13 Aug 2008, 5:15pm - 6:45pm

Parametric Study of the Response of Single Pile under Lateral Loading at the Pile Head

Naemeh Naghavi
Iran University of Science and Technology, Tehran, Iran

Mohammad Hassan Baziar
Iran University of Science and Technology, Tehran, Iran

6th International Conference on
Case Histories in Geotechnical Engineering, Arlington, VA, August 11-16, 2008

PARAMETRIC STUDY OF THE RESPONSE OF SINGLE PILE UNDER LATERAL LOADING AT THE PILE HEAD

Naemeh Naghavi
College of Civil Engineering,
Iran University of Science and
Technology, Narmak 16844,
Tehran, Iran

Mohammad Hassan Baziar
College of Civil Engineering,
Iran University of Science and
Technology, Narmak 16844,
Tehran, Iran

ABSTRACT

This paper presents the findings of numerical studies based on the finite difference method for assessment of single pile behavior under simple dynamic lateral loads. At first, the results of an experimental dynamic lateral load test on a pipe pile driven in to sandy soil are compared with the results of this numerical modeling and some parameters are back calculated. Then piles with different length to diameter ratio, subjected to simple harmonic vibrations (sinusoidal vibrations) with different magnitudes of load and with a range of frequencies, are modeled. The load transferred to the pile and pile head displacement is calculated. Finally, the effects of load frequency, soil- pile damping ratio and length to diameter ratio of pile on the behavior of pile foundation is determined. The results show that the magnitude of load and length to diameter ratio of pile have significant effect on pile response under harmonic lateral loads; displacement of the pile head increases, with increase in load magnitude and decrease in length to diameter ratio of pile. For the range of frequency studied in this paper (1 to 15 Hz), observed that this parameter doesn't affect the pile head response.

INTRODUCTION

Pile foundations are commonly used to transfer loads from a structure to the ground when the structural loads are very high or where the soil at shallow depths can not carry the imposed loads. Under moderate and strong seismic loading, pile foundations undergo large displacements and the pile-soil system would have strongly non-linear behavior.

Pile-supported structures can be subjected to dynamic loads from machines, traffic, ocean waves, and earthquakes. The frequency of loading from traffic and waves is usually low enough that p-y curves for static or cyclic loading can be used. (Reese and Van Impe, 2001) But in the case of earthquakes (high frequencies), it is necessary to study the behavior of pile-supported structures.

These foundations should be designed so that they satisfy three conditions: (1) The pile should be able to carry the imposed load with an adequate margin of safety against failure in bending; (2) the deflection of foundation under load should not be lager than the tolerable deflection for the structure it supports; and (3) the soil around the pile should not be loaded so heavily that it reaches its ultimate load-carrying capacity (Duncan et al., 1994).

Most design calculations are usually made for a single pile and the results are used to account for group action, so understanding the behavior of a single pile is important.

Analysis for the design of piles to resist static lateral loads is generally conducted either by using the approach of Reese and Matlock (1956, 1960), or by using the approach of p-y curves (Poulos and Davis, 1980).

Existing methods for the analysis of laterally loaded single piles can be generally classified into the following categories: the limit state method; the subgrade reaction method; the p-y method; the elasticity method; the finite element and finite difference method.

The response of a pile under dynamic load is generally obtained with one of the simplified approaches, such as: using the concept of elastic subgrade reaction for obtaining the equivalent soil springs; treating the pile as a cantilever fixed at the lower end and treating the pile problem as a case of one-dimensional wave propagation in a rod.

Methods of analyzing seismic soil-pile-structure interaction have included 2D and 3D modeling of the pile and soil continuum using finite-element or finite- difference methods, dynamic beam on a nonlinear Winkler foundation (i.e., "dynamic p-y") methods, and simplified two-step methods that uncouple the superstructure and foundation portions of the analysis. Dynamic p-y analyses have been developed and applied to seismic and offshore problems (Kagawa and Kraft, 1980).

Numerical models of soil-pile systems have been developed (O'Neill et al., 1982), and a variety of small scale model tests have been performed to improve the understanding of the effects of soil and pile parameters on the system response (Baka and Stokoe, 1983; Gaul, 1958; Novak and Grigg, 1976; Prevost et al., 1981). Consequently, the engineer's ability to predict pile foundation response to seismic and dynamic loads applied at the pile head has also been improved (Geoffrey et al., 1986).

Only a relatively small number of well-documented, full-scale, lateral dynamic pile load tests have been reported in the literature (Gle and Woods, 1984; Scott et al., 1982; Geoffrey et al., 1986; McVay et al., 1998; Mostafa and El Naggar, 2003; Anandarajah et al., 2005). Full-scale dynamic pile response is necessary as a point of reference to judge the results of numerical analyses. Scale-model dynamic tests need to be evaluated carefully since the effective stress around the piles and the stress-strain behavior of the soil are difficult to be modeled. In numerical analyses the adequacy of analytical soil stiffness and damping functions also are required to be verified.

The behavior of pile foundation depends on many factors such as nonlinear constitutive behavior of soils, soil-pile-superstructure interaction including slip and separation at the pile-soil interface, characteristics of the loading, geometry of single piles, arrangement of pile group, etc. When the amplitude of loading is large, most of these factors control the behavior. Accuracy and reliability of the predicted behavior however depend on the method of analysis and the accuracy of selected parameters for the modeling.

Because of the approximations implied in the analysis methods, static capacity of piles is in most cases determined directly from pile load tests performed in the in situ soil. A similar approach is highly desirable for the design of piles subjected to dynamic loads such as earthquake. The parameters needed for simplified analysis such as the Winkler foundation method and the equivalent-linear finite element method may be determined from measured response of the pile subjected to a large-amplitude dynamic load applied at the pile head level (Anandarajah et al., 2005).

This paper presents the findings of numerical studies based on the finite difference method for assessment of single pile behavior under simple dynamic lateral loads. At first, the results of an experimental dynamic lateral load test on a pipe pile driven in to sandy soil are compared with the results of this numerical modeling and some parameters are back calculated. Then piles with different length to diameter ratio, subjected to steady state harmonic vibrations with different magnitudes of load and with a range of frequencies, are modeled. The load transferred to the pile and pile head displacement is calculated. Finally, the effects of load frequency, soil- pile damping ratio and length to diameter ratio of pile on the behavior of pile foundation is determined.

CASE STUDY

In seismic regions, the analysis and design of pile-supported structures requires an accurate prediction of the pile head response and the load resistance to lateral shaking caused by earthquake ground motions. The results of a lateral load test (deflections, shears, and moments) can be directly used to design the foundations.

Experiments were conducted by Anandarajah et al. in a uniform granular soil deposit, filled in a test pit available at the test site. The tests were conducted in a 6.1 m deep pit with a plan area of 5.5 m × 5.5 m. The pit was filled with uniform sand in loose to medium dense state. When the tests were conducted, the water table was below the level of the pile tip. A 0.1 m diameter, 3.75 m long, pipe pile was driven into the soil to a depth of 2.8 m, with an overhang of 0.95 m. A weight of 0.54 kN was attached to the pile at the pile head. The lateral dynamic loading was to be applied by the Statnamic device (Middendorp et al., 1992). The Statnamic device produces a single-pulse, impact loading. In order to extract more cycles of vibrations from a single-pulse impact loading, a spring-mass oscillator was attached to the pile head, and the Statnamic load was applied in the horizontal direction to the pile at the pile-head level through this spring-mass oscillator. The load experienced by the pile head was measured directly by a load cell attached between the pile head and the excitation setup. The horizontal displacement response of the pile was measured at the pile-head and ground level. The load and acceleration time history, measured at the pile head, are shown in Fig. 1 and 2 (Anandarajah et al., 2005).

Finite element numerical analyses have been done on this case (Anandarajah et al., 2005). They used equivalent-linear approach to account for the nonlinearity of the soil (Idriss et al., 1973), where the damping is considered through Rayleigh damping model, defined at the element level. The results of their study are shown in the next section.

NUMERICAL ANALYSIS

Finite difference method used here study numerically the mechanical behavior of a continuous three-dimensional medium as it reaches equilibrium or steady plastic flow.

The nonlinearity of soil can be accounted for by using Mohr-Coulomb plasticity model and strain dependent values for dynamic shear modulus in 3D analysis. In these numerical analyses the Rayleigh damping is used in soil modeling, so the shear modulus G and damping β are assumed to vary as a function of the level of shear strain in the soil.

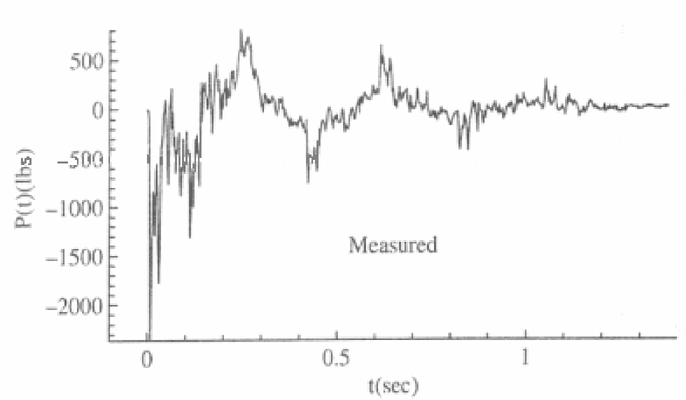

Fig. 1. Time history of load measured at the pile head.

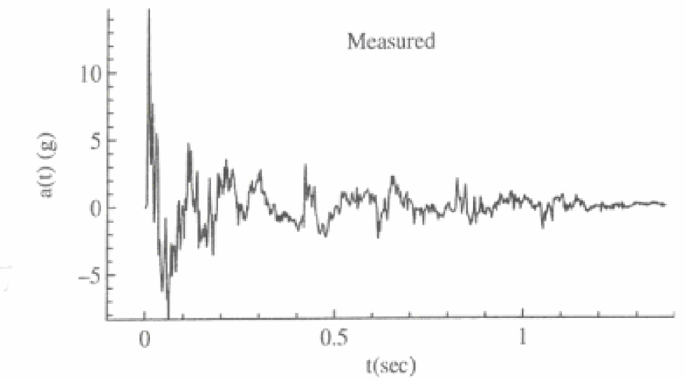

Fig. 2. Time history of acceleration measured at the pile head.

When the pile is shaken with a large-amplitude loading the material damping is more important than the Radiation damping (Brown and O'Neill, 2001).

In this study, soil density is 17.3 kN/m^3, the friction angle is 35 degrees, soil cohesion is 0, Poisson ratio is 0.3, and elasticity modulus is 25 MN/m^2; as the parameters of the real experiment.

Finite difference mesh of the pile- soil system is shown in the next figure. The model is symmetric and in this Figure half of it is shown. This mesh have dimension as the pit in the field and the boundaries are selected far enough from the pile.

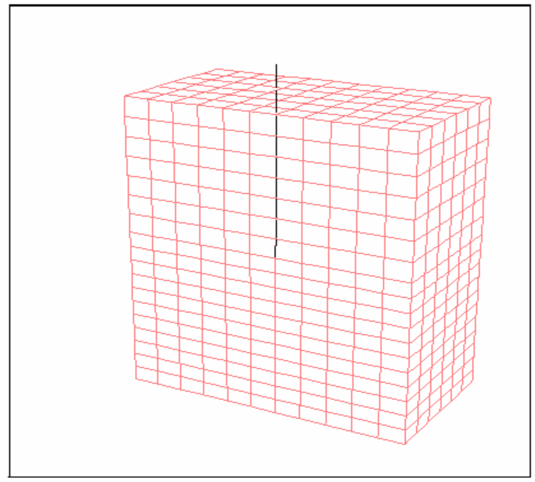

Fig. 3. Finite difference mesh of the model.

At first, some parameters of the pile-grid interface model were assumed, then the numerical model of the real experiment analyzed and the displacement response of the pile at the ground level was calculated by FDM and compared with the measured response at the site and calculated response by FEM reported (Anandarajah et al., 2005). Finally, the parameters that result in a good agreement between computed and measured response were selected. This comparison is shown in Fig. 4. In the next section, soil-pile system will be modeled with the use of selected parameters for soil-pile interface, and the effect of other parameters on the pile response, will be studied.

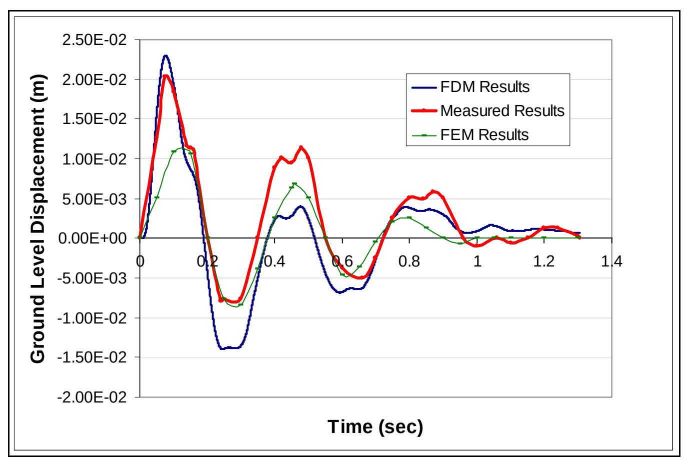

Fig. 4. Time history of load measured at the pile head.

PARAMETRIC STUDY

Accuracy and reliability of the predicted behavior of piles depend on the method of analysis and the accuracy of selected parameters for the modeling. So, it is often necessary to verify the required parameters through simple loadings of a single pile.

In this section the piles with different length to diameter ratio, subjected to simple harmonic vibrations (sinusoidal vibrations) with different magnitudes of load and with a range of frequencies, are modeled. The load transferred to the pile and pile head displacement is calculated. Finally, the effects of load frequency, magnitude of loading, soil- pile damping ratio and length to diameter ratio of pile on the behavior of pile foundation is determined.

RESULTS

Numerical dynamic analyses in the lateral mode were done on single pipe pile in a simulated half-space filled with sandy soil. Model piles with various lengths were subjected to steady-state harmonic vibrations with different magnitudes of force (1 to 5 kN) applied over a wide range of frequencies from 1 to 15 Hz. Selected frequencies for the applied loading are according to the range of earthquakes frequencies. During an earthquake, the first seismic wave arrivals are generally high-frequency compressional and shear body waves and later arrivals are lower-frequency Love and Rayleigh surface waves (Geoffrey et al., 1986). The equation of loading is as follows:

$$F = A\sin(2\pi f t)$$

That:

F : Harmonic loading (N);
A : Amplitude of loading (N);
f : Frequency of loading (Hz);
t : Dynamic time (Sec);

The effect of frequency of loading on the maximum response of the pile head is shown in Fig. 5. Frequency of loading changes while other parameters of the model and also loading are constant. The magnitude of the applied load is 2 kN. In each case one cycle of loading is applied to the pile head.

As can be seen in Fig. 5, in low frequencies the pile has approximately a linear response in cyclic loading, and in high frequencies the pile behaves nonlinearly. The pile head displacements in different frequency of loading are in the same range; so, Frequency of loading doesn't have significant effect on the pile head response.

Magnitude of loading affects the maximum response of the pile head, for evaluating the effects of this parameter harmonic load with a frequency of 5 Hz and different amplitude of load is applied to the pile head, while other parameters of the model remain constant. The frequency of harmonic loading (5 Hz) is selected according to the predominant period of Iranian earthquakes.

It is observed consistently that the magnitude of the applied force significantly affect the response of the soil–pile system (Fig. 6).

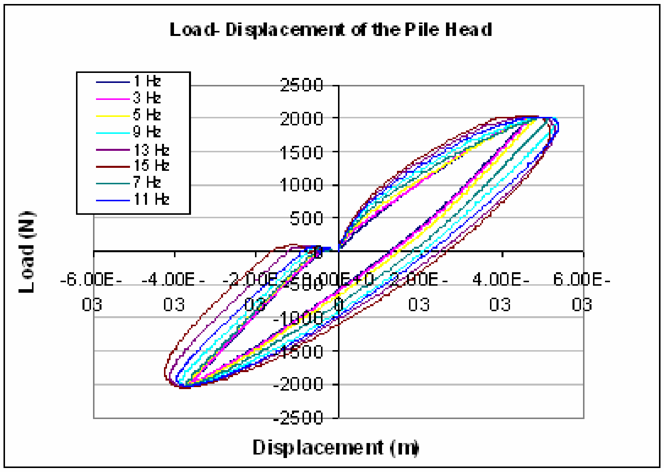

Fig. 5. Load-displacement of the pile head for different frequencies.

The effect of soil damping is studied for three value of Rayleigh damping (3, 5 and 10 percent of critical damping) for the soil; the result is shown in Fig. 7. As can be seen, the soil damping doesn't have significant effect on the lateral response of pile.

The effects of length to diameter ratio for three values of 10, 15 and 20 have been studied. In this case all the parameters remain constant and the embedded length of the pile varies from 10 to 20 times of diameter. As can be seen, the single pile with length to diameter ratio of 10 behaves as a rigid pile and deflects more than two other piles that behave as a long pile (Fig. 8).

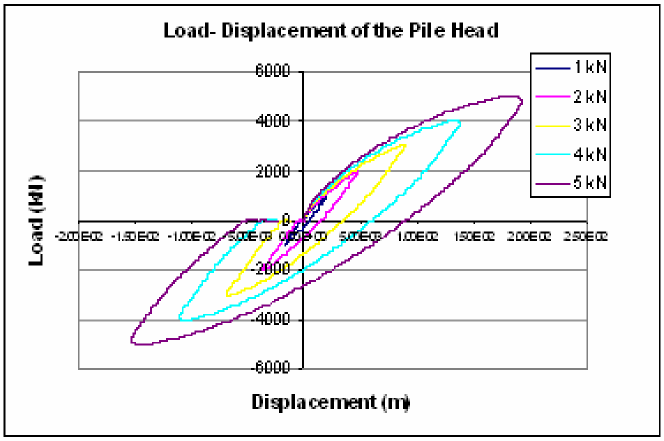

Fig. 6. Load-displacement of the pile head for different load magnitude.

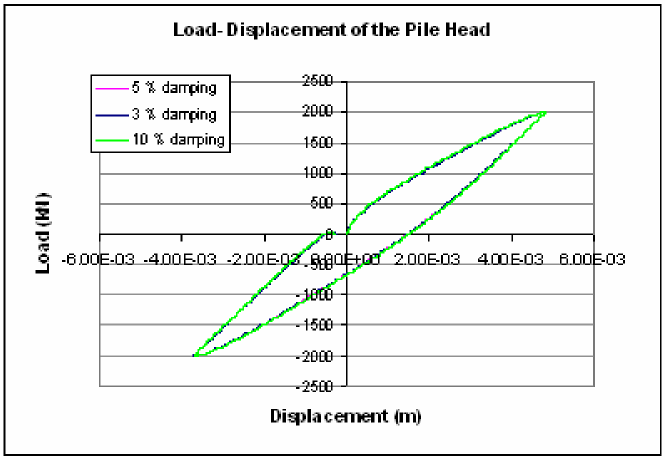

Fig. 7. Load-displacement of the pile head for different soil damping.

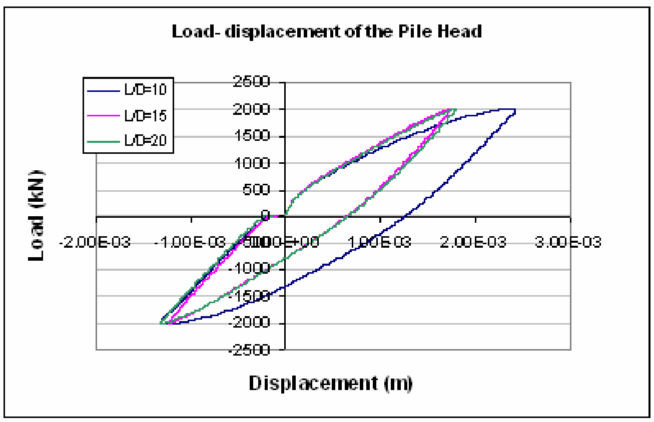

Fig. 8. Load-displacement of the pile head for different length to diameter ratio of pil

CONCLUSIONS

A series of finite difference numerical analyses were done on single piles driven into a homogeneous sandy deposit with different length to diameter ratio, subjected to simple harmonic vibrations (sinusoidal vibrations) with different magnitudes of load and with a range of frequencies. Effect of different parameters were studied and observed that the magnitude of load and length to diameter ratio of pile have significant effect on pile response under harmonic lateral loads; displacement of the pile head increases with increase in load magnitude and decrease in length to diameter ratio of pile. For the range of frequency studied here (1 to 15 Hz), it is observed that this parameter doesn't affect the pile head response.

REFERENCES

Anandarajah, A., J. Zhang and C. Ealy [2005], "Calibration of Dynamic Analysis Methods from Field Test Data", Soil Dynamics and Earthquake Engineering, No. 25, pp. 763-772.

Baka, J. E. and K. E. Stokoe [1983], "Dynamic Response of Vertically- Loaded, Small-Scale Piles in Sand", Geotechnical Report GR 83-2, Univ. of Texas at Austin, Austin, TX.

Brown DA, MW. O'Neill [2001], "Static and Dynamic Response of Pile Groups", NCHRP Study.

Duncan, J. M., L.T. Jr. Evans and P. S. K.Ooi [1994], "Lateral Load Analysis of Single Piles and Drilled Shafts", Journal of Geotechnical Engineering ASCE, Vol. 120, No. 5, pp.1018-33.

Gaul, R. D. [1958], "Model Study of a Dynamically Laterally Loaded Pile", Journal of the Soil Mechanics and Foundations Division. ASCE, Vol. 84, No. SM1.

Geoffrey, W., Blaney and M. W. O'Neill [1986], "Measured Lateral Response of Mass on Single Pile in Clay", Journal of Geotechnical Engineering ASCE, Vol. 112, No. 4, pp. 443-57.

Gle, D. R. and R. D. Woods [1984], "Suggested Procedure for Conducting Dynamic Lateral Load Tests on Piles", Laterally Loaded Deep Foundations: Analysis and Performance, ASTM STP 835, pp. 157-171.

Idriss, IM, J. Lysmer, R. Hwang and HB. Seed [1973]. "Quad 4: A Computer Program for Evaluating the Seismic Response of Soil Structures by Variable Damping Finite Element Procedure", Berkeley report no. EERC 73-16, University of California.

Kagawa, T. and L. M. Jr. Kraft [1980], "Lateral Load-Deflection Relations for Piles Subjected to Dynamic Loadings", Soils and Foundations, Japanese Society of Soil Mechanics and Foundation Engineering, Vol. 20, No. 4, pp. 19-36.

McVay , M., L. Zhang, T. Molnit and P., Lai [1998], "Centrifuge Testing of Large Laterally Loaded Pile Groups in Sands", Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Vol. 124, No. 10, pp. 1016-1026.

Middendorp, P., P. Bermingham and B. Kuiper [1992], "Statnamic Load Testing of Foundation Piles", Proc. 4th. Intl. Conf. Application of Stree-Wave Theory to Piles, The Hague, the Netherlands, pp. 581-588.

Mostafa, Y. E. and M. H. El Naggar [2004], "Response of Fixed Offshore Platforms to Wave and Current Loading Including Soil-Structure Interaction", Soil Dynamics and Earthquake Engineering, No. 24, pp. 357-368.

Novak, M. and R. F. Grigg [1976], "Dynamic Experiments with Small Foundations", Canadian Geotechnical Journal, Vol. 13, pp. 372-385.

O'Neill, M. W., G. G. Blaney and G. L. Muster [1982], "Behavior of Single Pile and Pile Group in Over consolidated Clay Under Relatively Low Frequency Loading", Fugro-Gulf, Inc., and Univ. of Houston-University Park.

Poulos, H. G. and E. H. Davis [1980]. "Pile Foundation Analysis and Design". John Wiley & Sons Inc., New York.

Prevost, J. H., J. D. Romano, A. H. Abdel-Ghaffar and R. Rowland [1981], "Dynamic Response of Laterally Loaded piles in Centrifuge", Proc. 2nd Specialty Conference on Dynamic Response of Structures, ASCE , pp. 386-400.

Reese, L. C. and H. Matlock [1956], "Non-Dimensional Solutions for Laterally Loaded Piles with Soil Modulus Assumed Proportional to Depth", Proc. 8^{th} Texas Conf. on Soil Mech. and Found. Eng. Spec. Pub. 21, Univ. of Texas, Austin; pp.1-41.

Reese, L. C. and W. F. Van Impe [2001]. "Single Piles and Pile Groups under Lateral Loading". A.A.Balkema, Rotterdam.

Reese, L. C. and H. Matlock [1960], "Numerical Analysis of Laterally Loaded Piles", Proc. Of the II Structural Division Conference on Electronic Computation, Pittsburgh, Pennsylvania, ASCE, pp. 657-668.