Effect of Liquefaction on Design of Pile Foundation - A Case Study

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Abstract

Soil liquefaction occurs when a saturated or partially saturated sand loses its strength and stiffness due to an earthquake shaking thus making soil behave like a liquid. Liquefaction affects the design of pile foundation in direct and indirect manner. Factors like vertical load carrying capacity of soil and unsupported free length decide total pile length, pile diameter and structural design. While global structural flexibility on account of liquefaction reduces seismic co-efficient, however, on the other hand, increase in lever arm requires higher pile reinforcement. This paper deals with the design of pile foundation in liquefiable soil and various parameters which affect the design. It consists of comparative study of seismic time period, pile moment factor, reinforcement requirement for various depth of liquefaction based on case study of an ongoing project.

Keywords : Liquefaction, Pile foundation, Time period, Moment factor.

1. Introduction

Liquefaction of soil is a state primarily observed in saturated or partially saturated cohesionless soils wherein the effective shear strength is reduced to negligible value. This generally happens when the pore pressure in soil approaches the total confining pressure during earthquake shaking. In this condition, the soil tends to behave like a fluid mass. For cohesionless soil which in common parlance is known as sand, shear strength is function of angle of internal friction and the effective stress acting on the soil grains. Their relation can be expressed as combination of two equations.

$$\tau = \sigma' \tan\phi \quad (1)$$

$$\sigma' = \sigma - u \quad (2)$$

here τ means shear strength, σ' is effective normal stress, σ is total normal stress, u is pore pressure and ϕ represents angle of internal friction. When saturated or partially saturated loose sand is subjected to earthquake shaking, they get settled on account of densification. Duration of shaking during earthquake is generally very short resulting in water entrapped in it not to get drained. This locked water progressively increases pore pressure.

Subsequently, when the pore pressure equals the total stress, then the effective stress gets equal to zero and soil indicates sudden loss of strength.

For liquefiable soil, well foundation and pile foundation are two most suitable types of foundations. They both can transmit loads and moments like vertical and horizontal loads to more suitable soil layers present below. This is specially required in case when the upper layer is susceptible to liquefaction. Loss of surface friction and corresponding loss of support of the soil are affected by the phenomenon. Hence, for soil susceptible to liquefaction, piles should be designed for lateral loads neglecting lateral resistance of those soil layers (if any), which are liable to liquefy.

In this paper, a case study is modelled by varying type of sand like very loose sand, loose sand, medium sand and dense sand. Reference is made to classification given as per IS 2911 (Part 1/ Sec 2): 2010. This classification is based on SPT values and their corresponding modulus of subgrade reactions. Depending on type of sand considered, value of subgrade modulus varies. Data as mentioned in Annexure C of IS 2911 (Part 1/ Sec 2): 2010 is reproduced in Table-1 below for reference.

These subgrade moduli are utilised to find spring stiffness values for piles. Spring stiffness are modelled to find actual moments in piles due to horizontal forces. They are also used in models where time period of structure is calculated for computing seismic coefficient. The lateral load capacity of pile depends on spring stiffness which in turn is dependent on modulus of subgrade reaction and pile stiffness.

Their function is taken from IS 2911

(Part 1/ Sec 2): 2010 Annexure C clause C-2.1

$$\frac{p}{y} = \eta_h Z \qquad (3)$$

Where p is lateral soil reaction per unit length of pile at depth of z below ground level, y is lateral pile deflection, η_h is modulus of subgrade reaction based on type of granular soil. Spring stiffness (K) is related to p (lateral soil reaction) per unit length of pile and pile diameter d as per equation.

$$K = \frac{((p.d))}{y} \qquad (4)$$

Thus, after combining eq. (3) and eq. (4), spring stiffness (K) is related to modulus of subgrade reaction as

$$K = \eta_h zd \qquad (5)$$

This equation is utilised to find out value of spring stiffness of sand and as evident is based on depth of sand layer below ground level and total length of that layer. In case of liquefaction, no contribution is considered for liquefiable layer of soil.

2. Case Study

Different parameters govern the design of pile foundation. These include depth of liquefaction, type of soil and others. In order to find out effect of all factors on pile foundation design, it will take a

Table 1 : Modulus of Subgrade Reaction for submerged Granular Soils

Sr. No.	Soil Type	N (blows/30cm)	Range of submerged η_h in KN/m^3 x 10^3
1	Very Loose sand	0-4	<0.2
2	Loose sand	4-10	0.2-1.4
3	Medium sand	10-35	1.4-5.0
4	Dense sand	>35	5.0-12.0

comprehensive study. However, this paper tries to vary fundamentally following parameters to understand their effect on pile reinforcement.

1. Type of soil
2. Depth of liquefaction

Thus, by varying these two parameters which are mainly geotechnical and related to seismicity, one can determine their impact on pile reinforcement. For this paper, ongoing project of Kishanganj flyover being constructed in state of Bihar is considered. Salient features of Kishanganj flyover are mentioned in figure 1 to figure 4 and Table 2.

Table 2 : Salient Features of Kishanganj Flyover, Bihar

Sr. No.	Description	Remarks
1	Typical structural details	Simply supported RCC girder span of 20m, pile foundation
2	Seismicity of site	Seismic zone V, soil susceptible to liquefaction.

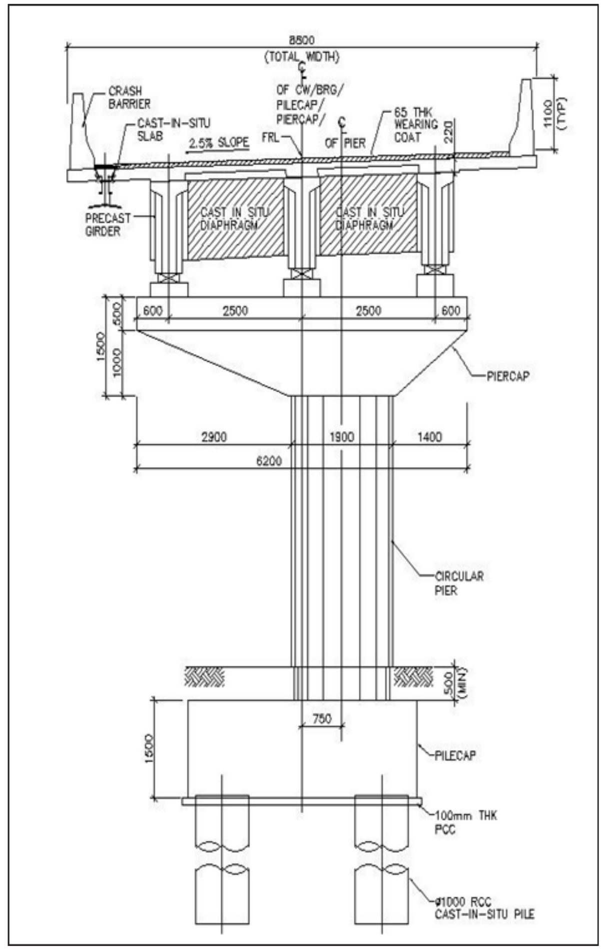

Fig. 1 : Typical section of pier

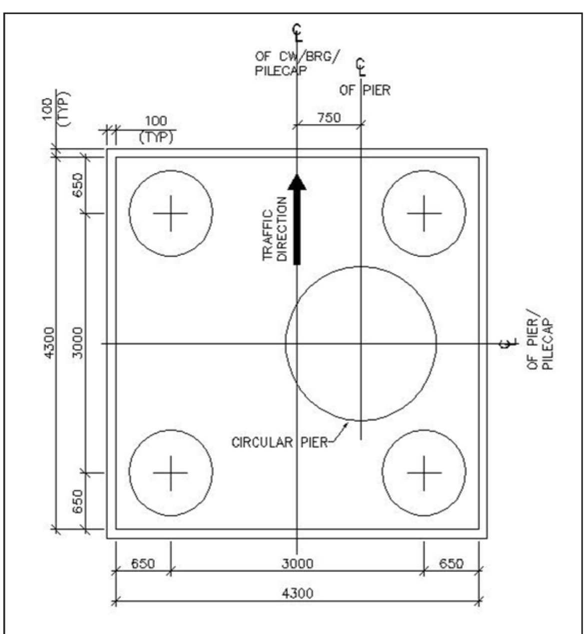

Fig. 2 : Typical plan of pile cap

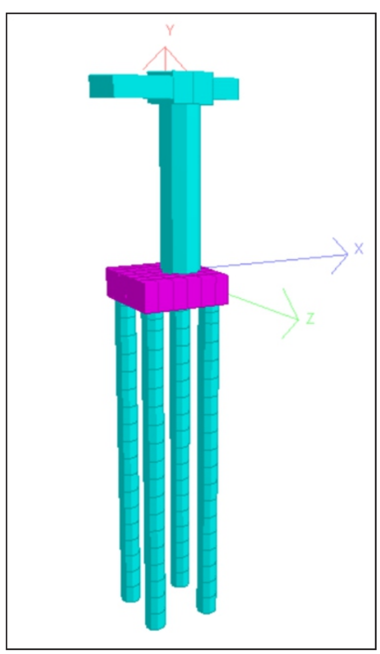

Fig. 3 : Staad.PRO model of Structure

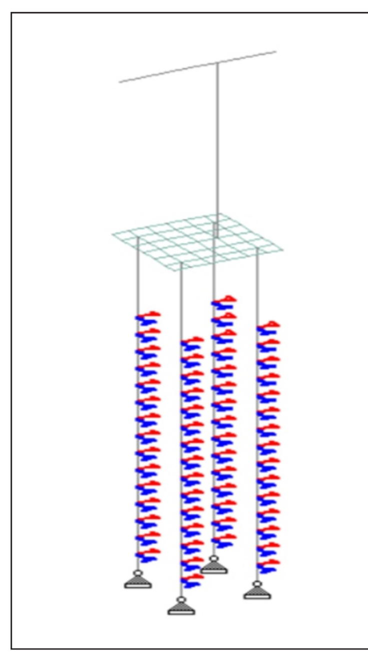

Fig. 4 : Staad.PRO model of pile foundation with spring stiffness

Total four iterations are done for four types of sands. Depth of liquefaction is varied from zero to 20m for all these four types of sand. As spring stiffnesses of these four types vary substantially along with depth of foundation, their direct effects in terms of moment factor and seismic co-efficient are plotted. Values of spring stiffnesses for all types of soil are enumerated in Table 4 as mentioned below. Time period variation for all types of soil is plotted from figure 5 to figure 8. Moment factor for pile is defined as moment corresponding to unit horizontal load at pile cut off level. When moment factor is multiplied by actual horizontal load, we get actual moment in that pile. Variation of moment factor is plotted from figure 13 to figure 16 while, variation in moment per pile is plotted from figure 17 to figure 20. Similarly, based on seismic co-efficient obtained by varying spring stiffness and depth of liquefactions, Pmax and Pmin loads on pile are plotted from figure 9 to figure 12. In the end, reinforcement in pile for corresponding moment factor and seismic coefficient are plotted for all of them. Reinforcement in pile is calculated based on actual ULS horizontal load and moment as enumerated in figure 21 to figure 24. The design has been checked as per limit state method as per IRC 112 for load combination given in IRC 6 under seismic condition. This study is only for seismic and effect of other forces under normal and wind has not been presented for arriving at the reinforcement. For all these graphs, care is taken to ensure that x axis indicate liquefaction depth below cut-off for easy comparison. Thus, a wide range of practical situations are covered to check influence of these parameters on pile. These graphs are enumerated below.

Table 3 : Deflection at cut-off level for dense sand for representation

Liquefaction Depth in m	Deflection at Cut off level in mm
0.0	2.0
2.5	3.2
5.0	6.8
10.0	20.2
15.0	40.5
20.0	71.7

In the design, for typical pier, four piles each of diameter 1m having grade of concrete M35 are considered. Length of each pile under various cases is considered constant i.e. 15m irrespective of length requirement from pile capacity point of view. Length of 15m is kept uniform so as to note down role of spring stiffness on relaxing seismic coefficient in structure. Deflection obtained at cut - off level for dense soil in enumerated in Table-3 for representation only. In actual structure, we have provided sufficient edge distance /seating at pier cap top as required by the code for type of soil and corresponding liquefaction depth.

Table 4 : Spring Stiffnesses for various types of submerged Granular Soils

Liquefaction Depth	Very Loose		Loose		Medium		Dense	
	Spring Stiffness		Spring Stiffness		Spring Stiffness		Spring Stiffness	
	Min	Max	Min	Max	Min	Max	Min	Max
m	kN/m	kN/m	kN/m	kN/m	kN/m	kN/m	kN/m	kN/m
0.0	200	3160	1430	22120	5100	79000	12230	189600
2.5	230	3870	1610	27120	5730	96840	13760	232420
5.0	710	4180	4990	29260	17840	104490	42810	250760
10.0	1220	7800	8560	54600	30580	195000	73390	468000
15.0	1730	9300	12130	65100	43320	232500	103980	558000
20.0	2240	10800	15700	75600	56070	270000	134560	648000

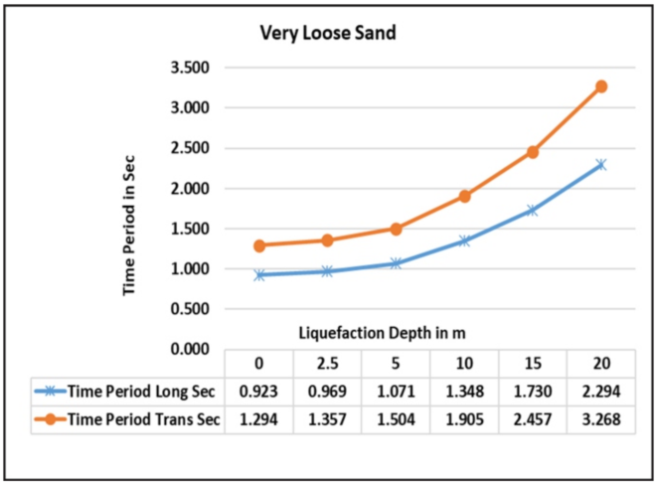

Fig. 5 : Time Period Vs LD for Very Loose Sand

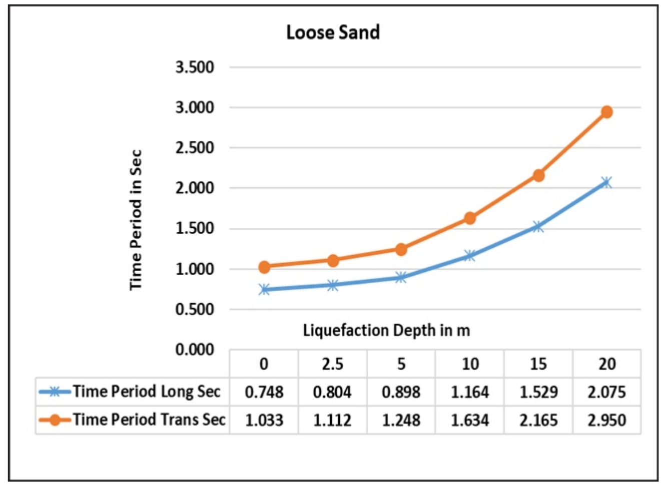

Fig. 6 : Time Period Vs LD for Loose Sand

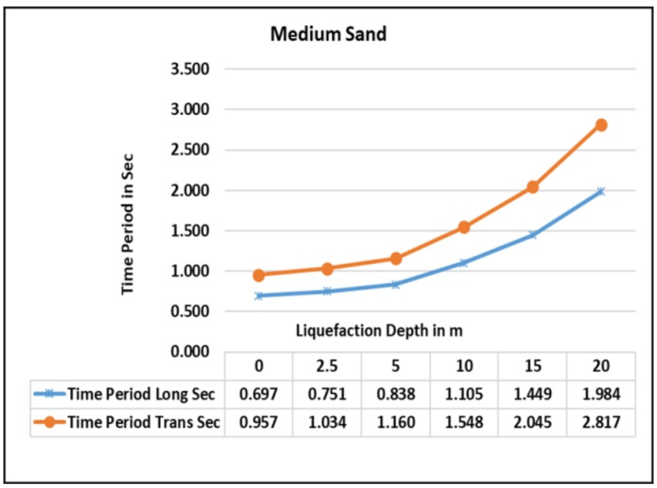

Fig. 7 : Time Period Vs LD for Medium Sand

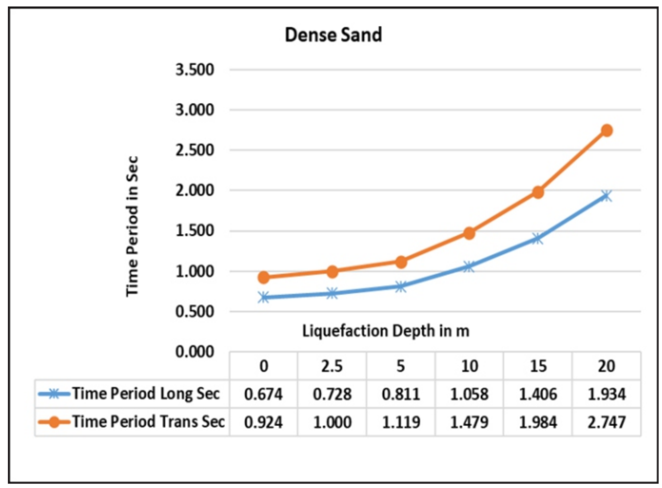

Fig. 8 : Time Period Vs LD for Dense Sand

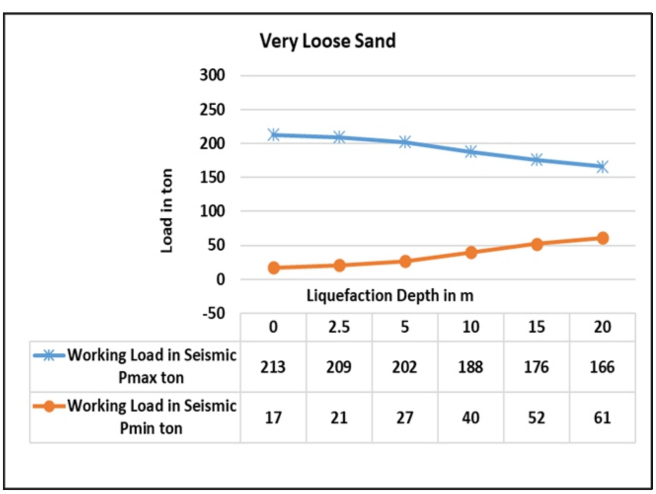

Fig. 9 : Load on Pile Vs LD for Very Loose Sand

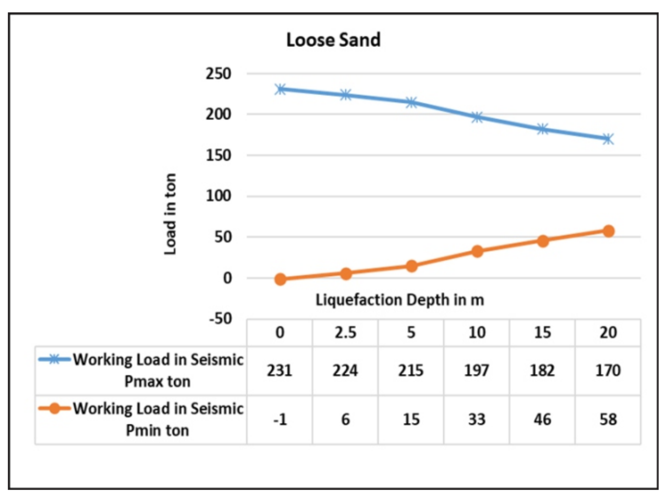

Fig. 10 : Load on Pile Vs LD for Loose Sand

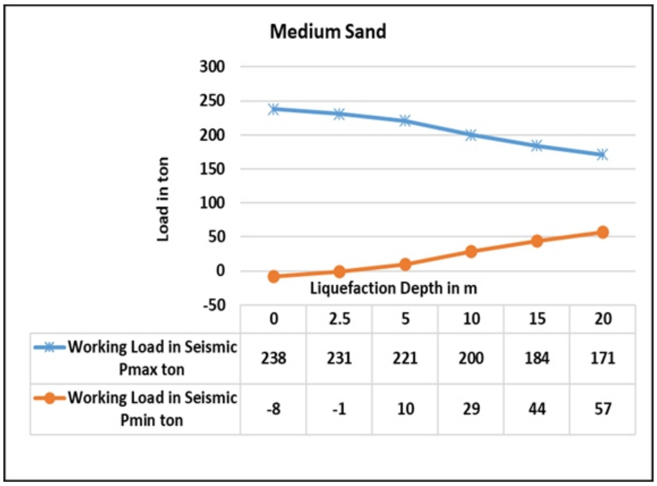

Fig. 11 : Load on Pile Vs LD for Medium Sand

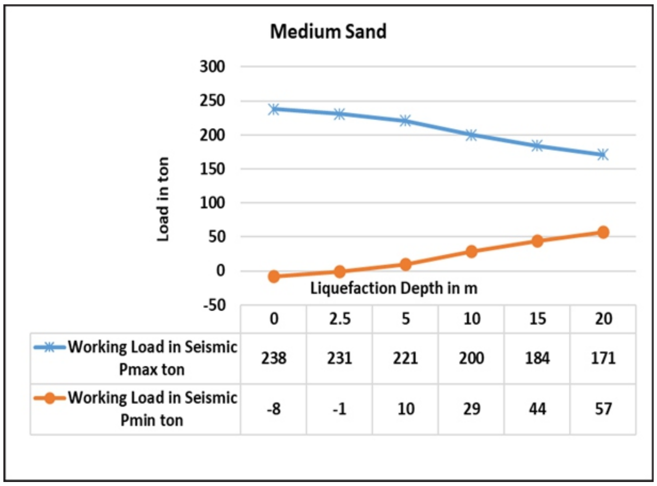

Fig. 12 : Load on Pile Vs LD for Dense Sand

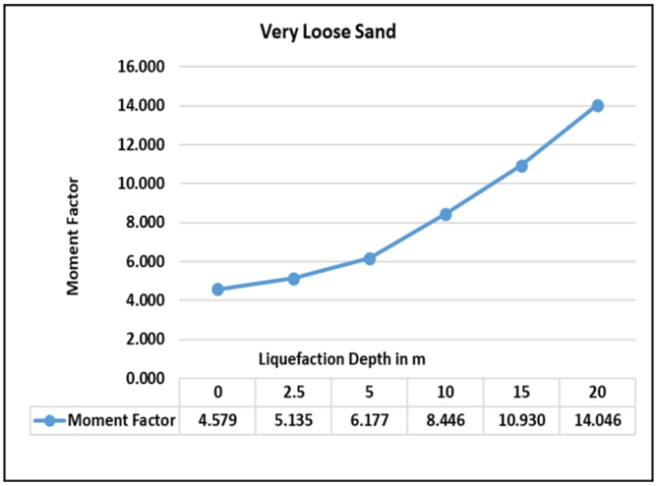

Fig. 13 : Moment Factor Vs LD for Very Loose Sand

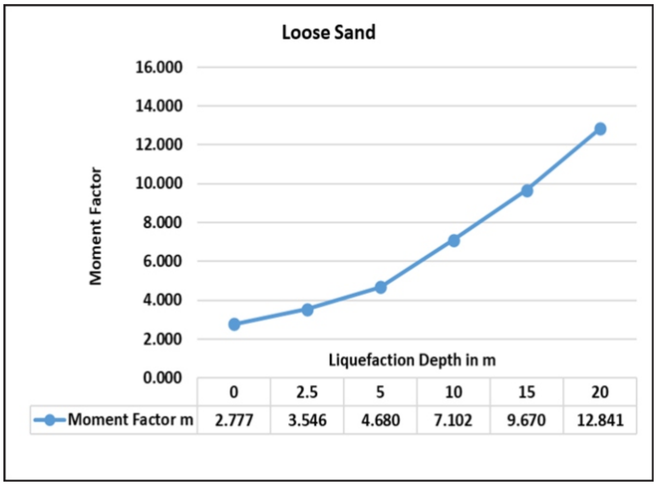

Fig. 14 : Moment Factor Vs LD for Loose Sand

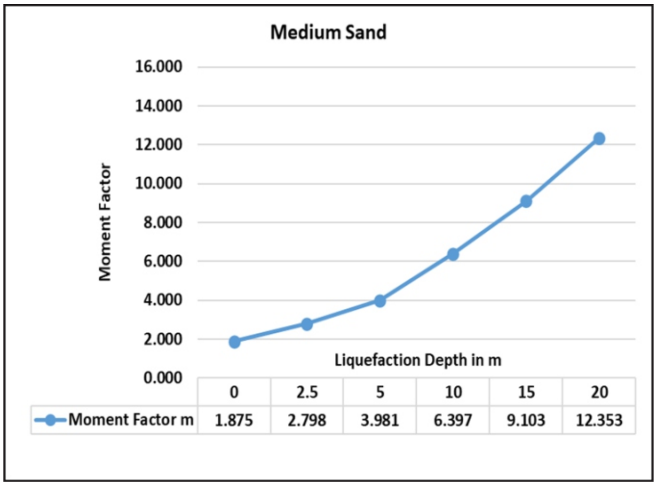

Fig. 15 : Moment Factor Vs LD for Medium Sand

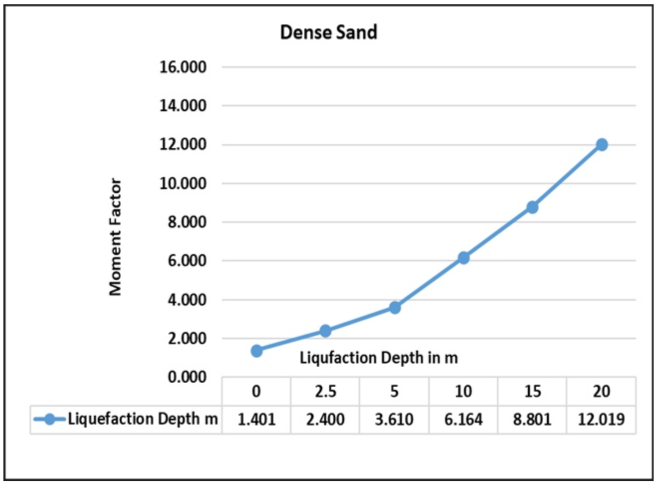

Fig. 16 : Moment Factor Vs LD for Dense Sand

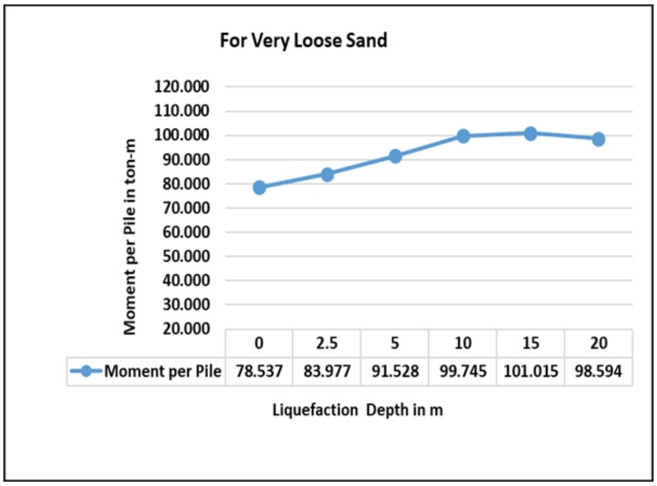

Fig. 17 : Moment per Pile Vs LD for Very Loose Sand

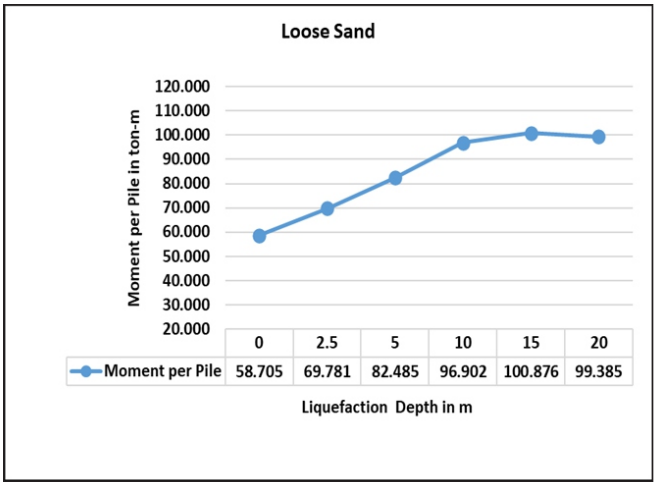

Fig. 18 : Moment per Pile Vs LD for Loose Sand

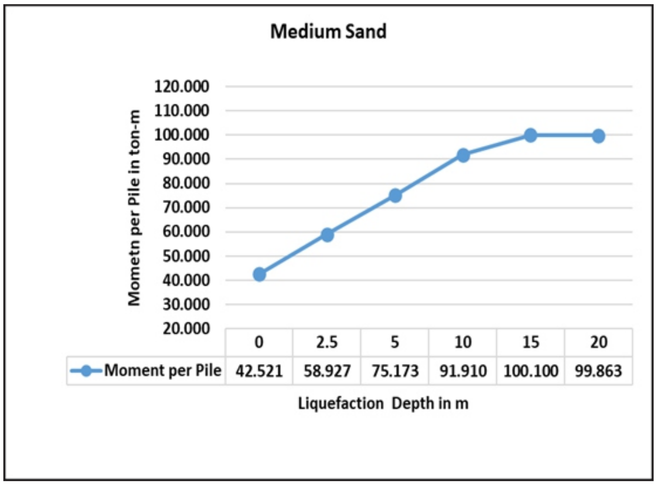

Fig. 19 : Moment per Pile Vs LD for Loose Sand

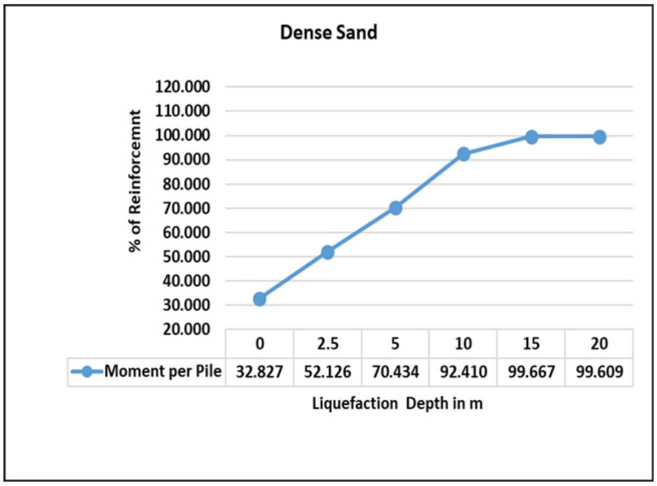

Fig. 20 : Moment per Pile Vs LD for Dense Sand

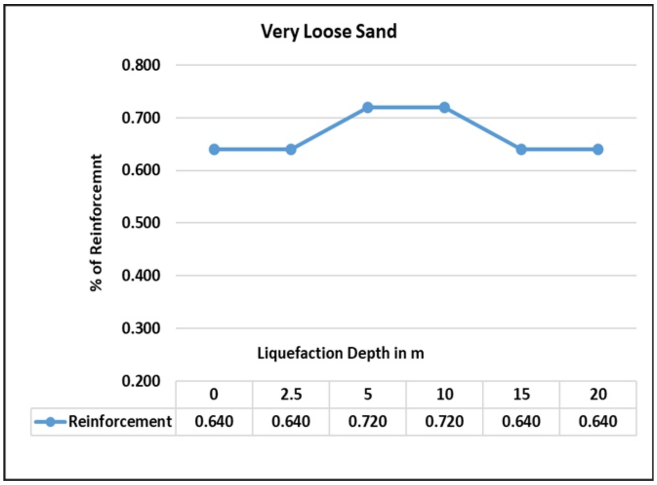

Fig. 21 : % of Reinforcement Vs LD for Very Loose Sand

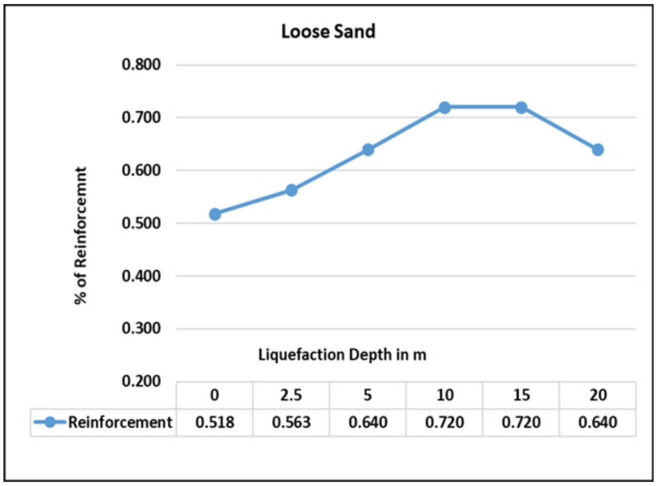

Fig. 22 : % of Reinforcement Vs LD for Loose Sand

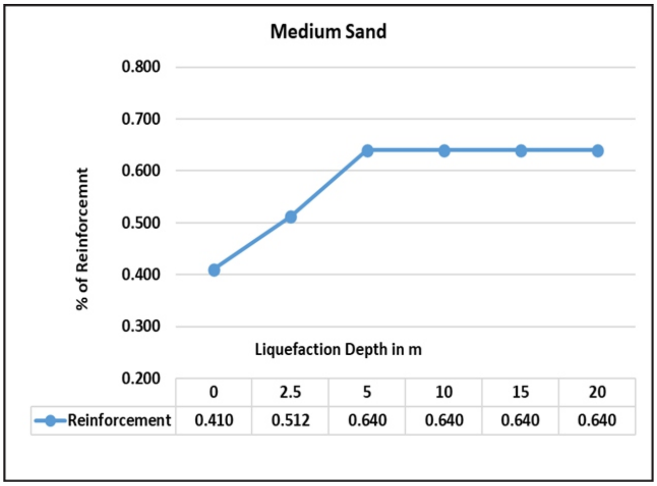

Fig. 23 : % of Reinforcement Vs LD for Medium Sand

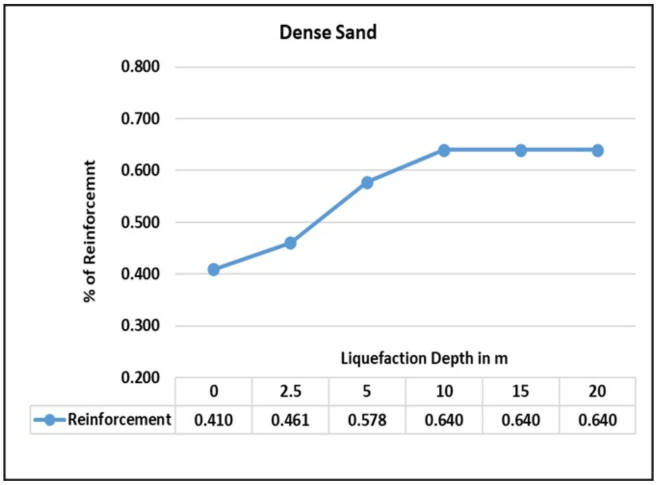

Fig. 24 : % of Reinforcement Vs LD for Dense Sand

Conclusion

Pile length is governed by vertical loads in normal and seismic / wind conditions. By varying spring stiffness of soil based on type of sand and depth of liquefaction, it is evident that for all four types of sand, as depth of liquefaction increases, vertical force Pmax on pile decreases. Thus, length of pile should ideally decrease in such scenario. However, though Pmax is decreasing, every pile must have adequate length below liquifiable layer so as to support vertical load. Hence, overall pile length gets increased with increase of liquefaction depth.

Moment factor in pile for unit force keeps on increasing with depth of liquefaction for all four types of sand. This is quite logical as there is increase of lever arm and thus for same amount of force, moment factor in pile will increase with increase in liquefaction. Higher moment factor in pile gets directly reflected in higher reinforcement of pile.

As depth of liquefaction is increasing, flexibility of structure increases. This means structure can deflect to larger extent under same force. This higher flexibility of structure increases fundamental time period of structure. Higher time period leads to lower seismic coefficient and lower seismic forces. This is evident from graphs as time period of structure is increasing as per liquefaction.

It can be concluded that increase of liquefaction has indirect effect of reducing reinforcement of pile by making structure more flexible. A combined effect of increase of moment factor and decrease of seismic co-efficient can be seen from the graph of reinforcement. It can be concluded that reinforcement in pile increases with increase in depth of foundation however this increase in reinforcement is not linear but at much slower gradient as two opposing effects of increase due to moment factor and decrease due to time period are simultaneously working.

Above study indicates various variables which govern pile length and pile reinforcement. Conclusions made above are based on theoretical calculations by assuming various fundamentals like uniformity of sand, equal length of pile in all depths of foundations etc. These assumptions cannot be true for real working projects and engineer's experience and acute engineering knowledge are required to decide length of pile and reinforcement requirement.

As seen in Fig. 21 & Fig. 22 care should be taken for reinforcement required under higher liquefaction which may be lesser but considering uncertainty of liquefaction depth, reinforcement should not be reduced, what is computed for lesser liquefaction, the same should be provided. Design should be checked for no liquefaction case too.

Reference

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About the Author

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Mr. Sandeep Pattiwar received Bachelor of Engineering in Civil Engineering from the NIT Raipur (Formerly Government Engineering College) in 1987 and post-graduation in Foundation Engineering from MACT Bhopal in 1991. He has over thirty year of experience in the field of designing various iconic mega structures including bridges, metros, flyovers, grade separators, jetties, chimneys and intake structures. Mr. Pattiwar started his career with Progressive Constructions from 1991 to 1993. From 1993 to 2011, he worked with Gammon designing numerous structures. Since 2011, Mr. Pattiwar is working as founder and director of "TANGENT Technical Solutions" & "Tech TANGENT Solutions Private Limited" respectively.

Mr. Sandeep Pattiwar is associated with member of various IRC Code Committees and has professional memberships of IABSE, life member of ISET and life member of ISWE. He has published many papers in various national and international conferences conducted by IABSE and fib.

Mr. Nishad Kulkarni

Mr. Nishad completed his graduation and post-graduation - B. Tech (Civil) & M. Tech (Structural) under dual degree programme of IIT Bombay in 2011. Since then, he has been involved in various infrastructure projects like major bridges, iconic structures, long flyovers and important rotaries. During one decade of experience, he has worked as Senior Bridge Design Engineer in organizations like STUP Consultants Pvt Ltd, SAI Consulting Engineers - Systra Group, Wadia Techno-engineering Services Ltd. and Tech Tangent Solutions Pvt. Ltd. Currently, Mr. Nishad Kulkarni is co-founder and partner of "Stellar Engineers" – a young dynamic firm providing civil structural consultancy services to complex engineering problems.

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Mr. Tushar received Bachelor of Engineering in Civil Engineering from the KIT's College of Engineering Kolhapur in 2016 and post-graduation in Structural Engineering from Sardar Patel College of Engineering, Mumbai in 2019. He is young, dynamic engineer having two year of experience in the field of designing various bridge structures including Major Bridge, Minor Bridge, Underpass, Interchange and ROB.