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Analysis of Pile Foundations for Liquefaction

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Abstract: Poor performance of pile foundations in liquefiable soils after major earthquakes remains a great concern to the earthquake engineering community. The current understanding of the pile failure in liquefiable soils considers either bending or buckling as a probable cause of failure. However, in reality, the two mechanisms interact. Hence, the pile foundations designed with these mechanisms separately might become un- conservative when the mechanisms interact. This paper compares and contrasts the two plausible theories on pile failure in liquefiable soils under seismic conditions. By using STADD Pro V8i software, a detailed analysis of pile behaviour under vertical load and lateral load separately is carried out and then the pile behaviour is analyzed by applying the loads simultaneously. Based on the deflection pattern charts are provided for all the analysed end conditions to arrive the length and diameter of the pile in a simple way, if the force acting at any point on the pile is known. The possible field observed failure mechanisms are analysed and the recommendations on % increase in diameter of the pile to withstand the bending-buckling interaction is provided.

Keywords —Bending, Bucking, Bending-Buckling Interaction, Change in dimension, Pile foundation, Liquefaction.

I. Introduction

A pile foundation is a deep foundation with depth more than the width of the foundation. A pile foundation will overcome problems of soft surface soils by transferring load to stronger, deeper stratum, thereby reducing settlements. Based on the way the resistance is derived, piles are classified as friction piles and end bearing piles. Pile foundations are regarded as a safe alternative for supporting structures in seismic areas and have been used for this purpose in non-liquefying as well as liquefying soils. The overall design problem in either case is complicated. The seismic loading induces large displacement/strains in the soil. The soil behavior becomes non-linear. The shear modulus of soil degrades and damping increases with increasing strain. The stiffness of piles should be determined for these strain effects. The stiffness of the pile group is estimated from that of the single piles by using the group interaction factors.

Pile foundations in liquefiable soil subjected to seismic shaking may fail due to (a) excessive settlement, (b) shear or (c) bending. These mechanisms are well understood and the codes of practice use them to set design guidelines.

Buckling instability has been cited as another possible mechanism of pile failure in liquefiable soils. In most of the cases where the axial load in pile was 50% or more of the buckling loads, the foundation suffered significant damage. These failure also hint that the lateral load during an earthquake combined with high axial load is the probable cause of pile failure which makes us to understand that piles designed for bending and buckling separately may fail due to their combined effect, despite the fact that a large factor of safety (against bending due to lateral loads and axial capacity) is employed in their design. This led to active research in this area. Most of the research carried out by [1] [2] [3] and [4] has investigated the importance of bending-buckling interaction in seismic design of piles in liquefiable soils and observed that piles designed for bending and buckling separately may fail due to their combined effect. Hence this work is focused on the bending- buckling interaction analysis of single piles which could show more realistic behaviour of pile response and could predict the pile failure.

II. Field Observed Failure Mechanisms of Single Piles

Single pile or row of single pile is used to support bridge piers [5]. Single pile carrying large axial load from the super structure and located in loose, liquefiable, saturated sandy layer overlying the bed rock is shown in Fig.1

The earthquake induced cyclic shear stresses generates excess pore pressure which degrades the stiffness of sandy layer. This degradation makes the pile undergo buckling instability, if sufficient length becomes unsupported and fail by formation of a plastic hinge as shown in Fig.1. The failure mechanism of single pile in liquefiable sandy layer with and without crusted layer are shown in Fig.2. Because of the earthquake induced liquefaction there is a buckling instability which makes the sufficient length of pile as unsupported. The slopy ground induces the lateral spreading. The Euler load will be comparatively lesser in the presence

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of lateral driving in the pile [5]. Presence of non-crystal layer over the non-liquefiable layer induces passive earth pressure on the pile, the P-Delta effects may be excessive and the lateral load causes the formation of plastic hinge as shown in Fig.2. Though the failed shape of piles in the above cause. (i.e) a & b are similar at certain specific circumstances, the pile case (b) may fail by flexural bending rather than buckling. Even gentle sloping ground of 2° or 3° to the horizontal can suffer lateral spreading [5].

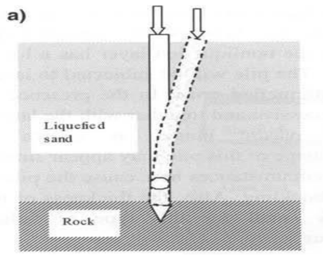


Fig.1 Buckling instability failure in level ground (After Madabhushi, 2010)

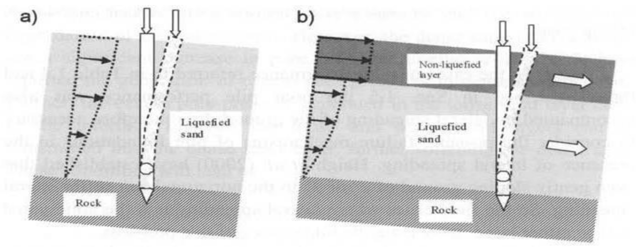
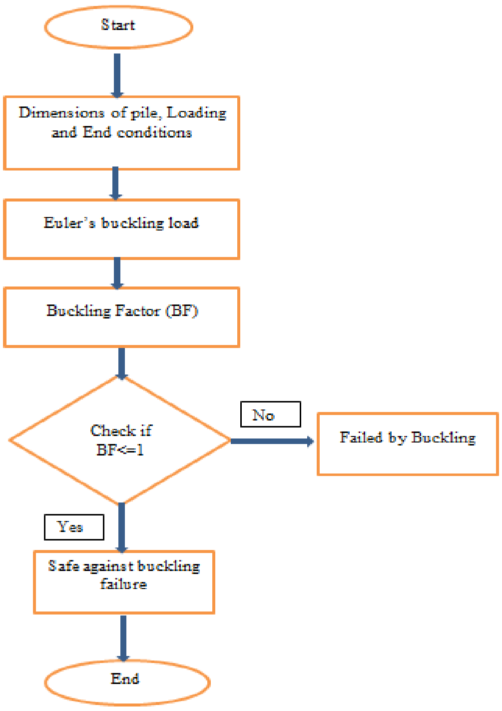


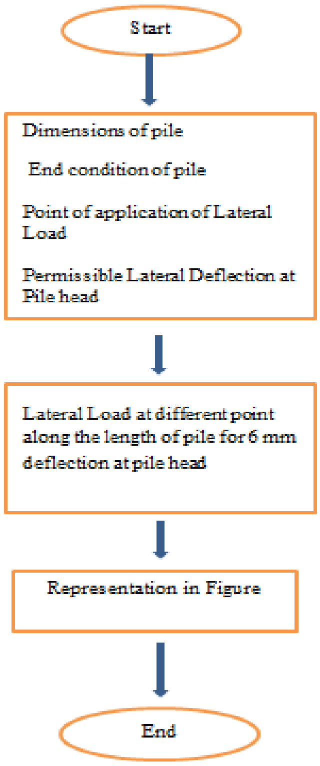
Fig.2 Failure of piles under lateral and axial loading in laterally spreading soil. (After Madabhushi, 2010)

The main objective of the present study is to determine the diameter of pile for three different combination of axial and lateral load for the permissible deflection of 6 mm, also to validate the results of present analysis with different case studies. The following flowcharts elaborate the methodology of analysis carried out in this paper.

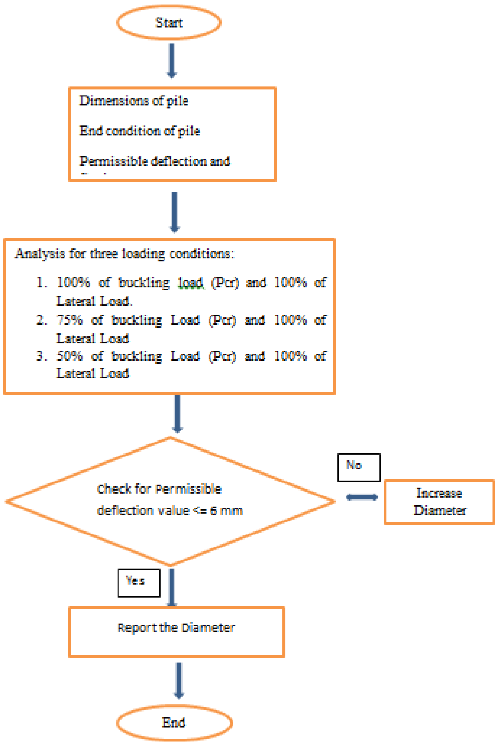
1. Axial Load Analysis



2. Lateral Load Analysis



3. Simultaneous analysis of Axial and Lateral loading.



III. AXIAL LOAD ANALYSIS

Under this analysis the pile is subjected to axial load alone and the buckling failure is analysed. During liquefaction the pile will act as an unsupported column and hence **Euler's buckling load equation** for long columns is used to calculate the buckling load of the piles. A pile of length 20 m and 0.6 m diameter is taken and its buckling load is calculated from the Euler's equation as 857.74 kN for fixed

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pile end and free pile head condition. The axial load analysis for the buckling load is analysed by STAAD Pro V8i, as shown in Fig.3.

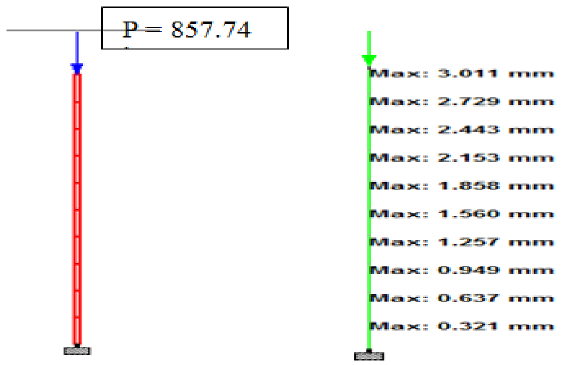

Fig.3 Axial loading and corresponding vertical compression

A. Buckling Factor

The buckling factor is defined as the ratio of buckling load to the applied load. In buckling analysis, as shown above, till the buckling load, there will not be any failure or buckling mode shape. If the given load exceeds the buckling load of the column then the software will display the buckling mode shape diagram and the buckling factor from which the corresponding buckling load of the column can be calculated. In this analysis a load of 1000 kN is applied to the above shown column of buckling load 857.74 kN, which gives a buckling factor of 0.858 and is shown in Fig. 4.

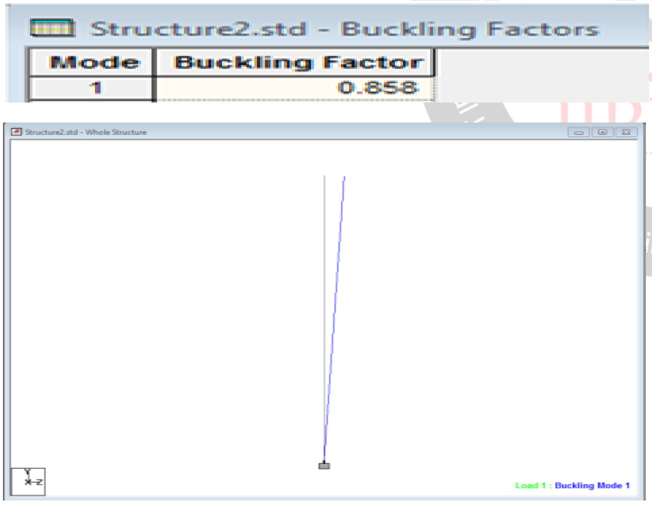

Fig.4 Buckling of column and its corresponding Buckling factor

IV. Lateral Load Analysis

The lateral permissible deflection is limited to 6 mm (1/4 inch) and the lateral load in the form of point load corresponding to the limited deflection for pile length of 10 m with diameter of 0.6 m of pile is analysed and arrived by trial and error. For instance, the lateral load at the pile head is loaded and the deflection is limited to 6 mm for 0.6 m diameter of 10 m pile as shown Fig. 5.

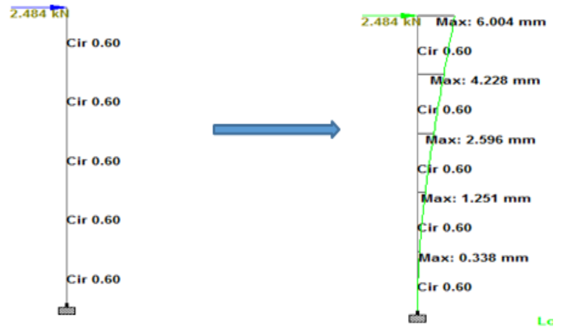

Fig. 5 Lateral load analysis for one end fixed and other end free, 0.6 m diameter pile

Analysis were also done for different pile length and lateral load for different point of application along the length of pile for 6 mm permissible deflection are obtained and are listed in Table.1. From Table.1, it is observed that increase in pile length decreases the permissible lateral load and the lateral load decreases as the length of the pile from the fixed end increases.

Table 1 Lateral load corresponding to 6 mm deflection for 0.6 m diameter pile

Pile Length (m)	Distance from fixed end (m)	Lateral load for 6 mm deflection (kN)	Pile length (m)	Distance from fixed end (m)	Lateral load for 6 mm deflection (kN)
10	10	2.484	30	30	0.09
	7.5	3.92		20	0.17
	5	7.94		10	0.62
	2	44.361		2	14.1
20	20	0.31	40	40	0.03
	15	0.49		30	0.06
	10	0.99		15	0.21
	3	9.68		3	4.71

V. Simultaneous Analysis of Axial Load and Lateral Load

The simultaneous analysis of axial load and lateral load is done based on three following combinations as, 100% of Crippling load (P_{cr}) and 100% of lateral load, 75% of Crippling load (P_{cr}) and 100% of lateral load, 50% of Crippling load (P_{cr}) and 100% of lateral load. It is observed that when the loads are given separately the deflection is within the limit but under their combination the deflection is beyond the permissible limit as P-delta effect comes into play, which can lead to pile failure by bending-buckling interaction. To overcome this, the diameter of the pile is increased as per the combination as follows to meet the required deflection.

For example, a pile of length 10 m and 0.6 m diameter is analysed by using P-delta analysis under the combination of loads and is shown in Figs. 6-8.

Under this combination of 100% of Crippling load (P_{cr}) and 100% of lateral load, the deflection is about 36 mm which can lead to failure. So the diameter of pile is increased from

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0.6 m to 0.74 m (by trial and error method) to meet the required permissible deflection.

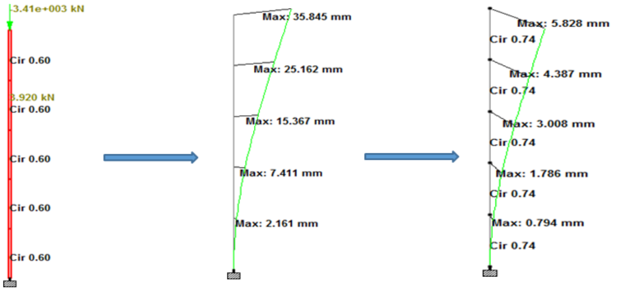

Fig.6 Deflection pattern and increase in diameter for 100% of Crippling load and 100% of lateral load

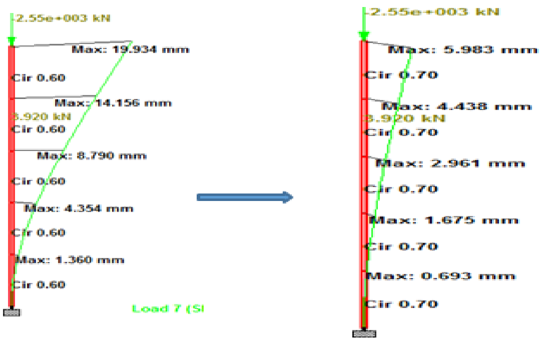

Fig.7 Increase in diameter for 75% of crippling and 100% of lateral load combination

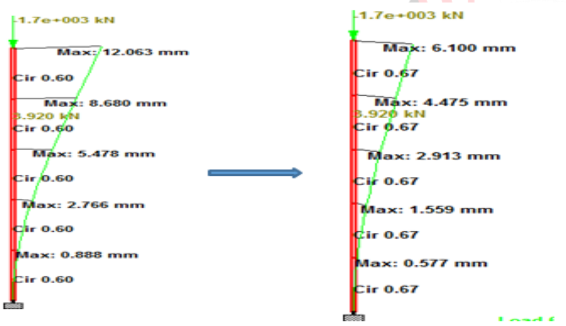

Fig. 8 Increase in diameter for 50% of crippling and 100% of lateral load combination

Under the combination of 75% of crippling load and 100% of lateral load, diameter is increased from 0.6 m to 0.705 m and for the combination of 50% of Crippling load and 100% of lateral load, diameter is increased from 0.6 m to 0.67 m respectively to meet the required permissible deflection.

VI. Results And Discussions

The results of the above discussed lateral load analysis is provided in the form of design charts by plotting the lateral load against distance from the fixed end. If the lateral load acting on the pile is known, then the length and diameter of the pile to be adapted to withstand the respective load with the permissible deflection can be calculated easily as shown below. The design charts for one end fixed and other end free end condition is shown in Figs. 9-12.

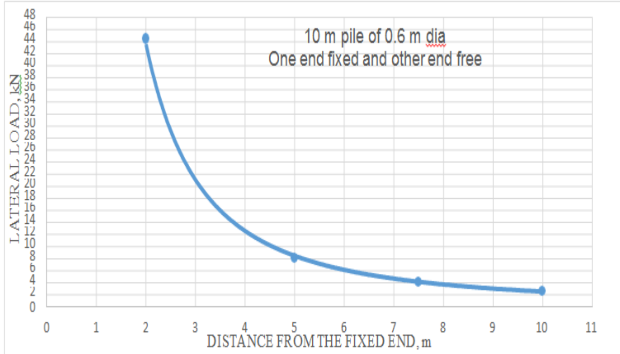

Fig. 9 Lateral load capacity of 10 m pile of 0.6 m diameter with one end fixed and other end free

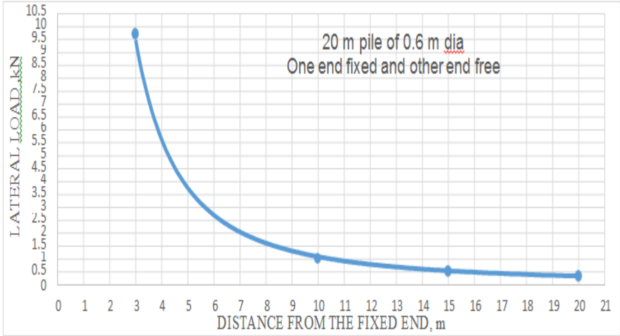

Fig.10 Lateral load capacity of 20 m pile of 0.6 m diameter with one end fixed and other end free

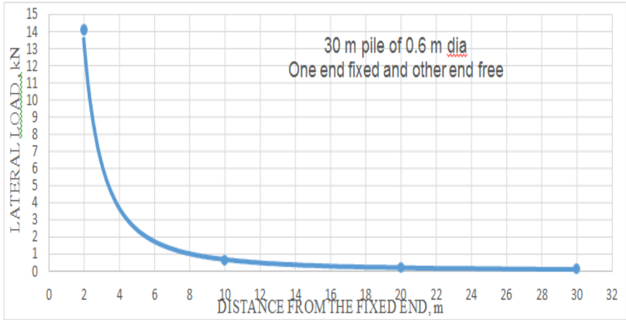

Fig.11 Lateral load capacity of 30 m pile of 0.6 m diameter with one end fixed and other end free

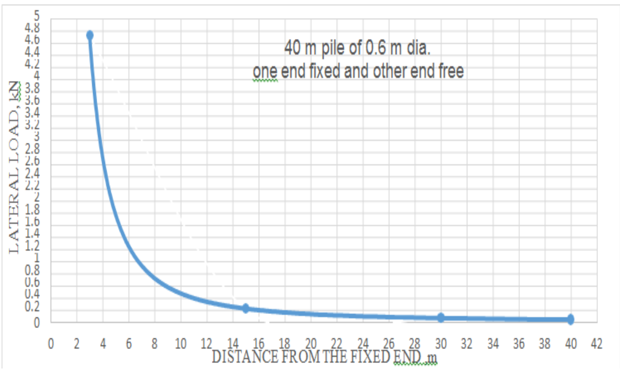

Fig. 12 Lateral load capacity of 40 m pile of 0.6 m diameter with one end fixed and other end free

Similarly, the design chart for other end conditions can be represented by using the same procedure and from which the pile of any length and diameter can be checked for its capacity to with stand the lateral load.

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The above charts are made by plotting the values and joining them by using trend line of power option and from these charts the pile length and diameter can be calculated approximately, if the lateral load acting at any point on the pile is known. An example to select the length and diameter of the pile from the known lateral load is shown below, For example, it is known that a force of 4 kN acts at 5 m from the top, then the length and diameter of the pile can be calculated by interpolating from the graphs.

Take the loads corresponding to the given distance (5 m from the top) from the graphs of different pile length (10m, 20m, 30m, and 40m) and diameter and plot it in the form of graph as shown below in Fig. 13. And interpret the length and diameter corresponding to the given force (4 kN).

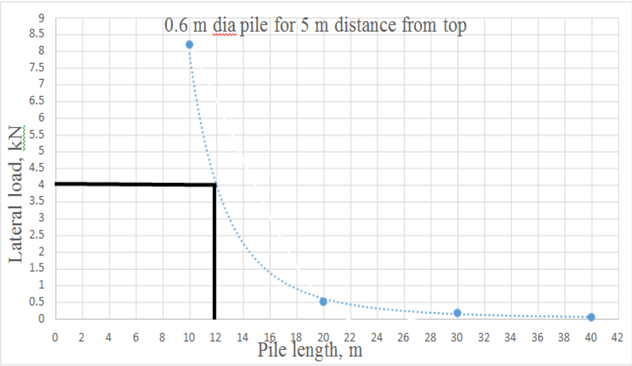

Fig. 13 Chart to find the length of 0.6 m diameter pile for 5 m distance from top

From the interpretation, it is calculated that for 4 kN of force acting at 5 m from top of the pile, pile of **length 12 m and 0.6 m diameter** is safe to withstand the given force. It is observed that the pile design is safe for axial and lateral load separately, but when simultaneous case comes into play it is observed that the pile is not safe due to bending-buckling interaction. To overcome this issue, diameter of the pile should be increased. As per the analysis done in section V, pile diameter is increased in the form of percentage as shown in Table 2.

Table 2 Change in diameter for combination of loads

LOAD CASES	CHANGE IN DIAMETER (%)
100% of P_{cr} and 100% of lateral load	23% increase
75% of P_{cr} and 100% of lateral load	17.5% increase
50% of P_{cr} and 100% of lateral load	12% increase

The above tabulation gives the percentage increase in the diameter of pile to meet the required stability to which it can be designed to allow the permissible deflection.

The given % increase in diameter of pile is based on the trial and error values on a 10 m length and 0.6 m diameter pile. To know the suitability of these % values to other pile lengths and diameters a pile of 20 m length and 0.8 m diameter is chosen whose buckling load is 2694.15 kN and lateral load capacity at the head is 0.980 kN. This pile is analysed under the combination of 100% buckling load and 100% lateral load by directly increasing the diameter by 23% which is of 0.98 m from 0.8 m as shown below on Fig. 14.

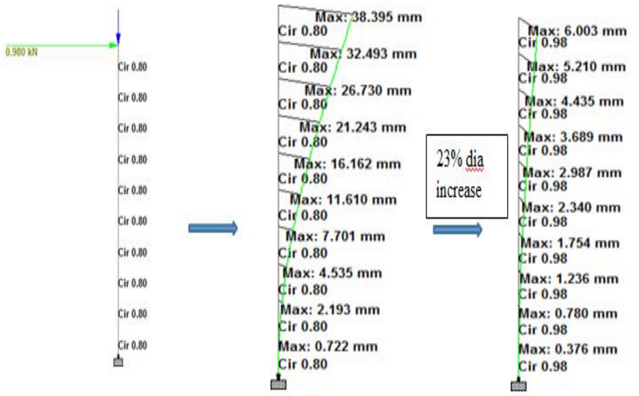

Fig.14 Check for percentage increase in diameter

From the above check, it is clear that the percentage increase is independent of length and diameter of the pile. It depends only on the end condition. For the other end conditions, which does not allow vertical compression on pile head, vertical and lateral load analysis is sufficient.

VII. Analysis And Comparison Of Field Observed Failure Mechanisms

Three types of failure mechanisms are observed as shown in section II and it can be analysed in STAAD.ProV8i as follows. The first observed mechanism is the buckling instability which is well analysed and discussed on section III of this paper. Other failure mechanism is due to the combination of lateral load in the form of UVL due to lateral spreading and axial load as in Fig. 2.a. For instance, pile of 10 m length and 0.6 m diameter is chosen for analysis and to know the UVL limit up to which the pile can withstand without any damage, UVL acting on 10 m length is converted to point load which acts at 6.67 m from the fixed end. From the charts provided above it is calculated that a point load of 4.5 kN acting at 6.67 m from fixed end, can be safe with a permissible deflection of 6 mm. In reverse this 4.5 kN is converted to an UVL of 0.9 kN/m for 10 m length which is the limiting UVL load for the chosen pile and is combined with the axial load and analysed as shown below on Fig.15.

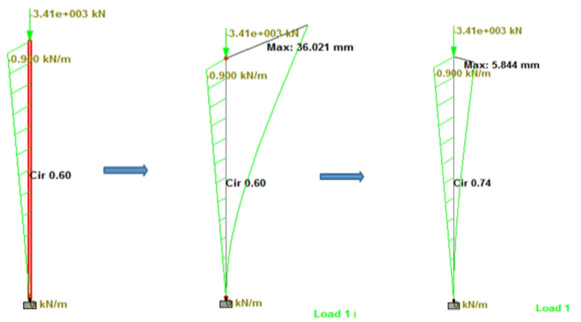

Fig. 15 Combination of UVL and axial load with change in diameter

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From the analysis limiting loads for the chosen pile is found and under the combination of 100% lateral and 100% axial load, 23% increase in diameter as per the results of table 2 holds good from which it is inferred that the results are independent of type of load too. For one end fixed and other end free end condition, increase in diameter can be done as per Table 2 based on their combination of loads.

Other failure mechanism is due to the combination of UDL, UVL and axial load as shown in Fig. 2.b. For instance, pile of 10 m length and 0.6 m diameter is chosen for analysis and their limiting loads are found similarly or by trial and error. It is assumed that the top 3 m is non-liquefiable which exerts UDL and the remaining 7 m is liquefiable which exerts UVL and their limiting loads corresponding to the deflection within the permissible limit is as shown in Fig. 16.

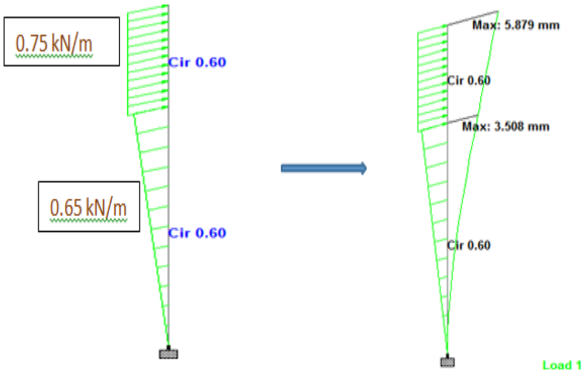

Fig.16 Combination of UVL and UDL and its deflection

Thus the possible failure mechanisms are analysed and the method to find the limiting loads are given and is important to make sure that the limiting loads depends on the dimension of the pile.

VIII. Analysis And Solution For A Case Study

In the failure of a 3-storied building at Fukae during the 1995 Kobe earthquake, extensive soil liquefaction as well as lateral spreading was observed at the building site. After the earthquake it is estimated that a pile of 0.4 m diameter and 16 m long with end condition of one end fixed and one end free is subjected to an axial load of 263 kN and an lateral load in the form of UVL of magnitude 0.5 kN/m, which makes it to **fail by a pile head displacement of 800 mm**. as mentioned in [8].

But from the analysis and by using the proposed design charts it is calculated that a pile of **diameter 0.85 m of same length** would have been safe for the same magnitudes of loading and is as shown in Fig. 17.

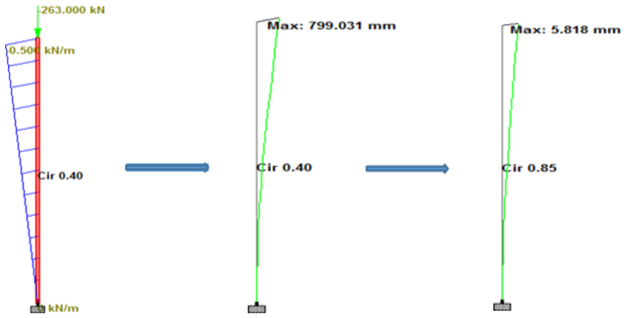

Fig.17. Solution for case study

IX. Conclusion

Based on Axial load analysis, Lateral load analysis and Simultaneous axial and lateral load analysis, the following conclusions were arrived for one end fixed and other free end conditions are discussed below:

1. The buckling factor for different pile length is calculated.
2. Increase in pile length decreases the permissible lateral load and the lateral load decreases as the length of pile from the fixed end increases.
3. Due to P-Delta effect for different combination of loading, the increase in pile diameter for permissible 6 mm diameter is obtained.
4. The solutions obtained for point load were validated with a combination of UVL and UDL load of a case study.
5. The case study of 1995 Kobe earthquake is analysed using the proposed method confirms that the pile failure may not have occurred if the pile diameter is increased.

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