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Development of the structural health record of containment building in nuclear power plant

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ABSTRACT

The main objective of this work is to propose a reliable routine standard operation procedures (SOP) for structural health monitoring and diagnosis of nuclear power plants (NPPs). At present, NPPs have monitoring systems that can be used to obtain the quantitative health record of containment (CTMT) buildings through system identification technology. However, because the measurement signals are often interfered with by noise, the identification results may introduce erroneous conclusions if the measured data is directly adopted. Therefore, this paper recommends the SOP for signal screening and the required identification procedures to identify the dynamic characteristics of the CTMT of NPPs. In the SOP, three recommend methods are proposed including the Recursive Least Squares (RLS), the Observer Kalman Filter Identification/Eigensystem Realization Algorithm (OKID/ERA), and the Frequency Response Function (FRF). The identification results can be verified by comparing the results of different methods. Finally, a preliminary CTMT healthy record can be established based on the limited number of earthquake records. It can be served as the quantitative reference to expedite the restart procedure. If the fundamental frequency of the CTMT drops significantly after the Operating Basis Earthquake and Safe Shutdown Earthquake (OBE/SSE), it means that the restart actions suggested by the regulatory guide should be taken in place immediately.

1. Introduction

The structural safety of nuclear power plants (NPPs) is often regarded as an important issue in civil engineering. Many guidance and researches have been proposed for seismic safety assessment and structural monitoring of nuclear power plants. Appendix A to Part 100 of the US-CFR regulations [1] defines 2 seismic levels, Operating Basis Earthquake (OBE) ground motion and Safe Shutdown Earthquake (SSE) ground motion. IAEA Safety Guide [2] defines the SL-2 and the SL-1 which can be compared to the SSE and OBE. IAEA Safety report [3] provides the guidance of shutting down and restarting a plant after the occurrence of an earthquake. IAEA [4,5] review the state of the art in on-line equipment monitoring for NPP applications.

In response to the downtime of the Kashiwazaki-Kariwa Nuclear Power Plant (KKNPP) after the 2007 Niigata-ken Chuetsu-oki Earthquake (M6.6), the power companies, equipment manufacturers, and related experts and scholars were called to form the Structural Integrity Assessment for Nuclear Power Components experienced Niigata-ken Chuetsu-oki Earthquake Committee (SANE). For the nuclear power plant to restart after the relevant inspection and evaluation standards, structural strength or seismic capacity improvement, etc., SANE conducted overall safety assessment operations. Related measures and guidelines were successively included in the safety report of the International Atomic Energy Agency (IAEA), and USNRC also included them in the relevant specifications for the restart procedures, and applied to the 2011 North Anna Nuclear Power Plant after the M5.8 Mineral Virginia Earthquake.

In order to provide a wide range of international exchanges, the Japan Nuclear Safety Institute (JANSI), former Japan Nuclear Technology Institute (JANTI), compiled the relevant documents established by the SANE into books and published the guidelines for the evaluation of the soundness of equipment after earthquakes [6]. Subsequently, all nuclear power plants in Japan have successively conducted restart assessments based on these guidelines. The development process of the US nuclear power plant's restart criteria after earthquake began in EPRI Report NP-6695 [7] published by the Electric Power Research Institute (EPRI) in 1989. In

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response to the guidelines, in 2002, the American National Standards Institute (ANSI) used it as the technical basis to formulate the US national standard ANSI/ANS-2.23-2002 [8] served as the guidelines and specifications of the nuclear power plant's response to earthquakes in the USA. Thereafter, EPRI made major changes to EPRI Report NP-6695 and published a new version of EPRI Report 3002000720 [9] in 2013, adding the experiences and lessons learned in the 1990s when some nuclear power plants encountered major earthquakes in the world. In 2016, ANSI used the EPRI Report 3002000720 as a blueprint and added several important changes and developed ANSI/ANS-2.23-2016 [10]. It is worth noting that the EPRI rewrote and updated the EPRI Report 3002000720 in 2015, adding important and detailed changes and additions to publish EPRI Report NP-3002005284 [11]. In 2019, the USNRC announced the new DG-1337 [12] draft guidelines to replace the old regulatory guides RG-1.166 [13] and RG-1.167 [14] released in 1997.

Apart from the abovementioned lengthy and rigorous guidelines, Hasan et al. [15] proposed a development of earthquake instrumentation to expedite the walk-down period when a seismic event exceeds the OBE. Nguyen et al. [16] investigate the relationship between 23 earthquake intensity measures (IMs) and seismic responses of NPP structures to identify the significant IMs to estimate damage of NPP. Hur et al. [17] and Lin and Li [18] performed seismic simulation and assessment on the CTMT, auxiliary building and non-structure components, respectively. It can be seen that structural safety of NPPs aftershock is getting more and more attention. System identification is the theory that uses the relationship between input and output data to build the dynamic model of target structure, and obtains system parameters from it. There are many methods have been developed in this field. These included the Recursive Least Squares method (RLS) (Caravani et al. [19]) for time-varying system and the Observer Kalman Filter Identification/Eigensystem Realization Algorithm (OKID/ERA) method (Juang [20]) for time-invariant system. Lin et al. [21] further modified the RLS method and introduced the variable trace method for nonlinear system identification. In recent years, many scholars applied the measurement signal to identify the parameters of the buildings and used the identification results as the indicator of damage assessment. Chu and Lo [22,23] proposed the real-time model-reference adaptive identification technique (MRAIT) and evaluate the Tai-Tung Fire Bureau Building by the RLS method with measured building-array data in Taiwan. Varpasuo [24] applied the sixth order Box-Jenkins model to identify the Kozloduy reactor building in Bulgaria subjected to the blast test in 1996. Naito and Niousha [25] adopted the SISO recursive ARX model for the analytical study on the parametric system identification of the fixed-base modal parameters of a simplified partly embedded reactor building modeling subjected to forced vibration and ground motion excitation. Niousha et al. [26] investigated the system identification of a reactor building, Hamaoka nuclear power plant unit-4 reactor building (H4-RB), under fixed-base conditions using forced vibration tests, microtremors and earthquake observation data. Niousha et al. [27] also conducted the system identification of the reactor building subjected to a forced vibration test and microtremor measurements conducted on Hamaoka Unit-5 ABWR-type reactor building. Furthermore, Niousha et al. [28] performed a series of forced vibration tests (FVT) in order to investigate the dynamic characteristics of a Steel-plate-reinforced-Concrete (SC) building served as the solid waste disposal incinerator building in Kashiwazaki-Kariwa NPP, Japan.

This paper wants to establish a reliable routine standard operation procedures (SOP) for structural health monitoring and diagnosis of CTMT buildings to achieve the goal of developing the structural healthy record by the identifying results. Furthermore, the walk-down period when a seismic event exceeds the OBE/SSE can be expedited. This paper will use the CTMT of KuoSheng Nuclear Power Plant (KSNPP) as the identification target and establish a structural health diagnosis process for it. Taiwan's Atomic Energy Council (AEC) performed the third ten-year safety assessment of KSNPP in 2012. The third "Ten-Years Integrated Safety Assessment Report" (TYINSAR) [29] was issued in public domain, which was equivalent to the Safety Evaluation Report (SER) recommended by the USNRC. The report included the results of the structural safety assessment of the nuclear power plant using the system identification method. The seismic data in the TYINSAR was only up to 2006. Since then, several earthquake events were occurred in Taiwan, and the time histories of these earthquake events had also been recorded. The standard operating procedures suggested in this article have been set as the mandatory requirement and is implemented in the regulatory review case: Research on Planning and Layout of Seismic Monitoring System in Nuclear Power Plants in Taiwan. It is expected that these earthquake events will be analyzed followed this SOP in the future.

2. Identification methods and analysis procedure

2.1. System identification

System identification is the process of building a mathematical model of a dynamic structure using measurement data. This method has been proposed by many experts to estimate the dynamic characteristics of a building. The identification methods used in this paper are the frequency response function (FRF) method, the RLS, and the OKID/ERA respectively. Through theoretical derivation [20], the formula of FRF can be defined as:

$$\begin{cases} \bar{S}_{yu}(k) = \dfrac{1}{N}\displaystyle\sum_{i=0}^{N} S_{yu}^{(i)} = \dfrac{1}{N}\sum_{i=0}^{N} Y_i^{(i)}(k) \times U_i^{*(i)}(k) \\ \\ \bar{S}_{uu}(k) = \dfrac{1}{N}\displaystyle\sum_{i=0}^{N} S_{uu}^{(i)} = \dfrac{1}{N}\sum_{i=0}^{N} U_i^{(i)}(k) \times U_i^{*(i)}(k) \end{cases} \tag{1}$$

$$G(z_k) = \frac{\bar{S}_{yu}(k)}{\bar{S}_{uu}(k)}$$

Assume that there are N data records available which are obtained either from N experiments or from N segments of a long record. $Y_i^{(i)}(k)$ and $U_i^{(i)}(k)$ are the discrete Fourier transform of the ith or the ith segment of output and input signals, respectively, $U_i^{*(i)}(k)$ is the conjugate of $U_i^{(i)}(k)$. Where $\bar{S}_{yu}(k)$ and $\bar{S}_{uu}(k)$ are the cross-spectral density function and the power-spectral density function, respectively. These two functions can be calculated by input and output signal, and the FRF can be obtained by dividing these two functions.

In addition to the conventional FRF for the time-invariant system, the other single-input single-output (SISO) method is the recursive least squares (RLS), which has also been used for identifying the time-varying parameters of structure [19,23]. The formula of RLS is as follows,

$$\hat{\boldsymbol{\theta}}(k) = \hat{\boldsymbol{\theta}}(k-1) + \mathbf{K}(k)\varepsilon(k)$$

$$\mathbf{K}(k) = \mathbf{P}(k-1)\boldsymbol{\phi}(k)\left(\lambda\mathbf{I} + \boldsymbol{\phi}(k)^{\mathrm{T}}\mathbf{P}(k-1)\boldsymbol{\phi}(k)\right)^{-1}$$

$$\mathbf{P}(k) = \left(\mathbf{I} - \mathbf{K}(k)\boldsymbol{\phi}(k)^{\mathrm{T}}\right)\mathbf{P}(k-1) \Big/ \lambda$$

$$\varepsilon(k) = y(k) - \phi(k)^T \widehat{\theta}(k-1) \tag{2}$$

Where $\widehat{\theta}(k)$ is the estimated parameters vector; $\phi(k)$ is the regression vector; $\varepsilon(k)$ is the error between the measured response y(k) and the system response calculated by using the $\phi(k)^T \widehat{\theta}(k-1)$. $\mathbf{K}(k)$ is the Kalman Gain Vector. By specifying the value of forgetting factor λ and initial values $\widehat{\theta}(0)$ and $\mathbf{P}(0)$ for the estimated parameter vector $\widehat{\theta}(k)$ of the ARX model and matrix $\mathbf{P}(k)$, the modal parameters for each time step then can be obtained.

The OKID/ERA is a multi-inputs multi-outputs (MIMO) identification method which is composed of two different system identification theory: the Observer/Kalman Filter Identification (OKID) and the Eigensystem Realization Algorithm (ERA). The schematic procedure of the methods is shown in Fig. 1 [20]. The system Markov parameter can be obtained by the OKID using the measurement data, and the system matrices of the discrete-time state space model then can be realized by the ERA method.

2.2. Standard operation procedure for structural health monitoring and diagnosis of the CTMT buildings

Because the measurement signals are often interfered with by the noise of vibrating machinery nearby, the identification results may introduce erroneous conclusions if the measured data is directly adopted. Therefore, this paper recommends the SOP for signal screening and the required identification procedures to identify the dynamic characteristics of the CTMT buildings of NPPs. The proposed SOP is shown in Fig. 2. It consists of two main parts, signal screening and system identification, respectively. The results of the proposed SOP in this paper will be verified in parallel with the third “Ten-Years Integrated Safety Assessment Report” (TYINSAR) [29] of AEC of Taiwan, which is equivalent to the Safety Evaluation Report (SER) recommended by the USNRC to ensure the accuracy of results. Finally, this report will establish the recommended structural health resume of the CTMT building of the nuclear power plant, and set the baseline for healthy status.

3. Description of structural characteristic and measurement system

The structure type of the CTMT building in the KuoSheng Nuclear Power Plant (KSNPP), the Second Nuclear Power Plant owned by the Taipower Company, is a typical MARK-III type. It is characterized by a reactor CTMT shell, which is a concrete wall with a thickness of about 3’ 6” and an inner diameter of 124 feet. Inside the CTMT, there is a concrete wall (Drywell Wall) with a thickness of about 5 inches and its inner diameter is 69 inches. Inside the Drywell Wall, there is the reactor. In addition, the top of the CTMT is semi-circular, but because it is connected to a square roof with a steel frame, its overall appearance is a cube. Accordingly, the structural system of KSNPP is divided into three independent systems, including auxiliary equipment room (outer layer), CTMT shell (intermediate layer) and Drywell Wall (inner layer). The CTMT shell and the Drywell Wall have the same concrete foundation, and are separated from each other except the foundation, so it is considered that they are independent structural systems.

There are two types of seismic measurement system in the KSNPP, the seismic monitoring system and the structural identification system, respectively. The seismic monitoring system and the structural identification system both can record the complete structural response. If the structural response exceeds a certain threshold value, the seismic monitoring system of KSNPP will activate the relevant on-line safety-check operating procedures independently. The configuration of seismic monitoring system of the KSNPP is shown in Fig. 3. The purpose of structural identification system is to use the seismic records of the base and each elevation response afterword to identify the dynamic parameters of the structural system as the basis for structural health diagnosis, and further provides the baseline data for seismic strengthening and verification.

4. Evaluation of the CTMT building in the KSNPP

4.1. Measurement signal screening and analysis

Three events, namely, the 1995/06/25 earthquake, the 1999/09/21 earthquake and the 2006/07/27 were selected for the investigation. Among them, 1999/09/21earthquake would be served as an example to show how to perform the SOP for structural health monitoring and diagnosis as mentioned above. Before identifying the dynamic parameters of the CTMT building, it is necessary to confirm which structural system the input seismograph and the output seismograph are located respectively in order to determine whether the identification result is the characteristic of the corresponding target building. First, it is necessary to clarify different identification structural models according to the original design of the KSNPP, which can be traced back from the final safety analysis report (FSAR) and the third TYINSAR. The auxiliary equipment room is connected to the CTMT building at the periphery, and the CTMT building and the drywell wall is located on the same concrete foundation, but these two systems are separated from each other.

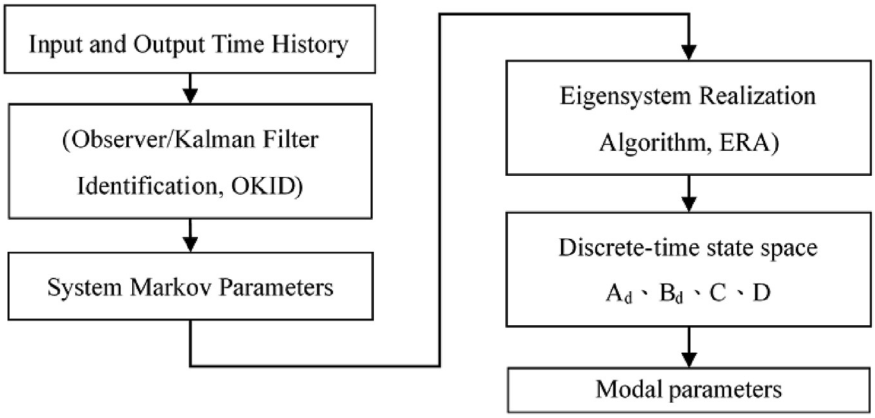


Fig. 1. The schematic procedure of OKID/ERA.

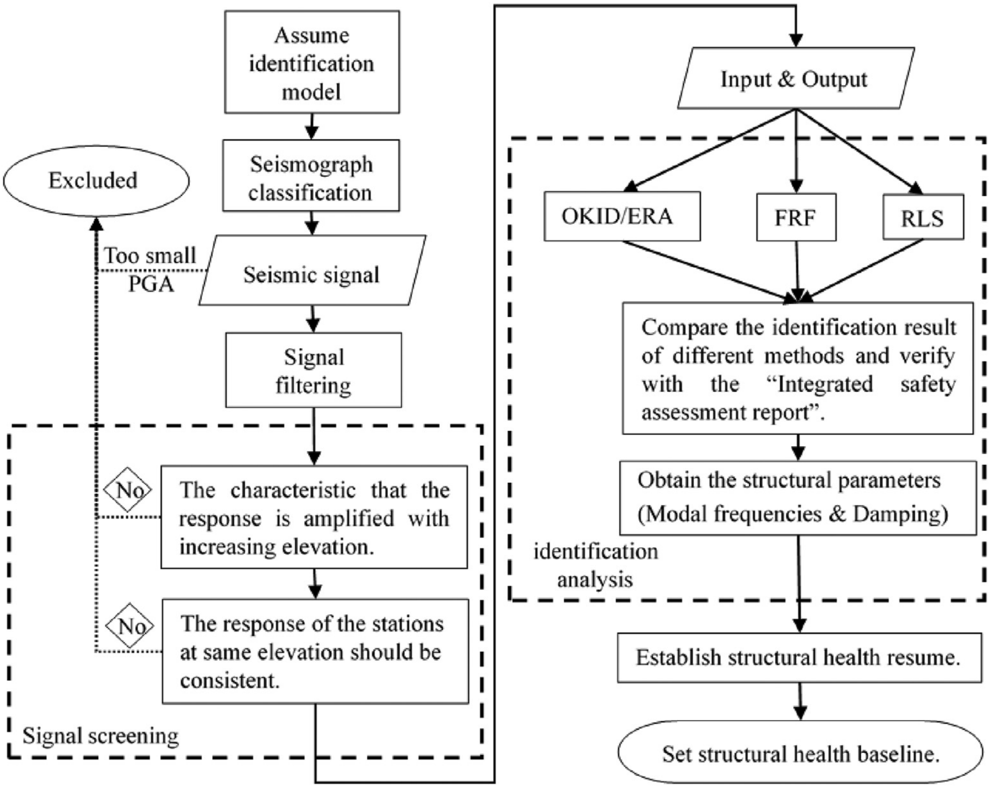


Fig. 2. Routine standard operation procedures (SOP) for structural health monitoring and diagnosis of CTMT buildings.

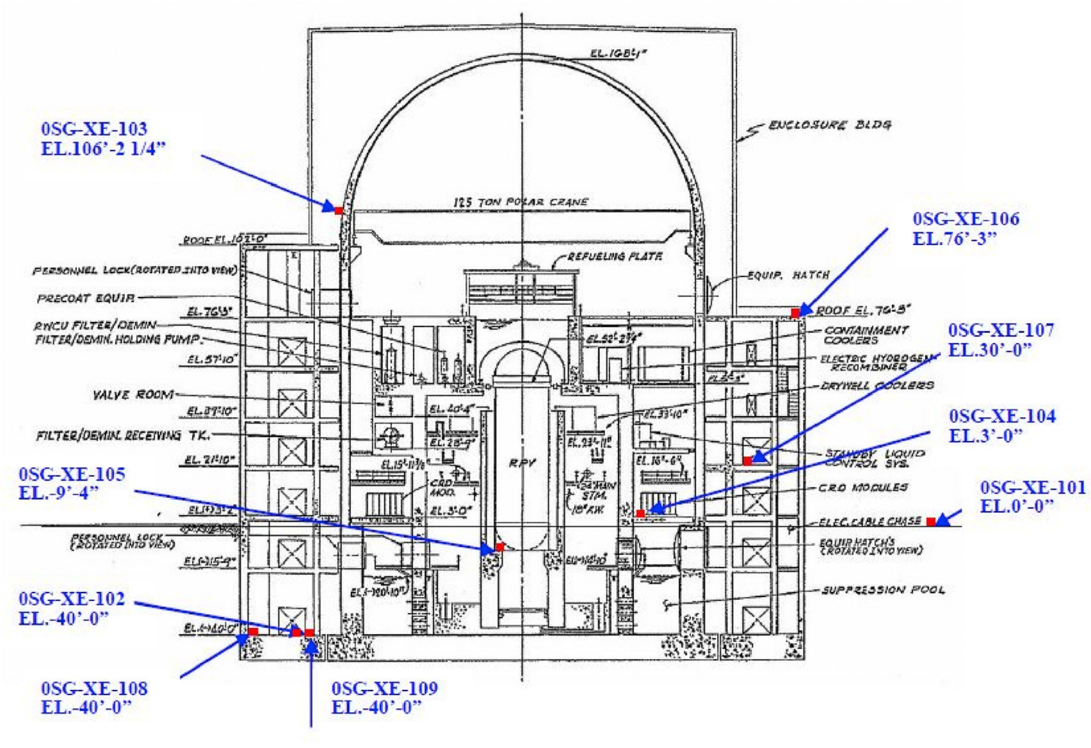


Fig. 3. Configuration of seismic monitoring system of the KSNPP.

Therefore, it is reasonable to divide the identification structures of the KSNPP into the auxiliary equipment room, the CTMT building, and the drywell wall, respectively. Then, the seismographs can be classified according to different structural systems. The configuration of each seismograph is shown in Fig. 4.

Since the intensity of the recorded earthquake event is relatively

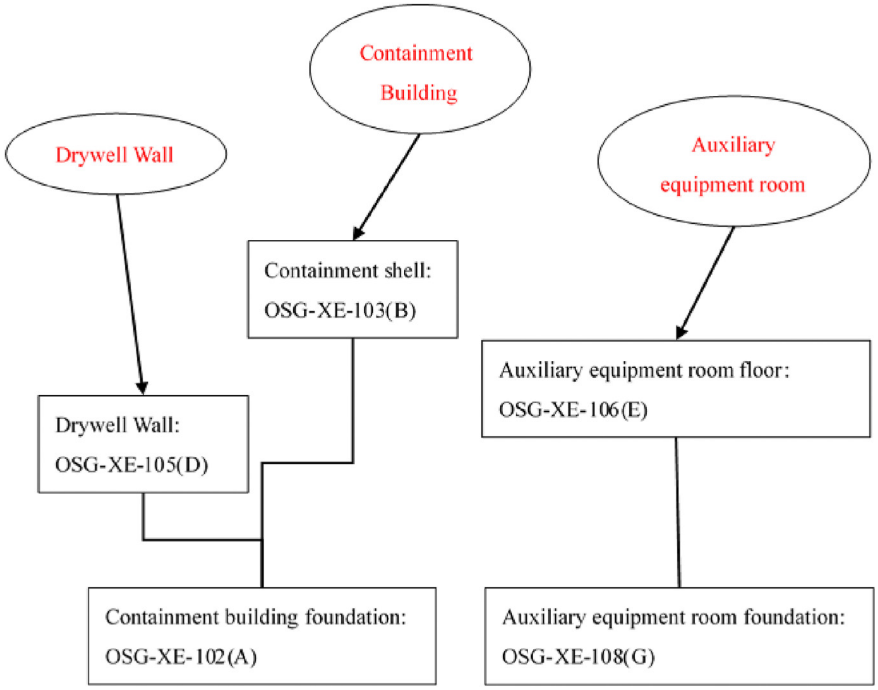


Fig. 4. Seismographs configuration in each identification system.

small, the interfered signal will introduce a relative larger noise-to-signal ratio. The identification results may introduce erroneous conclusions if the measured data is directly adopted. In the evaluation procedure of this paper, the original measurement signal is filtered by a 10Hz low-pass filter first, and then perform signal screening and identification analysis subsequently.

Considering that the CTMT is shaken by the earthquake, the acceleration response of the structure will be amplified with the increase of the height. This characteristic is used as the criteria for signal screening. That means two seismographs located in the same identification system but different elevations, the peak value of the response at the higher seismograph should be larger, otherwise, it should be excluded. It can be observed from Table 1 that the peak response of OSG-XE-105(D) in the east-west direction is smaller than the peak value of the foundation, so the measurement signal should be excluded. Because the Drywell wall model and the CTMT model (classified in Fig. 4) share the same foundation, therefore, the sensor OSG-XE-102(A) as shown in Fig. 3 installed on the same foundation at EL. −40′0”. However, OSG-XE-105(D) is used as the identification output seismograph in the third TYINSAR, so the signal of it is retained for the parallel verification purpose.

4.2. *Identification results and structural health record*

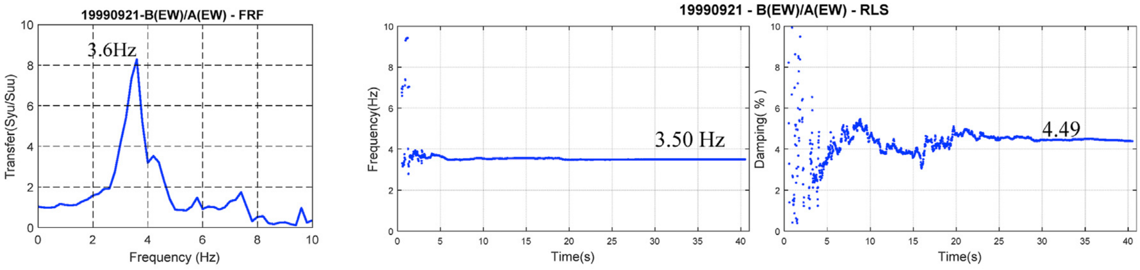
The identification results of the CTMT building can be compared with the original design frequency of 3.35Hz in the FSAR. It can also be checked whether the original design and the as-built characteristic of the CTMT are the same. According to the classified model defined previously, the identification result of the OSG-XE-103(B) as an output represents the characteristics of the CTMT building. In general, a structure with a higher stiffness requires a larger earthquake to excite the higher modal response of the structure. Therefore, when identifying such a high stiffness structure like CTMT building, larger earthquake events are also required to accurately identify the dynamic behavior of higher modes. This paper will concentrate on the results of the fundamental modal properties of the CTMT building. Furthermore, damping ratios identified by the RLS method are provided for reference, only frequency identification results will be discussed in this paper.

In the parameter setting of the frequency transfer function, we use Hann window function to reduce the influence of the leakage effect. The frequency interval (Δf) is set to be 0.2Hz in this paper in order to be able to compare the results provided by the third TYINSAR. The identification results of the frequency transfer function (FRF) of each station are shown in the left side of Fig. 5. It can be

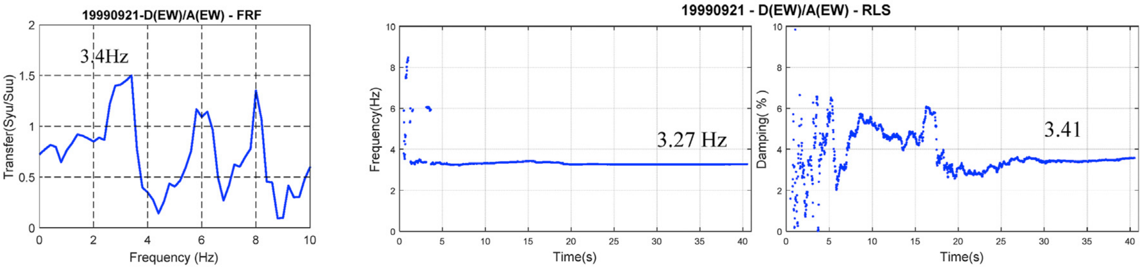
Table 1
Peak response of each seismographs in 1995.06.25 earthquake.

Maximum acceleration (gal)			
Seismograph number	direction		Identification model/Elevation
	E-W	N-S	
OSG-XE-102(A)	47.45	24.79	Drywell Wall、CTMT/EL. – 40′0″
OSG-XE-105(D)	*37.87	34.84	Drywell Wall/EL. – 9′4″
OSG-XE-103(B)	67.69	43.41	CTMT/ EL.106′2 1/4″
OSG-XE-108(G)	45.90	22.77	Auxiliary equipment room/EL. – 40′0″
OSG-XE-106(E)	60.64	28.89	Auxiliary equipment room/EL. – 9′4″

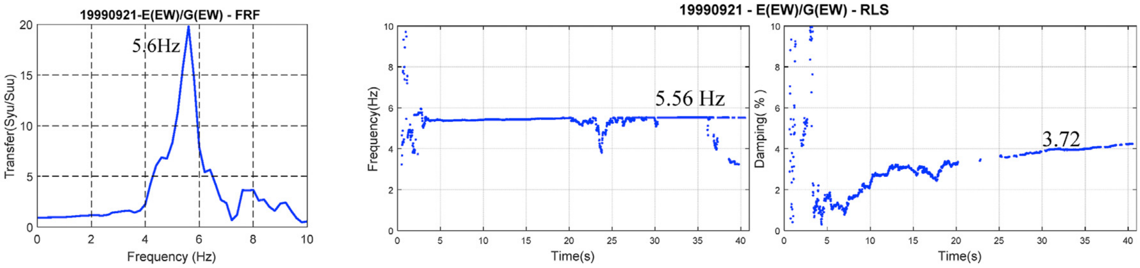
* seismographs that do not meet the screening criteria.



(a) Containment building



(b) Drywell wall



(c) Auxiliary equipment room

Fig. 5. Identification results of FRF and RLS (E-W).

observed from Fig. 5(a) that the identification result of the CTMT building is 3.6 Hz. In the parameter setting of the RLS method, if the identification target is a time-invariant system, the forgetting factor λ can be set to 1, $\mathbf{P}(0)$ and $\widehat{\boldsymbol{\theta}}(0)$ are diagonal matrices of elements 10^6 and 0, respectively. The identification results of the RLS of each station are shown in the right side of Fig. 5. It can be observed that the identification result of the CTMT building is about 3.50 Hz. In the parameter setting of OKID/ERA, the selection of the system order is based on whether the singular value converges or not. The identification result of OKID/ERA of each station is shown in Table 2, and the identified result of the CTMT is 3.50 Hz. It is observed that all results of different methods are similar to the original design frequency as per the FSAR. The identified FRFs and RLSs of the drywell wall and the auxiliary equipment room are also illustrated in Fig. 5(b) and (c).

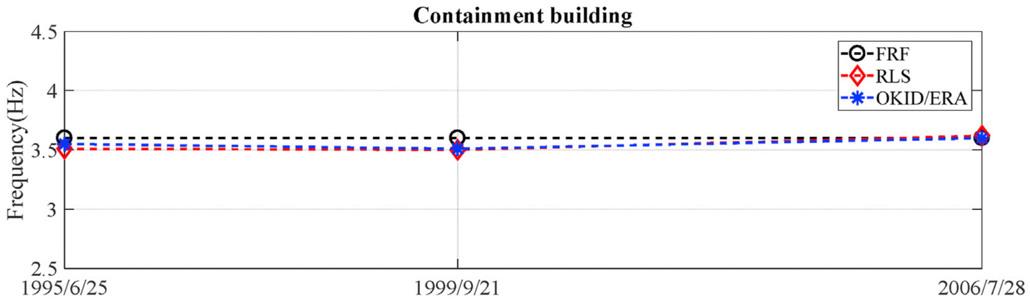
The identification results of this paper and the third TYINSAR are compared in Table 3. We can observe that the five results are close to each other from the table, which illustrates that the identification process can effectively and accurately identify the system parameters of each proposed structural model of the KSNPP. And the fundamental frequency of the CTMT building is about 3.5–3.6Hz; the fundamental frequency of the drywell wall is about 3.2–3.3Hz; the fundamental frequency of the auxiliary equipment room is about 5.5–5.6Hz. Finally, by adopting another two earthquake events (i.e. 1995/06/25 and 2006/07/28), the recommended structural health record of the KSNPP can be established. The health records of KSNPP are shown in Fig. 6. The structural health baseline

Table 2
Identification results of OKID/ERA (E-W).

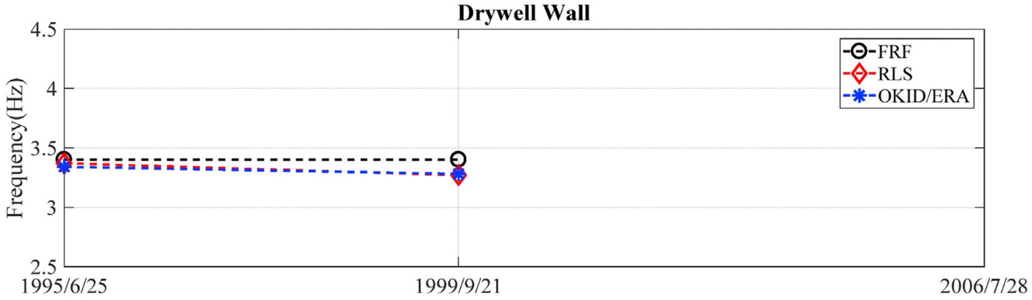
Method	OKIE/ERA	
Output channel/input channel	Frequency (Hz)	Damping ratio (%)
OSG-XE-103(B)/OSG-XE-102(A)	3.50	4.04
OSG-XE-105(D)/OSG-XE-102(A)	3.25	6.92
OSG-XE-106(E)/OSG-XE-108(G)	5.51	4.42

Table 3
Identification results of proposed methods.

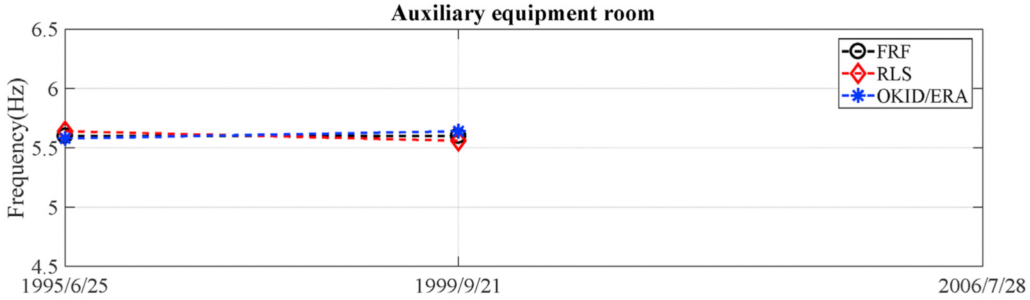
	Output channel/input channel	B/A	D/A	E/G
	method	Frequency (Hz)		
TYINSAR	Changing spectrum estimation	3.52	3.28	5.51
	RLS (Constant trace)	3.50	3.29	5.56
This paper	FRF	3.60	3.40	5.60
	RLS	3.50	3.27	5.56
	OKID/ERA	3.50	3.25	5.51



(a) Containment building



(b) Drywell wall



(c) Auxiliary equipment room

Fig. 6. Structural health record of each identification system.

is determined by the identified structural frequencies in the health status (undamaged). Since the structural frequency in the health status is supposed to be consistent, if there are many small earthquake measurement records, a reliable structural health baseline can be drawn based on the proposed SOP. With the health baseline, it can be quickly known whether the structural characteristics have changed significantly after a major earthquake. If the natural frequency of any model drops significantly after the OBE/SSE, it means that the actions suggested by the regulatory guide should be taken in place immediately.

5. Conclusion

The proposed routine SOP for structural health monitoring and diagnosis of CTMT buildings is adopted in this study based on real earthquake events measured on the KSNPP of Taiwan. Two main parts, signal screening, and system identification, are proposed in the SOP. The clarification of different structural models is also emphasized before implementing the proposed SOP. In the identification process, three recommend methods are proposed including the RLS, the OKID/ERA, and the FRF. This ensures the credibility of the identification results. The identified results are compared with the original design values of the FSAR and the third TYINSAR of the KSNPP. In this paper, the results of the three methods are quite consistent, so the results can be included in the average to find the healthy baseline. Finally, a preliminary building health record of the KSNPP can be established based on the limited number of earthquake records. These promising results also ascertain the objective to serve as the quantitative indicators and to expedite the walk-down restart period when a seismic event exceeds the OBE/SSE.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.net.2020.12.018.

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