symmetry

MDPI

Article

Prevention of Wave Propagation via Circular Arrangement of Seismic Metamaterials Formed with Concrete Piles

Selcuk Kaçın [1], Murat Özturk [2], Umur Korkut Sevim [1], Muharrem Karaaslan [3,*], Oğuzhan Akgöl [3], Zafer Özer [4], Mustafa Demirci [1], Emin Ünal [5], Bayram Ali Mert [6], Maide Erdoğan Alkurt [3], Fatih Özkan Alkurt [3], Mustafa Tunahan Başar [7,8] and Şeyda Gülsüm Kaya [1]

1 Department of Civil Engineering, Iskenderun Technical University, Hatay 31200, Turkey
2 Department of Civil Engineering, Faculty of Engineering, Bursa Uludag University, Bursa 16000, Turkey
3 Department of Electrical and Electronics Engineering, Iskenderun Technical University, Hatay 31200, Turkey
4 Vocational School of Mersin, Department of Electronics Technical, Mersin University, Mersin 33350, Turkey
5 Department of Electrical and Electronics Engineering, Necmettin Erbakan University, Konya 42080, Turkey
6 Iskenderun Vocational School, Iskenderun Technical University, Hatay 31200, Turkey
7 Department of Mechanical Engineering, Iskenderun Technical University, Hatay 31200, Turkey
8 Department of Motor Vehicles and Transportation Technology, Vocational School of Taşova Yüksel Akın, Amasya University, Amasya 05100, Turkey
* Correspondence: muharrem.karaaslan@iste.edu.tr

Abstract: It is known that the low frequencies of seismic surface waves have a destructive effect. The main purpose of seismic metamaterials is to protect structures from seismic waves at low frequencies, especially in a wide band. In this study, the effects of seismic metamaterials formed using circular array concrete piles on surface waves were investigated. Each concrete pile has been selected due to symmetric properties to investigate the band diagram. Therefore, the direction independence can also be determined with respect to frequency. This study was conducted both numerically and experimentally in the low-frequency range of 5–15 Hz. Two fields, with and without metamaterials, have been designed and compared. In numerical analysis, transmission loss graphs were drawn using the finite element method (FEM), and wave propagation at frequencies where the loss happened was simulated. In numerical analysis, optimum dimensions such as radius and depth were determined, and these dimensions were applied exactly in the experimental field. The results obtained from the experiment using a harmonic vibration device are mapped. In this numerical and experimental study, it has been revealed that the proposed structure prevents the propagation of seismic surface waves.

Keywords: seismic waves; metamaterials; concrete piles; earthquake

check for updates

Citation: Kaçın, S.; Özturk, M.; Sevim, U.K.; Karaaslan, M.; Akgöl, O.; Özer, Z.; Demirci, M.; Ünal, E.; Mert, B.A.; Alkurt, M.E.; et al. Prevention of Wave Propagation via Circular Arrangement of Seismic Metamaterials Formed with Concrete Piles. *Symmetry* **2023**, *15*, 1489. https://doi.org/10.3390/sym15081489

Academic Editor: Marco Montemurro

Received: 30 June 2023
Revised: 20 July 2023
Accepted: 24 July 2023
Published: 27 July 2023

1. Introduction

Earthquakes are one of the biggest natural disasters that cause the loss of life and nature and economic damage. Even though it is not possible to prevent earthquakes from happening, reducing the destructive effect of earthquake waves, preventing them from spreading over large areas, reducing their intensity, or damping earthquake waves have been significant research subjects for engineers. In particular, the use of metamaterials in seismic fields has been one of these study subjects recently. Metamaterials are generally specially designed periodic structures that cannot be found naturally in nature [1]. In studies conducted to examine acoustic metamaterials, it has been proven that acoustic metamaterials can attenuate waves [2]. By using these metamaterials, many features such as negative refraction [3,4], acoustic imaging [5], acoustic cape [6,7], band gaps [8], vibration attenuation [9,10], and wave direction [11] are provided. Numerical and experimental research has been carried out in order to prevent seismic surface waves from propagating similarly to acoustic waves. Seismic metamaterials have become a new method for preventing low-frequency waves corresponding to resonance frequencies in the range of 1–10 Hz [12]. Liu et al. [13], inspired by the vibration-damping properties of forests, used trees as large-scale natural metamaterials to prevent vibration at low frequencies. Miniaci et al. [14] used large-scale mechanical metamaterials to see the possibility of passive isolation. His work has had an impact on both surface and guided waves. Pu and Shi [15] investigated how surface waves are distributed in periodic structures formed in one and two dimensions. They showed the behavior of a surface wave when it encountered a finite periodic pile system and the efficiency of this weakening zone. Chen et al. [16] proposed a seismic metamaterial for wave attenuation in the low-frequency range considering the multilayer soil structure. Diatta et al. [17] examined two capes providing elastodynamic energy flow in Rayleigh waves in the frequency range of 5–10 Hz. The design of the first cape was made with thin plate theory. The design of the other cape was made using the transformation that led to the Willis equations. It has been observed that the second of these two capes is more efficient. Palermo et al. [18] proposed a metabarrier for Rayleigh waves. The metabarrier is designed by embedding resonant structures under the surface of the ground. With this design, seismic waves with wavelengths in the range of 10–100 m are controlled. As a result of the study, it was observed that the propagation of seismic waves was decreased by 50% at frequencies below 10 Hz, and consequently, the structure area could be protected. Pu et al. [19] studied the finite element method using periodic piles and considering the layered soil. They expressed the distribution relationship in order to calculate the attenuation areas of surface waves. Li et al. [20] used a series of concrete inclusions as seismic metamaterials to prevent ground vibrations from railways. This study is conducted based on the finite element method and perfectly matched layers theory in both frequency and time domains. It has been observed that the harmful effects of vibrations originating from railways can be prevented by using seismic metamaterials. Kaçın et al. [21] analyzed the seismic metamaterials obtained by applying cylindrical boreholes to the ground with a triangular array both numerically and experimentally. As a result of their study, they stated that the numerical results and field results are in harmony with each other and that metamaterials with triangular arrays can prevent surface waves. Mandal and Somala [22] used square-section pile barriers to prevent low-frequency surface waves. They changed the mechanical and geometric parameters with the shape of the pile in order to show the efficiency of the wave attenuation zones. They have shown that the designed piled system is successful in wave attenuation.

In this study, the ability of seismic metamaterials formed by placing concrete piles in a circular array on the ground to prevent surface waves was investigated. Both theoretical and experimental analyzes of the proposed structure have been made. In the theoretical analysis, a finite element method (FEM) based analysis program was used. This study was carried out in both frequency and time domains. Also, studies were made in the low-frequency range, which is dangerous for structures. The optimum dimensions obtained as a result of the simulation studies were applied to the experimental area on a full scale. The data obtained from the experimental field were mapped by transforming it into the frequency domain. The results of the experiments were discussed, and the advantages of the field where concrete piles were applied in a circular array are presented. The proposed structure could be a good method of preventing the propagation of seismic surface waves and could be a candidate for use in earthquake research.

2. Theory and Numerical Analysis

Numerical analysis was performed using the finite element method (FEM) based simulation program. A circular array was used to observe the result obtained by placing metamaterials on the floor differently from the literature. A circular array of concrete piles is shown in Figure 1.

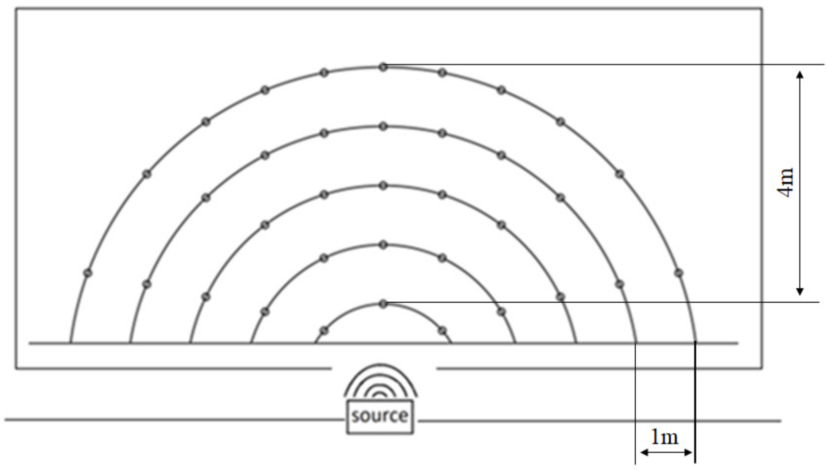


Figure 1. Circular array of concrete piles.

The dimensions of the concrete piles were determined optimally by trial and error. The aim of the trial–error method is to find the optimum design parameters in experimental studies because of the feasibility of the proposed idea. The concrete piles have been selected due to their symmetric characteristics. The band diagram of a unit cell with symmetry can be evaluated easily. Accordingly, the radius of the concrete piles was chosen as 7.5 cm and the depth as 2 m. It also has an aperiodic behavior in the Γ, X, and M directions due to the array shape. Therefore, unit cell analysis and band diagram could not be obtained. The mechanical properties of the materials used were determined using field measurement results and laboratory tests. The Young's modulus of the soil was defined as 20 MPa, the Poisson's ratio as 0.3 and the density as 1800 kg/m^3, the Young modulus of the concrete as 30 GPa, and the Poisson's ratio as 0.25 and the density as 2500 kg/m^3.

In order to see the damping effect of the concrete piles arranged in a circular array on the ground on seismic surface waves, two different fields were designed. One of these two fields is the original field, and the other is the field where concrete piles in a circular array were applied. Thus, the progress of seismic surface waves in both fields can be observed and compared. A boundary load is assigned to apply surface waves to each field. And measurement points are determined for each field. In Figure 2, the two field designs mentioned, boundary load, and measurement points are specified. The symmetric boundary conditions were applied to the ground to provide a continuous ground layer.

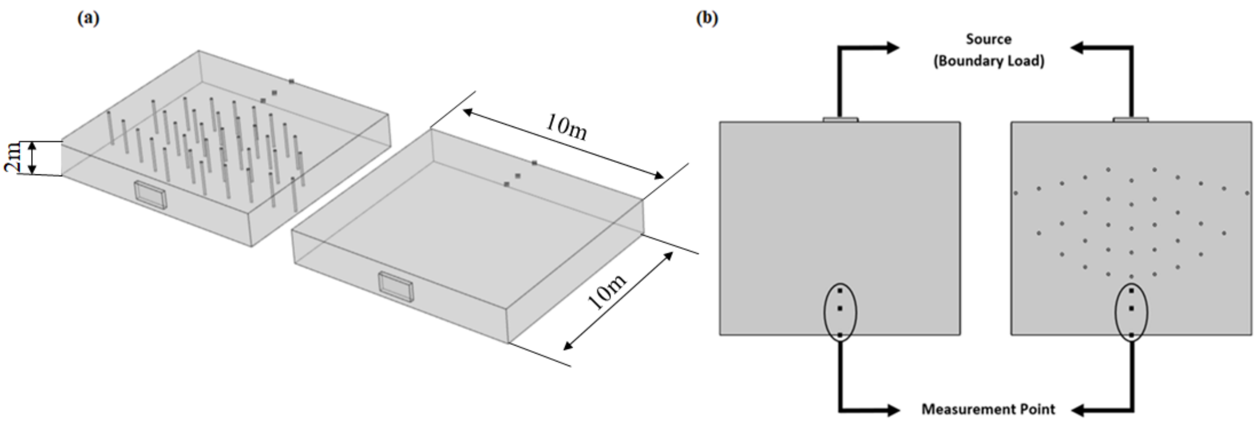
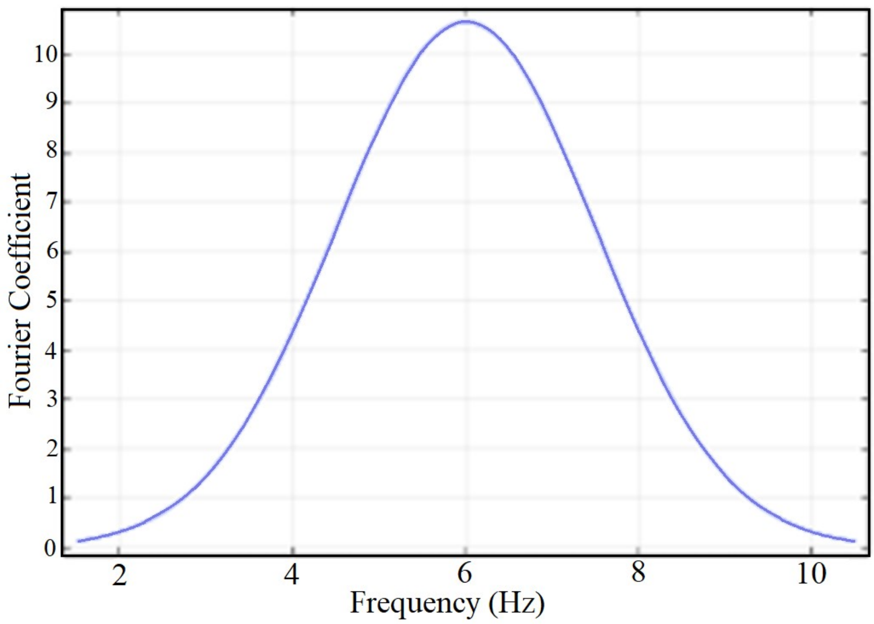


Figure 2. (**a**) Fields with and without metamaterial; (**b**) boundary loads and measurement points.

In both frequency and time domain studies, a 1 N test pulse was applied to each field. The test pulse was applied in the low-frequency range of 5–15 Hz, which has a very high destructive effect. Excitation pulses in Figure 3 were used to numerically evaluate the mentioned dimensions and parameters in the frequency domain and time domain.



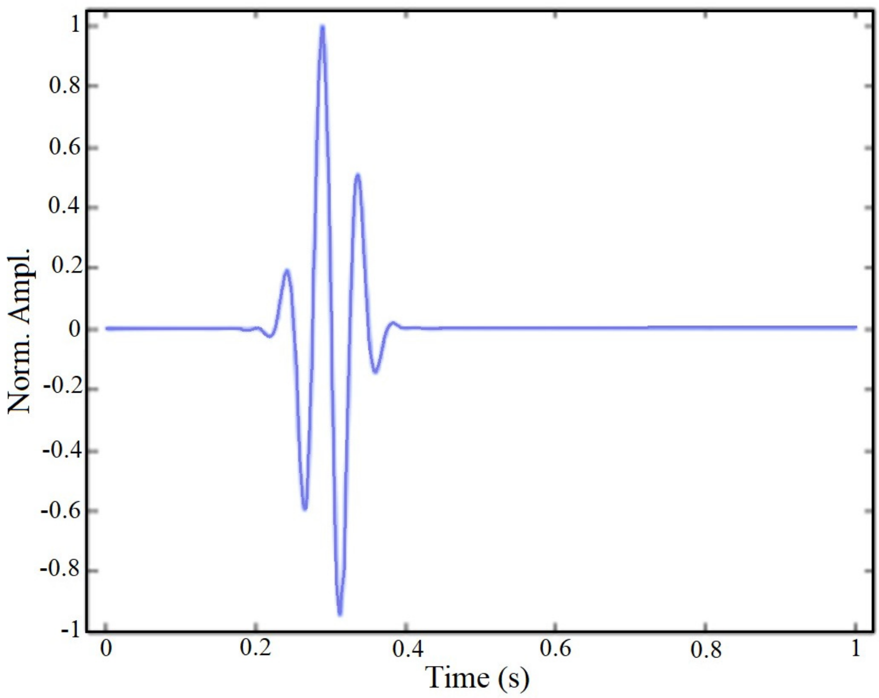


Figure 3. Excitation pulse.

The transmission losses caused by placing the concrete piles on the ground in the study conducted in the frequency field are given in Figure 4. As seen in this graph, at frequencies of 5.1 Hz, 6.2 Hz, 6.5 Hz, 8.5 Hz, 11.2 Hz, 12.3 Hz, 13.8 Hz, and 14 Hz, multispectral transmission losses of −16 dB, −11.73 dB, −20.6 dB, −13.3 dB, −23.28 dB, −28.1 dB, −18.85 dB, and −37.82 dB were observed, respectively.

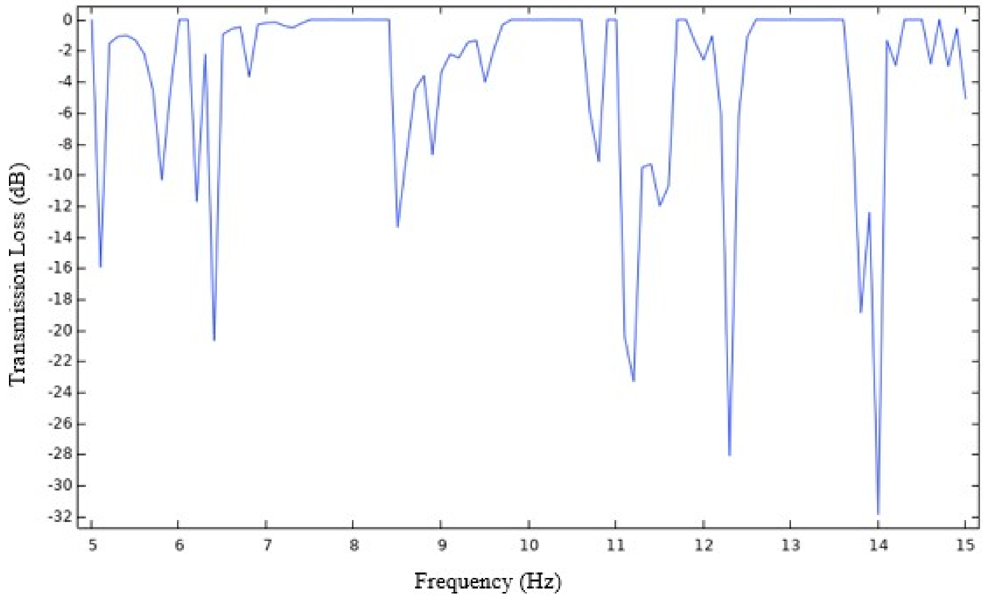


Figure 4. Transmission losses.

In order to clearly see the progress of seismic surface waves at frequencies determined based on transmission losses, fields with and without metamaterial were simulated in the frequency domain. It is aimed to compare the wave progression by applying surface waves in both areas. Wave progression at frequencies where transmission losses are obtained is given in Figure 5.

The total displacements on the field where the circular array concrete piles were applied and not applied are shown in Figure 5. Since the wave transmissions at each resonant frequency would be different, calculations have been made for each frequency. The total displacement is the highest in the regions shown in red and the minimum in the regions shown in blue. It was clearly seen that the wave propagation decreased in the field where the metamaterial was present.

Based on the study conducted in the frequency domain, studies in the time domain in frequencies that attenuate the wave propagation have been carried out. In this study, the attenuation of seismic surface waves in the xy plane has been investigated. Because the surface waves spread perpendicular to the concrete piles in the xy plane, they are very difficult to attenuate. The horizontal component (ux) of Rayleigh waves traveling on the soil ground resonates with boreholes. A phase difference occurs between the applied and reflected waves in resonance, and this difference leads to attenuation. The analysis in the time domain was performed with a finite element method (FEM) based program. The perfectly matched layer (pml) thickness at the edges of the block defined on a homogeneous soil is 1.5 m, and pml 0.375 m at the bottom of the finite model to provide symmetricity and periodicity of the overall structure. Figure 6 shows the analysis of seismic surface waves at frequencies 6.5 Hz, 8.5 Hz, and 14 Hz in the time domain.

By examining the wave propagation at the specified frequencies in the field where concrete piles were used, it was observed that the waves had damping after three rows of holes, the wave progressed by decreasing, and the entire wave could not pass behind the proposed structure. As a result of the experimental studies, it has been determined that the seismic metamaterial created from concrete piles and its circular array shape are effective on seismic surface waves.

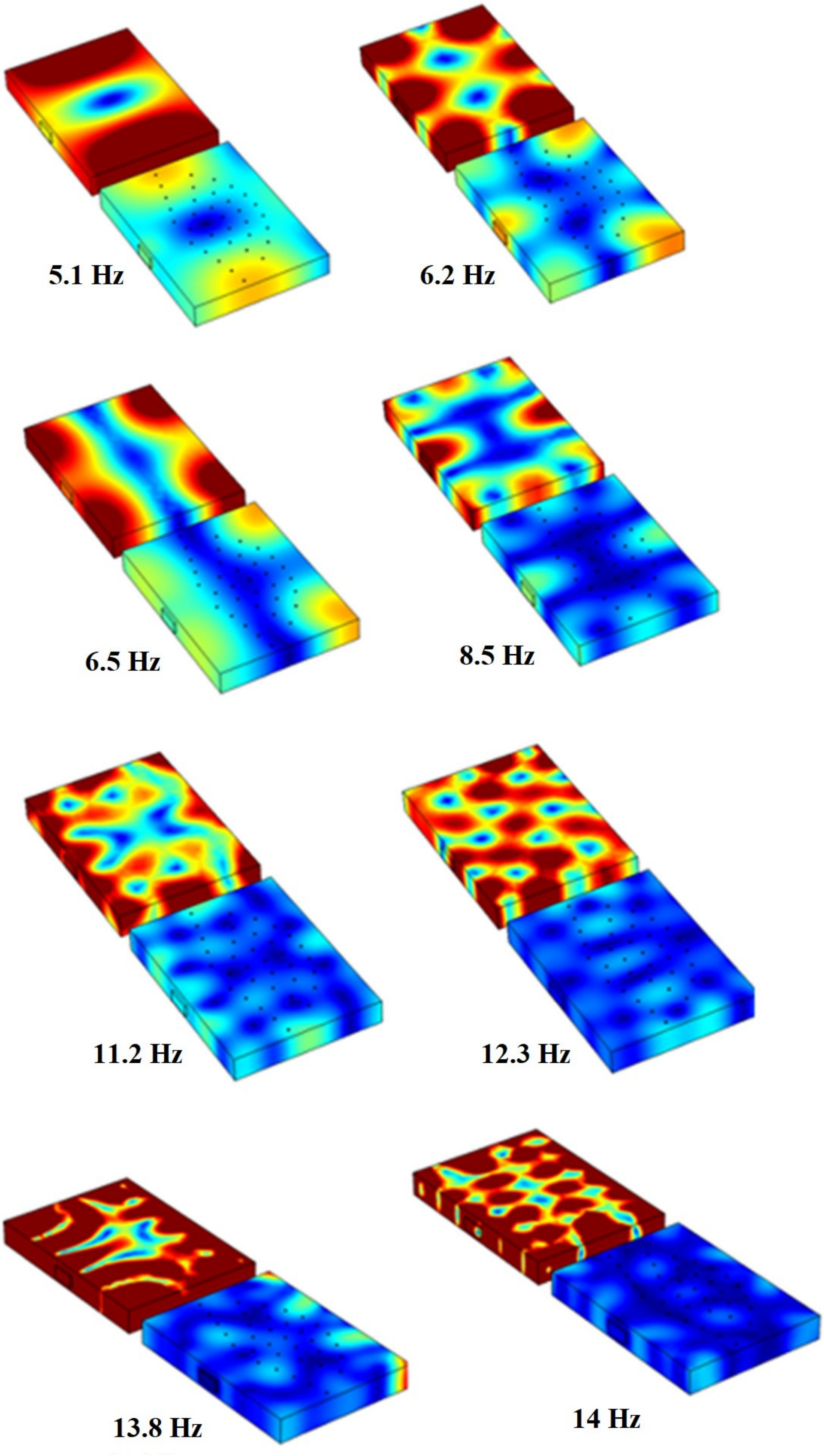


Figure 5. Total displacement areas in empty fields and air-filled boreholes at resonance frequencies.

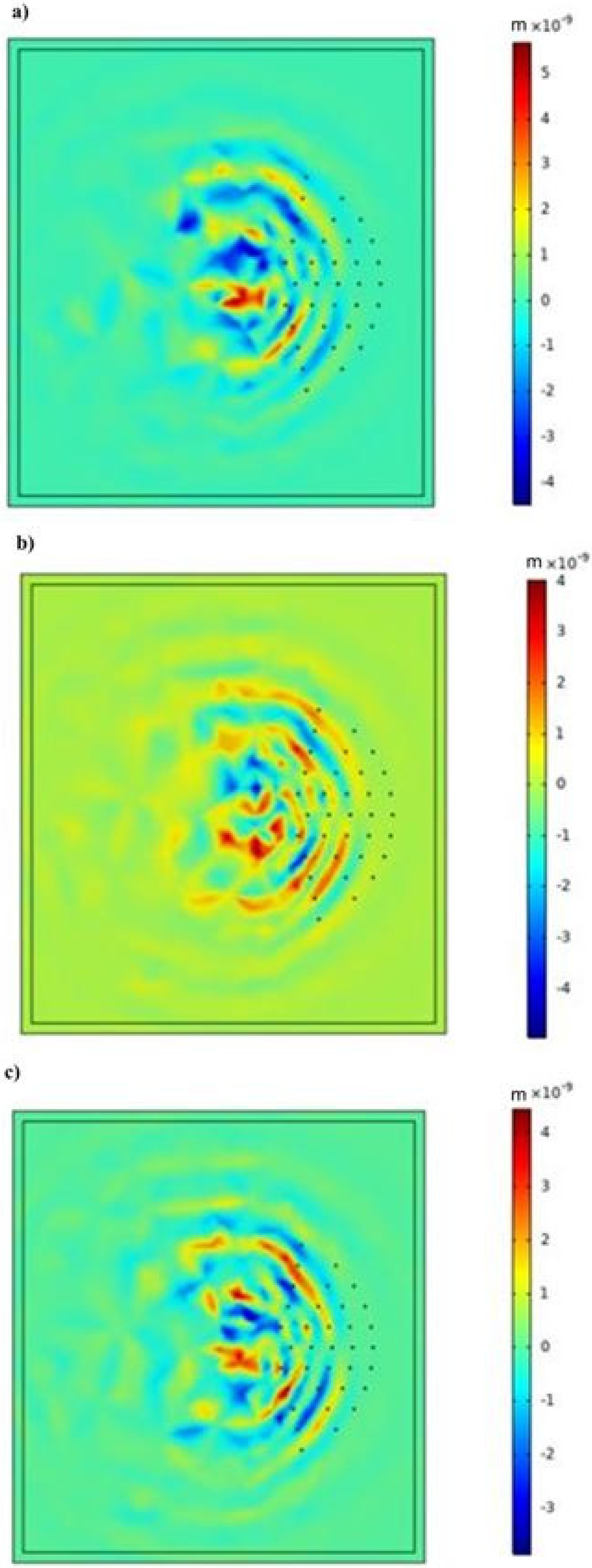


Figure 6. (**a**) In-plane displacement at a frequency of 6.5 Hz, (**b**) in-plane displacement at a frequency of 8.5 Hz, and (**c**) in-plane strain at a frequency of 14 Hz.

3. Experimental Setup

In order to confirm the accuracy of numerical and theoretical studies, an experimental field study was carried out on the campus of Iskenderun Technical University. All dimensions used in the experimental field were selected exactly the same as the optimum dimensions determined in numerical analysis. A total of 35 boreholes were drilled in a circular sequence in the designated test field. Concrete piles were obtained by filling the drilled boreholes with concrete. Each concrete pile has a diameter of 15 cm and a depth of 2 m. A harmonic source has been placed in the field in order to create vibration at the specified frequencies. The harmonic source used and the center of the vibration device shown in Figure 7a have two arms connected to a rotating motor. Each arm has a load of 660 g and rotates in opposite directions to create a harmonic load. Harmonic sources can perform 90–300 revolutions per minute and create vibrations in the frequency range of 0–15 Hz. The vibration source generates seismic surface waves along the x direction. In order to transfer these vibrations in the most accurate way, the harmonic source is placed at a distance where sufficient wave propagation can be possible. As shown in Figure 7b, a pit with a depth of 1 m was dug, which transfers the force to the ground layer, and the foundation was formed by pouring concrete into it. The source of vibration is rigidly attached to this foundation. In Figure 6c, the field where concrete piles are applied is given.

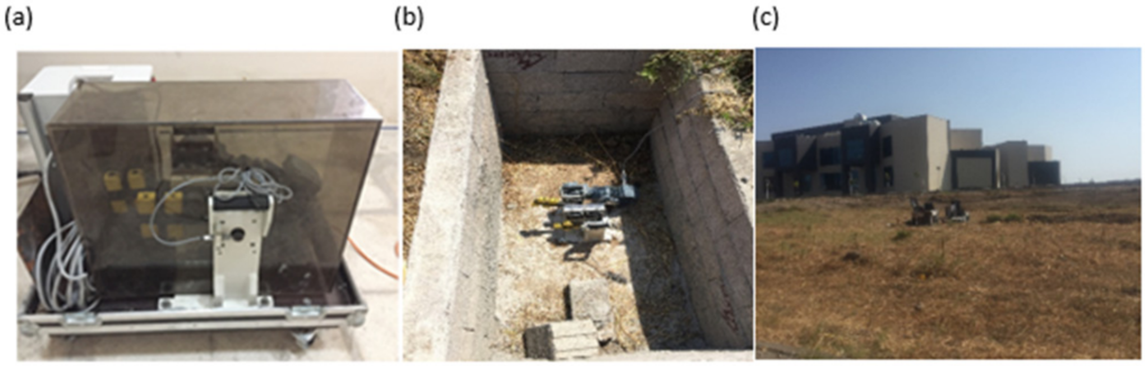


Figure 7. (**a**) Harmonic vibration source. (**b**) Location of harmonic source. (**c**) Experiment field.

Two separate field measurements were made in the experimental study. The first one is the measurement of the original site, where no action has been taken yet, and the other is the measurement of the application of concrete piles to the same site in a circular array. Measurement is performed by measuring seismic waves propagating from harmonic sources with accelerometers. The locations of the accelerometers are shown in Figure 8. Uniaxial accelerometers are placed in the same direction as the propagating seismic surface waves.

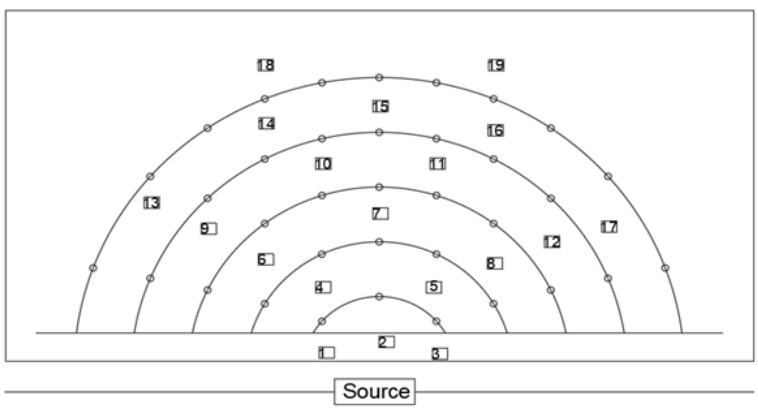


Figure 8. Locations of the accelerometers. The utilized number of the sensors are eighteen.

A total of 60 s of vibration was applied to the test field for each frequency in the frequency range of 5–15 Hz. Time domain data recorded using accelerometers were transformed into the frequency domain via Fast-Fourier (FFT) method. This transformation was carried out using the Matlab® program.

4. Results

The data obtained after the transformation were mapped using the geostatistical interpolation method. With this method, both distances and directions are considered. The frequencies determined with transmission loss in the numerical analysis were taken into consideration in the experimental study, and these frequencies were mapped because of field measurements.

In Figure 9, the propagation of seismic surface waves at a frequency of 6.5 Hz in the original field without metamaterial, and in Figure 9b, the propagation of surface waves at a frequency of 6.5 Hz in the field with concrete piles is mapped.

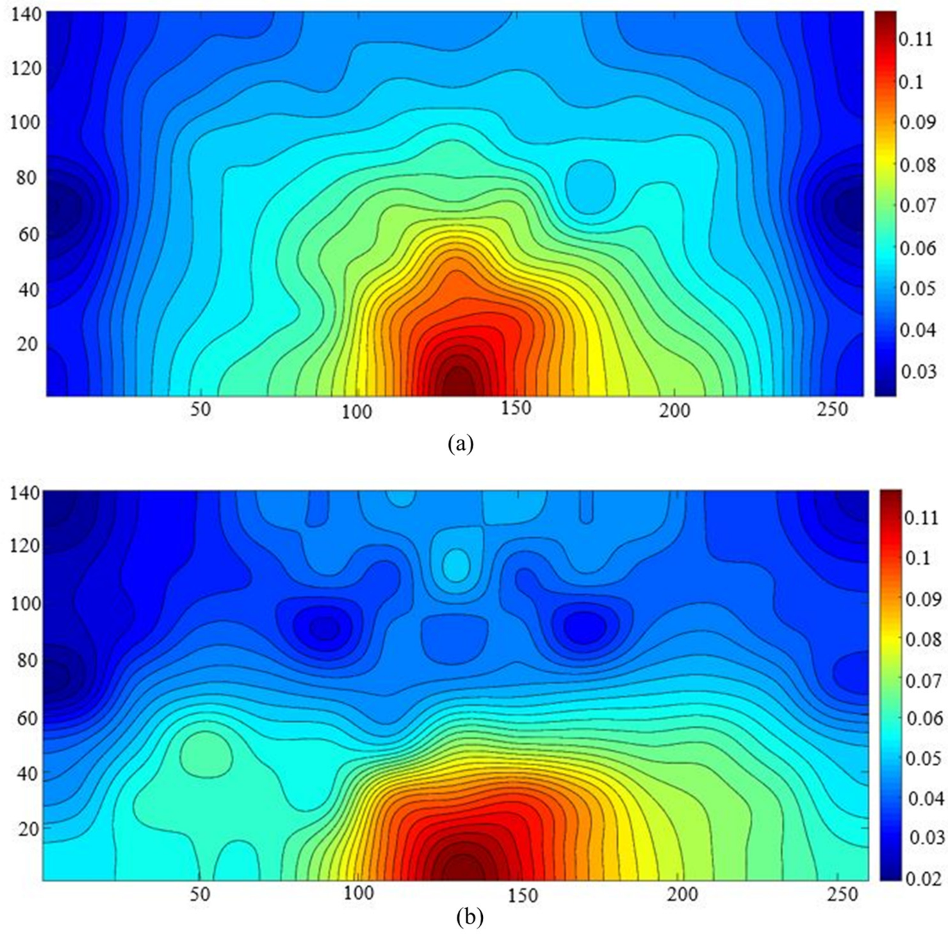


Figure 9. (**a**) Soil field at 6.5 Hz frequency. (**b**) Field where concrete piles at 6.5 Hz frequency are applied.

The magnitude of displacement measured in the soil field at the frequency of 6.5 Hz, shown in Figure 9, is 0.057. In the field where seismic metamaterials formed by the circular array of concrete piles are applied, the displacement magnitude is 0.032. Based on this result, it was seen that the proposed seismic metamaterial field weakened the wave propagation by 56% at a frequency of 6.5 Hz.

With the same method, in Figure 10a, the progress of seismic surface waves at 8.5 Hz frequency on the original ground, and in Figure 10b, the progress of seismic surface waves at a frequency of 8.5 Hz in the field where metamaterials were applied were mapped.

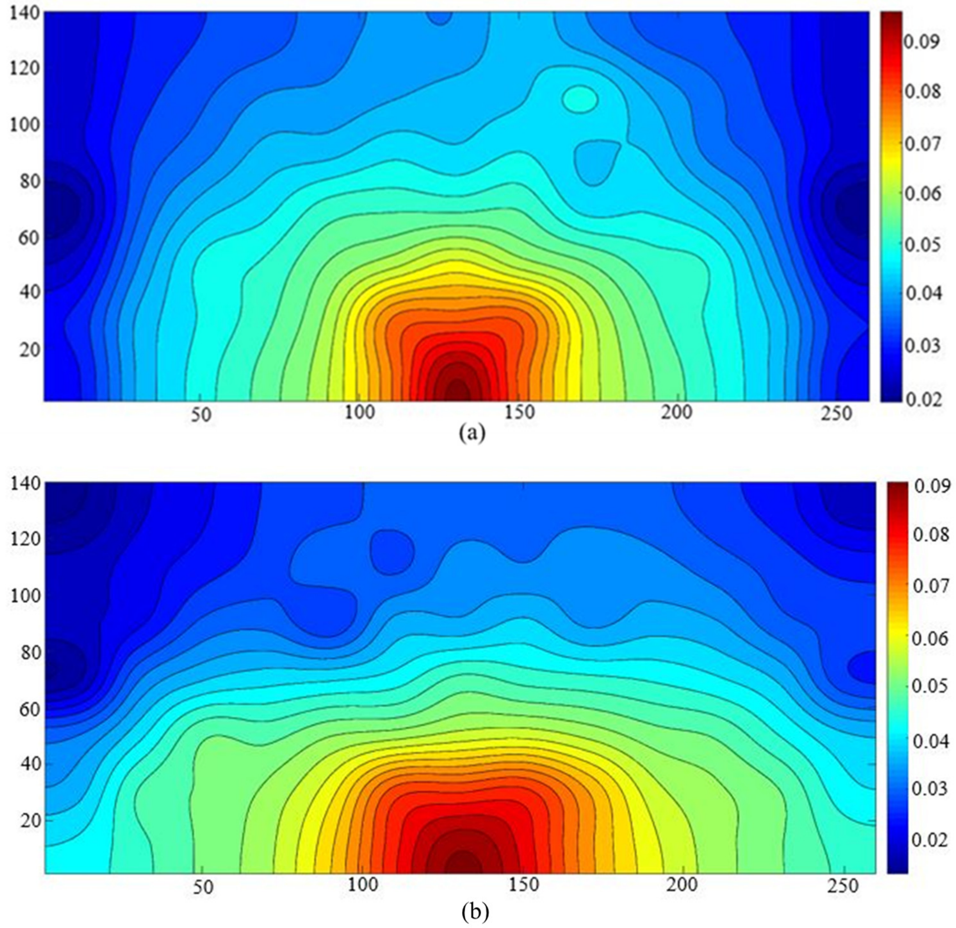


Figure 10. (**a**) Soil field at 8.5 Hz frequency. (**b**) Field where concrete piles at 8.5Hz frequency are applied.

The magnitude of the wave propagation at 8.5 Hz in the soil field given in Figure 10 is 0.049. In the field where seismic metamaterials are applied, the magnitude of the progress is 0.027. According to the result, it reduced the propagation of seismic waves by 54% at a frequency of 8.5 Hz.

Finally, the propagation of seismic surface waves at 14 Hz frequency has been mapped in both fields with and without seismic metamaterials. This mapping is given in Figure 11a,b.

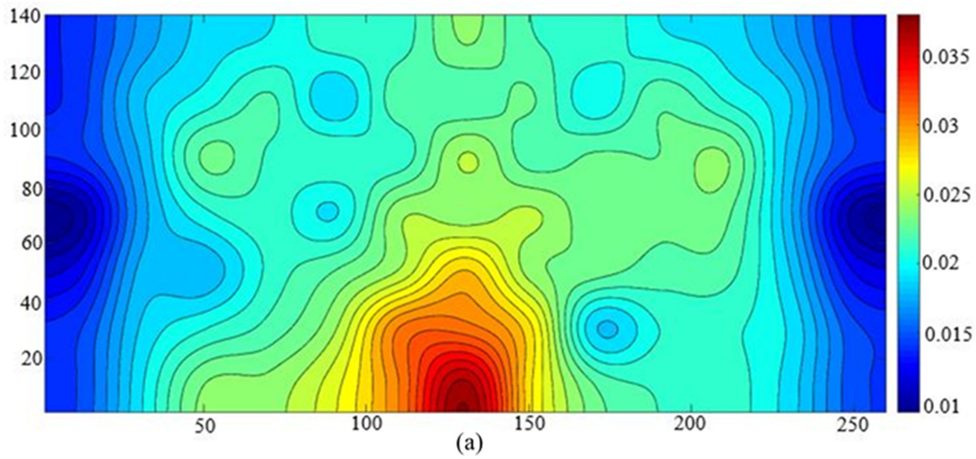
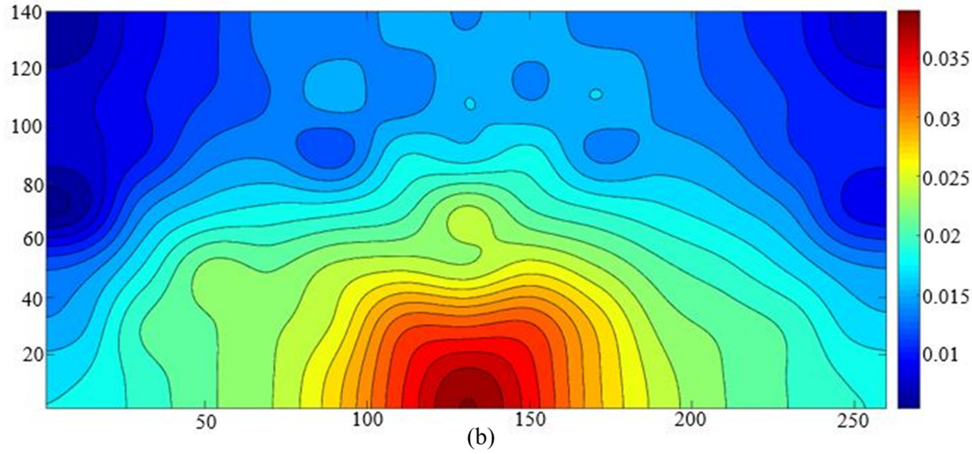


Figure 11. *Cont*.



(b)

Figure 11. (**a**) Soil field at 14 Hz frequency. (**b**) Field where concrete piles at 14 Hz frequency are applied.

As a result of the mapping shown in Figure 11, the magnitude of displacement in the soil field is 0.024. In the field where concrete piles with circular arrays are used, the displacement magnitude is 0.014. When the results of both sites were compared, it was seen that the wave attenuation of the proposed structure was 58%.

5. Conclusions

In this study, a new seismic metamaterial design is proposed to prevent the propagation of seismic surface waves. The proposed design is seismic metamaterials consisting of concrete piles arranged in a circular pattern on the ground. This study was carried out both numerically and experimentally. This study was carried out in the frequency range of 5–15 Hz, which has a very destructive effect and is difficult to prevent. Numerical analysis was performed with FEM based analysis program. Two fields with and without metamaterial were designed, and the boundary load was applied to both fields. The obtained multi-directional transmission losses are simulated, and the wave propagation at the frequencies where transmission losses occur has been shown in both fields. According to numerical analysis results, the propagation of seismic surface waves at 6.5 Hz, 8.5 Hz, and 14 Hz frequencies was prevented using the proposed structure. The experimental field was created with the data obtained from the numerical results, and the concrete piles were placed in a circular manner. The dimensions determined in the numerical analysis were applied exactly in the experimental analysis. A device that generates harmonic waves and accelerometers was used in experimental field studies. The data obtained from the accelerometers were transformed into a frequency domain via FFT transformation. Energy flows have been mapped using the geostatistical interpolation method. As a result of the experimental study, it was observed that the displacement amount of the surface waves was reduced by 56%, 54%, and 58%, respectively, at the frequencies of 6.5 Hz, 8.5 Hz, and 14 Hz. The results obtained from numerical analysis were supported by experimental analysis, and it was observed that seismic metamaterials absorbed seismic surface waves. The results show that this metamaterial-based approach can be applied. The proposed structure is a candidate for seismic shielding.

Author Contributions: Conceptualization, S.K. and Ş.G.K.; methodology, U.K.S.; software, F.Ö.A. and Z.Ö.; validation, M.D., M.Ö. and B.A.M.; formal analysis, M.K.; investigation, M.E.A.; resources, M.T.B.; data curation, S.K.; writing—original draft preparation, Ş.G.K.; writing—review and editing, E.Ü.; visualization, Ş.G.K.; supervision, O.A., M.K., E.Ü. and B.A.M.; project administration, U.K.S. and M.K; funding acquisition, S.K. All authors have read and agreed to the published version of the manuscript.

Funding: We would like to thank the Disaster and Emergency Management Presidency of Turkey (UDAP-Ç-19-21) for their financial support. We would like to thank the Disaster and Emergency Management Presidency of Turkey (UDAP-Ç-19-21) for their financial support.

Data Availability Statement: Not applicable.

Acknowledgments: We would like to thanks Emirullah Mehmetov for identifying the topic of the subject and for his valuable supports.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Prather, D.W.; Shi, S.; Murakowski, J.; Schneider, G.J.; Sharkawy, A.; Chen, C.; Miao, B.; Martin, R. Self-collimation in photonic crystal structures: A new paradigm for applications and device devel-opment. *J. Phys. D Appl. Phys.* **2007**, *40*, 2635. [CrossRef]
2. artínez-Sala, R.; Sancho, J.; Sanchez, J.V.; Gomez, V.; Llinares, J.; Meseguer, F. Sound attenuation by sculpture. *Nature* **1995**, *378*, 241. [CrossRef]
3. Zhu, R.; Liu, X.N.; Hu, G.K.; Sun, C.T.; Huang, G.L. Negative refraction of elastic waves at the deep-subwavelength scale in a single-phase metamaterial. *Nat. Commun.* **2014**, *5*, 5510–5510. [CrossRef]
4. Wen, J.; Shen, H.; Yu, D.; Wen, X. Exploration of amphoteric and negative refraction imaging of acoustic sources via active metamaterials. *Phys. Lett. A* **2013**, *377*, 2199–2206. [CrossRef]
5. Zhao, S.-D.; Wang, Y.-S.; Zhang, C. Acoustic imaging and mirage effects with high transmittance in a periodically perforated metal slab. *J. Appl. Phys.* **2016**, *120*, 194901. [CrossRef]
6. Bückmann, T.; Thiel, M.; Kadic, M.; Schittny, R.; Wegener, M. An elasto-mechanical unfeelability cloak made of pentamode metamaterials. *Nat. Commun.* **2014**, *5*, 4130. [CrossRef]
7. Stenger, N.; Wilhelm, M.; Wegener, M. Experiments on Elastic Cloaking in Thin Plates. *Phys. Rev. Lett.* **2012**, *108*, 014301. [CrossRef] [PubMed]
8. Yan, Y.; Cheng, Z.; Menq, F.; Mo, Y.L.; Tang, Y.; Shi, Z. Three dimensional periodic foundations for base seismic isolation. *Smart Mater. Struct.* **2015**, *24*, 075006. [CrossRef]
9. Gonella, S.; To, A.C.; Liu, W.K. Interplay between phononic bandgaps and piezoelectric microstructures for energy harvesting. *J. Mech. Phys. Solids* **2009**, *57*, 621–633. [CrossRef]
10. Zhang, K.; Zhao, C.; Zhao, P.; Luo, J.; Deng, Z. Wave propagation properties of rotationally symmetric lattices with curved beams. *J. Acoust. Soc. Am.* **2020**, *148*, 1567–1584. [CrossRef]
11. Gao, M.; Shi, Z. A wave guided barrier to isolate antiplane elastic waves. *J. Sound Vib.* **2019**, *443*, 155–166. [CrossRef]
12. Brûlé, S.; Javelaud, E.H.; Enoch, S.; Guenneau, S. Experiments on Seismic Metamaterials: Molding Surface Waves. *Phys. Rev. Lett.* **2014**, *112*, 133901. [CrossRef]
13. Liu, Y.-F.; Huang, J.-K.; Li, Y.-G.; Shi, Z.-F. Trees as large-scale natural metamaterials for low-frequency vibration reduction. *Constr. Build. Mater.* **2019**, *199*, 737–745. [CrossRef]
14. Miniaci, M.; Krushynska, A.; Bosia, F.; Pugno, N.M. Large scale mechanical metamaterials as seismic shields. *New J. Phys.* **2016**, *18*, 083041. [CrossRef]
15. Pu, X.; Shi, Z. A novel method for identifying surface waves in periodic structures. *Soil Dyn. Earthq. Eng.* **2017**, *98*, 67–71. [CrossRef]
16. Chen, Y.; Qian, F.; Scarpa, F.; Zuo, L.; Zhuang, X. Harnessing multi-layered soil to design seismic metamaterials with ultralow frequency band gaps. *Mater. Des.* **2019**, *175*, 107813. [CrossRef]
17. Diatta, A.; Achaoui, Y.; Brule, S.; Enoch, S.; Guenneau, S. Control of Rayleigh-like waves in thick plate Willis metamaterials. *AIP Adv.* **2016**, *6*, 121707. [CrossRef]
18. Palermo, A.; Krödel, S.; Marzani, A.; Daraio, C. Engineered metabarrier as shield from seismic surface waves. *Sci. Rep.* **2016**, *6*, 39356. [CrossRef]
19. Pu, X.; Shi, Z. Surface-wave attenuation by periodic pile barriers in layered soils. *Constr. Build. Mater.* **2018**, *180*, 177–187. [CrossRef]
20. Li, T.; Su, Q.; Kaewunruen, S. Seismic metamaterial barriers for ground vibration mitigation in railways considering the train-track-soil dynamic interactions. *Constr. Build. Mater.* **2020**, *260*, 119936. [CrossRef]
21. Kacin, S.; Ozturk, M.; Sevim, U.K.; Mert, B.A.; Ozer, Z.; Akgol, O.; Unal, E.; Karaaslan, M. Seismic metamaterials for low-frequency mechanical wave attenuation. *Nat. Hazards* **2021**, *107*, 213–229. [CrossRef]
22. Mandal, P.; Somala, S.N. Periodic pile-soil system as a barrier for seismic surface waves. *SN Appl. Sci.* **2020**, *2*, 1184. [CrossRef]