Optimization of sensors implemented in nuclear power plants considering the effect of stiffness degradation

Keyword:
SHM Nuclear power station
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Kalman method Mode and linear methods

○Zhuoran Yi *1 Hamood Alwashali *2
Benjamin Brito *3 Masaki Maeda *4
Matsutaro Seki *5

1. Introduction

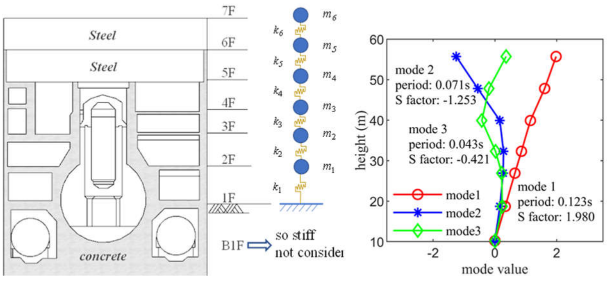
Structural health monitoring (SHM) using accelerometers for the displacement estimation of Nuclear Power stations (NPS) is getting much more attention. However, it is impractical to place accelerometers on each floor due to limited accessibility, such as in case of Fukushima NPS damaged by 2011 East Japan Earthquake.

This paper analyzes the optimization of the number and location of sensors applied to NPS case. Estimations of displacement based on three methods: linear assumption, mode method, and Kalman method are considered, taking the influence of stiffness degradation due to prior damage into consideration.

2. Background and methodology

2.1 Introduction of NPS Building

Based on basic building properties shown in documents [1], a lamped mass analytical model is assumed as shown in Figure 1(a), with parameters listed in Table 1.



(a) (b)

Fig.1 NPS model (a) front view (b) modes

Tab.1 Key parameters of an NPS model [1]

Floor	Mass (t)	Height (m)	Shear stiffness (10^{11} N/m)	Effective area (m^2)
7F	1900	7.9	0.286	21
6F	1600	7.9	0.382	28
5F	7500	7.6	1.449	103
4F	8800	5.4	2.988	151
3F	11000	8.2	2.663	204
2F	13000	8.5	2.852	227

The first three modal responses of the structure are shown in Figure 1(b). In this model, the base floor (BIF) is assumed stiff enough compared with other floors, and thus it is assumed as a fixed structure at the base and rocking or sway deformation of the base is not considered in this study.

2.2 Introduction of analyzed methods

The analysis target is estimating the maximum response of the floors that do not have sensors by interpolation of sensors data of in other floors. Three methods are applied to this research. Two of them assume the distribution of maximum displacement of each floor is directly linear (named in this study as linear method) or interpolation assuming the distribution of the first modal response (named in the study as mode method). Another different approach from these two schemes is the Kalman method. Kalman method assumes a mathematical model first and then tries to verify the properties of the model by finding the optimum solution of stiffness and damping from the data of limited measurement of floors [2]. The basic idea of these three methods is introduced in Figure 2. The average error Er presented in Equation 1 will be applied to analyze the workability of each method.

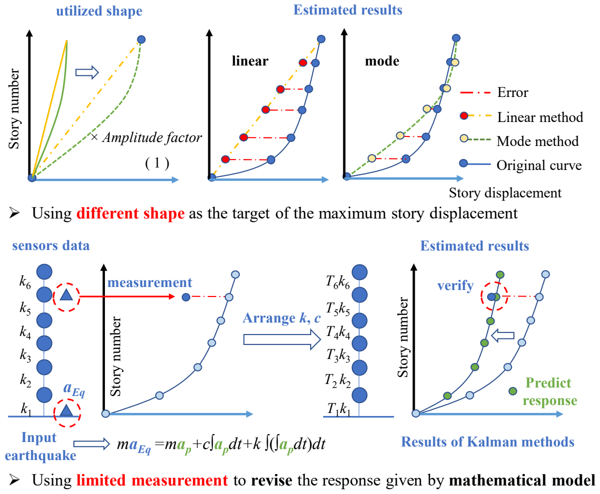


Fig.2 utilized estimation methods

$$Er = \sum_{i=1}^{6} Er_i / 6 \quad (1)$$

where Er_i is the estimated error of floor i defined by Equation 2.

$$Er_i = |Es_i - D_i| / D_i \quad (2)$$

where Es_i is the estimated relative displacement of Floor i obtained from three methods, D_i is the exact relative displacement of floor i.

3. Analysis for number of sensors

3.1 Estimation of the original model

The input ground motion to the analytical model is the record of the 2011 Great East Japan Earthquake, which is the same as the reference [1]. A limited number of sensors from 2 to 7 is assumed to be placed on the model. The optimum possible locations of sensors are based on stiffness distribution and considered at points with large variance in the stiffness between floors, as shown in Figure 3.

Then, the three methods are utilized to estimate the maximum relative displacement of the NPS. The initial stiffness and damping for Kalman method setting are shown in Table 2.

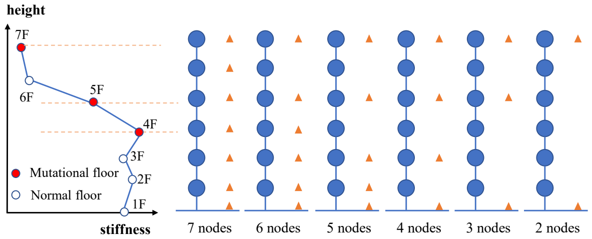


Fig.3 Selected groups

Tab.2 Parameters in Kalman method

Floor	2F	3F	4F	5F	6F	7F
Shear stiffness (10^{11} N/m)	2	2	2	1	0.5	0.5
Damping (10^{7} N*s/m)	10	10	10	5	2.5	2.5

The errors for three methods are shown in Figure 4. The error of linear method will increase with the decrease of the number of sensors, while the error of Kalman method and mode method keeps nearly constant. The 1st mode method showed better result since the mode shape is constant within elastic range of vibration.

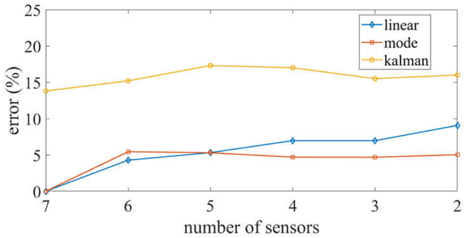


Fig.4 Results when number of sensors increased using 3 methods

3.2 Displacement Estimation with stiffness degradation

Then the stiffness degradation due to damage is assumed in story 5 to 6 and story 3 corresponding to case 1 and case 2, as shown in Figure 5. Based on stiffness distribution, two groups of sensor arrangement are applied for the two cases: Group A has three sensors attached in 1F, 5F, and 7F, Group B has two sensors in 1F and 5F, corresponding to the condition with 2 and 3 sensors.

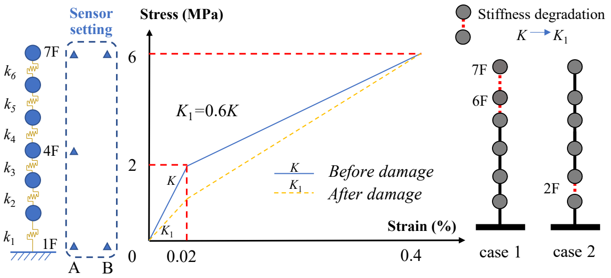


Fig 5. The selected case for stiffness degradation

3.2.1 Case 1

In this case, the stiffness from story 5 to 6 decreases to 60% compared with the initial setting. The error of the two groups is shown in Figure 6.

The estimation error for the condition after the damage has increased about 2 times and 5 times, corresponding to the linear and mode method compared with the condition before damage. However, for the Kalman method, the error keeps nearly constant, which indicates it can keep a relative constant ability to estimate relative displacement before or after damage.

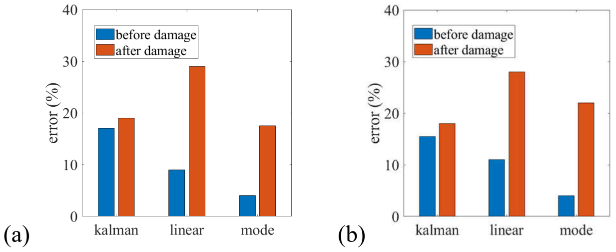


Fig.6 Error of case 1 (a) A-3 nodes (b) B-2 nodes

3.2.2 Case 2

In this case, the stiffness in story 3 is assumed to decrease to 60%. The error of two groups is shown in Figure 7.

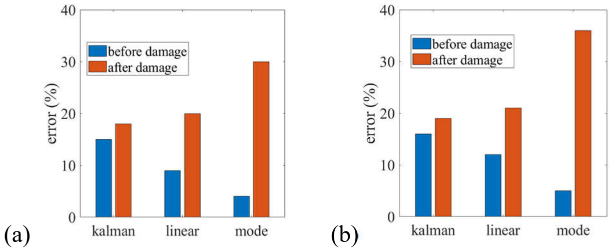


Fig.7 Error of case 2 (a) A-3 nodes (b) B-2 nodes

Case 2 shows similar tendency with Case 1. However, error of linear and mode methods increases to nearly 30% in the condition with stiffness degradation, though it was within 10% without considering stiffness degradation due to damage. Kalman shows similar results before or after damage, which shows its applicable for estimating relative displacement when the structure suffers damage.

4. Conclusion

In this paper, mode, linear and Kalman methods are applied to estimate the relative displacement of each floor using a limited number of sensors. Two conclusions can be drawn:

(1) In case the response remains within elastic range, mode method gives relatively better estimation (prediction) of displacement response for floors without observation sensor.

(2) When the response increase and reach to inelastic range, error in estimation increase due to differences in mode shape by stiffness degradation. Here, the error by the linear and the mode method increased much, but Kalman method gave stable prediction with same error regardless of stiffness degradation.

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6. References

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1* 東北大学大学院工学研究科 博士課程後期
2* 岡山大学大学院環境生命科学研究科 准教授・博士
3* 東北大学大学院工学研究科 研究員・博士（工学）
4* 東北大学大学院工学研究科 教授・博士（工学）
5* 建築研究所 特別客員研究員・博士 (工学)

1* Ph.D. student, Graduate School of Eng., Tohoku Univ.
2* Associate Professor, Graduate School of Env. & life science, Okayama Univ., Dr. Eng.
3* Research Fellow, Graduate School of Eng., Tohoku Univ., Dr. Eng.
4* Professor, Graduate School of Eng., Tohoku Univ., Dr. Eng.
5* Visiting Research Fellow, Building Research Institute, Dr. Eng.