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# Effect of seismic wave velocity on the dynamic response of multi-story structures on elastic foundation

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ABSTRACT

Traveling wave effects are generally considered with three main cases: (*i*) Wave passage effect that results with time delay in earthquake motion. (*ii*) incoherence effect which is defined as loss of coherency in the ground motion due to the reflection and refraction of waves, and (*iii*) local site effects. For multi-story structures whose supports are close to each other, the incoherence and local site effect may be omitted. In this case, traveling waves result only in a pure time delay in the earthquake motion (wave passage effect). Due to the wave passage effect of vertical and/or horizontal ground motion, the superstructure needs to be analyzed by multi-support excitation. Raft foundations cannot constrain vertical deformations and/or rotations, but they cause a diaphragm effect in the horizontal direction which results in uniform excitation. In this study, the effect of vertical earthquake motions onto multi-story buildings on elastic soil is investigated. Multi support excitation is considered by using displacement loading, which defines the equivalent seismic loads in terms of the ground displacement. According to the performed simulations of the selected structures, it is shown that structural height has a direct influence that results in member force magnifications with slow traveling wave effect. Among these, the ground floor column axial forces are most affected.

## 1. Introduction

Dynamic response analysis of structures subjected to multi-support excitation has an increased interest in the earthquake engineering society. Multi support excitation is a well-formed analysis tool that is widely used in earthquake response analysis of structures with large footsteps. Past research showed that seismic waves passing through the ground may cause considerable change in the response of structures, if the supports are far apart. The change in the earthquake wave is not only considered with a time delay, but also should contain the path attenuation, reflection and refraction effects. The local site effect is also prominent for this phenomenon due to the non-homogenous nature of the soil medium. In the literature, many researchers paid attention to local soil effect in multi-support excitation [1–9]. Cui and Gao [10] have investigated the traveling wave effect in long-span cable stayed bridges, and they concluded that long-span cable-stayed bridges not only need to consider traveling wave effect, but also study on refraction, reflection and scattering of the waves in different medium of the underlying soil. Jihong et al. [11] presented a simplified method to estimate multi-support excitation responses. In their study, the multi-support response spectrum was constructed by modification and extension of the existing response spectrum method under uniform excitation. Wang et al. [12] investigated the effect of apparent wave velocity on a long span suspension bridge and determined the design characteristics of long span bridges under traveling earthquake wave effect. Hızal and Turan [13] have investigated the seismic behavior of a cable stayed bridge subjected to different support displacements and concluded that the traveling wave results in a pure time delay in the base shear force response.

In the literature, only a few studies have been observed that deal with traveling wave effect in multi-story frames. Rambabu and Allam [14] investigated the effect of apparent wave velocity in open frame structures with soil structure interaction. Allam [15] investigated the same case by a filtered white noise function to model the local site effects such as reflections and refractions of earthquake waves in soil medium. In these studies, only the horizontal component of the ground motion was considered, and a change is observed in the dynamic response with small time delays in the ground acceleration. This observation may be reliable for the structures whose supports are able to move independently from each other. In many cases, multiple support excitation does not seem feasible to implement in multi-story buildings since they are built on raft foundations in which the supports are not able to move independently. However, the time delay in the vertical ground motion may cause a valuable change in the dynamic response of

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the structure since the foundation beam/or slab cannot be assumed infinitely rigid in the vertical direction. In addition, most of the conducted research that is available in the literature considers both incoherence effect and local site conditions in multi-support analysis. These effects, however, may be neglected if the supports of the structure are adequately close to each other. In this case, only the wave passage effect which comes up with time delay in earthquake motion will be prominent in multi-support excitation.

In multi support analysis, pseudo-static displacement effects have an important role on the dynamic responses. For this reason, a transformation is required between the relative and absolute dynamic displacements. The displacement loading which defines the general equation of motion with absolute coordinates appears to be more practical when compared to the conventional acceleration loading. This fact can be explained by the very sensitive behavior of acceleration records to little amplitude changes. For example, a small offset in the acceleration values may result in linearly increasing velocity and quadratic increasing displacements which may easily be overseen. To the contrary, displacement loading is robust with respect to amplitude changes. As a result, when multiple constraints need to be defined by different motions, displacement loading should be the preferred one, which is also validated by other researchers [16–18] and regulated in different software [19,20]. In modal analysis of displacement loading, higher modes become dominant because of the pseudo-static effects and it may require nearly all modes to obtain a reliable dynamic response. Tsai [17] summarized the general modal analysis procedure of displacement loading and proposed a static correction method for the consideration of higher mode effects. Hızal and Turan [21] pointed out pseudo static effects in the base shear force response of cable stayed bridges and comprehended on the physical meaning of the static correction method for modal analysis.

A study on traveling wave effect of vertical ground motion in multistory structures with soil structure interaction is not found in the reviewed literature. This study sheds light on the effect of the apparent wave velocity on the dynamic member forces is investigated by using finite element models of three soil-structure interaction systems.

## 2. Statement of the problem

As the earthquake wave velocity is low, a time delay effect can be seen at the support of the structure. To illustrate the problem, one frequency component of an earthquake motion is considered. Fig. 1 shows an example in which a single sine wave type vertical ground motion is propagating from left to right. At the extreme case, the left and right ends may deform in opposite directions with maximum amplitude. This situation is possible when the time delay is equal to half of the period of the sinusoidal ground motion, and the wave velocity should be equal to the raft foundation length divided by the time delay.

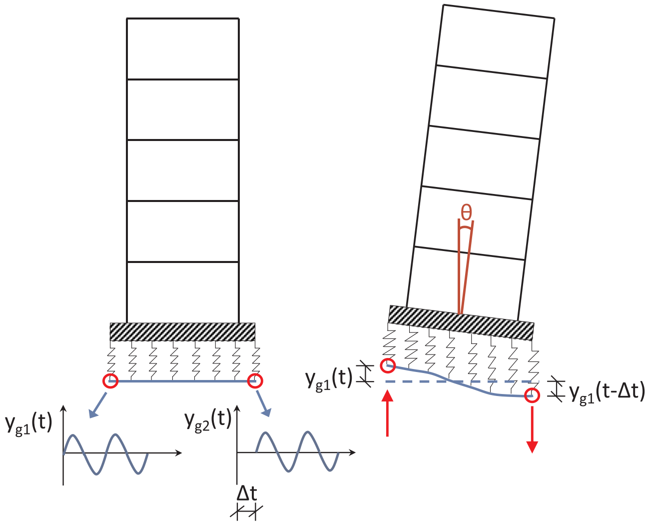

**Fig. 1.** Schematically representation of the traveling vertical ground motion effect.

$$V=\frac{L}{\Delta t}=\frac{2L}{T_{wave}} \tag{1}$$

As an example, for a foundation $L = 30$ m, and wave velocity $V = 100$ m/sec, the time delay would be 0.3 s. Then, the extreme case would be seen for a sine wave with a period $T_{wave} = 0.6$ s. The non-extreme cases in which the sine wave period, and/or the wave velocity is different may also cause rotation of the raft foundation.

The above-mentioned response stems from the earthquake wave characteristic and is not related to the inertial overturning effect of the superstructure with soil structure interaction. The two mechanisms, however, may interact leading to a resonance effect.

The ground motion that is investigated in this study is considered to result from surface waves which cause lateral, vertical, and rotational motion. The lateral and vertical motions are implemented in the base of the springs representing the soil medium. The rotational motion of a point on the ground surface (due to Rayleigh waves), however, is not considered. Instead, the modeled springs are placed close to each other so that a relative vertical displacement obtained from earthquake records may be considered as a rotational motion of the ground. The differential vertical ground displacements occur due to the ground motion traveling underneath the foundation. The ground motion at a point is a composition of P, S, and surface waves (e.g. Rayleigh wave) which according to Kramer (1996) have different propagation speeds. Fig. 2 shows the wave speed ratio to shear wave velocity, $V_s$, with respect to Poisson's ratio, μ, of the soil medium. The shear wave velocity is calculated as

$$V_s=\sqrt{\frac{G}{\rho}} \tag{2}$$

where G = shear modulus and ρ = unit mass of soil. For $\mu = 0$, the speed of Rayleigh waves is 20% less than the shear wave velocity and they are equal when $\mu = 0.5$, which corresponds to clay type soil. The P wave velocity exponentially increases as μ increases. The expected ground motion due to P waves, however, are not expected to be of important magnitude when compared to the S and surface wave effects. For this study, a differentiation of the Rayleigh and shear waves is not performed and their propagating velocity is assumed to be identical.

In the horizontal direction, the ground will experience different motion underneath the foundation. Raft foundations, however, are rigid and do not elongate. Therefore, a uniform lateral motion is expected in

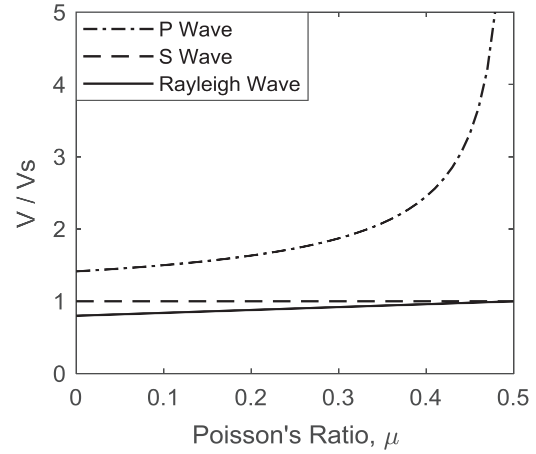

**Fig. 2.** Variations of seismic wave propagation speeds versus Poisson's ratio [22].