THE CAPACITY AND MECHANISM OF COUPLED SHEAR WALLS SUPPORTED BY PILE FOUNDATIONS

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SUMMARY

The simplified method to evaluate the characteristics of vertical restoring forces of pile foundations is proposed. The application of this method to the analysis of the capacity and mechanisms of coupled shear walls supported by pile foundations is presented.

INTRODUCTION

The investigations of vertical displacements of pile foundations is a requirement in order to analize the behavior of superstructure constructed with shear walls during an earthquake motion(Ref. 1,2). E.D'appolonia (Ref.3) H.G.Poulos (Ref. 4), R.Butterfield (Ref. 5) and S.Yao (Ref. 6) have studied on the vertical behaviors of single piles or pile groups in the half infinite elastic media, in static terms. As an extension of the methods employed in above studies, and taking the nonlinear property of the soil rigidity into consideration, the author was able to present an analysis on single pile or pile groups which are effective to the cyclic loading phenomena. Refering to these precise analysis and field experimental data observed (Ref. 7), the simplified method to predict the vertical displacements of piles or pile groups is presented in this report (Ref. 8).

THE SIMPLIFIED METHOD TO PREDICT THE SETTLEMENTS OF PILE FOUNDATIONS

Basic Concept

The load P_o acted at the pile head vertically is reacted in the ground by frictional force R_f and pile tip reaction force R_p as shown in the following eq.1.

$$P_o = R_f + R_p \qquad \text{or} \qquad P_t = R_{ft} + R_{pt} \qquad \text{-------- (1)}$$

The settlement of pile head δ is composed of the components S_1, S_2 and S_3 as shown in eq.2.

$$\delta = s_1 + S_2 + s_3 \qquad \text{or} \qquad \delta = s_{1t} + s_{2t} + s_{3t} \qquad \text{-------- (2)}$$

As illustratively explained in Fig.1, S_1 means the compressibility of pile shaft, S_2 means the settlement of the ground at pile tip generated by R_f and S_3, the settlement of the ground at pile tip generated by R_p which acts at the same pile tip. Although S_2 and S_3 should be solved by means of half infinite space media analysis, in this methodology the simplified method as shown in Fig.2, is presented. The original half infinite ground is substituted with the half infinite right truncated pyramid, where the calculated vertical displacement would be almost equal to that of the original. Thus, by limitting a scope of the description to a case of the pile groups, S_{2t} indicate the vertical displacement at the pile tip, due to the compressibility of half infinite right pyramid loaded by R_{ft} at it's truncated point. Similarly S_{3t}.

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is the vertical displacement of another half infinite truncated right pyramid at the pile tip level, due to the load R_{pt} acting on the same level. The symbols used are summerized and explained in Table 1..

Driven Piles

Driven piles give enough preloading or plastic strain to the surrounding soil of pile shaft or pile tip during it's driving process. Owing to the strain-hardening phenomena of ground materials, driven piles behave as perfectly elastic-plastic in vertical direction (Ref. 6,9). Accordingly, the following equations could be obtained in explaining the elastic state or pre-ultimate load. In this eq. η is an estimated constant from the ground-pile system, but it is not constant exactly. It is caused by the progressive plastic slip occurrence between soil and pile shaft surface.

Single Pile

$$s_1 = \frac{\{a+(1-a)\eta\}P_o \cdot L}{E_p \cdot A_p}$$

$$s_2 = \frac{(1-\eta)P_o}{E_s(L'\tan^2\alpha)\Pi} \quad , \quad s_3 = 0.817\,\frac{\eta \cdot P_o}{E_s \cdot d \cdot \Pi} \qquad \text{---(3)}$$

Pile Groups

$$s_{1t} = \frac{\{a+(1-a)\eta\}P_t \cdot L}{E_p \cdot A_p \cdot m}$$

$$s_{2t} = \frac{(1-\eta)P_t \cdot \log\dfrac{2L'\tan\alpha + l_{yo}}{2L'\tan\alpha + l_{xo}}}{2E_s(l_{yo}-l_{xo})\tan\alpha}$$

$$= \frac{(1-\eta)P_t}{2E_s(2L'\tan\alpha + l_o)\tan} \qquad (\text{if } l_{xo}=l_{yo}=l_o) \qquad \text{---- (4)}$$

$$s_{3t} = \frac{\eta \cdot P_t \cdot \log\dfrac{l_{yo}}{l_{xo}}}{2E_s(l_{yo}-l_{xo})\tan\alpha}$$

$$= \frac{\eta \cdot P_t}{2E_s \cdot l_o \cdot \tan\alpha} \qquad (\text{if } l_{xo}=l_{yo}=l_o)$$

Non-Displacement Piles

Compared with the driven piles, non-displacement piles(Cast in place piles or Bored piles) commonly do not give preloadings or plastic strains to the surrounding soils of pile shaft or pile tip during it's construction process, because of their peculiar construction method (Ref. 6,9). Therefor the vertical behaviors of these piles are characterized by the strain hardening settlement in case of virgin loading. The following equations are induced to predict the settlement of non-displacement piles in considering these situations(Ref. 6). The compressibility of pile shaft is still almost elastic. In addition, the settlement component S_{2t} or S_2 could be regarded as elastic because the distance between the loading level of R_{ft} or R_f and the pile tip level where the settlement should be estimated, is far enough to cause the stress due to R_{ft} or R_f to dissipate to small stress distribution level. So S_1 and S_2 for non-displacement piles are exact same formulae as S_1 and S_2 in eq.3 and eq.4 for the driven piles. On the settlement component S_3 or S_{3t}, the strain hardening behavior should be taken into account, as shown in the followings (Ref. 10).

Single Pile

$$S_3 = S_{3e} + S_{3pr} \qquad (5)$$

Where, S_{3e} is a purely elastic component which is the same S_3 given in eq.3. S_{3pr} is a plastic settlement component resulted from the strain hardening rule of soils near the pile tip and takes the quadric form of P_o as follows(Ref.6,10).

$$S_{3pr} = \frac{4.9\,\eta^2\,P_o^2}{R_{pu}\,\pi\,E_s\,D} \qquad (6)$$

Eq.6 is valid only when P_o is a virgin load.

Pile Groups As for the settlement component S_3, in case of pile groups, the term S_{3Br} is added to the right side of eq.5 for single piles. Thus it takes the following form eq.7.

$$S_3 = S_{3e} + S_{3pr} + S_{3Br} \qquad (7)$$

The terms $S_{3e} + S_{3pr}$ in the right side of eq.7 are exact the same as those of eq.5. The new term S_{3Br} means the plastic settlement component resulted from the strain hardening rule of soils as observed block settlement behavior of pile groups near pile tips and it takes the quadric form of P_t as described in the following eq.8.

$$\left.\begin{aligned} S_{3Br} &= \frac{6\eta^2 \cdot P_t^2 \log\dfrac{l_{yo}}{l_{xo}}}{2R_{ptu}\cdot E_s(l_{yo}-l_{xo})\tan\alpha} \\ &= \frac{6\eta^2\cdot P_t^2}{2R_{ptu}\cdot E_s\cdot l_o\tan\alpha} \qquad (\text{if } l_{xo}=l_{yo}=l_o) \end{aligned}\right\} \text{---} \quad (8)$$

These components expressed by eq.6 and eq.8 are also illustrated in Fig.3, where the shaded zone in Fig.3(a) shows nonelastic but strain hardening zone which induce the penetration settlement and the shaded zone in Fig.3(b) the similar zone for the block settlements (Ref. 6). In case of unloading process, the nondisplacement pile also shows the perfectly elastic behavior. Therefor $\Delta S_3=\Delta S_{3e}$, that is $\Delta S_{3pr}=\Delta S_{3Br}=0$. in eq.7, where Δ shows an incremental quantity of each component. The author should comment here that eq.5 and eq.7 tend to give almost upper limit of the plastic settlement quantity of nondisplacement piles compared with many field data which locate generally between the curves given by eq.3 and eq.4 and the curves given based on eqs.5 or 7, if the reasonable constants are employed as shown in the following paragraph.

Settlement Rigidity k

The analysis of pile-superstructure system could become available by employing an application of the load-settlement relations mentioned above. In conducting the analysis, the settlement rigidity of pile head $k=P_o/\delta$ or P_t/δ would be useful. As an example of actual use of eq.3 or eq.4 of driven piles, the author recommends the following constants, $a=0.5$, $\nu=0.4$, $\bar{L}'=1/3$, $\alpha=40^o$. Thus, from eq.3 and eq.4, k is derived as follows.

Single Pile

$$\frac{1}{k} = \frac{\delta}{P_o} = \frac{(1+\eta)L}{2E_p \cdot A_p} + \{0.484(1-\eta) + 0.093\frac{\eta}{\bar{d}}\}\frac{1}{G_s \cdot L} \quad \text{--(9)}$$

Pile Groups

$$\frac{1}{k} = \frac{\delta}{P_t} = \frac{(1+\eta)L}{2m \cdot E_p \cdot A_p} + \{\frac{(1-\eta)}{2.629+1.677\bar{l}_o} + \frac{\eta}{4.70\bar{l}_o}\}\frac{1}{G_s \cdot L} \quad \text{--(10)}$$

where, $\eta=0.2$ is to be recommended when P_o is small, and $\eta=(P_o-R_{fu})/P_o$ when $P_o \geqq P_f$. To estimate the ultimate strength of a pile, following formulae are recommended in Architectural Institute of Japan (AIJ). $30 \cdot \bar{N} \cdot A_p+(N_s \cdot L_s/5+q_u \cdot L_c/2) \cdot \psi$ tf for pushing down, and $(N_s \cdot L_s/5+q_u \cdot L_c) \cdot \psi$ tf for pulling up, where $\bar{N}$:SPT N value around pile tip, N_s:SPT N value of intermediate sandy layer of thickness L_s, q_u:uniaxial strength of intermediate clay layer of thickness L_c, ψ:perimeter of pile shaft. In this report, these formulae are recommended to be available for both driven piles and nondisplacement piles, and the ground elastic constants $G_s=100.N$ tf/m^2(N:SPT N) for sandy layer,and $G_s=50.Z$ tf/m^2 (Z:depth in meters from G.L.) for normally consolidated clay, could be recommended (Ref. 11).

BEARING CAPACITY AND RESTORING FORCE CHARACTERISTICS OF PILE FOUNDATION

The above mentioned vertical behaviors of piles are resulted from soil mechanics characteristics, but in estimating the overall strength of pile foundation, the strength of pile shaft or other parts should also be taken into accounts. Fig.4 shows the axial forces (P) - bending momement (M) - (shearing forces) interactive curve of a pile shaft member. After the analysis of combined stress condition in pile shaft, the ultimate axial strength should be obtained from Fig.4. The pulled up strength of a pile caused from soil-pile surface shear strength would be near R_{fu}, and the isotropic hardening rule with respect to pile surface shear behavior is to be assumed, then the displacement characteristics of pulled up piles could be the same as pushed down piles under the load $P \leqq P_f'$. In table 2, some critical loads at pile head are summerized and defined, which are important in considering the characteristic restoring forces of piles. At each critical load, the supporting mechanisms would somewhat change, accordingly the vertical displacement characteristics would also change. In Fig.5, a diagram on the vertical characteristics of restoring forces is illustrated. As shown in Fig.5, the load at pile head generated by seismic load Q should start from the point of the long term reaction force P_L on abscissa of Fig.5.

THE CAPACITY AND DEFORMATION OF PILE - COUPLED SHEAR WALL SYSTEM

Two coupled shear walls with coupling beams which are plane symmetry have been analysed as shown in Fig.6. The symbols used in the analysis are summerized in table 3. The fundamental equations are as follows which are the equibrium equations of vertical forces and moments(eq.11) about the half left of Fig.

6 and the constitutive relations(eq.12). Equations are formed under the intial condition where long term load W is working.

$$R_1 + R_2 + \Sigma\, 2M_i/l = 0. \quad , \quad Q\cdot H + R_1\cdot L - \Sigma\, M_i = 0. \quad \text{-------- (11)}$$

$$M_i = K_{Bi}(\theta - R)/2 \;,\; |M_i| \leq M_{iu} \;,\; R_j = k\cdot\delta_j \;,\; |R_j| \leq |R_{ju}| \quad \text{-------- (12)}$$

where $1/K_{Bi} = 1/K_{mi} + 1/K_{si}$, $\bar{K}_{mi} = 12E\cdot K_i^j$, $i = 0,1\sim n$, $j=1,2$

The assumptions on this analysis are the followings. ·Coupling beams and pile foundations behave as perfectly elastic-plastic and shear walls as rigid-plastic. ·Seismic load distributions are substituted with a equivalent total load 2Q which acts at an equivalent level H from the ground level. ·Coupling beams behave as bending members being dominant, therefor $K_{Bi} = K_{mi}$. ·The examined ground profile is shown in Fig.7, and the constants of the ground,piles and superstructures are summerized in table 4 and 5. ·For simplisity,$k_1 = k_2 = k$.

The Results of Analysis

The results of case I (for steel pile) and case II (for prestressed concrete pile) are shown in Figs.8 and 9. In both cases, the first yieldings occur at the footing beam and the second yieldings occur at the coupling beams. These are shown as breaking points Y1 and Y2 in the figures. The last yielding that is the formation of failure mechanisms, occurs at the pushing down pile (R_1') in case I, and at the pulling up pile(R_1) in case II where the tensile collapse of P.C.pile has occured. In case I, before getting this capacity load the yielding of shear walls should also be taken into account. To complete these mechanisms, some ductility of beam flexure should be required as shown in Figs. 8 and 9 with respect (θ-R). The ratio $\phi = K_B/K_F$ could be important parameter in the analysis, where K_B is the total rigidity of coupling beams and K_F is the rocking spring constant of the isolated cantilever wall. The symbols are summerized in table 6. The elastic deformations obtained are

$$\delta_1/\theta_o L = -\{1+\alpha(1+2\alpha)\phi\}/A \quad , \quad \delta_2/L\theta_o = (1-\alpha\phi)/A \quad \text{------------(13)}$$

where $A = 1 + \{(1+2\alpha)^2 + 1\}\phi/2$. And the ratios of some critical loads where some members reach ultimate states, are given as follows.using coefficients $CR_1 \sim CR_4$.

$$\left.\begin{aligned} Q_{um}/Q_{u1} &= \{m\cdot M_{iu}/R_{1u}\cdot L\}\cdot CR_1 \;, & CR_1 &= \bar{K}\,\{1+\alpha(1+2\alpha)\phi\}/K_i(1+\alpha)\phi \\ Q_{um}/Q_{u2} &= \{m\cdot M_{iu}/R_{2u}\cdot L\}\cdot CR_2 \;, & CR_2 &= \bar{K}(1-\alpha\phi)/K_i(1+\alpha)\phi \\ Q_{u1}/Q_{u2} &= (R_{1u}/R_{2u})\cdot CR_3 \;, & CR_3 &= (1-\alpha\phi)/\{1+\alpha(1+2\alpha)\phi\} \\ Q_{umi}/Q_{umo} &= (m\cdot M_{iu}/M_{ou})\cdot CR_4 \;, & CR_4 &= K_o/K_i \end{aligned}\right\} \text{---(14)}$$

From eq.13,the deformation modes of this structure can be classified as shown in Fig.10 according to the formula $1-\alpha\phi$. When $1-\alpha\phi \geqq 0$. the independent rocking, and when $1-\alpha\phi \leqq 0$. the entire rocking of this structure will be predicted. From substituting unit with the left sides of eqs.14,that is $Q_{um}/Q_{u1} = Q_{um}/Q_{u1} = Q_{u1}/Q_{u2} = Q_{umi}/Q_{umo} = 1.$, the discriminants can be obtained, using the critical strength ratios of members ($CR_1 \sim CR_4$) defined in eqs.14 as follows.

$$\left.\begin{aligned} R_{1u}\cdot L/m\cdot M_{iu} &= CR_1 \;, & R_{2u}\cdot L/m\cdot M_{iu} &= CR_2 \\ R_{2u}/R_{1u} &= CR_3 \;, & M_{ou}/m\cdot M_{iu} &= CR_4 \end{aligned}\right\} \text{----------- (15)}$$

If all of the four equations in eqs.15 are valid, it means that all members reach yielding simultaneously and at the same time the system forms the failure mechanism. Usually, various other cases are presumed based on eq.15.

For an example, if $R_{1u}\cdot L/m\cdot M_{iu} < CR_1$ is valid, it means that the yielding of rocking moment resulted from the ultimate strength of pile foundation (R_{1u}), occurs earlier than the yielding of coupling beams, that is the pseudo strong beam - weak foundation system. And the inverse sign of inequality means the pseudo strong foundation - weak coupling beam system.

CONCLUDING REMARKS

The simplified method to predict the characteristics of restoring forces of pile foundations was proposed and an application of this method was presented.

The discriminant for deformation modes of coupled shear wall structure was $1-\alpha\phi$, and the usefulness of critical strength ratio CR_1, CR_2, CR_3, CR_4 was discussed using eq.15.

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REFERENCES

(1) M.Wakabayashi, K.Minami, Y.Nishimura etal,"Experimental study on elasto-plastic deformations of R/C frames with coupled shear wall,part6", Abstracts of the Annual Convention of AIJ, 1979 (in Japanese)
(2) V.V.Bertero,"Seismic Behavior of R/C wall structural systems", Proc.7th WCEE,Vol.6,1980
(3) E.D'Appolonia and J.P.Romualdi,"Load transfer in end bearing steel H-piles",Jour. Soil Mechanics and Found. Division,ASCE,Vol.89,SM2,1963
(4) H.G.Poulos,"Analysys of the settlement of pile groups",Geotechnique, Vol.18,NO.4,1968
(5) R.Butterfield and P.K.Banerjee,"The elastic analysis of compressible piles and pile groups",Geotechnique,Vol.21,NO.1,1971
(6) S.Yao,"The load-deformation behaviors of piled foundations",Doctral thesis, 1979 (in Japanese)
(7) V.G.Berezantzev,etal,"Load bearing capacity and deformation of piled foundation",Proc.5th ICSMFE,Vol.2,1961
(8) S.Yao and K.Yamagata,"The simplified method to predict the settlements of piles or pile groups,part 1",The 16th Japan National Conference on Soil Mechanics and Foundation Engineering,1981 (in Japanese)
(9) K.Yamagata and S.Yao,"Studies on settlement characteristics of piles and pile groups,part 2",Transactions of AIJ,NO.270,Aug.,1978 (in Japanese)
(10) S.Yao and K.Yamagata,"The simplified method to predict the settlements of piles or pile groups,part 3",Abstracts of the ann. conv. AIJ,1983
(11) S.Yao and K.Yamagata,"On the settlements and bearing capacity considering for the design criteria of piled foundations",Abstracts of the ann. conv. AIJ, 1982 (in Japanese)

Table 1. Definitions of Symbols
(for input data)

A_p : net area of pile shaft section
d : pile diameter
L : embeded length of pile
a : distributing factor of frictional stress R_f
L' :distance of equivalent loading point of R_f or R_{f_t} from pile tip
η : load transmitting factor at pile tip, R_p/P_o or R_{pt}/P_t
m : number of piles in pile groups
l_{x_o}, l_{y_o} : scale of perimeter of pile groups
E_p : young's modulus of pile material
E_s : young's modulus of ground soil
ν : poisson's ratio of ground soil

P_o, P_t : load at pile head
R_f, R_{ft}: total frictional force
R_p, R_{pt}: reacting force at pile tip
R_{pu}, R_{ptu} :ultimate strength of R_p or R_{pt}
R_{fu}, R_{ftu} :ultimate strength of R_f or R_{ft}
S_1, S_2, S_3 :refer to Fig.1
δ : vertical displacement of pile head
α : angle of leaning in Fig.2
$\bar{d}$: d/L
$\bar{l}_o$: l_o/L
$\bar{L}'$: L'/L

(subscript t means the case of pile groups)

Table 3. Definitions of Symbols

R_1, R_2 : reaction force on pile foundation
R_{1u}, R_{2u} : ultimate strength of $R1, R2$
M_i : end moment of coupling beam i (i=0. means the footing beam)
M_{iu}: ultimate strength of M_i
Q : holizontal seismic load
H : the level where Q acts
n : number of floors of building
L, l: space of span of building in Fig.6
m : number of coupling beams which have the same K_i
θ : rocking angle of coupled shear wall
R : rotation angle of coupling beams
E : young's modulus of coupling beams
δ_1, δ_2 : vertical displacement of pile foundation,downwards as positive
K_i : rigidity of coupling beam i
k_1, k_2 : displacement rigidity of pile foundation
α : L/l
K_{mi}, K_{si} : bending or shearing rigidity of coupling beam i
K_{Bi} : refered to eq.12

Table 2. Definitions of Symbols

(Capital P means the load acting on one pile in the foundation where the reacting forces R_1 or R_2 are acting)

P_l : long term load
P_{pc}: ultimate compression strength of pile shaft
P_{pt}: ultimate tention strength of pile shaft
P_f : P under the condition of $R_f=R_{fu}$
P_1 : P under the condition of $R_p=R_{pu}/3$
P_2 : ultimate bearing capacity of P ($R_f=R_{fu}$ and $R_p=R_{pu}$)
P_f': ultimate bearing capacity of P of up lift ($R_f=R_{fu}$ and $R_p=0.$)

Table 4. Input Data for piles

		Case I	Case II	
A_p	:	0.016 ,	0.181	m^2
d	:	0.6 ,	0.6	m
E_p	:	21. ,	4. $\times 10^6$	t/m^2
E_s	:	4200.		t/m^2
L	:	25.5		m
l_o	:	1.5		m
m	:	3 piles		
η	:	0.2		
R_{fu}	:	209.		tf
R_{pu}	:	339.		tf
R_{1u} (m=3)	:	1646. for pushing 627. for pulling		tf tf
R_{2u} (m=3)	:	1646. for pushing 627. for pulling		tf tf
P_{pc}	:	501. ,	1000.	tf
P_{pt}	:	501. ,	100.	tf
k (m=3)	:	2.46 ,	3.01 $\times 10^4$	t/m

Table 5. Input Data for system

	L	:	6.	m
	l	:	6.	m
	H	:	31.5	m
	n	:	9 stories	
	K_o	:	6.94 $\times 10^{-3}$	m^3
K_1 ~	K_n	:	2.31 $\times 10^{-3}$	m^3
	E	:	2.1 $\times 10^6$	t/m^2
	M_{ou}	:	255.2	tm
M_{1u} ~	M_{nu}	:	127.6	tm

Table 6. Definitions of Symbols

$K_F = k \cdot L^2$
$K_B = 12E \cdot \bar{K} \qquad (\bar{K} = \Sigma K_i)$
$\phi = K_B/K_F$
$\Theta_O = Q \cdot H/K_F$
Q_{um_i} : critical load of Q when coupling beam i yield with M_{iu}
Q_{umo} : critical load of Q when footing beam yields with M_{ou}
Q_{um} : minor one of Q_{umi} and Q_{umo}
Q_{u1} : critical load of Q when pile foundation yields with R_{1u}
Q_{u2} : critical load of Q when pile foundation yields with R_{2u}
Q_u : capacity of Q due to failure mechanism of system

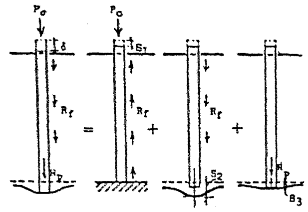

Fig.1 Illustrative explanation for eq.2

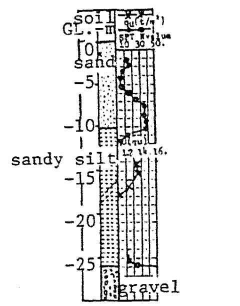

Fig.7 Soil profile employed in analysis

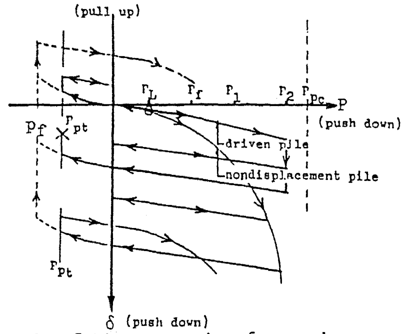

Fig.5 The restoring force characteristics of vertical displacements of piles

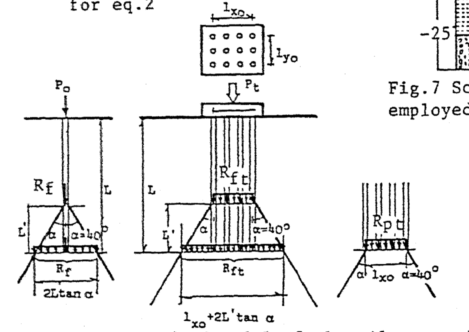

Fig.2 The simplified model of the pile-ground system

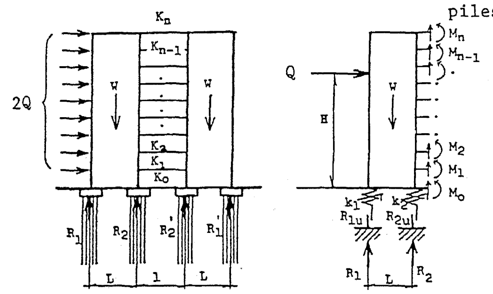

Fig.6 The model analized

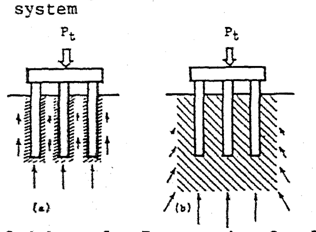

Fig.3 Scheme for Penetration Settlement(a) and Block Settlement(b)

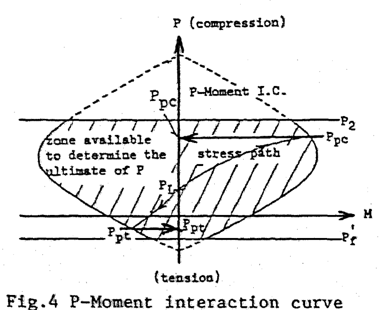

Fig.4 P-Moment interaction curve of a pile shaft

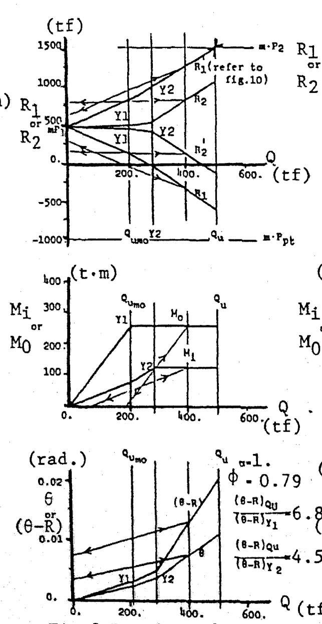

Fig.8 Results of analysis (Case 1)

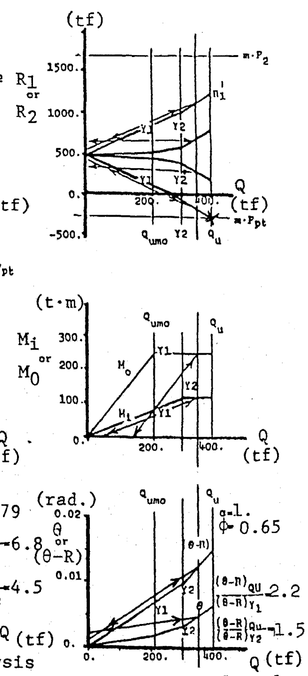

Fig.9 Results of analysis (Case II)

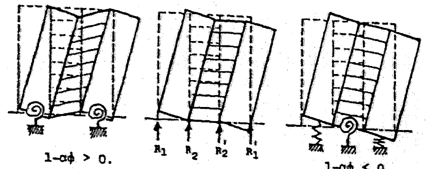

Fig.10 The classification of deformation of the system