Periodic Material-based Design of Seismic Support Isolation for Industrial Facilities

Witarto Witarto, S. J. Wang, Y. L. Mo, K. C. Chang, Yu Tang, and Robert P. Kassawara

***Abstract*—Seismic performance of industrial facilities, particularly piping systems, has received a lot of attention due to the reason that the operation of undamaged building may be stopped due to severe damage on the facilities. This paper proposed periodic-material based seismic support isolation for industrial facilities. The proposed device, inspired by the theory of phononic crystal, possesses a unique property, which can reduce the seismic response without having large relative displacement between the supports and the supported facilities. The study presented herein focuses on the response of the piping system supported by one–dimensional (1D) periodic foundations.**

***Index Terms*—Periodic foundation, phononic crystal, piping system, seismic isolation**

I. INTRODUCTION

INDUSTRIAL piping systems are regarded as one of the key nonstructural elements in many industries due to their important role in the transportation process. In some particular cases, such as: petroleum and nuclear industries, damages on the piping systems may force the entire facilities to shut down their operation. In the past decade, the major causes of the damages in piping systems have been observed to be seismically related. This issue has created an active area of research in seismic protection of piping systems.

Seismic protecting systems currently used in practice for piping system are categorized as either damper or elastomeric systems. The damper systems, such as: high viscous damper, elasto-plastic damper, and sliding friction damper, are effective in reducing the seismic response of piping systems. However, analysis of the piping systems with these supports is tedious and time consuming. The accuracy of the results also depends on the precise analytical modeling of the dampers [1]. The elastomeric systems, which are also effective in reducing the seismic response of piping systems, generally cause large relative displacement between the support and the piping systems during a seismic event. To accommodate this displacement, a large space gap is usually provided between the piping systems and the surrounding structures to avoid hammering. In addition, there is a concern that if a larger than expected seismic event occurs, the displacement may exceed the gap provided. Therefore, an isolation system that does not respond to seismic events with a large relative displacement and simple in analytical modeling would be much preferable.

Periodic material–based isolation systems or better known as periodic foundations have shown promising results, both analytically and experimentally [2]-[4], as a new and innovative seismic isolator. Inspired by the phononic crystal theory in solid state physics [5], periodic foundations utilize the so-called frequency band gaps to isolate the incoming seismic waves. In principle, the waves having frequencies falling within the frequency band gaps will not be able to propagate through the periodic foundations. Due to their unique wave isolation mechanism, periodic foundations can isolate superstructure from the incoming seismic waves without having a large relative horizontal displacement.

According to the number of directions where the unit cell is repeated, periodic foundations can be classified as: one-dimensional (1D), two-dimensional (2D) and three-dimensional (3D) periodic foundations. All three types of periodic foundations have been studied and have shown good seismic isolation performance [2]-[4]. In this study, 1D periodic foundation is selected as the isolation device for piping systems due to its simplicity in theory and modeling as compared to the other types of periodic foundations.

II. BASIC THEORY OF 1D PERIODIC FOUNDATION

In 1D periodic foundation, the unit cell possesses periodicity in one direction. In general, the unit cells would be periodically stacked in the vertical direction, as shown in Fig. 1. In this kind of configuration, the incoming seismic waves from the ground will be altered before reaching the supported structure, in this case the piping system.

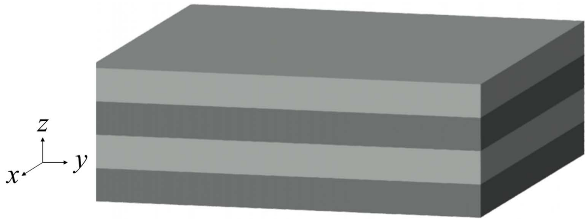

Fig. 1. One dimensional periodic foundation

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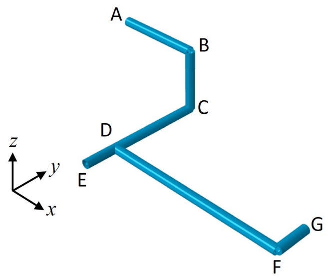
The frequency band gaps of periodic foundations can be obtained from dispersion relations of a single unit cell with periodic boundary conditions. For 1D unit cell, transfer matrix method is one of the easiest methods to obtain the dispersion curves. The detail derivation of the transfer matrix method can be found in [6]. The final equation of the transfer matrix method to obtain the dispersion curves is shown in (1).

$$\left|\mathbf{T}(\omega)-\mathrm{e}^{ika}\mathbf{I}\right|=0 \tag{1}$$

Equation (1) is the so called Eigenvalue problem, with e^{ika} equal to the Eigenvalue of the transformation matrix $\mathbf{T}(\omega)$. Thus, the relation of wave number k and frequency ω can be obtained by solving the corresponding Eigenvalue problem. The relationship between the wave number and frequency forms the dispersion curve, which provides the information of the frequency band gaps.

III. DESCRIPTION OF THE CASE STUDY

The piping system analyzed here refers to the small bore piping subsystem designed by Sargent and Lundy engineer [7]. A portion of the subsystem was cut and modified for the purpose of this study. Fig. 2 shows the piping system as the case study. To simplify the analysis, uniform cross section was assigned to all of the elements. The outer diameter of the pipe is selected to be 10.5 inch or 26.67 cm with a thickness of 1.27 cm.



Element	Length (m)
A–B	2.5
B–C	1.8
C–D	2.75
D–E	1.0
D–F	5.5
F–G	1.0

Fig. 2. Piping system

The piping system was assumed to be made of A36 steel. The analyses was carried out without considering additional mass due to fluid or gas carried by the pipes. Fix supports were assigned to nodes A, E and G. The first ten natural frequencies of the piping system are shown in Fig. 3. The first and the tenth natural frequencies are observed to be 21.2 Hz and 150 Hz, respectively.

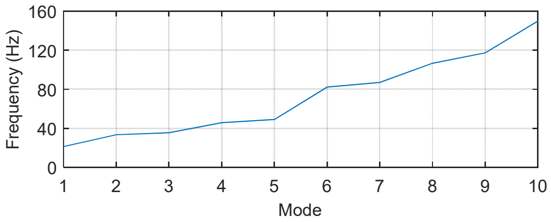


Fig. 3. Natural frequencies of piping system

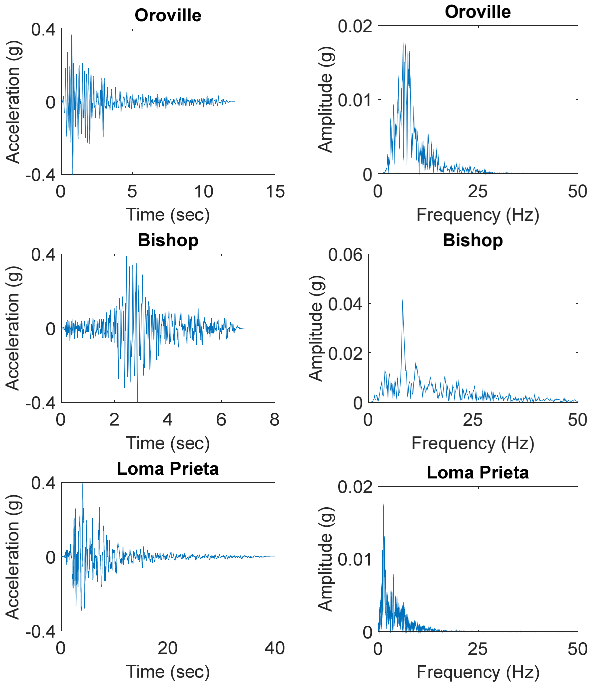
Six accelerograms are selected from PEER Database [8] as the input ground motions to perform time history analysis on the piping system. The six selected ground motions are listed in Table 1. The peak ground acceleration (PGA) of all six ground motions were scaled to 0.4 g to represent maximum considered earthquake as plotted in Fig. 4. The Fourier spectra were presented along the ground motions. It is observed that the main frequency content of all six ground motions are located within 0–20 Hz.

TABLE I
SELECTED GROUND MOTIONS

Event	Date	Station	Orientation
Oroville	8/1/1975	Oroville Seismograph Station	37
Bishop (Round Valley)	11/23/1984	MCGEE Creek Surface	360
Loma Prieta	10/18/1989	Corralitos	90
Imperial Valley	5/19/1940	El Centro Array #9	180
Lytle Creek	9/12/1970	Cedar Springs Allen Ranch	95
Northridge	1/17/1994	LA-UCLA Grounds	90

In practice, piping systems can be placed on the pipe-racks or hung under the floor slabs in multistory structures. Therefore, one piping system in a structure may extend several hundred meters long across different floor levels. In the midst of earthquake event, the seismic ground motion is generally amplified differently on different floor levels. Different accelerations of the floors may cause relative displacement among the pipe supports which in turns increase internal stresses developed in the pipe.

In order to consider the relative displacement between the supports, the input acceleration on node A of the piping was multiply by 1.2 while the input acceleration on nodes E and G remain unchanged. In addition, the time history analyses were conducted considering the combinations of directions of excitation. Two combinations were included, i.e: 100% in x direction + 30% in y direction and 30% in x direction + 100% in y direction.



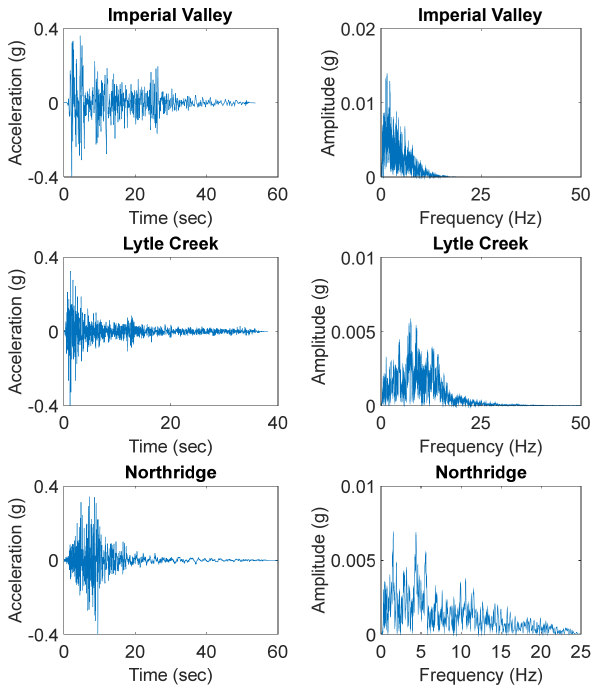


Fig. 4. Ground motions and corresponding Fourier spectra

IV. DESIGN OF 1D PERIODIC FOUNDATION

In the design of the unit cell of 1D periodic foundation, there are two main aspects that need to be carefully considered: the desired frequency band gap and the available space for the periodic foundation. As shown previously in Fig. 4, the main frequency content of the earthquakes are located below 20 Hz. Therefore, the designed frequency band gaps should be able to cover the main frequency content of the earthquakes. Study of 1D periodic foundation by Witarto et al. [6] has shown that one unit cell 1D periodic foundation provides fairly good response reduction of the waves having frequencies inside the frequency band gaps. Considering the limited space for the supports of the piping system, a four–layer type of one unit cell 1D periodic foundation is chosen as the design for seismic protection of the piping system. The four–layer unit cell is known to provide a very wide frequency band gaps. In order to bring the frequency band gaps to cover low frequency regions, the layers need to be constructed from materials with distinct difference in material properties.

The final design of the four–layer type one unit cell–1D periodic foundation is shown in Fig 5. The unit cell is composed of four layers, layers A to D. Layers A and C are made of polyurethane, a rubber like polymer, which is a light and flexible material. Meanwhile, layers B and D are made of tungsten metal which is a heavy and stiff material. The material properties of both polyurethane and tungsten are listed in Table II. The square size of the periodic foundation is 1 m with the thickness of each of the layers A, B, C, and D is 11 cm, 7 cm, 3.5 cm and 3.5 cm, respectively. The periodic foundation intentionally placed on a concrete base to provide uniform stress distribution at the base of periodic foundation.

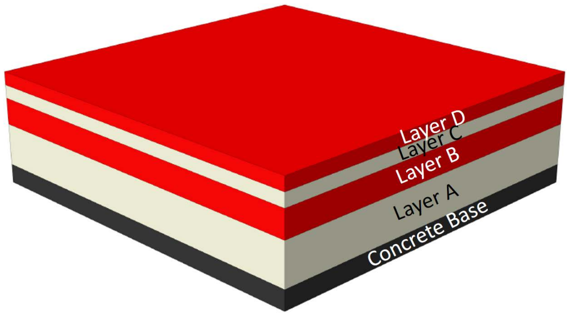


Fig. 5. Designed 1D periodic foundation

TABLE II
MATERIAL PROPERTIES FOR DESIGNED 1D PERIODIC FOUNDATION

Material	Young's modulus (MPa)	Density (kg/m^3)	Poisson's ratio
Polyurethane	0.1586	1100	0.463
Tungsten	411000	19250	0.2

Fig. 6 shows the dispersion curves of the designed unit cell subjected to transverse wave (S-Wave). The curves were obtained by solving the Eigenvalue problem stated in (1). In the frequency range of 0 to 50 Hz, two frequency band gaps were observed. The two frequency band gaps, highlighted in yellow bands, are observed at 4.77 Hz– 9.18 Hz and 10.52 Hz to 50 Hz. Both frequency band gaps are referred as theoretical band gaps which was derived under assumption of infinite number of unit cells and infinite size. The unit cell was designed so that the frequency band gaps covers the main frequency contents of Oroville, Bishop, and Lytle Creek ground motions. Therefore, the main frequency contents of Loma Prieta, Imperial Valley and Northridge ground motions are located outside the frequency band gaps or pass bands. The design was done in such a way to study the effect of the main frequency contents of the earthquake on the structural response.

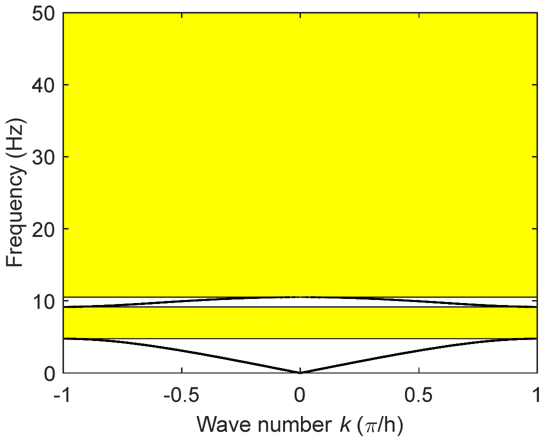


Fig. 6. Dispersion curves of designed periodic foundation

Since the designed periodic foundation has a finite size and made of only one unit cell, scanning frequency analysis was conducted on the finite element model to prove the existence of the wave reduction inside the theoretical band gaps. Each of the layers of the periodic foundation was modeled as multiple elastic solid elements. The periodic foundation was subjected to a scanning frequency ranging from 0 to 50 Hz. The responses of these foundations are presented in the form of frequency response function (FRF) defined as $20\log(\delta_o/\delta_i)$, where δ_o is the instantaneous displacement amplitude recorded at the top of the periodic foundation and δ_i is the amplitude of instantaneous displacement input at the base of the periodic foundation. The FRF the periodic foundation is presented in Fig. 7. The negative value shows that the output response is smaller than the input. The yellow gaps are the previously obtained theoretical frequency band gaps. It is observed that there exist significant response reduction inside the theoretical frequency band gaps.

Fig. 8 shows the piping system supported by the designed periodic foundations. The original fixed supports on nodes A, E, and G were replaced by periodic foundations with the fixed supports assigned at each bottom surface of the concrete bases. Time history analyses were conducted using six accelerograms listed in Section III. The analyses on piping system with periodic foundations were conducted considering relative displacement between the supports and the combined excitation similar to that on the piping system only.

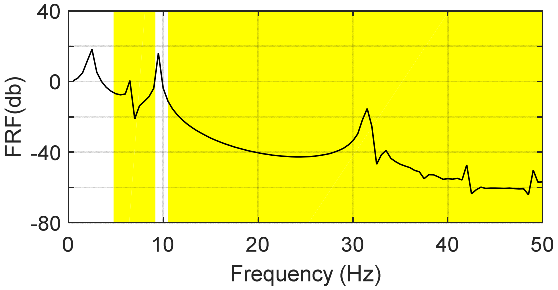


Fig. 7. Frequency response function of designed periodic foundation

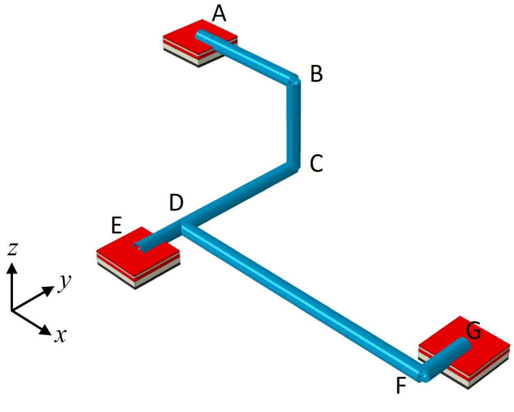


Fig. 8. Piping system supported by designed periodic foundation

V. ANALYSIS RESULTS AND DISCUSSIONS

A. Accelerations on Piping System

Fig. 9 shows the comparison of the original input of the Oroville seismic ground motion at the concrete base to the acceleration time history recorded at the top of the periodic foundation located at node G. Both accelerations are in the x direction. A significant reduction of the accelerations throughout the time domain is observed. The PGA of the acceleration record at the top of periodic foundation is found to be 0.2 g, which has been reduced by a half as compared to the PGA of the input ground motion. This filtered seismic ground motion is the one that will propagate into the piping system.

Since the random vibrations such as ground motions are composed of a series of harmonic waves, the waves with the frequencies associated with the frequency band gaps will be attenuated after passing through the periodic foundation. However, it has been reported that the presence of the structure on the periodic foundation might slightly change the location of the frequency band gaps [6]. In general, the frequency band gaps will shift to lower frequencies, which is very beneficial. Fig. 10 shows the comparison of Fourier transforms of the Oroville input acceleration and the acceleration at the top of periodic foundation. The yellow bands are the original frequency band gaps obtained from dispersion curves. It is observed that the response reduction (lower wave amplitude) started at frequency 3.7 Hz which means the first frequency band gap has shifted. The original second pass band is located at 9.18–10.52 Hz. However, in the Fourier spectra, non-reduction (equal wave amplitudes of the response acceleration and the input) is observed at frequency 8.11–8.36 Hz which means the pass band has squeezed and shifted to lower frequency. Although response amplification is observed in the first pass band, the main frequency content of the ground motion has been attenuated inside the frequency band gaps. Therefore, the acceleration at the top of the periodic foundation has decreased.

Contrary to the acceleration response due to Oroville ground motion, an amplification of acceleration response is observed at the top of the periodic foundation when the structure system is subjected to Loma Prieta ground motion, as shown in Fig. 11. The PGA of the acceleration record at the top of periodic foundation is found to be 0.66 g, which has increased by 52% from the PGA of the input ground motion. The Fourier spectra in Fig. 12 show that although the responses inside the frequency band gaps are attenuated, the main frequency content of Loma Prieta ground motion, which located on the first pass band, has amplified.

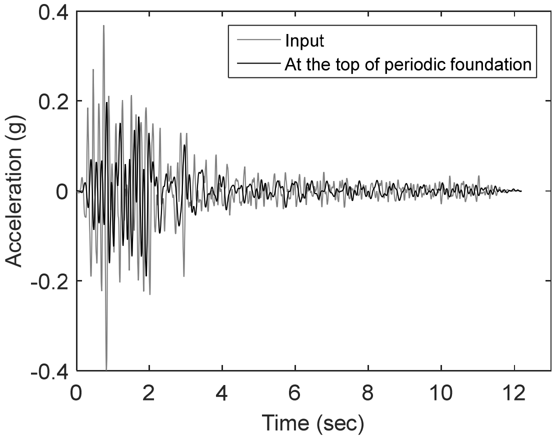


Fig. 9. Acceleration response of periodic foundation at Node G under Oroville ground motion

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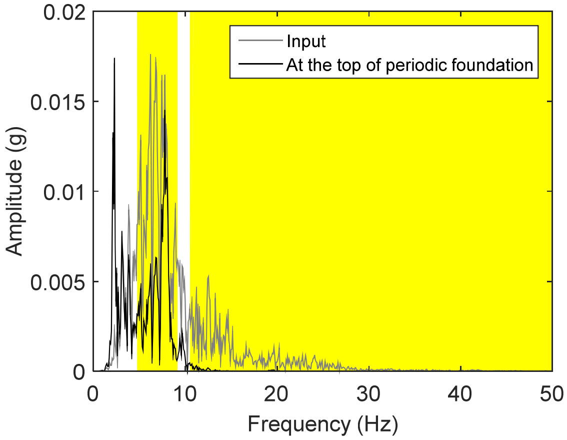

Fig. 10. Fourier transform of acceleration response of periodic foundation at Node G under Oroville ground motion

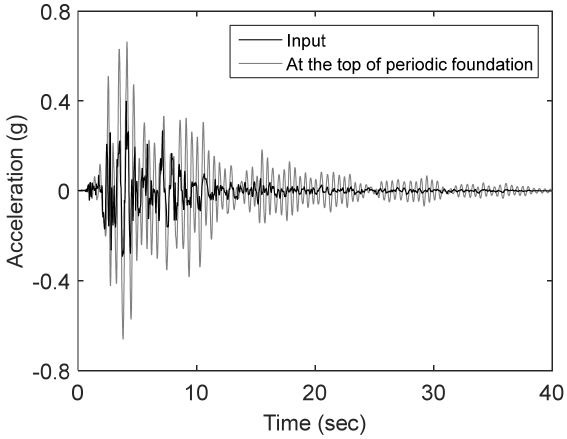

Fig. 11. Acceleration response of periodic foundation at Node G under Loma Prieta ground motion

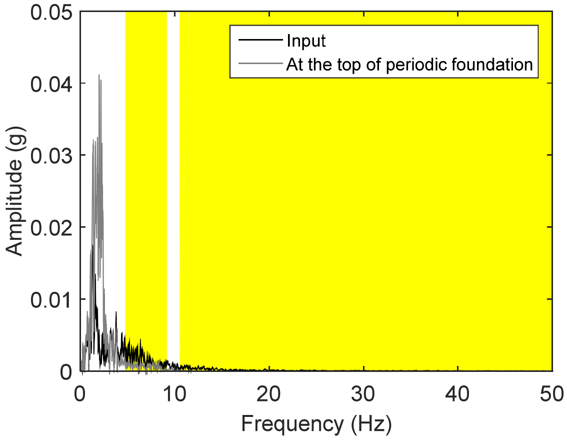

Fig. 12. Fourier transform of acceleration response of periodic foundation at Node G under Loma Prieta ground motion

The maximum accelerations on the piping system subjected to six accelerograms are tabulated in TABLE III. The maximum accelerations on the piping system with periodic foundation when subjected to Oroville, Bishop, and Lytle Creek are smaller than that in the no isolated piping system. In general, as long as the frequency band gaps cover the main frequency content of the seismic ground motions, the acceleration developed in the structure will be significantly reduced.

TABLE III
MAXIMUM ACCELERATION ON PIPING SYSTEMS

Earthquake Event	Direction of excitation 100% x + 30% y		Direction of excitation 30% x + 100% y	
	Acc on pipe only (g)	Acc on pipe with periodic foundation (g)	Acc on pipe only (g)	Acc on pipe with periodic foundation (g)
Oroville	0.50	0.29	0.48	0.30
Bishop	1.14	0.43	0.82	0.34
Loma Prieta	0.50	0.75	0.48	0.77
Imperial Valley	0.48	1.89	0.48	1.85
Lytle Creek	0.64	0.33	0.51	0.31
Northridge	0.88	0.89	0.89	0.85

B. *Stresses on Piping System*

As explained in Section III, internal stresses developed on the piping system may come from the inertia force and relative displacement of the supports. The time history analyses conducted on the case studies have considered both of the stress sources.

TABLE IV presents the maximum Von Mises stresses on the piping system due to a specific ground motion. The Von Mises stress on the piping system without periodic foundation is observed to be varied from 3.65 MPa to 166.9 MPa. The level of stresses shows that the piping system still behaves elastically under maximum considered earthquake.

In addition to the wave filtration, the presence of periodic foundations on the piping system allows more flexible supports on the piping. Even though the input excitation on each support is different, the flexibility of periodic foundations allows minimization of the relative displacement, which in turns significantly reduces the internal stress on the piping.

TABLE IV
VON MISES STRESS ON PIPING SYSTEMS

Earthquake Event	Direction of excitation 100% x + 30% y		Direction of excitation 30% x + 100% y	
	Stress on pipe only (MPa)	Stress on pipe with periodic foundation (MPa)	Stress on pipe only (MPa)	Stress on pipe with periodic foundation (MPa)
Oroville	3.99	2.30	3.65	3.92
Bishop	6.11	2.77	5.66	3.11
Loma Prieta	88.75	15.16	143.97	13.81
Imperial Valley	102.65	29.19	166.90	22.53
Lytle Creek	18.91	4.76	29.32	5.85
Northridge	47.55	14.09	75.84	10.46

C. *Maximum Drift of Periodic Foundation*

Periodic foundation has shown its effectiveness as a seismic isolation system. The goal, however, is to find an isolator device that does not produce large relative displacement between the superstructure and the ground.

In order to investigate whether periodic foundation satisfies the goal or not, maximum relative displacement at the top of the periodic foundations in the system under specific ground motion is recorded. The drifts, ratio of the relative displacement to the height of periodic foundation, are shown in TABLES V and VI. Under the direction of excitation 100% x+30% y, the maximum drift is found to be in x direction while under the direction of excitation 30% x+100% y, the maximum drift is found to be in y direction.

As mentioned in the previous section, the frequency band gaps of the designed periodic foundation cover the main frequency content of Oroville, Bishop, and Lytle Creek ground motion. The drifts on the periodic foundations under these three earthquake are found to be significantly smaller than the drift under Loma Prieta, Imperial Valley, and Northridge ground motions.

TABLE V
MAXIMUM DRIFT IN X DIRECTION SUBJECTED TO DIRECTION OF EXCITATION 100% X + 30% Y

Earthquake Event	Drift at node A (%)	Drift at node E (%)	Drift at node G (%)
Oroville	2.56	2.20	2.19
Bishop	2.51	2.13	2.10
Loma Prieta	14.93	15.34	15.50
Imperial Valley	35.58	38.46	39.18
Lytle Creek	5.11	5.49	5.49
Northridge	15.65	16.99	17.40

TABLE VI
MAXIMUM DRIFT IN Y DIRECTION SUBJECTED TO DIRECTION OF EXCITATION 30% X + 100% Y

Earthquake Event	Drift at node A (%)	Drift at node E (%)	Drift at node G (%)
Oroville	2.50	2.50	2.15
Bishop	2.11	2.36	2.13
Loma Prieta	14.20	17.58	15.65
Imperial Valley	32.39	41.58	36.92
Lytle Creek	5.03	6.07	4.95
Northridge	14.97	18.41	17.02

VI. CONCLUSIONS

Periodic material-based seismic isolation system or periodic foundation isolates the superstructure from the incoming seismic wave through waves filtering effect inside the frequency band gap. This unique ability has provided periodic foundation with many advantages over the current seismic isolation systems. When properly designed, periodic foundation can effectively reduce the acceleration response of the superstructure. In addition, the well-designed periodic foundation does not respond to seismic events with a large relative displacement and the flexibility of the periodic foundation decreases the internal stresses developed in the piping system. Moreover, the analytical model is very simple, straight forward, and easy to apply in any commercial finite element software since it only utilizes elastic solid elements. Overall, periodic foundation has shown promising results as the next generation seismic isolation system.

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