The evaluation method of soil-spring for mat slabs' analyses considering the inelastic behavior of bedsoil

S.Satoh & H.Konishi
Nuclear Structures Department, Kajima Corporation, Japan
Y.Hayami
Structural Design Department, Kajima Corporation, Japan

1 INTRODUCTION

When analyzing the stress of foundation structures by FEM (Finite Element Method), it is very important to correctly evaluate and model the soil-spring mechanism between the foundation and the soil. In recent years, studies have been made by the authors by use of the theoretical solution to the semi-infinite elastic body. However, doubts have been formed to evaluate the soil only as an elastic body, for example, for explaining the partial concentration of soil-reaction.

In view of these facts, this paper deals with the evaluation method of soil-spring for analyses of mat slab with considerations given to the inelastic behavior of the soil.

2 ELASTIC-PLASTIC ANALYSIS OF BEDSOIL

The elastic-plastic analysis is applied to bedsoil in order to investigate its inelastic behavior. The theories of plastic flow rule and isotropic hardening are assumed in this analysis, and Drucker Prager yield criterion is used as the yield function. The model of this analysis is shown in Fig. 1. Its boundaries are constrained in the side and downward direction. In the elastic-plastic analysis, the surface of the soil in this model (shaded zone in Fig. 1) is carrying the vertical and lateral loads. Bedsoil is assumed uniform, and its non-linear characteristic under unconfined compressive condition is shown in Fig. 2. The coefficient of volume expansion of the bedsoil is 0.08, and its own weight is not considered. As a result of this analysis, the next four items are derived.

1) Bedsoil does not yield easily under vertical loadings.

In this analysis, the elastic limit of vertical load is 36 kg/cm^2, that is the bedsoil maintains most of the elasticity when its surface is applied with the limit load for unconfined compression fracture test. On the other hand the elastic limit of lateral load is 12.6 kg/cm^2. Comparing with the application of vertical load, the bedsoil easily yields to lateral load.

2) Plastic zone of bedsoil is very small.

The typical distributions of plastic strain under vertical and lateral loads are shown in Fig. 7 and Fig. 8. These show that the plastic zone of the bedsoil is very small in spite of the soil supporting the over load of the elastic limit.

3) There is no great difference in the stress distribution between plastic zone and elastic zone.

The stress distributions in the vertical direction are shown in Fig. 3 and Fig. 4. There is no great difference in distribution in spite of respective loads differing more two times. However, there are many differences in the strain distribution, as shown in Fig. 5 and Fig. 6, at directly underneath of loaded parts where the plasticity is advanced. To examine the above-mentioned in detail, the ratios of the stress and strain derived from this analysis to the elastic theoretical solution are shown in Table 1 and 2. It shows that the difference of the stress between this analysis and theoretical solution is a few percent in spite of the applied load being more than three times as the load of elastic limit.

4) There is no great difference in the soil surface displacement between plastic zone and elastic zone.

The ratios of the soil surface displacement directly related with the foundation structures to the elastic theoretical solution are shown in Table 3. The values of applied lateral load are slightly different, but the vertical displacements of the applied vertical load, which have a great influence on the stress of the foundation structures, are in about 10 percent difference.

3 SOIL PLASTICITY ANALOGY WITH THEORETICAL METHOD

When the elastic-plastic analysis is applied to the semi-infinit bedsoil, it is necessary to evaluate the inelastic behavior of soil with certain practical and plain method. Effort is made to explain the inelastic behavior of bedsoil by the theoretical solution.

The fundamental assumption derived from results explained in the former chapters are shown as follows.

a) The stress distribution in plastic zone is almost equal to that in elastic zone.

b) The element rigidity in plastic zone uniformly falls in inverse proportion to the increased-amount of the strain corresponding to the equivalent stress.

Under these conditions the inelastic behavior of bedsoil and the soil surface displacements are obtained in following order.

1) The stress in each direction at each point is calculated from the theoretical solution for semi-infinite elastic body. (See equations 1-12).

2) The plastic strain (εp) and the coefficient of increase for the elastic strain (K) are obtained by the equations 13-14.

3) The soil surface displacement can be obtained by integrating the plastic strain, that is calculated by the elastic strain multiplied by K expressed by equation 14.

The ratios of the result of this method, which is applied to the model in previous chapter, to the result of FEM analysis are shown in Table 4-7. There is a difference from 10 to 25 percents when in elastic condition, and it is especially remarkable when lateral load is applied. So it is evident that this theoretical method has adequate accuracy in expressing the plastic strain of soil, and the soil surface displacement for vertical load condition. As it is the vertical displacement that has a great influence on the design of foundation structures, this method has adequate accuracy in expressing the inelastic behavior of the bedsoil.

4 STRESS EVALUATION OF THE FOUNDATION STRUCTURES

In this chapter the stress of foundation structures is obtained by the method described in Chapter 3. The calculation flow is shown in Fig. 9.

This method is examined by the axisymmetric model as shown in Fig. 10. The elastic-plastic analysis is applied to the model, the mat slab, modelled by shell element with consideration to the bending of plate and the plane stress, and applied to the soil surface, is applied with the increasing load in vertical direction.

The comparison between the result of the above method and the result of the presented report method in which the soil is evaluated by the theoretical solution is shown in Table 8-9, in which the value are the ratios of the result of inelastic analysis to that of elastic analysis. It shows that the difference, both in displacement and stress, is in about 10 percents except under lateral load condition. Considering that the distribution of stress and strain are slightly dispersed, it can be said that this evaluation method has adequate accuracy in expressing the deformation and stress of the mat slab regarding the inelastic behavior of bedsoil within a few percents error.

5 EXAMPLE OF MAT SLAB ANALYSIS

Effort is given to apply the theoretical method to a mat slab analysis. The mat slab, that has a square shape with side length of 80 meters and thickness of 7 meters, is placed on the surface of the bedsoil. The mat slab model as shown in Fig. 11 is cut in half due to the condition of symmetry. The elements are considered the bending of plate and the membrane stress. The various loads to the mat slab are; the vertical load (the total weight is about 380 thousands ton), the temperature load (the temperature difference between top and bottom is 25 degrees C), and the seismic load (the base shear coefficient is 0.7, the overturning moment with considerations to $e/\ell=0.8$)

The analysis is applied to the soil-spring presented in this report. The soil-spring is effective for compression and tension. According to the result, under the vertical or the temperature load the bedsoil is entirely elastic, but under the seismic load it is partially plastic at the corner. The plastic zone is very limited as shown in Fig. 12-14.

6 CONCLUSIONS

This report presents the evaluation method of soil-spring with considerations to the inelastic behavior of bedsoil for the purpose of understanding the stresses of the foundation structures. As a result of the stress analysis, the following are concluded.

1) When vertical loads are applied to the bedsoil, it does not yield easily, and the influence of its nonlinear behavior on the stress of mat slab cannot be found.

2) When vertical loads and lateral loads are applied simultaneously, the bedsoil easily becomes plastic, but there is no great affect if the base shear coefficient is not extremely large.

3) Under normal conditions when the stress analysis of the foundation structures are carried out, no problems are seen when the bedsoil is assumed as elastic material.

REFERENCES

Shunsaku, S. 1984. The evaluation method of soil-spring for stress analysis of foundation structures. Symposium of utilization of computer No.6. A.I.J.

Shunsaku, S. 1984. The evaluation method of soil-spring for Mat slab analysis with considerations given to the inelastic behavior of bedsoil. (Part 1) Abstract of general meeting A.I.J.

Equations

Soil stress under vertical load P

$$\sigma_x=\frac{3P}{2\pi}\left[\frac{zx^2}{R^5}+\frac{1-2\nu}{3}\left\{\frac{R^2-zR-z^2}{R^3(z+R)}-\frac{x^2(2R+z)}{R^3(z+R)^2}\right\}\right]\cdots\cdots(1)$$

$$\sigma_y=\frac{3P}{2\pi}\left[\frac{zy^2}{R^5}+\frac{1-2\nu}{3}\left\{\frac{R^2-zR-z^2}{R^3(z+R)}-\frac{y^2(2R+z)}{R^3(z+R)^2}\right\}\right]\cdots\cdots(2)$$

$$\sigma_z=\frac{3P}{2\pi}\frac{z^3}{R^5}\cdots\cdots(3)$$

$$\tau_{xy}=\frac{3P}{2\pi}\left\{\frac{xyz}{R^5}-\frac{1-2\nu}{3}\cdot\frac{xy(2R+z)}{R^3(R+z)^2}\right\}\cdots\cdots(4)$$

$$\tau_{yz}=\frac{3Pyz^2}{2\pi R^5}\cdots\cdots(5)$$

$$\tau_{zx}=\frac{3Pxz^2}{2\pi R^5}\cdots\cdots(6)$$

Soil stress under lateral load Q

$$\sigma_x=\frac{Qx}{2\pi R^3}\left\{\frac{3x^2}{R^2}-\frac{1-2\nu}{(R+z)^2}\left(R^2-y^2-\frac{2Ry^2}{R+z}\right)\right\}\cdots\cdots(7)$$

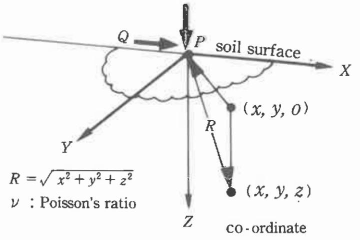
$$\sigma_y=\frac{Qx}{2\pi R^3}\left\{\frac{3y^2}{R^2}-\frac{1-2\nu}{(R+z)^2}\left(3R^2-x^2-\frac{2Rx^2}{R+z}\right)\right\}\cdots\cdots(8)$$

$$\sigma_z=\frac{3Qxz^2}{2\pi R^5}\cdots\cdots(9)$$

$$\tau_{xy}=\frac{Qy}{2\pi R^3}\left\{\frac{3x^2}{R^2}-\frac{1-2\nu}{(R+z)^2}\left(-R^2+x^2+\frac{2Rx^2}{R+z}\right)\right\}\cdots\cdots(10)$$

$$\tau_{yz}=\frac{3Qxyz}{2\pi R^5}\cdots\cdots(11)$$

$$\tau_{zx}=\frac{3Qx^2z}{2\pi R^5}\cdots\cdots(12)$$



$R=\sqrt{x^2+y^2+z^2}$

ν : Poisson's ratio

$$\varepsilon_p=(\sigma_{eq}-\sigma_y)/H'=\frac{(\sigma_{eq}-\sigma_y)(1-k_i)}{k_i E_0(1-\alpha)^2}\cdots\cdots(13)$$

$$K=(\varepsilon_e+\varepsilon_p)/\varepsilon_e=1+\varepsilon_p/\varepsilon_e\cdots\cdots(14)$$

Where σ_{eq} is the equivalent stress, σ_y is the elastic stress equivalent to σeq, k_i is the reduction coefficient of Young's modulus, α is the coefficient of volume expansion.

Table 1 Result under the vertical load

load	σ_y	σ_z	τ_{xy}	ε_y	ε_z	γ_{yz}
1.56W_e	1.152	1.002	0.9614	1.072	1.043	1.063
2.11W_e	1.384	1.007	0.9138	1.209	1.123	1.188
2.67W_e	1.517	1.015	0.8920	1.371	1.212	1.317

Table 2 Result under the lateral load

load	σ_y	σ_z	τ_{yz}	ε_y	ε_z	γ_{yz}
1.79Q_e	1.021	0.9062	1.013	1.070	1.851	1.121
3.38Q_e	1.210	0.9496	1.001	1.461	0.6766	1.810
4.17Q_e	1.278	1.037	1.001	1.590	0.8132	1.994

Table 3 Soil surface displacement at loading center

vertical load	z (I)	z (J)	y (J)	lateral load	y (L)	y (M)
1.56W_e	1.021	1.017	1.040	1.79Q_e	1.057	1.046
2.11W_e	1.067	1.057	1.086	3.38Q_e	1.380	1.332
2.67W_e	1.127	1.112	1.064	4.17Q_e	1.479	1.428

Table 4 Result under vertical load

load	σ_z(A)	ε_z(A)	σ_z(B)	ε_z(B)	σ_z(C)	ε_z(C)
W_e	0.9135	0.9688	0.9325	0.9587	0.8500	0.9596
1.28W_e	0.9144	0.9667	0.9348	0.9570	1.097	1.005
2.11W_e	0.9074	1.119	0.9380	1.102	0.8158	1.091

Table 5 Result under lateral load

load	τ_{yz}(E)	γ_{yz}(E)	τ_{yz}(F)	γ_{yz}(F)	τ_{yz}(G)	γ_{yz}(G)
Q_e	0.7591	0.7590	0.7707	0.7708	0.7423	0.7424
1.79Q_e	0.7495	0.6804	0.7743	0.6968	0.7420	0.6810

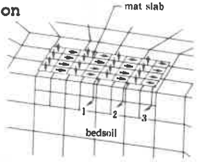
Table 6 Soil surface displacement under vertical load

load	z(I)	z(J)	z(K)
W_e	1.173	1.182	1.162
1.28W_e	1.172	1.186	1.164
2.11W_e	1.107	1.128	1.136

Table 7 Soil surface displacement under lateral load

load	y(L)	y(M)	y(N)
Q_e	0.5926	0.5840	0.4926
1.79Q_e	0.5606	0.5584	0.4777

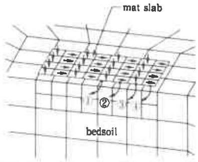
Table 8 Comparison of displacement and soil-reaction



load		displacement at y and z			soil-reaction at y and z		
		1	2	3	1	2	3
vertical 2.042We	FEM	z1.056	1.049	1.032	0.9745	.0.9841	1.011
	PRM	z1.180	1.177	1.178	0.9728	0.9733	1.013
lateral 3.574Qe	FEM	y1.226	1.225	1.225	0.9838	0.9421	1.152
	PRM	y1.230	1.232	1.235	0.9088	0.9424	0.9987
vertical + and lateral 2.384We	FEM	z1.063	1.058	1.024	0.9825	0.9687	0.6259
	PRM	z1.168	1.165	1.177	0.9934	0.9905	0.9920
	FEM	y1.095	1.100	1.105	1.040	0.9960	0.8693
	PRM	y1.103	1.097	1.095	1.639	2.609	1.121

PRM : presented report methed

Table 9 Comparison of **mat slabs' stress**



load		bending moment(My) axial force(Ny)			
		①	②	③	④
vertical 2.042We	FEM	My1.136	1.100	1.056	1.023
	PRM	My1.240	1.196	1.123	1.071
lateral 3.574Qe	FEM	Ny0.7639	0.7071	0.6973	0.6955
	PRM	Ny0.6670	0.1509	0.6253	0.9970
vertical and lateral 2.384We	FEM	My1.135	1.145	1.152	1.162
	PRM	My1.167	1.165	1.167	1.177
	FEM	Ny0.6104	0.0983	2.081	1.305
	PRM	Ny1.103	1.097	1.096	1.095

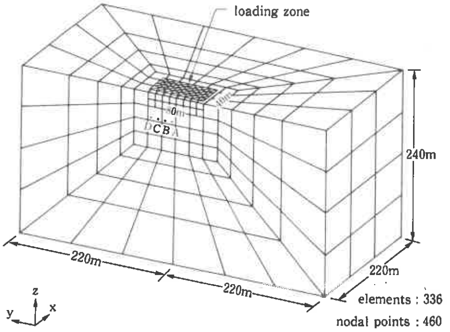


Fig. 1 Analysis model

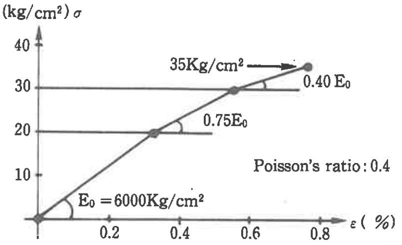


Fig. 2 Stress strain relation of bedsoil

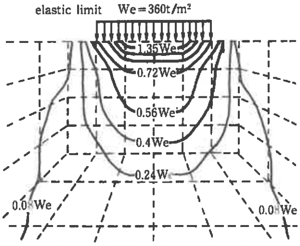


Fig. 3 Stress distribution in the vertical direction

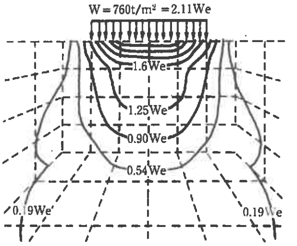


Fig. 4 Stress distribution in the vertical direction

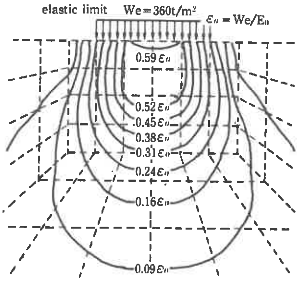


Fig. 5 Strain distribution in the vertical direction

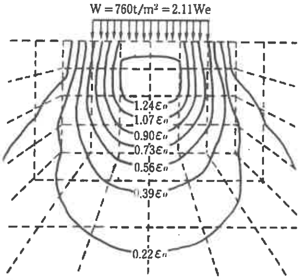


Fig. 6 Strain distribution in the vertical direction

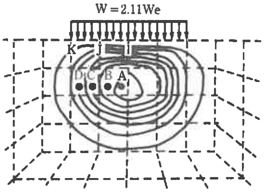


Fig. 7 Plastic strain distribution (Pεz)

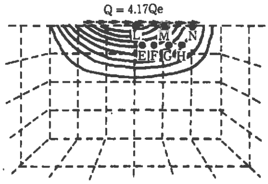


Fig. 8 Plastic strain distribution (Pγyz)

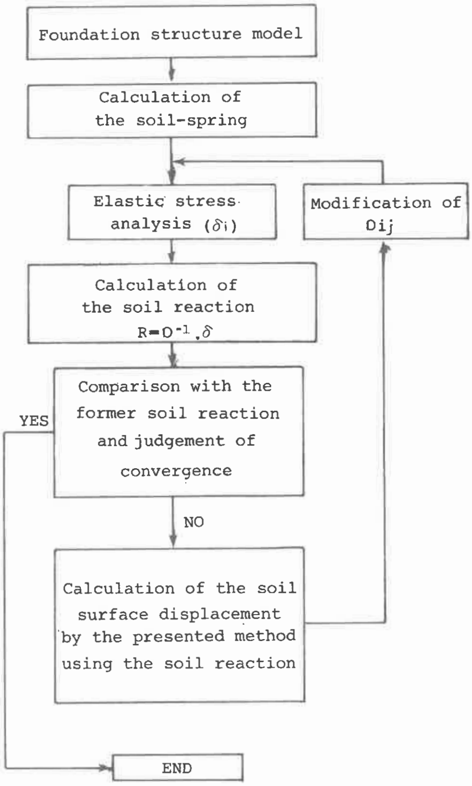


Fig. 9 Calculation flow

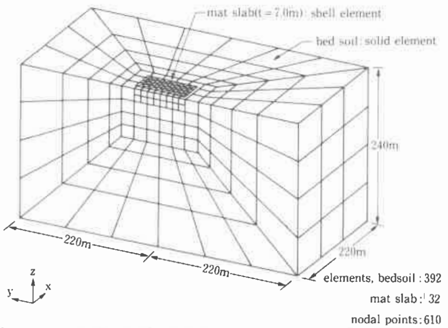


Fig. 10 Analysis model

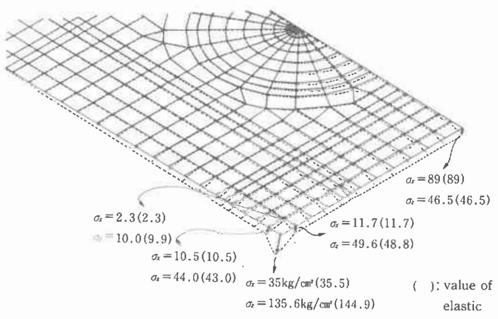


Fig. 12 Soil reaction under seismic load

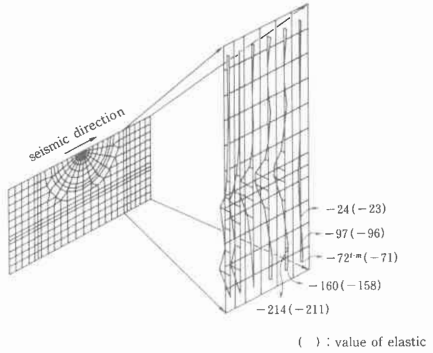


Fig. 13 Bending moment distribution under seismic load

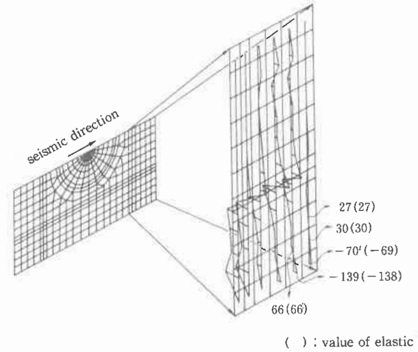
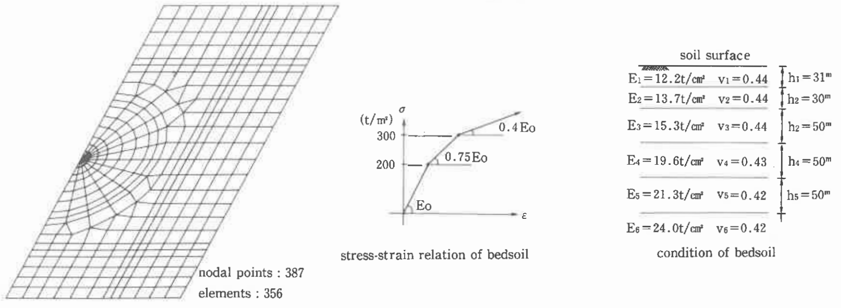


Fig. 14 Shear force distribution under seismic load



stress-strain relation of bedsoil

condition of bedsoil

Fig. 11 Examination model