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Analysis of the Variability of Axial Bearing Capacity of Piles in Cohesionless Soil in the Development of Meyerhof Formula

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Abstract

Meyerhof (1976) formula for calculation of pile axial bearing capacity is quite familiar in Indonesia. It is essential to quantify the variability of soil in a design. This also means that it is essential to quantify the variability of axial pile bearing capacity versus N-SPT inherited in a commonly used formula like Meyerhof (1976) formula. An analysis to quantify the variability inherited in Meyerhof (1976) formula for calculation of pile axial bearing capacity was performed. The data in the publication of Meyerhof (1976) were used in the analysis. The relationship between the probability of failure for pile and the factor of safety in terms of the axial bearing capacity formula was quantified. It was found that the factors of safety for formula of unit pile tip bearing capacity are 1.54, 2.17, and 1.35 for driven pile in sand, driven pile in silt, and bored pile in sand, respectively. Also, it was found that the factors of safety for formula of unit pile shaft bearing capacity are 1.54 and 1.14 for driven pile in sand and silt and bored pile in sand, respectively.

Keywords: *Axial pile bearing capacity, Meyerhof (1976) formula, probability of failure, factor of safety, variability of axial pile bearing capacity*

Abstrak

Rumus daya dukung pondasi tiang dari Meyerhof (1976) banyak digunakan di Indonesia. Adalah sangat penting untuk menguantifikasi variabilitas dalam perancangan. Ini juga berarti sangat penting untuk menguantifikasi variabilitas daya dukung aksial tiang terhadap nilai N-SPT dalam rumus yang banyak digunakan seperti rumus Meyerhof (1976). Analisis untuk menguantifikasi variabilitas yang terkandung dalam rumus daya dukung aksial Meyerhof (1976) dilakukan dalam makalah ini. Dalam analisis, digunakan data dalam publikasi Meyerhof (1976). Hubungan antara probabilitas kegagalan dan faktor keamanan untuk rumus daya dukung formula dikuantifikasi. Dari studi ini didapatkan bahwa faktor keamanan untuk rumus daya dukung aksial ujung pondasi tiang adalah sebesar 1,54, 2,17, dan 1,35 untuk pondasi tiang pancang pada tanah pasir, pondasi tiang pancang pada lanau, dan pondasi tiang bor. Selain itu, juga didapatkan bahwa faktor keamanan untuk rumus daya dukung aksial selimut tiang adalah sebesar 1,54 untuk tiang pancang di tanah pasir dan lanau, dan 1,14 untuk tiang bor.

Kata-kata Kunci: *Daya dukung aksial tiang, rumus Meyerhof (1976), probabilitas kegagalan, faktor keamanan, variabilitas daya dukung aksial tiang*

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1. Introduction

Meyerhof (1976) formula for calculation of pile axial bearing capacity is quite familiar in Indonesia (e.g., BSN, 2017; Wika, 2017). Meyerhof formula utilizes the N-SPT value (ASTM D1586-11, 2011; Terzaghi *et al*., 1996) as an important input. The N-SPT value is a very popular method in Indonesia to obtain information related to the shear strength of soil (e.g., Building Construction Advisory Committee Jakarta, 2016; Indonesian Bridge and Tunnel Road Safety Committee, 2018; Krisnanto *et al*., 2021).

It is essential to quantify the variability of soil in a design (Casagrande, 1965; Phoon *et al*., 2016; Prakoso, 2018; Phoon, 2019; Ching *et al*., 2020; Prakoso, 2020). Tomlinson (1977) and Tomlinson (1994) reported that using factor of safety, FS equal to 2, from 78 data of measured skin friction, 2 of measured skin frictions are below the calculated values. This means that for that variability of data, factor of safety, FS equal to 2 results in the probability of failure of 0.026. Since it is a comparison between the measured and predicted values, this factor of safety equal to 2 does not include the variability of load. This brings a consequence that it is essential to quantify the variability of axial pile bearing capacity versus N-SPT inherited in a commonly used formula like Meyerhof (1976) formula. By knowing this, a factor of safety that fulfills the probability of failure can then be calculated. This brings a safe design procedure.

This paper presents an analysis to quantify the variability inherited in Meyerhof (1976) formula for calculation of pile axial bearing capacity. The data in the publication of Meyerhof (1976) were used in the analysis. The relation between the probability of failure for pile and the factor of safety in terms of the axial bearing capacity formula was quantified in this paper.

2. Methodology

In the analysis, the data used in the publication of Meyerhof (1976) were first obtained. The data were then classified for each value of length of embedment into the cohesionless layer over diameter, D_b/B. This was performed for the driven and bored piles data in the publication. The probability of failure for the design proposed in Meyerhof (1970) was used as a criterion to obtain the probability of failure for a pile. Finally, the factors of safety of pile tip and pile shaft axial bearing capacity of Meyerhof (1976) formula were obtained. This was calculated from the ratio between the minimum measured pile tip and pile shaft axial bearing capacity over those obtained from Meyerhof (1976) formula. The minimum measured pile tip and pile shaft axial bearing capacity is the value that is still accepted by the probability of failure criterion.

3. Literature Review

Meyerhof (1976) formula for axial bearing capacity of piles are as follows:

For driven piles in sand, the unit pile tip axial bearing capacity can be calculated as:

$$q_p = 40N\frac{D_b}{B} \le 400N \quad (\text{kN/m}^2) \tag{1}$$

and the unit pile shaft axial bearing capacity can be calculated as:

$$f_s = 2\overline{N} \quad (\text{kN/m}^2) \tag{2}$$

where q_p is the unit pile tip axial bearing capacity, N is the N-SPT value around pile tip, D_b is the depth of pile in the corresponding cohesionless layer, B is the pile diameter, f_s is the shaft axial bearing capacity, and $\overline{N}$ is the average N -SPT values along the considered pile shaft.

For driven piles in non-plastic silt, the unit pile tip axial bearing capacity can be calculated as:

$$q_p = 30N\frac{D_b}{B} \le 300N \quad (\text{kN/m}^2) \tag{3}$$

For bored piles in sand, the unit pile tip axial bearing capacity can be calculated as:

$$q_p = 12N\frac{D_b}{B} \le 120N \quad (\text{kN/m}^2) \tag{4}$$

and the unit pile shaft axial bearing capacity can be calculated as:

$$f_s = \overline{N} \quad (\text{kN/m}^2) \tag{5}$$

Data for the development of the formula (**Equations (1)** to **(5)**) are shown in **Figures 1** and **2**.

Meyerhof (1970) proposed criteria of probability of failure for earthworks, foundations, and earth retaining structures. The probability of failure criterion for foundation suggested by Meyerhof (1970) is shown in **Table 1**. The probability of failure ranges from the minimum value of 1.00 x 10^{-4} to the maximum value of 3.57 x 10^{-4} with the average value of 2.28 x 10^{-4}. In this paper, the number of events of failure was obtained by multiplying the probability of failure to the

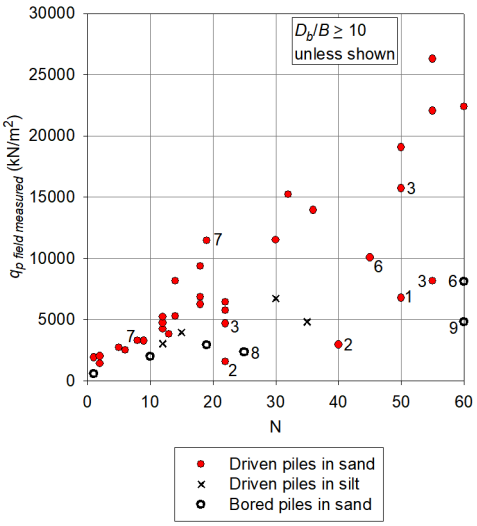

Figure 1. Data for the development of end bearing capacity of driven and bored piles shown in Meyerhof (1976).

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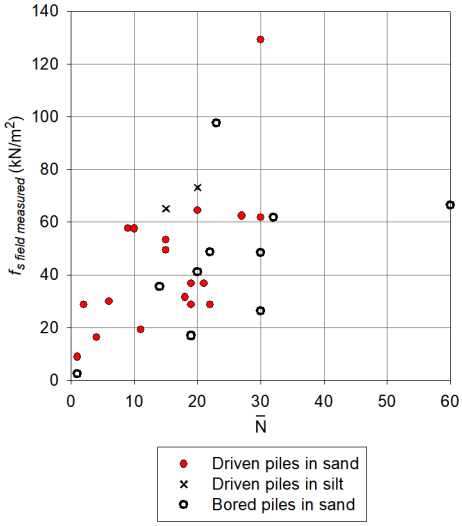

Figure 2. Data for the development of shaft bearing capacity of driven and bored piles shown in Meyerhof (1976).

Table 1. Probability of failure criterion for foundation suggested by Meyerhof (1970).

Category	Probability of Failure
Minimum probability of failure	1.00×10^{-4}
Maximum probability of failure	3.57×10^{-4}
Average probability of failure	2.28×10^{-4}

numbers of data of the measured pile axial bearing capacity. This is based on the condition that total sum of the standard probability function curve is 1 (e.g., Benjamin and Cornell, 1970; Ang and Tang, 2007; Gujarati and Porter, 2009; Montgomery and Runger, 2014). Therefore, the number of an expected event is calculated as the product between the probability of failure and the total number of event.

4. Analysis and Discussions

The number of data used in the development of **Equations (1)**, **(3)**, and **(4)** is shown in **Table 2**. The data shown in **Table 2** is obtained from the digitization of **Figure 1**. The numbers of data used in the development of **Equations (2)** and **(5)** is shown in **Table 3**. The data shown in **Table 3** is obtained from the digitization of **Figure 2**.

Tables 4 and **5** show number of allowed failed calculated axial capacity for the data showed in **Tables 2** and **3**, respectively. The number of allowed failed pile is calculated utilizing the of expected frequency (Illowsky and Dean, 2018) as:

Number of allowed failed pile = probability of failure x number of measured pile capacity (6)

The line that marks the number of allowed failed pile is plotted as the dashed line in **Figures 3** to **8**. Since the line marks the number of allowed failed pile according to the probability of failure criterion (**Table 1**), the line also serve as the line of allowable bearing capacity.

The allowable unit point bearing capacity can then be calculated as:

$$q_{p\,all} = \frac{q_{p\,formula}}{FS_{formula}} \tag{7}$$

where $q_{p\,all}$ is the allowable unit point bearing capacity, $q_{p\,formula}$ is the unit point bearing capacity calculated using **Equations (1)**, **(3)**, and **(4)**, and $FS_{formula}$ is the factor of safety in terms of formula. The allowable unit shaft bearing capacity is calculated as:

$$f_{s\,all} = \frac{f_{s\,formula}}{FS_{formula}} \tag{8}$$

where f_{s} all is the allowable unit shaft bearing capacity, $f_{s\,formula}$ is the unit shaft bearing capacity calculated using **Equations (2)** and **(5)**, and $FS_{formula}$ is the factor of safety in terms of formula.

Table 2. Number of data used in the development of Equations (1), (3), and (4) shown in Meyerhof (1976)

Reference Number in This Paper	Pile Type	Soil	D_b/B	Number of Pile
A1	Driven pile	Sand	10	24
A2	Driven pile	Sand	7	2
A3	Driven pile	Sand	6	1
A4	Driven pile	Sand	3	3
A5	Driven pile	Sand	2	2
A6	Driven pile	Sand	1	1
A7	Driven pile	Silt	10	4
A8	Bored pile	Sand	10	3
A9	Bored pile	Sand	9	1
A10	Bored pile	Sand	8	1
A11	Bored pile	Sand	6	1

Table 3. Number of data used in the development of Equations (2) and (5) shown in Meyerhof (1976).

Reference Number in This Paper	Pile Type	Soil	Number of Pile
B1	Driven pile	Sand	18
B2	Driven pile	Silt	2
B3	Driven pile	Gravel	1
B4	Bored pile	Sand	10

Utilizing the line of allowable bearing capacity, the factor of safety in terms of the bearing capacity formula, $FS_{formula}$, is calculated as the inverse of the gradient of the dashed line in **Figures 3** to **8**. The $FS_{formula}$ for unit pile tip and unit pile shaft bearing capacity are shown in **Table 6**. The corresponding number of data obtained from **Tables 2** and **3** are shown in **Table 6**.

The factor of safety in terms of formula, $FS_{formula}$ in **Equations (7)** and **(8)** can be related to the factor of safety, FS used in the allowable stress design as:

$$FS = FS_{formula} FS_{loading} \tag{9}$$

where FS is the global factor of safety, $FS_{formula}$ is the factor of safety in terms of formula, and $FS_{loading}$ is the

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Table 4. Number of allowed failed calculated axial capacity for Table 2.

Reference Number in This Paper	Number of Pile	Number of Allowed Failed Piles for Each Probability of Failure		
		Probability of Failure		
		1.00×10^{-4}	3.57×10^{-4}	2.28×10^{-4}
A1	24	0	0	0
A2	2	0	0	0
A3	1	0	0	0
A4	3	0	0	0
A5	2	0	0	0
A6	1	0	0	0
A7	4	0	0	0
A8	3	0	0	0
A9	1	0	0	0
A10	1	0	0	0
A11	1	0	0	0

Table 5. Number of allowed failed calculated axial capacity for Table 3.

Reference Number in This Paper	Number of Pile	Number of Allowed Failed Piles for Each Probability of Failure		
		Probability of Failure		
		1.00×10^{-4}	3.57×10^{-4}	2.28×10^{-4}
B1	18	0	0	0
B2	2	0	0	0
B3	1	0	0	0
B4	10	0	0	0

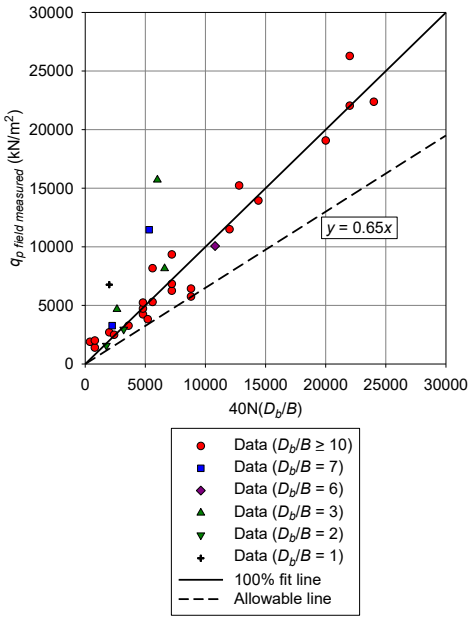

Figure 3. Plot of Figure 1 in terms of Equation (1) for driven pile in sand.

factor of safety in terms of loading. Terzaghi *et al.* (1996) write **Equation (9)** in the following form:

$$FS = \frac{\sum \text{resistance}}{\sum \text{load effects}} \qquad (10)$$

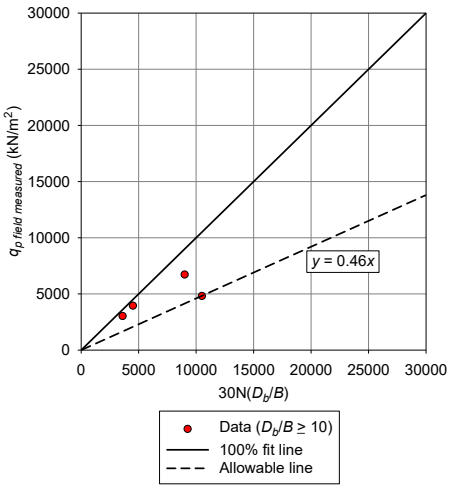

Figure 4. Plot of Figure 1 in terms of Equation (3) for driven pile in silt.

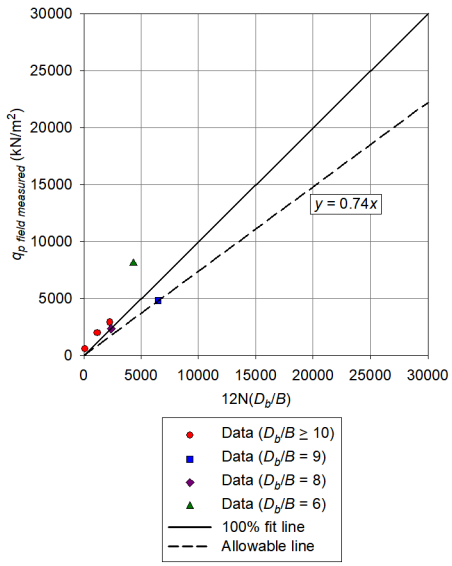

Figure 5. Plot of Figure 1 in terms of Equation (4) for bored pile in sand.

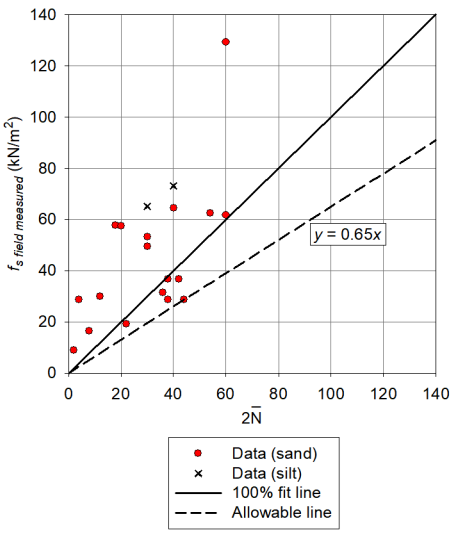

Figure 6. Plot of Figure 2 in terms of Equation (2) for driven pile in sand and silt.

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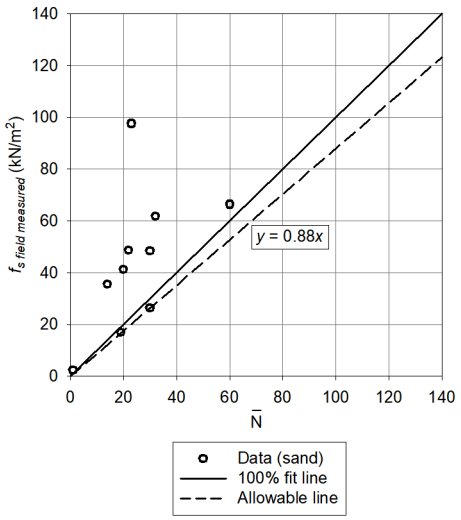

Figure 7. Plot of Figure 2 in terms of Equation (5) for bored pile in sand.

where Σresistance is the sum of all resistance to the loading and Σload effects are the sum of all loading. In the context of this paper, Σresistance is the axial bearing capacity calculated from the bearing capacity formula. **Equation (10)** follows format of the factor of safety in allowable stress design (ASD) method. In geotechnical design using ASD method, the global factor of safety, FS is recommended by the code (e.g., in BSN, 2017). Since the factor of safety in terms of formula, $FS_{formula}$ (which is the Σresistance in **Equation (10)**), this means the analysis presented in this paper serves as a step into the load and resistance factor design (LRFD) method in foundation design. Using LRFD method, **Equation (9)** can be written as (Terzaghi *et al*., 1996):

$$\frac{\sum \text{factored resistance}}{\sum \text{factored load effects}} = 1 \qquad (11)$$

Using **Equation (11)**, the factors of safety in **Equation (9)** can be written as:

$$\sum \text{factored load effects} = FS_{loading} \qquad (12)$$

and

$$\text{factored resistance} = 1/FS_{formula} \qquad (13)$$

The value of $1/FS_{formula}$ equals to the gradient of the line of allowable bearing capacity in **Figures 3** to **7** (see also the calculation of $FS_{formula}$ in **Table 6**). While $FS_{formula}$ can be developed using the method of analysis presented in this paper, $FS_{loading}$ can be obtained from the existing code (e.g., BSN, 2013).

The factors of safety shown in **Table 6** are calculated based on the data shown in Meyerhof (1976). A similar analysis as in this paper can be performed using local data to check the variability of the formula. A criterion for the probability of failure can then be selected (e.g., in **Table 1**). Once the variability of the formula is known, the factor of safety for the formula (as in **Table 6**) can then be formulated. By using this method, the bearing capacity formula can be used safely (i.e., fulfill the criterion of the probability of failure).

The calculation of $FS_{formula}$ is influenced by the number of data used in the analysis. The number of data used in the calculation for each $FS_{formula}$ is shown in **Table 6**. In the analysis of histogram of axial bearing capacity, the data need to be put into several bins of bearing capacity value. Montgomery and Runger (2014) recommends the use of 5 to 20 bins in the histogram. Furthermore, the recommended number of bins is equal to the square root of the number of observations. Using 5 bins as the minimum, the minimum number of data is equal to the square of 5, which is 25 data. From this, the analysis results provided in **Table 6** valid for the driven pile in sand. The analysis results for the driven pile in sand and silt may still be valid. This conclusion is made based on the number of data shown in Meyerhof (1976).

It is also important to consider the energy corresponding to the hammer used in SPT in the development of Meyerhof (1976) formula. This is because hammer energy is affected by several factors (Skempton, 1986). The SPT used in the development of Meyerhof (1976) formula refers to SPT used in Meyerhof (1956) and SPT used in Meyerhof (1956) refers to SPT used in Terzaghi (1948). Terzaghi *et al*. (1996) refer to the N value as N_{60} (i.e., N value corresponds to 60% of its hammer free-fall energy). This SPT hammer energy should be considered when use Meyerhof (1976) formula.

This quantification of the variability of axial bearing capacity of piles in Meyerhof (1976) formula is useful in order to have a safe design in engineering practice. It is important to quantify the variability of the soil resistance as investigated by Krisnanto *et al*. (2023).

Table 6. Factor of safety for formula: (a) Factor of safety for formula of unit pile tip bearing capacity, q_p; (b) Factor of safety for formula of unit pile shaft bearing capacity, f_s.

(a)

Pile Type	Formula	$FS_{formula}$	Number of Data
Driven pile in sand	Equation (1)	1/0.65 = 1.54	33
Driven pile in silt	Equation (3)	1/0.46 = 2.17	4
Bored pile in sand	Equation (4)	1/0.74 = 1.35	6

(b)

Pile Type	Formula	$FS_{formula}$	Number of Data
Driven pile in sand and silt	Equation (2)	1/0.65 = 1.54	20
Bored pile in sand	Equation (5)	1/0.88 = 1.14	10

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From the data used in the derivation of Meyerhof (1976) formula, the factor of safety (**Table 6**) can be used to obtain allowable pile axial bearing capacity that fulfills the allowable failure criterion shown in **Table 1**. Similar types of formula can be developed for any soil (with its corresponding variability in shear strength) and any failure criterion other than that shown in **Table 1**.

5. Conclusions

1. An analysis has been performed that relates the factor of safety to the probability of failure. The factor of safety is calculated based on a selected probability of failure criterion. The factor of safety was calculated for the unit pile tip bearing capacity, q_p and unit pile shaft bearing capacity, f_s. The factor of safety is designated as the factor of safety for formula, $FS_{formula}$.
2. The factors of safety for formula, $FS_{formula}$ of unit pile tip bearing capacity, q_p are 1.56, 2.17, and 1.35 for driven pile in sand, driven pile in silt, and bored pile in sand, respectively.
3. The factors of safety for formula, $FS_{formula}$ of unit pile shaft bearing capacity, q_p are 1.54 and 1.14 for driven pile in sand and silt and bored pile in sand, respectively.
4. The analysis performed in this paper, the factor of safety in terms of the allowable stress design (ASD) method can be related to the factor of safety in terms of the load and resistance factor design (LRFD) method. Also, the load factor from the existing code can be used.
5. Using the criterion of numbers of data of histogram bins from Montgomery and Runger (2014), the factor of safety for formula in this study are valid for the driven pile in sand. The analysis results for the driven pile in sand and silt may still be valid. This conclusion is only made based on the number of data shown in Meyerhof (1976).
6. The value of N used in Meyerhof (1976) formula may refer to N_{60} (i.e., N value corresponds to 60% of its hammer free-fall energy).
7. The factor of safety (**Table 6**) can be used to obtain allowable pile axial bearing capacity that fulfills the allowable failure criterion shown in **Table 1**. Similar types of formula can be developed for any soil (with its corresponding variability in shear strength) and any failure criterion other than that shown in **Table 1**.

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