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Quantification of soil induced vibrations caused by the demolishing of buildings – limits of code regulations

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ABSTRACT

During the demolition of large structures, especially in the power plant sector or other infrastructure, major ground-induced vibrations often occur. This is mainly caused due to falling debris during demolition. To be able to assess and exclude retroactive effects of such vibrations on adjacent structures, there are codes and regulations that provide reference values of maximum allowable vibrations. In Germany, for example, this is the national standard DIN 4150-3. In the context of this paper, two aspects are elaborated which show that the applicability of this standard is, however, only possible within certain limits.

The first aspect involves the assessment of retroactive effects from ground vibrations. In the aforementioned standard a given vibration signal (vibration velocity) is compared to maximum tolerable velocity values which depend on the dominating frequency of the signal. The dynamic properties of the buildings affected by the vibrations are not considered in the standard. Based on self-executed vibration measurements and evaluations, restrictions on the applicability of this assessment concept is shown.

The second aspect comprises the prognosis of occurring ground vibrations in the form of vibration velocities. In the aforementioned standard, a formula is used for vibration prognosis, which takes into account effects of the type of demolition (e.g. conventional or blasting) as well as of the specific shape of the building to be demolished by means of a free parameter that is not specified in detail. Based on self executed vibration measurements and evaluations it is shown that the type of demolition procedure and building shape have a great effect on the measured vibration velocity. This indicates that the applicability of the mentioned standard requires extensive experience.

The investigation of these aspects is supplemented by an examination of international regulations on the subject. The own vibration measurements used in this publication include the demolition of cooling towers of nuclear power plants, bridges and a high-rise building.

INTRODUCTION

The assessment of ground vibrations resulting from construction activities, such as demolition, is a critical aspect of ensuring the stability and safety of surrounding structures. In recent years, this issue has become increasingly prominent, particularly in the context of large-scale demolition projects, such as those involving power plants, bridges, and high-rise buildings. One of the most challenging aspects of these demolitions is the destruction of hyperbolic cooling towers in power plants, which release significant amounts of energy into the ground during their collapse. The magnitude and intensity of these vibrations pose unique risks to the structural integrity of nearby buildings. However, the problem extends beyond power plant decommissioning and affects various types of demolition activities, including the dismantling of bridges and the demolition of high-rise buildings, where the generated vibrations can also be substantial.

In this context, the DIN 4150 standard has long been used to guide the evaluation of vibration-induced effects on buildings. The standard primarily relies on vibration velocity as a key parameter to assess the potential for damage. However, this approach has raised concerns due to its oversimplification of the complex dynamics that influence the behavior of buildings under vibratory loads. Ground vibrations caused by demolition debris, especially from large structures such as cooling towers, bridges, or high-rise buildings, can vary significantly in both magnitude and frequency. Yet, the standard's reliance mainly on vibration speed alone fails to account for other critical factors, such as the frequency content of the vibrations, the building's dynamic response, and the interaction between the ground and structure.

This paper critically examines the methodological deficiencies within the DIN 4150 standard, with a focus on the limitations of using vibration velocity as the sole indicator for assessing potential damage to buildings. The issue is addressed by evaluating a large database of vibration measurements, primarily consisting of data collected from the demolition of hyperbolic cooling towers. The presented data will demonstrate that the prediction of vibration velocity is highly sensitive to the type of building being demolished. To further highlight the limitations of vibration velocity as a sole parameter, the data is transformed into acceleration response spectra, a methodology commonly used in earthquake engineering. This approach not only underscores the shortcomings of relying primarily on vibration velocity but also provides a more comprehensive understanding of the factors influencing building responses to demolition-induced ground vibrations.

By exploring these deficiencies, this work aims to contribute to a more thorough understanding of the complex dynamics that govern vibration impacts and provide insights into more effective and reliable assessment methods for safeguarding the structural and functional integrity of buildings neighbouring to zones with demolition and dismantling of structures. These findings are a result of decommissioning activities in Germany where large cooling towers have been dismantled, as well as other large-scale demolition projects like bridges and a high-rise building.

Assessment of ground vibrations according to DIN 4150 and its methodological deficiencies

In assessing vibrations induced by debris during building demolition, the vibration velocity forecast in DIN 4150-1, Section 5.1.3, provides the following formula to predict vibration levels based on falling masses.

$$v_{max} = k \left(\frac{E}{E_0}\right)^{0.5} \left(\frac{R}{R_0}\right)^{-m} \qquad (1)$$

v_{max}	max. value of vibration velocity (open field) in mm/s
E	potential energy in kJ
E_0	reference energy 1 kJ
R	distance to center of vibration in mm
R_0	reference distance 1 m
k	empirical value in mm/s
m	empirical dimensionless value

There are many other international codes like USBM-RI-8507 (USA), BS 7385-2: 1993 (UK) or SN 640312-a (Switzerland) which rely on the same methodology to provide treshold values for vibration velocities. The findings of this work can therefore be expanded to these codes as well. A literature review on international regulations concerning using vibration values as assessement criterium can be found in Malam (1993).

It is emphasized in DIN 4150-1 that the shape of the load-time function significantly influences the resulting vibration level. This function can be notably altered arranging a drop bed and is highly sensitive to the shape of the demolished structure and its energy-dissipating behaviour during the demolition process.

Formula (1) includes two free parameters, *k* and *m*, which must be chosen based on the user's experience. The standard assumes the user has extensive knowledge of how to determine these values.

DIN 4150-3 provides reference values for tolerable vibration velocities associated with short-term vibrations, below which no or only minor damage to structures is to be expected. These values are categorized based on different building types, with the evaluation areas divided into three categories depending on the frequency content of the vibration. The reference values for three building types as function of frequency content of the vibration signal are shown in Figure *1*. It is important to note that the vibration velocities refer to those measured at the building foundation.

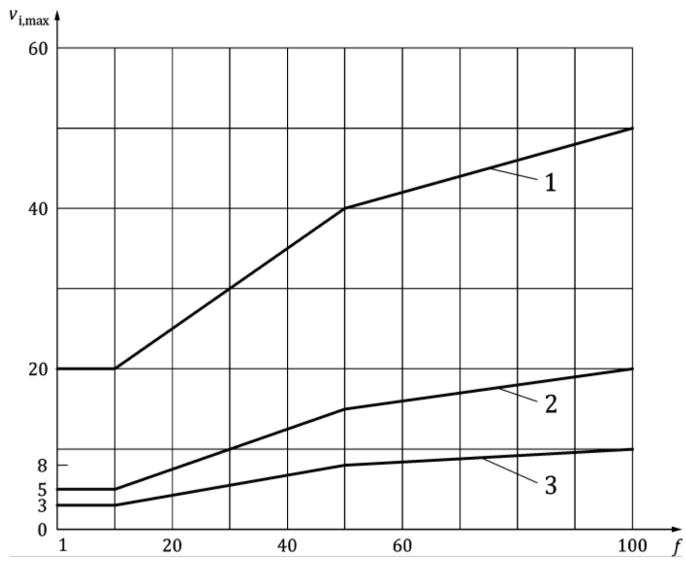

Figure 1: Reference values for maximum vibration velocity at the building foundation according to DIN 4150-3 (line indicated with “1” is for industrial or commercial buildings – horizontal axis f in [Hz], vertical axis in [mm/s])

In the context of demolition and dismantling activities, vibration signals in the frequency range of 1 to 10 Hz are particularly relevant. The standard’s reference value of 20 mm/s for commercially used, industrial and other similar buildings is often referred to later in this paper, as it is commonly used in demolition scenarios. It is important to emphasize that within a frequency range of 1 to 10 Hz only a single reference value for vibration velocities is given and no further differentiation is made.

To summarize: The following methodological deficits in DIN 4150 were identified and are the subject of further investigations in this paper:

1. The prediction of vibration velocities requires extensive experience on the part of the user and is dependent on many boundary conditions. These dependencies are shown qualitatively and quantitatively in the following using specific examples.

2. To assess the damaging effect of vibrations, only a single value for a vibration velocity is given in the standard within a range of 1 - 10 Hz. A more precise differentiation, particularly with regard to the frequency content or the dynamic properties of vibration-excited structures, is not made. This point is examined in more detail by examining existing vibration velocity measurements.

Methodological approach in this work

The database to address the above-mentioned methodological deficits in DIN 4150 consists of 186 vibration velocity-time datasets and maximum vibration velocity values measured during the demolition of hyperbolic cooling towers, bridges, and a high-rise building by blasting. Most of the data is from cooling tower demolitions. The database includes measurements taken on building foundations as well as vertical and horizontal components in the open field.

To address the deficit in vibration velocity forecasting according to DIN 4150-1 (deficit 1), values from bridge and high-rise building demolitions are excluded from the dataset, resulting in a reduced dataset focused on hyperbolic cooling towers (58 measurements). Using this reduced database, a vibration velocity forecast is made according to formula 1 for building foundations, and the results are then compared to the data sets for bridge and high-rise building demolitions.

To address the deficit of DIN 4150-3 solely relying on vibration velocities to assess structural damage in the first step, selected velocity-time datasets are transformed into frequency-dependent velocity spectra. This transformation reveals significant differences between the frequency content of cooling tower blasts and the data from bridge and high-rise building demolitions. These differences highlight the need for further investigation into how frequency content influences vibration-induced damage, providing motivation for a more detailed analysis.
In the second step, the selected velocity-time datasets are converted into acceleration response spectra and compared to a reference spectrum. Acceleration response spectra are a well-established tool in earthquake engineering, commonly used to quantify the seismic load on a structure. By comparing the response spectra of the velocity signals with the reference spectrum, the consequences of DIN 4150-3 solely relying on vibration velocity to assess damage are discussed.
For the comparison of transformed velocity data a response spectrum according to Eurocode 8 is used which is typical for south-west Germany (Rhine river area where many large industrial facilities are located). The input parameters for the reference spectrum as well as the spectrum itself are shown in Table *1* and Figure *2*.

Table 1: Input data for reference response spectrum (horizontal – 5 % damping ratio)

importance coefficient	γ_I	1.0	[-]
peak ground acceleration	a_g	0.400	[m/s²]
soil parameter	S	1.000	[-]
lower boundary of area of constant acceleration (horizontal)	T_{B-H}	0.150	[s]
upper boundary of area of constant acceleration (horizontal)	T_{C-H}	0.400	[s]
additional reference period value	T_{D-H}	2.000	[s]
behaviour factor	q	1.000	[-]

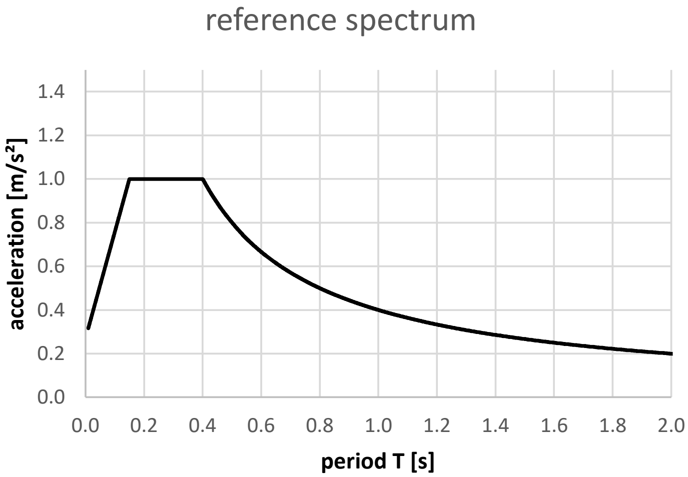

Figure 2: Reference spectrum (horizontal – 5 % damping ratio)

Results and interpretation

The prognoses of vibration velocity bases on a reference dataset, measured at building foundations in both the horizontal and vertical directions. The reference data varies according to the potential energy of the demolished structure and the distance to the centre of vibration. The reference dataset used for the analysis was collected during the demolition of cooling towers. The following figures present the analysis:

- Figure *3*: This figure displays the reference dataset along with an arithmetic mean approximation trendline, derived from formula (1).
- Figure *4*: This figure shows the dataset with the 90th quantile trendline (derived from formula (1)), where 10% of data points exceed this velocity. It also includes additional data for vibration velocity measurements taken during two bridge demolitions.
- Figure *5*: This figure presents the dataset with the 10th quantile trendline (derived from formula (1)), where 10% of data points fall below this velocity. It includes additional data for vibration velocity measurements taken during a high-rise demolition.

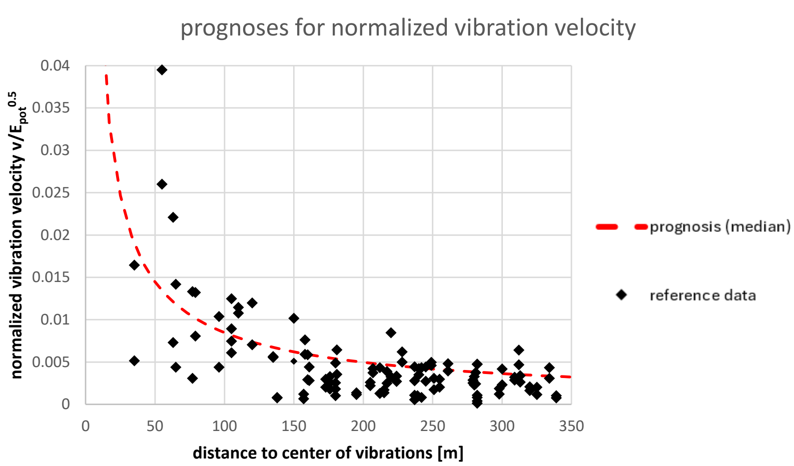

Figure 3: Vibration velocity prognosis with trendline for arithmetic mean

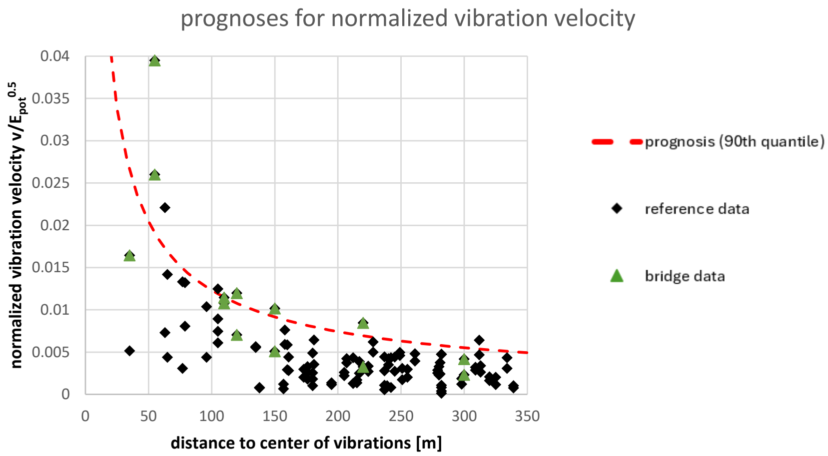

Figure 4: Vibration velocity prognosis with trendline for 90th quantile and additional dataset for two bridge demolishings (green)

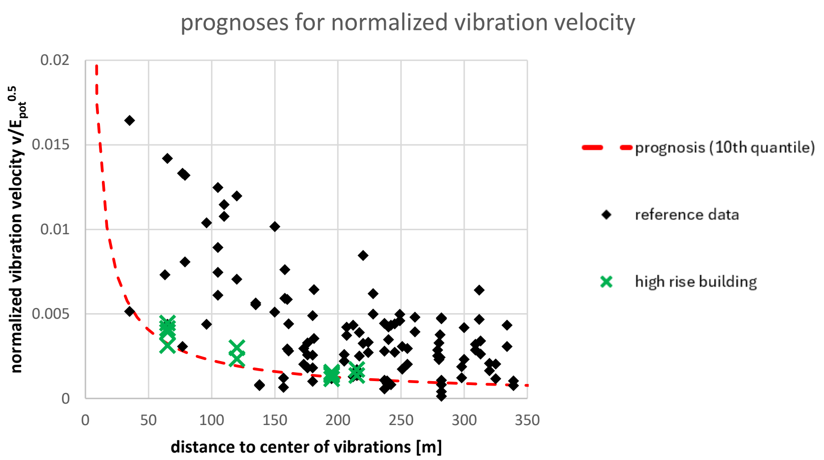

Figure 5: Vibration velocity prognosis with trendline for 10th quantile and additional dataset for a high rise demolishing (green)

The measured vibration velocity data for bridge blasting and high-rise building blasting were directly compared with the vibration velocity forecast created using the reference dataset. While this comparison cannot be considered conclusive proof of the unsuitability of the forecast based on the reference data, the following observations can be made:

- The vibration velocity forecast (based on the reference data) underestimates the vibration velocities observed during the bridge demolitions.
- In contrast, the forecast overestimates the vibration velocities observed during the high-rise building demolitions.

The high sensitivity of vibration velocities to the type of demolished building motivated further investigation into the frequency content of the different vibration velocity signals. To explore this, representative signals are first converted into their spectral representation. This is followed by a classification of the maximum accelerations within the response spectrum, as shown in Figure *2*.

Vibration signals from a representative cooling tower demolition and a high-rise building demolition were selected for comparison. These signals have comparable intensity and are measured at similar distances from the center of vibration. Both signals were converted into a standardized spectral representation, as shown in Figure *6*. The signal from the cooling tower demolition is primarily dominated by amplitudes in the period range of 0.25 s to 0.5 s (2 to 4 Hz), whereas the signal from the high-rise building demolition is dominated by amplitudes in the period range of 0.2 s to 0.8 s (1.25 to 5 Hz). The displayed spectra are based on measurement data with comparable maximum vibration velocities, but they show distinct differences in frequency content.

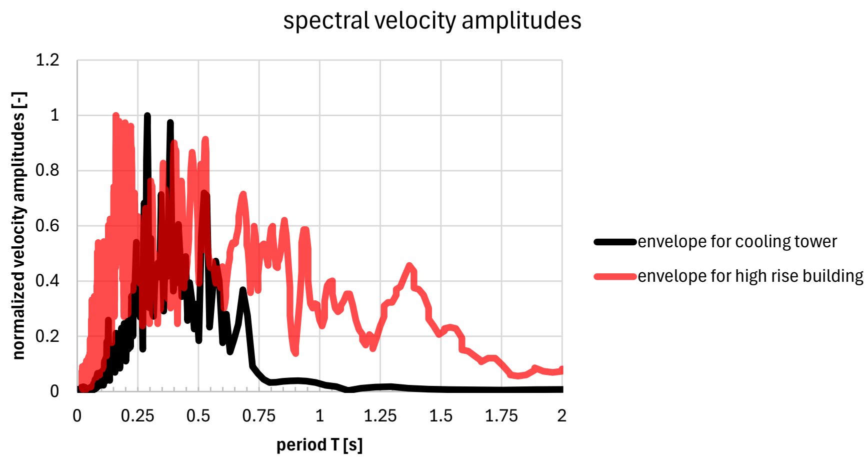

Figure 6: Comparison between spectral velocities between cooling tower and high-rise building data

To quantify the impact of the different frequency contents, all data are transformed into an acceleration response spectrum. This method for assessing the dynamic characteristics of vibration data has also been used in the vibration assessment during the cooling tower demolition at the Philippsburg Nuclear Power Plant in Germany (cp. Walendy et al. (2021, 2022)).

Figure *7* shows three measurement datasets that have been converted into an acceleration response spectrum and compared with the reference spectrum. The legend lists the maximum vibration velocity associated with each dataset. It is clear that the accelerations occurring in some cases exceed the plateau range of the reference spectrum. Figure *7* also illustrates the approach used to establish a direct relationship between the maximum vibration velocities and the corresponding accelerations within a frequency range relevant for structures (alternative assessment criterion basing on acceleration data). In the period range of 0.15 to 0.4 s (2.5 to 6.6 Hz), marked in red in Figure *7*, the maximum acceleration is determined from the response spectrum for each measurement signal. This results in a pair of values for each measurement signal: the maximum occurring vibration velocity and the corresponding acceleration in the relevant frequency range. All value pairs derived by this procedure are shown in Figure *8*.

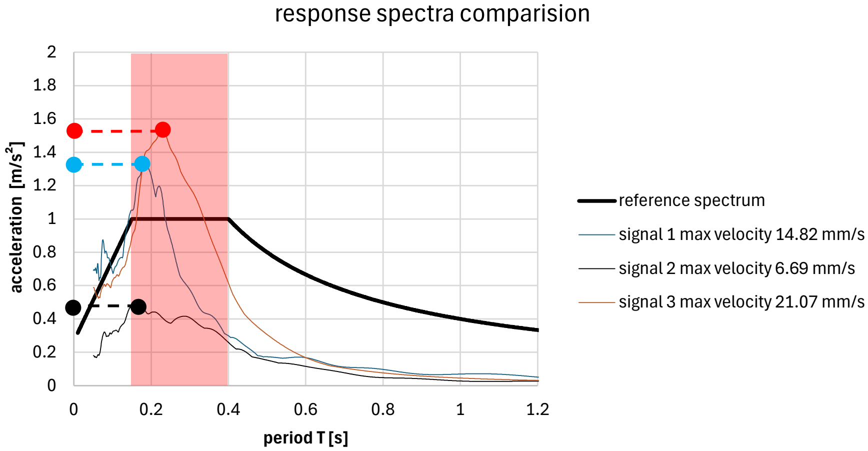

Figure 7: Response spectra (5 % damping ratio) – comparison between measured data and reference spectrum (signals from cooling tower data – distance 100 m to center of vibrations)

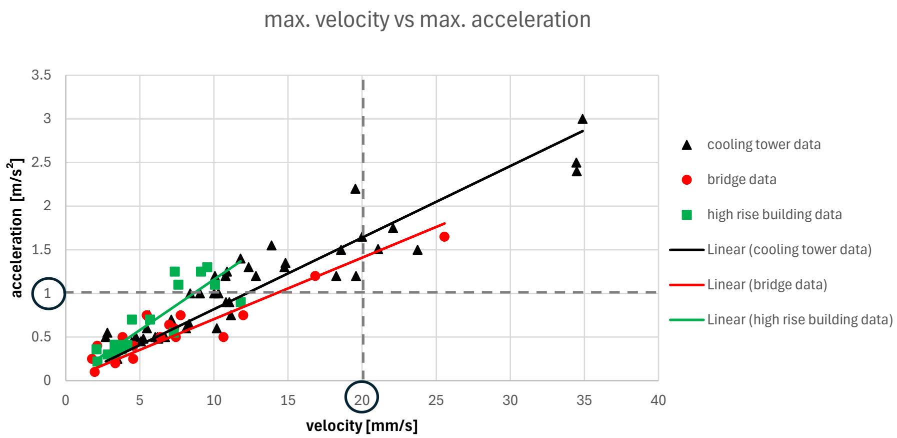

Figure 8: Max. velocity vs max. acceleration and corresponding linear trend lines – reference values for velocity according DIN 4150-3 and reference acceleration (spectral acceleration) according to Figure 2 marked as well

The following conclusions can be drawn from Figure *8*:

1. There is a good linear correlation between vibration velocity and maximum acceleration for each type of demolishing. The idea of a reference value for vibration velocity as an assessment criterion for vibrations according to DIN 4150-3 is thus supported. However, the resulting deficiencies become clear, which are explained in the following.
2. For the same vibration velocities, the high-rise building data show significantly higher accelerations than the cooling tower data.
3. In contrast, for the bridge data, the situation is reversed, although the differences to the cooling tower data are much smaller.

4. For the cooling tower data, when the threshold value for vibration velocities of 20 mm/s is reached, accelerations of approximately 1.6 m/s² are observed, significantly exceeding the plateau accelerations of the reference spectrum.
5. If the reference spectrum is interpreted as a standard for achieving a required safety level, this safety level is not met with the current threshold for vibration velocities of 20 mm/s.
6. This issue is particularly exacerbated for the high-rise building data.

Conclusion

In this paper a vibration velocity prognosis according to DIN 4150-1 was presented. This reference prognosis based on vibration measurements from cooling tower demolitions, incorporating the parameters of potential energy (E) and distance from the center of vibration (R). It was shown that this reference prognosis of vibration velocities performed poorly for other types of buildings, such as for two bridges and for a high-rise building. This highlights significant limitations of the reference prediction and reinforces the need for substantial expertise when applying DIN 4150-3, as large datasets for each use case are neccessary.

DIN 4150-3 uses a maximum vibration velocity value as assessment criterium for vibration induced damage to buildings. This paper introduces a new assessment criterion based on acceleration data by converting selected vibration velocity signals into acceleration response spectra and comparing them to a reference spectrum. It was shown that this new criterion is exceeded at significantly lower vibration velocities than the threshold defined by DIN 4150-3 (20 mm/s). Specifically, for high-rise demolitions, the acceleration-based criterion was exceeded at vibration velocity amplitudes of less than 10 mm/s, while for cooling tower demolitions, it was exceeded at around 13 mm/s. This indicates that the 20 mm/s threshold in DIN 4150-3 corresponds to accelerations in the relevant period range for buildings, at which, according to Eurocode 8, damage is expected in structures that are not designed with special earthquake resistance.

Furthermore, the results suggest that different building types should have different threshold criteria for vibration velocities during demolition. However, this paper provides only weak evidence for this conclusion, and further data analysis is required to support this hypothesis.

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