PACE-2021
International Congress on the Phenomenological Aspects of Civil Engineering
Research Article
20-23 June 2021

Soil densification effect on the seismic response of structures taking into consideration soil-structure interaction

Radhwane Boulkhiout*, Salah Messast
Laboratory of Materials, Geotechnical, Habitat and Urbanism (LMGHU), Department of Civil Engineering, University of 20 Aout 1955-Skikda, 21000, Algeria
Corresponding Author E-mail:r.boulkhiout@univ-skikda.dz *Corresponding Author ORCID: 0000-0001-7061-775X*

Keywords

Compaction techniques,
Soil-structure interaction,
Impedances functions,
Conan,
Cone method,
Lateral displacement,
Equivalent static method.

Abstract

In this work, the effect of improving soil characteristics by compaction techniques on the dynamic response of foundations and structures, taking into account the effect of soil-structure interaction was determined. The dynamic response of foundations is presented by the impedances functions, which are determined numerically by the CONAN program, based on the cone method. In addition, the response of the structure will be presented according to the lateral displacement in each level of it. This motion vector is a function of the forces in each level; for this, the equivalent static method was applied, which allows to calculate the seismic force at the base and the distribution of it on the height of the structure. The results obtained show the efficiency of soil densification on the seismic response of MDOF frames.

1. Introduction

Compaction techniques (otherwise known as mass densification) are now widely used techniques to improve certain soil characteristics significantly [1]. More specifically, dynamic compaction, which consists of improving the mechanical properties of the soil by transmitting high energy impacts to the loose soils, which initially have a low bearing capacity and high compressibility potentials, which produces the body and the surface waves propagating through the middle of soil. In unsaturated soils, the waves move the grains and rearrange them into a more dense configuration. In saturated soils, the soil is liquefied and the grains rearranged into a more compact state. In both cases, decreasing voids and increasing internal granular contact will directly result in improved soil properties, as shown in Figure 1.

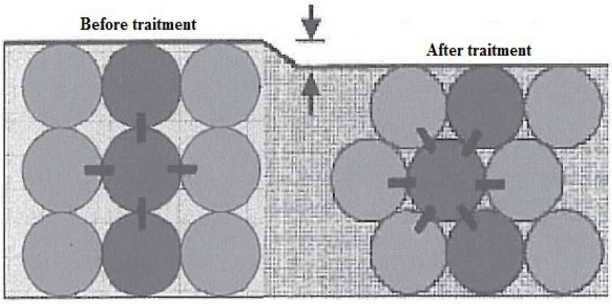

Figure 1. Displacement of soil grains under the effect of dynamic compaction

The foundations considered as elements of contact between the soil and the structure. They have played the role of intermediary between the upper and the lower parts; it allows the transformation of the loads of the structures on the soil or the opposite, because of that the foundations must be well dimensioned for achieving this objective. In the literature, the dynamic response of foundations presented by the impedances functions [2,3]. These functions using in rheological modeling by springs and dampers at the base of structures [4], for which the movement of a foundation in any direction will impose.

The earthquake considered one of the most complex phenomena in soils, because of its random propagation in the soil, which makes it difficult to adapt. The equivalent static method considered a one of the methods used in the seismic analysis of structures, which allows calculating the seismic force at the base of the structure as shear force, and the distribution of it at each level of the structure as static forces [5].

2. Reference model

The structure is three degrees of freedom reinforced concrete frame each level has a 5m long span with a section of (40x70cm^2). Column height is equal to h = 4m with a section size of (40x40cm^2). The structure rests on (2x2m^2). It has the characteristics shown in the Table 1.

Table 1. Parameters of structure

ρ_c (g/cm^3)	f_{ck} (GPa)	E_c (GPa)	ν_c	ξ_c
2.5	0.035	25	0.2	0.05

The frame rests on two square foundations (2×2m^2), founded on four types of seating soil (see Figure 2) with the parameters given in Table 2.

Table 2. Parameters of seating soil before and after compaction

Soil condition	Soil type	V_s (cm/s)	ρ_s (g/cm^3)
Before compaction	E	17000	1.8
After compaction	D	18500	2.0
Before compaction	D	30000	2.0
After compaction	C	36500	2.2

Shear modulus and elasticity modulus of the soil are defined by Equations (1) and (2), respectively.

$$G_s = V_s^2 \rho_s \tag{1}$$

$$E_s = 2G_s\left(1+\nu_s\right) \tag{2}$$

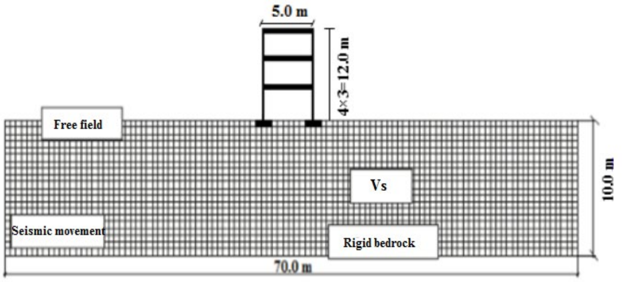

Figure 2. Dimensions of reference model

3. Calculation method

The semi-analytical method used in this work combining two methods one numerical allowing to calculate the dynamic impedances of foundation by CONAN program, and the other analytical allowing to calculate the seismic forces in each level of the frame by the equivalent static method ESM. This method makes it possible to calculate the vector of the lateral movement of the three degrees of freedom frame, which considered free at the base as defined by Equation 3:

$$\begin{Bmatrix} \Delta_1 \\ \Delta_2 \\ \Delta_3 \end{Bmatrix} = \frac{1}{K}\begin{Bmatrix} F_1 \\ F_2 \\ F_3 \end{Bmatrix}\begin{bmatrix} 1 & 1 & 1 \\ 1 & 2 & 2 \\ 1 & 2 & 3 \end{bmatrix} + \frac{1}{K_h}\begin{Bmatrix} F_1 \\ F_2 \\ F_3 \end{Bmatrix} + \frac{1}{K_\phi}\begin{Bmatrix} F_1.h_1^2 \\ F_2.h_2^2 \\ F_3.h_3^2 \end{Bmatrix} \tag{3}$$

3.1. Cone method

The cone model generally used to determine the values of the rheological models considered in the modeling of subdomain by the substructures method. In this model, the components of the displacement field will vary along the depth in the shape of a truncated cone, as shown in Figure 3, for the horizontal translational degree of freedom [6].

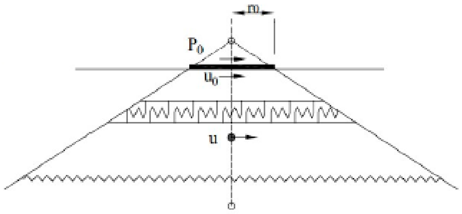

Figure 3. Cone model

One of the numerical programs based on the cone model is the CONAN tool, which allows to determine the static stiffnesses, the stiffness coefficient and the damping coefficient as a function of the dimensionless frequency. For example, in the case of applying a horizontal force to a foundation placed on a homogeneous medium, the terms of the dynamics impedances are given by Equation 4 as follows:

$$\begin{cases} k_s = \dfrac{G_s \pi r_0}{\cot(\alpha)} \\ k_1 = 1; \forall a_0 \\ c_1 = \cot(\alpha); \forall a_0 \end{cases} \tag{4}$$

3.2. Equivalent static method

The equivalent static method is a simplification technique, makes it possible to replace the dynamic calculation under the effect of a seismic excitation at a force distributed laterally on a structure (see Figure 4) [7]. The total seismic force at the base given by Equation 5 as follows:

$$V = \frac{S_{DS}}{R/I_e} W \tag{5}$$

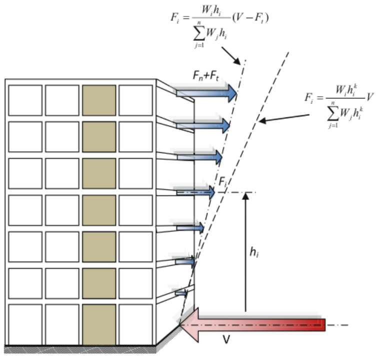

Figure 4. Vertical distribution of the lateral static force

4. Results and analysis

Dynamic impedances are absolutely influenced by the shear wave velocity of the soil. The effect of changing the latter will be determined using densification technique on the values of dynamic impedances using the same previous calculation tool. Figures 5-6 shows the horizontal and rotational impedance variations function of dimensionless frequency respectively.

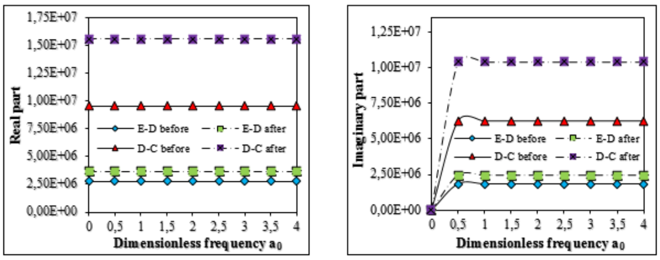

Figure 5. Effect of soil densification on the horizontal impedance

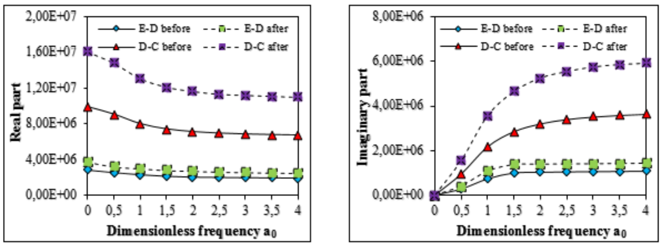

Figure 6. Effect of soil densification on the rotational impedance

The results show the efficiency of densification of the supporting soil on stiffness and damping which are highly affected by its effect. A considerable increase in stiffness and damping in all dynamic impedances was observed. Therefore, compaction has a direct influence on soil damping and stiffness in a proportionate manner.

The effect of the supporting soil on the response of three degrees of freedom frame through dynamic impedances was calculated after compaction of seating soil. Maximum lateral displacements at each level of the frame before and after the densification of the supporting soil are set out in Table 3, and are presented in the Figure 7.

Table 3. Maximum lateral displacements of the frame before and after densification of the supporting soil

	Soil E-D		Soil D-C	
	Before	After	Before	After
Displacement at level 1 (cm)	0.210	0.200	0.198	0.181
Displacement at level 2 (cm)	0.374	0.370	0.365	0.333
Displacement at level 3 (cm)	0.500	0.490	0.471	0.428

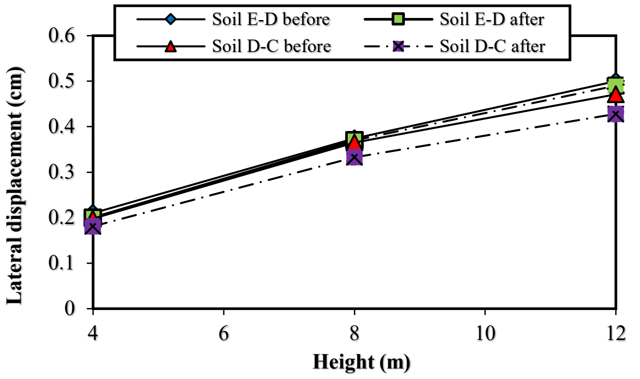

Figure 7. Effect of soil densification on the lateral displacement of the three levels of the frame

The effect of soil densification on the lateral displacement of the three levels of the frame is well illustrated in the figure 7. The lateral displacement of the structure is significantly reduced after the densification of the supporting soil, particularly in the upper level. The temporal variation of this displacement in the three levels of the frame is presented in Figure 8.

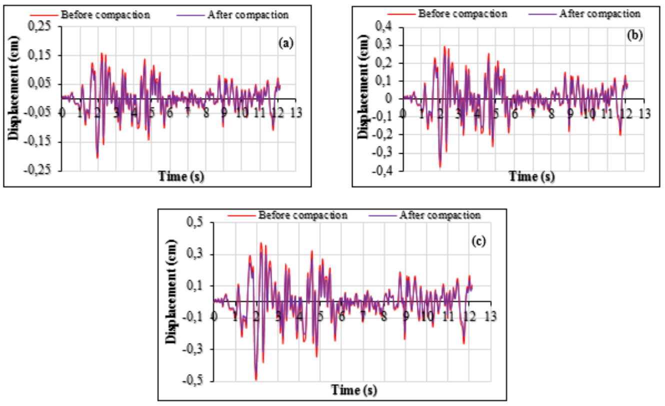

Figure 8. Effect of soil densification on the lateral displacement at: (a) first level, (b) second level, and (c) third level

Figure 8 shows the effect of the densification of the seating soil on the temporal variation of lateral displacement in the three levels of the frame. This effect was greatest in the upper level of the frame when soil acceleration was greatest. Therefore, dynamic compaction increases the shear wave velocity in the soil, which causes a decrease in lateral displacement in all levels of the structure.

5. Conclusion

In this work, a semi-analytical method was presented, for which we determined the effect of soil densification by dynamic compaction on the lateral displacement of a three degrees of freedom frame. This method combines the cone method with the equivalent static method, which makes it possible to achieve the following points:

- Only the horizontal and the rotational impedances influenced on the lateral displacement of structures.
- The equivalent static method makes it possible to transform the dynamic calculation to a static calculation, for which, the seismic force in the soil was determined as a shear force distributed on the height of the structure.
- The dynamic compaction of supporting soils increases the shear wave velocity in them, which causes an increase of translation and rotation dynamics impedances, as well as a decrease of lateral displacement of the structures.
- Dynamic compaction minimizes the lateral displacement of structures, which gives an economic reserve concerning the dimensioning of the sections.

Nomenclature

S_{DS} : Acceleration response at short periods

α : Angle

I_c : Column inertia

K_i : Column stiffness on the i^{th} floor

c_1 : Damping coefficient

a_0 : Dimensionless frequency

$\overline{\Delta}_i$: Lateral displacement of the i^{th} floor

E_c : Elastic modulus of columns

r_0 : Equivalent radius of foundation

h_i : Height of the static forces on the i^{th} floor

R : Response modification factor

I_e : Seismic importance factor ensures a seismic force of a superior design for larger structures

F_i : Static forces on the i^{th} floor

k_s : Static stiffnesses

k_1 : Stiffnesses coefficient

W : Total seismic weights

Declaration of Conflict of Interests

The author(s) declare(s) that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1.] Hamidi, B., Nikraz, H., Varaksin, S., A review of impact oriented ground improvement techniques. Australian Geomechanics Journal 44 (2009) 17-24.

[2.] Lee J.H., Kim J.K., Tassoulas, J.L., Dynamic analysis of foundation in a layered half-space using a consistent transmitting boundary. Earthquake structure 3 (2012) 203-230.

[3.] Borghei, A., Ghayoomi, M., Centrifuge testes to evaluate dynamic impedance functions of square surface foundation. 7th

International Conference on Earthquake Geotechnical Engineering, Rome, Italy, 17-20 June, 2019, 1495-1502.

[4.] Chen, Y., Zhao, W., Jia, P., Han, J., Guan, Y., Dynamic behavior of an embedded foundation under horizontal vibration in a poroelastic half-Space. Applied Science 9 (2019) 1-18.

[5.] Koukouselis, A., Chatziioannou, K., Mistakidis, E., Katsardi, V., Development of an equivalent static method for the approximation of the dynamic response of offshore structures. Engineering Computations 36 (2019) 1121-1141.

[6.] Farajian, M., Khodakarami, M.I., Kontoni, D.N., Evaluation of Soil-Structure Interaction on the Seismic Response of Liquid Storage Tanks under Earthquake Ground Motions. Computation 5 (2017) 1-12.

[7.] Bourahla, N., Equivalent Static Analysis of Structures Subjected to Seismic Actions. Encyclopedia of Earthquake Engineering (2013) 1-13.