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SEISMIC LATERAL EARTH PRESSURES ON RETAINING STRUCTURES

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ABSTRACT

Various methods are available to estimate seismic earth pressures on soil retaining structures which cane be grouped to experimental, analytical and numerical methods. 1G model shaking table studies or high-g level centrifuge model shaking studies give some insight on the variation of seismic earth pressures along height of the retaining structure. In the simple analytical methods, M-O method based pseudo-static analysis is extensively used to evaluate seismic earth pressure variation and its probable resultant location. Pseudo-dynamic analysis method based analyses are also developed and are in progress for the same. Besides, these experimental and analytical methods, FEM or FDM based numerical simulations of the retaining structures provide much information on the seismic lateral earth pressure variation. In this paper, the methods available and the procedures to be followed to determine the lateral seismic earth pressures and their recent developments are summarized. Numerical simulations of seismic behavior of cantilever retaining walls was performed using FLAC and the results obtained regarding seismic earth pressures are discussed.

INTRODUCTION

Use of various types of soil retaining structures is tremendously increasing in different infrastructure projects from the last two decades. Being one of the important permanent public structures, earth retaining structures attract more concern for earthquake resistant design. The devastating effects of earthquakes make the problem more significant in the earthquake prone regions. Recent earthquake experiences demand design and construction of public infrastructure works for efficient functioning in such or even more intense hazardous events. Design of these structures to sustain such or stronger quakes may further assure the efficient functioning. Among several aspects to be considered for seismic design, seismic lateral earth pressures are the important parameters for proper designing to sustain during seismic events.

There are various types of retaining structures in practice for different applications. Over the time, the classical gravity retaining walls transitioned into reinforced concrete cantilever walls, with or without buttresses and counter forts. These were then followed by a variety of crib and bin-type walls. All these walls are externally stabilized walls or conventional gravity retaining walls. A paradigm shift occurred in the 1960s with the advent of mechanically stabilized earth (MSE) masses, i.e., reinforced layers of soil allowing for modular construction, which was clearly recognized as being advantageous in most situations (Koerner and Soong 2001) . Several methods are available to estimate seismic earth pressures on soil retaining structures which cane be grouped to experimental, analytical and numerical methods. 1G model shaking table studies or high-g level centrifuge model shaking studies give some insight on the variation of seismic earth pressures along height of the retaining structure. In the simple analytical methods, M-O method based pseudo-static analysis is extensively used to evaluate seismic earth pressure variation and its probable resultant location. Pseudo-dynamic analysis method based analyses are also developed and are in progress for the same. Besides, these experimental and analytical methods, FEM or FDM based numerical simulations of the retaining structures provide much information on the seismic lateral earth pressure variation.

This paper summarizes the methods available and the procedures to be followed to determine the lateral seismic earth pressures and their recent developments. Classical pseudo static and recent pseudo dynamic methods will be discussed along with other methods and the factors influencing the pressure distribution and resultant seismic force are presented. Numerical simulations of seismic behavior of cantilever retaining walls was performed using FLAC and the results obtained regarding seismic earth pressures are discussed.

BACKGROUND

Seismic Earth Pressures on Conventional Retaining Walls

Research on seismically induced lateral earth pressures on retaining structures has received significant attention from many researchers over the years since the pioneering work by Okabe (1926) and Mononobe and Matsuo (1929), which is popularly known as Mononobe-Okabe (M-O) method, following the Great Kanto Earthquake of 1923. The Mononobe-Okabe (M-O) method is based on Coulomb's theory of static soil pressures and was originally developed for gravity walls retaining cohesion less backfill materials. Several researchers have developed a variety of analytical and numerical models or performed various types of experiments to predict/study the dynamic behavior of retaining walls with main focus on the mechanisms behind the development of seismic earth pressures. The classical methods available in practice in evaluating the seismic earth pressures on the retaining walls include: Mononone-Okabe method, known as pseudo-static method (Okabe 1926; Mononobe and Matsuo 1929); Steedman-Zeng method, known as pseudo-dynamic method (Steedman and Zeng 1990); and Wood method (Elastic method) (Wood 1973) etc. (Kramer 1996). Recent works in this area include: Richards et al. (1999); Psarropoulos et al. (2005); Choudhury and Singh (2006); Dakoulas and Gazetas (2008). All the above studies use pseudo-static/pseudo-dynamic analytical methods or Finite element method of discrete system. Some of the experimental studies on seismic behavior of retaining walls or seismic soil structure interaction studies include: Richardson et al. (1977); Koseki et al. (1998); and Ghosh and Madabhushi (2007); Al Atik and Sitar (2008).

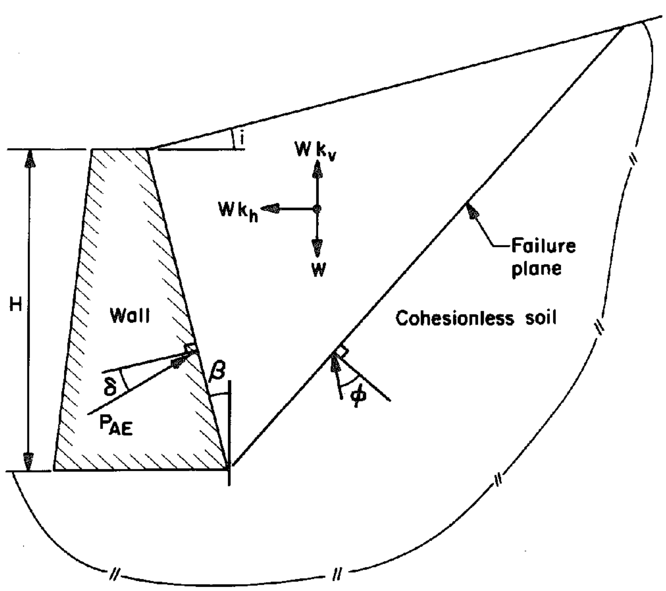

Fig. 1 Forces and geometry used in pseudo-static Mononobe-Okabe seismic analysis (after Wood 1973)

The well-known Mononobe-Okabe (M-O) method is used to calculate dynamic earth forces (Okabe 1926) by using pseudo-static rigid body approach. The method is restricted to a limit-equilibrium approach. A failure surface will be assumed and the earthquake forces will be considered as equivalent static forces using horizontal and vertical acceleration coefficients. Selection of seismic acceleration coefficients depends on the seismicity of the area/locality under consideration. Generally, local standards can be used for this purpose. Selection of geometry of failure surface is another key aspect of this method. A Failure surface can be linear, bi-linear, circular, log-spiral and composite of the above. All the classical works were based on the linear or bi-linear failure surface. Figure 1 shows the typical forces and geometry used in pseudo-static seismic analysis for a linear failure surface. Figure 2 compares the total active earth pressures in normalized form that were obtained for different failure surface (Bathurst et al. 2002). Morrison and Ebeling (1995) adopted composite log spiral and straight line failure and a complete log spiral failure surface to evaluating the dynamic passive earth pressure Recent study using pseudo-static method was by Basha and Babu (2009b) for earthquake resistant design of reinforced soil structure by considering the log spiral failure surface. Figure 3 shows the typical failure surface geometry and various forces acting along the failure surface.

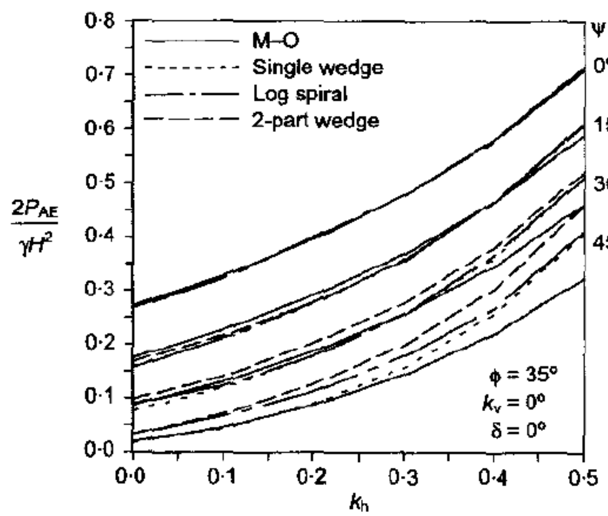

Fig. 2 Comparison of wedge and log-spiral failure surface pseudo static methods (after Bathurst et al. 2002)

In the pseudo-dynamic method, the time and phase change effects, due to vertical propagation of shear and primary waves through the backfill, will be considered along with other seismic input parameters. In this method the finite shear and primary wave velocities are considered for the analysis. However, it is assumed that the shear modulus is constant with depth through the backfill (Steedman and Zeng 1990). Choudhury and Nimbalkar (2005, 2007); Nimbalkar and Choudhury (2007); Basha and Babu (2009a) and Hazarika (2009) used the pseudo-dynamic method to determining the dynamic earth pressures of retaining walls. Kolathyar and Ghosh (2009) adopted pseudo-dynamic method to determine the seismic active earth pressures on a bi-linear wall (Fig. 4). They considered both amplification and the phase angle difference of the acceleration along the height of the wall. Advantages of pseudo-dynamic method over pseudo-static method were discussed by Choudhury et al. (2006). Figures 5 and 6 present the comparison of pseudo-static and pseudo dynamic methods in terms of seismic active pressure distribution along the height of wall and total active earth pressures, in normalized form, respectively.

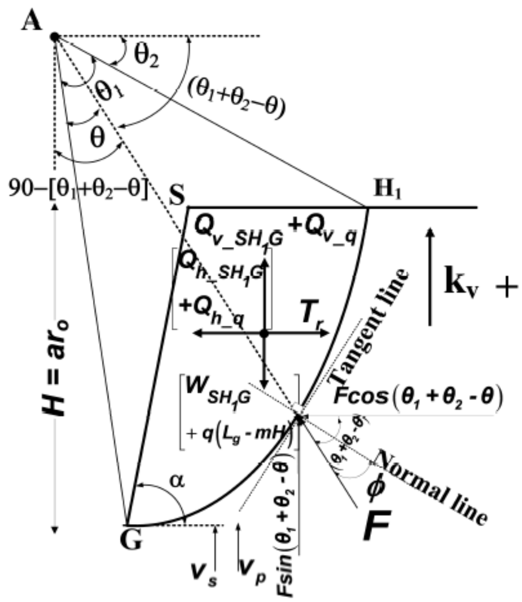

Fig. 3 Geometry and forces considered for log-spiral failure surface (after Basha and Babu 2009b)

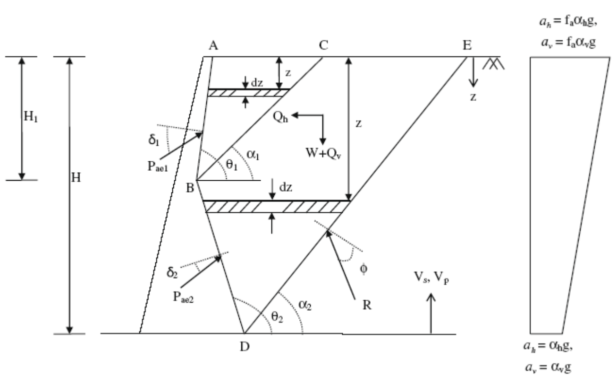

Fig. 4 Geometry and forces considered in pseudo-dynamic method for the analysis of a bilinear wall (after Kolathyar and Ghosh 2009)

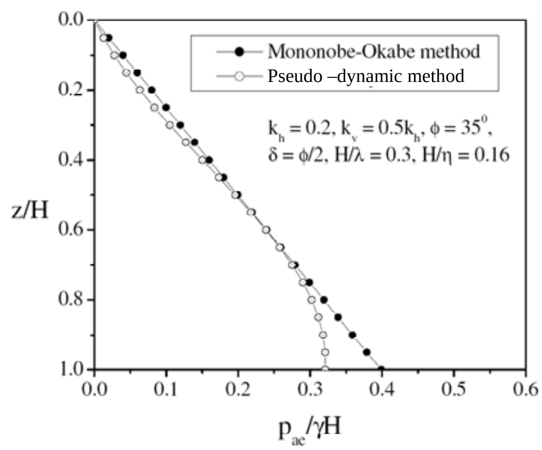

Fig. 5 Comparison of typical results of non dimensional seismic active earth pressure distribution (after Choudhury et al. 2006)

Seismic Earth Pressures on Reinforced Soil Retaining walls

Design and analysis of reinforced soil retaining walls under seismic conditions are, generally, done by the methods that were originally developed for conventional retaining soil structures. To begin with, the pseudo-static or pseudo-dynamic methods will be used to estimate the dynamic earth pressures for the expected seismic acceleration levels. The estimated dynamic earth pressures are then used to determine/design the reinforcement configuration. The number of reinforcement layers, length of reinforcement and the tensile strength of the reinforcement material will be governed by these estimated dynamic pressures. Bathurst and Cai (1995) used pseudo-static method for the seismic analysis of reinforced segmental retaining walls. Basha and Babu (2009b) adopted pseudo-static method for earthquake resistant design of reinforced soil structure by considering the log spiral failure surface. Nimbalkar et al (2006) used pseudo-dynamic method for evaluating seismic stability of reinforced soil wall and presented parametric study.

Besides, the above discussed some analytical methods experimental studies and numerical simulations of model reinforced soil walls provide insight regarding the distribution of seismic earth pressures along the height of wall. Ling et al. (2005) conducted large scale shaking table tests on modular block reinforced soil retaining walls to investigate their seismic behaviour. Figure 6 shows the model configuration used in the study and lateral earth pressures recorded at various stages of shaking. They concluded that the pressure distribution was not consistent for all three walls and it was hard to conclusively infer the shape of pressure distribution during shaking. Latha and Krishna (2008) investigated the seismic response of reinforced soil retaining wall models using shaking table model tests. Figure 7 shows the typical dynamic lateral incremental pressures obtained in different model tests. Gazetas et al. (2004) performed finite element numerical simulations of seismic behaviour of various types of flexible retaining structures (Fig. 8).

Discussion

Several researchers presented different methods to predict the seismic earth pressure on variety of retaining walls like rigid

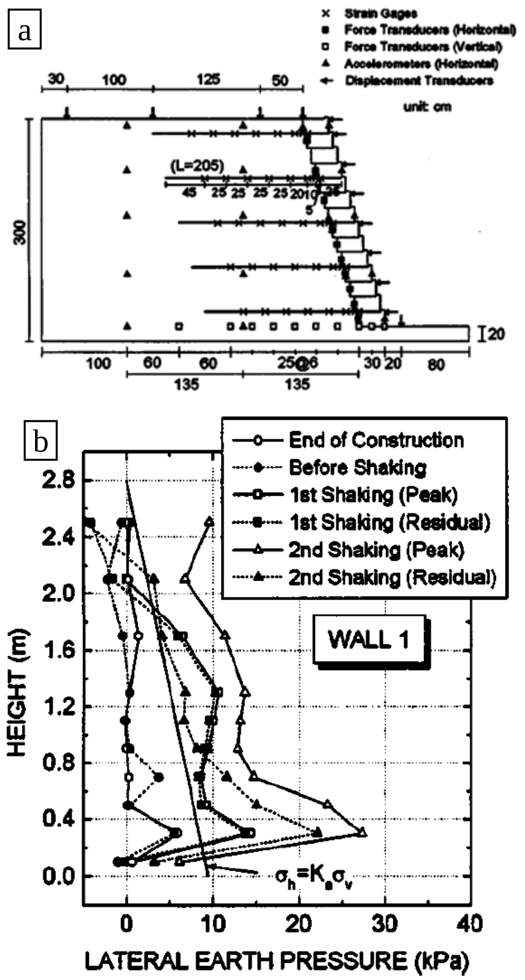

Fig. 6 Experimental studies a) Model configuration b) Lateral earth pressure distribution (after Ling et al. 2005)

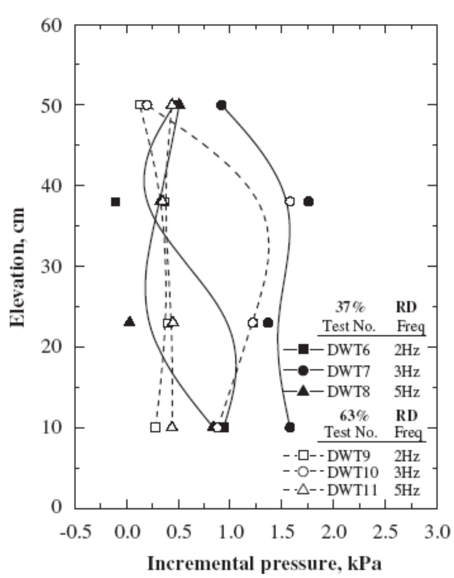

Fig. 7 Incremental pressures recorded in various tests (after Latha and Krishna 2008)

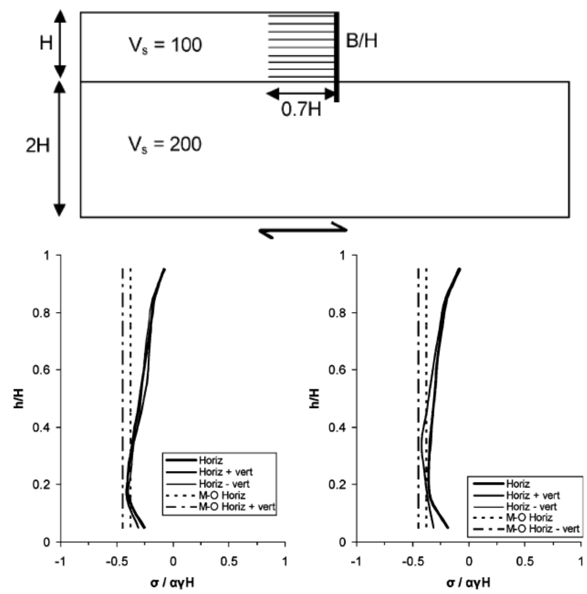

Fig. 8 Numerical studies by Gazetas et al. (2004)

walls, flexible walls and reinforced soil walls. Moreover, there is no clear guideline regarding the distribution pattern and the point of resultant application consideration. There is sure need for further research in this challenging and interesting topic.

NUMERICAL SIMULATIONS OF CANTILEVER RETAINING WALLS

Numerical modeling of cantilever retaining walls is performed to study the seismic behavior of cantilever retaining walls and to get insight about the seismic earth pressures variation and their dependence on different wall parameters. Two dimensional numerical models were developed using FLAC. FLAC is an explicit, dynamic, finite difference code based on the Lagrangian calculation scheme. Various built-in constitutive models are available in the FLAC and can be modified by the user with minimal effort through FISH programming code. FLAC also provides some built-in structural elements, which can be used as reinforcement or structural supports, and interface elements as well (Itasca, 2008).

Geometry of the cantilever wall section considered for the present study is shown in Fig. 9. A cantilever wall with total height of 4.75 m including 0.75 m embedment depth and 0.5 m thick was considered with back fill soil length of 8.5m. A stiff foundation soil of 2.0 m thick was considered in the numerical modeling. The foundation soil and the wall section was modeled as elastic material with typical rock and cement concrete properties, respectively. The back fill soil was modeled as Mohr-Coulomb material with typical properties corresponding to uniform-coarse sand (16 kN/m^3 of unit weight; Elastic modulus: 25 MPa; Poisson's ratio: 0.25; and friction angle of 34°). Perfect rough contacts were considered between the cantilever wall section and foundation soil and backfill soil. Hence, no interface elements were considered in the present model. The model was solved for static equilibrium prior to the application of dynamic load. The dynamic load was applied in the form of velocity corresponding to sinusoidal excitation of targeted acceleration and frequency. Each numerical model was subjected to 10 cycles of sinusoidal excitation of different acceleration an frequency levels. Acceleration levels with in the range of 0.1g to 0.5g and frequency levels of 2Hz to 10 Hz were considered. Results obtained at the end of dynamic excitation with different excitation levels were compared and discussed.

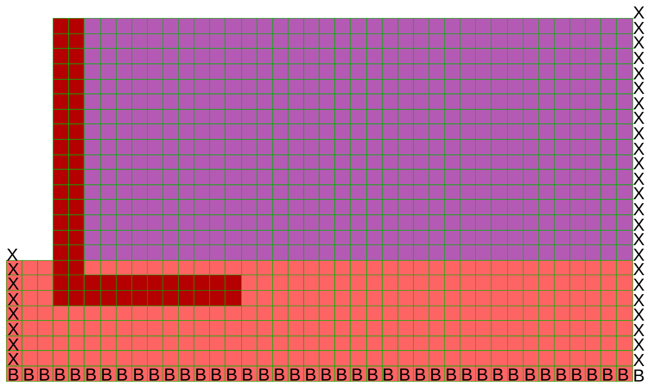

Fig. 9 Typical model cantilever retaining wall considered for the numerical simulation

Results

Horizontal earth pressures acting on the wall were observed and compared. The results were presented in the normalized form: normalized elevation vs normalized horizontal pressure. Elevation, *z*, from the ground surface was normalized with total height, *H*, of the wall. Horizontal pressure, σ_h, at any elevations was normalized by γH, γ being the unit weight of the back fill soil. Figure 10 shows the comparison of the lateral earth pressures obtained from the classical soil mechanics theory ($K_a\gamma z$, where K_a is the active earth pressure coefficient and the result obtained from the numerical simulation. Fair comparison among these two results justifies the validation of the numerical model.

Figure 11 presents the variation of seismic earth pressures at the end of 10 cycles of sinusoidal dynamic excitation obtained for different horizontal acceleration levels. The accelerations varied from 0.1 g to 0.5g with same frequency of 3 Hz. From the figure it can be observed that the seismic lateral earth pressures are very significantly affected by the acceleration level. Further it is noticed that the variation of the earth pressures along the height of the wall and probable resultant location also changing with the acceleration level.

Figure 12 shows the effect of the frequency of the excitation on the variation of seismic lateral earth pressures along the height of the wall. Frequency of the excitation was changed from 2 Hz to 10 Hz at 0.2 g acceleration. From the figure it can be mentioned that the frequency of the excitation has very significant effect on the magnitude of the earth pressures and its trend in variation along the height of the wall. Among the different frequency levels testes, 2 Hz and 7 Hz frequency levels resulted higher seismic lateral earth pressures which are very significant even at the same level of acceleration comparing to other levels of frequency.

Effect of the damping on seismic lateral earth pressures can be observed from the Fig. 13. The damping levels are varied from 0% to 15 % with the same dynamic excitation of 0.2 g acceleration at 3 Hz frequency. Among the range of damping values varied the change in the seismic lateral earth pressures is not very significant.

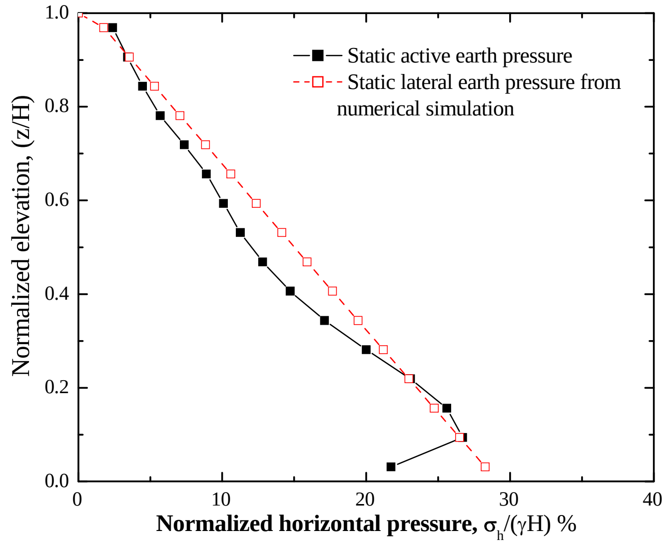

Fig. 10 Comparison of static lateral earth pressures for validation

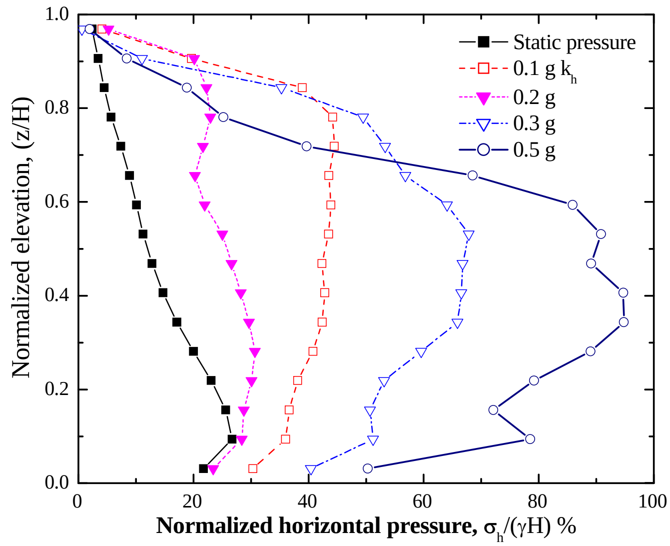

Fig. 11 Seismic earth pressures at different acceleration levels

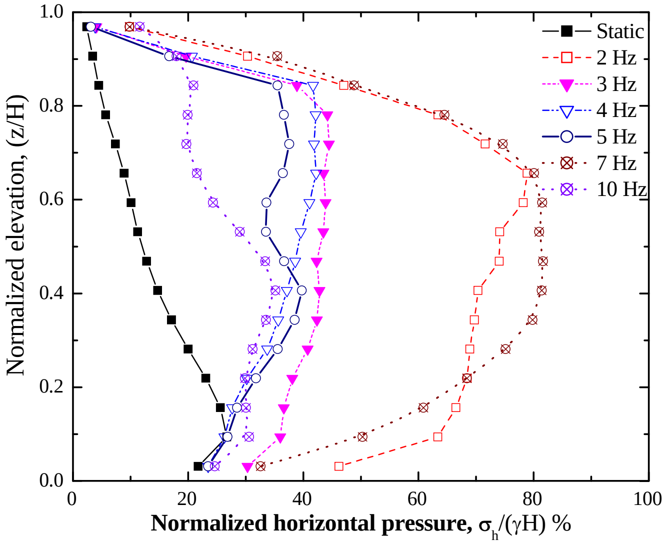

Fig. 12 Seismic earth pressures at different frequency levels

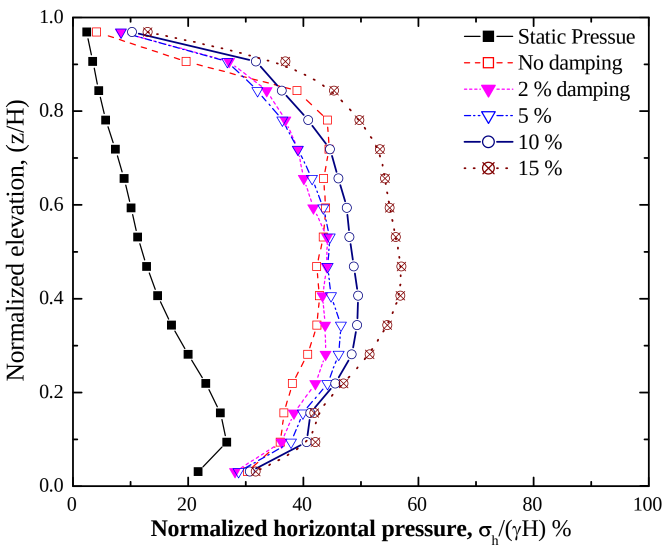

Fig. 13 Seismic earth pressures at different damping levels

CONCLUSIONS

Several methods are in practice to predict the seismic earth pressure on variety of retaining walls like rigid walls, flexible walls and reinforced soil walls. The methods available to determine the lateral seismic earth pressures and their recent developments are briefly summarized for both the conventional and reinforced soil retaining structures. Numerical simulations of seismic behavior of cantilever retaining walls were performed using FLAC and the results obtained regarding seismic earth pressures are discussed with variations in the acceleration and frequency levels and the damping property of the material.

The numerical model developed in the present study is very basic in nature and need further refinement in terms of the interface between the wall and neighboring soil material and adopting advanced constitute model like hyperbolic model for modeling the backfill material. Hence, the results discussed here are of only qualitative and provide comparison with the variation of acceleration and frequency of excitation and damping of the backfill material.

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