A single pile located on sloping ground under dynamic loading

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Abstract. The laterally loaded structure is broadly supported by pile foundations. In addition to the vertical load, structures including high-rise construction, transmission tower, energy station and offshore structures are subject to lateral load. Because of the huge continuous displacement, the conduct of the piles on sloping ground under earthquake loading is distinct from the conduct of the pile on the horizontal ground surface. The numerical analysis was performed using PLAXIS 2D in the current studies. The analysis is performed under dynamic loading on a single model pile to determine the soil-pile system behaviour. On the horizontal ground surface and slope angle of 1V:1.5H, 1V:2H and 1V:3H have situated a single pile of embedded length to diameter ratio (L / D) of 16, 25 and 33. At its basis, the pile was subjected to dynamic loading (Bhuj earthquake, Gujarat). The acceleration, displacement and bending moment of the pile was examined under each case from the analysis. Based on the results, the pile's acceleration and peak displacement and bending moment reduce as the L / D ratio increases.

Keywords: Dynamic loading; Numerical analysis; Sloping ground; Single pile, PLAXIS 2D

1 Introduction

For more than three decades, developers and scientists have been paying significant attention to research of laterally loaded piles under dynamic loading. The dynamic response of a pile subjected to external excitation is a complex phenomenon resulting from the interactions between the pile and the surrounding soil. Because of strong winds or earthquakes, structures such as high-rise buildings, transmission towers and offshore structures are subject to massive lateral loads. Under earthquake loading, the behavior of pile foundations is really a significant problem that commonly influences structure performance. And many of the world's major cities are also built on sloped ground. Due to increased lateral loads, the majority of constructions that are built on soft clay with sloped ground surface are subject to huge displacements. Most of the coastline have surface which are sloping towards the waterfront. Considering the safe operation of the superstructure, the design of the pile foundation in the coastal region for resisting lateral load is mainly based on the restricting deflection criterion. Because of wave and earthquake loadings, lateral loading on pile foundations is cyclic in nature, adding extra complexity to the soil-structure interaction problem. In such instances, it is important to study the soil-pile foundation interaction subject to lateral load. The numerical analysis is performed in this article to determine the impact of acceleration, displacement and bending moment on piles of varying embedding length to diameter ratio (L / D) installed under different sloping ground conditions.

2 Literature Review

The dynamic response of pile subjected to horizontal excitation is a complex matter involving the non-linearity at large displacements, pile separation and slippage.Gaul (1958) conducted static and dynamic model tests on instrumented aluminium pipes embedded in bentonite soil medium. The dynamic load is applied by means of a mechanical oscillator and highly amplified strain variations during the vibrations are recorded. Their study shows that at relatively low frequency, magnitude and location of maximum bending moment does not vary significantly as compared with static case. Hayashi and Miyajima (1962) performed tests on vertical steel H-piles installed in sand of different relative density. Forced vibration tests are conducted and bending moment, lateral deflection of pile head and acceleration response is measured. Frequency response curves of single piles are plotted and natural frequency of single pile is obtained from these tests. However, the results of such dynamic 1-g model tests are affected by the ‘box effect’ and inappropriate stress levels. Prakash and Aggarwal (1965) reported that the zone of influence of a dynamically loaded pile can extend to greater distances such as 30 times the width of pile in the direction of loading and 15 times the pile width in the orthogonal direction. Tajimi (1969) proposed an analytical model considering the pile to support a concentrated mass and the underlying soil is assumed as viscoelastic (linearly elastic material with frequency dependent viscous damping). Nogami and Novak (1977) obtained closed form solutions for the same problem neglecting the effect of superstructure on the pile head response but considering hysteretic type material damping of the soil layer. Nogami and Konagai (1988) worked on the analytical expression in frequency-domain for the dynamic response of a single pile assumed as a massless cylinder embedded in an elastic infinite medium. El Naggar and Novak (1996) developed a computationally efficient model that accounts for non-linear behavior of soil, discontinuity conditions like slippage and gapping at soil-pile interface and energy dissipation through different types of damping. Dou and Byrne (1996) applied dynamic loading through shake table test and preserved the stress levels of the prototype for the model through hydraulic gradient similitude technique. It is observed that the bending moment in model pile reached its peak value when the frequency applied is close to the resonant frequency. It is also found that the location of maximum bending moment shifted downwards as the pile head load is increased. In addition to this, dynamic p-y curves in dense sand are also presented which exhibited highly non-linear characteristics up to a depth of four times the pile diameter for a strong level shaking. Dou and Byrne (1997) demonstrated that wave reflections at the boundary walls are negligible when the loading frequencies are far below the fundamental frequency of the soil layer. Bentley and El Naggar (2000) used 3D FE program ANSYS to develop a model that can account for kinematic soil-structure interaction of piles and used it to evaluate the dynamic pile response with respect to input ground motion. It is shown that for an elastoplastic soil with separation allowed, the lateral response of pile head is very close to the free field response at very low frequency of seismic excitation. Abdoun and Dobry (2002) discuss the critical locations in shear and bending response of deep foundations in liquefied soil based on the reported case history. Maheshwari et al. (2003) studied the effects of plasticity and work hardening of soil on the free field response and also the kinematic response of single piles using the advanced plasticity-based model in a finite element formulation. Maheshwari et al. (2004) confirmed that the material non-linearity significantly affects seismic response of pile foundation which in turn is dependent on the frequency of excitation. Boominathan and Ayothiraman (2007) carried out a comprehensive investigation on single piles installed in soft clay under static and dynamic lateral loads. It is noted that the dynamic magnification factor reduces with an increase in magnitude of load due to large hysteretic damping originating from the extreme non-linear behaviour of soft clay. The active length under dynamic lateral load is increased by about 1.5 times compared to that under static lateral load. Maiorano et al. (2009) performed 3D finite element analysis on a pile subjected to dynamic lateral load to examine the kinematic bending moments in different subsoil conditions. The piles are represented as elastic beams while the soil is modelled using linear elastic constitutive model. The results are used to predict the transient peak bending moments at the soil layer interface. Yang et al. (2011) through his shaking table test demonstrates that the dynamic p-y curves are highly affected by the input acceleration amplitude. Di Laora and Rovithis (2015) carried out a numerical treatment using the rigorous finite element technique to evaluate the kinematic bending moment of long piles embedded in a continuously non-homogenous soil resting over a rigid base. During the analysis, soil stiffness is allowed to vary with depth in a parabolic fashion with its initial value at the ground surface to be zero or a finite quantity. The active length of pile in non-homogenous soil layer is finally proposed considering the effect of kinematic interaction. Deendayal et al. (2016) investigated the effect of the earthquake on a single pile located on the sloping ground. A single pile was located on varying slope with different length to diameter (L/D) ratios. It is observed that the acceleration, displacement and bending moment decreases with the increase in L/D ratio. And also, the displacement and bending moment increases significantly as slope increases from horizontal ground surface to the slope under consideration.

3 Numerical Modeling

3.1 Governing Factor

Finite element method needs multiple approximations during numerical modeling to achieve the solution. The appropriateness of the approximation used in the modeling strategy is based on field circumstances. In the plastic deformation system created during the dynamic loading, plane strain conditions are presumed to persist. The problem being modeled is complex and has to be simplified to obtain a solution. Two major factors affecting the lateral response of piles are: (1) the properties of the soil (2) soil-pile interaction at the interface.

3.2 Constitutive Model

In order to be adequate, a constitutive model must be able to describe the material behavior for the range of stress and strain involved, identify the model parameter by normal material test and physically represent the material reaction to changes in stress and strain applied. A two-dimensional finite element pro-gram PLAXIS 2D is used for assessment in the current research. PLAXIS automatically imposes a set of general boundary conditions (standard fixities) on the current geometry model. The Mohr-Coulomb model is used to depict the soil behavior. The Mohr-Coulomb model is simple and fast and accounts for the soil's elastoplastic conduct with utmost simplicity.

3.3 Geometry Model

A model of geometry is a composition of points, lines and clusters. Points and lines are established in the draw region by entering the command line coordinates. Then the clusters are generated by program. Each cluster provides the properties to simulate soil behavior. During mesh generation, the clusters are split into soil elements. In addition to this, the geometry can be assigned to structural objects such as the beam representing a pile. Once the geometry model has been developed, the parameters of the pile are assigned to the respective geometry element. When the complete geometry model is defined and all geometry components have their initial properties, the finite element mesh is generated. Fig. 1 shows the typical models in case of L/D 33 for sloping ground.

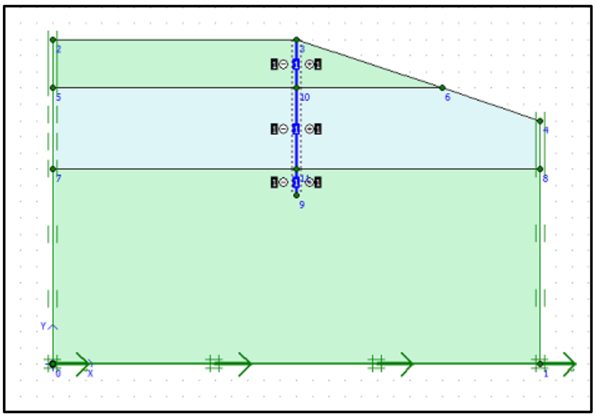

Figure 1. Geometric model for L/D = 33, 1V:3H.

3.4 Soil-Pile Interaction

The Mohr-coulomb model defines the interface behavior for soil-pile interaction modeling. The pile consists of the beam element with special interface elements that provide the interaction between the pile and the surrounding soil. The pile is regarded as linear elastic and its behavior is represented by the use of stiffness characteristics. In the present research, the interface strength reduction factor that accounts for the impact of soil-structure interaction at the interface is selected on a conservative basis.

3.5 Boundary Condition

An absorbent boundary is intended to absorb the increasing stress in the boundaries induced by the dynamic load; otherwise, it will be reflected within the soil body. In this model, the absorbent boundaries are produced at the left, right and bottom boundaries.

3.6 Material Properties

The parameter values for soil and pile are obtained from (Abdoun, T and Dobry R, 2002). In the current research, a single concrete pile of 0.6 m diameter is used for the FEM assessment. An axial modulus (EA) is taken as 3.56 x 105 (kN/m) and Rigidity modulus (EI) is taken as 8000 (kN/m^2). An embedded pile consists of a beam element and provides the interface between the beam and the soil enclosed by the pile. The angle of internal friction (ϕ) and dilatancy angle (ψ) for sand-1 is 32 and 2, and for slightly cemented sand-2 is 35 and 5 respectively. The detailed properties of soil and pile used for modeling are listed in Table 1 and 2.

Table 1. Values of soil and interface properties.

Description	Sand - 1	Slightly cemented sand -2
Unit weight (γ) (kN/m3)	25	28
Material model	Mohr-coulomb	Mohr-coulomb
Young's modulus(Es) (kN/m2)	38000	49000
Poisson's ratio (μ)	0.25	0.3
Angle of internal friction (ϕ)	32°	35°
Dilation angle (ψ)	2°	5°
Interface strength reduction factor (Rinter)	0.67	0.8

Table 2. Values of pile properties.

Description	Pile
Axial modulus (EA) (kN/m)	3.56 x 10^5
Rigidity modulus (EI) (kN-m^2)	8000
Equivalent thickness (t) (m)	0.519
Diameter (D) (m)	0.6

3.7 Finite Element Mesh Generation and Calculation

The soil-pile model's geometry is segregated into finite elements that form the mesh. After the finite element mesh is generated, the actual finite element calculations are executed. There are two stages in the calculation. First, the prescribed displacement is activated while defining the calculation phases. Second, the earthquakes have been simulated in the dynamic analysis. The displacements are reset to zero in order to evaluate the impact of the earthquake in detail. Earthquake loads are generally implemented through prescribed horizontal displacements. The loading of the earthquake is implemented at the bottom of the pile. In the present study, aftershock of the Bhuj Earthquake (Gujarat) data presented in Fig. 2 is used. Analysis was performed for all instances and variation of bending moment and peak displacement is noted. Fig. 3 shows the deformed mesh for L/D ratio 33 on 1V:3H slope.

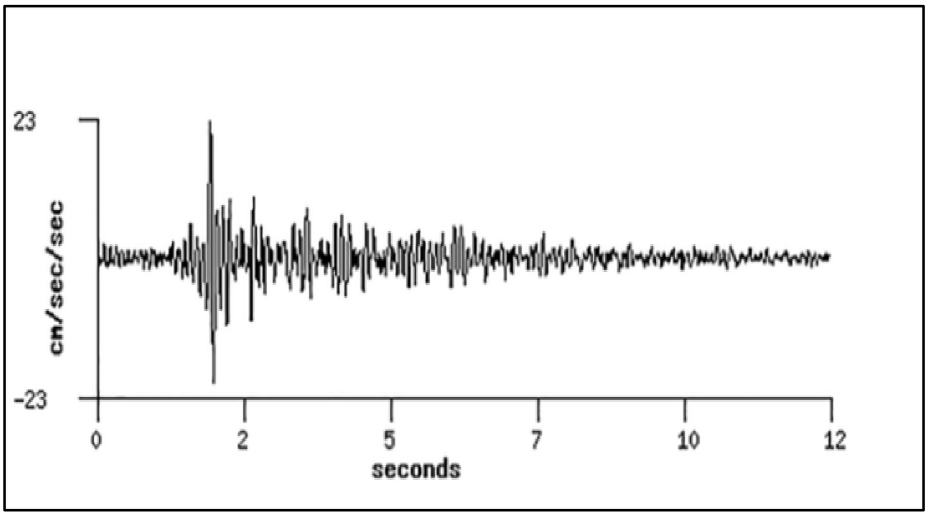

Figure 2. Acceleration-time data for the Bhuj/Kachchh aftershock recorded at the Bhuj station

4 Result and Discussions

Due to dynamic loading, the lateral load behavior of a single pile is analyzed using lateral load–deflection curves. In case of horizontal and sloping ground, the differences of acceleration are determined for distinct L / D ratios. The effect of slope and L/D ratio on maximum bending moment and maximum displacement is also analyzed.

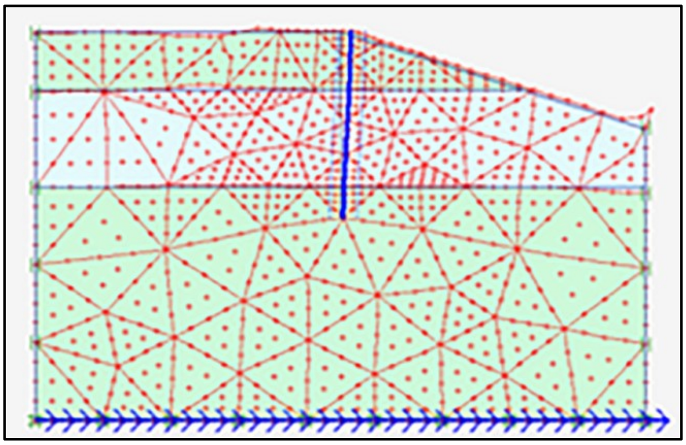

Figure 3. Deformed Mesh for L/D = 33, 1V:3H

4.1 Effect of L/D Ratio on Acceleration Curves for horizontal and sloping ground.

Due to reduced soil resistance along its shaft and also owing to increased pile slenderness, the pile head / cap is more prone to failure. Maximum acceleration is measured at the head of the pile in the present study. Fig. 4 shows the variation of acceleration versus time graphs of a pile (at pile head) for different L/D ratios (16, 25 and 33) for horizontal ground surface. From the findings, it is indicated that the peak acceleration declines as the L / D ratio increases. When the L / D ratio transitions from 16-25, the peak acceleration decreases by 59.82 percent. This behavior is noted owing to a rise in embedded pile length or an increase in soil-pile system flexibility. Fig. 5 shows the variation of acceleration with time for a pile (at pile head) with different L/D ratios (16, 25 and 33) installed at the crest of 1V:1.5H slope. The percentage decrease in maximum acceleration with change in L/D ratio 16-25, 25-33 and 16-33 for the horizontal ground and slope of 1V:3H and 1V:1.5H are shown in Table 3, Table 4 and Table 5 respectively. From the findings, it is noted that as the L / D ratio increases, the peak acceleration reduces regardless of the slopes. When L/D ratio changes from 16-33, the maximum acceleration is observed to decrease by 61.50% and 43.25% on slopes of 1V:3H and 1V:1.5H respectively. The magnitude of maximum acceleration recorded on relatively steeper slope of 1V:1.5H is much higher for L/D ratio of 33. This is due to the decreased passive wedge of soil in front of the pile, which may result in lower inertial resistance from the soil present in the active pile length region. This can cause the net earthquake force to predominate over the weaker resistance forces resulting in greater acceleration at the top of the pile.

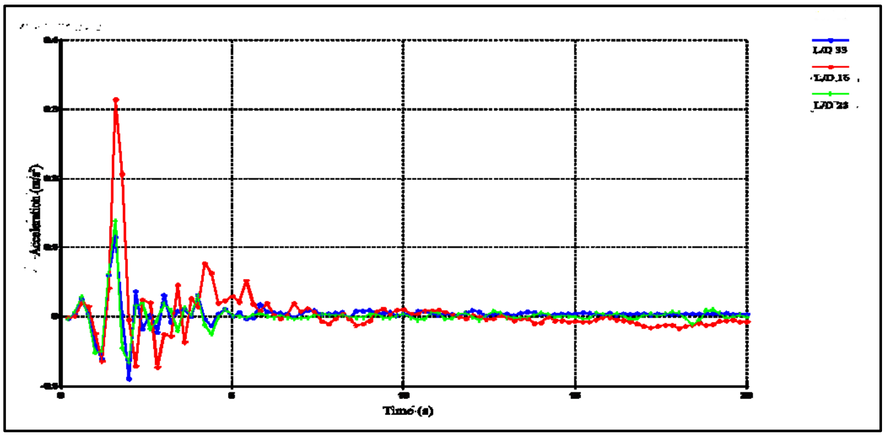

Figure 4. Acceleration-time response for different L/D ratio's on horizontal ground

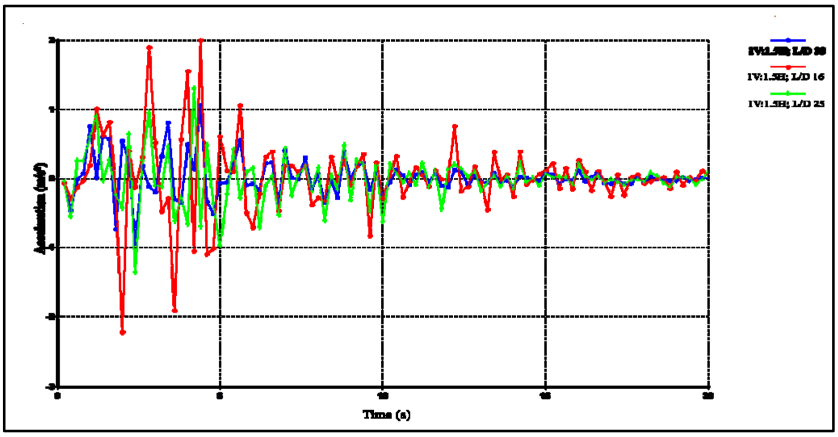

Figure 5. Acceleration-time response for different L/D ratio's on 1V:1.5H slope

Table 3. Percentage decrease in maximum acceleration due to change in L/D ratio for horizontal ground.

	Horizontal ground Surface		
L/D ratios	16	25	33
Max. Acceleration (m/s^2)	0.326	0.131	0.110
Change in L/D ratios	16-25	25-33	16-33
% Decrease	59.82%	16.03%	66.25%

Table 4. Percentage decrease in maximum acceleration due to change in L/D ratio for 1V:3H slope

	Slope 1V:3H		
L/D Ratio	16	25	33
Max. Acceleration (m/s^2)	1.46	0.985	0.562
Change in L/D ratio	16-25	25-33	16-33
% Decrease	32.53%	42.94%	61.50%

Table 5. Percentage decrease in maximum acceleration due to change in L/D ratio for 1V:1.5H slope

	Slope 1V:1.5H		
L/D Ratio	16	25	33
Max. Acceleration (m/s^2)	2.00	1.459	1.135
Change in L/D ratio	16-25	25-33	16-33
% Decrease	27.05%	22.20%	43.25%

4.2 Effects of L/D Ratio and Slope on Displacement

Fig. 6 shows the variation of maximum displacement with slope for different L/D ratios. From the graph, it is indicated that the peak displacement reduces because the L / D ratio relation will increases. It is also observed that as the slope rises from the horizontal ground to the steeper 1V:3H, 1V:2H and 1V:1.5H slope, the peak displacement will increase significantly. The maximum displacement determined on a slope of 1V:1.5H for L/D=16 increased considerably for the present dynamic loading considered at the pile base. This is primarily owing to the severe decrease in inertial resistance from the soil in the wedge. The present result is found to be good agreement with the literature results (Deendayal R and Sitharam T G, 2016).

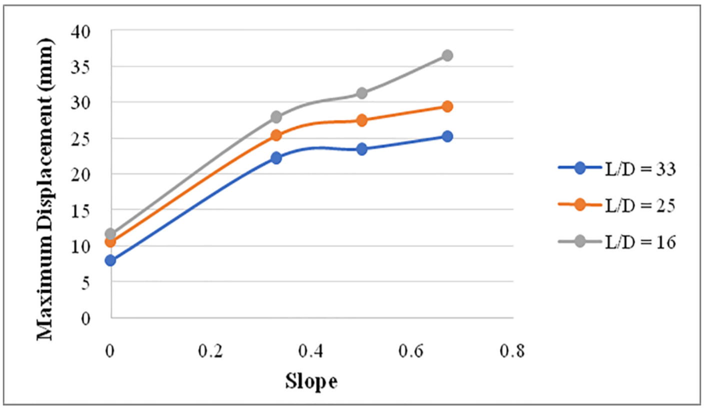

Figure 6. Maximum Displacement vs Depth curve for L/D = 16 with different slope.

4.3 Effects of L/D Ratio and Slope on Bending Moment

The impact of slope on the peak bending moment is shown in Fig.7 for the different L / D ratio. From the graph, it is noted that the rise in the proportion of embedment length to diameter ratio, the maximum bending moment of the pile decreases. This behavior is due to the enhanced depth of fixity resulting from the soil-pile system's larger relative stiffness. Also, if the slope increases from the ground surface (zero slope) and becomes steeper (1V:1.5H), the bending moment also enhances. This is due to the decrease of the soil's passive resistance in front of the pile. It can be noted that the bending moment increases by 50-80% as the slope approaches 1V:1.5H for the range of L/D ratio's (16-33) considered in the study.

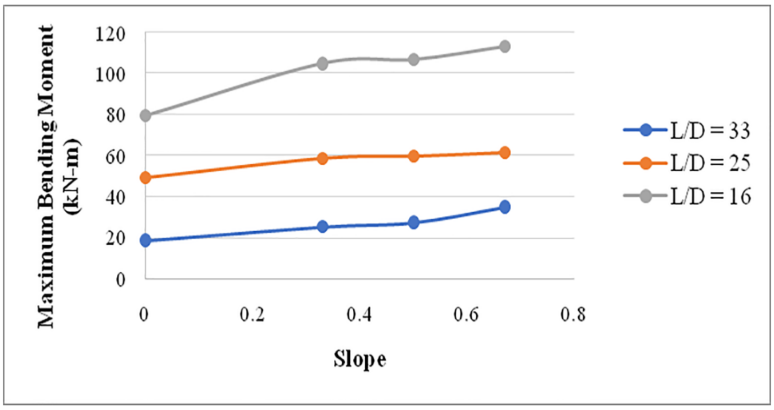

Figure 7. Variation of maximum bending moment with slope for different L/D ratio.

5 Conclusion

A finite element analysis has been performed to evaluate the seismic response of a single pile installed on slopes. The developed analysis has been validated with the similar study carried out by Deendayal et al. (2016). The major conclusions from the study are presented below.

1. As L/D ratio increases, the maximum acceleration decreases irrespective of slopes. When L/D ratio increases from 16-25, 25-33 and 16-33 the maximum acceleration observed a percentage reduction of 16.03-66.25%, 32.53-61.50% and 27.05-43.25% for horizontal ground surface, 1V:3H slope and 1V:1.5H slope respectively. This behavior was due to the increase in embedded length that enhanced the flexibility of soil-pile system.
2. From the study, it is very clear that as L/D ratio increases, the maximum displacement has been reducing. This is due to the decrease in active pile length that contributes to deflection as L/D ratio increases. And also, when ground surface changes from

horizontal to steeper slopes, the maximum displacement increases tremendously especially for the case of L/D = 16.
3. It is noted that the bending moment decreases significantly with increase in L/D ratios. It is also observed that steeper slopes like 1V:1.5H has a considerable effect on increasing the bending moment.

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