VOL. 11, NO. 4, FEBRUARY 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

CHANGES IN THE PUSHOVER ANALYSIS RESULTS OF OFFSHORE JACKET PLATFORMS DUE TO THE INCORPORATION OF THE AGING EFFECT OF PILES

Jerin M. George, V. J. Kurian and M. M. A. Wahab
Civil and Environmental Engineering Department, Universiti Teknologi Petronas, Bandar Seri Iskandar, Tronoh, Perak, Malaysia
E-Mail: jerinmplathottam@gmail.com

ABSTRACT

The pushover analysis of jacket platforms in the past has revealed that most of the collapse failures occur due to the lack of strength of the pile foundation. However, when the jacket platforms which have been collapsed due to extreme conditions were looked into, it was found that most of them had their foundations intact. These contrasting facts can be explained with the help of the phenomenon called 'aging of piles'. Aging effects of piles have been experimentally proven to improve the pile capacity with time, but due to lack of proper understanding and suitable techniques to incorporate them, these aging effects were ignored when the pushover analysis was done. In this study, a simple technique of stepping up of the soil curves in order to accommodate the increase in capacity of pile foundation due to aging is utilised. Three different jacket platforms were employed to study the changes of Reserve Strength Ratio (*RSR*) after the pushover analysis incorporating aging effect of piles. The incorporation aging effect of piles has created both improvement as well as reduction in *RSR* of the jacket platforms. The maximum improvement in *RSR* was found to be about 122 % and the maximum reduction in *RSR* was about 12 %. The adequacy of the new pushover analysis results in explaining the actual case scenarios are also discussed. The study has provided a deeper knowledge into the behaviour of aged offshore jacket platforms.

Keywords: aging effects of piles, pushover analysis, jacket platforms, reserve strength ratio.

INTRODUCTION

The design life of an offshore jacket platform is normally around 25 years. During the service life of the platform, it will be required to take more than its designed capacity due to the changes in environmental loading, modifications in the use of the platform and work over demands (Nichols, Goh, & Bahar, 2006). Also, the life of a jacket platform will be required to be extended beyond its design life due to the Enhanced Oil Recovery (EOR) requirements. In all such cases, the integrity of the structure needs to be examined. Pushover analysis of the jacket platform is the most commonly applied technique to evaluate the integrity of the structure.

Pushover analysis in the past has shown that the failure of a platform happens mostly due to the foundation failure. But the actual case scenarios of platforms which were acted upon by extreme environmental conditions like storm and hurricanes have shown that the foundation remained intact when the platform failed (Gilbert *et al*., 2010). This disagreement between the simulations and the actual conditions can be explained by the phenomenon of aging effect of piles which causes the pile foundation capacity to increase with time. The aging effect of piles are incorporated into the pushover analysis using a simple technique of stepping up of pile soil interaction curves to model the improvement in pile capacity. The main objectives of the study are to identify the effect of the incorporation of aging effects of piles using the multi-directional pushover analysis results and to establish the scope of this technique based on the effectiveness of the results in explaining the discrepancies between simulations and actual cases in the past.

AGING EFFECT OF PILES

The capacity of piles is known to be changing with time. The correct mechanisms behind these changes have not been fully understood. Researchers have been trying to study the mechanisms behind the change in capacity of piles and represent them as mathematical equations known as 'time functions for capacity of piles'. The gain in capacity of piles is known as setup. The gain in capacity from the end of driving of pile to the end of consolidation phase is known as short term effects. Short term effects are mainly due to equalization of excess pore water pressure built up during driving (also known as consolidation) (Komurka, Wagner, & Edil, 2003). The gain in capacity after end of consolidation is known as long term effects or aging effects and it can be the result of a combination of mechanisms such as (Lied, 2006):

- Increase in the earth pressures against the pile surface on the long term, due to creep of the soil structure.
- Long-term build-up of new diagenic bonds between soil particles, after the complete destruction of the soil structure due to the severe displacements and disturbance resulting from the driving of the pile into the ground.
- Chemical bonding due to the interaction between the steel pile surface and the soil minerals (cation exchange).
- Effects of sustained loads on the piles, gradually causing a more stable soil structure and increased strength.
- Effects of previous loading and unloading cycles of the piles, which may have similar effects as sustained loading.

The most popular time function for capacity of piles was presented by Skov and Denver (1988), which models aging as linear with respect to the log of time. They proposed a semi-logarithmic empirical relationship to describe aging as (Anders Hust Augustesen, 2006; A.H. Augustesen, Andersen, & Sørensen, 2005a, 2005b, 2006):

$$Q_t/Q_o = 1 + \Delta_{10}\,[\log(t/t_o)] \quad (1)$$

Q_t = axial capacity at time t after consolidation,
Q_o = axial capacity at the reference time t_o,
Δ_{10} = setup factor, a constant depending on soil type
t_o = the reference time at which Q_o is measured

The average setup factor for offshore clayey soil conditions were found to be 0.215 for a reference time of 100 days (George, Wahab, & Kurian, 2015). This setup factor value has been used in (1) to find the ratio of the pile capacity after design life (25 years) to the pile capacity at the reference time (100 days) as 1.42.

SACS is the commercial structural analysis software which was used in this study. In SACS, the pile-soil modelling is done in a module known as PSI (Pile Structure Interaction). In PSI, the soil is defined in terms soil curves namely side shear curve (t-z), end bearing curve (Q-z) and lateral strength curve (p-y) ("SACS Software Manual," 2010). The soil curves modifications should accommodate the improvement in capacity of the piles with time due to aging. To improve the axial capacity of a pile, t and Q values in the t-z and the Q-z curves should be stepped up by a factor for the same axial displacement. By studying the variation of capacity of piles with the application of random t factor and Q factors, it was observed that Q factor will produce an extra improvement in capacity than intended whereas t factor will produce improvement within the desirable amount. Although the lateral capacity improvement is not backed up by literature, logically it seems to be appropriate to include lateral aging into the study. The p values of the p-y curve were also stepped up in order to accommodate lateral aging effect of piles. The factors used for the soil curve modification are calculated from the capacity ratio found out earlier. Since the Q factor produced elevated capacities, it was normalised by using a reduction factor of 0.90 on the capacity ratio.

The actual and aged foundation capacities of all the platforms are given in the Table-1 along with the required and obtained capacity ratios. The obtained capacity ratio for jacket A and C are in close agreement with the required ratio. The observed capacity ratio for the pile foundation system of jacket B is slightly lower than the required capacity. The slight reduction in capacity is due to the 0.90 reduction factor used in Q-z modification. But if this reduction factor is not used, the capacities will reach very high values than required and hence the conservative option is utilised for this study. Since the software did not plan on using the method of stepping up of soil curves, they did not provide high precision input facility for the Q and t factors. So the PSI modifications cannot be done with more accuracy with the current version of the software.

Table-1. Obtained foundation capacity ratios.

Jacket	Required Capacity Ratio	Actual Capacity (kN)	Aged Capacity (kN)	Obtained Capacity Ratio
A	1.42	190337.4	271099.6	1.424
B		288699.4	403063.6	1.396
C		471124.2	669835.2	1.422

PUSHOVER ANALYSIS

The pushover analysis was conducted for jacket platform A, B and C using the actual and the aged soil curves. Jacket A and B are four-legged platforms while jacket C is a six-legged platform as shown in the Figure-1. The self-weight of the jacket platforms, buoyancy, installed equipment, live load were applied on the platform in the first phase of the pushover analysis with load factor of 1.0. The second phase of the pushover analysis was applying the environmental load on the platform with increasing load factor until the platform collapsed. Pushover Analysis was carried out separately for eight selected loading direction using SACS namely; N (0o), NE (45o), E (90o), SE (135o), S (180o), SW (225o), W (270o), and NW (315o) for jacket A and B, while jacket C is being assessed at N (0o), NE (61o), E (90o), SE (118o), S (180o), SW (241o), W(270o), and NW (298o). The slight difference in the direction is mainly due to the difference of geometry between the jackets.

Reserve Strength Ratio (RSR) is a measure of structure's ability to withstand loads in excess of those determined from platform design and this can be obtained using the ultimate strength of the platform through pushover analysis. This reserve strength can be used to maintain the platform in service beyond their intended service life. Knowledge from this analysis can be used to determine the criticality of components within the structural system for prioritizing the inspection and repair schemes (Narayanan & Kabir, 2009).

$$RSR = BS_{collapse} / BS_{design} \quad (2)$$

$BS_{collapse}$ = the ultimate base shear capacity of the jacket prior to collapse,
BS_{design} = the design base shear loading on the jacket

The design base shear can be identified when the environmental load factor = 1.0, while collapse base shear is the maximum base shear prior to collapse.

VOL. 11, NO. 4, FEBRUARY 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

Figure-1. Jacket models.

RESULTS AND DISCUSSION

Pushover analysis results of jacket A incorporating the aging effects of piles in clayey soil are given in Table-2. The RSR of jacket A improved in all pushover directions for aged than actual, thus proving the hypothesis. The maximum improvement of 16 % was observed in NW pushover direction.

Table-2. Pushover analysis results of jacket A.

Pushover direction	Design Base Shear (kN)	Actual		Aged		Improve ment (%)
		Base Shear (kN)	RSR	Base Shear (kN)	RSR	
N	5317	17809	3.350	19615	3.689	10.14
NW	9981	17465	1.750	20261	2.030	16.01
W	6063	23278	3.840	24171	3.987	3.84
SW	4470	25620	5.731	26118	5.843	1.95
S	5391	22007	4.082	23388	4.338	6.50
SE	6886	23407	3.399	24584	3.570	5.03
E	7338	22968	3.130	26346	3.591	14.71
NE	6091	17909	2.940	19616	3.220	9.53

Pushover analysis results of jacket B incorporating the aging effects of piles in clayey soil are given in Table-3. The results shows that there is improvement in RSR than actual RSR in half of the pushover directions and reduction in the rest. The RSR exhibited a maximum reduction of 12.45 % in NW direction and showed a maximum improvement of 15.72 % in S direction. The reductions in RSR are comparatively lower than the improvements. The improvement in RSR is in alignment with the hypothesis, but the reduction in RSR values were not anticipated.

Table-3. Pushover analysis results of jacket B.

Pushover direction	Design Base Shear (kN)	Actual		Aged		Improve ment (%)
		Base Shear (kN)	*RSR*	*Base Shear (kN)*	*RSR*	
N	9317	30642	3.289	32037	3.439	4.55
NW	8953	38406	4.290	33626	3.756	-12.45
W	6253	31889	5.100	31350	5.014	-1.69
SW	4282	34626	8.086	32096	7.496	-7.31
S	4329	31105	7.185	35994	8.315	15.72
SE	6081	23948	3.938	23773	3.910	-0.73
E	7811	20697	2.650	21625	2.769	4.48
NE	8927	24541	2.749	25817	2.892	5.20

Pushover analysis results of jacket C incorporating the aging effects of piles in clayey soil are given in Table-4. The results show that there is improvement in seven pushover directions and reduction only in one direction for Aged RSR. The RSR exhibited a maximum reduction of 0.23 % in NW direction and showed a maximum improvement of in 121.82 % in NE direction. The aged RSR in NE and SE directions showed massive improvements than most of the other pushover directions.

Table-4. Pushover analysis results of jacket C.

Pushover direction	Design Base Shear (kN)	Actual		Aged		Improvement (%)
		Base Shear (kN)	*RSR*	*Base Shear (kN)*	*RSR*	
N	8480	14662	1.729	15273	1.801	4.17
NW	5017	43196	8.611	43096	8.591	-0.23
W	5305	40529	7.640	40577	7.649	0.12
SW	3557	26420	7.429	30552	8.590	15.64
S	3445	13127	3.810	13337	3.871	1.60
SE	9423	33238	3.527	54053	5.736	62.62
E	10217	40511	3.965	44651	4.370	10.22
NE	9920	19981	2.014	44321	4.468	121.82

The improvement contour shows the comparative improvements the RSR of the three different jacket in the eight pushover directions as shown in Figure-2. The actual contour depicts the ground level or zero percentage improvement. Jacket A has almost a steady contour showing comparable improvements in all directions. Jacket B has a fluctuating contour which is higher than actual in half of the directions and lower in the remaining directions. Jacket C has a highly unsteady improvement contour which is slightly lower than zero in one direction and massive improvement peaks in two directions. The improvement contour is mostly higher than the actual contour for all jackets.

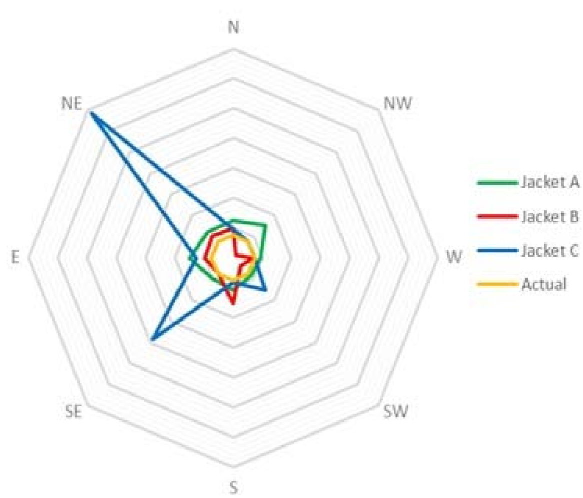

Figure-2. Improvement contour.

CONCLUSIONS

The increase in RSR proves that an aged platform contains higher capacity than the designed capacity. Hence giving a scientific base for the foundation failure of jacket observed in simulations in the past and the rarity of such failure in actual collapse events. However, the reduction in the RSR does not convey the exact opposite sense. Even when the structure has collapsed, the foundation had more capacity to be utilised. So the improved foundation capacity of the platform due to aging has triggered an earlier failure mechanism in the jacket structure. Also for most of the cases where the RSR was improved, the foundation capacity was not completely used. Therefore, the performance of the jacket platforms can be further improved with careful planning and execution of the maintenance and strengthening of the critical member in the jacket which contributed to the structure collapse.

The study had drawn certain conclusions which are listed below.

- Disagreement between the simulation and actual cases in terms of their collapse strength is due to the aging effects of piles.
- The incorporation of aging effect of piles into the pushover analysis of offshore jacket platforms can produce both improvements and reductions in the RSR of the structure.
- The aged foundation capacity is not utilised to its maximum potential in most of the collapse scenarios, but this can be averted if a target based maintenance and strengthening of the jacket is performed.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support and project data given by PETRONAS and for the facilities and staff support provided by Universiti Teknologi PETRONAS.

REFERENCES

[1] Augustesen, A. H. (2006). The Effects of Time on Soil Behaviour and Pile Capacity. Aalborg University, Denmark.(DCE Thesis No. 4)

[2] Augustesen, A. H., Andersen, L., & Sørensen, C. S. (2005a). Capacity of Piles in Clay. Aalborg University, Denmark.

[3] Augustesen, A. H., Andersen, L., & Sørensen, C. S. (2005b). Capacity of Piles in Sand. Aalborg University, Denmark.

[4] Augustesen, A. H., Andersen, L., & Sørensen, C. S. (2006). Assessment of Time Functions for Piles Driven in Clay Department of Civil Engineering. Denmark Aalborg University.

[5] George, J. M., Wahab, M. M. A., & Kurian, V. J. (2015). Estimation of aging effects of piles in Malaysian offshore locations. Journal of Engineering Science and Technology, (In publication).

[6] Gilbert, R. B., Chen, J.-Y., Materek, B., Puskar, F., Carpenter, J., & Young, A. (2010). Comparison of Observed and Predicted Performance for Jacket Pile Foundations in Hurricanes. Paper presented at the

Offshore Technology Conference, Houston, Texas, USA

[7] Komurka, V. E., Wagner, A. B., & Edil, T. B. (2003). Estimating soil/pile set-up: The Wisconsin Highway Research Program (WHRP).

[8] Lied, E. K. W. (2006). A Study of Time effects on Pile Capacity NGI Report: Norwegian Geotechnical Institute.

[9] Narayanan, S. P., & Kabir, M. (2009). Structural Integrity Management for Fixed Offshore Platforms in Malaysia. World Academy of Science, Engineering and Technology.

[10] Nichols, N. W., Goh, T. K., & Bahar, H. (2006). Managing Structural Integrity for Aging Platform. Paper presented at the SPE Asia Pacific Oil and Gas Conference and Exhibition, Adelaide, Australia

[11] SACS Software Manual. (2010). from Engineering Dynamics Inc.