PUSHOVER ANALYSIS OF PILES IN STRATIFIED SOIL

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ABSTRACT :

Pile foundations have been the subject of interest for earthquake engineers since last several decades. The devastations caused in major earthquakes of the world can be the reason enough to carry out the research on the topic of seismic behavior of piles. One definite concern is liquefaction induced ground movement after the shaking in an earthquake, causing extra lateral loads acting on piles. Several numerical models have been proposed so far to obtain the response of piles in such situations. These include the Beam on Nonlinear Winkler Foundation (BNWF) model, Finite Element models, etc. On the other hand, strength and deformation demands of multi-degree of freedom systems have been obtained by methods like Response History Analysis (RHA), nonlinear static procedures (NSP) and modal pushover analysis. But the solution for pile capacity under earthquake loading with pile in a generalized multilayer soil profile is still scarce. The monotonic pushover method (force based) has been employed to study the responses of pile foundations in liquefiable soil for a single layer and for multilayered systems to study the effect of change in pile head deflections. A worldwide available robust 3D finite element tool, OpenSEES PL is used to model the soil and pile properties using 8-noded brick elements. The pile is discretized using nonlinear beam elements and extended up to the depth of last soil layer. Results for different stratified cases are presented in terms of pile head deflections. They are also compared for different positions of liquefiable layers with respect to non-liquefiable layers.

KEYWORDS: Single Pile, Pushover, OpenSEES, Earthquake, Layered Soil, Liquefiable Layer

1. INTRODUCTION

Analysis of pile foundations is an important topic of research for geotechnical engineers for several decades. It is more important when the analysis has to be carried out under earthquake conditions. In the present paper, nonlinear static procedures (NSP) mentioned in FEMA-356 (2000) has been used to obtain the seismic responses of piles. Pushover analysis, a common method to analyze any structure, is used for the present study of pile. In pushover analysis, the structure is first discretized into elements connected to each other at nodes. A base load is selected and imposed on the structure, under which the structure is analyzed. The deformations at all the nodes of the structure are recorded from the deflection profile. Among all such nodes, one is chosen as the control node, whose deflections are most significant compared to the other nodes. For the analysis of superstructure like high rise buildings, this node is usually at the roof-slab level. Static analyses using equivalent/ pseudo-static seismic loads are conducted only in case the higher modes of vibration do not contribute to the structure's deformation as compared to the fundamental mode. This assumption leads to selection of the control node at the top of a structure, because it is seen that in the first mode of vibration, the structure usually deforms maximum at that point. Nonlinear analysis of the structure ensures that the inelastic behavior of the structure under high-magnitude seismic loads is considered. When the load increases from lower to higher magnitude, it actually acts on the structure which has already deformed by lower-magnitude load. For the structure already deformed by the load in first phase of the earthquake, the deflection in the second phase becomes excessive with higher magnitude of load. Such case can only be simulated by conducting nonlinear analyses.

Dynamic analyses of structures conducted by conventional methods like Response History/ Response Spectra (see Chopra, 2001) methods are often complex and time consuming. Further, they don't account for the nonlinear behavior of the structure arising out of the deformation caused due to initial lower magnitude loads. Dynamic methods do not provide the simple option to obtain responses of an already deformed structure. As a replacement, static pushover analysis is found to be effective. As the analysis is static, it requires less time, and it is done by pushing the structure by cumulatively increasing load, taking into account the nonlinearity in deformation behavior of the structure. Even though it is nonlinear static analysis, it can be used in seismic design as it can simulate the equivalent peak load that occurs on the structure during an earthquake. The pushover analysis is therefore intended to represent the peak demand during actual earthquake loading. The ability of pushover loading to simulate peak dynamic response of structure decides the accuracy of this method. When peak response is dominated by the first mode of vibration, the pushover method is usually accurate. The advantages (see Kircher, 1997) of pushover analysis are listed below:
1. Improve understanding of post-yield structural behavior
2. More accurate prediction of global displacement
3. More realistic prediction of earthquake demand in individual structural elements
4. More reliable identification of weak elements in the system
5. Reduce impact and cost of seismic retrofit
6. Advance the state of practice

Many researchers, like Brandenberg et al. (2001), Boulanger et al. (2004), Ashford & Juirnarongrit (2006), and few others had taken up the pushover analysis of piles to obtain results for validation with dynamic centrifuge test results. However, all the works were more into finding out the displacement and bending moment profiles rather than obtaining the ideal pushover curves, which give the load-displacement behavior of the pile to obtain the capacity. Also the main focus of all previous researches was to study the behavior of pile under one loading condition, but not for the case with varying loads. In the present analysis, more emphasis have been given to obtain the load-displacement behavior of the structure in the elastic/plastic ranges and to compare results with those obtained from dynamic analysis to compute the yield loads.

A software application, namely OpenSEES with a Graphical User Interface (GUI) extension exclusively for piles, i.e. OpenSEES PL (see Yang et al., 2004) is used in the present analysis. The single pile model is extended for the present analysis to consider multiple layers of soil. The results are reported for different stratified soil conditions, and also with the results obtained by linear analysis. The clear differences in the pile head deflections by linear and nonlinear analysis show the significance of conducting nonlinear analysis. In the present analysis, the pile is pushed up to a lateral pile head deflection of about 2% of its length. The reason for analyzing up to such high deflections is justified by the results of dynamic analysis (base shaking) conducted using OpenSEES PL.

2. STATIC ANALYSIS OF PILES

The conventional mathematical model used for static analysis of pile is the 'Beam on Winkler Foundation' (BWF) model (see Brandenberg et al., 2001). Here the pile is modeled as a beam and discretized into small elements connected by nodes. The lateral support from the soil is modeled at those nodes using either linear or nonlinear springs (Fig.1). The spring stiffness is determined from the known soil properties. Stiffness can be taken as a constant value or may linearly increase with depth owing to the increasing overburden pressure.

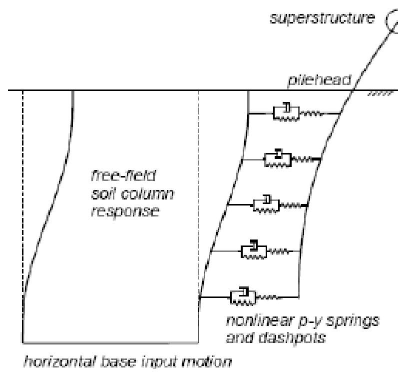


Figure 1 BWF model proposed by Brandenberg et al. (2001)

The soil around the pile may be classified into two cases, near and far fields, with the pile causing maximum movement in the near field. In OpenSEES PL, other than specifying the soil properties in far field, one can define the soil properties separately for near field also. The superstructure is modeled as a vertical point load acting on the head of the pile as shown in Fig. 1. Generally, the superstructures supported by pile foundations are multi-degree of freedom (MDOF) systems, but in analysis of pile foundations, the superstructure is considered as a single mass at the pile head. The structure is loaded and analyzed using finite difference method to solve the following governing Eqn. (2.1) for beam on elastic foundations.

$$EI\frac{d^4y}{dx^4} + P\frac{d^2y}{dx^2} + ky = q \qquad (2.1)$$

where, EI = flexural rigidity of the pile; P = axial load on pile from superstructure; k = Winkler spring stiffness, q = lateral load intensity on the pile, and y = lateral deflection of pile.

The soil reaction is given by the term 'ky'. It acts opposite to the direction of lateral deflection. The bending moment (M) can also be obtained once deflection 'y' is obtained, using Eqn. (2.2)

$$M = EI\frac{d^2y}{dx^2} \qquad (2.2)$$

Spring stiffness can be calculated by integrating Mindlin's equation (see Poulos & Davis, 1980). For better results, the soil springs can be taken as nonlinear springs (see Takahashi et al., 2006). The free field soil movement profile can be obtained from *p-y* curves of Reese et al. (1974) for cohesionless soils and from Matlock (1970) for clayey soils.

3. PUSHOVER ANALYSIS OF SINGLE PILE

Pushover analysis is done on structures to obtain their ultimate load carrying capacity under severe conditions of load, for example in case of earthquakes. The structure is first analyzed under a given load by using any standard method, and then the load is monotonically increased for the next iteration, in which the structure is reanalyzed following the same method. The process is continued until the target displacement of the structure is reached or exceeded. The analysis is then stopped and the results of all the iterations (from the beginning) are plotted in a curve called the pushover curve. The curve plotted is usually load applied (points y_i for i = 0(1)5) on the structure vs. displacement of the control node (points x_i for i = 0(1)5) as shown in Fig. 2.

Any structure under small loads behaves elastically. When this load increases to a large extent, so that the structure starts to yield, the curve between load and displacement no longer remains straight, but bends toward the displacement axis, and the point on the curve which has maximum curvature is usually referred to as the yield point of the structure (Fig 2). This phenomenon is analogous to the behavior of a material, which also shows yielding under increased loads. Similar curves for any material can be obtained from load tests in the laboratory (tensile or compressive load tests). This analogy between the two cases is further extended in the applications as well. While stress-strain curves for a material helps to obtain the ultimate (failure) load of that material and hence the allowable load (ultimate load divided by a certain factor of safety), the pushover curve for a pile helps in obtaining the ultimate elastic load that can be applied to that pile.

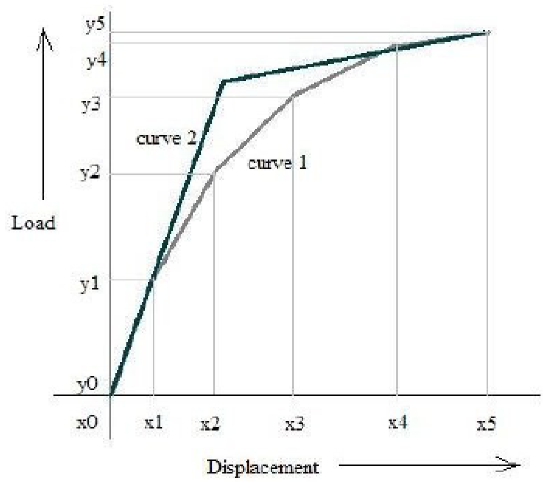


Figure 2 Approximation of pushover curve 2 from load-displacement curve 1

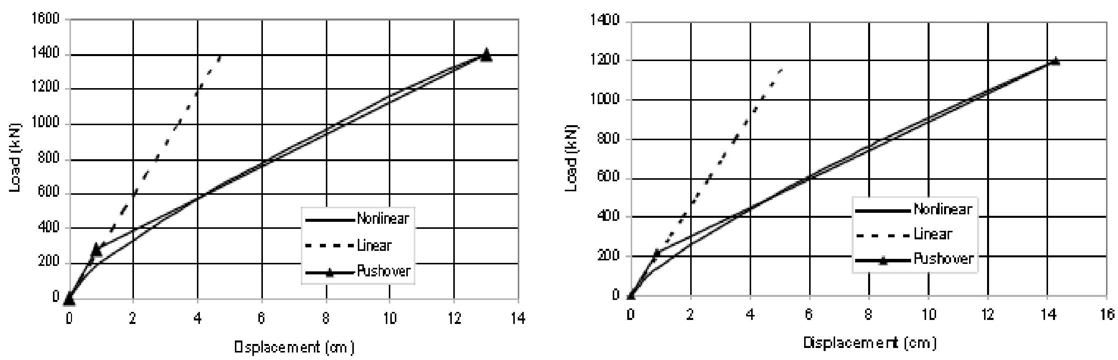
The pushover curve can be used to obtain the plastic stiffness (see Krawinkler & Seneviratna, 2004) of the structure. The curve is initially straight and then bends after a certain load value. If the curve is approximated as a combination of two straight lines (Fig. 2, curve 2), the slope of the second line (plastic portion) will be less than that of the initial (elastic) part, as expected from theory.

The results of a pile embedded in ten different combinations of soil strata have been produced using OpenSEES PL. A 12m soil profile is taken with the pile length up to the bottom of last layer. It is assumed that the pile is fixed at bottom. The main focus was to study the seismic effects of the pile in liquefiable soil, hence the liquefiable layer is used at different positions with respect to the non-liquefiable soil layers. The combinations of soil layers are given below:

1. Single Layer (12m of U-Sand)
2. Double Layer (6m of U-Sand + 6m of Dense Sand)

3. Double Layer (6m of Cohesive Soft soil + 6m of U-Sand)
4. Double Layer (9m of U-Sand + 3m of Cohesive Stiff soil)
5. Triple Layer (3m of Cohesive Soft soil + 6m of U-Sand + 3m of Cohesive Stiff soil)
6. Triple Layer (3m U-Sand + 6m Cohesive Medium soil + 3m U-Sand)
7. Triple Layer (6m of U-Sand + 3m of Cohesive Soft soil + 3m of Cohesive Medium soil)
8. Triple Layer (6m of U-Sand + 3m of Medium Sand + 3m of Dense Sand)
9. Tetra Layer (3m of U-Sand + 3m of Medium Sand + 3m of Dense Sand + 3m of Cohesive Medium soil)
10. Tetra Layer (3m of Cohesive Soft soil + 3m of Cohesive Medium soil + 3m of Cohesive Stiff soil + 3m of U-Sand)

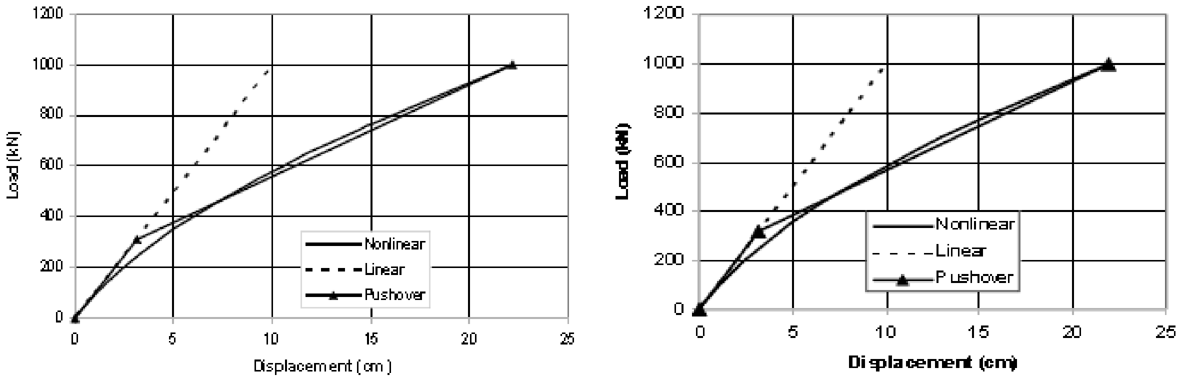
The 'U-Sand' type was taken as the liquefiable layer. Its properties are defined through the user defined soil properties facility in OpenSEES PL. The unit weight of soil is taken as 19 kN/m^3. Maximum shear modulus (G_{max}) is considered as 100 MPa. Friction angle of the soil is taken as 34^0. Other soil properties are taken as per the default definitions provided in OpenSEES PL; i.e. Medium and Dense Sand, and cohesive soils in soft, medium and stiff varieties. The base load applied on the pile head is 10 kN. Load factors in multiples of 10 were taken to step up the load in subsequent iterations for pushover. The limit up to which the pile was pushed was obtained by either lateral deflection of pile equal to 2% of its length or the deflection obtained by dynamic analysis using ground motion records of 1940 El-Centro Earthquake motion (Chopra, 2001), whichever was smaller. The pipe pile was of circular cross section with a diameter of 1m. The pile was 12.1 m long; with 12 m as embedment depth in soil. The extra 0.1 m modeled the gap between the pile head and superstructure. The superstructure was modeled as a point mass of 10 tonnes. The pile was discretized into nonlinear beam elements, having flexural rigidity (EI) of 1.223x10^5 kN-m^2; yield moment of 1200 kNm; shear rigidity of 6.85995x10^6 kN and torsional rigidity of 9.40523x10^4 kN-m^2. An axial rigidity of 17.835x10^6 kN was also provided for completion of material properties.



(a) (b)

Figure 3 Load-displacement curves for (a) single layer U-sand; (b) 6m of U-Sand + 6m of Dense Sand

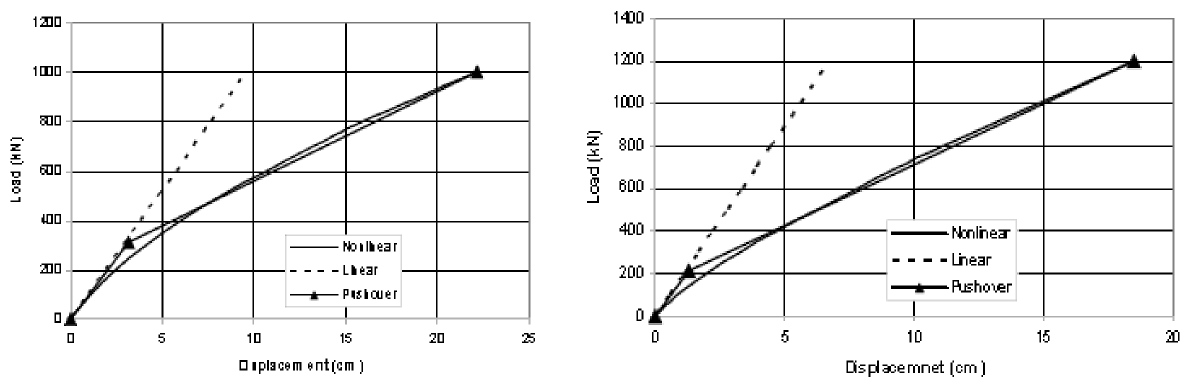
The pile in the single layer is deformed at the pile head to 20.5cm after 200 steps of push, using a base load of 10 kN. The linear analysis yielded a deflection of only 6.8cm at the end of 200 steps. Hence nonlinear analysis produced almost three times the deflection obtained by a linear analysis. However, the curves in Fig. 3a are shown only till a deflection of 13cm only, as the amount of deflection obtained by base shaking using the El Centro ground motion was only 12.2cm. As can be seen from Fig. 3a, the curves were almost same only up to the first two iterations. In case of the double layer with two layers of sand, the deflections were found to be more in pushover analysis but not that much in case of El Centro base shaking (Fig. 3b). While the latter caused only 13cm deflection, the pushover analysis reached a deflection of 14.3cm in just 140 steps. In 200 steps, the deflection reached was as much as 27cm, which was almost 2.5% of the pile length. Here also, the linear analysis caused a deflection about one-third of that obtained by nonlinear analysis.



(a) (b)

Figure 4 Load-displacement curves for double layers: (a) 6m Cohesive Soft soil + 6m of U-Sand; (b) 9m of U-Sand + 3m of Cohesive stiff soil

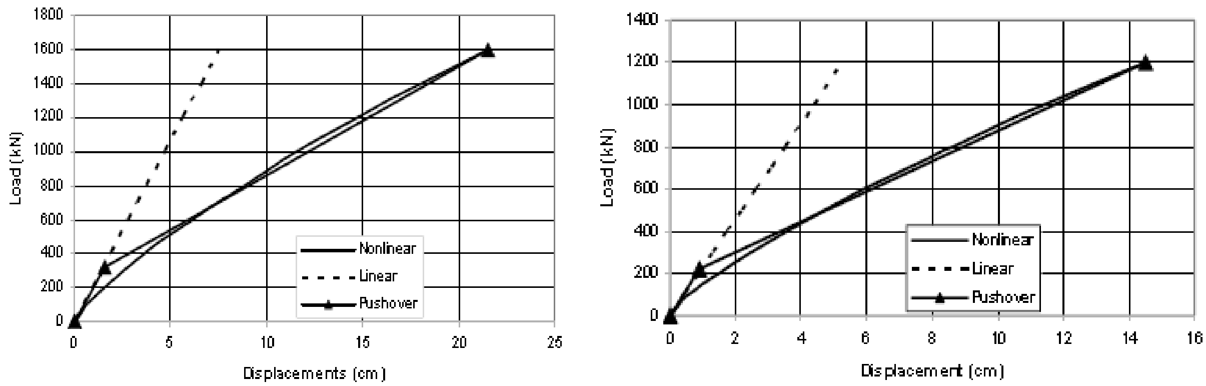
When the U-Sand layer was put below a cohesive soft stratum, the deflections increased. It was seen that the dynamic analysis produced a deflection of 35cm, and the pushover produced 22.2cm in 100 steps. The pile was not pushed further as beyond this it would exceed the deflection limit of 2% of pile length, which was taken initially as benchmark. However, the difference in the deflections by linear and nonlinear cases was less than that in the previous two cases. At 100 steps, linear analysis gave 10.1cm, which is seen to be almost half of the nonlinear results (Fig. 4a). In another case of double strata, where 75% of the profile was taken to be U-Sand resting on cohesive stiff soil, base shaking produced as high as 61cm of pile head lateral displacement. This was the maximum deflection obtained in all cases analyzed in this paper. Pushover analysis was therefore conducted only up to the deflection equal to 2% of pile length, which was reached in 100 steps. The ratio of linear to nonlinear deflections again came out to be about 1:2 (Fig. 4b).



(a) (b)

Figure 5 Load-displacement curves for triple layers: (a) 6m U-Sand between two 3m layers of cohesive soil; (b) 6m of cohesive soil layer between two 3m layers of U-Sand

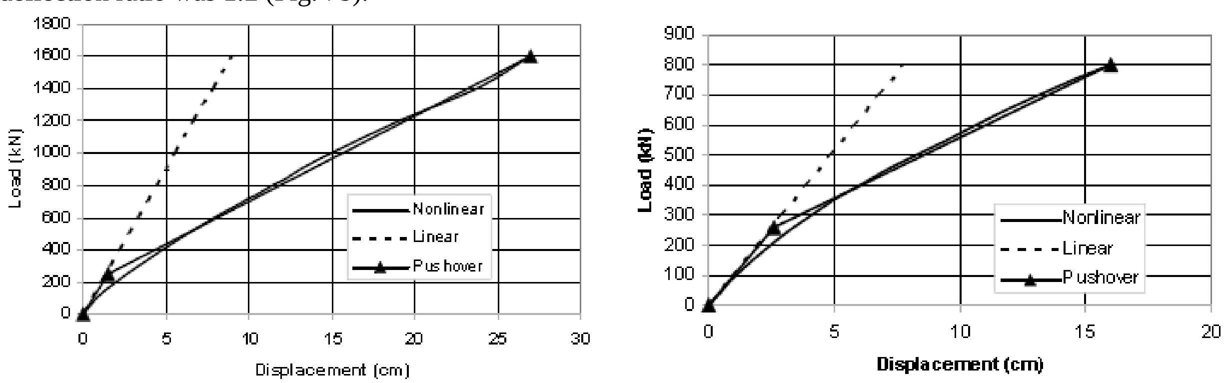
In triple soil strata, first the U-Sand was sandwiched between cohesive layers. The deflections were however almost same as the previous case for pushover, even though the dynamic analysis gave about half of the previous result (only 17.9cm). The structure was pushed by 10 kN up to 100 steps which produced 22.2cm deflection. Linear analysis (Fig. 5a) also gave a final deflection of 9.6cm. In Fig. 5b, the results where U-Sand was enveloped around cohesive medium are produced. The gap between linear and nonlinear curve has widened here, with nonlinear deflections again almost thrice that of the linear analysis. The El Centro base shaking produced 18.5cm deflection only, which was reached in nonlinear pushover analysis at 120 steps itself.



(a) (b)

Figure 6 Load-displacement curves for triple layers: (a) 6m U-Sand over two 3m layers of cohesive soil; (b) 6m of U-Sand over 3m layers of medium and dense sand respectively

The next case of soil profile considered the layer of U-Sand at the top followed by two cohesive layers in increasing densities. The ratio of linear to nonlinear deflections remained at 1:3 (Fig. 6a), but the dynamic analysis results were as high as 57cm! This was almost double than that obtained by pushover analysis after 200 steps. The analysis was restricted to 160 steps only, when the deflection obtained was 21.5cm, which is almost 2% of the pile length. When three different types of sand are taken, the deflections by base shaking are obtained as 14.2cm. This amount of deflection (Fig. 6b) was reached by pushover analysis in about 120 steps. Ratio of linear to nonlinear deflections came out to be 1:3. In four layered strata, base shaking produced final deflection of 28cm. Nonlinear pushover reached this deflection in 160 steps. The ratio of linear to nonlinear deflections was 1:3 (Fig. 7a). In the other combinations of soil layers with 3 cohesive soil layers, the El Centro ground motion produced 16cm of deflection; which was reached by pushover analysis in 80 steps. Here the linear to nonlinear deflection ratio was 1:2 (Fig. 7b).



(a) (b)

Figure 7 Load-displacement curves for (a) 3 sand layers over a cohesive soil layer; (b) 3 cohesive soil layers over U-Sand

4. CONCLUSIONS

Pushover analysis was conducted for a single circular pile in various formations of soil strata with major emphasis on results due to the change in relative position of a liquefiable layer under seismic loading. The extent to which the pushover was to be conducted was determined from the results of base shaking using the time histories of 1940 El-Centro earthquake, subject to a maximum pile head deflection of approximately 2% of pile length, whichever was lower. It was seen that nonlinear analyses produced maximum deflection when there was a combination of sand with clayey layers, rather than in cases where the strata contained cohesionless soil only. Among all the analyses, maximum deflection by El-Centro base shaking was obtained in a case of double strata where the sand constituted top 75% of the profile over a cohesive stratum. Such shaking produced lower results in case of the strata entirely filled with sand layers or a single sand layer. The nonlinear load-deflection curve obtained was approximated into pushover curve to separate the range of elastic behavior from plastic one. It was seen that maximum limit of elasticity was about 32% of the ultimate load to which the pile was pushed laterally. The case of three soil layers with a cohesive layer between two sand layers showed maximum range of plastic behavior; about 82.22% of the load deflection curve showed plastic behavior when approximated as pushover curve. The pushover curve approximation method has a limitation for the fact that the position of yield point actually depends on the extent to which the structure is pushed. Hence if the pile was pushed with more magnitude of lateral load, it would have shown a wider range of elastic behavior. Therefore it requires wise judgment on the part of the analyst to determine the extent to which pushover analysis should be done. It was seen that pushover analysis is the only way to understand the process through which a structure is loaded in steps. For every load, an idea of the deflection that will occur at the control node can be obtained. With greater flexibility of selecting the target displacement, this definitely gives engineers a better understanding of the structure, rather than assuming a factor of safety for computation of allowable load.

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