Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Vibration analysis of liquid-storage tank-pile-soil under seismic excitation

Jiang Xinliang & Ding Xuecheng
Tianjin University, People's Republic of China

ABSTRACT: In this paper, the soil-pile system is simulated as a anisotropic elastic solid. The displacment of the soil-pile system is approached by spline function so that the origin condition and the boundary condition can be satisfied. According to the above-mentioned theory and precedure, a special computer program SXJG is complied to analyze the dynamic behaviour of liquid-structure-pile-soil system, some regularities of these systems have been obtained.

1 INTRODUCTION

The determination of the behaviour of soil-pile system is a complex interaction problem expecially the behaviour of pile group becomes more complex not only due to the interaction between the piles in the group but also due to the interaction between the pile and the soil. If the aim is analysis of the behaviour of the structure under influence of the pile foundation, the physical model of the pile group can be properly simplified. Therefore, in this paper, the soil-pile system is simulated as anisotropic elastic solid. The displacements of the soil-pile system and the soil system are approached by spline function so that the origin $(r=0)$ condition and the boundary condition can be satisfied. Due to the nature of the spline finite element, only a few elements are required for three-demensional analysis.

2 THE PILE-SOIL PHYSICAL MODEL

Consider a pile-soil unite (Fig. 1). It be simulated as a anisotropic elastic solid. Let the cross sections of the unite $S=a\times b$; the cross sections of the pile $\bar{S}=\bar{a}\times\bar{b}$. E_e, E_p, G_e, G_p represent respectively elactic modulus and shearing modulus for the soil and the pile; E_1, G_1 represent respectively elactic modulus and shearing modulus in z direction for the equivalent unite; E and G are elactic modulus and shearing modulus in x and y direction for the equivalent unite.

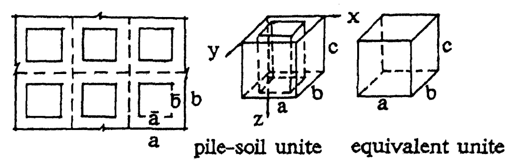

Fig. 1

2.1 The determine of the elactic modulus E_1 in z direction

Total summation of the normal stress is equal under same lode action

$$\sigma_p\bar{a}\bar{b}+\sigma_e(ab-\bar{a}\bar{b})=\sigma ab \quad (1)$$

where σ_e, σ_p, σ are respectively the normal stress of the soil, pile and equivalent unite. Let the deformation is equal in z direction

$$\frac{\sigma_p}{E_p}=\frac{\sigma_e}{E_e}=\frac{\sigma}{E_1}=\varepsilon_z \quad (2)$$

Substituting (2) in formulas (1), we obtain

$$E_1=E_p\xi+E_e(1-\xi) \quad (3)$$

where $\xi=\bar{a}\bar{b}/ab$.

According to the circumstances of pile-soil unite, we assume $E=E_e$ in x and y direction.

2.2 The determine of the shearing modulus G_1 in xz(or yz) direction

Total summation of the shearing stress is also equal under same lode action

$$\tau_p \bar{a}\bar{b} + \tau_e(ab - \bar{a}\bar{b}) = \tau ab \tag{4}$$

Where τ_e, τ_p, τ are respectively the shearing stress of the soil, pile and equivalent unite. Let the shearing deformation is also equal

$$\gamma_p = \gamma_e = \gamma \tag{5}$$

We obtain

$$G_1 = G_p \cdot \xi / 1.2 + G_e(1-\xi) \tag{6}$$

Where 1.2 is revisional coefficient similarly, we assume $G = G_e$.

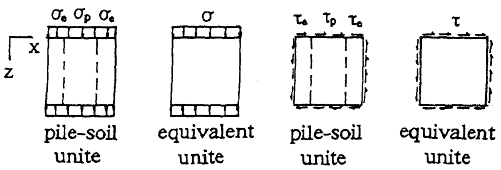

Fig. 2

2.3 The elastic coefficient of the anisotropic elastic solid physical equation

$$\begin{aligned}
\varepsilon_r &= \frac{\sigma_r}{E_e} - \frac{\mu_3}{E_e}\sigma_\theta - \frac{\mu_1}{E_1}\sigma_z \\
\varepsilon_\theta &= -\frac{\mu_3}{E_e}\sigma_r + \frac{\sigma_\theta}{E_e} - \frac{\mu_1}{E_1}\sigma_z \\
\varepsilon_z &= -\frac{\mu_2}{E_e}\sigma_r - \frac{\mu_2}{E_e}\sigma_\theta + \frac{\sigma_z}{E_1} \\
\gamma_{r\theta} &= \tau_{r\theta}/G_e \\
\gamma_{\theta z} &= \tau_{\theta z}/G_1 \\
\gamma_{zr} &= \tau_{zr}/G_1
\end{aligned} \tag{7}$$

According to work-energy principle, we obtain

$$\mu_1/E_1 = \mu_2/E_e \tag{8}$$

According to the circumstances of pile-soil unite, we assume $\mu_1 = \mu_3 = \mu_e$, then

$$\mu_2 = \frac{E_e}{E_1}\mu_e \tag{9}$$

Substituting (9) in formulas (7), we obtain

$$\{\varepsilon\} = [A]\{\sigma\} \tag{10}$$

where $\{\varepsilon\} = [\varepsilon_r\ \varepsilon_\theta\ \varepsilon_z\ \gamma_{r\theta}\ \gamma_{\theta z}\ \gamma_{zr}]^T$;
$\{\sigma\} = [\sigma_r\ \sigma_\theta\ \sigma_z\ \tau_{r\theta}\ \tau_{\theta z}\ \tau_{zr}]^T$.

3 THE DISPLACEMENT FUNCTIONS

Consider liquid-structure-pile-soil structure system as shown in Fig. 3. The liquid-shell are divided into the layer elements, and the pile-soil and the surrounding soil are also divided into the layer elements along z axis direction. The displacement functions are written respectively as follows

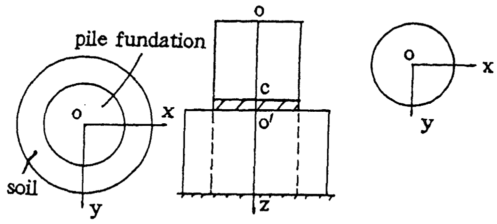

Fig. 3

3.1 The displacement function of the liquid

The liquid is idealized and assumed to be irrotational and non-viscous.

$$\begin{aligned}
P(z,\theta,r,t) = &\sum_{f=1}^{F+1}\sum_{j=0}^{N}[(1-\eta)S_{fj} + \eta\bar{S}_{fj}]\Phi_f(r)\cos j\theta \\
&+ [(1-\eta)S_{1.1} + \eta\bar{S}_{1.1}]\Phi_{-1}(r)\cos\theta \\
&+ [(1-\eta)S_{1.0} + \eta\bar{S}_{1.0}]\Phi_0(r) = [N_W^e]\{\delta_W^e\}
\end{aligned} \tag{11}$$

3.2 The displacement function of the shell

$$\begin{aligned}
W_z &= \sum_{j=0}^{N}[(1-\eta)w_{zj} + \eta\bar{w}_{zj}]\cos j\theta \\
W_\theta &= \sum_{j=0}^{N}[-(1-\eta)w_{\theta j} - \eta\bar{w}_{\theta j}]\sin j\theta \\
W_r &= \sum_{j=0}^{N}[1 - 3\eta^2 + 2\eta^3)w_{rj} + R(\eta - 2\eta^2 + 3\eta^2)b_{rj} \\
&\quad + (3\eta^2 - 2\eta^3)\bar{w}_{rj} + R(\eta^3 - \eta^2)\bar{b}_{rj}]\cos j\theta
\end{aligned} \tag{12}$$

3.3 The displacement function of pile-soil

$$\begin{aligned}
U_r &= \sum_{m=0}^{M+1}\sum_{j=0}^{N}[(1-\eta)a_{mj} + \eta\bar{a}_{mj}]\Phi_m(r)\cos j\theta \\
&\quad + [(1-\eta)a_1 + \eta\bar{a}_1]\cos\theta \\
U_\theta &= \sum_{m=0}^{M+1}\sum_{j=0}^{N}[(1-\eta)b_{mj} + \eta\bar{b}_{mj}]\Phi_m(r)\sin j\theta \\
&\quad + [(1-\eta)a_1 + \eta\bar{a}_1]\sin\theta \\
U_z &= \sum_{m=1}^{M+1}\sum_{j=0}^{N}[(1-\eta)c_{mj} + \eta\bar{c}_{mj}]\Phi_m(r)\cos j\theta \\
&\quad + [(1-\eta)d_{1.1} + \eta\bar{d}_{1.1}]\Phi_{-1}(r)\cos\theta \\
&\quad + [(1-\eta)d_{1.0} + \eta\bar{d}_{1.0}]\Phi_0(r)
\end{aligned} \tag{13}$$

3.4 The displacement function of the surrounding soil

$$V_r=\sum_{l=-1}^{L+1}\sum_{j=0}^{N}[(1-\eta)x_{lj}+\eta\bar{x}_{lj}]\bar{\Phi}_l(r)\cos j\theta$$
$$V_\theta=\sum_{l=-1}^{L+1}\sum_{j=0}^{N}[(1-\eta)y_{lj}+\eta\bar{y}_{lj}]\bar{\Phi}_l(r)\sin j\theta \qquad (14)$$
$$V_z=\sum_{l=-1}^{L+1}\sum_{j=0}^{N}[(1-\eta)z_{lj}+\eta\bar{z}_{lj}]\bar{\Phi}_l(r)\cos j\theta$$

Where $\eta=(z-z_1)/z_{12}$; z_1 is co-ordinate values on the surface of the layer element; z_{12} is thickness of the layer element; $\Phi_m(r)$, $\bar{\Phi}_m(r)$, $\bar{\Phi}_t(r)$, $\bar{\Phi}_l(r)$ are the B spline functions of the third order.

4 CALCULATION MATRIX

4.1 The hydrodynamic pressure function

Change of the formulas (11) should satisfy laplace equation

$$\frac{\partial^2 p}{\partial r^2}+\frac{1}{r}\frac{\partial p}{\partial r}+\frac{1}{r^2}\frac{\partial^2 p}{\partial \theta^2}+\frac{\partial^2 p}{\partial z^2}=0 \qquad (15)$$

boundary condition

$$\frac{\partial p}{\partial n}=-\rho_0\frac{\partial^2 W_n}{\partial t^2} \qquad (16)$$

Where W_n is the normal component of the boundary displacement; ρ_0 is the liquid density.

Laplace equation and boundary condition are equivalent to extreme value problem of functional χ

$$\chi=\iiint_\Omega 1/2[(\partial p/\partial r)^2+1/r^2(\partial p/\partial\theta)^2+1/Z_{12}^2(\partial p/\partial\eta)^2]d\Omega+\iint_S(\rho_0\partial^2 W_n/\partial t^2)p\,ds \qquad (17)$$

Where Ω is the body of the water, S is the surface of contact for the liquid and the structure. According to $\partial\chi/\partial\{\delta_w\}=0$, we obtain

$$[H]\{\delta_w^e\}-\{f\}=0 \qquad (18)$$

Substituting (18) in formulas (11), we obtain

$$P=P_R+P_H=[N_w^e]_R[H]^{-1}\{f_1\}+[N_w^e]_H[H]^{-1}\{f_2\} \qquad (19)$$

where $[N_w^e]_R$, $[N_w^R]_H$ are respectively the values of $[N_w^e]$ at $r=R$ and $z=H$, P_R and P_H are the hydrodynamic pressure of the shell in r direction and the bottom in z direction.

4.2 The displacement of the rigid fundation

Consider the case of the rigid circular plate for higher h is on top of the layer element, and U_{ro}, U_{zo}, ψ_o represent respectively three displacement

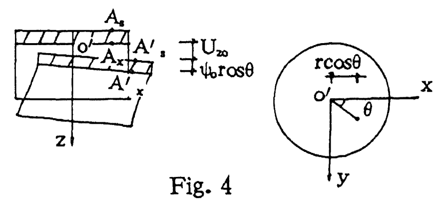

Fig. 4

components of the bottom of the plate, then displacement for the bottom of the plate at a point A_x is

$$U_r=U_{ro}\cos\theta$$
$$U_\theta=-U_{ro}\sin\theta$$
$$U_z=\psi_o r\cos\theta+U_{zo} \qquad (20)$$

Displacement for the top of the circular plate at a point A_s is

$$U_r=(U_{ro}+h\psi_o)\cos\theta$$
$$U_\theta=-(U_{ro}+h\psi_o)\sin\theta$$
$$U_z=\psi_o r\cos\theta+U_{zo} \qquad (21)$$

where U_{ro}, U_{zo} and ψ_o are respectively horizontal, vertical displacement of the origin and the angle of rotation towards the axis y.

The displacement functions are writen form of the matrix. According to energy methods, stiffness matrix and mass matrix of the system are obtained, finally, we obtain

$$[M]\{\ddot{\delta}\}+[C]\{\dot{\delta}\}+[K]\{\delta\}=[F]\{\ddot{B}\}+[F]\{\ddot{A}\} \qquad (22)$$

where $\{\ddot{A}\}$, $\{\ddot{B}\}$ are respectively horizontal and vertical acceleration of the ground surface.

5 CALCULATION EXAMPLE AND RESULTS OF ANALYSES

Liquid-tank radius is R = 15m, higher are respectively H = 24m and H = 60m, thickness of the shell is t = 0.4m, thickness of the fundation plate is 3m, length of the pile is 24m, the bottom of the pile rest on rock. Material property

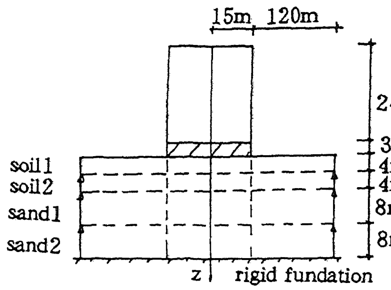

Fig. 5

Table 1. Material property and geology material

	$E(N/m^2)$	μ	$\rho(kg/m^3)$
liquid			1000
concrete	2.6×10^{10}	0.3	2500
Soil 1	1.642×10^{8}	0.45	2033
Soil 2	1.839×10^{8}	0.45	1984
Sand 1	3.134×10^{8}	0.4	2086
Sand 2	3.932×10^{8}	0.4	2044

Table 2. results of the part calculation (H = 24m)

		rigid foundation	$\xi=0.09$	$\xi=0.0576$	$\xi=0.0277$
full tank	$U_t(m)$	0.01977	0.01697	0.01638	0.01648
	$U_e(m)$	0.01977	0.01574	0.01577	0.01632
	$Q_d(kN\times10^5)$	1.264	1.005	1.044	1.091
half tank	$U_t(m)$	0.00497	0.00478	0.00477	0.00478
	$U_e(m)$	0.00497	0.00406	0.00425	0.00441
	$Q_d(kN\times10^4)$	8.463	6.879	6.896	7.032
empty tank	$U_t(m)$	0.00087	0.00083	0.00089	0.00086
	$U_e(m)$	0.00087	0.00078	0.00079	0.00081
	$Q_d(kN\times10^3)$	3.995	3.508	3.679	3.626

Table 3. results of the part calculation (H = 60m)

		rigid foundation	$\xi=0.09$	$\xi=0.0576$	$\xi=0.0277$
full tank	$U_t(m)$	0.09251	0.06493	0.05899	0.05548
	$U_e(m)$	0.09251	0.01899	0.02732	0.03475
	$Q_d(kN\times10^5)$	2.934	1.877	1.975	1.966
half tank	$U_t(m)$	0.02326	0.02290	0.02505	0.02768
	$U_e(m)$	0.02326	0.00756	0.01877	0.01929
	$Q_d(kN\times10^5)$	2.278	1.674	1.732	1.807
empty tank	$U_t(m)$	0.00671	0.00765	0.00779	0.00770
	$U_e(m)$	0.00671	0.00511	0.00530	0.00561
	$Q_d(kN\times10^4)$	1.187	0.903	0.918	1.067

and geology material are shown in table 1. where U_t is total displacement of the top, U_e is elactic dispacement of the top, Q_d is shearing force of the fundation.

According to nature property of the soil, the layer element is divided into four layer. The edge of the soil is assumed simply supported boundary. On the ground surface it is considered that the incident EL Centro waves (1940. 5. 18. NS, $a_{max}=3.14171m/s^2$). The damping factors of the shell, pile and soil respectively are 0.05, 0.1 and 0.15. Results of the part calculation are shown in table 2 and table 3.

According to the above calculation results, some regularities of these systems have been obtained:

1. A general regularity between the top total displacement of the rigid foundation is not obtained. However, the top elastic displacement in the case of the interaction system is less than the case of the rigid foundation.

2. The relative stiffness of the structure and the foundation is important paramenter of the system. As the stiffness of the pile foundation is raised, the elastic displacement of the structure is reduced.

3. The influence of the interaction of the full tank due to action of additional mass is far greater than that of the interaction of the empty tank.

REFERENCES

Jiang Xinliang and Ding Xuecheng, 1991. The pole conditions of a three-dimensional cylinder and its method of the spline functions. Journal of Tianjin University 2:84-91.

Ahlberg, H. H., E. N. Nilson, and J. L. Walsh, 1967. The theory of splines and their applications. Academic press, New York.