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Viscoelastic Behaviour of Composite Piles Used in the Construction of Quays

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Abstract

The purpose of this study was to investigate the viscoelastic behaviour of a concrete-filled steel tube pile with circular section used in quay constructions under long-term steady load. Deformations that depend on time are important for designing this type of pile. In order to determine these deformations, an experimental study was done on a real size pile. Variations in deformations were observed over seven months. The observed deformations were compared with the calculated deformations according to the proposed calculation methods. The experimental results and calculated results were in agreement. A creep coefficient was determined for long-term behaviour calculations.

Key words: Pile, Creep, Shrinkage, Numerical analysis, Strain, Stress.

Introduction

The design of concrete-filled steel tube piles used for the construction of quays may be carried out using one of various calculation methods. Previous studies carried out on concrete-filled steel tube piles were about short-term behaviour. In these studies, the short-term behaviour of concrete filled steel tube piles under axial and eccentric loads were investigated. However, the long-term behaviour of these type of piles under constant loads is different, hence the design should be done accordingly. There is no experimental study carried out on the long-term behaviour of concrete-filled steel tube piles. These composite piles were made of steel and concrete. Therefore, stress transfers occur from concrete to steel under constant loads in the long term. This experimental study was needed in order to observe these stress transfers. The study was carried out on a real size pile. In the concrete and steel part at the cross-section of the pile dial gauges were installed. Measurements of the time-dependent deformations were obtained by reading the dial gauges. As a result of this experimental work, a creep coefficient for the design of these composite piles was determined.

Models of Shrinkage and Creep for Concrete

These models are given as follows:

CEB-FIP-1990

Creep

The creep coefficient is estimated from the sum of delayed elastic strain, initial flow and delayed flow components,

$$\phi_{28}(t_1, t_o) = \beta_a(t_o) + \phi_d \beta_d(t - t_o) + \phi_f[\beta_f(t) - \beta_f(t_o)] \tag{1}$$

$$\beta_a(t_o) = 0.8\left[1 - \frac{f_c(t_o)}{f_c\infty}\right] \tag{2}$$

In the above equations, β_a is the initial flow and strength ratio $f_c(t_o)/f_c\infty$ can be expressed as

$$\frac{f_c(t_o)}{f_c\infty} = \frac{1}{1.276}\left(\frac{t_o}{4.2 + 0.85t_o}\right)^{3/2} \tag{3}$$

The following expression can be used for the delayed elastic strain:

$$\phi_d\beta_d(t-t_o) = 0.4\left[0.73\left(1-e^{-0.01(t-t_o)}\right)+0.27\right] \tag{4}$$

The last term of Equation (1) can be written as

$$\phi_f[\beta_f(t)-\beta_f(t_o)] = \phi_f\left[\left(\frac{t}{t+H_f}\right)^{1/3}-\left(\frac{t_o}{t_o+H_f}\right)^{1/3}\right] \tag{5}$$

ϕ_f is the flow coefficient $= \phi_{f1} \times \phi_{f2}$

H_f is a function of h_o (notional thickness)

$$h_o = \lambda\frac{2A_c}{u} \tag{6}$$

where A_c= Cross-sectional area of the member (mm^2)
u = Perimeter exposed to drying (mm)
λ = Coefficient for ambient humidity

The elastic strain-plus-creep deformation under unit stress, or creep function (10^{-3} per MPa), is given by

$$\Phi(t,t_o) = \frac{1}{E_c(t_o)} + \frac{\phi_{28}(t,t_o)}{E_{c28}} \tag{7}$$

Now

$$E_c(t_o) = 9.5[f_{cy1}(t_o)]^{1/3} \text{ (considering stress)} \tag{8}$$

and the following equation is a restatement of CEB-FIP:

$$E_c(t_o) = E_{c28}\left[\frac{t_o}{4.2+0.85t_o}\right]^{1/2} \tag{9}$$

(considering elasticity modulus)

in (7) to (9), the units for modulus of elasticity E_c and strength f_{cy1} are GPa and MPa respectively.

Shrinkage

The strain due to shrinkage which occurs in an interval of time ($t-t_{sh,o}$) is given by:

$$\varepsilon_{sh}(t,t_{sh,o}) = \varepsilon_{sh,o}[\beta_{sh}(t)-\beta_{sh}(t_{sh,o})] \tag{10}$$

where $\varepsilon_{sh,o}$= Basic shrinkage coefficient $= \varepsilon_{sh1} \times \varepsilon_{sh2}$
β_{sh} = A function for the development of shrinkage with time
t = Age of concrete
$t_{sh,o}$ = Age at which drying starts

American Concrete Institute (ACI)-1992

Creep

The creep coefficient is the ratio of creep at any age t, after application of load at time t_o, to the elastic strain at the age at application of load t_o:

$$\phi(t,t_o) = \frac{(t-t_o)^{0.6}}{10+(t-t_o)^{0.6}}\phi_\infty(t_o) \tag{11}$$

where ($t-t_o$)= Time since application of load
ϕ_∞ = Ultimate creep coefficient which is given by

$$\phi_\infty(t_o) = 2.35k_1'k_2'k_3'k_4'k_6'k_7' \tag{12}$$

$k_1' = 1.27 - 0.006h$	h = Relative humidity $\geqslant 40$
$k_2' = 1.13t_o^{-0.095}$	
$k_3' = 0.82 + 0.00264S_f$	S_f = Slump of fresh concrete (mm)
$k_4' = 1.14 - 0.00091d$	for ($t-t_o$) $\leqslant$ 1 year, d is the average thickness of concrete
$k_6' = 0.88 + 0.0024s/a$	s/a = Fine aggregate/total aggregate
$k_7' = 0.46 + 0.09A$	A = Air content (percent)

The elastic strain-plus-creep deformation under a unit stress (10^{-3} per MPa), is given by

$$\Phi(t,t_o) = \frac{1}{E_c(t_o)}[1+\phi(t,t_o)] \tag{13}$$

where $E_c(t_o)$ = Modulus of elasticity at the age at application of load t_o, which is related to the 28-day compressive strength, $f_{cy(28)}$ by

$$E_c(t_o) = 42.8\times10^{-6}\left[\rho^3 f_{cy1}(t_o)\right]^{1/2} \tag{14}$$

$$f_{cy1}(t_o) = \frac{t_o}{A+Bt_o}f_{cy1(28)} \tag{15}$$

where E_c is in GPa
$f_{cy1}(t_o)$, $f_{cy1(28)}$ are in MPa
ρ = Density of concrete (kg/m^3)
A and B depend on the type of cement and curing conditions
A = 4 and B = 0.985 for normal cement

Shrinkage

Shrinkage at time t, measured from the start of drying $t_{sh,o}$ is expressed as follows:

$$\varepsilon_{sh}(t,t_{sh,o}) = \frac{(t-t_{sh,o})}{55+(t-t_{sh,o})}\varepsilon_{sh\infty} \tag{16}$$

where ε_{sh}= Shrinkage (10^{-6})

$$\begin{aligned}\varepsilon_{sh\infty} &= \text{Ultimate shrinkage}\\ &= 780\times10^{-6}k_5'k_1'k_4'k_3'k_6'k_8'k_7'\end{aligned} \tag{17}$$

Bazant and Panula's model II-1978

Creep

The basic creep function, elastic strain-plus-basic creep under unit stress at any time t for concrete loaded at the age of t_o, is expressed as

$$\Phi_b(t,t_o) = \frac{1}{E'}[1+\phi_b'(t,t_o)] \tag{18}$$

where $\Phi_b(t,t_o)$ = Basic creep function (10^{-3} per MPa)
$\phi_b'(t,t_o)$ = Basic creep coefficient which given by

$$\phi_b'(t,t_o) = B\big[(t_o)^{-m}+0.05\big](t-t_o)^n \tag{19}$$

The parameters E′, B, m and n are all functions of the 28-day strength.

$$\frac{1}{E'} = 0.01306+3.203(f_{cy1/(28)})^{-2}(10^{-3}/\mu Pa) \tag{20}$$

$B = 0.3+152.2(f_{cy1(28)})^{-1.2}$
$m = 0.28+47.541(f_{cy1(28)})^{-2}$
$n = 0.115+0.183\times10^{-6}(f_{cy1(28)})^{3.4}$
$f_{cy1/(28)}$ = 28-day cylinder strength (MPa)

Shrinkage

Shrinkage of concrete $\varepsilon_{sh}(t,t_{sh,o})$ at any time t, measured from the start of drying $t_{sh,o}$ is given by

$$\varepsilon_{sh}(t,t_{sh,o}) = k_1''\varepsilon_{sh\infty}\left[\frac{(t-t_{sh,o})}{t_{(1/2)sh}+(t,t_{sh,o})}\right]^{1/2} \tag{21}$$

Numerical Analysis

The elasto-plastic behaviour of a pin-ended, concrete-filled steel tube pile, loaded eccentrically about one axis, is studied numerically. It is assumed that complete interaction takes place between the steel and concrete and each material is subjected to a uniaxial state of stress. The eccentrically loaded column is analysed by assuming the deflected shape to be part of a cosine wave; this assumption greatly simplifies the analysis and gives only slightly lower maximum loads.

The following assumptions are made:

1- The uniaxial stress-strain curves are applicable for steel and concrete, the concrete having no tensile strength,

2- Both stress-strain curves are reversible,

3- Failure due to local buckling or due to shear does not occur.

Eccentrically loaded pile

The differential equation governing the bent equilibrium configuration of an eccentrically loaded pile is derived by equating internal and external forces and moments at a displaced section (figure 1). The calculation can be greatly simplified by assuming the deflected shape to be part of a cosine wave, in which case equilibrium is satisfied only at the mid-length. To determine the complete load-deflection curve of the pile, lateral deflection and axial load values are calculated for a series of equilibrium shapes defined by increments of curvature at the central cross-section (Neogi *et al.*, 1969).

The peak of this curve gives the maximum load. Equating the external and internal moments gives

$$EI.\frac{d^2y}{dz^2}+P.y=0 \tag{22}$$

Since the flexural stiffness EI is not constant but is a complicated function of P, y and z, analytical integration of equation (22) is not possible and numerical integration is required.

The linear strain distribution at any section can be completely specified by the curvature ρ and the distance y of the neutral axis from the central axis (Figure 2). The internal axial force and moment can be calculated from the strain distribution by the following equations:

$$P_i = \int_A \sigma dA = \sum_{i=1}^{j} \sigma_{si} A_{si} + \sum_{i=1}^{k} \sigma_{ci} A_{ci} = F_1(\rho, y)$$

$$M_i = \int_A \sigma G_i dA = \sum_{i=1}^{j} \sigma_{si} G_i A_{si} + \sum_{i=1}^{k} \sigma_{ci} G_i A_{ci} = F_2(\rho, y) \tag{23}$$

where j and k are numbers of strips (Figure 2) in steel and concrete. The values of ρ and y are initially guessed, and then successively improved by an iterative procedure.

Part-cosine wave-deflected shape

The total deflection and curvature at any point (z,y) (Figure 1) is given by

$$y = y_o.Cos\frac{\pi z}{L} \tag{24}$$

$$\rho = \frac{d^2y}{dz^2} = -\frac{\pi^2}{L^2} y_o Cos\frac{\pi z}{L} \tag{25}$$

L, the half cosine wave length, can be calculated from the condition y = e at z = L/2 for z = 0, equation (25) then becomes

$$\rho_o = -\frac{4}{L^2}\left[Cos^{-1}\frac{e}{e+\delta_o}\right]^2.[e+\delta_o] \tag{26}$$

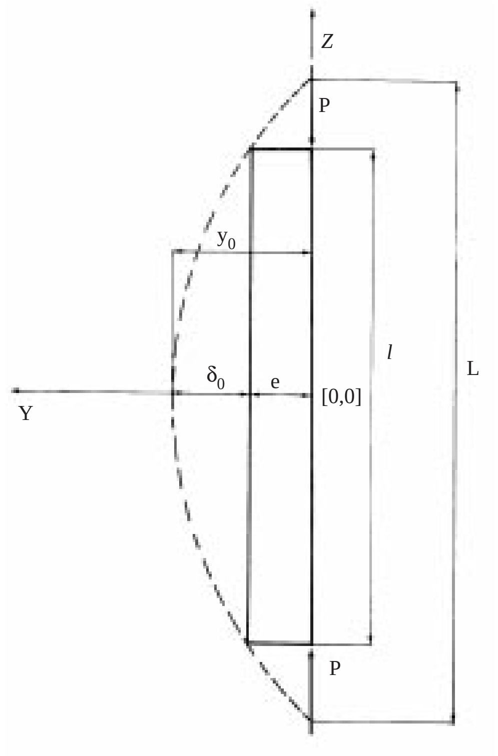

Figure 1. Eccentrically-loaded pile

In this case the central deflection is related directly to the central curvature. The procedure used for calculating the load-deflection curve is given below:

1- Choose a value of central deflection δ_o,

2- From equation (26) calculate ρ_o,

3- Select a trial value of Y_o,

4- Calculate P and M_{io}corresponding to $\rho_o$and Y_o,

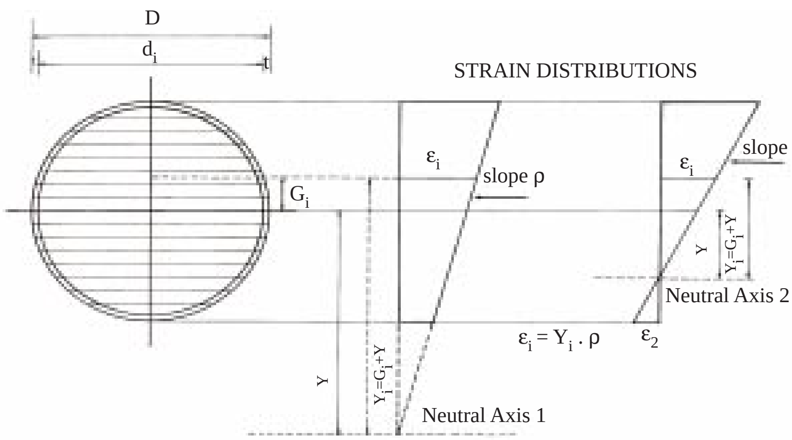

Figure 2. Strain distributions

5- If the condition $M_{io} = M_{eo} = P.y_o$ is satisfied, proceed to step (6), otherwise improve the value of Y_o by using the Newton-Rapson Method in successive iterations and repeat step (4) until the condition is satisfied to a pre-assigned tolerance,

6- By successively incrementing the value of δ_o and repeating steps (2) to (5) for each value δ_o, trace the load-deflection curve.

It should be noted that equilibrium is satisfied only at the mid-height of the pile.

Experimental Work

Creep and shrinkage experiment on the concrete-filled steel tube pile

The purpose of this experiment was to determine the value of creep coefficient to be used in the design of the concrete-filled steel tube pile. The length, diameter and tube wall thickness of the pile utilized in this experiment were 450 cm, 32.5 cm and 0.75 cm, respectively. The mixture of the concrete was 400 kg/m^3 cement and 786 kg/m^3 sand. The mechanical properties of the concrete and steel are given below:

$\sigma_c(18) = 32$ MPa compressive strength of the concrete age of t_o,

$\sigma_c(28) = 38$ MPa compressive strength of the concrete age of 28 days,

$E_c(18) = 37 \times 10^3$ MPa elasticity modulus at the age of t_o,

$E_c(28) = 37.6 \times 10^3$ MPa elasticity modulus at the age of 28 days,

$\sigma_s = 386$ MPa yield stress of the steel,

$E_s = 206 \times 10^3$ MPa elasticity modulus of the steel.

In order to measure the deformations in the concrete and steel, five dial gauges were installed in the section at the half of the pile length, and four dial gauges were installed on the steel tube (Figure 3). The experiments were carried out in an environment in which the conditions were adjustable to the atmospheric conditions (temperature: 21°C, humidity: 55%). When the pile was installed in the test chamber, a constant load of 500 KN with a 7.5 eccentricity was applied to it (Figure 4). The elastic deformations were measured by the dial gauges 6 h after the application of the load. Then deformations depending on time were measured in the concrete and steel. The measurements were not done separately, only the total deformation (creep + shrinkage) was measured. In order to determine the creep and shrinkage deformation one by one, the shrinkage deformations were found at the same time from a 7 × 7 × 28 cm unloaded concrete prism (Figure 5).

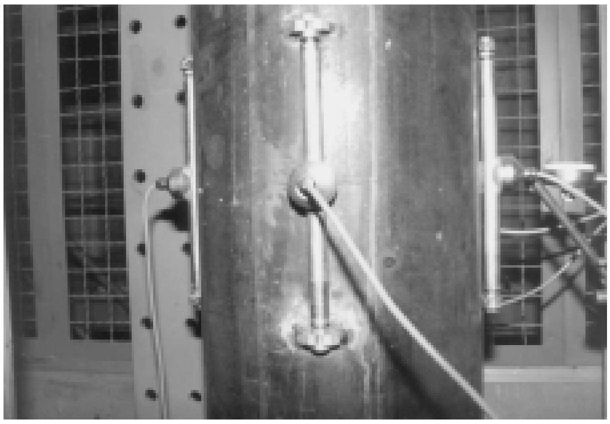

Figure 3. Installation of the dial gauges on steel tube

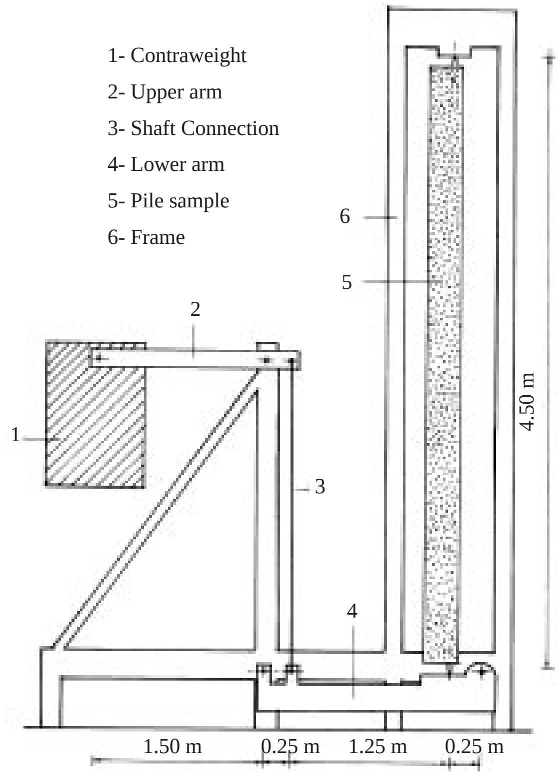

Figure 4. Loading over a long time

Comparison of the Test Results with Numerical Analysis

The concrete-filled steel tube pile was loaded 18 days after the casting of the concrete (t_o = 18 days). It was found that the elastic deformations gathered from the measurements fitted well with the deformations at the concrete and steel section pressure area (Figure 6). Hence, the elastic deformations indicated a 10% difference at the tension region. This might have resulted from the installation positions of the dial gauges in the concrete and steel section.

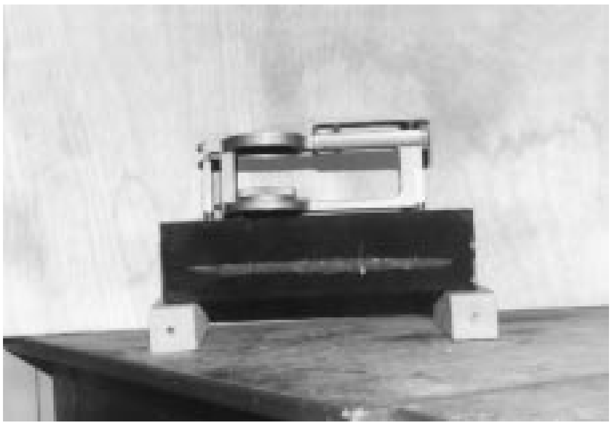

Figure 5. Measurement of shrinkage deformations with mechanical extensometer

Measurements obtained at the end of the 70^{th} day indicated that experimentally gathered deformations depending on time at the pressure section of the concrete were larger than the deformations calculated by the proposed models. At a later stage of the experiment, the test and calculation results were in agreement. Here, the hardening effect of the concrete was perceived in the first three months. Afterwards, the deformations became stabilised. This indicates a decrease in the creep deformation rate. At the steel tube pressure region and traction region of the concrete and steel the test and calculation results were in agreement.

As a result, the deformation values were determined from the creep coefficient and shrinkage models proposed by the CEB-FIP Model Code for Concrete Structures (1991), ACI Committee 209 (1992) and Bazant and Panula (1978) (Figures 7-10). Therefore, it was observed that the experimental and theoretical results were in agreement.

Stress variations at the concrete and steel sections were obtained according to the calculated deformation values.

The load taken by each section at the beginning (t_o = 18 days) was 190 KN for the steel section and 310 KN for the concrete section. This corresponds to 38% of the total load for the steel.

At the end of the test (t - t_o = 200 days), it was seen that the load taken by the steel section increased because of the decrease in the elasticity modulus of the concrete. This is the creep effect. Thus, the load taken by the steel section and the concrete section was 280 KN, respectively. The load taken by the steel section formed 56% of the total load.

The test results raised the possibility of obtaining a creep coefficient value at the infinite time interval. Finally, the calculations indicated that the creep coefficient value at the infinite time interval can be taken as ϕ_∞= 2.

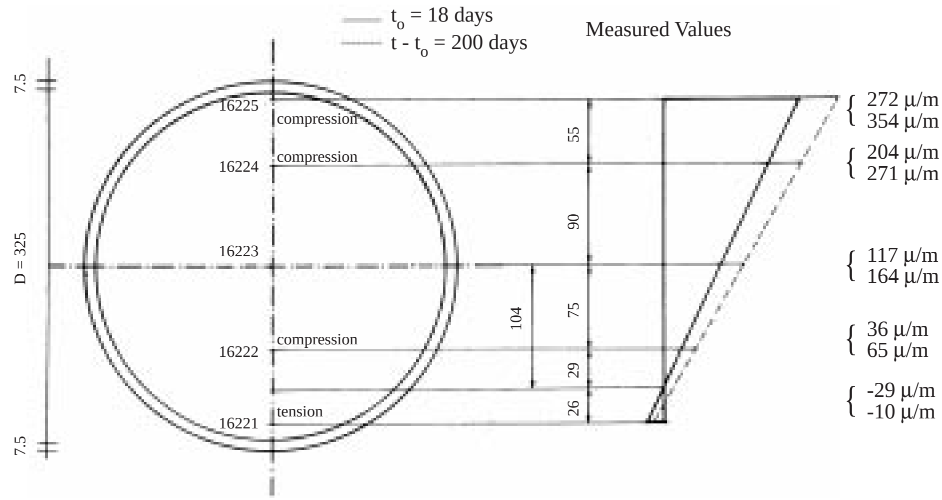

Figure 6. Installation of dial gauges in the section of concrete

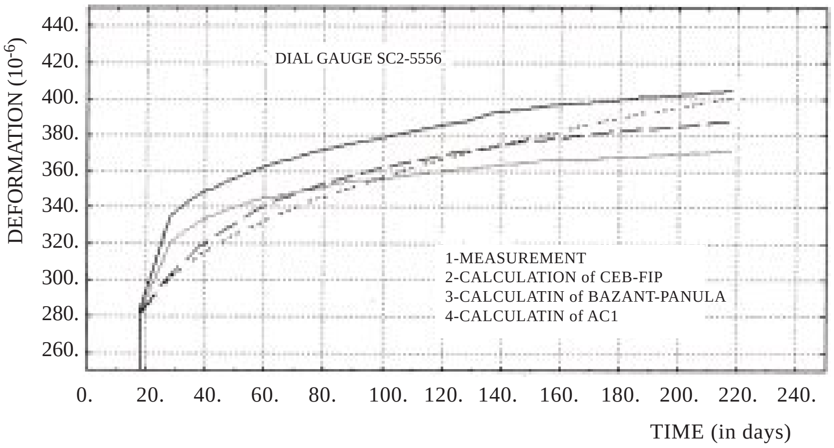

Figure 7. Variation of deformations in steel tube

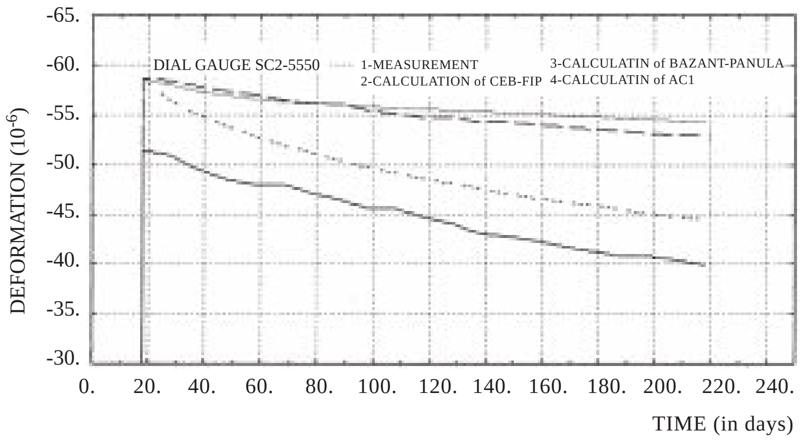

Figure 8. Variation of deformations in steel tube

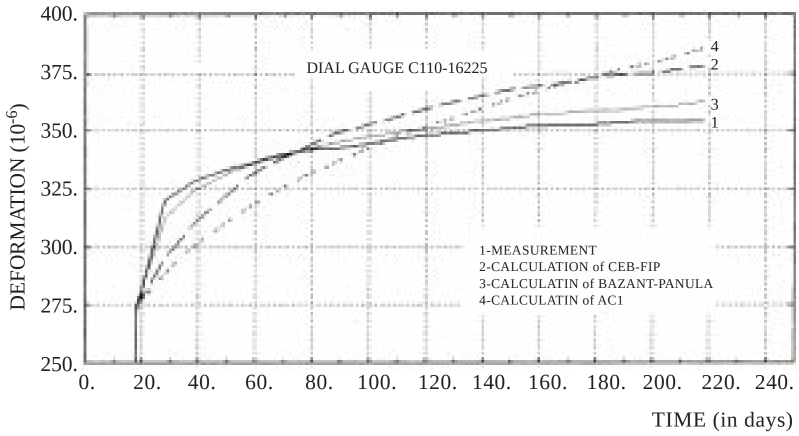

Figure 9. Variation of deformations in concrete

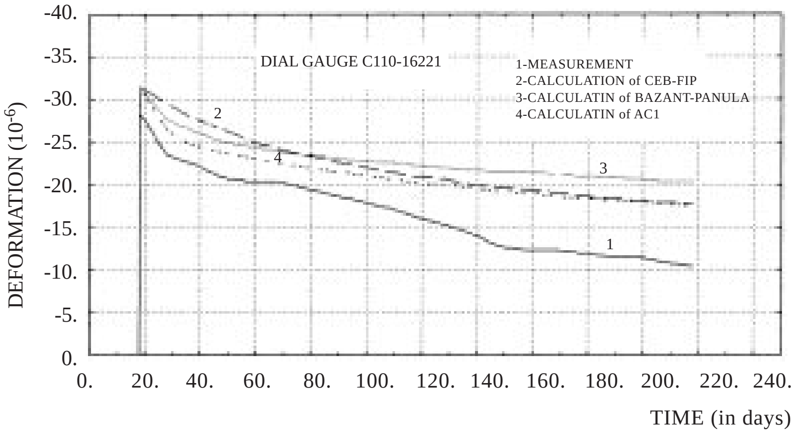

Figure 10. Variation of deformations in concrete

Conclusions

The purpose of this work was to investigate the viscoelastic behaviour of concrete-filled steel tube piles. The creep occurred with the decrease in the elasticity modulus of the concrete under a constant load. In order to determine the creep coefficient value used in the design of this type of pile, a creep test was carried out on a real size pile. It was observed that the results of the experimental work fitted well with those gathered from numerical analysis.

Although the applied stress was small, the effect of creep in comparison with shrinkage was unimportant. The viscoelastic behaviour of concrete as a composite material was considered since because the adherence between steel and concrete is complete, the steel was adapted to the behaviour of concrete. The measured values agreed well with the creep and shrinkage coefficient models prepared by the CEB-FIP Model Code for Concrete Structures (1991), ACI Committee 209 (1992) and Bazant and Panula (1978). The creep coefficient varies between 0.8 and 1 for 200 days. This value reaches up to 1.8 $\sim$ 2 for an infinite time. Stress transfer from concrete to steel occurs at the creep coefficient function. In the design of concrete-filled steel tube piles, in order to take the effect of creep into account, applied permanent load must be multiplied by the value of $(1+\phi_\infty)$.

Nomenclature

A_{si}	:	area of the steel in a strip, cm^2
A_{ci}	:	area of the concrete in a strip, cm^2
EI	:	flexural stiffness, MPa
$E_c(t_o)$	:	modulus of elasticity at the age at application of load t_o, MPa
E_{c28}	:	modulus of elasticity at the age of 28 days, MPa
e	:	end eccentricity of the load, cm
$f_{cy1}(t_o)$	:	compressive strength of concrete at the age of t_o,MPa
$f_{cy1(28)}$	:	compressive strength of concrete at the age of 28 days, MPa
$f_c\infty$	:	ultimate compressive strength of concrete, MPa
L	:	the half cosine wave length, cm
l	:	effective length of the pile, cm
t_o	:	time at application of load, day
$(t_o$-t)	:	time since application of load, day
y	:	total deflection of a displaced section, cm

$\phi_{28}(t_1, t_o)$	:	creep coefficient	$\varepsilon_{sh}(t, t_{sh,o})$	:	shrinkage strain
$\phi_d\beta_d(t - t_o)$	:	delayed elastic strain	$\varepsilon_{sh\infty}$	:	ultimate shrinkage strain
$\phi_f[\beta_f(t) - \beta_f(t_o)]$	:	delayed flow	σ_{si}	:	longitudinal stress in the steel, MPa
ϕ_f	:	flow coefficient			
ϕ_∞	:	ultimate creep coefficient	σ_{ci}	:	longitudinal stress in the concrete, MPa
$\phi'_b(t, t_o)$	:	basic creep coefficient			
$\beta_a(t_o)$	:	initial flow	ρ	:	curvature, cm^{-1}
$\Phi(t, t_o)$	:	creep function	δ	:	additional deflection due to a load P, cm
$\Phi_b(t, t_o)$	:	basic creep function			

References

ACI Committee 209, "Prediction of Creep, Shrinkage and Temperature Effects in Concrete Structures (209R-92)", American Concrete Institute, Detroit, 47, 1992.

Bazant, Z.P. and Panula, L., "Practical Prediction of Time-Dependent Deformations of Concrete", Materials and Structures, Research and Testing, (RILEM, Paris), 11, 65, 307-329, 1978.

CEB-FIP Model Code for Concrete Structures 1990, "Evaluation of the Time Dependent Behaviour of Concrete", Bulletin d'information No.199, Comité Europeen du Beton / Federation Internationale de la Precontrainte, Lausanne, 201, 1991.

Gardner, N.J. and Zhao, J.W., "Creep and Shrinkage Revisited", ACI Materials Journal, 90, 2, 236-246, May-June 1993.

Neogi, P.K., Sen, H.K. and Chapman, J.C., "Concrete-Filled Tubular Steel Columns under Eccentric Loading", The Structural Engineer, 47, 5, 187-193, May 1969.

Neville, A.M., Dilger, W.H. and Brooks, J.J., "Creep of Plain and Structural Concrete", Construction Press, Longman, 361, 1983.