Evaluating the Applicability of Scaling Laws for Mitigated Pile Driving Noise to Highly Frequency Dependent Mitigation Systems

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Abstract: *The installation of offshore wind turbines usually requires the driving of piles into the seabed. The pile driving activity leads to underwater noise with the potential of negative consequences for the marine fauna, such as behavioral changes or hearing impairments. To address these concerns, many countries have established noise limits for pile driving activities, necessitating effective noise mitigation measures. To assess the sound levels and to optimize noise mitigation measures several modelling approaches have been developed in the last decade. These include numerical and empirical models. A semi-empirical approach for the estimation of the sound levels are the scaling laws for unmitigated and mitigated impulsive pile driving scenarios. It has been shown that these lead to reliable estimates for several different scenarios.*

The recently published scaling laws for mitigated pile driving noise consider the influence of the strike energy, pile diameter, ram weight, water depth, and mitigation system such as double big bubble curtain (DBBC) and the combination of a noise mitigation screen and a DBBC. However, the noise mitigation combination that has been most widely used in Germany is the combination of a Hydro Sound Damper (HSD) system directly at the pile and a DBBC. The insertion loss of the HSD, the DBBC and a combination thereof is strongly frequency dependent. Within this paper, publicly available measurement data is compared to the trends derived for mitigated pile driving to determine whether the scaling laws can also be applied to the popular HSD/DBBC combination.

Keywords: *pile driving, scaling laws, noise mitigation*

1. INTRODUCTION

The installation of offshore wind farms usually requires the driving of piles into the seabed. A common method to drive the pile is impulsive pile driving, which generates high impulsive underwater noise levels. The emitted noise can impact the marine fauna. These impacts may include behavioral changes or hearing impairment. Therefore, the associated noise levels and their impacts need to be assessed and noise limits need to be obeyed in many countries. Usually noise mitigation systems are necessary to fulfill the noise limits. These noise mitigation systems are often based on a system in the direct vicinity of the pile and one or two bubble curtains further away.

For the assessment of the underwater noise levels, several different modeling approaches have been developed. These include detailed numerical models [1] as well as empirical [2] and semi-empirical models. Scaling laws have been developed for unmitigated [3] and mitigated pile driving [4]. These enable to scale the influence of the strike energy, pile diameter, ram weight, and water depth from one scenario to another. The scaling laws for mitigated pile driving include scenarios with one big bubble curtain, two big bubble curtains (DBBC), a fully absorbing noise mitigation screen directly at the pile and the combination of the noise mitigation screen with a DBBC. However, the noise mitigation combination that has been most widely used in Germany is the combination of a Hydro Sound Damper (HSD) [5] system directly at the pile and a DBBC. The insertion loss of an HSD/DBBC combination is strongly frequency dependent and not simple to apply within a numerical model. Therefore, the scaling laws derived for the estimation of the sound exposure levels (SEL) with the application of a DBBC are tested with publicly available measurement data from six wind farms in order to identify, if they are applicable for the highly frequency dependent mitigation system combination HSD/DBBC.

2. SCALING LAWS FOR PILE DRIVING SCENARIOS WITH A DBBC

It is important to note that the scaling laws derived in the following are based on generalizations, assumptions and numerical model runs that come along with uncertainties, as shown in [4]. Aspects such as the geo-acoustic profile, specific pile design, the interaction between pile head and hammer parts as well as the bubble curtain layout such as radii and air supply are not incorporated within the scaling laws. However, given a general comparability between the two considered scenarios, scaling laws have shown to capture the trends of the four considered parameters.

Scaling laws for an HSD/DBBC combination have not been developed.

In the following the scaling laws for the SEL that were developed for the application for scenarios with a DBBC are repeated and applied. This is done due to the similarity in the shape of the frequency dependent insertion loss with a DBBC and the HSD/DBBC combination as shown in [2]. The definition of the SEL follows [6].

The influence of the strike energy E is scaled with

$$\Delta \mathrm{SEL}_E = 10 \log_{10} \left(\frac{E_i}{E_0} \right) . \tag{1}$$

The best-fit approximation for the influence of the SEL on the pile diameter d led to a scaling law of

$$\Delta\mathrm{SEL}_d = 15.7\log_{10}\left(\frac{d_i}{d_0}\right) . \tag{2}$$

The influence of the hammer type is usually taken into account in detailed numerical models by computing the interaction between hammer and pile [1]. A simplified approach is the scaling of the hammer influence by considering the ram weight. The influence of the ram weight m_r on the SEL is scaled by

$$\Delta\mathrm{SEL}_{m_r} = -8.5\log_{10}\left(\frac{m_{r,i}}{m_{r,0}}\right) . \tag{3}$$

The influence of the water depth h is summarized by

$$\Delta\mathrm{SEL}_h = 0.13\,(h_i - h_0) . \tag{4}$$

meaning that the SEL is expected to increase by 1.3 dB per 10 m increase in water depth.

3. APPLICATION OF SCALING LAWS WITH TO HSD/DBBC SCENARIOS

In the following, the scaling laws derived for a DBBC are applied to measurement data from six different wind farms at which pile driving was conducted with the application of a HSD/DBBC combination.

3.1. AVAILABLE MEASUREMENT DATA

The evaluation is based on publicly available data sets, primarily sourced from the German MarinEARS portal [7]. These include measurements from six offshore wind farms: Arkona in the Baltic Sea, and Deutsche Bucht, Kaskasi, Sandbank, Trianel, and Veja Mate in the North Sea. Additionally, data from the Vineyard Wind project in the United States were incorporated, covering both monopile and skirt pile installations for the converter platform [8].

The ranges of the considered parameters such as strike energy, pile diameter, water depth, and ram weight is summarized in Table 1.

To ensure consistency, only measurements taken at distances between 670 m and 800 m from the pile were considered. All sound exposure levels (SELs) were scaled to a nominal distance of 750 m using the damped cylindrical spreading model described in [9]. Water depth values

Table 1: Details of the piling configurations used for the validation.

wind farm	data points	strike energy	pile diameter	water depth	ram weight
unit	[-]	[kJ]	[m]	[m]	[t]
Arkona	56	579 - 3220	7.5	22.6 - 36.9	200
Deutsche Bucht	27	1349 - 2146	8.0	39.6 - 40.5	200
Kaskasi	31	1341 - 2656	6.5	21.1 - 27.0	150
Sandbank	60	1516 - 1935	6.8	25.1 - 34.1	175
Trianel	14	1369 - 1892	8.0	28.6 - 33.9	200
Veja Mate	55	1509 - 2252	7.8	39.0 - 40.6	200
Vineyard	12	2488 - 4091	9.6	39.5 - 43.7	200
Vineyard conv	1	1216	2.45	38.6	100

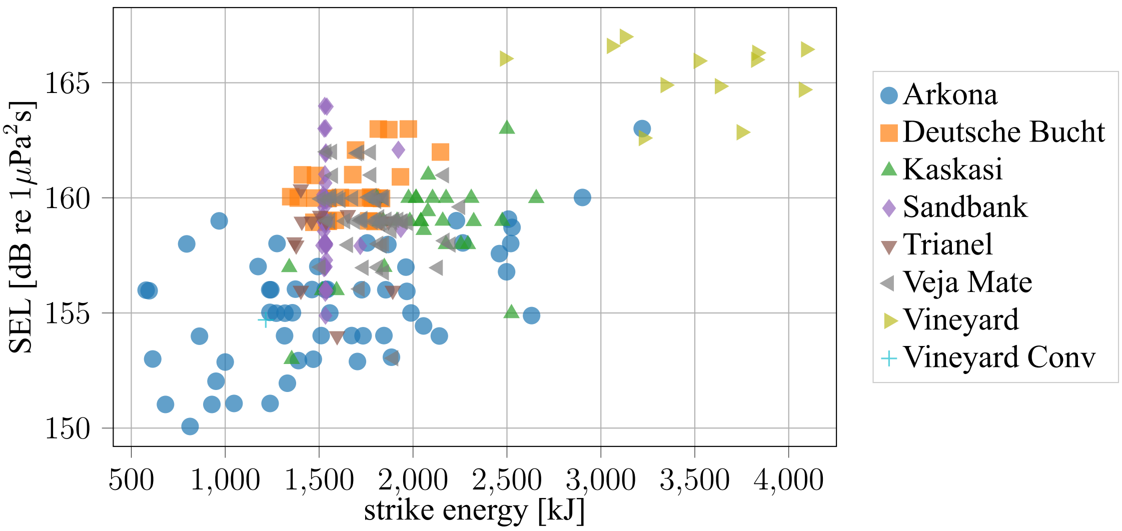

Figure 1: All measured SEL over the maximum strike energy.

for each site were obtained from EMODnet [10]. For the Vineyard Wind project, SELs were available from two directions around 750 m. Therefore, the arithmetic mean of the SEL_{05} values was used in the analysis.

Furthermore, all data points are displayed within Figure 1 over the maximum of the applied strike energy. Therein, the spread of the data from every individual wind farm is visible.

3.2. COMPARISON OF TRENDS

In the following, the scalability of the measurements is evaluated. If not stated differently, all measured data points are scaled to a strike energy of 3000 kJ, a ram weight of 200 t, a water depth of 40 m and a pile diameter of 8 m.

3.2.1. WATER DEPTH

The validation of the influence of the water depth on the SEL with the application of a HSD/DBBC combination is challenging. On the one hand, the water depth variation within a wind farm is usually relatively small and at the same time the water depth influence is expected to be around 1.3 dB per 10 m change in water depth, which is in the range of measurement uncertainties.

Furthermore, the data provided within MarinEARS is rounded and pile designs are also influenced by the water depths.

The influence of the water depth can be evaluated for each wind farm individually or by considering all data points. Only data of two wind farms with changing bathymetry were available. These are Arkona and Sandbank. The measured SELs of these two wind farms are scaled to the same strike energy, ram weight, and pile diameter and displayed within Figure 2 over the water depth. A linear best-fit approximation is conducted that shows a positive relation between the SEL and the water depth. However, quite a large variation around the trend-lines remains. This can partly be linked to the influence of the water depth on the pile design, associated penetration depth, operational parameters of the DBBC, or the site-specific geo-acoustic conditions. Since

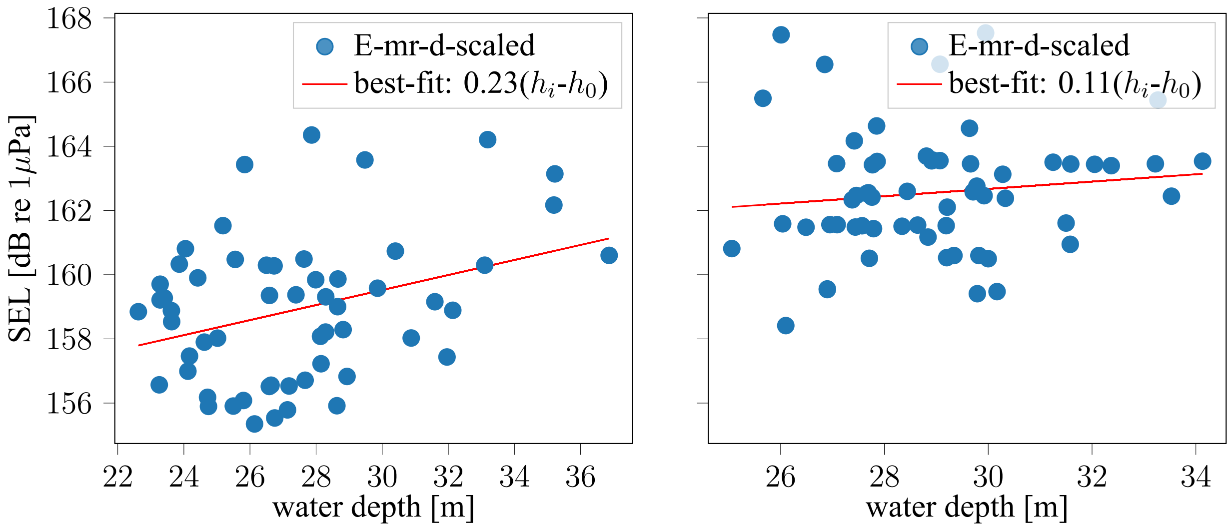

Figure 2: Two examples of energy, ram weight, and diameter scaled SEL for the Arkona (left) and Sandbank (right) offshore wind farm in dependence on the water depth combined with a best-fit approximation of a linear trend-line.

only a relative small water depth is covered by the two examples, the individual data points of all six wind farms are displayed within Figure 3 over the water depth.

Therein, a spread between the different wind farms can be observed. However, a best-fit approximation of a linear trend-line is leading to a 0.13 dB$(h_i - h_0)$-trend line, which is between the two individual results derived for Arkona and Sandbank and the same trend as derived for the DBBC only, cf. Equation (4). Therefore, the 1.3dB/10m scaling law is also considered in the following evaluations.

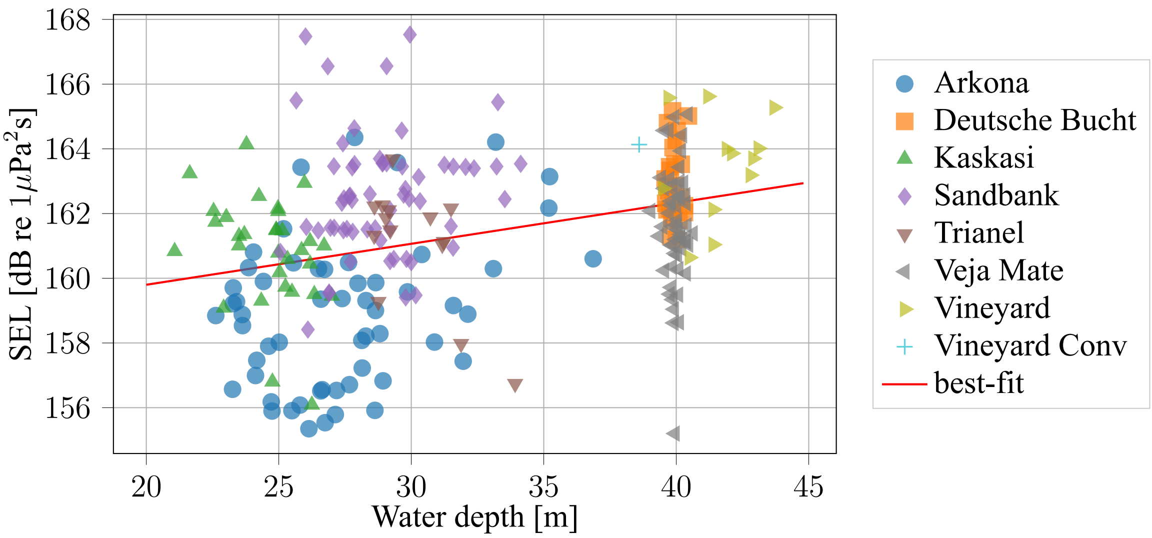

Figure 3: All strike energy, ram weight, and pile diameter scaled SEL over the water depth.

3.2.2. PILE DIAMETER

The comparison of the dependence of the SEL on the pile diameter is conducted by comparing statistical evaluations of the individual wind farms after scaling all data points to the same strike energy, ram weight, and water depth. The resulting median and the 25^{th} and 75^{th} percentile of the results are displayed within Figure 4. The percentiles are shown as the min and max errorbars. The data sets of the German wind farms have pile diameters between 6.5 m and 8 m. The comparison of the German wind farms shows a good agreement in the SEL. The only Baltic Sea data set from Arkona had generally the lowest SELs. Only the converter station of Vineyard Wind and the Vineyard Wind monopiles have considerably deviating diameters. However, the scaled German North Sea scenarios show a good agreement with both the Vineyard monopiles and the skirt pile. Furthermore, a good match between the converter station and the monopile of Vineyard can be seen.

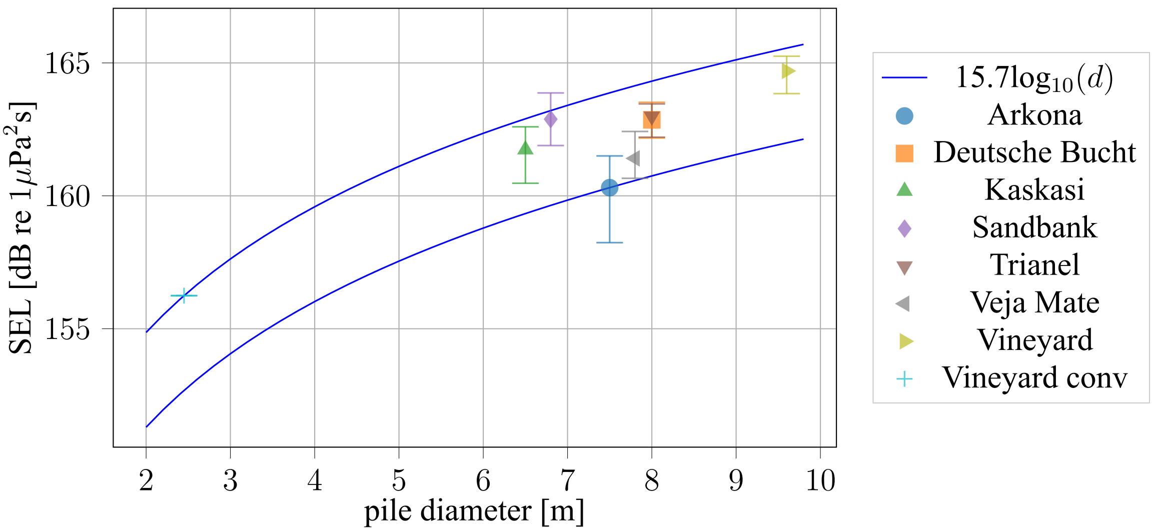

Figure 4: The median and the 25^{th} and 75^{th} percentile represented by the errorbars of every wind farm after scaling to the same strike energy, ram weight, and water depth over the pile diameter in combination with the pile diameter scaling law.

3.2.3. DISCUSSION

The statistical evaluation of the application of all four scaling laws to the measurements is displayed within Figure 5. All resulting median of German wind farms from the North Sea are within a range of 2.5 dB. Arkona is the only wind farm in the Baltic Sea and generally shows slightly lower results and quite a high variation from turbine to turbine. Furthermore, the results from Vineyard wind are very well comparable to the SELs measured in Germany.

The application of the scaling laws initially developed for scenarios with the application of a DBBC shows that their application to HSD/DBBC scenarios of different wind farms leads to reasonable agreement.

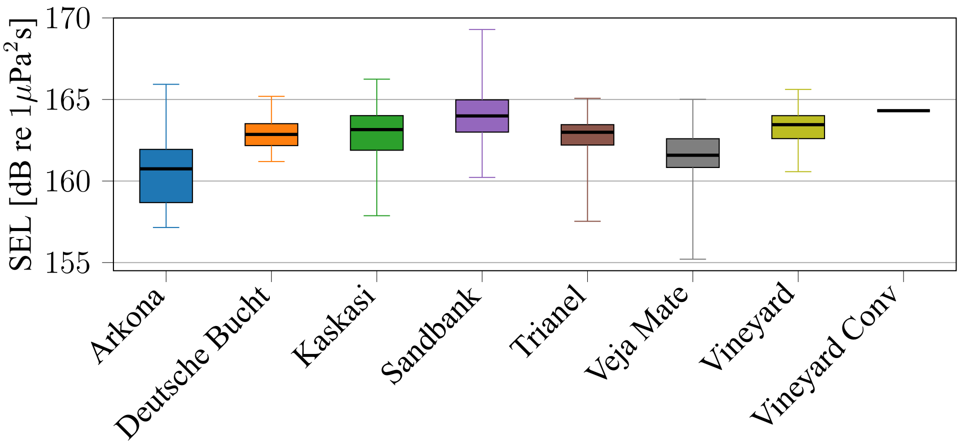

Figure 5: The statistical evaluation of the scaled SEL of every considered wind farm. All measured SEL are scaled to a strike energy of 3000 kJ, a pile diameter of 8 m, a ram weight of 200 t, and a water depth of 40 m. The box represents the 25$^{\text{th}}$ and 75$^{\text{th}}$ percentile and the errorbars represent the minimal and maximal scaled SEL.

4. COMPARISON OF MEASURED AND SCALED INSERTION LOSS

Scaling laws have shown to be a sufficient tool to get estimations of the SEL for mitigated and unmitigated pile driving. The MarinEARS data base also provides SEL levels for unmitigated pile driving for the six German wind farms considered in Table 1. These can be used to derive the insertion loss achieved with the HSD/DBBC combination. When comparing the unmitigated and mitigated values, they need to be adjusted such that they are scaled to the same strike energy. The available data sets were evaluated this way. If more than one reference measurement was available, they were averaged. The achieved broadband insertion losses are displayed within the left part of Figure 6.

The same evaluation was done but the unmitigated SEL was scaled with the data set provided in [3] combined with a few newly published data sets. The mean of the scaled results were considered as the reference SEL. This leads to a more condensed representation of the insertion loss, cf. right plot in Figure 6. This indicates that the consideration of scaled unmitigated SEL levels can help reduce the influence of potential local outliers.

Both results are well in line with the insertion loss stated by Bellmann *et al.* [2] who provide a range between 18 and 19 dB.

A comparison of the measured and scaled SEL of the unmitigated case is provided in Table 2. The comparison shows that the measured reference SELs of Arkona and Sandbank were relatively high, suggesting on the other hand a relatively high insertion loss.

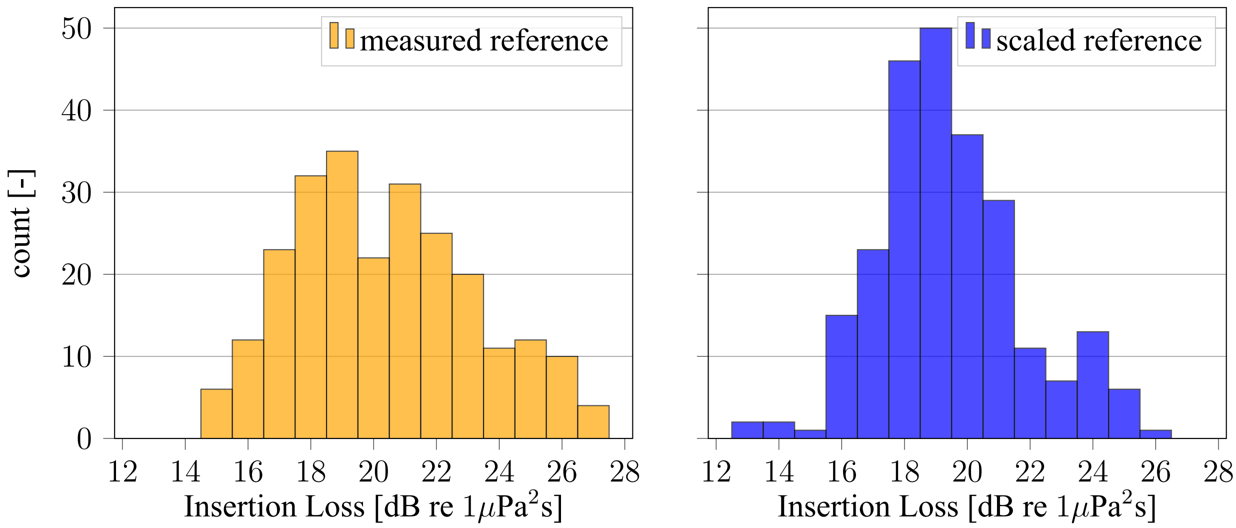

Figure 6: The distribution of the insertion loss derived by comparing the measured unmitigated SEL to the measured HSD/DBBC results (left) and a scaled unmitigated SEL to the measured HSD/DBBC results (right).

Table 2: Comparison of the measured and scaled SEL [dB re 1μPa^{2}s] for unmitigated pile driving in German wind farms.

wind farm	measured SEL	scaled SEL
Arkona	179.0	177.1
Deutsche Bucht	177.8	178.3
Kaskasi	178.5	178.4
Sandbank	180.5	177.1
Trianel	176.1	177.8
Veja Mate	177.9	178.4

5. CONCLUSIONS AND OUTLOOK

The shown comparisons indicate that the scaling laws originally developed for mitigated pile driving with the application of a DBBC can similarly be applied to scenarios where the HSD/DBBC combination is planned to be applied. While the scaled medians showed very good agreement across different sites, significant variability in the measured SELs was observed. This variation was present within each wind farm and is likely linked to differences in DBBC operational parameters, site-specific soil conditions, pile designs, and measurement uncertainties.

As always, great care needs to be taken when choosing the baseline scenario in order to ensure meaningful comparisons between the baseline and evaluated piling scenarios.

The evaluation of the insertion loss demonstrated that applying a scaled reference value reduces variability in the results.

A next step is the investigation of other highly frequency dependent mitigation solutions such as the AdBm system.

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