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〈Original Paper〉

Study on Input Baseline Correction in Nonlinear Seismic Analysis

비선형 지진해석에서 입력의 기준선 조정에 관한 연구

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ABSTRACT

When sliding or tipping seismic analysis is performed for a nonlinear structure, horizontally bidirectional analysis is highly recommended. It is because the result of nonlinear analysis can be very sensitive to the baseline correction of earthquake input and because single horizontal component analysis may mislead the design to an excessively conservative or unconservative one. Special care should be taken in analyzing by using the computer programs which are limited to one dimensional modeling and solving. In this paper, it is investigated how the baseline correction of earthquake input affects to the nonlinear responses by horizontally one component excitation and by two components simultaneously. On this purpose, the example analyses for a free standing system are performed. As a result, we could see that horizontally bidirectional analysis and set-up of a standardized guideline for input baseline correction are very necessary to avoid excessive conservatism or nonconservatism in one dimensional nonlinear analysis.

요 약

비선형 구조물에 대하여 미끄러짐 또는 기울어짐 해석을 수행할 때에는 수평 두 방향 입력을 동시에 고려하는 해석을 수행할 것을 추천한다. 그 이유는 단일 방향 입력만을 고려한 비선형 해석의 결과가 입력지진의 기준선 조정 여부에 아주 민감하고 자칫 과도하게 보수적이거나 또는 오히려 비보수적인 결과를 초래할 수 있기 때문이다. 특히, 오래 전에 작성되어 일차원 해석만 가능한 전산 프로그램을 사용하여 해석하는 경우 주의가 요구된다. 본 논문에서는 입력지진의 기준선조정에 의한 영향을 수평 단일방향 입력만을 고려하는 해석과 수평 두 방향 입력을 동시에 고려하는 해석에 대하여 살펴본다. 이를 위하여 자립형 계에 대한 예제 해석을 수행한 결과, 단일방향 비선형 해석시 나타날 수 있는 이러한 불확실성을 피하기 위하여 두 방향 입력을 동시에 고려하는 해석이 필요하고 입력 지진의 기준선 조정과 연계된 표준화된 지침이 필요하다는 것을 알 수 있었다.

1. Introduction

In seismic design of free standing structures like the fuel storage racks in nuclear power plant, sliding and

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tipping are normally considered as the most important nonlinear behaviors. In analyzing sliding and tipping, the peak response is one of the major concerns. It is because such equipment are normally designed to keep enough margin of space based on the analysis result.[1] To assure no impact between structures and to prevent overturning of structures during earthquake, reliable prediction of response is required. To solve the equations of motion of a mathematical model such as a nonlinear structure on a computer, accelerograms are used as input excitation. Whether it is recorded or artificially generated, design earthquake is mostly baseline corrected before it is given to the equipment designer as an input. If not, however, input baseline correction should be performed by the equipment designer prior to use for sure to avoid potential unconservative result. In linear seismic analysis, all the equipment designers have to do is just to apply the accelerograms as an input without any treatment, in most cases. In nonlinear seismic analysis of the structures expected to slide or tip during earthquake, however, the analysis method and result should be basically checked in viewpoint of reasonability and conservatism. In the following chapters, it is discussed why baseline correction of seismic input is emphasized and why bidirectional analysis is recommended for the structure with nonlinear behaviour like sliding or tipping.

2. Methods of Baseline Correction

Baseline correction has been performed to compensate for the baseline translation of the accelerograms caused by instrument or digitizing error. To much extents in general, those errors can be reduced through the operator training and calibration by test signal and etc. Without enough information about the cause of errors, anyway, correction should be made because the integration process is critical for the long period motions like the design earthquake for nuclear power plant. Only by looking at the accelrogram records, specific trend or errors can hardly be found. If the zero baseline of the accelerogram is translated by a small amount, it is equivalent to add a step function error to the accelerogram. By integrations, this error firstly yield a linearly increasing velocity curve, and secondly yield a parabolically increasing displacement curve. This type of

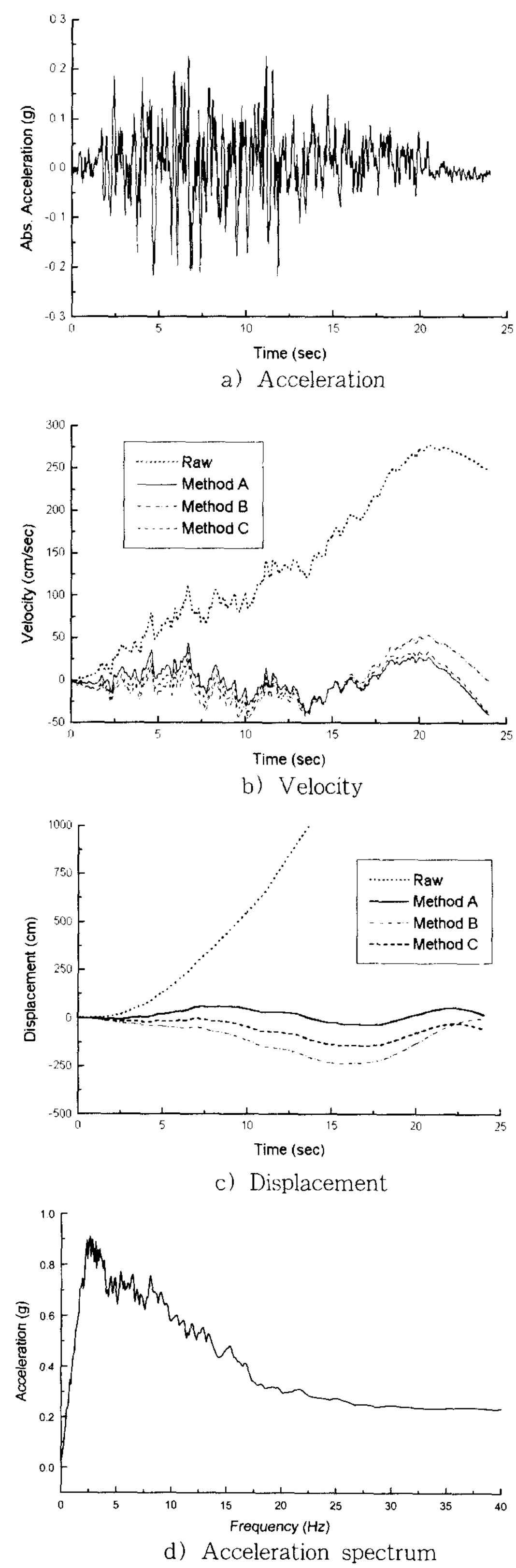


Fig. 1 Change of input earthquake by baseline correction

error or unwanted trend insertion can be removed by baseline correction This can be easily seen in Fig. 1. For reference, the acceleration spectrum is shown in Fig. 1(d), and on which the baseline correction does not have any effect visually in general.

Unfortunately, however, there seem to be no generalized rules or guidelines for the method of baseline correction by regulatory authorities yet. Therefore, the vendors in charge of nonlinear seismic analysis seem to make and use their own methods of baseline correction when necessary. Followings are a couple of representative methods which are used by engineering vendors.[1]

Method A : This is used in commercial analysis program ABAQUS[2], which is based on the method proposed by Newmark. The raw data is subtracted by a parabolic calibration function which satisfies the condition of minimization for the average square sum of integrated velocity history.

Method B : This is used by vendors. The raw data is subtracted by a linear calibration function which satisfies the condition of zero velocity and zero displacement at the end of earthquake.

Method C : This has been also used by vendors. It uses a constant value as calibration function which satisfies the condition of minimization for the average square sum of integrated velocity history.

In this paper, method A and B are representatively used as an example analysis for investigating and comparing the effects of input baseline correction and analysis dimension on the results of nonlinear analysis.

3. Description of Analysis

3.1 Equations of Motion

To investigate the effect of baseline correction on nonlinear system, four different types of model were set up. They are a rigid sliding block, a rigid tipping block, a lumped mass spring-damper system with sliding base and a lumped mass spring-damper system with fixed base as shown in Fig. 2. The governing equation of motion for sliding system in Fig. 2(d) can be expressed as follows.

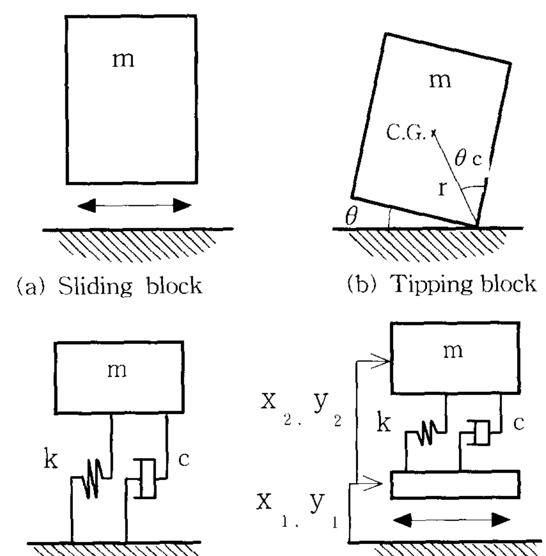
$$m\ddot{x}_1 - cdot\dot{x}_2 - kx_2 + f_x = -m\ddot{x}_g \tag{1-a}$$

$$m\ddot{y}_1 - c\dot{x}_2 - ky_2 + f_y = m\ddot{y}_g \tag{1-b}$$

$$m\ddot{x}_2 - c\dot{x}_2 - kx_2 = -m(\ddot{x}_g + \ddot{x}_1) \tag{1-c}$$

$$m\ddot{y}_2 - c\dot{y}_2 - ky_2 = -m(\ddot{y}_g + \ddot{y}_1) \tag{1-d}$$

where, m, c, k are mass, stiffness, damping of the system whose dynamic characteristics in two orthogonal horizontal directions are assumed to be the same as analysis purpose. f_x, f_y are friction forces in x, y direction at the system base, respectively. x_g, x_1, x_2 and y_g, y_1, y_2 are the earthquake ground motion, displacement of system base relative to ground, displacement of system superstructure relative to its base in x and y direction, respectively. Therefore, equation (1) becomes the equation of motion for the linear system shown in Fig. 2(c) by making x_1 and y_1 equal to zero, and becomes the equation of motion for the rigid block shown in Fig. 2(a) by putting x_1, y_1, c, k equal to zero. For unidirectional sliding analysis, equation (1-a)&(1-c) and (1-b)&(1-d) sets are treated separately at first. Then, the whole equation (1) are treated together to consider the bidirectional effects.[3] For the tipping analysis, a rigid block is assumed free to rock without sliding on either side of its base corners as shown in Fig. 2(b). The governing equation of motion for the tipping block can be expressed as follows[4].



(a) Sliding block (b) Tipping block
(c) Fixed system (d) Sliding system

Fig. 2 Models for sliding and tipping analysis

$$I\ddot{\theta} + mr\ddot{x}_g \cos(\theta_c - \theta) + mgr \sin(\theta_c - \theta) = 0, \quad \theta \geq 0 \qquad \text{(2-a)}$$

$$I\ddot{\theta} + mr\ddot{x}_g \cos(\theta_c - \theta) - mgr \sin(\theta_c + \theta) = 0, \quad \theta \leq 0 \qquad \text{(2-b)}$$

where, I is the moment of inertia of the block about base corner, m the block mass, r the distance from center of gravity to base corner, θ tipping angle of the block with respect to the ground, θ_c critical angle between the center of gravity and the block edge with respect to the base corner. The moment of inertia I and the coefficient of restitution e are assumed to satisfy following relations.

$$I = \frac{4}{3} mr^2 \qquad \text{(3-a)}$$

$$e = 1 + \frac{3}{2} \sin^2\theta_c \qquad \text{(3-b)}$$

And, $\ddot{x}_g$, g are the earthquake ground acceleration and the gravitational acceleration, respectively.

3.2 Numerical Analysis

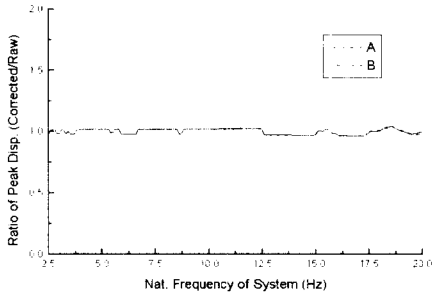
Numerical analyses are performed for the mathematical models described above using the raw data of seismic inputs and baseline corrected ones. For the sliding system, the peak responses are obtained from each analysis by varying the natural frequency of model from 2.5 Hz to 20 Hz which can represent the dynamic characteristics of major equipment in nuclear power plant. Two of unidirectional analyses and a bidirectional analysis were done by a set for each sliding model to study their sensitivity in displacement response with respect to input baseline correction methods. Two of unidirectional analyses were done for a tipping model to study their sensitivity in angular displacement response with respect to input baseline correction. Bidirectional tipping analysis is omitted because it is meaningless for a rectangular block. Typical parameters used in the analysis are 0.04 for the damping ratio of the system and 0.01 for the friction coefficient commonly for the block and sliding system. The raw input data of earthquake is sampled from the used ones for the equipment design of Ulchin Nuclear Unit 3 & 4. The sixth order Runge-Kutta scheme and double precision were chosen for numerical integration of the equations of motion in FORTRAN. A time step of 0.0005 second was used for the numerical integration when sliding and non-sliding phases were involved due to the friction mechanism.[5] The response time histories during the first 24 seconds were used to calculate the peak responses of the system. The units of displacement and acceleration are respectively cm and g.

4. Result and Discussion

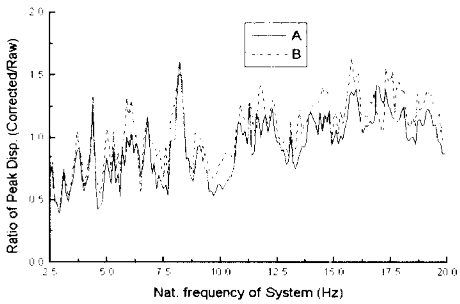
4.1 Linear System and Nonlinear System

To compare the effect of input baseline correction on the peak responses of linear system and nonlinear system, systems with fixed base and sliding base are chosen as the representatives for each. And, peak displacements are investigated by varying their natural frequencies. As shown in Fig. 3(a), the linear systems are hardly affected by baseline correction for displacement response. That is, the ratio of peak responses by corrected input are divided by the ones with raw input sticks to unit with the variation which is less than 5% regardless of the system natural frequencies.

On the contrary, the displacement response of nonlinear system as shown in Fig. 3(b) seems to be somewhat sensitive to input baseline correction. The peak displacement of nonlinear system shows almost twice than the one of linear system, which can be explained as the input effect as shown in Fig. 1. So to speak, the one-sided trend in the raw acceleration input make the nonlinear system leave cumulative displacement little by little during the sliding motion of back and forth.



(a) Displacement of linear system

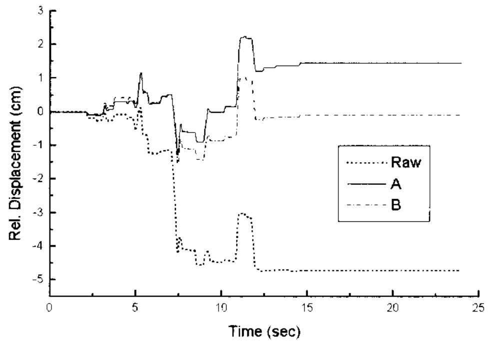


(b) Displacement of nonlinear system

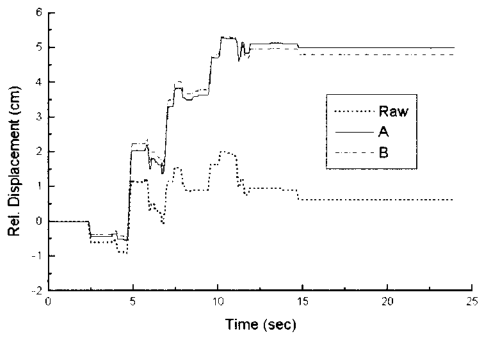
Fig. 3 Effect of input baseline correction

4.2 Sliding Block

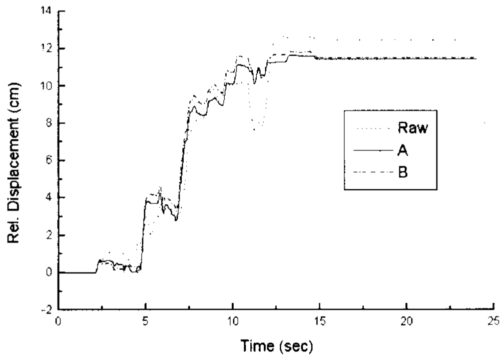
In Fig. 4, the relative displacements versus time are plotted for a sliding rigid block in Fig. 2(a), using inputs in EW direction(a), NS direction(b), and both directions (c). An interesting fact is found from Fig. 4. The absolute value in the displacement response for raw input data is greater than those for the corrected input in EW directional analysis as shown in Fig. 4(a). This is also based on the effect by one-sided trend in the raw acceleration input on the cumulative displacement of nonlinear system. The difference between the responses of method A and B seems to be by the effect of corrective functions.



(a) EW direction analysis



(b) NS direction analysis



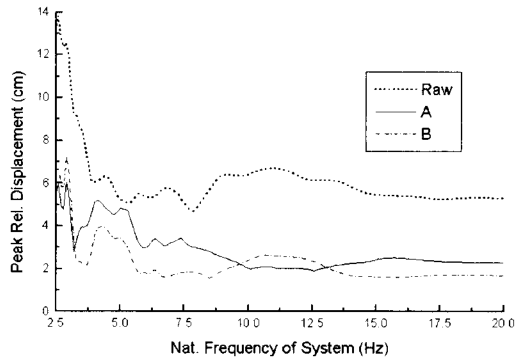
(c) Bi-direction analysis

Fig. 4 Displacement of sliding block vs. time

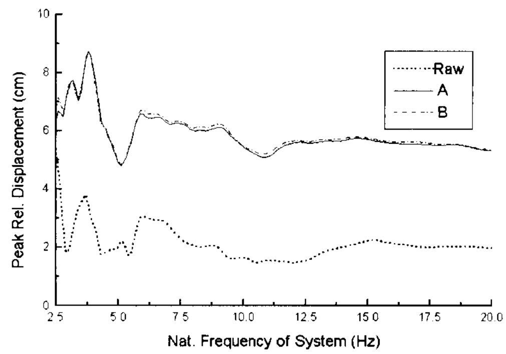
But this trend turns out in reverse way in NS directional analysis showed in Fig. 4(b). Therefore, a slight difference is seen from the result of sliding analysis considering bidirectional effect as shown in Fig. 4(c). This is based upon the offset effect of two opposite trends.

4.3 Sliding System

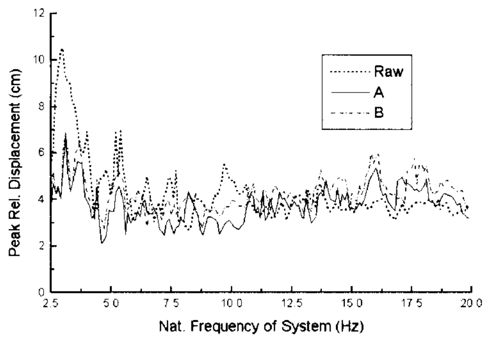
Fig. 5 shows peak of relative displacements versus natural frequencies which is in between 2.5 Hz to 20 Hz of sliding system for unidirectional and bidirectional analyses. Fig. 5(a) is plotted for EW direction sliding analysis using



(a) EW direction



(b) NS direction

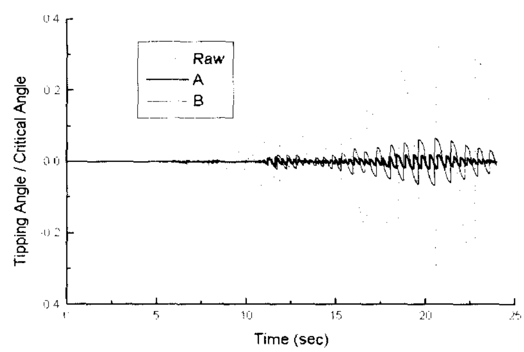


(c) Bi-direction analysis

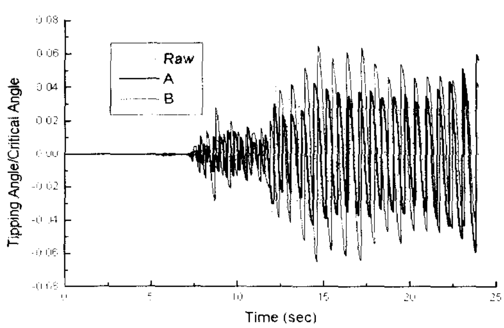
Fig. 5 Peak displacement of sliding system vs. natural frequency three different input excitation. In all frequency range, the response by corrected input significantly exceeds the response by raw input. On the contrary, the response by raw input largely exceeds the response by corrected input in NS direction sliding analysis as shown in Fig. 5(b). This means the unidirectional sliding analysis can potentially yield excessively conservative result or rather a much less conservative result. In addition, there exist a level of difference even between the baseline correction methods more than twice in some frequency range. In sliding analysis considering bidirectional effect as shown in Fig. 5(c), the peak responses by three different inputs are roughly within some allowable limit by the offset of two opposite trend, while there still remains some frequency ranges with the ratio of about two. The difference between the responses of method A and B is considered to be the cross effect of different corrective functions.

4.4 Tipping Block

Figure 6 shows comparison of tipping angle history of rigid block by unidirectional analysis using EW or NS directional input. The vertical axis represents the ratio of tipping angle to critical angle. In this analysis, a value of



(a) EW direction



(b) NS direction

Fig. 6 Angular displacement of tipping block

400 cm as width and a value of 5 as the ratio of height to width are applied to both of horizontal two directions for reference. From the result of EW direction analysis, it can be concluded that the tipping angle is quite sensitive to the baseline correction of seismic input. Analysis result using the corrected input by method A yields the least tipping. With the raw data, it may easily lead to a result of overturning for a slightly increased slenderness case while the result using corrected data has still enough margin as shown in Fig. 6(a). By the way, the trend of result analysed using the NS input in orthogonal direction is somewhat different from that of sliding cases as shown in Fig. (6) It depicts the resultant tipping angle by NS direction analysis remains much less than EW one about by one order of difference. In tipping analysis, it seems hard to predict the result of bidirectional analysis and to judge like sliding cases because of the lack of method considering bidirectional effect at present.

5. Conclusions

A study of these results leads to the following conclusions.

(1) In an unidirectional seismic analysis of a sliding or tipping system, baseline correction of input does not always make a conservative result.

(2) The variation of result by the difference of baseline correction methods of input earthquake being used by vendors is not within the level of concern as far as bidirectional analysis is performed in a sliding system.

(3) Horizontally bidirectional analysis is strongly recommended for a sliding system to avoid potential nonconservatism by a unidirectional analysis.

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