The concept of Earthquake-proof seismic negative belt which blocks seismic wave is introduced. The belt is composed of effective negative density or effective negative modulus. It converts the velocity of the seismic wave imaginary, and then creates a stop-band for the seismic frequency range. Passing the belt underground, the seismic energy turns into sound and heat in air and the magnitude of the seismic wave is weakened to be defended by conventional method.

Keywords: metamaterials, seismology, negative density, negative modulus

1. Introduction

Earthquakes are the result of sudden release of huge amount of energy in the Earth’s crust. The hypocenter or focus is the point where the stored strain energy is first released and the earthquake rupture begins. There are two types of seismic waves: body waves and surface waves. Primary (P) and Secondary (S) waves are body waves, and Rayleigh (R) and Love (L) waves are surface waves. The surface wave is generated when the body waves arrive at the surface of the earth. The epicenter is the main point of the generation. The amplitudes of the surface waves decrease exponentially with the depth.

R waves can exist only in a homogeneous medium with a boundary and have transverse motion. Earthquake motions observed at the ground surface are mainly due to R waves. L waves are polarized shear waves guided by an elastic layer. It is this fact that causes horizontal shifting of the Earth during earthquakes. L waves have both longitudinal and transverse motion and this is what most people feel directly during earthquakes. Surface waves travel slowly as 1 ~ 3 km/sec, but the wavelengths are much larger than that of the body waves. The frequencies of seismic waves are just below the audible frequency. Those are of low frequencies of long durations and of large amplitudes, which produce the most destruction causing serious hazards to life and property. Therefore, earthquake engineering is not to defend the vertical body waves but to defend the horizontal surface waves. By these reasons epicenter is more important than hypocenter in earthquake engineering.

Recently totally new methods based on acoustic metamaterials have been introduced [1, 2, 3, 4]. Metamaterials are man-made effectively homogeneous structures with dimensions potentially much smaller than that of a wavelength. There are two approaches in the metamaterial methods in earthquake engineering. One is an acoustic cloaking method to protect an individual building [3, 4]. It is omnidirectional and there is no energy dissipation by the impedance matching. However, it is a point protection which are good for buildings smaller than seismic wavelength. The other is an artificial seismic shadow zone method to protect a whole city instead of individual buildings [1, 2]. It builds an acoustic attenuator underground by creating a stop-band of the seismic wave. In this paper we focus the second method because it is the only macroscopic protection known till now [5].
2. Negative density and negative modulus

Seismic wave is a kind of acoustic wave and, then, its velocity is decided by the two mechanical constituent parameters of the medium: the density $\rho$ and the compressibility $\kappa$ or the inverse of the modulus $E$ as

$$ v = \frac{1}{\sqrt{\kappa \rho}} = \sqrt{\frac{E}{\rho}}, \quad (1) $$

The modulus $E$ could be any type: Young’s modulus at 1D, Shear modulus at 2D, and Bulk modulus at 3D. If one of the acoustical constituent parameter is negative effectively at some specific frequency ranges, then the velocity in Eq. (1) becomes imaginary in that frequency range. It makes the wave decay exponentially and, therefore, creates the stop-band of the seismic wave. It is the key concept of the seismic negative belt that dissipates the seismic energy. The energy turns into sound and heat. Note that the acoustical impedance $Z = v = \sqrt{\rho E}$ becomes imaginary because it is an energy absorption. If the two constituent parameters are negative simultaneously, it creates a backward wave without the dissipation.

![Diagram of a multiple mass system and a modified Helmholtz resonator.]

Figure 1: (a) The multiple mass system for the effective negative density. (b) The modified Helmholtz resonator and its electrical analogy for the effective negative modulus.

The effective negative density has been realized already [6, 7, 8, 9]. From the Newton’s law, the mass $m$ is related with the force which is applied as

$$ -m = \frac{F}{-a}, \quad (2) $$

where $a$ is the linear acceleration. If the mass responds against to the applied force, it acts as a negative mass effectively. An effective negative density is a multiple mass system as in Fig. 1(a). If a force is applied to the outer bone structure, then the inertia of the ball inside reacts against the force in the mass-in-mass coordinate. They oscillate against external force creating an anti-phase motion, and then cancel out the seismic vibration. A membrane structure behaves an effective negative density, too. The effective negative moment of inertia is similar in a cylinder-in-cylinder system. A simple harmonic motion of a spring-mass system which acts as $a = -\omega_0^2 x$ is the simplest case of the negative density. If the mass of the central ball in Fig. 1(a) is $10^2 \sim 10^3$ kg, and the spring constants are $10^5 \sim 10^7$ N/m, then the oscillation frequency of the structure matches approximately with the seismic surface waves: $\omega_0 = \sqrt{k_{eff}/m}$, where $k_{eff}$ is the effective spring constant. The system should have different oscillation frequencies because the surface waves are inhomogeneous.

An effective negative modulus has been realized by mechanical resonances [10, 11]. The resonance of accumulated waves in the resonator reacts against the applied pressure at some specific frequency ranges. Then, the negative modulus is realized by passing the acoustic wave through the array of modified Helmholtz resonators in Fig. 1(b). The Helmholtz resonator is a realization of an
electrical resonance circuit by mechanical correspondence. Because the wavelength of the seismic wave is much longer than the size of the holes, the incoming wave will be diffracted strongly into the meta-boxes. Note that the more the number of holes, the higher the resonant frequencies. The shape of the meta-box is neither necessary to be circular nor to have 6 holes. It could be any form of a concrete box with a few side holes such as cubic or hexagonal shapes. In this way the acoustic intensity decays just above the resonant frequencies \[1, 2\]. The resonance frequency of a Helmholtz resonator is \( \omega_0 = c \sqrt{\frac{S}{lV}} \), where \( S \) is the area of the entrance, \( V \) is the volume, and \( c \) is the background velocity. \( l' \) is the effective length which is given by \( l' \simeq l + 0.85d \), where \( l \) is the length of the hole or thickness of the resonator and \( d \) is the diameter of the hole \[1, 2\]. Multi resonance frequencies creates multi stop-band of the wave.

![Figure 2: Pressure distribution by a negative belt. Acoustic wave comes from the left side. Freq. = 10Hz. The units are m.](image)

A numerical simulation of the negative belt is shown in Fig. 2. The amplitude of the seismic wave that passes through the negative belt is reduced critically. The left border of the belt in Fig. 2 is breaking by the impedance difference, but could be fixed after the earthquakes. Epicenters are located in the left side of the belt and the other side is the seismic shadow zone. The use of a variety of resonators will cover a wide range of seismic wave frequencies. There are enough data of epicenters for one hundred years, and new earthquakes take place around previous epicenters like volcanoes.

### 3. Summary

A negative belt method of acoustic metamaterials for the attenuation of seismic waves are introduced. This method which is different from the conventional cloaking technology produces an artificial seismic shadow zone that reduces the seismic wave using effective negative density or modulus. The application of the negative density is found everywhere. It has been used as a damper for very high buildings. The negative belt is to build the damper region underground between epicenters and residential areas. The negative modulus method has been used for long time in civil engineering. There has occurred a large earthquake in Mexico in 1985, and it was found that some buildings of specific size destroyed completely compared with other buildings were relatively safe. It was the seismic energy dissipation by resonances. It is common sense for civil engineers to avoid resonances from external forces or torques including seismic waves. The negative belt of the effective negative modulus is the reverse concept of it.
The negative belt is constricted underground anyplace between possible epicenters and the areas to be protected. It changes the seismic wave-vector to an imaginary one and reduces the amplitude of the seismic wave exponentially. Besides the large scale of the protection, there is more advantage of the negative belt. It is the construction cost at large magnitude of earthquakes. In principle the conventional earthquake engineering is to reduce the amplitude of buildings be seismic wave. The depth of the seismic underground belt should be at least the foundation work of the building to protect, but it is not necessary to be more than the wavelength of the surface waves.

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REFERENCES