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Simplified methods in Soil Dynamics

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ABSTRACT

After a brief description of the main characteristics that define Soil Dynamics and its engineering applications, the role of Simplified Methods is discussed. Despite the current wide availability of powerful computer simulations, it is concluded that Simplified Methods will continue to play an important role in Soil Dynamics as they do in the rest of Geotechnical Engineering. Simplified Methods allow the engineer to conduct calculations by hand or with a minimum computational effort, including parametric variations. In the process, the engineer has the possibility to develop a feel for the physical meaning and relative importance of the various factors, with more personal control of calculations and decisions including use of engineering judgment as needed. A list of simplified procedures proposed by the author is provided, covering systems that range from the free field and earth dams to shallow and deep foundations, subjected to excitations that include both seismic shaking and machine vibrations. Basic understanding of the basic theory and simplifications behind the simplified procedure can be very helpful to engineers, including Dynamics and Wave Propagation concepts. Some of this understanding is developed in the paper, with focus on shallow machine foundations and other dynamic soil–structure interaction applications.

The Lecture concentrates on shallow machine foundations on a half-space subjected to dynamic loads in any of the six degrees of freedom of the foundation, and the Simplified Methods that have been proposed over the years to characterize the corresponding equivalent soil springs and dashpots. This includes both frequency-dependent and frequency-independent springs and dashpots. It started with the circular surface foundation which was studied over much of the 20th Century, until the breakthroughs by Lysmer and others in 1966–1971, and continued with the cases of surface and embedded foundations of arbitrary shape that culminated in the two summary publications by Gazetas in 1990 and 1991. The development of these simplified equivalent springs and dashpots for both surface and embedded foundations of arbitrary shape is discussed in some detail, including the contribution of the author in the early part of the process.

1. Introduction

It is a great honor for me to be asked to present the Twenty-first *Nabor Carrillo* Lecture, and to be associated this way with Dr. Nabor Carrillo and his many accomplishments. It is also an honor to be associated with the people who have been Carrillo Lecturers over the years and who have made such gigantic contributions to the geotechnical field. Let me add that I am especially proud to follow two Carrillo Lecturers who were also my professors and who had an extraordinary influence over my career. One of them is Tamez [68], who directed my Master Thesis on Sand Liquefaction During Earthquakes at the UNAM in México City many years ago, and who inspired me to specialize in Soil Dynamics and Earthquake Engineering. The other is Whitman [71], who unfortunately died this year, and who directed my Doctoral Thesis at MIT, also on Soil Dynamics. I would not be here without them, both of them were great teachers and mentors to me, and this is a good opportunity to say Thanks to both of them.

Finally, let me say that it is just a pleasure to be once again back in México, where I have so many friends and colleagues. One of them is Prof. Eulalio Juárez Badillo, who together with Prof. Alfonso Rico taught me so well the ABC of soil mechanics during my graduate studies at the División de Posgrado of UNAM.

The theme of my presentation today is the Simplified Methods in Soil Dynamics. This immediately poses two questions: What is Soil Dynamics, and what kind of Simplified Methods are we talking about?

In his Fifteenth Carrillo Lecture, Whitman [71] defined problems in Soil Dynamics as those in which the inertia force of the soil plays a significant role. I would add to this a few other characteristics common to most Soil Dynamics problems: (i) the loads tend to act much faster than in typical soil mechanics

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problems; (ii) the loads change direction periodically because they are associated with vibrations, and therefore produce cyclic rather than monotonic stresses and strains in the soil; and finally (iii) many of the problems that worry us most in Soil Dynamics, are associated with shear strains in the soil which are much smaller than those we are familiar with in regular soils testing, like 0.1%, or 0.01% or even smaller.

Table 1, reproduced from that same Carrillo Lecture by Whitman, lists some of the most important practical applications of Soil Dynamics. It includes the problems of machine foundations, earthquake engineering, pile driving, techniques used to compact sands in the field, problems of ocean wave loading of offshore structures, etc.

Let me say a couple of things, first about earthquakes and then about machine foundations, so as to give a better idea of some of the complexities of analyzing Soil Dynamics systems and the need for Simplified Solutions. Fig. 1 shows the amplification of the earthquake waves by the soft clay in Mexico City in the 1985 earthquake, which caused a lot of damage to buildings and killed thousands of people, and which has been studied in detail by a number of Mexican engineers.

The curves in the figure are acceleration response spectra, and they measure the maximum lateral force experienced by a building that behaves elastically during the earthquake in number of accelerations of gravity, or g's, versus the period of the building in seconds. In 1985 essentially all collapsed buildings and fatalities were on soil and not on rock. This happened because the earthquake inertia forces on these assumed elastic buildings due to the shaking, were much greater on soil than on rock, as much as ten times higher, as can seen in the figure by how much bigger is the recorded acceleration spectrum on soil at the building of the Secretaría de Comunicaciones y Transportes (SCT), compared with the same recorded spectrum on rock at the University (UNAM) [11,63,66].

Table 1
Applications of Soil Dynamics [71].

Applications/Aplicaciones

- Machine foundations/*Cimentaciones de Maquinaria*
- Earthquakes/*Temblores*
- Pile driving/*Hincado de pilotes*
- Dynamic compaction/*Compactación dinamica*
- Vibratory compaction/*Compactación por vibración*
- Offshore structures/*Estructuras fuera de costa*
- Traffic vibrations/*Vibraciones debidas al tránsito*
- Weapons effects/*Efecto de proyectiles*
- Exploration/*Exploración*
- Blasting/*Explosiones*
- Missile penetration/*Penetración de misiles*
- Equipment isolation/*Aislamiento de equipos*

The way we analyze the earthquake amplification by the soil in a situation like this, is by feeding into a computer program the motions on the rock, together with a dynamic profile of the soil which must include for each layer properties like the density of the soil, the shear wave velocity V_s, and the internal damping. Then the computer program will calculate the motion on top of the soil. This computer program is relatively complex, becoming even more so if you include 2D and 3D effects due to the presence of hills nearby, or the effect of inclined or irregular soil layers.

The shear wave velocity of the Mexico City clay is quite low, of the order of 70 or 80 m/s, and this low shear wave velocity played a significant role in the large site amplification during the 1985 earthquake. Shear wave velocity is by far the most important soil property needed for these earthquake calculations. The shear wave velocities for most soils in the world range from about 60 to 800 m/s; a factor of about fifteen. It turns out that to know with some precision the value of this parameter for your particular problem is also key to the analysis of most Soil Dynamics problems, not only earthquake soil amplification. In fact, shear wave velocity is clearly the single most important soil parameter in the whole of Soil Dynamics, as important as soil shear strength is for slope stability calculations.

Fig. 2 illustrates another important category of Soil Dynamics problems: machine foundations, where a structure on a shallow or deep foundation is excited by dynamic loads above ground, typically due to unbalanced inertia forces caused by operation of industrial machinery. The loads can be complicated, ranging from sinusoidal forces having one amplitude, direction and frequency, to very irregular loads and moments, and combinations of vertical, horizontal, rocking and torsional vibrations. Other parameters that add complication to the solution include the type, geometry, mass, degree of embedment, and flexibility of the foundation; and the soil layering and soil properties of each layer including most prominently the shear wave velocity.

This machine foundation problem is mathematically very similar to other problems that involve dynamic soil–structure interaction. For example, the dynamic forces and moments acting

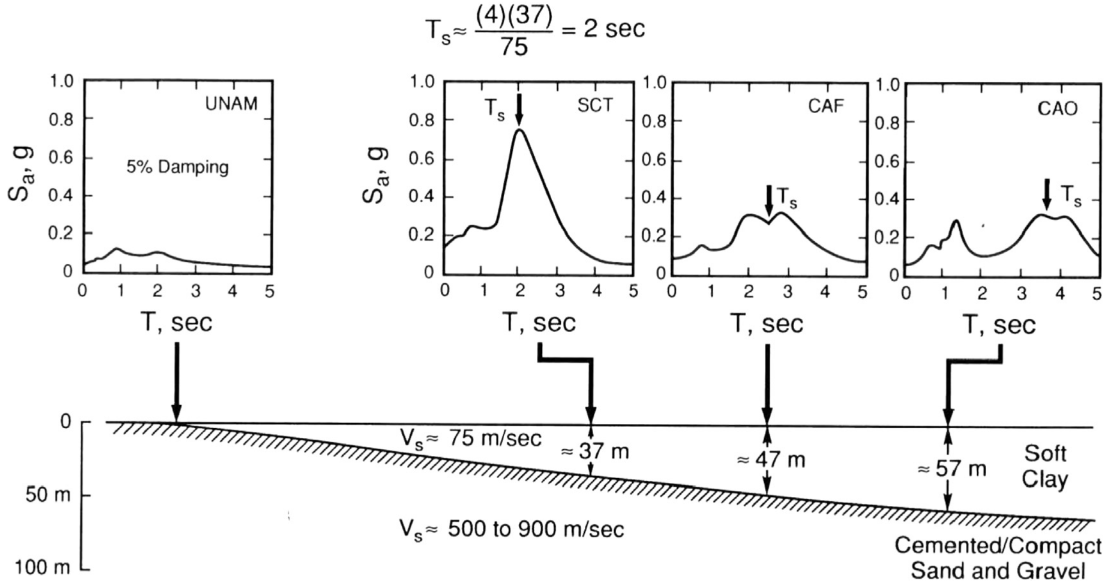

Fig. 1. Earthquake amplification on the Mexico City soft clay in 1985 [63,66,11].