

## Influence of Nonlinearity of Soil-Pile Interface on the Seismic Interaction of Nonlinear Soil-Piles-Bridge System

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### Abstract

Post-seismic observations of recent devastating earthquakes have shown that the nonlinear behavior of the soil plays an essential and definitive role in development the damage to the system of soil-piles- structure during the earthquake. Similarly, slips or collapse the soil-piles interface may cause harmful ruptures. Consequently, an analysis of these problems is necessary to take into account the non-linearity of the soil and the possibility of a slip or collapse at the interface of soil-pile under intensive seismic loading. This study aims to investigate these interaction aspects for soil-piles-structure under real earthquake record using a global approach with a three-dimensional finite difference code – FLAC 3D (Fast Lagrangian analysis of continua in 3 dimensions). The results confirm that the non-linearity of soil and soil-pile interface has a great influence on the response of piles and structure. They show that the consideration of the plasticity of the soil leads to attenuation of efforts, especially for soft loose soils. The simulation carried out in this study illustrate that the use of weak soil-pile interface leads to an increase of bending moment accompanied by a reduction of shear and normal forces in the piles. While, for a medium or high resistance interface, the efforts induced in the piles approaching of those induced in the case of perfect contact.

**Keywords:** Interaction; Piles; Interface; Seismic; Plasticity; Three-dimensional

### Introduction

Often piles ensure the stability of structures supported by weak soils or located in seismic zones, but under strong seismic loadings, they could be probably subjected to efforts exceeds their allowable limit of seismic resistance. These efforts are particularly dangerous when the piles are anchored in nonlinear soil. The post- seismic observations and analysis have showed the fundamental role of soil-foundation-superstructure in determining the seismic damage suffered by piles and structures [1-7]. The analytical and numerical analyses show that the seismic piles damage is mainly due to the kinematic interaction between piles and soils or /and the inertial interaction between the superstructure and the foundation which can cause damage to the piles, particularly at the piles cap [8-12]. Subsequently, a number of analytical and numerical studies was performed on the seismic behavior of piles. These works show that the behaviour of piles under seismic loadings is a very complex problem, as it involves soil-pile interaction, piles-piles, pile-cap and all piles-cap-soil and the superstructure. Due to the complexity of the nonlinear analysis of soil-piles-structure, most research in this domain was performed for elastic behaviour analysis with rigid contact between piles-soil. However, under intensive seismic loading, the nonlinear behaviour of soil is very pronounced and the rupture of the soil-piles interface is very likely. Full 3D analyses considering the effect of nonlinearity behaviour of soil- pile interface coupled with the soil nonlinear behaviour on the seismic behaviour of soil-piles-structure are very limited. Such studies were conducted in the nonlinear domain for the soil only without coupling that with the nonlinear behaviour of the soil-pile interface which is very likely to come about under strong earthquakes. The research works conducted in this study provide a thorough analysis of soil-piles-bridge interaction under seismic loads, particular attention is paid to the influence of nonlinearities behaviour of soil and soil-piles interface on the seismic response of the soil-piles-bridge system. The study is performed using a three-dimensional modelling code (FLAC 3D) [13].

This paper includes a full 3D coupled modelling of the soil-pile-superstructure interaction under seismic loading considering the elastoplastic behaviour of the soil and soil-pile interface. The analyses provide valuable information's about the domain of validity of the linear

theory. The soil behaviour is described using the non- linear Mohr-Coulomb criterion.

### Research Methodology

#### Soil-pile structure system and numerical model

The model consists of an implanted group of piles in the soil. The modeling of behavior of such system under seismic loading requires specific methods to take in consideration the interaction between those different components, namely the soil-piles, pile-pile, piles-cap interaction and all piles-cap-soil with the structure. The boundaries of the model should be put sufficiently away from the structure to minimize the effect of waves reflection which leads to dense mesh. To overcome this difficulty, we use specific borders which prevent them from reflecting on the model. FLAC 3D is used in this study; this code uses the Lagrangian representation of movement. It is based on the explicit finite difference method to solve the equations of dynamic equilibrium.

#### Flac 3D

Since FLAC is described as an “explicit, finite difference program” that performs a “Lagrangian analysis”. In the finite difference method, every derivative in the set of governing equations is replaced directly by an algebraic expression written in terms of the field variables (e.g., stress or displacement) at discrete points in space; these variables are undefined within elements (Figure 1).

#### Lagrangian analysis

Instead of forces, Lagrangian mechanics uses the energies in the

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Received June 29, 2018; Accepted August 17, 2018; Published August 22, 2018

Citation: Alfach AT (2018) Influence of Nonlinearity of Soil-Pile Interface on the Seismic Interaction of Nonlinear Soil-Piles-Bridge System. J Civil Environ Eng 8: 321. doi: 10.4172/2165-784X.1000321

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system. The central quantity of Lagrangian mechanics is the Lagrangian, a function which summarizes the dynamics of the entire system. Overall, the Lagrangian has units of energy, but no single expression for all physical systems. Any function which generates the correct equations of motion, in agreement with physical laws, can be taken as a Lagrangian. It is nevertheless possible to construct general expressions for large classes of applications. The non-relativistic Lagrangian for a system of particles can be defined by

$$L \equiv T - V$$

Where T is the kinetic energy,  $T = m\dot{x}^2 / 2$ ; and V is the potential energy  $V = kx^2 / 2$

So we have,

$$L = \frac{1}{2} m\dot{x}^2 - \frac{1}{2} kx^2$$

$$\frac{d}{dt} \left( \frac{\partial L}{\partial \dot{x}} \right) = \frac{\partial L}{\partial x}$$

If T or V or both depend explicitly on time due to time-varying constraints or external influences, the Lagrangian L (r1, r2, ... v1, v2, ... t) is explicitly time-dependent. If neither the potential nor the kinetic energy depend on time, then the Lagrangian L (r1, r2, ... v1, v2, ...) is explicitly independent of time. In either case, the Lagrangian will always have implicit time-dependence through the generalized coordinates.

With these definitions Lagrange's equations of the first kind are

$$\frac{\partial L}{\partial r_k} - \frac{d}{dt} \frac{\partial L}{\partial \dot{r}_k} + \sum_{i=1}^c \lambda_i \frac{\partial f_i}{\partial r_k} = 0$$

Where k=1, 2, ..., N labels the particles, there is a Lagrange multiplier  $\lambda_i$  for each constraint equation  $f_i$ , and

$$\frac{\partial}{\partial r_k} = \left( \frac{\partial}{\partial x_k}, \frac{\partial}{\partial y_k}, \frac{\partial}{\partial z_k} \right), \quad \frac{\partial}{\partial \dot{r}_k} = \left( \frac{\partial}{\partial \dot{x}_k}, \frac{\partial}{\partial \dot{y}_k}, \frac{\partial}{\partial \dot{z}_k} \right)$$

The Euler-Lagrange equations, or Lagrange's equations of the second kind

$$\frac{d}{dt} \left( \frac{\partial L}{\partial \dot{q}_j} \right) = \frac{\partial L}{\partial q_j}$$

### Reference example: Elastic

The reference example consists from a group of (2 × 3) floating

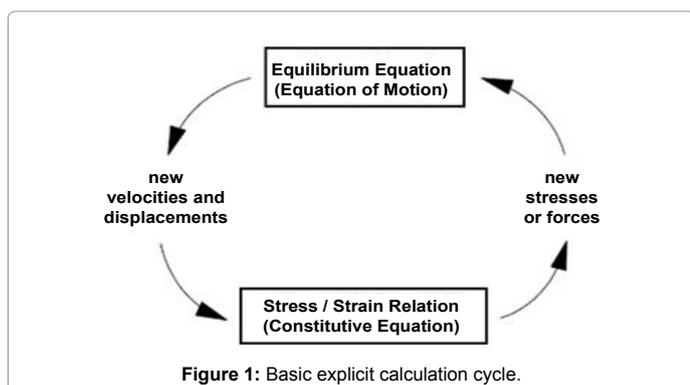


Figure 1: Basic explicit calculation cycle.

piles with length ( $L_p=10.5$  m). The group is implanted into a layer of homogeneous soil with a depth of (15 m) and embedded in a cap of (1 m) thick (Figure 2). The characteristics of soil, piles, and superstructure are given in Tables 1 and 2. The mechanical and geometrical characteristics of reference example are plotted in Figure 2a. The pile's heads ( $D_p=80$  cm) are embedded in cap of thick ( $e_c=1$  m) with rigid contact, the spacing between piles is ( $S=3.75D_p=3$  m). To avoid the complexity of soil-cap interaction, the cap was placed in (0.5 m) above the soil. The piles were modeled as embedded structural pile (2D) elements with perfect contact with the soil in this reference example. In this reference example, the behavior of soil-pile-structure is assumed to be elastic with Rayleigh damping for the soil, the factor of damping used is (5%) for the soil and (2%) for the structure. The equations of Rayleigh damping are expressed in damping matrix form C with components proportional to the mass (M) and stiffness (K) matrices:

$$C = \alpha M + \beta K$$

Where  $\alpha$  the mass-proportional damping constant; and  $\beta$  the stiffness-proportional damping constant.

The Shear modulus of the soil  $G=2.76$  MPa, while, the bulk modulus of the soil  $K=26.66$  MPa, which have calculated by using the following equations:

$$G = \frac{E}{2(1 + \mu)}$$

$$K = \frac{E}{3(1 - 2\nu)}$$

Where E Young modulus in (N/m<sup>2</sup>); and  $\mu$  Poisson ratio.

The fundamental frequency of soil is (0.67 HZ) which was calculated in two ways: firstly by using the following equation for  $V_s=40$  m/sec in the first mode of vibration, secondly the value has been checked by frequency analysis of free field soil by using Flac 3D.

$$T_n = \frac{4H}{(2n-1)V_s}$$

Where  $T_n$ , The fundamental period of the soil in (sec);

H, The depth of the soil under the structure in (m);

$V_s$ , Shear velocity in the soil in (m/sec); and n Mode number.

The superstructure is modeled by a column which supports mass in its head ( $M=350$  Tons). The rigidity of the superstructure and its frequency (assumed fixed at the base) are equals to  $K_{st}=86840$  KN/m and  $F_{st}=2.5$  HZ. They were determined by the following expressions:

$$k_{st} = \frac{3(E_{st} I_{st})}{H_{st}^3}$$

$$F_{st} = 1 / 2\pi \sqrt{\frac{K_{st}}{m_{st}}}$$

Where  $E_{st}$ , Young modulus of the superstructure in (N/m<sup>2</sup>);

$I_{st}$ , Inertia moment of the Super structure in (m<sup>3</sup>);

$K_{st}$ , Bulk modulus of the superstructure in (N/m);

$m_{st}$ , Mass of the superstructure in (Kg);

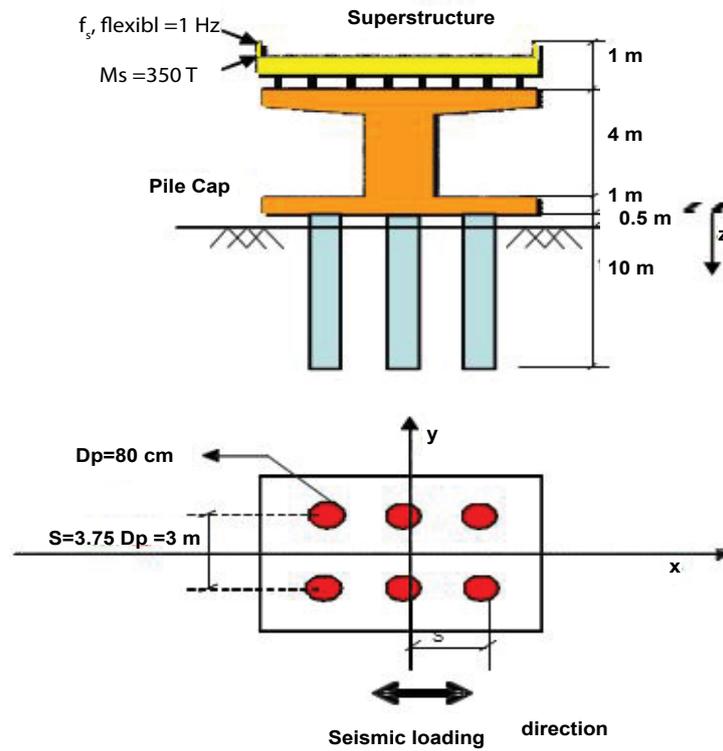


Figure 2a: Problem under consideration (System geometry).

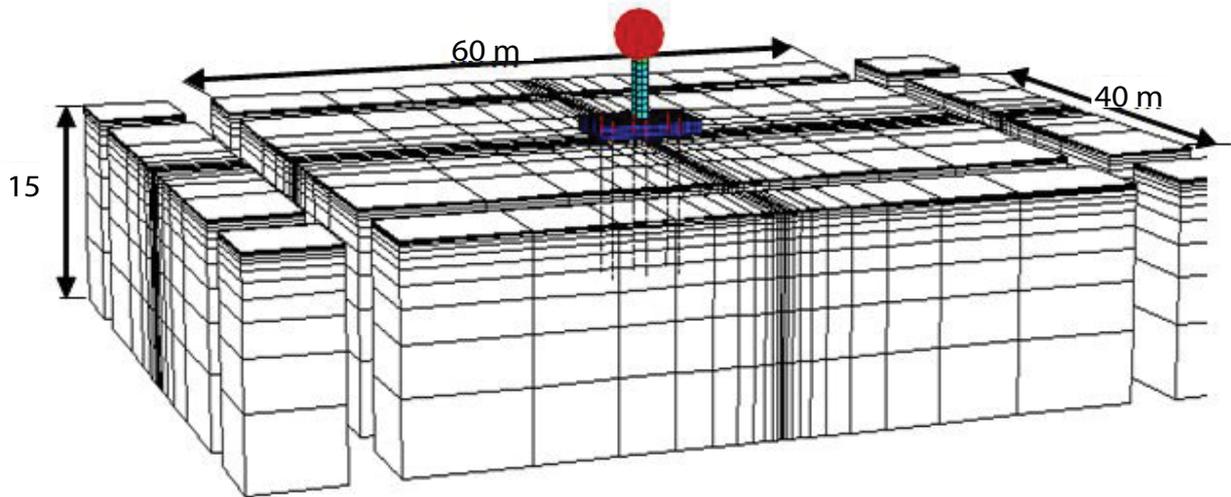


Figure 2b: Problem under consideration (System geometry).

$H_{st}$ , Height of the superstructure in (m).

The frequency of the superstructure taking in consideration the soil-structure interaction is  $f_{st,flex} = 1.1$  Hz (including SSI), which was calculated by frequency analysis of the global problem of soil-structure interaction in Flac 3D.

$\rho$ ,  $E$  and  $\nu$  are the density, young modulus and the coefficient of Poisson.  $\xi$  is the factor of damping.  $D_p$  is the pile diameter.  $E'A$  and  $E'I$ : are the axial and flexural rigidity, noting  $E'A = 1005.3 \times 10^6$  N/m and  $E'I = 40.2 \times 10^6$  N.m<sup>2</sup> for the reference example. The used mesh shown

in Figure 2b includes (3856) zones of (8) nodes and (138) three-dimensional beams of 2 nodes. The mesh was refined around the piles and near the superstructure where inertial forces induce high stresses.

### Real seismic loading record

The seismic loading chosen in this research is the one recorded in Kocaeli at Turkey on 17/08/1999 (Station AMBARLI; KOERI source). This loading which is applied in (X) direction as a speed at the base of the soil is shown in Figure 3. The maximum amplitude of this loading is (40 cm/s) (acceleration maximum=0.247 g).

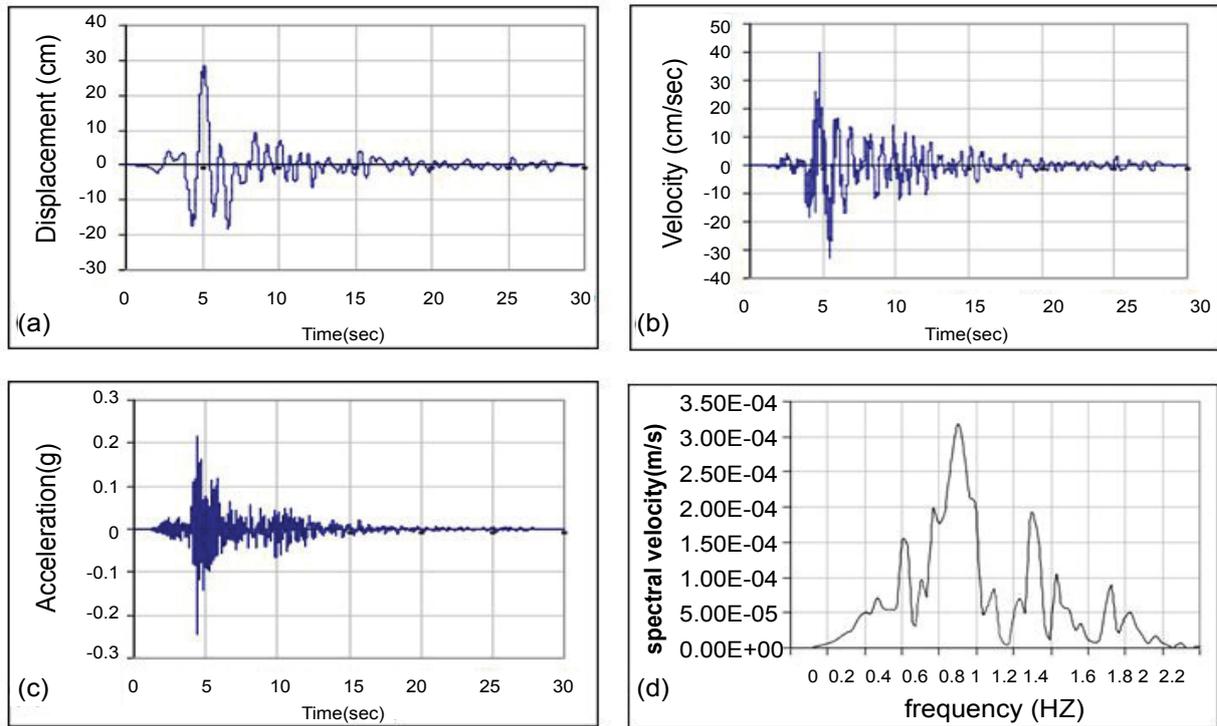


Figure 3: Kocaeli earthquake record (1999) - a) Displacement, b) Velocity, c) Acceleration, d) Fourier spectra of Velocity component.

The spectrum of Fourier corresponding to the used seismic loading illustrated in Figure 3. We note that the frequencies involved are less than (3) Hz with the maximum peak for (F=0.9 Hz) which is between the fundamental frequency of the soil (F<sub>1</sub>=0.67 Hz) and the frequency of structure (F<sub>ss</sub>=1.1 Hz), Hence, the choice of this loading in our analysis. Also, note that a first peak is observed for frequency (F=0.6 Hz) which is very close to the fundamental frequency of soil.

Table 3 shows the efforts induced in the piles under Kocaeli earthquake loading. Since we have interaction between the three components of the structural system (superstructure, cap, and the piles), the internal forces induced at the base of the superstructure affect the internal forces induced in the piles, so we can't compare correctly the internal forces induced in the piles without normalized these efforts to the forces induced at the base of the superstructure. Hence, in order to compare the obtained results, induced efforts are normalized to inertial forces of the superstructure as follows:

$$T^* = \frac{T}{T_{cap}}$$

$$M^* = \frac{M}{m_{st} a_{st} H_{st}}$$

Where:

$m_{st}$  The bending moment at the base of the superstructure;

$T_{cap}$  and  $a_{st}$  denote the inertial force induced at the cap and the acceleration of the superstructure mass; and  $H_{st}$  Superstructure height.

### Influence of soil-pile interface on the seismic response of the soil-piles-structure system

When we take in consideration the interaction of solids in contact with deformability characteristics very different such as soil and concrete, rupture is often likely to occur at the interface. Actually, the contact between soil-pile is not perfect which leads very likely to rupture at the soil-pile interface under intensive seismic loading.

**Presentation of the soil-pile interface:** The soil-pile interface is modeled by spring and dashpot. The behavior of this interface is described by its rigidity K and the parameters of its resistance  $C_s$  and  $\varphi_s$  (Figure 4). We assume an elastic behavior in the normal direction of this interface by introducing a resistance in this direction. On the other side, a possible rupture in this interface occurs when the shear stress reaches its limit. The rigidity of the interface taken equal to shear modulus of adjacent soil. The inelastic interface logic works in the following way:

The Coulomb shear-strength criterion limits the shear force by the following relation:

$$F_{s_{max}} = cA + \tan \varphi (Fn - pA)$$

where c is the cohesion along the interface;

$\varphi$  is the friction angle (degrees) of the interface surface;

and p is pore pressure (interpolated from the target face),

If the criterion is satisfied (if  $|Fs| \geq F_{s_{max}}$ ), then sliding is assumed to occur, and  $|Fs| = F_{s_{max}}$ , with the direction of shear force preserved. During sliding, shear displacement may cause an increase in the effective normal stress on the joint, according to the relation.

$$\sigma_n = \sigma_n + \frac{|F_s| - F_{s_{max}}}{Ak_s} \tan \psi k_n$$

where  $\psi$  is the dilation angle [degrees] of the interface surface; and  $|F_{s0}|$  is the magnitude of shear force before the above correction is made.

The shear behavior of the pile, during relative shear displacement between the pile/soil interface, as shown in Figure 4, is described numerically by: (1) The soil shear stiffness  $k_s$ ; (2) The soil cohesive strength  $c_s$ ; (3) The soil friction angle  $\phi_s$ ; (4) The soil exposed perimeter  $p_s$ ; and (5) The effective confining stress  $\sigma_m$ .

The effective confining stress  $\sigma_m$  acts in the plane perpendicular to the pile axis, and is computed at each nodal point along the pile axis, based on the stress acting in the zone to which the nodal point is linked. Denote the pile-axis direction as  $x$ , and denote the principal stresses acting in the  $yz$  plane as  $\sigma_1$  and  $\sigma_2$ , such that  $\sigma_1 > \sigma_2$  (tension positive). Then the value of  $\sigma_m$  is taken as

$$\sigma_m = -\left(\frac{\sigma_1 + \sigma_2}{2} + p\right)$$

Where  $\psi$  is the dilation angle [degrees] of the interface surface; and  $|F_{s0}|$  is the magnitude of shear force before the above correction is made.

### Case of frictional soil

In order to study the nonlinear behavior of frictional soil under seismic loading, the simulation analyses in this section have carried out for frictional soil ( $C=2$  KPa,  $\phi=30^\circ$ ,  $\psi=20^\circ$ ) firstly in case of perfect soil-pile contact, then, coupled with elastic and nonlinear behavior interfaces. Cohesive interfaces with several values for the resistance of the soil-pile vary from moderate to relatively strong interfaces  $C_s=50, 100, 150$  KPa were examined. The responses of the piles in case of using nonlinear interface were compared with responses to an interface infinitely resistant (perfect contact). The applied seismic loading is the real record of Turkey [14].

### Results and Discussion

The results of the seismic analyses of soil-pile-bridge system in cases

of using elastic and non-linear behavior for the soil-pile interface are given in Table 4 and Figures 5, 6 and 7. It is noted that the non-linearity of the interface leads to a sharp decrease of the internal force in case of using weak interface ( $C=50$  KPa), while, these induced forces increase gradually for ( $C=100-150$  KPa) and become for ( $C=150$  KPa) very close of the induced forces in case of using elastic interface. Moreover, pay regard to the interface conduct to decrease the amplification of the structure. This pronounced decrease for poor interface characteristics ( $50$  KPa), was accompanied with an amplification of lateral acceleration (35%) less than that obtained for perfect contact between soil and piles. This trend is confirmed for internal forces in piles. The profiles of shear force and bending moment (Figure 5) show that the responses for rigidities of the interface ( $100$  and  $150$  KPa), are very close to those obtained for perfect contact. For weak resistance interface ( $C_s=50$  KPa), the profiles of the bending moment and shear force are completely changed.

We observe reduction of maximum shear force at pile head in accordance with that of the lateral acceleration. However, the bending moment increases significantly. The value of the maximum bending moment normalized obtained for ( $C_s=50$  KPa),  $M'=0.223$  is 4 times higher than that obtained for an elastic interface which can be attributed to the sliding of the interface or rather separation soil-piles reflected in the relative displacements between the pile and surrounding soil, this significant increase in bending moment indicates a reduction in the rigidity of soil-piles and leads to high deformability in piles. As for the normal force, we note higher sensitivity depending on the resistance of the interface. The decreasing of interface resistance translates into a decrease of normal force in piles. For a strong resistance of the interface ( $C_s=150$  KPa), the response obtained is very close to that obtained for perfect contact. For medium resistance ( $C_s=100$  KPa), we obtain a drop in maximum normal force of about (22%). For weak resistance ( $C_s=50$  KPa), the profile of normal force is strongly effected with a very sharp decline of over (85%). This is due to slippage at the soil/pile interface. Finally, the consideration of a soil/pile interface is essential in case of weak resistance. In case of strong resistance of the interface, taking account soil plasticity is sufficiently, and the soil/pile interface can be modeled by a perfect contact.

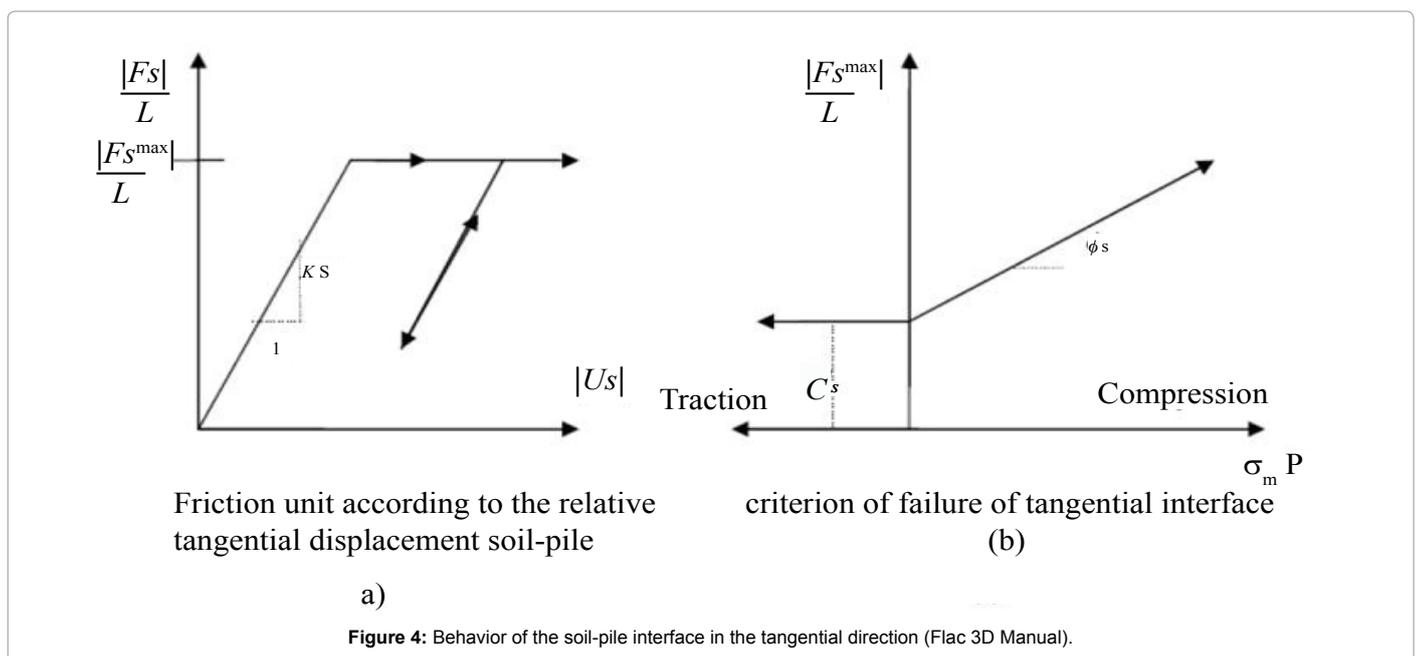


Figure 4: Behavior of the soil-pile interface in the tangential direction (Flac 3D Manual).

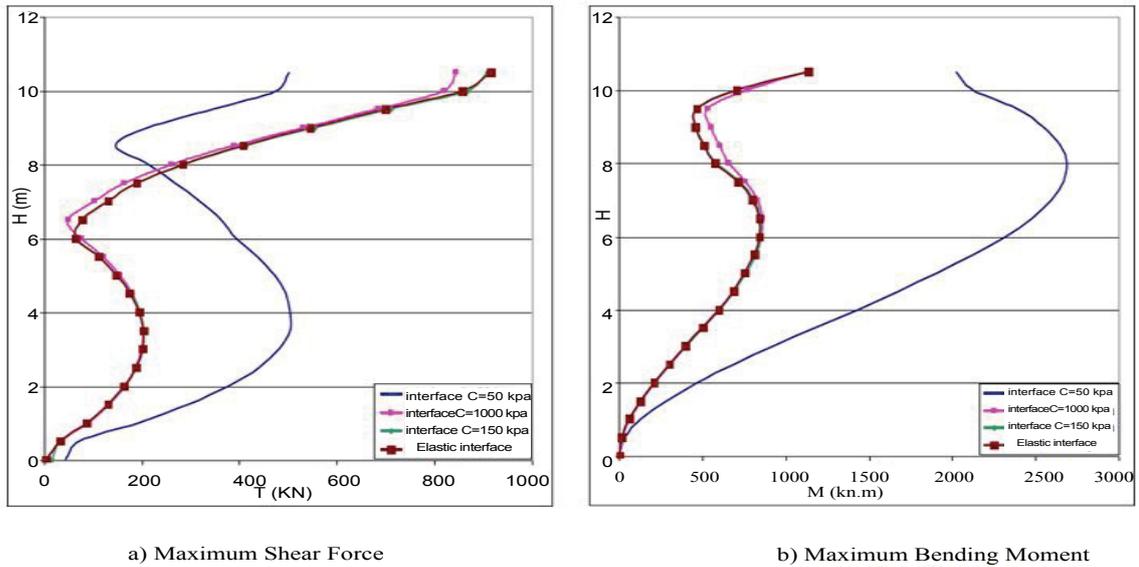


Figure 5: Influence of soil-pile interface on the dynamic forces in the corner piles (Frictional soil, Earthquake of Turkey,  $V_g = 40$  cm/s).

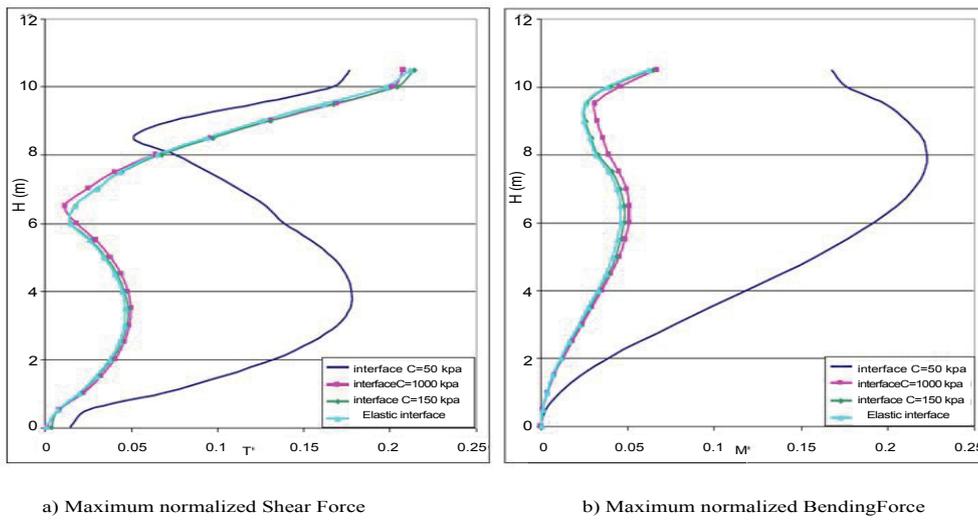


Figure 6: Influence of soil-pile interface on the normalized dynamic forces in the corner piles (Frictional soil, Earthquake of Turkey,  $V_g = 40$  cm/s).

Material	Diameter (m)	Mass Density ( $\rho$ ) (kg/m <sup>3</sup> )	Young Modulus E (Mpa)	Poisson ratio ( $\nu$ )	Damping ratio $\xi$ (%)	Height (m)
Pile	0.8	2500	420000	0.3	2	10
Soil		1700	8	0.45	5	15

Table 1: Elastic property of the soil and piles materials.

(kg/m <sup>3</sup> )	$E_{st}$ (Mpa)	$\nu_{st}$	$\xi$ (%)	Mass (Ton)
2500	80000	0.3	2	350

Table 2: Elastic property of the super-structure.

Seismic Loading	ast (m/s <sup>2</sup> )	Cap (m/s <sup>2</sup> )	Internal forces				Normalized forces	
			Central piles		Corner Piles		Corner piles	
			$T_{max}$ (kN)	$M_{max}$ (kN.m)	$T_{max}$ (kN)	$M_{max}$ (kN.m)	$T^*_{max}$	$M^*_{max}$
Turkey	11.28	8.385	675.8	954.4	1016.1	1099	0.196	0.05

Table 3: Reference example: Response of a group of (2 × 3) piles for turkey loading.

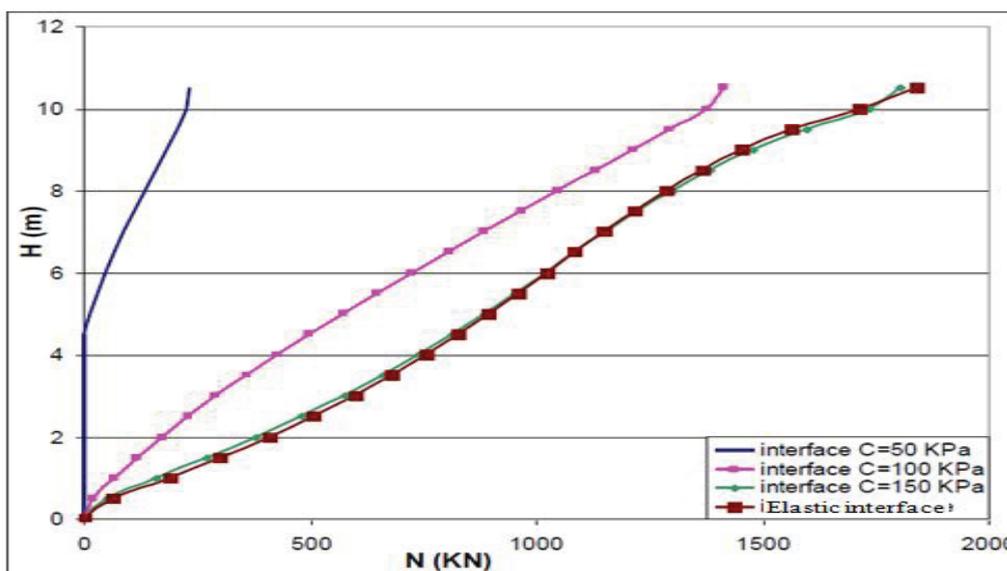


Figure 7: Influence of soil-pile interface on the normal force in the corner pile (Frictional soil, Earthquake of Turkey,  $V_g = 40$  cm/s).

Interface (kPa)	$A_{cc}$ mass (m/s <sup>2</sup> )	$A_{cc}$ Cap (m/s <sup>2</sup> )	Dynamic forces			Normalized forces	
			Corner Piles			Corner piles	
			$N_{max}$ (kN)	$T_{max}$ (kN)	$M_{max}$ (kN.m)	$T'_{max}$	$M'_{max}$
Elastic	9.567	6.592	1840.2	917.3	1140	0.2	0.062
50	6.304	4.19	235.3	504.8	2690	0.178	0.223
100	8.81	6.585	1413.2	844.7	1132	0.2	0.067
150	9.27	6.718	1804.2	909.1	1145	0.21	0.064

Table 4: Influence of soil-pile interface (Frictional soil, Earthquake of Turkey,  $V_g = 40$  cm/s).

## Conclusion

This study was devoted to comprehensive numerical modeling of soil-pile-bridge interaction under seismic loading. Attention particular has been paid to the influence of nonlinearities of soil and soil-pile interface on the seismic response. The research in this study was conducted using a three-dimensional modeling by finite difference program (FLAC 3D). The plasticity of soil influence significantly the seismic response of the system for cohesive soil, the plasticity propagating from the base of this massive which damped the transmission of energy to the surface and the superstructure. Taking into account the plasticity of the soil leads to attenuation of efforts, especially for soft loose soils. The introduction of specific elements of the soil-pile interface becomes possible grace the advances in numerical calculation methods. The simulations performed show that for a poor resistance of soil-piles interface, the use of interface elements leads to an increase of bending moment accompanied by a decline of shear and normal forces in the piles. For a medium or high resistance interface, the efforts in the piles approaching of that in the case of perfect contact, in this case, the taking into account the soil plasticity is sufficient and the use of a more expensive model with interface elements is no longer justified.

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