The influence of settlement on flood prevention capability of the flood-control wall along the Bund in Shanghai

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Abstract: Based on the measurement of the flood-control wall along the Bund, the influence of land subsidence and structural settlement of the flood-control wall on the flood-prevention capability is studied in this paper. The main research aspects include calculation of the equivalent elastic modulus of the main soil layer with the help of visco-elastic FEM back analysis and prediction of the structural settlement of flood-control wall in future. The flood prevention capability of the control wall along the Bund was assessed by combining the predictions of structural settlement and land subsidence with the tide level standards made in 1984. The results of these studies can provide a technical basis for the construction and management of flood-control walls in Shanghai.

Résumé: Basé sur la mesure de tassement du mur contre l'inondation le long du Bund, l'influence d'affaissement de terrain et du tassement structurel de mur contre l'inondation sur la capacité de prévention d'inondation est étudiée en cet article. Les aspects principaux de recherches incluent cela, a calculé le module élastique équivalent de la couche de sol principale, avec l'aide de l'analyse inverse de FEM visco-élastique, et prévus le tassement structurel de mur contre l'inondation dans l'avenir; Combinant les prévisions du tassement structurel et de l'affaisement de terrain, étudié la capacité de prévention d'inondation du mur contre l'inondation le long du Bund selon les normes de niveau de marée faites en 1984. Le résultat de ces études peut être le soutien technique en faveur de la construction et de l'administration de mur contre l'inondation à Shanghai.

Keywords: floods, revetment**,** settlement, land subsidence

INTRODUCTION

The flood-contol walls (FCW) on both sides of Huangpu River were designed and constructed according to the water levels associated with the flood occurring once in a thousand years. The influences of earthquakes and the tidal variation was also taken into account. The flood-control walls have become an important barrier for the city of Shanghai avoiding potential flood disaster from typhoons, storms, high tides and floods waters from Tai Lake. For the flood control in the urban area, the FCW is one of the lifeline projects (Yang et al. 1997).

The soils under the river banks are very soft clays which have high water content, low strength and evident rheological behaviour. Under certain loads the soil deformation increases with time, and causes settlement, horizontal displacement and declination of the FCW. Significant deformation may cause ground subsidence behind the wall. Since the 1990s, the settlement of the FCW has become more serious, especially in the urban area. Measurement data show that there is a part of the FCW more than 20~30km long whose total settlement is about 20 -30cm, including settlement of the FCW structure and that caused by land subsidence. If the level of the FCW cannot be maintainted, the city would face the potential risk of flood disaster (Liu 1998). Therefore safety prediction for the FCW structure should include consideration of the time-dependency of the soil deformation. If the controlling factors of the rheological behaviour of the soil can be determined then future displacement can be predicted from the former measurement.This will permit preventative measures to be taken before failiure occurs (Xie and Sun 1996). It is therefore important to analyse the deformation based on the displacement monitoring and predict the future pattern of deformation and the safety of the FCW.

BACK-ANALYSIS THEORY FOR SETTLEMENT

Visco-elastic model

The three-element visco-elastic model is a form of steady creep model which can simulate the instantaneous elastic deformation and delayed post-elastic deformation of saturated soil .Xie and Sun (1996) did some rheological tests on three kinds of typical saturated soils in Shanghai, i.e. muddy clay, dark-green silty clay and brownish-yellow silty clay. The experimental curves of deformation and time showed evident visco-elasticity similar to that presented by a three-element visco-elastic model. Lin et al. (1997) analysed the displacement measurement data of a road project along the Bund in Shanghai, and concluded that the time-dependent behaviour of an old subgrade soil could be described with the three-element model. Furthermore, the displacement of the FCW structure agrees well with this model. In order to predict the displacement and safety of the FCW in the future, the three-element model will be adopted in this paper for establishing the prediction method by optimum back analysis.

Figure 1 shows a three-element visco-elastic model that is composed of one spring element in series with a Kelvin model (one spring element connected parallel with a Newton element). When $\sigma=\sigma_0$ is a constant, the creep equation can be written as:

$$\varepsilon(t)=\frac{\sigma_0}{E_1}+\frac{\sigma_0}{E_2}(1-e^{-\frac{E_2}{\eta_2}t_i})=\frac{\sigma_0}{E_{t_i}}$$

Here, E_1 and E_2 are elastic moduli, η_2 is the coefficient of viscosity and E_{t_i} is the equivalent elastic modulus, and

$$E_{t_i}=\frac{1}{1/E_1+1/E_2\cdot(1-e^{-\frac{E_2}{\eta_2}t_i})}$$

The linear visco-elastic problem can be simplified and solved with the corresponding theory. At any time t_i, there is an equivalent elastic modulus E_{t_i}, which can be used to describe the comprehensive effect of E_1, E_2 and η_2, so as to simplify the two-dimensional visco-elastic plane-strain problem into a linear problem. The equivalent elastic modulus E_{t_i} decreases with time, and tends towards a constant value (Figure 2).

$$E_{ti}\big|_{ti\to\infty}=E_1E_2/(E_1+E_2)$$

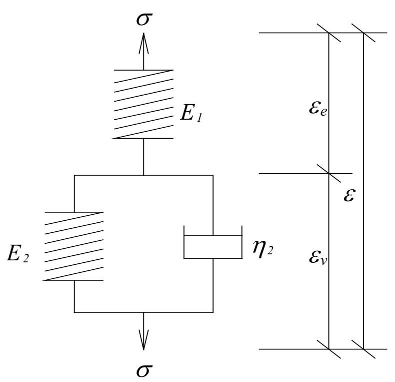

Figure 1. Three-element visco-elatic model

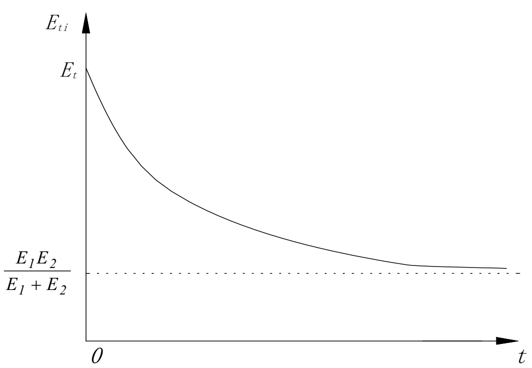

Figure 2. Relationship between equivalent elastic modulus and time of three-element visco-elatic model

The behaviour of soil layer agrees well with that presented by the three-element model. When the stress boundary and drainage conditions are kept unchanged, at $t=t_i$ the basic equation of FEM is :

$$[K']\{u\}=\{F\}$$

Here, the expression of the elements in $[K']$ is similar to that of the ordinary stiffness matrix $[K]$, the difference is at $t=t_i$ using the equivalent elastic modulus E_{t_i} instead of E.

The parameters of the three-element model can be gained from back analysis method using measurement information from the site.

Principles of back-analysis

The optimum back analysis theory provides the concepts of the optimum solution and discussed the uniqueness of the solution. In this theory, to have an optimum solution the basic condition is that the objective function of the required parameters should be a convex function. However, for most actual complex problems, it is difficult to judge if the objective function is convex or not. In order to avoid this problem, the following method was used to establish the objective function for the back analysis of two-dimensional visco-elastic problem (Yang et al. 2001).

For any one point of measurement, the variety of displacement with time can be described as a displacement series $\{u_1, u_2, \cdots u_k\}$ according to the time series $\{t_1, t_2, \cdots t_k\}$, and there exists a series of equivalent elastic modulus $\{E_{t_1}, E_{t_2}, \cdots E_{t_k}\}$. The E_{t_j} at time t_j can be calculated with back analysis of elastic problem. In order to avoid the influence of too much difference between quantities and units on the results of back analysis, the objective function can be written as:

$$F(E_{t_j}) = \min \sum_{j=1}^{k} \sum_{i=1}^{n} w_i \left(\frac{u_{ij}}{u_{ij}^*} - 1\right)^2 \qquad \text{(i=1,n; j=1,k)}$$

Here, u_{ij} and u_{ij}^* are the calculated displacement and measured displacement respectively at the time of t_j; n is the total number of the measurement points; k is the group number of the data series; w_1 is the weight constant of different measurement information, normally w_1=1. Because u_{ij} changes with E_{t_j}, so F is the function of the parameter E_{t_j}. When F is its minimum value, the relevant E_{t_j} is the optimum solution of the back analysis. Using FEM to solve the equivalent elastic modulus E_{t_j} at time t_j, the control equation is the formula above.

Usually the objective function F is a non-linear function of parameter E_{t_j}, and cannot be solved with normal theoretical methods but it can be achieved by mathematic programming. In this paper, the simplex algorithm is adopted for the optimum back analysis.

PREDICTION OF FCW'S SETTLEMENT

FEM mesh

The numerical analysis of the FCW structure is regarded as a plane-strain problem. In view of the influence of the water in the river and the loads on roads and pavements along the bank, the computed domain is selected as 180m long (120m on bank, and 60m for the inside of FCW), and 63.5m (50m for the inside of FCW) high.

The initial conditions are divided into the stress condition and the boundary condition. The initial stress condition is calculated from the density of the soil layers. The initial boundary conditions are: the left and right lateral boundaries are supported with horizontal bearing rods, the bottom boundary with vertical bearing rods, and the upper surface is z free boundary under certain known loads. The normal water table of the river is 2.2m and the ground water table under the bank side is –1.0m

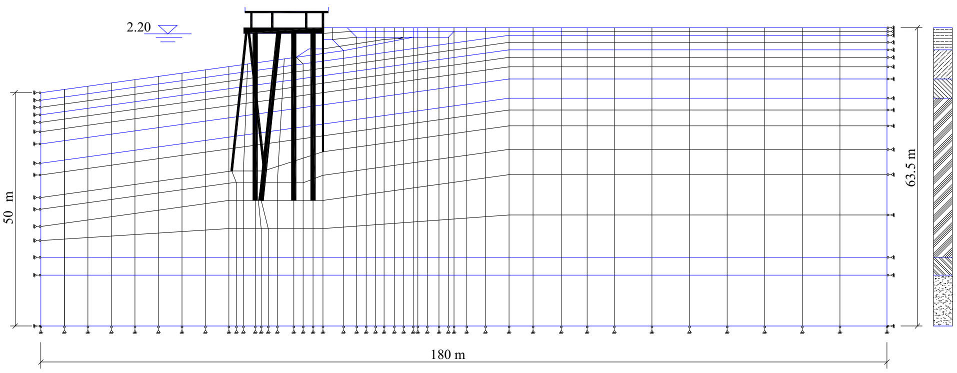

Figure 3. FEM mesh for settlement analysis of flood-control wall

The FEM mesh is shown in Figure 3. The mesh has 818 nodes and 830 elements. There are 730 quadrangle elements for simulating the soil layers, asphaltic pavement and subgrade with geotextile; 100 beam elements for PHC pipes and the caisson of the FCW.

Loads

The pavement structure is also analysed as a plane-strain problem with a width of 1m. The surface load on the FCW caisson, pavement and non-traffic lane is selected as 3.5kN/m^2. The traffic load is modelled as a uniform equivalent load of 11.79kN/m^2

The buildings along the Bund are far from the FCW, their foundations are quite deep and the consolidation of the soil layer is considered to be almost complete, so the influence of these building on the FCW's settlement is not taken into account.

Parameters

Asphaltic pavement

For the old asphaltic pavement, the elastic modulus is taken as E=900MPa, Poisson's ratio ν=0.30; while for the new asphaltic pavement, E=700MPa and ν=0.30.

Subgrade material

For the subgrade material consisting of the fly ash fill, gravel and geotextile, its elastic modulus is taken to be E_0=228.85MPa and Poisson's ratio ν=0.30.

Soil

The soil parameters from the geological investigation are shown in Table 1. The parameters for the soil layers which mainly influence the settlement of the FCW, will be calculated with back analysis.

Table 1. Parameters of soils under road subgrade

Soil name	Thickness (m)	γ (kN.m^{-3})	Elastic modulus E(kPa)	ν	K_0	c (kPa)	ϕ (°)
Muddy clay	1.6	18.4	1959	0.42	0.72	9	8
Fill	3.1	18.9	9222	0.35	0.54	12	19.3
Grey muddy clay	6.2	17.4	4247	0.40	0.67	10	9.5
Grey clay	4.1	17.5	7586	0.35	0.54	16	9
Grey silty clay	22.8	18.4	9015	0.38	0.61	18	12.4
Dark green silty clay	3.8	19.9	14851	0.38	0.61	41	10.5
Yellow fine sand	15.3	19.5	49474	0.3	0.43	9	25.2
Asphaltic pavement	/	20	700000	0.3	0.43	700	30
Subgrade material	/	20	228850	0.3	0.43	229	30

Foundation and structure

The foundation and structure of the FCW are mainly composed of tube pipes (4 rows of PHC pipes ϕ1000×32000mm), retaining pipes (350×750×2400mm) and reinforced concrete caisson. The main material parameters of the FCW are shown in Table 2.

Table 2. Material parameters of foundation and structure of FCW

Structure type	Size (m)	Spacing (m)	γ (kN.m^{-3})	Area (m^2)	moment of inertia (m^4)	E (kPa)
PHC pipe	ϕ1000	3.5-4	25	0.08883	0.0086	3.25×10^4
Retaining pipe	0.35×0.5	Closely	25	0.35	0.003573	3.25×10^4
Pipe of slab	0.45×0.55	3.5-4	25	0.2475	0.00418	3.25×10^4
Bottom longitudinal beam slab	1.2×0.8 0.35	4 entire	25	0.59	0.038133	3×10^4
Column	0.4×0.4		25	0.04	0.00053	3×10^4
Top beam plate	0.55×0.25 0.15	4 entire	25	0.1844	0.001148	3×10^4

Settlement prediction of FCW structure

The measurement points were set along the FCW, and the settlements of the FCW structure monitored. Based on the measured settlement and the results of the back analysis, the structural settlements of the FCW in the future are predicted. The measured settlement and the calculated settlement are shown in Table 3, and settlement curves with time are shown in Figure 4.

Table 3. Measured and calculated structural settlements

Date (y-m-d)	Outer measured point		Inner measured point	
	Measured settlement (mm)	Calculated settlement (mm)	Measured settlement (mm)	Calculated settlement (mm)
1994-5-5	0.00	0.00	0.00	0.00
1994-9-6	2.11	3.98	3.14	3.56
1994-12-2	3.41	5.67	6.21	5.08
1995-5-9	7.50	10.06	11.25	9.66
1995-8-14	10.46	12.03	12.85	11.71
1996-4-15	12.44	16.30	18.55	16.14
1996-10-20	11.97	14.88	16.61	14.66
1999-7-15	36.21	44.90	51.60	45.67
1999-11-6	37.36	45.98	53.04	46.77
2000-4-6	38.48	48.28	55.62	49.10
2000-9-7	40.24	49.28	56.45	50.12
2001-11-8	51.90	67.61	79.15	68.60
2002-12-2	59.22	75.78	87.95	76.79
2010-1-1		99.73		100.7
2030-1-1		125.2		126.0
2050-1-1		130.7		131.5
Final		132.0		132.7

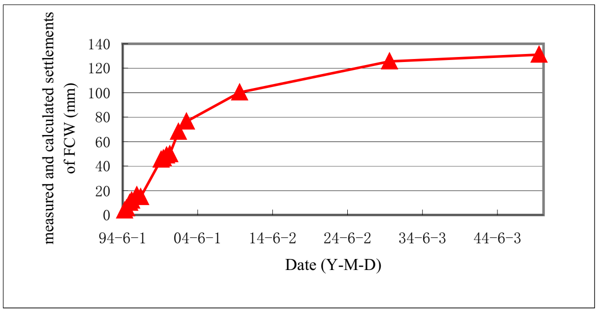

Figure 4. Increase of calculated structural settlement of FCW with time

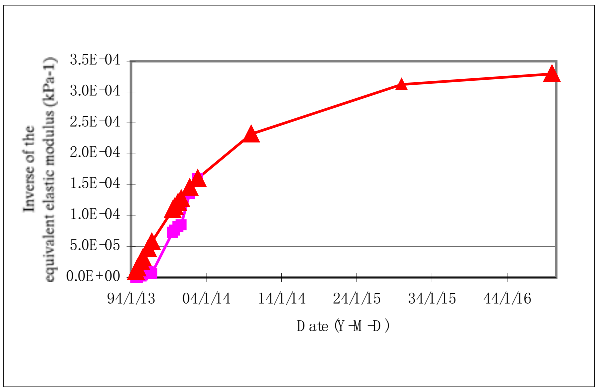

Figure 5. Relationship between equivalent elastic modulus and time

The decrease of the equivalent elastic modulus with time is shown in Figure 5. The parameters of the three-element model were derived accordingly:

$E_1=1.0\times10^6$kPa, $E_2=3.0\times10^3$kPa, $\eta_2=1.45\times10^7$kPa.d

The long-term equivalent elastic modulus is $E_{t\infty}$=3000kPa, and with this parameter the final settlement of the FCW was predicted to be more than 132mm.

Prediction of land subsidence along the bund

Shanghai Geological Investigation Institute has predicted the land subsidence along the Bund base on the observation data from 1961 to 1998. The land subsidence increments near the Bund from 1994 when the FCW was reconstructed is shown in Table 4.

Table 4. Land subsidence prediction of along the Bund from 2003

Time / Item	1994~2002	1994~2010	1994~2030	1994~2050
Land subsidence(mm)	210	354.31	751.54	1147.77

EVOLUTION OF THE FLOOD PREVENTION CAPABILITY OF THE FCW ALONG THE BUND

The total settlement of the FCW can be obtained by combining the predicted structural settlement of the FCW and the land subsidence near the Bund from 1994~2010, 1994~2030 and 1994~2050. These results indicated a reduction of the flood prevention capability. The future flood prevention capability of the FCW along the Bund for the thousand year flood levels for Shanghai approved in 1984, are shown in Table 5).

Table 5. Evolution of the flood prevention capability of flood-control wall

Year	2010	2030	2050
Flood prevention level of 1984 standard (m)	5.86	5.86	5.86
Actual level of FCW (m)	5.42	4.97	4.55
Height shortage of FCW (m)	0.44	0.89	1.31

From Table 5 it can be seen that the present height of the FCW will not satisfy the requirement of flood prevention, because the FCW will be 0.44m, 0.89m and 1.31m lower than the flood water level for a thousand year return event occurring 2010, 2030 and 2050 respectively. This represents a potential risk for the urban city of Shanghai, and indicates that measures should be taken immediately to raise the height of FCW to compensate for the predicted future height loss caused by the land subsidence and structural settlement.

CONCLUSION

The background of this paper is the reconstruction of the flood-control wall along the Bund in Shanghai. Based on the settlement measurement of the flood-control wall, the structural settlement of the wall was predicted by means of a visco-elastic FEM Back Analysis.

A two-dimensional FEM analysis was used to determine the soil layers that have the major influence on the the settlement, and then derived the equivalent elastic modulus of this layer with FEM Back Analysis, so as to predict the development of the settlement in the future. The influence of structural settlement and land subsidence on the flood-prevention capability of flood-control wall was then examined by combining the settlement with subsidence to determine the flood-prevention capability of the flood-control wall at present and in the future against the tide levels of the once in a thousand year flood.

The results presented in this paper are pertinent to the construction and technical management of the flood-control wall in Shanghai.

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