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CURRENT DEVELOPMENTS TOWARDS SEISMIC METAMATERIALS

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ABSTRACT

The origin of metamaterials is in electromagnetics in the end of 19th century. By using the analogy between electromagnetic and elastic waves, the application of metamaterials starts to grow in the field of optics, acoustics and nowadays also in the field of earthquake engineering. Large-scale metamaterials can be used as shield against seismic waves in hazardous area.

There are two main concepts of seismic metamaterials: Bragg scattering and locally resonant metamaterials. The first concept is based on the periodic arrangement of scatterers embedded in a matrix that obey the Bragg's law, which connects the lattice parameter of the system (distance between the centers of the scatterers) with the wavelength. This means that in order the system to distribute the wave energy inside the grid, the periodicity of the system has to be comparable to the wavelength and this link is unfavorable for application in the low-frequency range domain because it would require unpractical, large structures. With introduction of locally resonant structures instead of scatterers this limitation has been overcome. The resonators couple with the propagating waves and pluck their energy at frequencies near their resonance. In this way the periodic constant can be below the wavelengths of interest.

The concept of metamaterials (Bragg scattering and locally resonant metamaterials) can be applied for filtering and manipulation of seismic waves and this opens new possibilities in the earthquake engineering. With specific design (geometry, material) and specific periodicity (periodic scheme and periodic constant), these systems can attenuate the waves before they reach the targeting structures in that way minimizing the damaging effect of the earthquake. This approach is efficient for protecting multiple structures at ones. Current and emerging research activities regarding seismic metamaterials will be summarized in this paper.

Keywords: *Seismic metamaterial; Seismic waves; Resonator; Bandgap; Dispersion curve*

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1. INTRODUCTION

In recent years, seismic metamaterials have received great attention from the scientific community, which has rendered several concepts for their potential engineering use. The trigger for their origin was the analogy between the electromagnetic and elastic waves and the findings in the band theory of solids throughout the concept of photonic crystals followed by the concepts of phononic crystals, sonic crystals and locally resonant metamaterials. Photonic crystals are artificial periodic structures that alter the motion of photons, by analogy, phononic and sonic crystals (fluid medium), affect the motion of acoustic waves. These periodic arrangements obey Bragg's law, which connects the lattice parameter of the system (distance between the centers of the elements) with the wavelength. This means that in order the system to distribute the wave energy inside the grid, the periodicity of the system has to be comparable to the wavelength and this link is unfavorable for application in the low-frequency range domain, that would require unpractical, large structures. With the introduction of locally resonant structures in this kind of periodic systems, in 2000, by Liu and co-workers [1], this limitation was overcome. The resonators couple with the propagating waves and pluck their energy at frequencies near their resonances. In this way the periodic constant can be below the wavelengths of interest. With these findings locally resonant metamaterials were established as artificial periodic structures with unique wave-manipulation performance that arise from the influence of their locally resonant units. The concept of metamaterials (phononic crystals and locally resonant metamaterials) can be applied for filtering and manipulation of the seismic waves that opens new possibilities in earthquake engineering.

2. DISPERSION CURVES

Metamaterials are artificial structures that manifest unique properties that cannot be found in the nature. They have ability to suppress the propagation of free waves in a certain frequency region that is called bandgap. To identify the formation and the width of the bandgap, the dispersion diagrams (band structure) are used. These diagrams show the relation between frequency and wave number and give information about the wave propagation behavior of the metamaterial. There are different techniques for deriving the dispersion curves. Finite element method is the most used. The band structure is obtained by solving the eigenvalue problem that is formed by FEM modelling of the parametric unit cell and by setting Floquet-Bloch periodic boundary conditions. This Floquet-Bloch theorem reduces the study of the infinite periodic system to the analysis of a single unit cell. Although the wavenumber k is unrestricted, it is only necessary to consider the wavenumbers going around the edges of the first Brillouin zone, Figure 1.

In an ideal homogeneous material, a plane propagates non-dispersively with linear relation between frequency and wave number, but for a structured material, bandgaps can occur, Figure 2, where R is the resonance frequency, that form the band-gap.

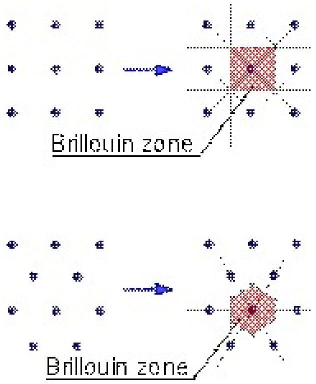

Fig. 1. Brillioun zone.

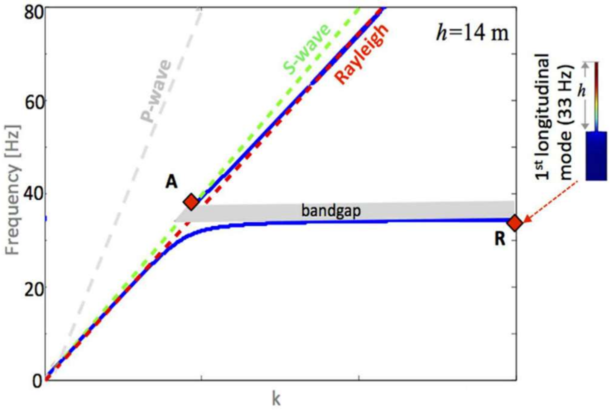

Fig. 2. Dispersion curves, [10].

3. CURRENT DESIGNS OF SEISMIC METAMATERIALS AND EXPERIMENTAL VALIDATION

Seismic waves are more complex than electromagnetic and acoustic waves. They propagate through the Earth in form of body waves (primary – longitudinal waves and secondary - shear waves) and surface waves (elliptically polarized Rayleigh waves and horizontally polarized Love waves and guided modes especially when waves are trapped in sedimentary basins – site effects). Earthquake Engineering is concerned with the horizontal component of bulk and surface waves. Most of the vibrational energy affecting nearby structures is carried by Rayleigh surface wave, therefore, most of the investigations that follows relate precisely to these types of waves.

The surface wavelengths range from a few meters to a few hundred meters corresponding to frequencies from less than 50Hz to a few Hz. These lengths are similar to the sizes of buildings, which would lead to potential building resonance phenomena in the case of earthquakes. For civil engineering applications, seismic isolation should work for frequencies below 10 Hz, that is the range of the first vibration mode of many manmade buildings [14].

To protect the buildings from the earthquake effect, traditionally, different passive, active and hybrid control techniques are used. Regarding some limits and disadvantages of these traditional systems, metamaterials can find suitable use.

Regarding the two concepts: Bragg’s scattering and locally resonant sub-wavelength structures, different designs for seismic metamaterials exists. Usually the periodic structures are buried in the soil, around the building or near the soil-structure's interface, sometimes they can be, at the same time, the fundaments of the building and they can be built as above-surface resonators.

Metamaterials can be one, two and three-dimensional, Figure 3.

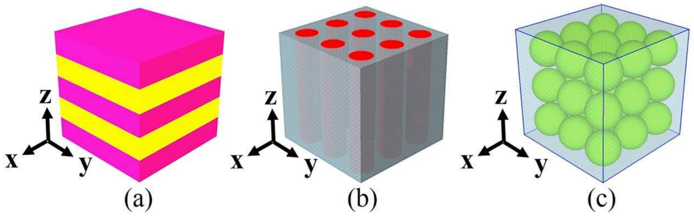

Fig. 3. Types of metamaterials, [4].

Brulé et al. [7] designed and tested large-scale seismic phononic crystal constructed of a mesh of vertical empty inclusions bored in the soil, Figure 4. The source wave (50 Hz) was comparable to the periodicity of the system, not too far off the Bragg’s regime and partial stop-band was created. Unfortunately, 50Hz is still above the most damaging excitations in a common earthquake spectrum.

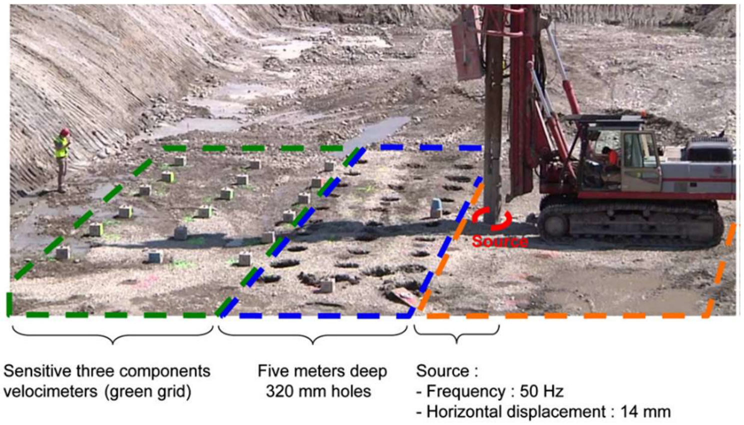

Fig. 4. Large-scale seismic phononic crystal.

Kim and Das [17] suggested Helmholtz-like resonators in order to create a seismic shadow zone and possible solutions to transform elastic wave energy into sound and heat. The resonators were designed like empty boxes with a few side-holes, corresponding to the targeting resonance frequencies of seismic waves, envisioned to be buried in the soil around the building, Figure 5.

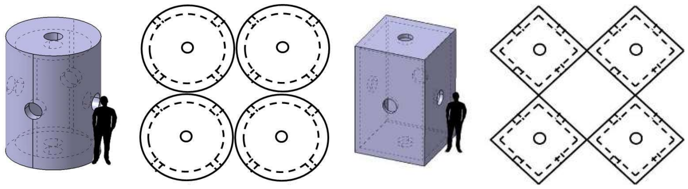

Fig. 5. Configuration of Helmholtz-like resonators buried in the soil.

Qiujiao et al. [2] proposed design of periodic array of different shapes of steel piles embedded in the soil, Figure 6. The first three piles are hollow and the last one is filled with soil/concrete. From the numerical analysis it was obtained the formation of bandgaps for these systems is in the range 8-25 Hz. Geometrical parameters such as the filling fraction, thickness and height of the piles affect the results. In addition, material parameters such as the Young's modulus and mass density of the soil have significant impact on the location and width of the bandgaps.

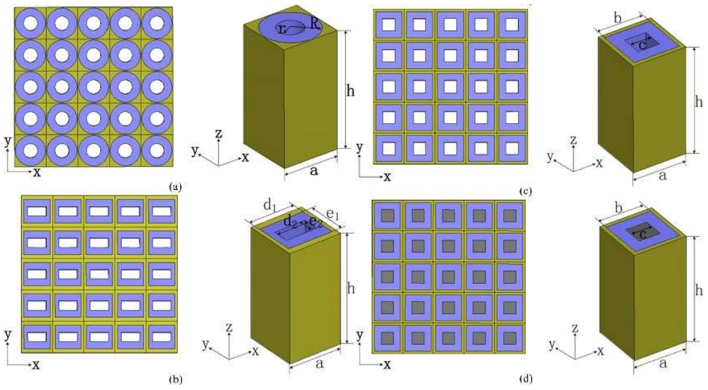

Fig. 6. Periodic array of steel piles embedded in soil.

Miniaci et al. [15] considered different type of seismic metamaterials: a cross-like cavity, a hollow cylinder filled with soil and a locally resonant inclusion made of a soft rubber layer around a heavy core cylinder as inclusions in the soil, Figure 7. Furthermore, the authors investigate the influence of some geometric and mechanical parameters like ratio between the Young's modulus of the inclusion and matrix, cylinder thickness, filling fraction. Depending on the type of the element, different parameter has different influence. The bandgaps for the considered metamaterials are registered in the region bellow 10 Hz.

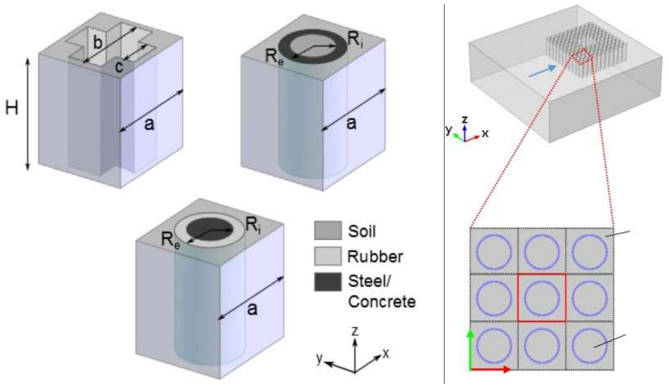

Fig. 7. Metamaterial with different types of inclusions.

Achaoui et al. [8] used cubic array of steel spheres connected to a bulk concrete via steel or rubber ligaments, Figure 8. With modification of the parameter of the ligaments the bandgaps can be tailored and achieve multiple-resonance. This infrastructures, creates large stop band between 8 and 49 Hz, depending upon the ligaments used.

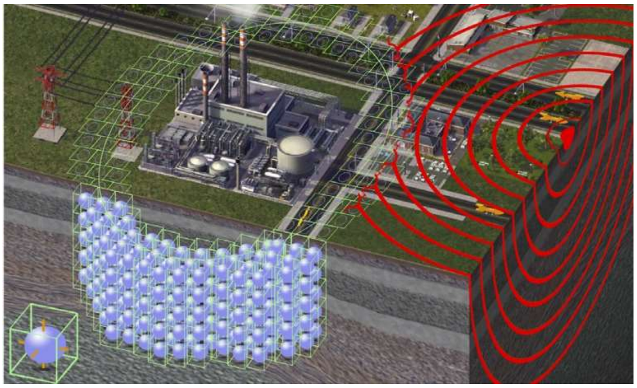

Fig. 8. Array of steel spheres connected to a concrete with ligaments.

Krodel et al. [9] designed array of resonating structures buried around sensitive buildings. The periodical elements were constructed as cylindrical tubes containing a resonator suspended by soft bearings, Figure 9. To obtain broadband attenuation characteristics, each resonator in the array was designed to exhibit a different eigenfrequency by changing the stiffness in the connecting soft springs.

To verify the design, a 1:30 scaled model was build with array of resonators constructed from aluminum tube, containing a resonant mass made of a cylindrical steel rod and connecting springs of polymeric material, build in a soil, Figure 10. The formed bandgaps are in the region bellow 10 Hz.

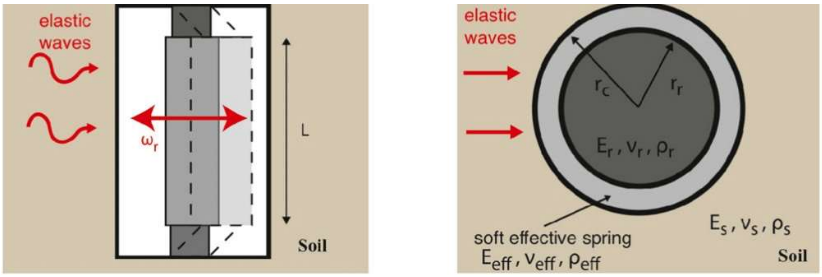

Fig. 9. Cylindrical tubes containing a resonator suspended by soft bearings.

Fig. 10. Experimental setup for array of resonators.

Achaoui et al. [13] proposed periodic array of steel columns, in a layer of soil, that are clamped to underlying bedrock, Figure 11. With this metamaterial, zero-frequency stop-band stretching all the way to 30 Hz is achieved. Some parameters like the filling fraction, periodicity, diferent boundary condition, different shape of the colums are investigated. The coupling of each column to its neighbours via steel plates is shown to be essential for obtaining broad ultra-low frequency stop-bands.

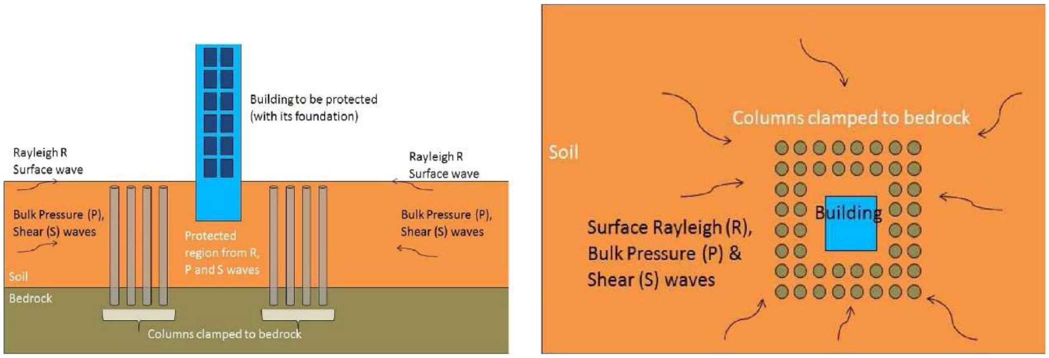

Fig. 11. Array of steel columns in a layer of soil clamped to underlying bedrock

Yan et al. [16] designed three dimensional periodic foundations with steel mass, rubber spring, embeded in the concrete matrix, Figure 12. Theoretical frequency band gaps can be as low as 32.9 Hz. When the input wave falls into the attenuation zones the response of the upper structure could be greatly reduced in comparison to the same structure without the periodic foundation.

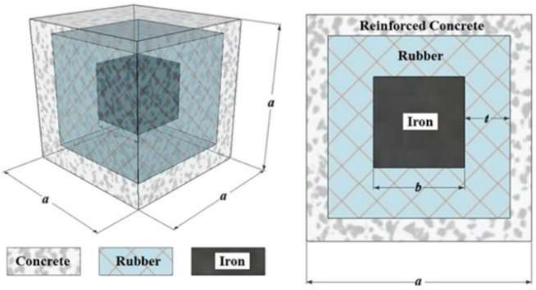

Fig. 12. Unit element of the metamaterial.

Fig. 13. Experimental setup for 1D metamaterial.

Witarto et al. [4] designed and fabricated one-dimensional periodic foundation for small modular reactor using reinforced concrete and synthetic rubber (polyurethane) materials. The experimental test could not be performed at a full-scale size so a scaled model was designed for the study. Different excitations were used: white noise, frequency sweeping, seismic, and harmonic signals. Band gaps between 10-50 Hz were registered with 90% efficiancy of reduction of the acceleration response.

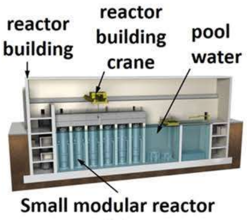

Fig. 14. The original structure.

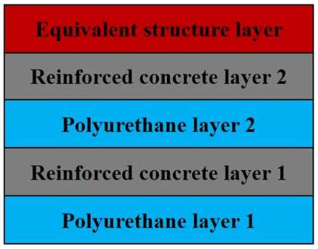

Fig. 15. One-dimensional periodic foundation.

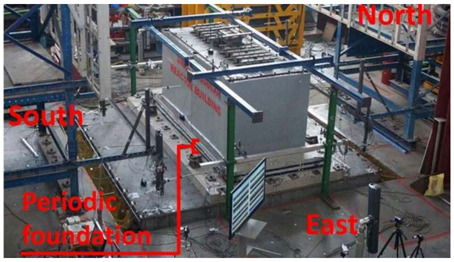

Fig. 16. The test for the scaled model of superstructure and periodic foundations.

Casablanca et al. [3] create composite foundations based on metamaterials - local resonance and a dual-stiffness structure, Figure 17. The foundations are made from reinforced concrete plates that are disconnected with an ultra-low damping surface of layers of steel and Teflon. Each plate has a matrix of nine cylindrical inclusions divided from the host with rubbers. The proposed design was experimentally validated, Figure 18. This system forms a bandgap above the frequency of 4.5 Hz and in the bandgap region it can filter more than 50% of the wave energy.

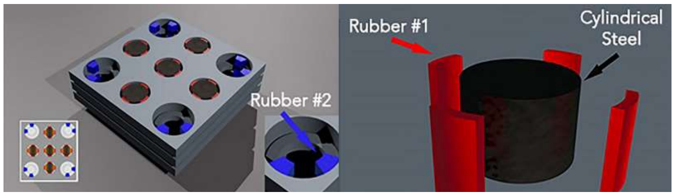

Fig. 17. Composite metamaterial foundation.

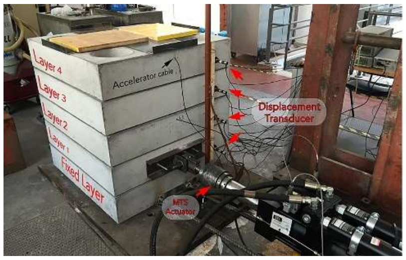

Fig. 18. The experimental set-up for the composite metamaterial foundation.

Colombi et al. [10] designed array of rods placed on an elastic substrate that act like resonators - metawedge, Figure 19. These structures are capable of creating effective band-gaps for surface waves or filters that transform surface waves into bulk waves. The coupling between Rayleigh waves and the first longitudinal mode of the vertical resonators, creates large bandgaps bounded below by frequencies inversely proportional to the resonator height h. Nice results for frequencies around 50 Hz are obtained, but unfortunately higher than the relevant from earthquakes.

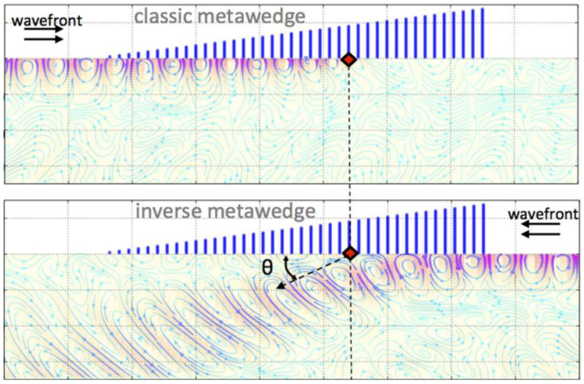

Fig. 19. Array of rods placed on an elastic substrate.

Colombi et al. [12] explore the thesis that the trees from the forests can act like locally resonant metamaterials for Rayleigh surface waves, Figure 20. A geophysical experiment (seismometers-ambient noise) demonstrates that a Rayleigh wave, propagating in soft sedimentary soil at frequencies lower than 150 Hz, experiences strong attenuation, when interacting with a forest, over two separate large frequency bands, but still, at frequencies higher than those primarily present in earthquakes.

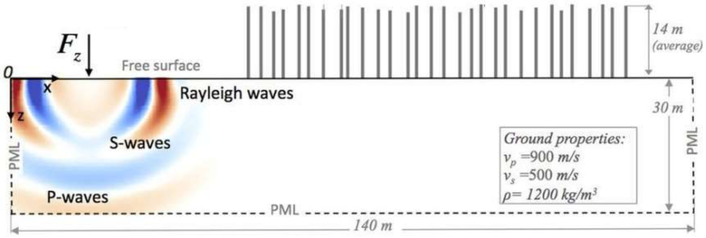

Fig. 20. Trees from forests as resonators.

Brulé et al. [5] explore the idea that a district of buildings could be considered as a set of above-ground resonators. This comes from a fact that the urban patterns reminisce of the geometry of the metamaterials, Figure 21.

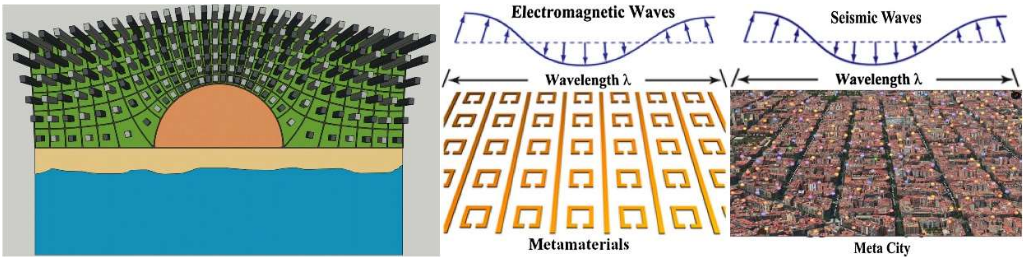

Fig. 21. Urban districts as metamaterials.

4. CONCLUSIONS

Metamaterials has unique properties not found in nature. They can be used for controlling the propagation of seismic waves overcoming the disadvantages and limitations of classical system for seismic protection. Classical SI devices introduces a shift in the natural oscillation periods of the building, have significant fatigue, can produce large horizontal displacements, they ignore the soil-foundation interactions, they are incapable of isolating vertical earthquakes and can act only on one individual structure etc.

With specific design and specific periodicity, seismic metamaterials can attenuate waves before they reach the targeting structures. This approach is efficient for protecting multiple structures at ones. Resonant seismic metamaterials are better than the ones that relly on Bragg's law, but they have narrow bandgap. The width of the bandgap can be broaden [8], [9], but this kind of metamaterials are hard to build. The current designs are promising but still there is needs for further investigation.

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