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Wave Propagation Through Soil and Seismic Metamaterials

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***Abstract* - Loss of human lives due to the devastating effects of earthquakes was found to be more than half of all lives lost due to all Natural disasters put together during the period 1998-2017. This brings out the fact that Earthquakes are the most devastating among all natural disasters.**

While earthquakes cause landslides, tsunamis, ground rupture and several other damages; collapse of buildings is the most concerning of them all, in congested and thickly populated cities. Hitherto the philosophy for earthquake resistant design of buildings included making the buildings strong enough to withstand the foreseeable ground motion during an earthquake. While a new concept, which is still under study deviates from this philosophy by the principle of preventing or reducing the effect of earthquake waves travelling to the buildings itself. This is made possible by what are called "Seismic Metamaterials".

The main objectives of this study include:

- **Study of Wave propagation through Sandy Soil media**
- **Performance of seismic metamaterials in attenuation of the waves.**

I. INTRODUCTION

From the past incidents, we are aware of the devastating effect of earthquake on manmade structures. As Structural Engineers, we design buildings to withstand the vibrations envisaged during an Earthquake and each Country has provided its own Earthquake Resistant Design Philosophy and design basis in their respective standards and codes.

Earthquake Design Philosophy:

The severity of an earthquake at a given location may be minor, moderate, or severe. Minor earthquakes occur frequently, moderate ones occur occasionally, and severe ones occur rarely. Thus, a question arises on whether to design all buildings to be earthquake proof (to withstand even the rarest earthquake which has a chance of occurrence once in 500 years or even 2000 years, which is likely to have a huge impact on the cost and thus impacting the economy) or do we do away with earthquake effect in the design? The answer surely lies mid-way between these two extremes.

Hence, the design approach is to ensure that structures possess minimum strength to withstand, without damage, all minor earthquakes that occur frequently; resist moderate earthquakes without significant damage to structure though non-structural damage may occur; and withstand a major earthquake without collapse.

The important parameters for Earthquake Resistant Design of Buildings are:

- Ground Motion
- Load Combinations
- Acceleration Spectrum
- Type of Soil
- Seismic Zone
- Desirable attributes of a building:
    - Robust Structural Configuration
    - At least a minimum elastic lateral stiffness
    - At least a minimum lateral strength
    - Adequate ductility
- Regular and Irregular Configuration
- Importance Factor
- Seismic Weight
- Type of Structure

Several of these parameters restrict the Architect of a building to freely adopt the design that is in his/her mind. If there was something like a cover for earthquake, buildings could be designed just to withstand the other forces and to have shape and form as desired by any Architect. To achieve this, the concept of Seismic Cloak has come up in the minds of several Civil Engineering designers. Thus, the concept of Seismic Metamaterials arrived.

Over the past decade, significant study has been done in the field of Seismic Metamaterials and this dissertation work is an extension and validation of one such study.

Metamaterials and Seismic Metamaterials:

Welcome to the fascinating world of Metamaterials!!!

The word Metamaterial is coined from the Greek word "Meta", meaning "beyond" and the Latin word "Materia", meaning "matter" or "material". Metamaterial is any material engineered to have a property that is not found in naturally occurring materials. They are made from assemblies of multiple elements such as metals and plastics. They are usually arranged in repeating patterns, at scales smaller than the wavelengths of the phenomena they influence. Metamaterials derive their properties not from the properties of the base materials, but from their newly designed structures.

The history of metamaterials begins with artificial dielectrics in microwave engineering. Since then, metamaterials have been developed for several applications in the entire electromagnetic spectrum. Its application to visible light has been challenging due to the very low wavelength of these waves (750 to 400 nanometers). L'eon Brilloiun (1946) stated that "All waves behave in a similar way, whether they are longitudinal or transverse, elastic or electric". This leads to the possibility of attenuating seismic waves too, using metamaterials which are then called "Seismic Metamaterials."

What is fascinating about seismic metamaterials is the amazing behavior exhibited by metamaterials which includes the concept of invisibility cloaks. The concept leading to making a building or structure invisible to seismic waves.

Seismic Metamaterial is a Metamaterial that is designed to counteract the adverse effects of seismic waves on artificial structures. Current designs of seismic metamaterials utilize configurations of boreholes, trees, or underground resonators to act as a large-scale material. Experiments have shown both reflections and bandgap attenuation from artificially induced seismic waves. The challenge with Seismic waves is their wavelength which is in the range of 40 meters to 250 meters. However, several studies including experiments have been done over the past decade on different types of Seismic metamaterials, which include:

- Outer Shield Metamaterials
- Metamaterial Foundations
- Buried Mass Resonators
- Above Surface Resonators (Forest of Trees)
- Auxetic Materials

Several of these studies have yielded positive results in terms of excellent agreement between theory and lab/field experiments.

II. METHODOLOGY

The dissertation work is carried out in two stages which are detailed below:

Stage-1:

- Study of Wave Propagation
- Tool: Numerical Tool using Computer Software (Ansys)
- The study:
  - Create simulation models
  - Generate vibrations at one source and check the measured amplitude of waves at several Points of Interest.
  - Simulate different vibrations and observe the results in the presence and the absence of Metamaterials.

Stage-2:

- Create a lab model to replicate the simulation; use a wave generator (oscillator) and a receiver inside a tank filled with sand and observe the readings. Compare these with the results from the computer software for validation.

III. FINITE ELEMENT MODEL AND ANALYSIS

A. Engineering Material Properties:

The following five materials are defined under this module:

1. Acrylic
2. Sandy Soil
3. Structural Steel
4. Rubber

Table 4.1: Engineering Properties of Materials

Material	Young's Modulus (MPa)	Poisson's Ratio	Density (Kg/Cu.m.)
Acrylic	2200	0.402	1200
Structural Steel	2,00,000	0.3	7850
Rubber	1.5	0.499	910

Properties of Soil (Defined as Porous Elastic Material):

Initial Void Ratio	Swell Index	Elastic Limit of Tensile Strength (MPa)	Poisson's Ratio	Density (Kg/Cu.m.)
0.3	0.2	0.001448	0.2	1860

B. Geometry:

Table 4.2: Geometry Dimensions

Sl.No.	**Description**	**Dimensions (mm)**
1	Acrylic Box	1600 x 600 x 400
2	Soil Media	1576 x 476 x 376
3	Loading Plate	400 x 300 x 20
4	Steel Cylinder	94mm diameter
5	Rubber Cylinder	78mm diameter

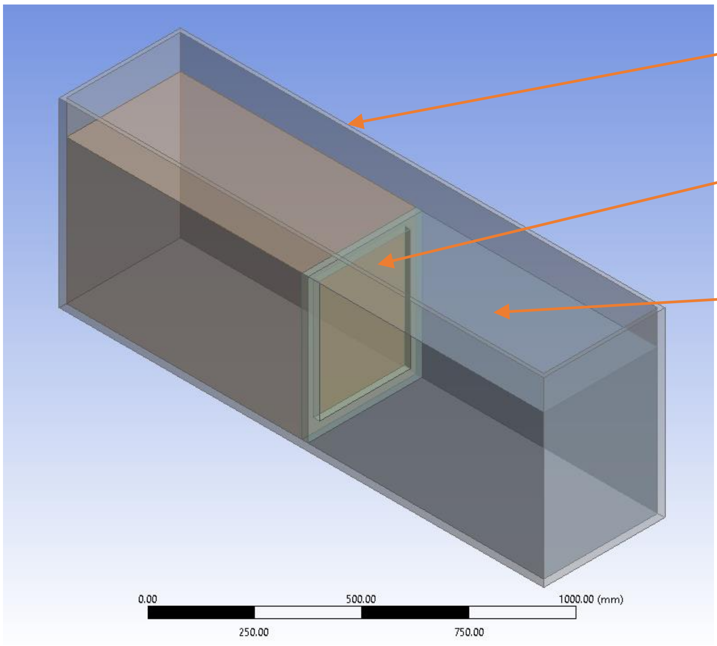

Fig 4.1: Geometry of Model without Metamaterial

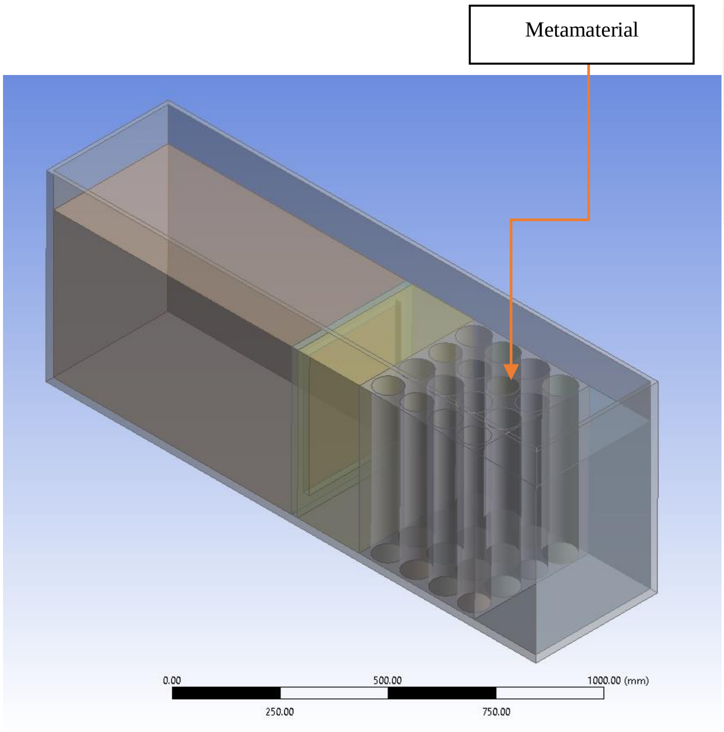

Fig 4.2: Geometry of Model with Metamaterial

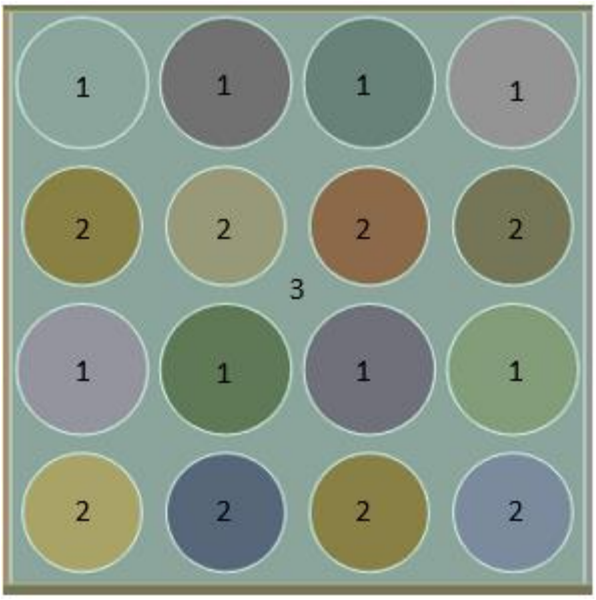

Fig 4.3: Structure of Periodic Metamaterial

1 – Steel Cylinders
2 – Rubber Cylinders
3 – Soil Media

C. Boundary Conditions:

The following two boundary conditions are defined:

1. Fixed support (base of the acrylic box)
2. Displacement (as a function of time on the face of the loading plate)

D. Input Oscillation:

The input oscillation is applied as a Displacement boundary condition which is defined by the following equation, which provides a sinusoidal oscillation:

$$Y = A \times \mathrm{Sin}\ (\omega \times \mathrm{time})$$

Table 4.4: Input Oscillation data (Case-1)

Frequency (Hertz)	Amplitude(A) (mm)	Omega(ω) (Deg/Sec)	Time for 1.25 Cycles (Sec)
0.125	0.5	45	10
1	0.5	360	1.250
2	0.5	720	0.625
3	0.5	1080	0.417
4	0.5	1440	0.313
5	0.5	1800	0.250
6	0.5	2160	0.208
7	0.5	2520	0.179
8	0.5	2880	0.156
9	0.5	3240	0.139
10	0.5	3600	0.125

Table 4.5: Input Oscillation data (Case-2)

Frequency (Hertz)	Amplitude(A) (mm)	Omega(ω) (Deg/Sec)	Time for 1.25 Cycles (Sec)
0.125	1.5	45	10
1	1.5	360	1.250
2	1.5	720	0.625
3	1.5	1080	0.417
4	1.5	1440	0.313
5	1.5	1800	0.250
6	1.5	2160	0.208
7	1.5	2520	0.179
8	1.5	2880	0.156
9	1.5	3240	0.139
10	1.5	3600	0.125

Table 4.6: Input Oscillation data (Case-3)

Frequency (Hertz)	Amplitude(A) (mm)	Omega(ω) (Deg/Sec)	Time for 1.25 Cycles (Sec)
0.125	2.5	45	10
1	2.5	360	1.250
2	2.5	720	0.625
3	2.5	1080	0.417
4	2.5	1440	0.313
5	2.5	1800	0.250
6	2.5	2160	0.208
7	2.5	2520	0.179
8	2.5	2880	0.156
9	2.5	3240	0.139
10	2.5	3600	0.125

IV. RESULTS OF COMPUTER ANALYSIS

The analysis is carried out for three different amplitudes (0.5mm, 1.5mm, and 2.5mm) and 11 different frequencies (0.125Hz, and 1Hz to 10Hz) for the model with soil only, and with an amplitude of 0.5mm for the model with metamaterials The summary of results of these forty-four analyses are represented in Fig 5.1 to 5.4.

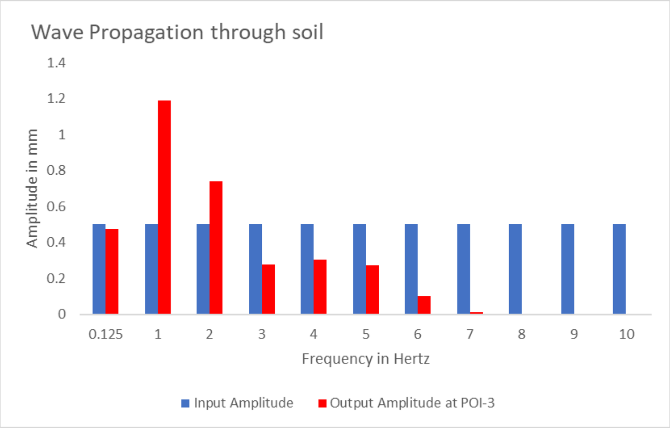

Fig 5.1: Wave Propagation through Soil (Input Amplitude = 0.5mm)

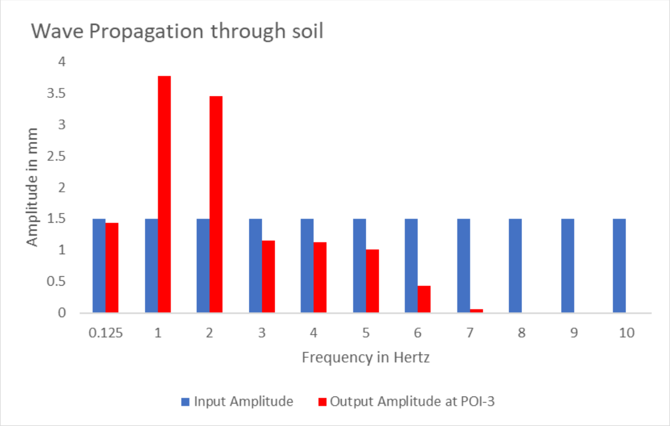

Fig 5.2: Wave Propagation through Soil (Input Amplitude = 1.5mm)

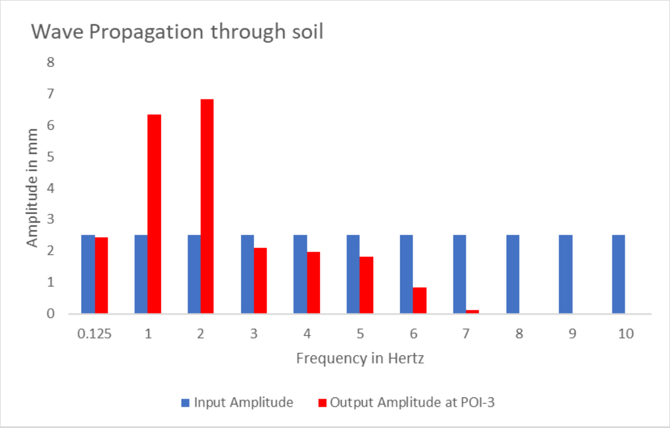

Fig 5.3: Wave Propagation through Soil (Input Amplitude = 2.5mm)

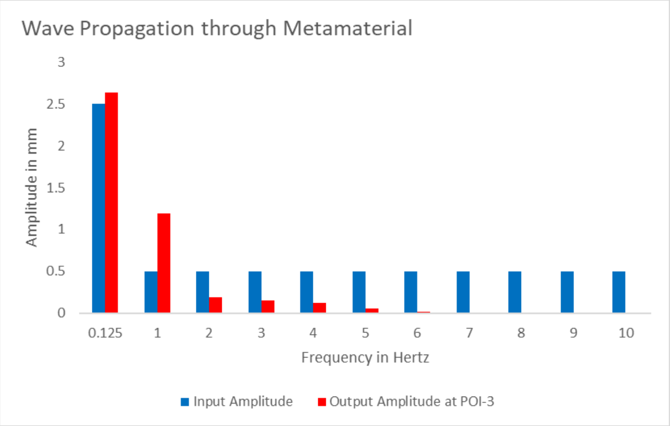

Fig 5.4: Wave Propagation through Metamaterial

V. LABORATORY EXPERIMENT

For study of wave propagation through Soil, a miniature model (soil filled box) is created. Oscillator arrangement (resembles loading plate in the computer model) is made using the shaking table in Earthquake Laboratory. The arrangement is as shown in Photos 6.1 and 6.2.

Photo 6.1: Oscillator arrangement.

Photo 6.2: Oscillator arrangement attached to shaking table & box filled with Soil.

An Accelerometer sensor is attached to the face of the oscillator to pick up input signals of oscillation. While another accelerometer sensor is embedded in the soil, a little away from the oscillator to pick up output signals as the oscillation travels through the soil. The sensors are connected to a data acquisition system which is further connected to a computer enabled with the software to capture the data. This entire arrangement is depicted in photo 6.4.

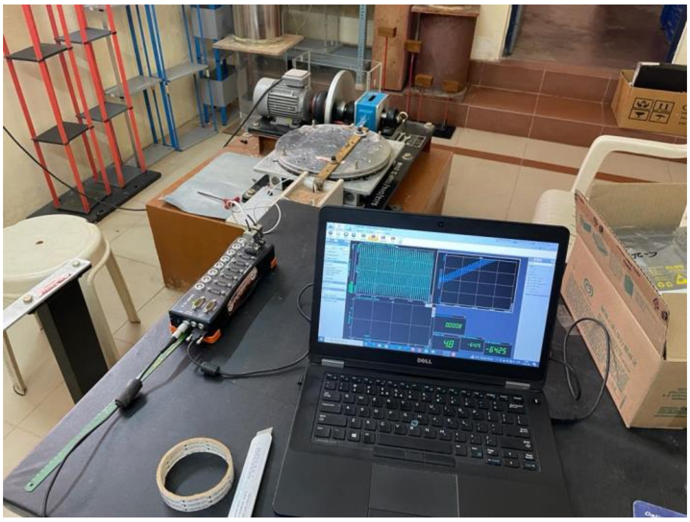

Photo 6.4: Oscillator connected to Data Acquisition System & Computer

The experiment is carried out for varied input frequency and amplitude and data are recorded. The recorded data are then analyzed and processed to provide the desired information on input and output oscillation (Acceleration, Velocity, Displacement etc.). To compare the results of the laboratory experiments with the computer simulated model in terms of the trend; input oscillations were varied by changing amplitude and frequency as per table 6.1.

Table 6.1: Input oscillation parameters for laboratory experiment.

Frequency (Hz)	1	1	2	2	2
Amplitude (mm)	2	2.5	1	1.5	2

Frequency (Hz)	2	2	3	3	3
Amplitude (mm)	2.5	4	1	1.5	2

Frequency (Hz)	3	4	4	4	4
Amplitude (mm)	2.5	1	1.5	2	2.5

Frequency (Hz)	4	5	5	6	6
Amplitude (mm)	4	2	4	2	4

The results of the experiment data are captured as input and output oscillations. A summary of the relevant results is shown in Fig 6.1.

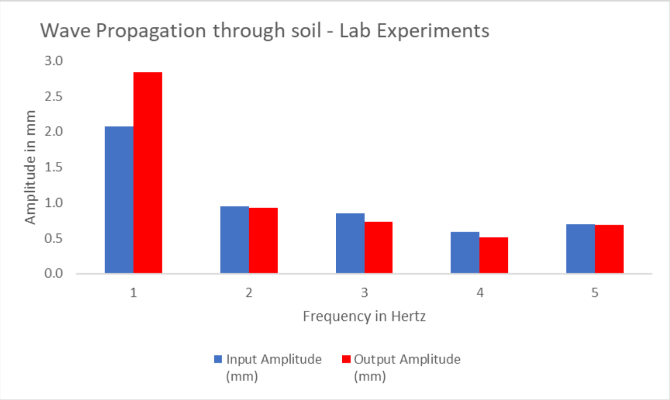

Fig 6.1: Wave Propagation through soil - Lab Experiments

VI. RESULTS AND DISCUSSIONS

Wave Propagation through Soil:

The results of analysis from the computer analyzed model are presented in chapter 5 and those from the laboratory experiment in chapter 6. A comparison is drawn on the trend of amplitude of the input oscillation to that of the output oscillation in both cases. This is calculated as a percentage of output amplitude to input amplitude. These percentages are then compared between the computer analyzed results and the lab experiment results. For this purpose, the output parameters in POI-2 of the computer analysis are considered, as it is similar in location to the laboratory experiment setup.

The comparison is presented in Fig 7.1.

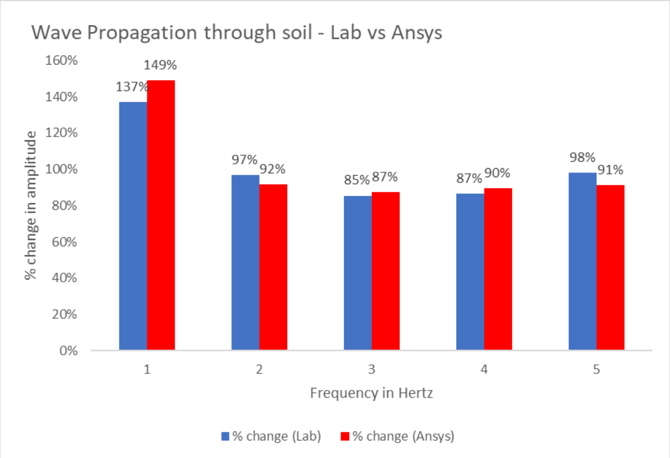

Fig 7.1: Wave Propagation through soil - Lab vs Ansys

It is heartening to observe that the trend in computer analysis closely matches with that in the laboratory experiment.

Wave Propagation through Seismic Metamaterials:

The computer simulated model provided oscillation within and just after passing the seismic metamaterials (The type used is periodic seismic metamaterials). The % reduction in amplitude at different frequencies after the wave just crosses the metamaterials is plotted and the same is depicted in Fig 7.2.

The results of this analysis are comparable with the study by Arpan Gupta et al. under reference-1.

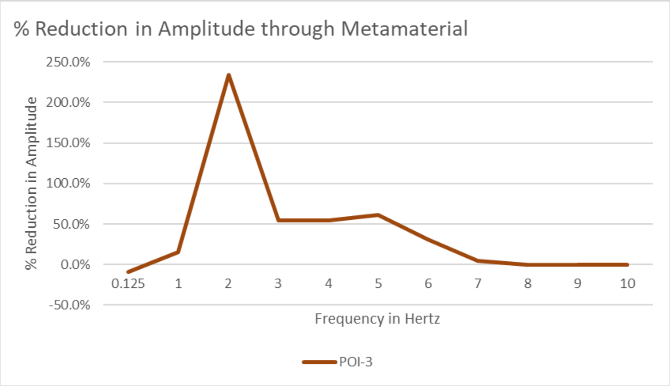

Fig 7.2: % Reduction in Amplitude through Metamaterial

VII. CONCLUSIONS

Wave Propagation through Sandy Soil Media:

Comparing the analysis of results from the computer-generated finite element model and laboratory experiments, the following conclusions are drawn:

1. At frequencies less than 2 Hz, waves are amplified (peak is higher).
2. Damping of waves is observed in the frequency range 3 to 6 Hz.
3. At higher frequencies (> 6 Hz) waves die off very close to the source and transmission is limited.
4. The amplitude of wave does not have any significant change in the above pattern.

5. The results of analysis from the numerical model agree with the results from the Laboratory Experiment which validates the computer model.

Wave Propagation through Metamaterials:

From a detailed analysis of the results from the computer-generated finite element model, the following conclusions are drawn:

1. Wave propagation through Metamaterials follow a similar trend as through Sandy Soil Media

2. Over 50% attenuation of waves (amplitude reduction) is recorded just as the waves cross the metamaterials at frequencies from 2 to 6 Hz

3. The analysis results compare well with those brought out in the article under reference 1.

4. There is a definite possibility of developing Metamaterial foundation or Seismic Cloaks in the future which can completely change our approach towards Earthquake Resistant Design and Design Philosophy.

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