Study on the seismic stability of a power plant structure and foundation (2) analysis

S.Setogawa & M.Kobayashi
The Kansai Electric Power Corporation, Inc., Osaka, Japan
J.Terada
The New Japan Engineering Consultants, Inc., Osaka
S.Kawamura & M.Yamada
Taisei Corporation, Yokohama, Japan

1 SUMMARY

In the analytical studies of uplift phenomena distribution of subgrade reaction is usually assumed as uniform for vertical motion and triangular for rotational motion. But the validity of such assumption and the applied analytical methods have been scarcely verified experimentally. In this paper a new analytical method is verified by small scale model tests which can consider the distribution of subgrade reaction. Based on the justification the analytical method is applied to typical PWR 4-Loop Reactor Building. According to the results of simulation analysis, the test data were well simulated by the method. And it was made clear that the difference of subgrade reaction gives large difference to the uplift ratio and little difference to the response acceleration and spectra.

2 INTRODUCTION

For the purpose of rational evaluation of seismic uplift of foundation it is necessary to verify the validity of the method of analysis using test data.

Usually the distribution of subgrade reaction is assumed as triangular for the rotational motion of foundation. But the influence of the mode of distribution on the uplift behavior has scarcely been discussed.

Static and dynamic loading tests were conducted on small scale model by the authors as introduced in another paper (S. Setogawa et al. (1987)).

Using the data of the tests simulation analysis was done as described.

3 SIMULATION ANALYSIS OF THE TEST DATA

3.1 Proposed three dimensional method

A new analytical method is proposed taking the distribution of subgrade reaction into consideration to calculate the uplift response more exactly. Apart from the assumption of subgrade reaction, this method is same as the method proposed by Takaki et al. (1985). Six freedoms are considered at the base slab and every node of the model: three translations and three rotations along and around X, Y and Z axes. Subgrade reaction is calculated at each time step of response based on the following assumptions.

i) Vertical soil reaction is calculated by coefficient of vertical spring Kv (Fig. 1).

$$Kv(X, Y) = A_1 + A_2/\sqrt{R^2 - r^2} \quad (1)$$

Where, A_1 and A_2 are calculated by solving the following equations.

$$KR = \int Kv(X,Y)*X \, dA, \quad KV = \int Kv(X,Y) \, dA \quad (2)$$

Where KR and KV are rotational and vertical soil spring obtained by the results of static loading tests. In the case that A_2 is zero, the distribution of subgrade reaction becomes uniform for vertical loading and triangular for rotational loading. And in the case that A_1 is zero the distribution becomes that of rigid base.

ii) Horizontal subgrade reaction is assumed as constant over contact area.

In this method vertical response induced by uplift can be estimated even in the case of horizontally uni-axial excitation.

3.2 Simulation analysis of static loading tests

Static loading tests and shaking table tests were performed using three small scale structure models set on soil model. Silicone rubber was used as a soil model. As a structure model three models were used. One is a rigid body with rigid foundation (RR model). Another one is an elastic body with rigid foundation (RE model). The other one is an elastic body with elastic foundation (EE model). The results of the tests are shown by S. Setogawa et al.(1987).

Fig.2 shows the relationship between the overturning moment and rotation in case of RR model. In usual analysis triangular distribution is assumed for subgrade reaction in rotational mode. But the results of the test differ from the analytical results assuming such a distribution. The distribution obtained by the proposed method turned out to be more suitable to simulate the test data.

Fig.3 shows the relationship between shear force and displacement. In this case the stiffness of translational spring decreases in proportion to the 1/4 power of the contact area.

Fig.4 shows the relationship between normalized overturning moment and uplift ratio, where two models give different results. As shown in the figure, the test result of RR model which has rigid base well coincides with the analytical results assuming rigid base distribution.

But the test result of EE model which has elastic base is not in agreement with the analytical result. In this case the change of distribution of the subgrade reaction must be considered according as the uplift ratio increases. In other words, by varying the coefficient A_1 and A_2, analytical uplift ratio shows good agreement with the experimental result.

Before the uplift begins coefficient A_1 and A_2 are determined by eq.(1) and (2). As uplift area becomes wide coefficient A_2 is decreased and A_1 increased. A_1 is determined as eq.(3).

(3) $$\int A_1 dA = KV - \int (A_2/\sqrt{R^2 - r^2}) dA$$

In the analysis of this model A_2 is chosen as zero when the uplift ratio becomes 60%, which means distribution of subgrade reaction becomes triangular.

3.3 Dynamic analysis of test data

RR model is analytically modeled by rigid body. EE and RE model are modeled by lumped mass models with five and two masses respectively.

Fig.5,6 and 7 show the resonance curve obtained by RR, RE and EE model respectively. The decrease of resonance frequency and amplification ratio shows good coincidence with that of experimental results.

4 APPLICATION TO THE TYPICAL PWR 4-LOOP REACTOR BUILDING

4.1 Analytical model and conditions

The influence of the analytical conditions such as distribution of subgrade reaction and analytical method on analytical results (uplift ratio, response acceleration and response spectra) is discussed.

Typical PWR 4-Loop Reactor Building is modeled as shown in Fig. 8 which have three vertical beams with lumped masses expressing PCCV, IC and REB respectively. Two kinds of ground condition are assumed: soft rock (Vs=1.0km/sec) and hard rock (Vs=2.0km/sec).

Three types of method are used for the analysis: proposed 3D method, nonlinear rocking method, and conventional linear method. In the proposed 3D method two types of subgrade reaction are assumed for rotational mode. The one is the triangular distribution and the other one is that of rigid base. In the other methods distribution of subgrade reaction is assumed as triangular. In nonlinear rocking method, two types of moment-rotation relation are assumed. The one is tri-linear type and the other one is curvilinear type. In this method vertical response induced by uplift can not be taken into account. In the conventional linear method the nonlinearity of rocking spring can not be taken in account.

4.2 Results of the analyses

Fig.9 shows the maximum uplift ratio. Triangular distribution gives large uplift ratio than that of rigid base. In the range of small uplift ratio the difference is more than 10%. But according to the growth of uplift ratio, the difference becomes small. This tendency is not changed by the difference of shear wave velocity of the ground. As for the analytical method, uplift ratio obtained by the nonlinear rocking method which can not estimate vertical response induced by uplift is larger than that obtained by proposed 3D method in most cases. The conventional linear method which can not consider the nonlinearity of rocking spring gives large uplift ratio than the nonlinear rocking method. Even in the same nonlinear rocking method, M-θ relation of tri-linear type gives large uplift ratio than that of the curvilinear type.

From these analytical studies it can be made clear that the result of exact solution by the proposed 3D method gives smaller uplift ratio than those of the conventional calculation.

Table 1 shows the maximum response acceleration of typical points in the case of soft rock. As shown in previous explanation, difference of distribution of subgrade reaction gives large difference in the uplift ratio, but it gives little difference in the response acceleration. This tendency is same with the case of hard rock.

Fig.10 through 14 show the example of response spectra. In this calculation ground is assumed as soft rock and input acceleration is assumed as 800 Gal. To calculate response spectra the response acceleration is normalized as 100 Gal.

Fig.10 shows the spectra of point IC03. By this figure difference of distribution of subgrade reaction gives little difference in the spectra, and the difference of analytical method gives large difference than that of the distribution of subgrade reaction.

Fig.11,12 and 13 show spectra of PCCV (PC18), REB (RE23) and base mat (BS32) respectively. The spectra show the same tendency with that of IC (IC03) and even in the case of the other conditions of shear wave velocity and input acceleration, same tendency is obtained.

5 CONCLUSIONS

From the static and dynamic analysis of the test model and typical assumed plant the following conclusions are obtained.

(1) By appropriately considering the distribution of subgrade reaction, analytical M-θ relation and uplift ratio show good agreement with the experimental results. In the static analysis and in the dynamic analysis the resonance curve obtained by the proposed 3D method shows good agreement with the experimental results.

(2) The proposed 3D method gives smaller uplift ratio than those of conventional methods.

(3) The difference of distribution of subgrade reaction gives large difference in the uplift ratio. But it gives little difference in the response acceleration.

(4) The mode of distribution of subgrade reaction has less influence on the response spectrum than the method of analysis.

REFERENCES

S.Setogawa et al. 1987. Study on the Seismic Stability of Power Plant Structure and Foundation (1) Experiment, Lausanne, Trans. of 9th SMIRT K5/10

M.Takaki et al. 1985. Three Dimensional Uplift Response Analysis of a Nuclear Reactor Building, Brussel, Trans. of 8th SMIRT K5/9

T.Takemori et al. 1976. Nonlinear Dynamic Response of Reactor Containment, Nuclear Engineering and Design 36,p.463-474

Table 1 Maximum amplification ratio obtained by response analysis

Input Acc. (Gal)	Point and Direction		Proposed 3D Method Triangular	Proposed 3D Method Rigid Base	Conventional Linear Method	Nonlinear Rocking Method Tri-Linear Type	Nonlinear Rocking Method Curvilinear Type
200	IC03		1.64	←	←	←	←
	PC18		3.77	←	←	←	←
	RE23		1.44	←	←	←	←
	BS32	X	1.15	←	←	←	←
		Z	0.00	←			
800	IC03		1.84	1.84	1.63	1.59	1.60
	PC18		3.70	3.75	3.76	3.88	3.93
	RE23		1.46	1.40	1.44	1.32	1.31
	BS32	X	1.20	1.23	1.15	1.30	1.33
		Z	0.13	0.10			
1,200	IC03		1.84	1.82	1.63	1.88	1.94
	PC18		3.64	3.72	3.76	3.86	3.80
	RE23		1.45	1.52	1.44	1.31	1.42
	BS32	X	1.15	1.14	1.15	1.36	1.33
		Z	0.32	0.25			

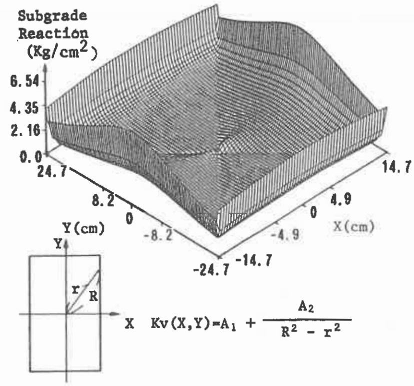

Fig.1 The assumed subgrade reaction

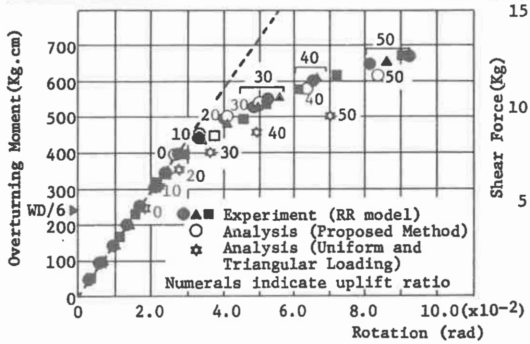

Fig.2 Relationship between overturning moment and rotation

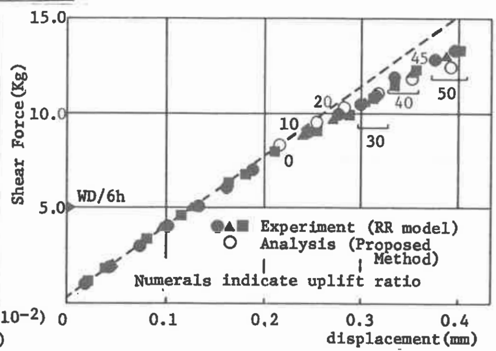

Fig.3 Relationship between shear force and displacement

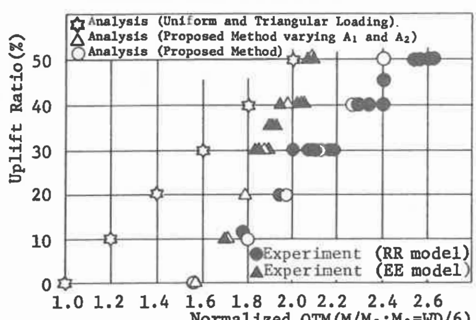

Fig.4 Relation between normalized overturning moment and uplift ratio

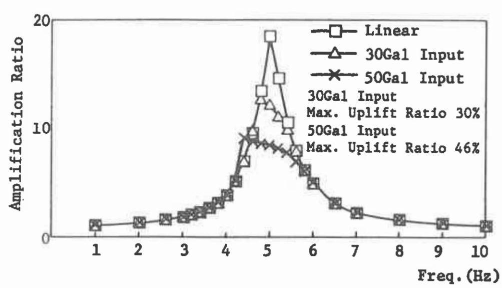

Fig.5 Resonance curve of RR model

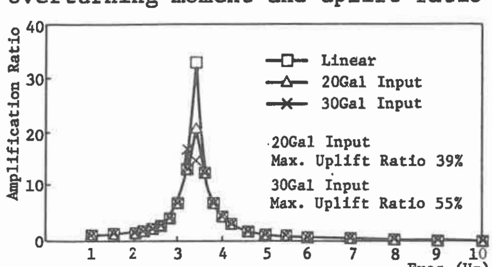

Fig.6 Resonance curve of RE model

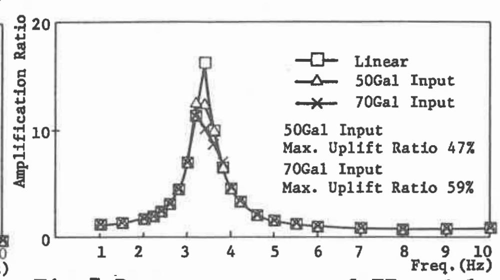

Fig.7 Resonance curve of EE model

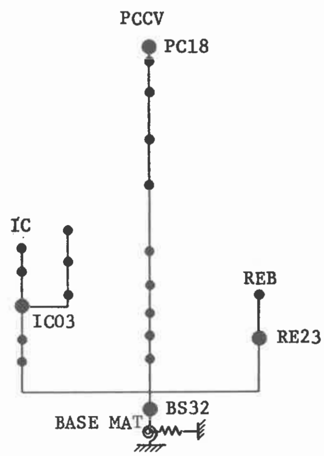

Fig.8 Analytical model of typical 4-Loop Reactor Building

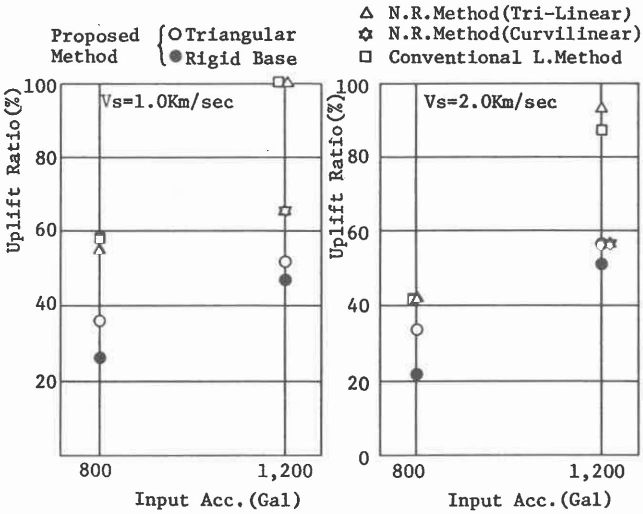

Fig.9 Uplift ratio obtained by analysis

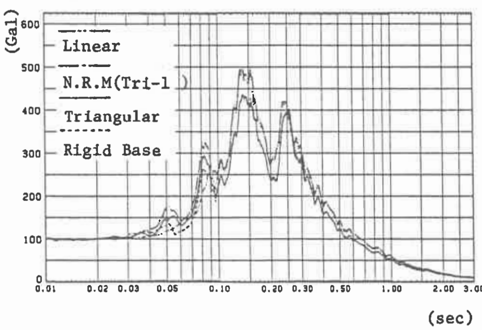

Fig.10 Response spectra of IC03

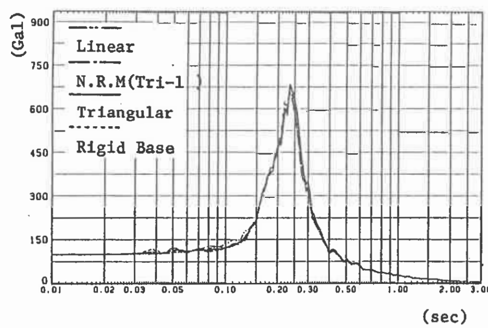

Fig.11 Response spectra of PC18

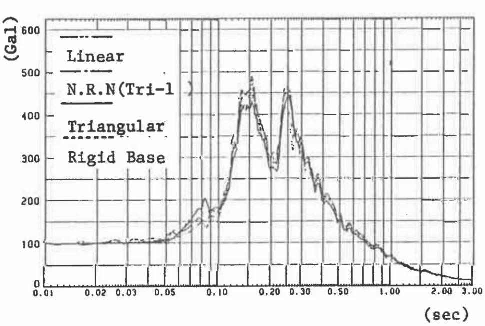

Fig.12 Response spectra of RE23

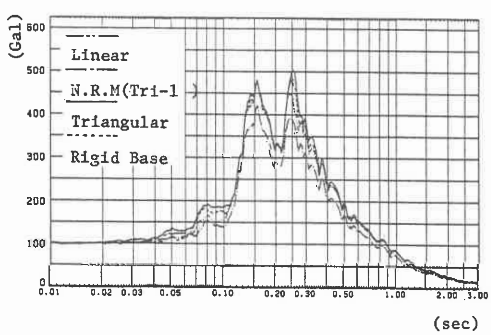

Fig.13 Response spectra of BS32