the building onto the underground subway tunnels. A pile foundation was therefore proposed to transfer loads into deeper soil layers. High resilient polyurethane pads for loads up to 6 N/mm² and a thickness of 50 mm were applied onto the pile heads. These pads were pre-cut to the diameter of the pile and glued onto the pile heads to prevent from moving during construction process. In-between piles, it was required to use especially soft filling material to prevent any additional loads occurring. The solution was a 100 mm thick layer of low density polyurethane material in four layers of 25 mm above each other. This material was cut on-site to fit around the pile heads and placed between them.

Foundation Level -2, Cantilever above the subway tunnel

Level -2, which is directly beneath the subway tunnel, was equipped with a full-surface solution using 25 mm closed-cell polyurethan mats ranging from approximately 0.050 N/mm² to 0.230 N/mm².

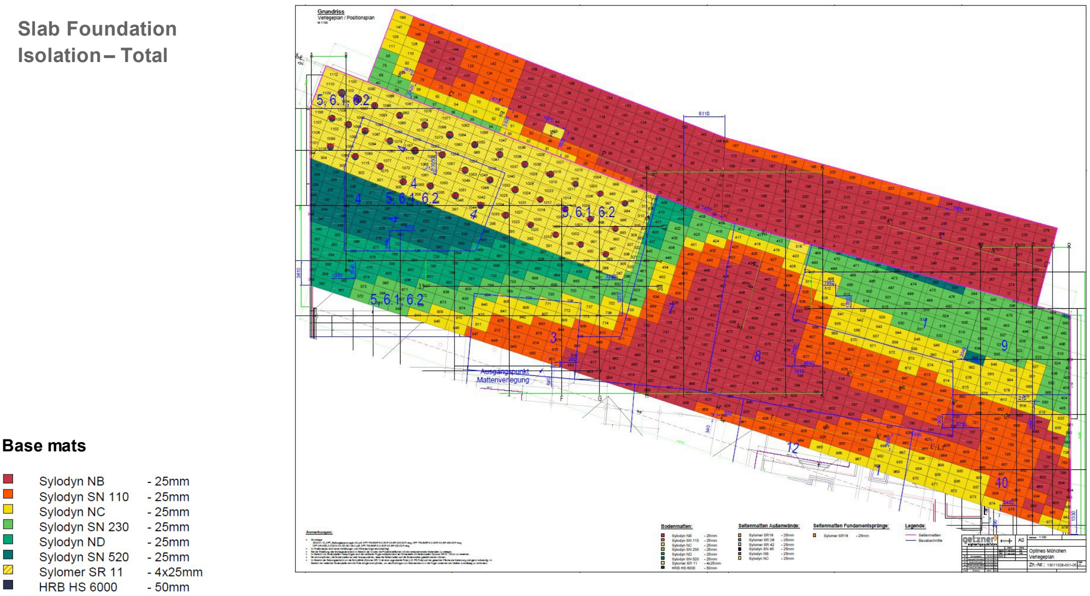

Figure 7: Elastic solution of full-surface closed-cell polyurethane mats, high resistance polyurethane pads and polyurethane filling material, © Getzner Werkstoffe

Side Walls

As specified, the building had also to be equipped with elastic side wall decoupling against the surrounding soil. Different materials were used between levels above the groundwater and those below, where pressurized water needed closed-cell materials to keep performance. Above the groundwater, mixed-cell polyurethane mats were with different types according to the existing soil pressure. Below the groundwater level, closed-cell polyurethane mats were applied. All side mats came with 25 mm thickness.

4 RESULTS

To verify the effectiveness of the elastic building isolation, final vibration and secondary airborne noise measurements were carried out during the shell construction phase, with predictions made regarding their impact on the finished state, including ceiling systems.

A total of eight measurement points were analysed on the ground slab and the centre points of the ceiling slabs in Level -3 and on ground level. As expected, the highest vibration levels were measured at the centre points of the ceiling slabs, with $K_{bmax} \leq 0.09$. Vibrations caused by the subway were detectable around the third-octave frequencies of f_{Tn} = 62.5 Hz and f_{Tn} = 31.5 Hz. The ceiling slab's natural frequency of approximately 12.5 Hz was clearly identifiable.

Regarding subjective perception, the maximum vibration emissions were recorded at $KB_{FTm} \leq 0.05$, well below the perceptibility threshold. The requirements of DIN 4150-2 were also reliably met at all measurement points. The average secondary airborne noise levels, $F_{AF,max,mittel}$, including the effects of the transfer functions from the flooring and ceiling resonances, were calculated to be between 17 dB-A and 33 dB-A, and therefore significantly below the emission guideline value of 45 dB-A.

No further airborne noise measurements were conducted in the finished state. However, no disturbances from vibrations or secondary airborne noise have been reported, further confirming the effective performance of the elastic solution.

5 CONCLUSION

The OPTINEO in Munich gives a perfect example of an efficient elastic building isolation precisely tailored to predefined requirements. Through a series of vibration measurements - initially on the existing site, then in drillholes, and finally at the foundation level - vibration and secondary airborne noise levels were accurately modelled. This process made it possible to precisely specify a 12.5 Hz full-surface solution just for selected areas of the building for the most economic and efficient solution. A high knowledge of technical expertise was needed for an area where no additional loads were permitted on the subsoil. There, a solution with pile foundation and high resilient elastic polyurethane bearings was used including softest filling material out of polyurethan avoiding any additional loading. The elastic solution was completed with polyurethane mats decoupling the sidewalls against the surrounding soil.

Subsequent measurements impressively confirmed the compliance with the given limit values for both, vibration and secondary airborne noise levels, validating the effectiveness of the mounting elastic building isolation.

The OPTINEO project highlights how interdisciplinary collaboration between structural engineers, structural dynamics experts, and bearing manufacturers can result in innovative and effective vibration isolation solutions in urban construction.

6 REFERENCES

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