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# Nonlinear analysis of single model piles subjected to lateral load in sloping ground

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**Abstract**

Uncertainty associated due to soil-pile interface and unreliable assessment of the pile bearing capacity constructed in sloping ground have been cited as barriers to the wide utilizations of the deep foundations in sloping ground. Extensive studies were conducted concerning the failure mechanism of laterally loaded piles penetrated in horizontal ground. However, the number of studies regarding the pile in sloping ground is scarce in literatures. In this research, a detailed of numerical modelling using Winkler theory is discussed on the basis of finite element and experimental tests for models input parameters to examine the behaviour of the model piles penetrated in sandy soil subjected to lateral load. An Aluminium of open-ended model piles were utilized embedded in dense dry sloping sand of 1.5 horizontal to 1 vertical (1.5H: 1V). Three piles aspect's ratio of (18, 24 and 30) were selected to examine the behaviour of both flexible and rigid pile. The results revealed that lateral soil stiffness, effective passive wedge, flexural rigidity, EI, pile slenderness' ratio *($l_c/d$)* and sand morphology as confirmed by scanning electronic microscopy, SEM observation play a key-role on the factors effecting the pile capacity and its lateral response.

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*Keywords:* Pile-soil interface; slenderness ratio; Winkler thoery; Ssloping ground.

## 1. Introduction

Vertical piles are often design to resist lateral loads at pile head, owing to wind waves, ships impacts, retaining wall, earthquakes and lateral earth pressures. The mechanism involved in sand-pile interface in the effective soil zone and the subsequent load-settlement conditions are still an area of high uncertainty in the field of geotechnical

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engineering and providing an accurate closed form solution is difficult [1-4]. The main sources of uncertainty is induced from materials properties characteristics, soil stiffness, method of pile advancement, site conditions, expected applied loads, pile design depth, load transfer system (end bearing and/or skin friction), soil stress history and pile geometry. Furthermore, elastic-plastic approach applied for laterally loaded pile in soft clay soil using boundary-element procedure was conducted by Budhu and Davis [5]. Moreover, the impact of soil relative density and angle of sloping ground on ground resistance, bending moment and lateral pile deflection under the action of surcharge load has been documented by Muthukkumaran, Sundaravadivelu [6]. Numerical study considering the non-linearity for piles penetrated in horizontal ground using the Drucker-Prager theory of plasticity was investigated by Faruque and Desai [7]. Kumar [8] conducted study exploring the behavior of laterally loaded pile group and single model pile using three dimensional finite element approach

Currently, despite extensive studies on a composite soil-pile interaction of laterally loaded pile in horizontal ground, to date, the problems to simulation soil-pile interaction of piles in sloping ground have not fully understood. Therefore, development a close form solution on the basis of numerical modelling to laterally loaded open-ended model piles in sloping ground with scaling factor for full-scale pile would be a breakthrough in deep foundations research. Therefore, an investigation has been conducted to improve our understanding of soil-pile interface and the main factors effecting the behavior of the three types of open-ended model piles having different slenderness' ratio (lc/d) of 18, 28 and 30. The scanning electronic microscopy (SEM) observation, direct shear test for both sand-sand and Aluminium-sand at low effective normal stress, sand particle seize distribution and the roughness of the pile surface (Rmax) was also investigated using Perthometer were adopted as real calibrated input parameters (parametric study). The advantage of the developed constitutive model is that few input parameters can be utilized and they can be found by carrying out simple laboratory tests.

**Nomenclature**

| | |
|---|---|
| EI | model pile stiffness |
| $y_i$ | lateral pile displacement |
| $p_i$ | lateral soil stiffness |
| $l_c/d$ | slenderness' ratio |
| SEM | scanning electronic microscopy |
| K | soil subgrade reaction |
| SP | poorly graded sand |
| USCS | unified soil classification system |

## 2. The numerical setup

The numerical models were developed in a calibrated sand chamber as schematically illustrated in Figure 1. For modelling the high non-linearity induced from the soil-pile interaction, this was achieved by adopting a reasonable level of repeatability and using parameter sensitivity testing. An elasto-perfectly plastic approach along with the application of Mohr-Coulomb failure criterion and were applied in the application of the elastic solutions in an iterative procedure to simulate the behavior of the soil-pile interaction. The most common application to precisely examine of the combined soil-structure interaction is referred to as the "*p-y*" method [9-13]. The (*p-y* curves) application along with the theory of the Winkler Beam on Elastic model (WBEM) have been utilized for analysis. According to Winkler theory, the elasto-plastic sand domain was defined as a series of narrowly spaced independent springs, Figure 1. Furthermore, the spring modulus stiffness is equal to horizontal modulus of subgrade reaction ($K_h$) as shown in Equation 1.

$$k_h = \frac{p_i}{y_i} \qquad 1$$

Where $y_i$ is the lateral pile displacement and $p_i$ is the lateral soil stiffness.

The ground depth relationship with the soil subgrade reaction, $K_h$ becomes necessary when trying to explain the non-linear differential equation that describes the behaviour of an elastic beam as give details in Equation 2:

$$EI\frac{d^4y_i}{dz^4}+p_i=0 \tag{2}$$

EI is the model pile stiffness, and $k_h$ x $y_i = p_i$. Thus, equation Eq. 2 can be revised as follows:

$$\frac{d^4y_i}{dz^4}+\frac{k_h(z)\ \mathrm{x}\ y_i}{EI}=0 \tag{3}$$

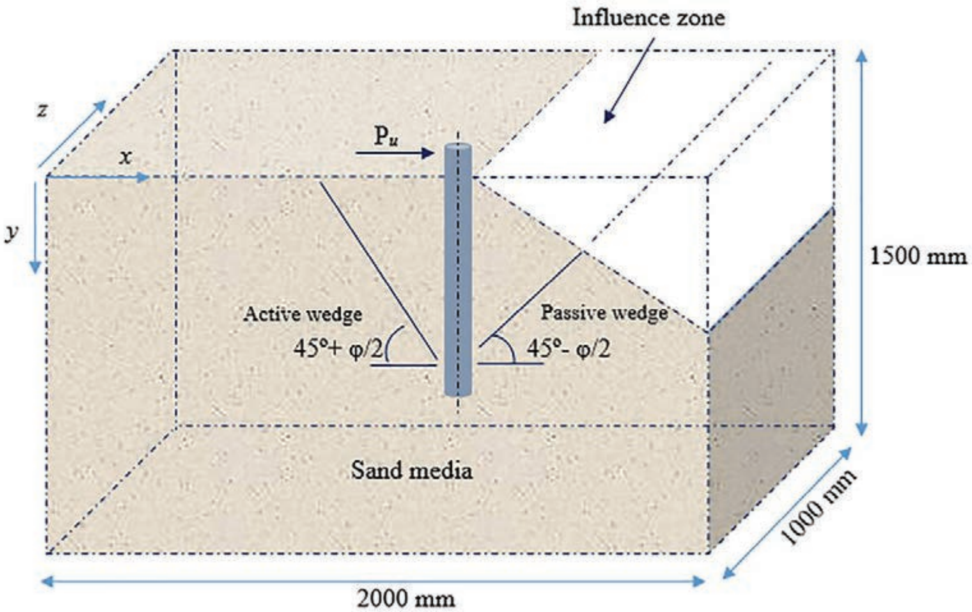
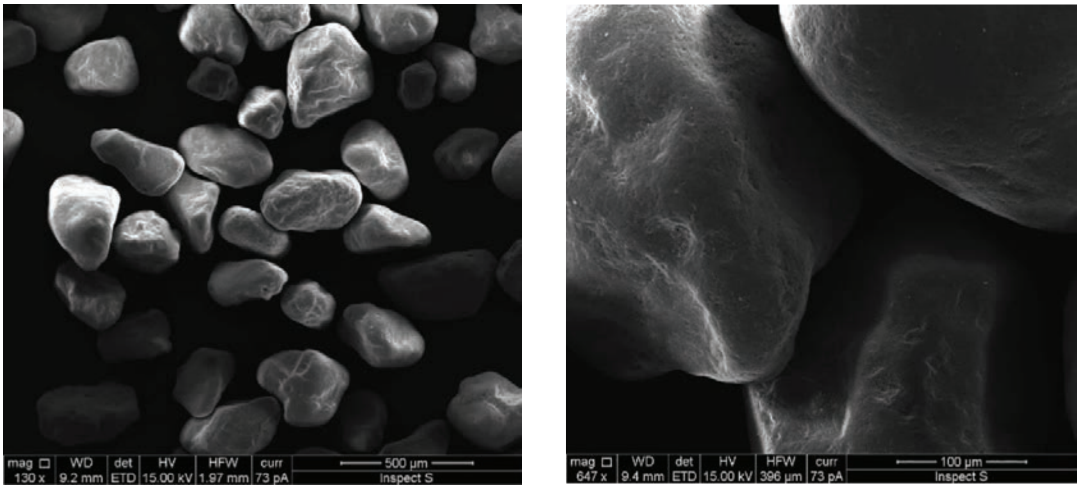


Fig. 1. Problem under consideration: Numerical setup of the pile on sloping ground

## 3. Sand properties

As cited previously, one of the advantages of the applied the constitutive model is the few input parameters required. As confirmed by the SEM observation result, the sand composed of sub-rounded particles, Fig. 2. Based on the Unified Soil Classification System (USCS), the sand can be classified as a poorly graded (SP). The sand coefficient of uniformity, Cu and the coefficient of curvature, Cc are 1.78 and 1.14. The grain size distribution is stated in Fig. 3. To maintain the influence of the grain size distribution on the combined pile-soil interaction, the ratio between the proposed pile diameter to the medium diameter (d50) of the sand specimen should be at least (45) [14]. It was proposed by Remaud [15] that the ratio must be at least 60 times pile diameter. Whereas, Taylor [16] stressed that the ratio should be at least (100) to minimize the scale effect limitation on the soil-pile interaction in the effective zone. In this research, the ratio between pile diameters to minimum medium diameter (d/d50) is about (133) matching the scaling law criteria. Moreover, Bolton [17] discussed that the dilation angle is highly effected by the normal effective stress as an increase in the normal effective stress or overburden pressure will results a decreasing in the angle of dilation. Therefore, the direct shear tests were carried out at low effective stress to avoid the reduction in the soil angle dilation.




Figs. 2a, b. Scanning Electronic Microscopy, SEM observation of sand samples

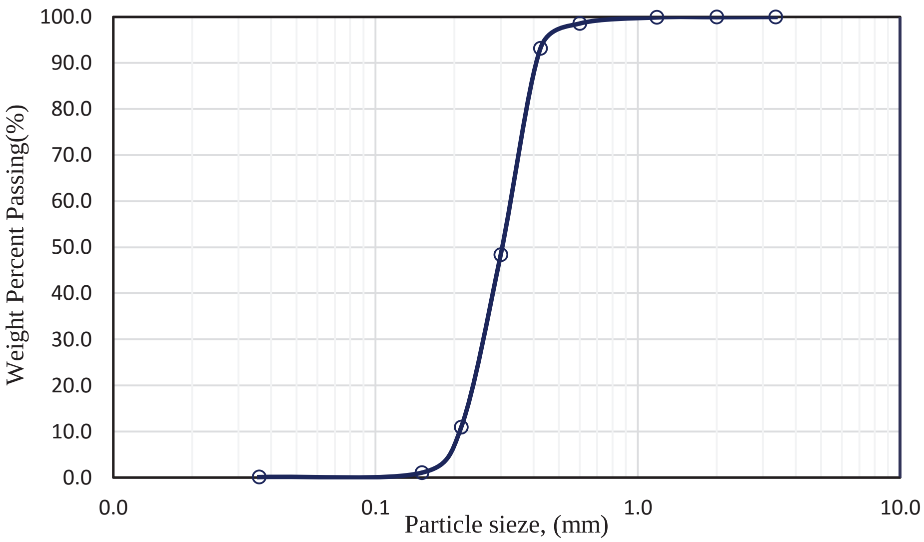



Fig. 3. Particle seize distribution results of the sand sample.

## 4. Soil-pile formulation and loading system

Circular an Aluminium alloy 6061-T6 model piles were chosen in this simulation. Three different aspect ratios were adopted to simulate the response of both long piles and short piles. Additionally, 95 N max lateral load was applied at the tip of the model piles. It should be noted that an extra length of about 50 mm to serve as the load support and to minimize the contact load with the soil surface with the model pile head. To overcome the issues of the effective stress and to minimize the failure wedge from extending up to the wall of the sand domain, Robinsky and Morrison [18] documented that the distance between the sand and the pile varies from (3-5) times the pile diameter. However, the pile diameter utilized in this study is (25.4) mm and 1 mm thickness giving D/t ratios of 25.4 within the range of the D/t (15-45) as recommended by Jardine and Chow [19] and the sand domain size is (2000 x 1000 x 1500) mm to limit the size effect limitation. The material properties of the model piles (ID) are taken from Gere and Timoshenko [20] and the test as presented in Table, 2.

Table 2: Properties of the model pile input parameters and testing ID.

| Test ID | T AO1-1 | T AO1-2 | T AO1-3 |
|---|---|---|---|
| Poisson's ratio, υ | 0.33 | 0.33 | 0.33 |
| slenderness' ratio, l/d | 18 | 24 | 30 |
| Sand mass relative density, Dr % | 70 % | 70 % | 70 % |
| Initial modulus of Elasticity, E, GPa | 70 | 70 | 70 |
| Thermal coefficient | 0.9 *10-5 | 0.9 *10-5 | 0.9 *10-5 |
| Effective Test depth (mm) | 457.2 | 609.6 | 762 |
| Shear modulus of Elasticity, G, GPa | 26 | 26 | 26 |

The model pile diameter is 25.4 mm and having different slenderness ratios are as reported in Table 2. The dimensions for the range of the prototypes piles were chosen 300 mm diameter, 6 mm thickness with 12000 mm length for Aluminum pile. The flexural rigidity, E for both the model pile and the prototype where chosen to have the same value 70 GPa for the Aluminum alloys 6061-T6. Based on Equation 4, the scale factor, (n) for prototype Aluminum pile is 5.67.

## 5. Results and discussion

This section presents the numerical results of the applied lateral load and the corresponding pile lateral displacement, moment profiles, ground reaction at each point from the applied load on model Aluminium piles penetrated in 1.5H: 1V sloping ground. Fig. 4, presents the pile head displacement profile versus soil depth for three slenderness', ratio. It can also be noticed that the pile head displacement markedly decreases with increasing pile penetrated depth from 457.2 mm to 762 mm, due to an increase in the annular skin friction, confining pressure in front of the pile, and resistance of the sand in the passive wedge.

The moment distribution profile along the pile shaft was calculated and plotted in Fig. 5. As reported previously, one of the major advantages of using Winkler theory (Beam on Elastic Foundation) is that it has the ability to accommodate the non-linearity of the elastic-plastic constitutive model at each point from the applied load. It can be clearly observed that for all model piles the moment profiles are markedly non-linear, and varies with maximum and minimum values of about 24 N.m and 16 N.m for rigid and flexible piles at depth of about 9.44D and 10.24D (D is the pile diameter) respectively. It can also be seen that the depth of contra-flexure point at which the maximum bending profile changed from 19.68D to about 25.59D as the pile penetrated depth increased. This is due to the decrease in the pile stiffness, EI and increase in the domain mass within the contacted soil mass in the effective stress passive zone.

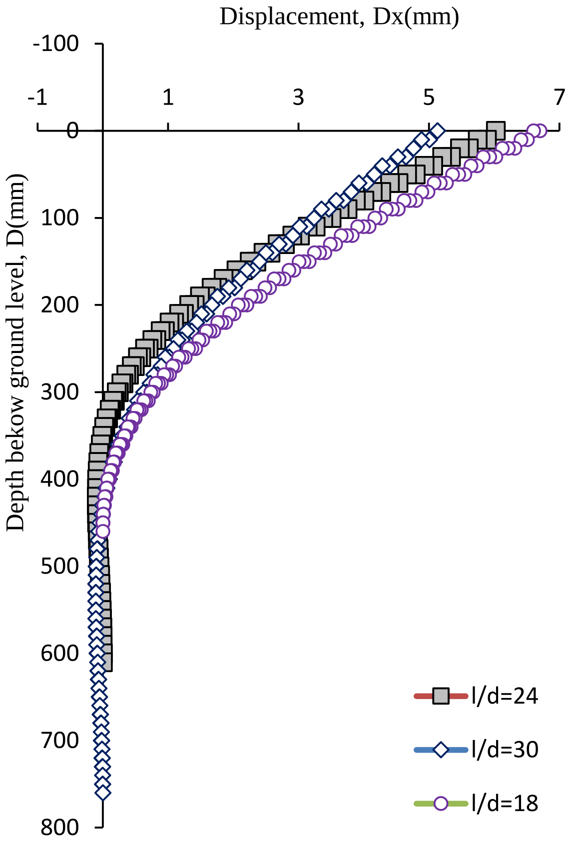



Fig. 4. Piles dispalcement profile versus depth.

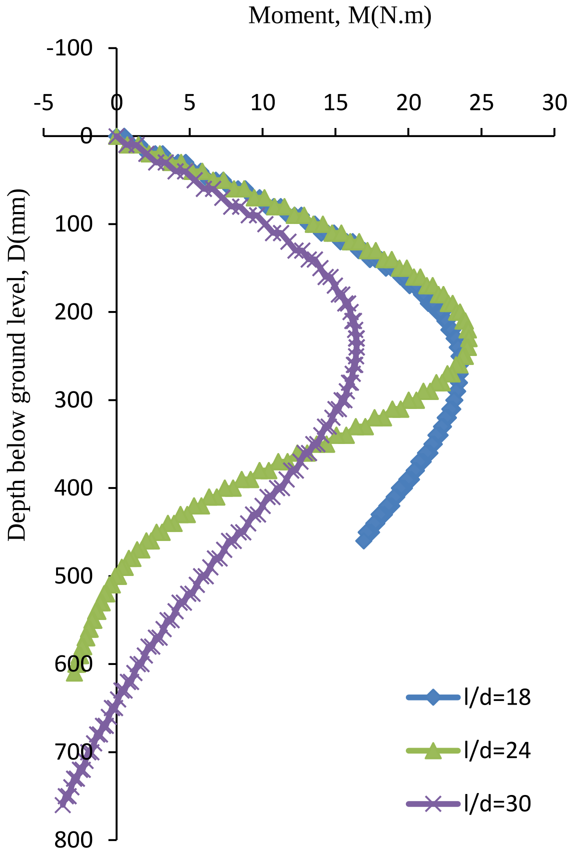



Fig. 5. Piles dispalcement profile versus depth.

For experimental validation. The results of the bending moment profile were compared with experimental model conducted by Muthukkumaran and Begum [21] on the laterally loaded model pile penetrated in sloping ground with 70 % sand relative density as shown in Figure 6. From the figure it can clearly be seen that the estimated bending moment profile is very close with the experimental results with high correlation coefficient of (r2 = 0.985), which reveal that the proposed close form solution is follows the experimental results with high accuracy.

The soil resistance profile versus ground depth is illustrated in Fig. 7. Comparison of the ground reaction for combined soil-pile interface, the maximum soil resistance of 1700 N/m$^2$ occurred for a pile with $l_c/d=24$. While, for a model pile with ($l_c$/d=30) the ground reaction is markedly decreased by about 700 N/m$^2$. It can also be observed that the point of fixity for model pile with $l_c/d$=24 is 13.78D. Whereas, for model piles with lc/d=18 and 30 the point of fixity shifted down slightly to a depth of about 17.71D. Therefore, the net soil resistance decreases with increase of ($l_c$/d) ratios this is due the increase in the modulus of subgrade reaction, K*h* with depth in the pile effective zone. In soil pile interaction, this observation is crucial, as it clarify that the soil resistance to the lateral pile deflection start from the top zone of the soil layers where the radial confining pressure in the passive wedge zone is very low. This observation is similar to the results of the centrifuge model conducted by Mezazigh and Levacher [22].

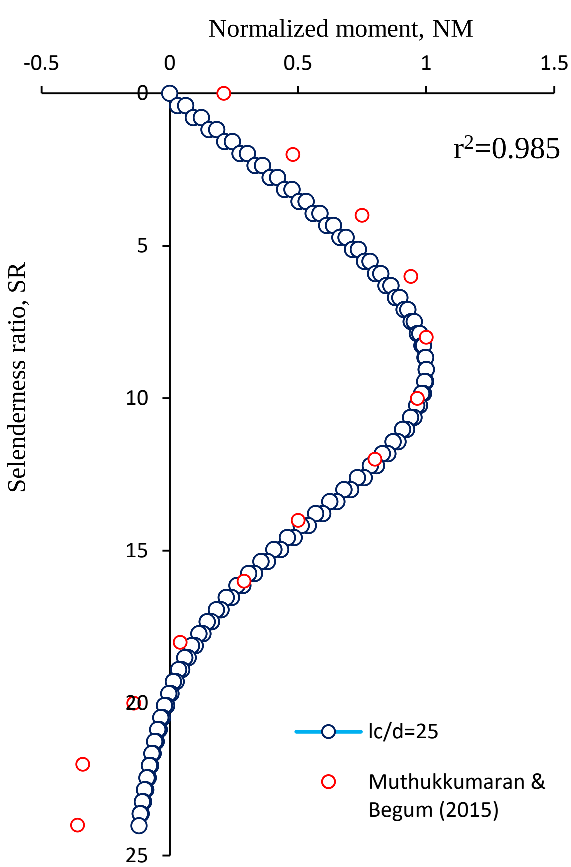



Fig. 6. Piles dispalcement profile versus depth.

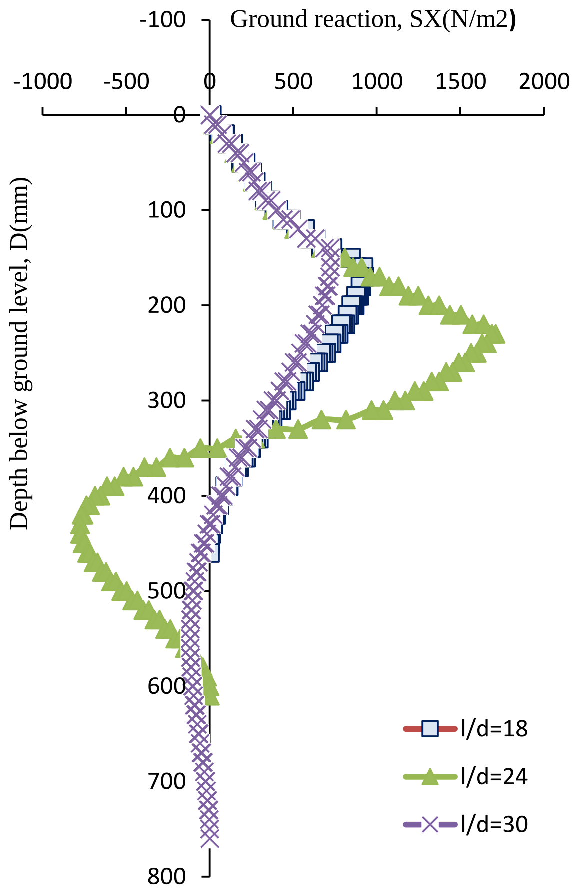



Fig. 7. Soil resistance profile versus ground depth

## 6. Conclusion

The following conclusion can be drawn

- A developed finite element code (FEC) was adopted to analyse the response of Aluminium open-ended model piles penetrated in (1.5H:1V)with outside diameter equal to 25.4 mm and 1mm thickness having three slenderness ratio ranging from 18, 24 and 30. The piles were laterally loaded of 95 N. In the numerical model, pile dimensions were accurately scaled down. To minimize the influence of the pile stress zone, the analysis setup and the size of the sand bed were carefully designed and calibrated.
- Winkler beam on elastic foundation (BEF) with adopted p-y application is able to capture the full range of inelastic laterally loaded pile responses.
- The pile bearing capacity subjected to lateral load increases with increase pile length due to increase in the pile shaft resistance and sand stiffness in the effective passive wedge zone.
- With increase in the pile-penetrated depth, lc, the maximum bending moment markedly decreases and the contra-flexure point depth was shifted down. This is due to the increase in the sand stiffness and the capacity (skin friction) of the model pile within the effective penetrated depth.
- Good agreement was achieved when comparing the application of this modelling approach with experimental physical modelling carried out by another researcher.

- The sand resistance was found to increase with the increase in the pile penetration depth. The maximum lateral soil resistance occurred at depth of about 9.84D from the point of the applied load.

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