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BEHAVIOUR OF PILE SUPPORTED WHARF IN LIQUEFIED SOILS

*Mohamed Faizur Rahaman Khazi and Mahammood Vazeer

Dept. of Civil Engineering, Andhra University, India

*Corresponding Author, Received: 17 March 2017, Revised: 15 April 2017, Accepted: 23 May 2017

ABSTRACT: A parametric study is carried out to study the performance of pile supported wharf structure under liquefying and lateral spreading soil conditions using nonlinear static pushover analysis. Displacement-based approach is adopted to study the soil pile interaction. Piles are modelled as beam elements and the parts of the piles embedded in soil are modelled as beams on Winkler foundation. The structure is modelled and analyzed using SAP2000. Pile yielding and hinge formation patterns in the piles during soil liquefaction and lateral spreading states are observed and compared with field observations. It is observed that when soil liquefied the base shear resistance dropped drastically and hence effected the performance of structure. Piles yielded at the interface of liquefied and non-liquefied layers when soil liquefied. It is also observed that the structure performed poorly when liquefied depth factor and slenderness ratio are increased. The method of analysis is simple and gives results confirming to the field observations and hence is an easy tool for assessment of existing port structures and preventing future disasters.

Keywords: Pushover analysis, Liquefaction, Lateral spreading, Pile supported wharf, Performance point

1. INTRODUCTION

Several methods of analysis of piles in liquefying soils are available in literature. However these methods are similar in concept but differ in modelling details and analysis procedures. All the methods of analysis are burdened with lot of uncertainties arising as a result of highly complex dynamic soil-structure interaction (SSI) problem involving liquefying and lateral spreading soils. In recent years, for the seismic analysis of buildings and bridges, nonlinear static procedures (NSP) are being adopted by different codes and standards around the world on account of their simplicity and relative accuracy.

However the works on the seismic analysis of pile supported wharf structures are limited. The response of pile supported wharf under seismic loading conditions was studied by different researchers and the modes of failure of structure depending on the seismic response of surrounding soil were identified as shown in Fig.1. The third type of failure, due to the deformation (liquefaction) of loose subsoil, has been identified in Loma Prieta and Kobe earthquakes [1].

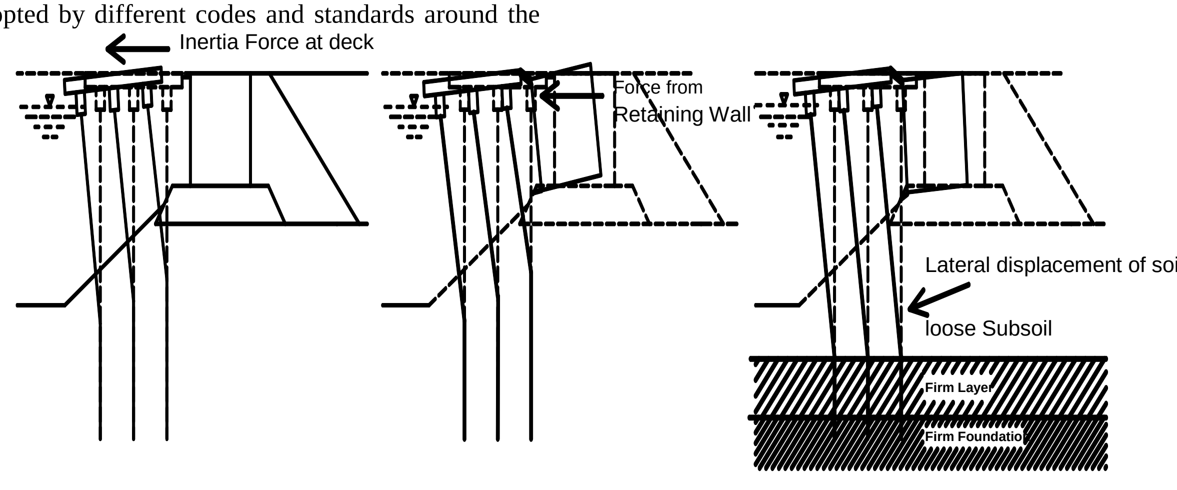


Fig.1. Failure modes of pile supported wharf due to seismic response of surrounding soil, redrawn from [1].

The Japan Road Association (JRA) method [2], which is specifically for highway bridges, adopts a forced-based approach where piles are considered very stiff and strong due to their large diameters, and hence generally resist the ground movement and show stiff pile behaviour. As per the code the piles are designed against bending failure such that the non-liquefied crust offers passive earth pressure to the pile and the underlying liquefied soil layer offers thirty percent of the total overburden pressure. Effects of liquefaction are accounted for by multiplying stiffness, ultimate soil reaction and skin friction capacity by a degradation coefficients. USA code BSSC 2000 and Eurocode 8 also consider the bending strength of the pile for the design [3]-[4].

The Architecture Institute of Japan (AIJ) method [5], which specifically addresses piles for building foundations, adopts the displacement-based approach using bi-linear soil springs models for soil and tri-linear moment-curvature relationships for the pile. To simulate the effects of transient ground displacements free field ground displacements are applied at the end of the soil springs.

Cubrinovski et al., [6] used beam-spring model for pseudo-static analysis of piles in liquefying soils. Murashev A, et al., [7] conclude that the Cubrinovski et al., [6] method focuses on a simplified, but sufficiently accurate, modelling of the soil-pile-bridge system where uncertainties in the applied loads and characteristics of liquefying soils are addressed through modelling considerations and parametric studies.

In the force-based method the lateral force on pile body is assessed either by directly using empirical relations or by means of viscous flow concept. It would be difficult to introduce a parameter which is indicative of amount of ground displacement for both the relations. Whereas in the case of displacement based method amount of ground displacement can be assigned to the spring system. Therefore displacement based method is used for the seismic analysis of pile supported wharf in this work. However the displacement based analysis is a rigorous numerical approach [8] and hence finite element based software is used in this work.

2. MODELLING AND ANALYSIS

The numerical modelling of soil pile interaction has been based on Winkler foundation models, where SSI is incorporated by p-y curves [9] or by modified p-y curves [10]. In this paper for the analysis of pile supported wharf soil spring models are used for SSI and piles are modelled as beam elements and the embedded parts of the piles as beams on Winkler foundation. Pushover Analysis is adopted for the analysis and finite element based software SAP2000 [11] is used.

2.1. Soil Spring Stiffness

For a non-liquefied layer, the soil spring stiffness (K) for a pile of diameter D_0 (in cm) and spring spacing s (in m) is calculated as;

$$K = k_{nh}\ s\ D_0/100 \tag{1}$$

where, k_{nh} = modulus of subgrade reaction as proposed by Architecture Institute of Japan [5] and Japan Road Association [2].

$$k_{nh} = 80\ E_0\ (D_0)^{-3/4} \tag{2}$$

$$E_0 = 0.7\ N \tag{3}$$

in which E_0 is the modulus of deformation in MN/m^2, N is the SPT value, and D_0 is the pile diameter in centimetre.

When soil liquefies its stiffness degrades. The soil stiffness degradation factor S_f was found in case studies conducted by different researchers [12]-[13] and was found to vary between 0.1 and 0.02 for liquefying soils and between 0.02 and 0.001 for laterally spreading soils.

2.2. Pile Modelling

The pile is modelled as a string of beam elements along its length. These elements are connected with soil springs at their nodal points. The load-deformation characteristic of each beam element is defined by a moment-curvature (M-φ) relationship. This relationship may change along the pile length in accordance with changes in pile properties. FEMA 356 [14] provides a generalized load-deformation relation model for the nonlinear static analysis procedure, which is the default model in SAP2000 for the Axial-Moment hinge. The Post-yield behaviour is described in SAP2000 by general backbone relationship with additional limit states such as immediate occupancy(IO), life safety (LS) and collapse prevention (CP). To study this behaviour concentrated plastic hinges are assigned to the beam elements at discrete locations as hinges cannot be assigned all along the pile length in SAP2000 and hence the deformation beyond the elastic limit occurs entirely within hinges. However elastic behaviour occurs over the entire length of the member.

2.3. Pushover Analysis

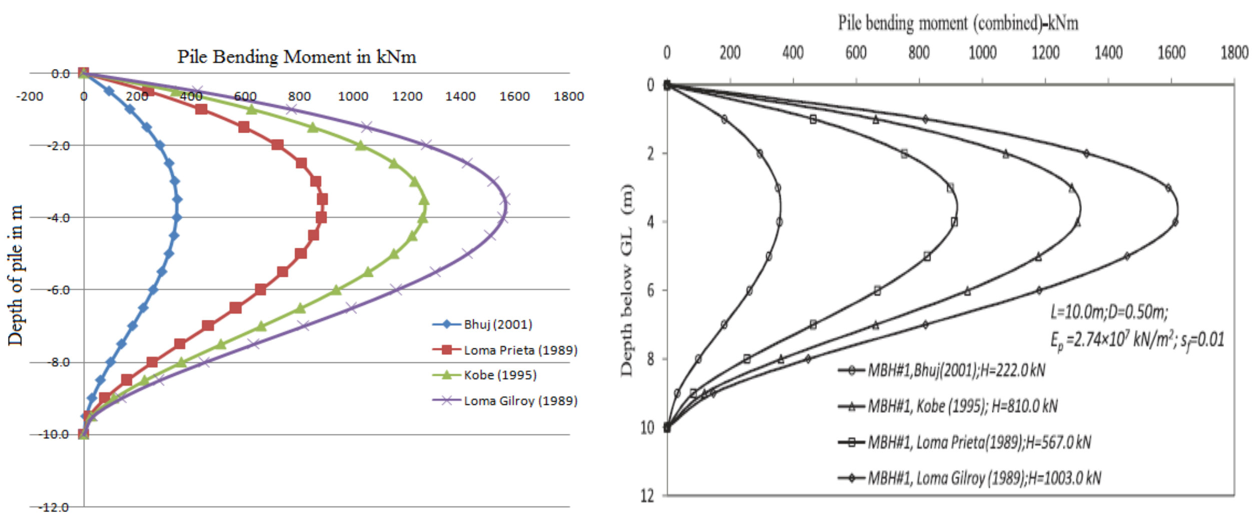
Pushover analysis involves step-by-step development of the capacity curve of pile-deck system. The capacity curve can be obtained by plotting the lateral force applied to the deck versus the lateral displacement of the deck at various increments of loading. The displacement demand on the pile-deck system is obtained using nonlinear demand spectra and then the performance point is identified. To determine the performance point, the capacity and displacement demand curves should be plotted in the Acceleration-Displacement Response Spectra (ADRS) domain in which spectral acceleration is drawn against spectral displacement.

The nonlinear displacement demand spectra is derived from the elastic 5% damped response design spectrum after applying spectral reduction factors [15]. Thus the determination of performance point is a trial and error procedure and hence is an approximation. Therefore the authors in this research work used all the four methods (Capacity Spectrum Method, Coefficient Method, Equivalent Linearization Method and Displacement Modification Method) of ATC 40, FEMA 356 and FEMA 440 [16] in the analysis while finding the performance point of the structure so as to take into account the approximate nature of these performance based seismic design (PBSD) procedures.

3. VALIDATION

The method is verified and validated with the available examples from literature. The analysis of free head and floating tip type pile subjected to different Peak Ground Accelerations (PGA) in liquefied soil (S_f = 0.01) by V.S. Phanikant, et al. [17] is considered for verification and validation of pile response under liquefying conditions. They used finite difference program for the analysis of soil pile interaction and solution was obtained using MATLAB program. Their results are compared for validation. The comparison of bending moments and deflections at different levels along the pile length are shown in Fig.2 and Fig.3 respectively. The comparison of peak deflections and maximum bending moments are given in Table 1. From Table 1 it can be observed that the percentage variation is around 14% in case of peak deflections and 3% in case of maximum bending moments. This variation may be attributed to the method of analysis and its accuracy. As finite element based analysis is more accurate compared to finite difference analysis better results are expected. However the overall solution obtained in this analysis is in agreement with their solution and hence validated.

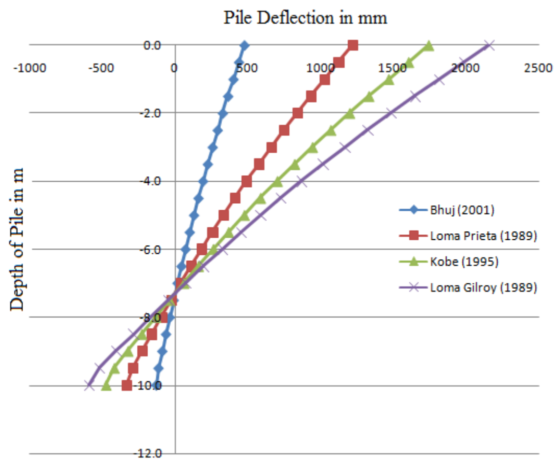
In another study the authors conducted pushover analysis on the RC pile 2 of Family Court House (FCH) building affected due to liquefaction and lateral spreading during Niigata earthquake (1964). The hinge formation results were compared with the original findings of Yoshida N and Hamada M [18] as shown in Fig.4. It was found that the hinge formation pattern in the analysis was almost in agreement with field observations [19].



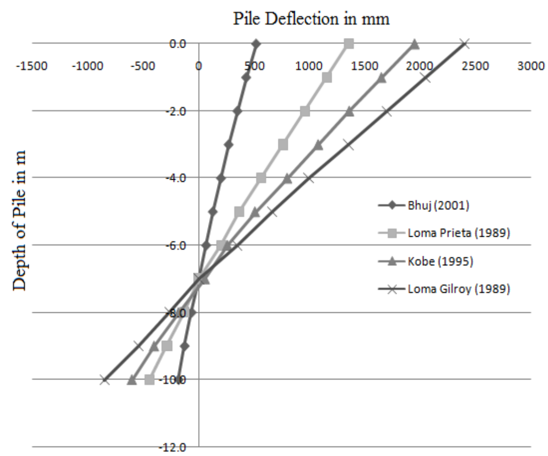
(a) Present Study

(b) V.S. Phanikant, et al. [17] work

Fig.2. Bending moment diagrams for free head and floating type pile subjected to different PGAs in liquefied soils (Sf = 0.01) for validation of pile response with V.S. Phanikant, et al. [17] work.



(a) Present Study

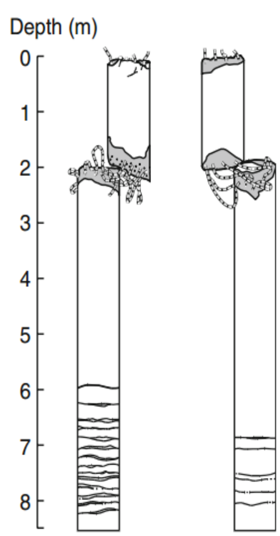


(b) V.S. Phanikant, et al. [17] work

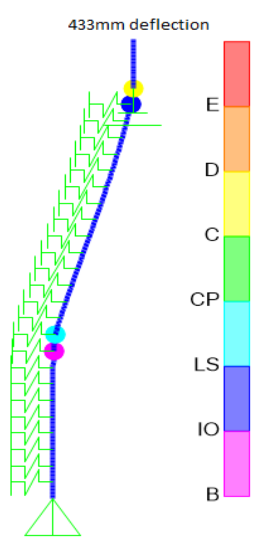
Fig.3. Deflection diagrams for free head and floating type pile subjected to different PGAs in liquefied soils (Sf = 0.01) for validation of pile response with V.S. Phanikant, et al. [17] work.

Table 1. Comparison of peak deflection and maximum bending moment in liquefying soil (S_f = 0.01)

Ground Motion	Deflection at top (mm)			Peak bending moment (kNm)		
	Present Study	V.S. Phanikant, et al. [17]	Percentage Variation (%)	Present Study	V.S. Phanikant, et al. [17]	Percentage Variation (%)
Bhuj (2001)	478	542	12	542	356	3
Loma Prieta (1989)	1220	1426	14	1426	911	9
Kobe (1995)	1744	2117	18	2117	1301	3
Loma Gilroy (1989)	2159	2513	14	2513	1611	3



(a) Damaged piles [18]



(b) Hinge formation pattern in piles [19]

Fig.4. Comparison of hinge formation in Pile 2 of Niigata FCH Building.

4. RESULTS AND DISCUSSIONS

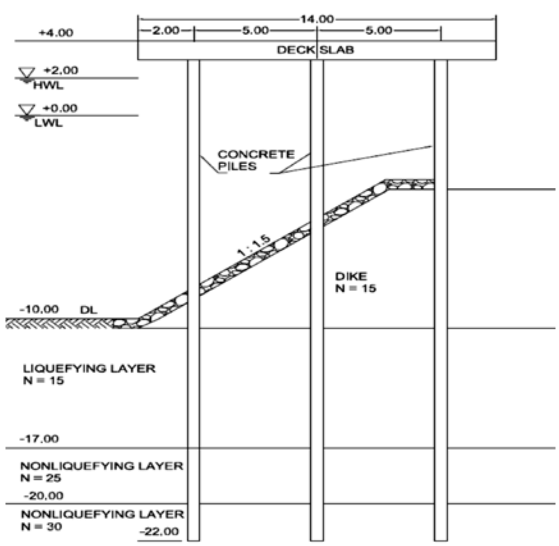
For the parametric study a typical pile supported wharf is considered as shown in Fig.5. The wharf is modelled and analysed using software SAP2000. One meter wide and two meters deep reinforced concrete deck slab is considered in the analysis. Reinforced concrete piles of varying diameters are considered in the study with different L/D ratios and pile flexibility factors. L/D ratios from 26 to 52 and pile flexibility factors from 15e-4 to 3e-4 are considered. The strength properties used in the study for concrete are; E = 25GPa, poison's ratio 0.2 and f_c = 30MPa. The strength properties used for steel are; f_y = 415MPa and f_{ys} = 415MPa. The load combinations used include dead load, live load on deck 200 kN/m^2 and response spectrum load as per IS 1893 [20]. In the analysis only vertical forces are considered and mooring and birthing forces are not considered.

The study is carried out to find the influence of various parameters on performance point (PP) of the wharf structure and hinge forming patterns in piles. The results of all the four NSP procedures of ATC40, FEMA 356 and FEMA 440 are considered in this study. The analysis is carried out with different values of stiffness degradation factor (S_f) to take into consideration the effect of liquefaction and lateral spreading. It is observed that when the soil liquefied base shear resistance decreased (Fig.6(a)) and hence performance point of the structure fell as shown in Fig.6(b). The reduction in base shear resistance is 40% when S_f = 0.01 and 50% when S_f = 0.001.

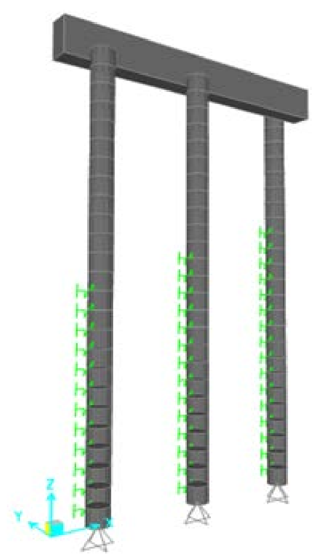
The influence of liquefied depth factor (LDF), which is the ratio of depth of liquefied layer to the total length of pile, is also studied in the analysis and it is observed that base shear at performance point reduced when LDF increased as shown in Fig.6(c). When liquefied depth is increased by 25% of the total length of pile the reduction in base shear resistance is 12%, 25% and 35% respectively for S_f values equal to 0.1, 0.01 and 0.001.

The performance of wharf structure with different slenderness ratios (SR) is also studied and it is observed that the base shear reduced as SR increased as shown in Fig.6(d). A 70% reduction in base shear at performance point is observed as SR increased from 26 to 52.

Pushover analysis gives in detail the sequence of yielding and the hinge formation pattern. It has been observed that the hinge formation pattern changes as the soil stiffness softens and this change continues with decrease in soil stiffness and liquefaction. Fig.7 shows the hinge formation pattern as the soil liquefies. It can be seen that the yield generally starts from the pile heads most landward and moves to those at seaward and then down to the embedded portion of the piles. It is also observed that the piles yielded at deeper levels in the embedded portion when the soil stiffness degraded and the yield was seen at the interface of liquefied and non-liquefied layers during lateral spreading phase (Fig.8). Same results are obtained when lateral spreading is modelled by earth pressure as well as by stiffness degradation factors as shown in Fig.8.

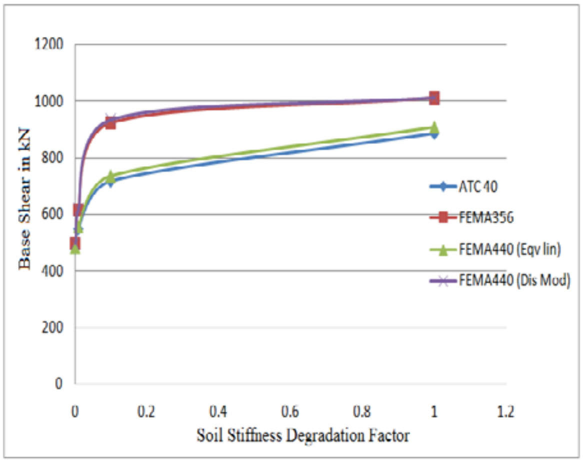


(a) Typical pile supported wharf

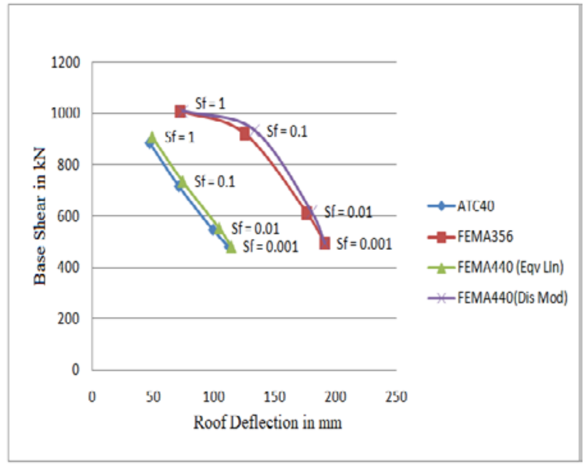


(b) Model of pile supported Wharf

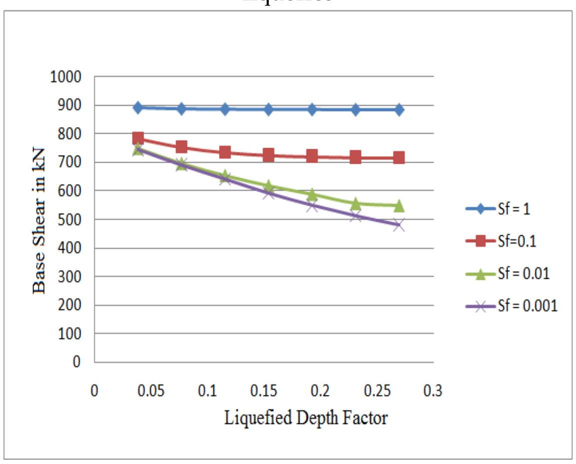
Fig.5. Typical pile supported wharf for parametric study and its model



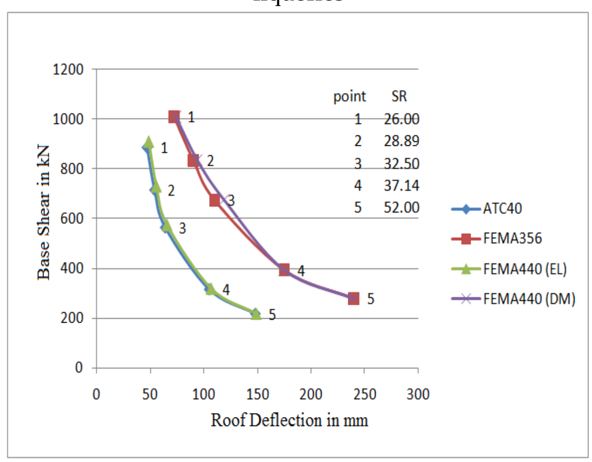
(a) Base shear variation at performance point as soil liquefies



(b) Variation of performance point of the wharf as soil liquefies

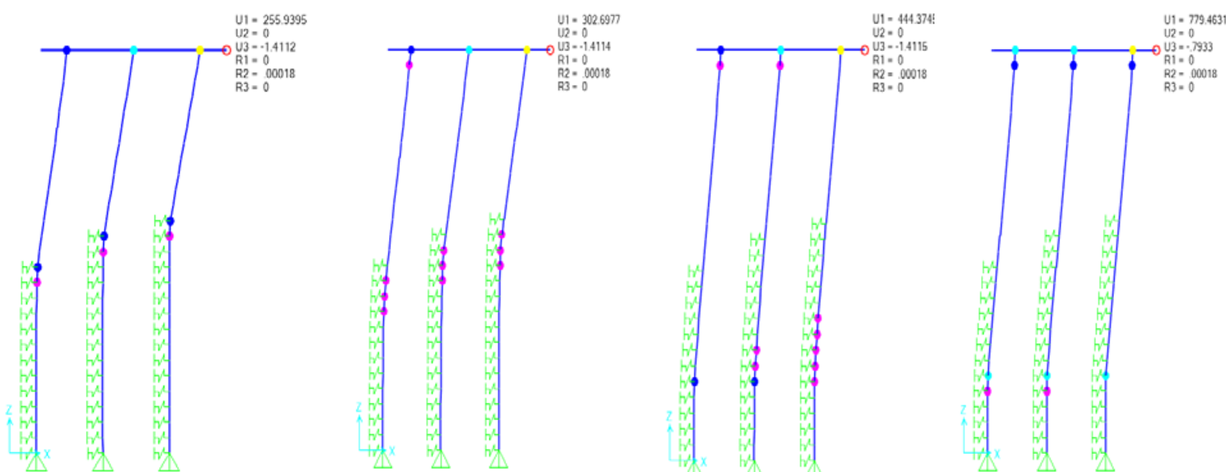


(c) Effect of liquefied depth factor (LDF) on base shear



(d) Effect of slenderness ratio on performance point

Fig.6. Post-yield performance of pile in liquefying soils.



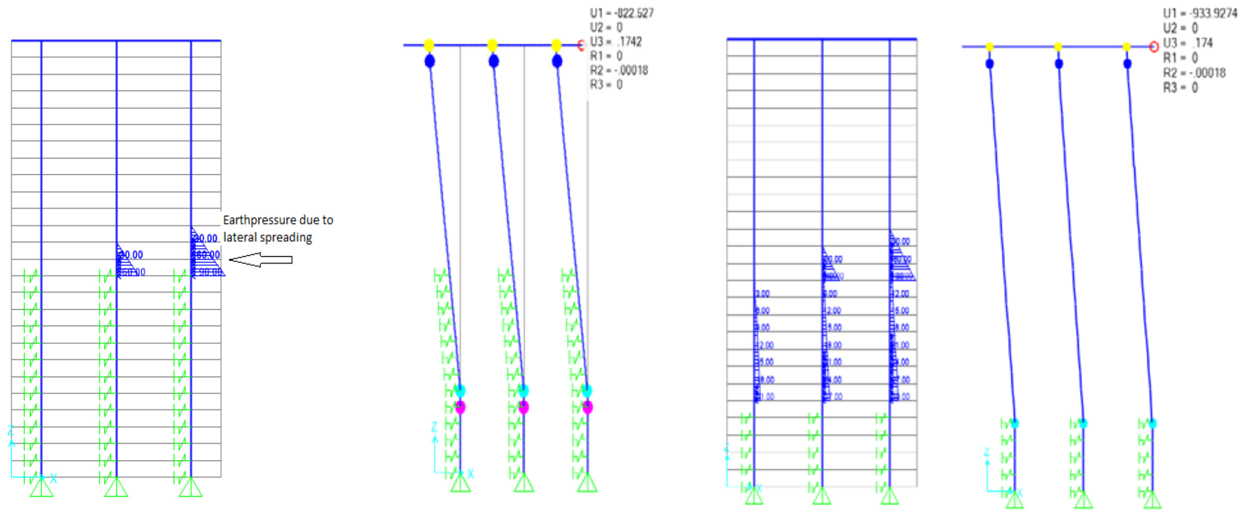
Sf = 1
PP (886KN, 46.7mm)

Sf = 0.1
PP (717KN, 71mm)

Sf = 0.01
PP(548KN, 99mm)

Sf = 0.001
PP (482KN, 112mm)

Fig.7. Yield sequence and hinge formation



Model with Sf = 0.001 and earth pressure for lateral spreading

With lateral spreading PP (477KN, 113mm)

Modelling with earth pressure for lateral spreading

With lateral spreading PP (440KN, 112mm)

Fig.8. Yield sequence and hinge formation during lateral spreading

5. CONCLUSIONS

A detailed study has been conducted on the performance of pile supported wharf structure under liquefying and lateral spreading soil conditions using nonlinear static pushover analysis. Methods of modelling and analysis are validated with available solutions in the literature. From the parametric study it is found that the structure performed poorly when the soil liquefied. When the soil liquefied piles yielded at the interface of liquefied and non-liquefied layers. Yielding is also observed at deeper levels in the embedded portion of piles when LDF increased. It is also observed that larger diameter piles with less SR performed well as compared to thinner piles with higher SR. By comparing the results of this study with the available field observations it can be concluded that pushover analysis is a good tool for the analysis of pile supported wharf which gives results confirming to field observations and can be very useful for practicing engineers.

6. REFERENCES

[1] PIANC, "Seismic Design Guidelines for Port Structures", Working Group No. 34 of the Maritime Navigation Commission. International Navigation Association, A.A. Balkema, Rotterdam, The Netherlands, 2001.

[2] JRA Part V, "Specification for highway bridges: seismic design", Japanese Road Association, 1996.

[3] BSSC, "NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures", Part 1, Provisions, and Part 2, Commentary, FEMA 368 and 369, prepared by the Building Seismic Safety Council, published by the Federal Emergency Management Agency, Washington, D.C. 2000.

[4] Eurocode-8, "Design Provisions for Earthquake Resistance of Structures", Part l-l:General Rules - Seismic Actions and General Requirements for Structures(ENV-1998–1–1); Part 5: Foundations, Retaining Structures and Geotechnical Aspects, (ENV 1998–5).

[5] Architectural Institute of Japan (AIJ), "Recommendations for designing of building foundations", Tokyo (in Japanese), 2001.

[6] Cubrinovski M., Ishihara K. and Poulos H., "Pseudo-Static Analysis Of Piles Subjected To Lateral Spreading", Special Issue, Bulletin of the NZ Society for Earthquake Engineering, Vol.42, No.1,2009, pp.28-38.

[7] Murashev A., D. Kirkcaldie C. Keepa M. Cubrinovski and Orense R., "The development of design guidance for bridges in New Zealand for liquefaction and lateral spreading effects", NZ Transport Agency research report-553, 2014.

[8] Chatterjee, K., Choudhury, D. and Poulos, H.G., "Seismic analysis of laterally loaded pile under influence of vertical loading using finite element method", Computers and Geotechnics, 67, 2015, pp.172-186.

[9] American Petroleum Institute (API)., “Recommended practice for planning designing and constructing fixed offshore platforms.” APIRP2A-WSD, 21st Ed., Washington, D.C. 2003.

[10] Lombardi D. and Bhattacharya S., "Evaluation of seismic performance of pile-supported models in liquefiable soils". Earthquake Engineering & Structural Dynamics 45 (6), 2016, pp.1019–1038.

[11] SAP2000, "Integrated Software for Structural Analysis and Design", Computers and Structures, Inc(CSI). Berkeley, CA.

[12] Ishihara K., and Cubrinovski M., "Soil-pile interaction in liquefied deposits undergoing lateral spreading", Proc., XI Danube-European Conf., Geotechnical Hazards. A. A. Balkema, Rotterdam, 1998, pp.51–64.

[13] Hayden J. Bowen and Cubrinovski M., "Pseudo-static analysis of piles in liquefiable soils: parametric evaluation of liquefied layer properties", Bulletin of the New Zealand Society for Earthquake Engineering, Vol. 41, No. 4, December 2008.

[14] FEMA 356, "Handbook for the Seismic Evaluation of Buildings—A Prestandard and Commentary for the Seismic rehabilitation of buildings", Prepared by the American Society of Civil Engineers for the FEMA, Washington, D.C. 2000.

[15] ATC-40, "Seismic Evaluation and Retrofit of Concrete Buildings", Volume 1, Applied Technology Council, Report No. SSC 96-01, 1996.

[16] FEMA 440, "Improvement of Nonlinear Static Seismic Analysis Procedures", Applied Technology Council (ATC-55 Project), California 94065 for the Department of Homeland Security. Federal Emergency Management Agency. Washington, D.C. 2005.

[17] Phanikanth V. S, Deepankar Choudhury and Reddy G. R., "Behaviour of Single Pile in Liquefied Deposits during Earthquakes", International Journal of Geomechanics © ASCE/July/August 2013.

[18] Yoshida N., and Hamada M., "Damage to foundation piles and deformation pattern of ground due to liquefaction-induced permanent ground deformation", Proceedings of 3rd Japan-US Workshop on Earthquake resistant Design of Lifeline Facilities and Counter measures for Soil Liquefaction, 1991, pp. 147–156.

[19] Mohamed Faizur Rahaman K, and Mahammood Vazeer, "Parametric Study on Post-Elastic Behavior of Single Pile in Liquefied and Lateral Spreading Soils Using Nonlinear Static Procedures". Electronic Journal of Geotechnical Engineering, 2016 (21.23), pp. 7527-7545.

[20] IS:1893, "Part 1: Criteria for Earthquake Resistant Design of Structures: General Provisions and Buildings", Bureau of Indian Standards. New Delhi, 2002.