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An Approach to Characterise Cyclic Deflection of Piles in Calcareous Soil Media Under Offshore Wave Loading Conditions

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SYNOPSIS : Behaviour of piles subjected to cyclic lateral loads due to wave action is an important aspect which needs to be evaluated for analysing and designing these piles supporting offshore structures. The study on the model piles in calcareous soil media was therefore undertaken to investigate the cyclic pile deflection response under offshore wave loading conditions. The test results are analysed and interpreted to evolve an approach to characterise the cyclic deflection behaviour of piles under critical storm loading effect and normal wave loading action.

1. INTRODUCTION

Piles supporting offshore structures are constantly subjected to cyclic lateral loads due to wave action. The lateral load response of these piles under various conditions of wave loading is an important consideration in their analysis and design. The locations where offshore construction activities are carried out have in many instances calcareous subsurface deposits. However, the present knowledge about the behaviour of piles in calcareous soils under cyclic lateral loading is limited. A study to investigate the lateral load response of model piles in calcareous soil media under idealised wave loading action was therefore undertaken. The experimental investigations carried out under controlled laboratory conditions have specific relevance to Bombay High pile foundation problems. The paper highlights the analysis of the results of the investigation with respect to the following aspects :

(i) Characteristics and prediction of cyclic deflection of piles under storm loading,
(ii) Application of the basic resistance concept to pile-soil system to evaluate the cyclic pile deflection response with number of cycles.

2. EXPERIMENTAL INVESTIGATIONS

2.1 Soil Media

The soil used in the investigations was the artifically prepared calcareous model mix equivalent to Bombay High calcareous deposits in respect of their plasticity, strength and stress-strain nature. The mix with 40% beach sand, 56% calcium carbonate, 1.5% calcium hydroxide and 2.5% sodium-meta-silicate was prepared.

2.2 Pile Models

The model piles of length-to-diameter ratios (L/d) of 10, 15, 20, 30, 40 and 50 were made of stainless steel pipe of 25.4 mm outside diameter and with flexural rigidity (EI) of 1.055×10^6 kg-cm^2 . An additional pile model with L/d=50 and EI =0.331×10^6 kg-cm^2 (test denoted as 50(A)) was also used. The surface of piles was knurled to a particular grade in order to induce roughness equivalent to that of the prototype M.S. pipe piles used for offshore foundation.

2.3 Scheme of Testing Methodology

Three types of lateral loading conditions were considered viz. (i) static loading (ST), (ii) two-way cyclic loading for simulated storm wave effect (CYS) and (iii) two-way cyclic loading for simulated normal wave effect (CYN). Fig. 1 illustrates this scheme of loading. In CYS test series the two-way cyclic load amplitudes of different magnitudes were applied in stages each of 45 cycles with 0.05 Hz frequency till the pile deflection at ground level (y_g) was more than about 20-25% of pile diameter. The CYN tests were conducted by applying two-way cyclic load P of a fixed magnitude for 200 cycles, thereafter piles being tested statically. Thus CYS tests are viewed to represent extreme environmental condition whereas CYN tests are devised to simulate normal environmental effect of offshore wave loading conditions.

2.4 Experimental Set up and Procedure

Experiments were carried out in a masonary tank of size 1.34m x 1.0m x 2.0m (height). A simple and easy-to-operate mechanical system was developed and used for applying static as well as two-way cyclic lateral loads on model piles. It consisted of a lever arrangement on one side of the pile, a load hanger suspended over a pulley at the other side, a hinge type loading collar on the pile, cable connected spring balances, a supporting system, pulley adjusting brackets etc. Fig.2 shows schematically this set up.

The pile was positioned in place in the tank and the calcareous soil mix was uniformly compacted to the void ratio of 1.0 ± 0.05. The loading test was carried out after saturation and curring of soil media in 3% salt solution for 7 days.

3. CHARACTERISATION OF LATERAL DEFLECTION RESPONSE OF PILES

Some features of load-deflection curves with respect to ST, CYS and CYN loading conditions are reported earlier (Golait & Katti, 1988). Present discussion is focussed on further analysis of the test data to evolve an approach to characterise the cyclic deflection response of piles under CYS and CYN loadings.

3.1 Cyclic Deflection of Piles under Storm Loading

The deflection response of piles of various length ratios under

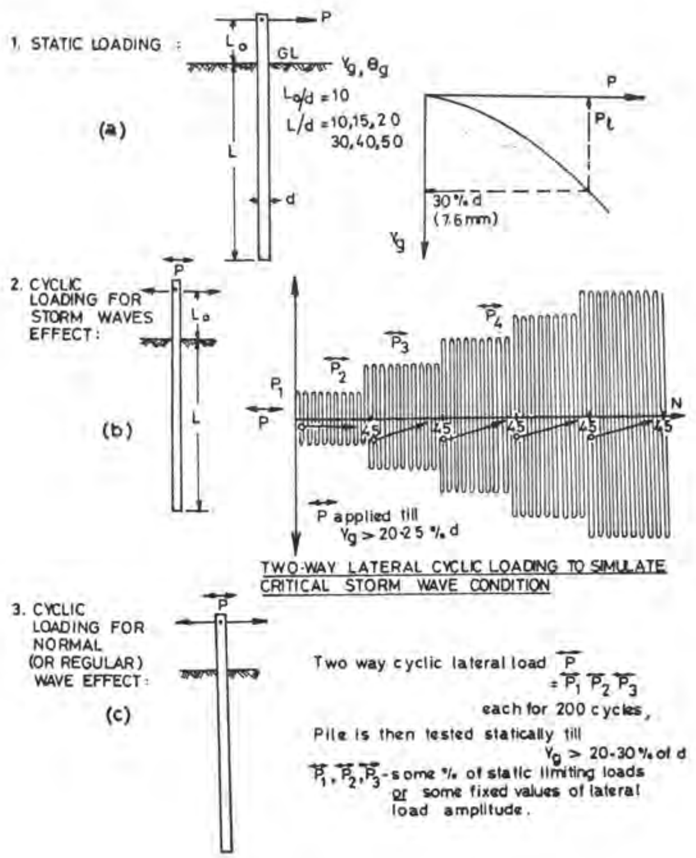

Figure 1. Idealised scheme of lateral loading on pile

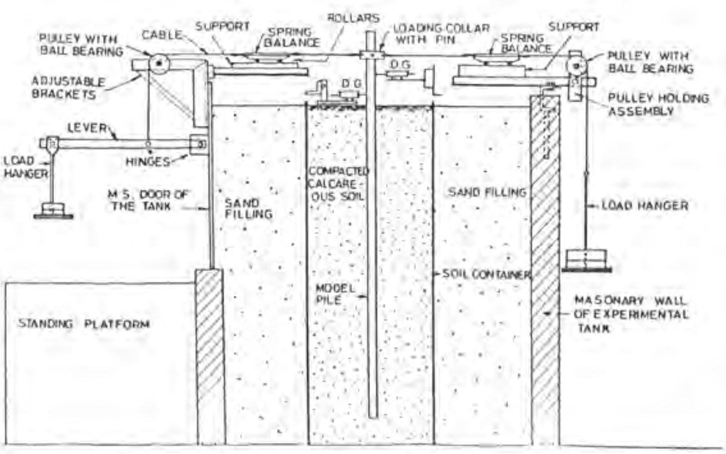

Figure 2. Experimental set up

multistage two-way cyclic loading simulating storm wave effect is shown in Fig. 3. It is seen that the cyclic pile deflection at ground level (y_g) under a particular load amplitude increases with number of cycles. However, large amplitudes cause continuous pile deflection at considerable rate. Thus, the cyclic load amplitude (i.e. height of waves in a particular wave parcel during storm) governs the progressive deflection with number of cycles. In the study, 45 cycles were applied in each loading stage. Fig. 4 depicts the schematic representation of the observed nature of pile deflection during various cyclic loading stages.

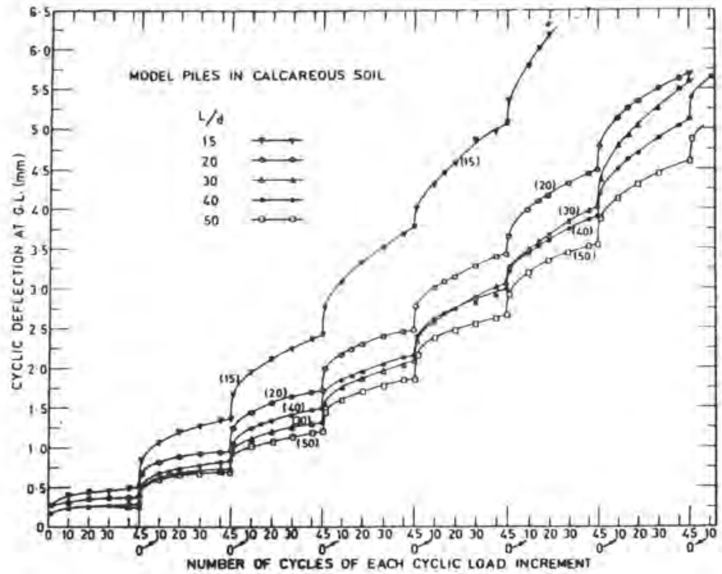

Figure 3. Cyclic deflection with number of cycles during CYS loading on piles

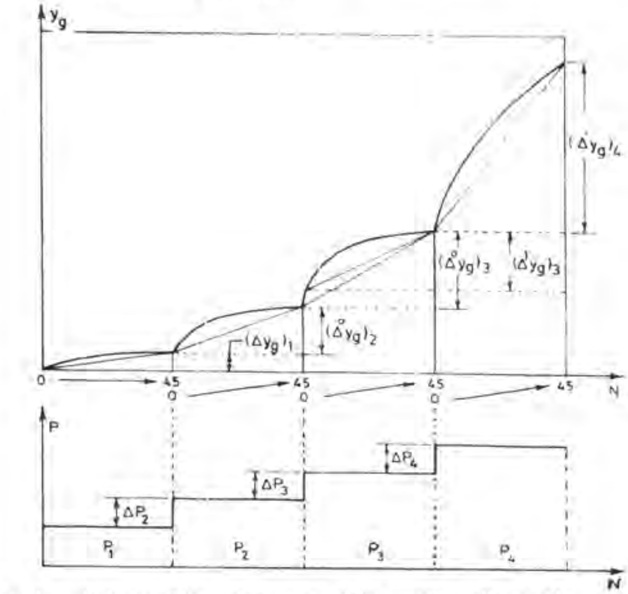

Figure 4. Schematic representation of observed cyclic deflection during storm loading

Let $\overset{o}{\Delta} y_g$ = differential deflection during 45 cycles of a loading stage

$$= (y_{45} - y_0) \tag{1}$$

where, y_{45} is the deflection at GL at the end of 45 cycles of the particular loading stage, and y_0 is the deflection before application of that loading stage.

Similarly, $\overset{1}{\Delta} y_g$ = differential deflection during the 1st and the 45th cycle of a loading stage

$$= (y_{45} - y_1) \tag{2}$$

where, y_1 is the deflection at the end of 1st cycle of that loading stage.

From the CYS test data, the values of $\overset{o}{\Delta} y_g$ and $\overset{1}{\Delta} y_g$ are

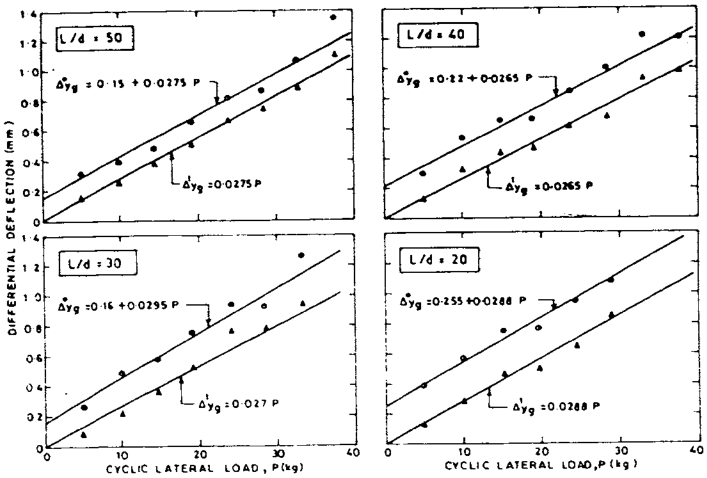

Figure 5. Differential deflections during CYS loading stages

calculated and are plotted against cyclic load amplitude P as shown in typical Fig. 5. It is evident that these differential deflection values increase with increasing cyclic load amplitude. The relations are linear and can be represented as :

$$\Delta \overset{o}{y}_g = a + b.P \tag{3}$$

$$\Delta \overset{1}{y}_g = b_1.P \tag{4}$$

where, a is the intercept on differential deflection ordinate and b & b_1 are the slopes of straight lines. It is clearly observed that the slopes of the two differential deflection lines are almost the same. Hence,

$$\Delta \overset{1}{y}_g \approx b.P \tag{5}$$

These expressions are empirical in nature and are valid for finite values of cyclic load amplitudes. The values of coefficients a,b and b_1 are found to depend on flexural rigidity of pile (Refer Table 1).

The characteristics of deflection response as expressed by Eq.3 is used in predicting the cyclic deflection of piles during strom wave loading.

A design storm is idealised to consist of n number of wave parcels of increasing wave heights. Thus, there will be n number of cyclic loading stages during generation of this storm.

Let, N = number of cycles in each loading stage

ΔP = increment in cyclic lateral force after N number of cycles of a loading stage

$P_1, P_2, \dots P_n$ = cyclic lateral force amplitudes during 1st, 2nd .... nth stage respectively

y_{gn} = pile deflection at the end of N cycles of load P_n.

Hence,

$$y_{gn} = \Delta \overset{o}{y}_{g1} + \Delta \overset{o}{y}_{g2} + \Delta \overset{o}{y}_{g3} + \dots + \Delta \overset{o}{y}_{gn}$$

$$= (a+b.P_1) + (a+b.P_2) + (a+b.P_3) + \dots + (a+b.P_n)$$

$$y_{gn} = n.a + b\sum_{i=1}^{n} P_i \tag{6}$$

Table I. Differential deflection coefficients

L/d	$EI \times 10^{-6}$ (kg-cm^2)	a (mm)	b (mm/kg)	b_1 (mm/kg)
15	1.055	0.28	0.0520	0.0520
20	1.055	0.25	0.0288	0.0288
30	1.055	0.16	0.0295	0.0275
40	1.055	0.22	0.0265	0.0265
50	1.055	0.15	0.0275	0.0275
50(A)	0.331	0.12	0.0650	0.0590

Table II. Comparison of experimental and computed deflections for pile L/d = 20 under CYS loading

Cyclic lateral load (kg)	Pile deflection, y_g(mm)	
	Experimental	Computed from Eq.6
0.00	0.000	0.000
5.00	0.392	0.395
10.00	0.957	0.942
15.00	1.710	1.629
19.50	2.473	2.446
24.25	3.427	3.399
28.75	4.508	4.482
33.20	5.686	5.693

If the design storm is idealised to cause the same ΔP in all the loading stages, the above equation is simplified as:

$$y_{gn} = n.a + b.\Delta P \sum_{i=1}^{n} i \tag{7}$$

A comparison of experimental and computed deflections (a typical case for a pile of L/d = 20 is shown in Table II) indicates that the predicted values using a and b coefficients in Eq.6 are closely in agreement with the experimental results. Equations of the form of 6 and 7 can thus be useful in predicting the deflection of pile during idealised design storm. However, for prototype pile behaviour the appropriate values of a and b need to be evaluated from large scale tests or from field test results.

3.2 Application of Basic Resistance Concept to Pile-Soil System

Janbu (1969) advocated the concept of resistance to deformation of soil based on cause-effect relationship. He defined the resistance as the ratio of differential cause to differential effect.

At BOSS-76, he suggested the application of this concept to effective stress interpretation of repeated loads. The approach of analysing the geotechnical problems, especially pertaining to cyclic loading, using this concept appears to be promising. However, not much work is reported in the literature on the application of this concept to foundation problems. An attempt is made in this section to extend this concept to pile-soil system and to evaluate the resistance to cyclic deflection of pile subjected to storm and normal wave loadings. A methodology for its possible application to pile foundation for predicting the cyclic deflection response is evolved.

The deflection of laterally loaded pile is inversely proportional to the flexural rigidity of pile (Matlock & Reese, 1960).

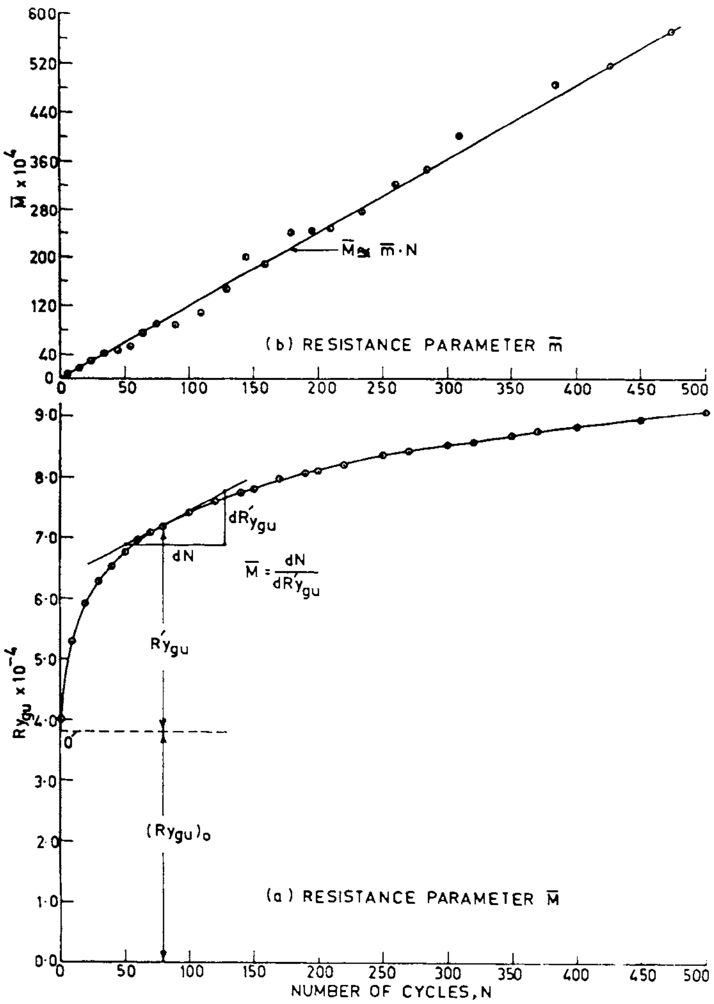

Figure 6. Cyclic deflection resistance parameters $\bar{M}$ & $\bar{m}$

A dimensionless parameter Ry_{gu}, defined as relative deflection per unit value of flexural rigidity of pile (i.e., say EI_u = 1.0 kg-cm^2) can therefore be expressed as :

$$Ry_{gu} = (y_g/d) \cdot (EI/EI_u) \tag{8}$$

A typical variation of Ry_{gu} with number of cycles N under lateral load amplitude of 15 kg (CYN-15k test on model pile of L/d = 50) is shown in Fig. 6(a). In this phenomenon, the cause is N and the effect is Ry_{gu}. Using Janbu's concept, the cyclic deflection resistance $\bar{M}$ is a dimensionless parameter expressed as :

$$\bar{M} = \frac{dN}{dRy_{gu}} \tag{9}$$

$\bar{M}$ is thus the slope of a tangent to the curve of Ry_{gu} vs. N at a point. In the cases of piles in calcareous soil media studied under the investigation programme, it has been found that $\bar{M}$ increases almost linearly with number of cycles (Fig. 6b). Hence,

$$\bar{M} = \bar{m} \cdot N \tag{10}$$

where, $\bar{m}$ = cyclic deflection resistance parameter. Combining Eqs. 9 & 10 and integrating between N = 1 and N,

$$Ry_{gu} = \frac{1}{\bar{m}} \cdot \log N \tag{11}$$

Eq. 11 essentially gives the effect of load cycles from 1 onwards. If the curve Ry_{gu} vs. N is extrapolated to zero cycle (i.e. the state of no-load-cycling condition) it intersects the ordinate at a point (shown as O' in Fig.6a) with respect to which values of Ry_{gu} are given by Eq. 11. Hence, the total cyclic deflection under given cyclic load will be,

$$Ry_{gu} = (Ry_{gu})_o + R'y_{gu} \tag{12}$$

where, $(Ry_{gu})_o$ = Ry_{gu} value corresponding to no-load-cycling condition and $R'y_{gu}$ = Ry_{gu} value corresponding to load cycling from N = 1 to N (as given by Eq.11). Hence,

$$\frac{y_g}{d} \cdot \frac{EI}{I} = Ry_{gu} = (Ry_{gu})_o + \frac{1}{\bar{m}} \cdot \log N$$

$$\text{or, } y_g = \frac{d}{EI}\left[(Ry_{gu})_o + \frac{1}{\bar{m}} \cdot \log N\right] \tag{13}$$

(a) **Deflection under CYN loading**

For the diameter and flexural rigidity of piles used in the investigations, the cyclic deflection resistance parameter $\bar{m}$ and the $(Ry_{gu})_o$ values are determined. (Refer Table III).

Table III. Values of $\bar{m}$ & $(Ry_{gu})_o$ - CYN load tests

Normal wave load amplitude P (kg)	L/d	$\bar{m} \times 10^4$	$(Ry_{gu})_o \times 10^4$	Remarks
10	20	2.00	2.45	Tests carried out
	40	2.50	2.35	upto 200
	50	1.80	2.50	cycles
15	50	1.20	3.80	...500...
20	20	0.63	6.50	
	40	0.55	5.50	...200...
	50	0.60	5.50	

For all the piles tested, the cyclic deflection response under CYN loading with various load amplitudes was evaluated using the resistance parameter, and the same was compared with the experimental results. A close agreement is observed between the two. This indicates the usefulness of the resistance concept in prediction of pile deflection under cyclic loading. A comparison of the computed and the experimentally observed deflection nature for a typical case of a pile of length ratio 50 under CYN loading of 10,15 and 20 kg load amplitudes is shown in Fig. 7 and 8.

In Fig. 9 is shown the normalised plot for variation of cyclic deflection with number of cycles for all the pile test results. In this presentation, the deflection at any cycle y_{gn} is normalised with respect to deflection at the end of 200th cycle y_{g200}. The average trend of the variation clearly indicates that the increase in pile deflection during initial cycling is very fast, and that with increasing number of cycles the rate of increase in deflection diminishes continuously. It is seen that the deflection at 10th, 30th and 50th

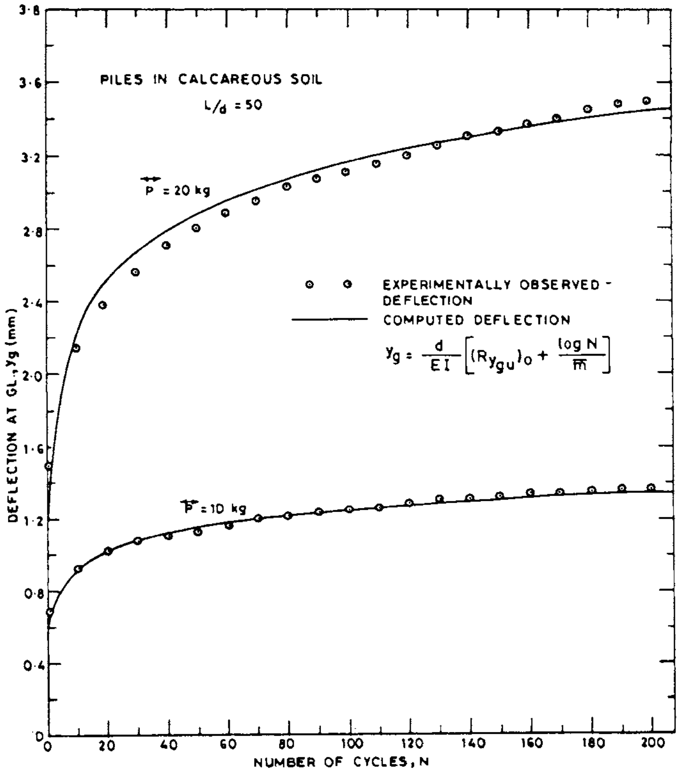

Figure 7. Cyclic deflection response of pile (L/d=50) under CYN loading of 10 kg and 20 kg

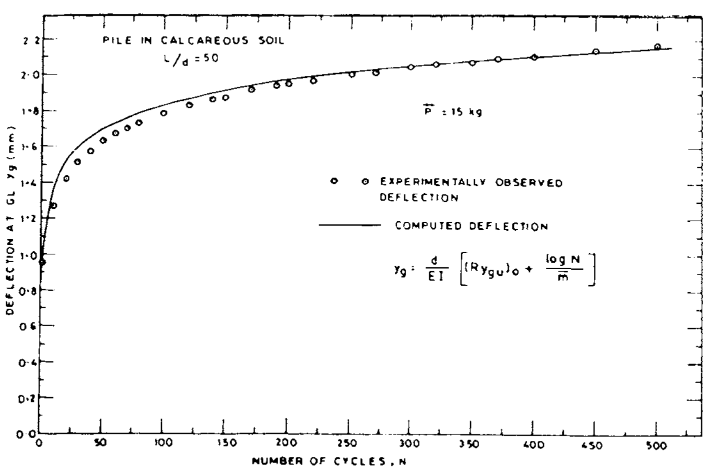

Figure 8. Cyclic deflection response of pile (L/d=50) under CYN Loading of 15 kg

cycles y_{gn} is about 60, 73 and 80% respectively of y_{g200}. Beyond 50 cycles or so, the deflection increase is at very small rate.

This nature of deflection response with number of normal wave load action has an important implication in the evaluation of pile stability. In general, for normal environmental conditions of offshore, the wave action causes lateral forces

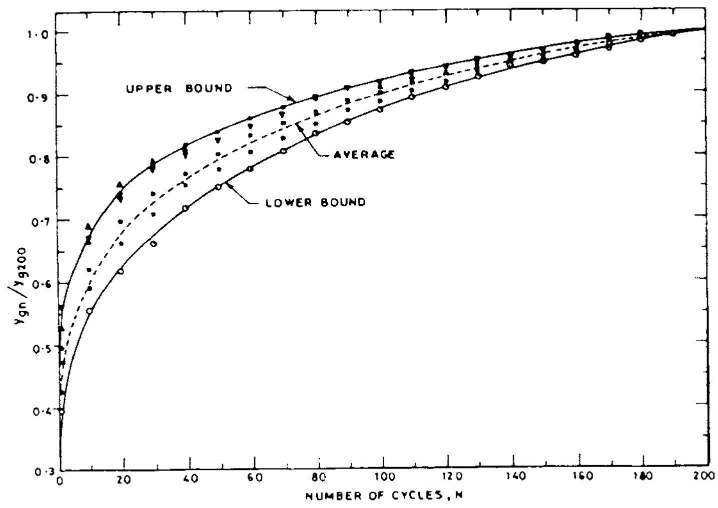

Figure 9. Normalised cyclic deflection nature of piles under CYN loading condition

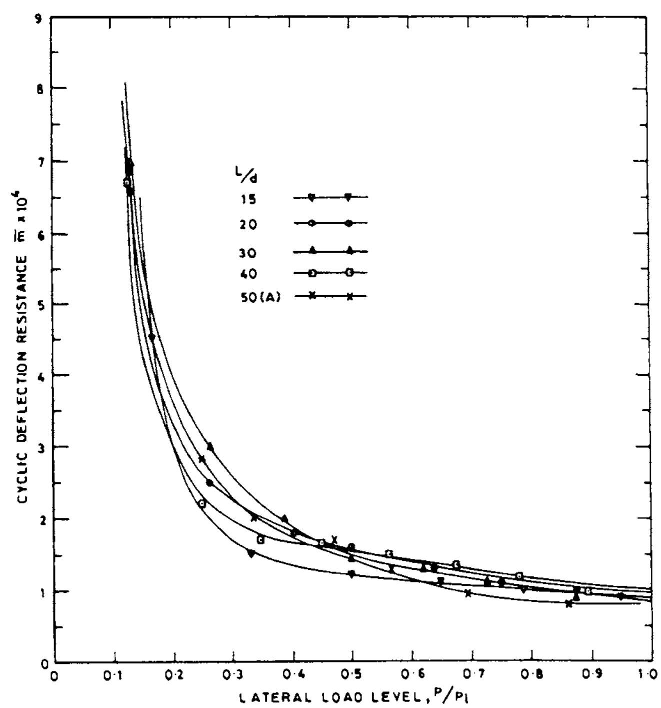

Figure 10. Variation of $\bar{m}$ with lateral load level-CYS loading

on pile foundation which may be very small as compared to the limiting lateral loads caused by the design storm etc. Thus, low amplitude lateral force will induce deflection of pile with number of cycles spread over a very long period of time. However, the rate of deflection increase will be small after initial cycles. The normal wave effect is therefore insignificant as compared to the storm wave effect. Regular waves of comparatively large dimensions may, however, pose problems of structural and functional stability of pile-supported platform.

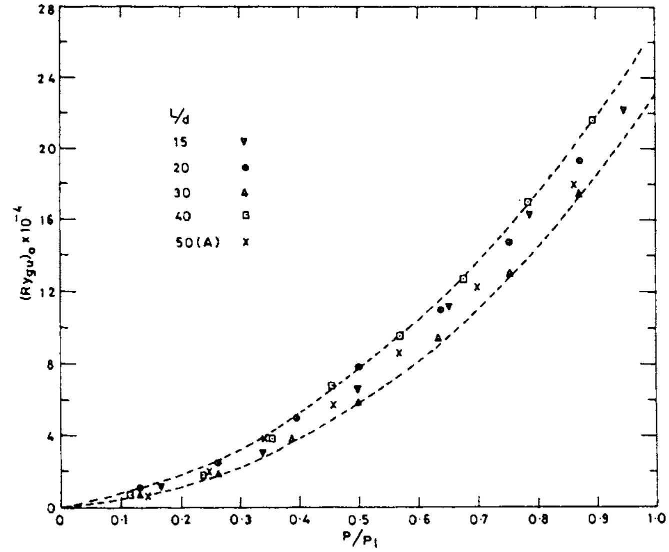

Figure 11. Variation of $(Ry_{gu})_o$ with lateral load level-CYS loading

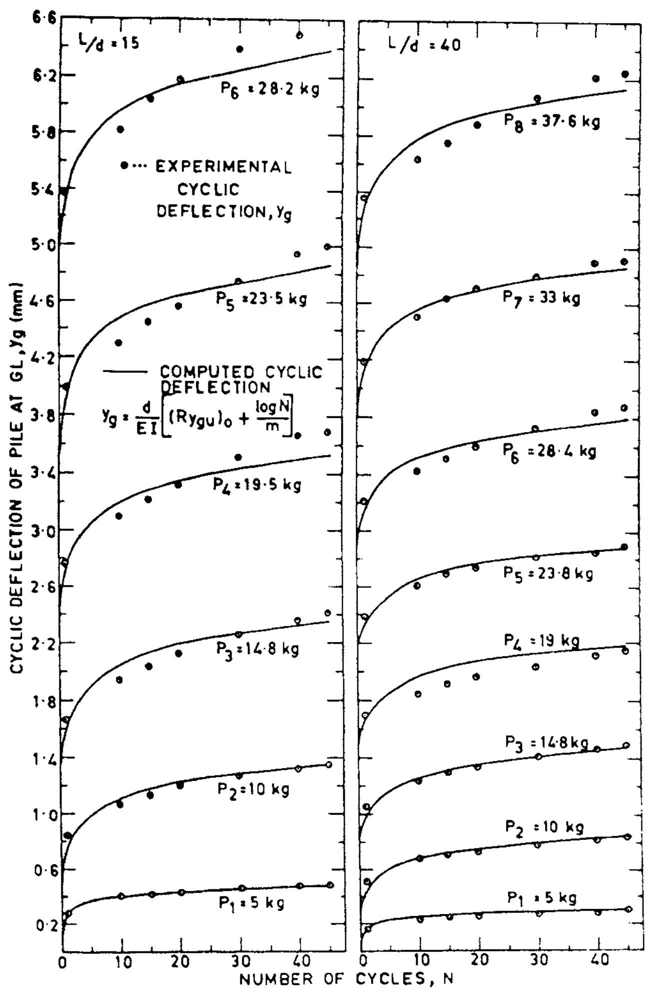

Figure 12. Experimental and computed deflection response of piles under CYS loading

(b) **Deflection under CYS loading**

Cyclic deflection resistance values for $\bar{m}$ and $(Ry_{gu})_o$ are calculated for all the loading stages of CYS load tests on all pile models. The cyclic lateral load is normalised for the respective limiting load values P_l for y_g = 0.3d criteria. The plots for $\bar{m}$ and $(Ry_{gu})_o$ vs. P/P_l are shown in figures 10 and 11 respectively. It is clearly seen that $\bar{m}$ decreases at a very rapid rate during lower range of loads upto about 35-40% load level. However, after this stage further decrease is very small and $\bar{m}$ tends to attain more or less a stable value.

$(Ry_{gu})_o$ being correlated to deflection corresponding to no-load cycling condition for a given load amplitude, it is observed to exhibit the variation similar to load-deflection nature. The cyclic deflections at various loading stages in CYS tests are computed using $\bar{m}$ and $(Ry_{gu})_o$ parameters in Eq. 13. A comparison of the computed cyclic deflection and the experimental results for typical cases of piles of L/d = 15 and 40 is shown in Fig. 12. A close agreement between the two is clearly seen from this figure.

4. CONCLUSIONS

The analysis of the experimental data of lateral load tests on piles in calcareous soil media under wave loading conditions is attemped to characterise the cyclic deflection response of piles. A simple approach is suggested to evaluate the cyclic deflection under idealised storm loads. The basic resistance concept relating cause to effect can be made applicable to a pile-soil system under cyclic loading. An approach based on this concept can be advantageously used to evaluate the cyclic deflection of piles with number of cycles of storm loading and normal wave action.

ACKNOWLEDGEMENTS

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