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SEISMIC ANALYSIS OF TUNNEL SURROUNDED BY SOFT SOIL IN SHANGHAI

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SUMMARY

Based on the test results, the analysis of earthquake resistance of tunnel surrounded by soft soil in Shanghai is presented in this paper. The tunnel is located in the soft soil and sand, respectively. The reaction acceleration, pore water pressure and the settlement of the tunnel under 7-degree earthquake are given and compared.

INTRODUCTION

Shanghai is located in the Yangtze River delta in China. The depth of the overburden of soil is about 280m-300m. The underground water level is about 0.8m-1.0m from the surface of ground and the soil conditions consist essentially of a thin surface layer of mixed silty clay, clay and fill, followed by a 20-40m thick soft clayey soil layer with interbedded seams of silt, fine sand or silty sand. Based on the method of dynamic effective stress analysis, the seismic analysis of tunnel surrounded by the soft soil in Shanghai is presented in this paper. The tunnel is located in soft clay and sand in different region, respectively.

This study is carried out with a 2-D dynamic FE analysis procedure. Based on the results of test, the formulations of pore water pressure and residual strain of soft soil in Shanghai is given and the parameters are determined. The four different earthquake records are adopted as different input motion. The acceleration, pore water pressure and the settlements of the tunnel are given and compared.

TEST RESULTS

Based on the results of cyclic triaxial tests on the soft soil of shanghai nearby the tunnel, the following model of residual pore-water pressure and model of residual strain of saturated soft soil can be derived:

Cyclic shear strength and parameter: If the cyclic stress σ_d is normalized by the mean stress $\sigma_0'(\sigma_0' = (\sigma_a + 2\sigma_r)/3)$, the relation between the cyclic strength R_f (σ_d / σ_0') and the number of load cyclic N_f can be approximated by a straight line in the logarithmic form for both isotropic and anisotropic consolidated conditions:

$$R_f = aN_f^b \tag{1}$$

Where N_f is the number of load cycles required to achieve a 5% double amplitude shear strain for isotropic condition and 5% maximum amplitude shear strain for anisotropic condition respectively, and a and b are experimental constants.

Excess pore pressure and parameter: A uniformed relation can be obtained between the cyclic-induced pore water pressure U and the cyclic stress ratio η^* for both isotropic and anisotropic consolidated conditions as shown in fig.1 and fig.2 .

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$$U / U_f = \eta^* / [C_3 - (C_3 - 1)\eta^*] \tag{2}$$

$$\eta^* = (\eta_{p,e} - \eta_s) / (\eta_f - \eta_s) \tag{3}$$

where $\eta_{p,e}$ is the current effective dynamic stress ratio, η_s is initial effective stress ratio, η_f is effective stress ratio at failure point, U_f is the maximum residual pore water pressure while the 5% double amplitude shear strain for isotropic condition and 5% maximum amplitude shear strain for anisotropic condition is reached, C_3 is the experimental parameter.

Residual axial strain and parameter: The relation between the undrained residual axial strain and the cyclic stress ratio for anisotropic consolidated condition is formulated as shown in fig.3 and fig.4.

$$\varepsilon^p = \eta^* / [d - (d - 20)\eta^*] \tag{4}$$

Where d is the experimental parameter.

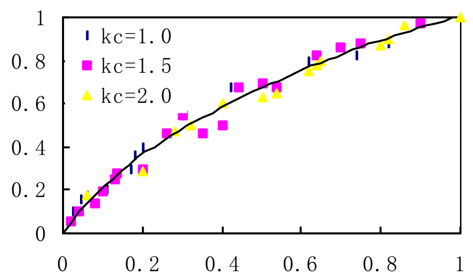

Fig.1 Relation between U and η^*(sandy silt)

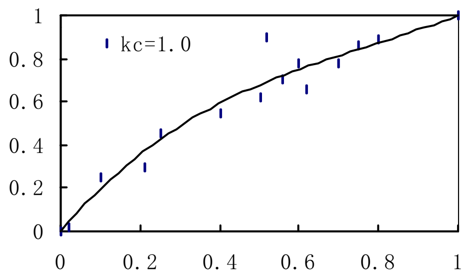

Fig.2 Relation between U and η^*(very soft silty clay)

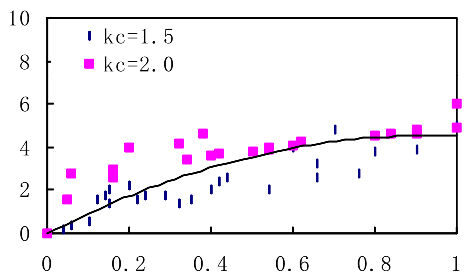

Fig.3 Relation between ε_p and η^*(sandy silt)

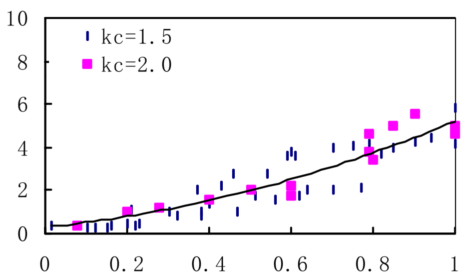

Fig.2 Relation between ε_p and η^* (very soft silty clay)

DYNAMIC ANALYSIS METHOD

Substituting the pore water pressure and residual strain due to dynamic loading into Biot's basic dynamic consolidation equations, and omitting the acceleration of pore water pressure, we got the dynamic differential equation. Then, Galerkin's weighted residual method and 2-D isoparametric element with four nodes is used to formulate the following set of finite equation:

$$K\delta + Qp + M\ddot{\delta} = F \quad (5)$$

$$Q^T\delta + Sp = \overline{F} \quad (6)$$

Where K is stiffness matrix; Q is couple matrix; M is mass matrix; S is permeability matrix; p is nodal pore water pressure; δ , $\ddot{\delta}$ is nodal displacement vector and nodal acceleration vector respectively; F is nodal load vector; $\overline{F}$ is nodal seepage discharge vector.

The equation (5) and (6) is solved by front solution method (Zhou Jian et al. 1991).

CASE ANALYSIS

The tunnels of Shanghai No.1 subway sections between Hanzhong road and Shanghai railway station and between Shanghai gymnasium and Xujiahui station are taken as examples. The outer diameter of the tunnel is 6.2m, and the inner diameter is 5.5m. The thickness of the slurry outward of the tunnel is from 0.05m on the top and 0.01m at the bottom. The tunnel is 10m under the soil layer surface.

As no major earthquake has been recorded in the city, we use Tangshan, Sunan nuclear power station, Niyasaki gawa and Lotung earthquake motion as input motion. Two depths of 50m and 280m from the soil layer surface are considered as the input base boundary, respectively.

Parameters

Limited by the length of this paper, here we just list the soil properties and parameters within 50m.

Tab.1 soil properties and parameters (sandy Soil)

No.	Material	ρ / $(t \cdot m^{-3})$	depth/ (m)	γ' / $(kN \cdot m^{-3})$	c' / kPa	$\sin\phi$	D_{max}	K_{2max}	μ	S $(m \cdot s^{-1})$	E_0/ kPa
1	Injection material	1.80	0.8	8.00	0.00	0.342	0.300	6170	0.30	4.0×10^{-6}	8000
2	Filling	1.90	1.5	19.00	22.3	0.375	0.325	10000	0.29	1.5×10^{-8}	6000
3	Fine sand	1.90	3.6	9.00	6.50	0.370	0.320	10000	0.29	2.0×10^{-5}	5000
4	Fine sand	1.86	8.1	8.60	5.10	0.414	0.320	1500	0.26	9.0×10^{-5}	3500
5	Fine sand and very soft clay	1.80	7.9	8.00	3.59	0.440	0.300	1500	0.30	3.0×10^{-6}	2000
6	Very soft clay	1.71	6.1	7.10	11.0	0.208	0.320	3500	0.29	1.4×10^{-9}	4000
7	Clay	1.82	13.9	8.20	14.0	0.120	0.320	10000	0.26	7.1×10^{-8}	10000
8	Clay	2.00	5.0	10.00	31.1	0.292	0.320	5200	0.26	1.5×10^{-8}	6000

Notes: S is coefficient of penetrability

Tab.2 soil properties and parameters (clayey Soil)

No.	Material	ρ / $(t\cdot m^{-3})$	depth/ (m)	γ' / $(kN\cdot m^{-3})$	c' / kPa	$\sin\phi$	D_{max}	K_{2max}	μ	S $(m\cdot s^{-1})$	E_0/ kPa
1	Filling	1.90	2.0	19.0	22.3	0.375	0.325	10000	0.29	1.5×10^{-8}	6000
2	Fine sand	1.91	9.9	9.1	14.2	0.208	0.325	10000	0.29	1.5×10^{-8}	5000
3	Very soft clay	1.75	1.0	7.5	9.7	0.225	0.320	1500	0.26	3.0×10^{-9}	3500
4	Very soft clay	1.74	6.0	7.4	10.7	0.122	0.300	1500	0.30	3.0×10^{-9}	2000
5	Clay	1.80	6.0	8.0	9.8	0.208	0.320	3500	0.29	9.0×10^{-8}	4000

The analysis result shows that the maximum value of dynamic shear stress ratio occurs near the top of the tunnel. The maximum pore water pressure ratio also occurs near the top of the tunnel. Fig5~fig10 show the distribution of calculated pore water pressure ratio and settlement of soils for different section. Tab.3 and Tab.4 show the main results of maximum dynamic response for different case.

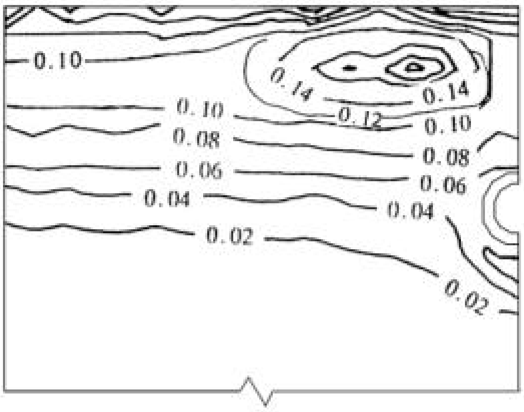

Fig5. Distribution of PWP ratio of cross section (sandy soil)

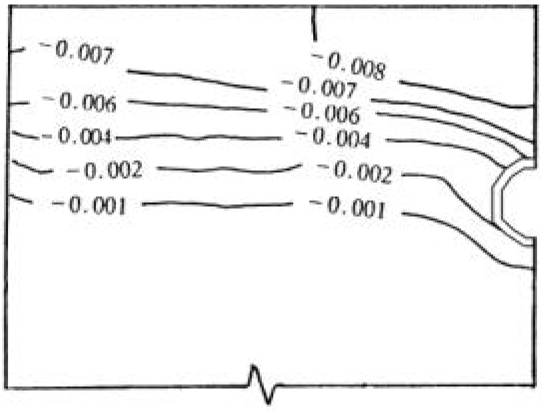

Fig6 Distribution of settlement of cross section (sandy soil)

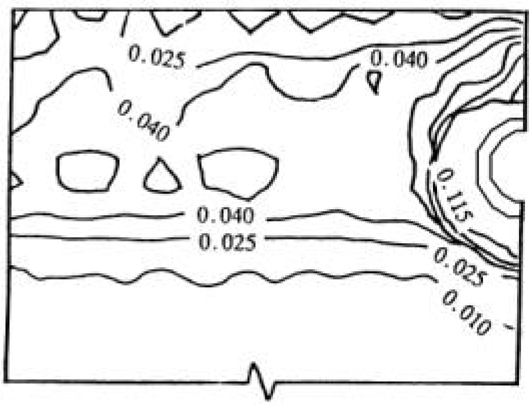

Fig7. Distribution of PWP ratio of cross section (clayey soil)

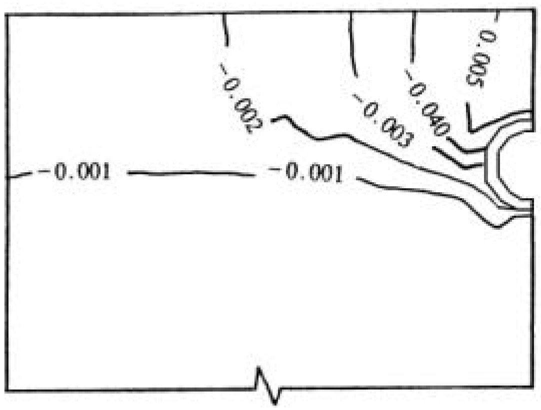

Fig8 Distribution of settlement of cross section (clayey soil)

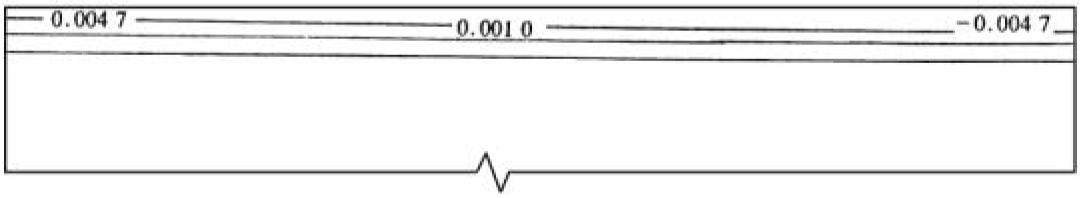

Fig9. Distribution of settlement of longitudinal section (clayey soil)

Fig10 Distribution of settlement of longitudinal section (clayey soil)

Tab.3 Results of maximum dynamic response (sandy soil)

Input motion	location	50m, cross section			50m, longitudinal section			280m, cross section			280m, longitudinal section		
		DSS* or DSSR	PWPR	S	DSS* or DSSR	PWPR	S	DSS* or DSSR	PWPR	S	DSS* or DSSR	PWPR	S
Tang shan	Soil	0.16	0.25	-8.4	0.16	0.38	-14.8	0.18	0.27	-14.9	0.16	0.33	-15.4
	Injection material	0.10	0.09	-2.2	0.10	0.15	-0.4	0.11	0.07	-3.4	0.11	0.14	-5.6
	Flake of pipe	69.27*	--	-2.1	60.90*	--	-0.1	84.95*	--	-3.2	94.12*	--	-4.0
Sunan T=0.15	Soil	0.15	0.14	-10.6	0.07	0.00	0.0	0.15	0.07	-12.2	0.12	0.06	-1.2
	Injection material	0.11	0.12	-4.8	0.07	0.00	0.0	0.13	0.03	-5.9	0.06	0.03	-0.3
	Flake of pipe	32.12*	--	-4.6	18.32*	--	0.0	137.11*	--	-5.7	44.14*	--	-0.3
Sunan T=0.30	Soil	0.55	0.16	-15.7	0.16	0.37	-12.7	0.10	0.07	-19.2	0.13	0.34	-20.1
	Injection material	0.12	0.13	-4.9	0.10	0.15	-0.4	0.10	0.04	-9.3	0.11	0.19	-11.3
	Flake of pipe	58.57*	--	-4.5	58.13*	--	-0.1	53.35*	--	-8.9	101.94*	--	-10.1
Niyasaki gawa	Soil	0.12	0.08	-1.9	0.14	0.23	-4.6	0.09	0.14	-10.6	0.12	0.24	-20.0
	Injection material	0.10	0.06	-2.0	0.12	0.09	-0.2	0.07	0.05	-3.6	0.10	0.19	-6.9
	Flake of pipe	96.69*	--	-2.0	103.93*	--	-0.1	95.60*	--	-3.4	108.61*	--	-5.5
Lotung	Soil	0.14	0.09	-5.6	0.16	0.29	-7.5	0.13	0.08	-18.5	0.15	0.39	-28.7
	Injection material	0.08	0.09	-2.4	0.10	0.12	-0.1	0.11	0.03	-8.9	0.16	0.19	-15.8
	Flake of pipe	40.82*	--	-2.3	44.23*	--	-0.0	89.89*	--	-8.6	109.24*	--	-13.4

Notes: DSS is dynamic shear stress, unit (kPa); DSSR is dynamic shear stress ratio;

Tab.4 Results of maximum dynamic response (clayey soil)

Input motion	Location	50m, cross section			50m, longitudinal section			280m, cross section			280m, longitudinal section		
		DSS* or DSSR	PWPR	S	DSS* or DSSR	PWPR	S	DSS* or DSSR	PWPR	S	DSS* or DSSR	PWPR	S
Tang shan	Soil	0.19	0.23	-12.6	0.17	0.21	-9.4	0.19	0.32	-12.4	0.16	0.36	-20.4
	Injection material	0.13	0.23	-7.1	0.13	0.14	-0.6	0.12	0.23	-7.3	0.14	0.34	-10.5
	Flake of pipe	62.85*	--	-6.8	76.81*	--	-0.5	54.32*	--	-7.0	102.40*	--	-11.3
Suanan T=0.15	Soil	0.10	0.01	-0.5	0.11	0.17	-4.2	0.13	0.09	-1.3	0.12	0.19	-5.3
	Injection material	0.07	0.01	-0.2	0.09	0.12	-0.2	0.09	0.06	-0.4	0.15	0.16	-1.4
	Flake of pipe	30.90*	--	-0.2	38.04*	--	-0.1	38.12*	--	-0.4	39.70*	--	-1.2
Suanan T=0.30	Soil	0.15	0.16	-11.2	0.16	0.27	-11.8	0.12	0.21	-11.2	0.14	0.30	-24.0
	Injection material	0.11	0.18	-4.5	0.12	0.20	-0.6	0.12	0.14	-4.9	0.13	0.29	-13.1
	Flake of pipe	63.35*	--	-4.0	46.99*	--	-0.3	75.54*	--	-4.7	87.33*	--	-12.6
Niyasaki gawa	Soil	0.16	0.13	-7.4	0.13	0.17	-4.7	0.13	0.25	-10.9	0.09	0.28	-22.8
	Injection material	0.10	0.15	-3.0	0.08	0.12	-0.4	0.08	0.16	-4.1	0.08	0.26	-7.9
	Flake of pipe	90.97*	--	-2.7	73.05*	--	-0.3	79.31*	--	-3.9	75.13*	--	-8.2
Lotung	Soil	0.18	0.16	-9.9	0.15	0.17	-4.5	0.13	0.26	-10.2	0.13	0.25	-17.1
	Injection material	0.12	0.18	-6.7	0.09	0.12	-0.7	0.12	0.18	-6.4	0.10	0.23	-14.0
	Flake of pipe	32.07*	--	-6.5	22.81*	--	-0.7	66.49*	--	-6.1	56.84*	--	-24.2

Tab.5 Results of maximum dynamic response of every process

Dynamic properties	In the case of sandy soil			In the case of clayey soil		
	Soil	Slurry	Pipe-flake	Soil	Slurry	Pipe-flake
MPWPR	0.38	0.186	--	0.36	0.341	--
MS	0.029m	--	0.013m	0.024m	--	0.014m
MDSS	--	--	137.1kPa	--	--	102.4kPa

Where, MPWPR, MS and MDSS is the abbreviation of maximum of pore water pressure ratio, maximum of settlement and maximum of dynamic shear stress respectively.

CONCLUSIONS

The main conclusions are as follows: 1).The maximum pore water pressure ratio in soil and grout occurs near the top of the tunnel and it almost has no effect on the tunnel. 2).Using different depth of input base boundary will affect the results of dynamic analysis of the tunnel. The response values with the depth of 280m of input base boundary are larger than that with the depth of 50m of input base boundary. 3).Using different input motion will also affect the results of dynamic analysis of the tunnel. Using Tangshan earthquake and Lotung earthquake record as input motion will get relatively larger response values of dynamic analysis of the tunnel.

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