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The interaction of high intensity seismic rayleigh and rayleigh – lamb waves with structures

A V Ilyashenko[1]*, N F Morozov[2], T R Rashidov[3], V A Bratov[2,4], B MMardonov[5]

[1]Moscow State University of Civil Engineering, 26, Yaroslavskoe highway, Moscow, 129337, Russia
[2]St. Petersburg State University, 7-9, Universitetskaya emb., St. Petersburg, 199034, Russia
[3]Institute of Mechanics and Seismic Stability of Structures, 31, Hadjaeva str., Tashkent, 100125, Uzbekistan
[4]Institute for Problems in Mechanical Engineering RAS, 61, Vasilievsky island, Bolshoy ave., St. Petersburg, 199178, Russia
[5]Tashkent University of Information Technologies, 3, Bogishamol str., Tashkent, 100125, Uzbekistan

E-mail: avi_56@mail.ru

Abstract. The arrivals of high intensity seismic Rayleigh and Rayleigh – Lamb waves to the buildings and structures with a relatively large footprint are analysed. The most frequent cases of the foundation structures' fracture and damage are discussed. The methods for seismic protection from the main types of surface seismic waves, Rayleigh, Rayleigh – Lamb, Love and some more peculiar evanescent (head) waves are considered. The analytical and numerical methods for modelling interaction of building structures with these types of surface seismic waves are analysed. The comparative analysis of the wave dynamic method and the methods based on the spectral decomposition is given.

1. Introduction

Equation Section 1

Rayleigh waves arising in a vicinity of the epicentre of a tectonic earthquake propagate along the Earth surface of the assumed homogeneous and isotropic half space with the phase speed c_R not exceeding the speed of the shear bulk wave c_S [1]:

$$c_R \approx \frac{1.12 + 0.84\nu}{1+\nu} c_S, \qquad c_S = \sqrt{\frac{\mu}{\rho}},$$

where ν is the Poisson's ratio; μ is the corresponding Lame constant; and ρ is the material density. The expression for c_R is known as the Bergman – Viktorov's formula due to its originators; see [2]. A slower Rayleigh wave's velocity than the bulk waves' velocity results in delays of the characteristic peak values in seismograms related to the Rayleigh waves' arrivals [3]. That

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circumstance along with the dominant vertical polarization of Rayleigh waves [1], ensures relatively easy disclosing these waves in seismograms.

However, taking into account the layered structure of the upper crust, makes the analysis more complicated. In a layered half space, the corresponding surface seismic wave, known as the Rayleigh – Lamb wave, becomes dispersive with the noticeable dependence of the phase velocity upon frequency [4, 5]. Such a dispersive property remains inherent for the waves propagating in functionally graded (FG) substrate, see [6, 7]. The following asymptotic formulas provide an upper limit for the phase speed of the Rayleigh – Lamb wave in a stratified half space [4]

$$\lim_{\omega\to 0} c_{R-L}(\omega) = c_{R_0}, \qquad \lim_{\omega\to\infty} c_{R-L}(\omega) = c_{R_{upper}}$$

where c_{R-L} denotes the phase velocity of the dispersive Rayleigh – Lamb wave; ω is the circular frequency; c_{R_0} stands for the undispersed Rayleigh wave's velocity propagating in the bottom homogeneous half space; and $c_{R_{upper}}$ stands for the Rayleigh wave velocity in the uppermost layer. Thus, the limiting velocities of Rayleigh – Lamb waves are restricted by c_{R_0} and $c_{R_{upper}}$ values [5]. In case of FG substrate the situation becomes more complicated; see [7].

Knowing the velocities of these waves, defined by Eqs. and the distance from the epicentre along with the depth of the origin (hypocentre) of the earthquake, it is possible to find the peaks in the seismograms relating to the Rayleigh or Rayleigh – Lamb wave arrivals. That information along with wave polarisation is essential for knowing what types of the seismic waves caused damages to building and structures.

It should be noted also that the intermediate velocities of the Rayleigh – Lamb waves corresponding to finite circular frequencies lie in the range are confined by the limiting values, thus:

$$c_{Rupper} < c_{R-L} < c_{R_0}$$

where a natural geophysical assumption, asserting that the upmost layer is acoustically the softest one is made [1].

2. Case studies

The recent tectonic earthquakes that have occurred in various parts of the world, having been discussed below, led to unexpected destruction of the structures that seemingly had to withstand the earthquakes, the intensity of which does not exceed the calculated value.

2.1. Damages caused by the foundation flexural movements

Figure 1 shows the presidential palace complex in Port-au-Prince before and after the destruction of the earthquake in March 2010.

Figure 1. Presidential palace in Port-au-Prince (left) before and (right) after the distracting earthquake in March 2010

The epicentre of the earthquake was located at a depth of 13 km and is located 25 km from Port-au-Prince. The historic building of the palace complex built in 1912-1920, was constructed from reinforced concrete [8] in accordance with the French design rules of that time. In 2004 the palace complex has been renovated and equipped with seismic protective system [9] mainly composed of the laminated rubber bearings. Analysis of destruction revealed numerous cracks in the foundation constructions of the central part of the complex.

In Japan, in March 2011, an earthquake of magnitude 8.9 points (according to some sources in the earthquake was about 9 by the Richter scale [10]), the epicentre of the earthquake was located at the depth of 13 km and 35 km away from the capital city of Fukushima Prefecture. Despite the fact that the buildings in the area are designed to withstand the earthquakes of intensity nine, quite a lot of buildings and structures were destroyed. Some of the destructions are shown in Figure 2; see [11, 12].

Figure 2. A trunk cracks in foundation slabs: (left) Fukushima NPP and (right) one of industrial building

Figure 3 shows the foundation slab destruction in the commercial building in Niigata Prefecture [13]. The destruction caused by the earthquake in July 2007, the intensity of 6.6 on the Richter scale with its epicentre at a depth of 10 km and the subsequent deep earthquakes of magnitude 6.8 points with hypocentre located at a depth of 350 km and occurred after 13 hours after the first quake. It is believed that major damage produced the first short-focus earthquake in Niigata.

Figure 3. Damage of the foundation slab of the commercial building in Niigata, Japan

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According to the Russian geophysicists [14], enormously large Rayleigh wave along with arrivals of *S* and *P* waves, defeated Ashgabat city in 1948, causing catastrophic damages of civil and industrial buildings and structures see Figure 4.

Figure 4. The devastating Ashgabat earthquake of 1948; according to [14] the earthquake caused "enormously large Rayleigh wave, accompanied by the *S* and *P* waves' arrivals"

2.2. Damages caused by combination of liquefaction, flexural movements and pile damages caused by surface seismic wave arrivals

Destruction associated with unforseen bend of the viaduct columns in San Francisco, is shown in Figure 5, caused by the earthquake intensity of 6.9 points occurred in October 1989. Northern California (Loma Prieta) [15].

Figure 5. Destruction associated with the unforeseen bend of viaduct columns in San Francisco, after Loma Prieta earthquake in 1989

It should also be noted that another very common cause of the bridges' destruction, along with unforeseen bend supporting structure, is the loss of bearing capacity of the soil. Figure 6 shows the bridge damaged by the February 27th earthquake, seen on March 9, 2010 in Concepcion, Chile after the devastating 8.8 earthquake [16].

Figure 6. Bridge collapse caused by the February 27th earthquake is seen on March 9, 2010 in Concepcion, Chile after the devastating 8.8 earthquake

Another example of damages caused by the Rayleigh arrival, and possibly the Rayleigh – Lamb waves due to distinct layered structure of the upper ground structure beneath water level, delivers damage some of the peripheral piles in the foundation of the Rion – Antirion bridge in Southern Greece [17, 18]; see Fig. 7, caused by a strong earthquake in 2008 by magnitude 6.5 of the Richter scale. However, despite the pile damage, the main structural elements safely withstood the sever earthquake.

a. b.

Figure 7. (a) Rion – Antirion bridge, which peripheral piles were damaged by 2008 earthquake of m_w=6.5; (b) metal – concrete piles used to reinforce ambient soil [17, 18]

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Another remark related to the Rion – Antirion bridge construction concerns the design of its foundation, constructed by (1) the pile field used to reinforce soft soil, (b) separation of the upper ends of pile field from the grillage, and (c) use of a pad between bottom of the grillage and reinforced soil to dissipate energy of *S* waves and thus, protect the upper structure of the bridge from diffraction of *S* waves. It should be noted that the pad was made of calibrated stones. Such a solution was also applied at constructing Vasco Da Gama bridge in Lisbon, Portugal.

3. The earthquake's focuses and the seismic waves' principal types

3.1. The earthquakes' focuses

Depending on the source nature the earthquakes are subdivided into three principal classes [19]: (1) the tectonic, i.e. caused by the tectonic plates' interaction; tectonic earthquakes are typically medium and short throw arrangement with the focal depth not exceeding 100 km; note that the tectonic earthquakes occur much more often than other types of earthquakes; (2) igneous or deep-earthquake with a hearth located at depths of 100 - 600 km; (3) volcanic - foci of these earthquakes are usually short throw.

In case of earthquakes tectonic hearth, usually lies on the fracture of the crust and in accordance with the movement of tectonic plates, belongs to one of three major classes [19]: (1) discharge (normal dip-slip); (2) reverse fault (reverse dip-slip); (3) a horizontal shift (strike-slip). In the case of faults related to the first two classes, bulk and surface Rayleigh waves occur in earthquakes; in the latter case the surface Love waves may occur along with bulk waves [19]. The first two classes of tectonic fractures occur more often than fractures of the third class [19]. Some other problems of the seismic sources and waves are considered in [20 – 27].

3.2. Theoretical studies on Rayleigh surface waves

The pioneering Rayleigh work [20] on the surface waves' propagation in harmonic isotropic elastic half-initiated methods of mathematical modelling of surface seismic waves in the earth's crust away from the earthquake source.

Several fundamental results of this paper are of exceptional importance for the seismic waves' mathematical modelling in the distance from the epicentre: (1) the Rayleigh wave is formed of two partial waves that are polarized in the sagittal plane; in the plane formed by the vector normal to the free surface and the wave propagation vector; (2) the speed of propagation of the Rayleigh wave in the isotropic half-space is less than the slow speed (transverse) bulk wave, the speed does not depend on the frequency, i.e., no dispersion; (3) the Rayleigh wave decays exponentially with depth, so that its energy is localized in the surface layer; (4) the vertical component of Rayleigh waves of approximately half times larger than the horizontal component. In the same the article Rayleigh suggested that, these waves can cause severe damages due to their energy localization within a relatively thin layer at the Earth's surface.

3.3. Other types of surface seismic waves

In further studies, the results in the Rayleigh anisotropic medium [22, 23] and complicated environment with properties that account poro-elasticity [24], and the speed deceleration effects and propagation wave damping caused by the viscoelastic properties of the medium [25] were summarized.

It should also be noted that along with the surface seismic waves (Rayleigh, Rayleigh – Lamb, Love) there can be other types of near surface waves (mainly SP evanescent waves) that may be dangerous for both under-surface and the above ground level structures (superstructures).

Summary

The analysis of the destruction caused by the recent earthquakes occurred in different parts of the globe, along with the results of computer simulation shows that the inclusion of the wave nature of seismic actions necessary to adequately assess the safety of design decisions made in the construction of earthquake-resistant.

It appears that taking into account the wave nature is particularly important in the design of structures on soft soils, where the rate of proliferation of all types of seismic waves is small. Naturally, this applies primarily to Rayleigh and Rayleigh – Lamb waves. However, these results can also be applied to arrivals of the evanescent SP waves in some extent, as well as Love and surface SH waves. It should also be mentioned that the short period surface and evanescent waves especially propagated in soft soil formations, can cause a serious danger to both under-surface and above-surface structures, because of relatively small wavelength (for the short period waves) comparable with the footprint of the structure.

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