The Effect of Rigid Inclusions on the Dynamic Response of Highway Embankment

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ABSTRACT

Soft soils are widespread in many areas of the East-West highway of Algeria, covering large areas. Construction projects such as highway embankments, airfields, roads, and railways in such areas experience several problems due to their low strength and permeability. This study used a fully dynamic analysis to evaluate the dynamic response of a highway embankment. The numerical analysis was carried out using the FLAC 2D version 8.10 software. The main objective was to evaluate the effect of rigid inclusions on the dynamic response of highway embankments by monitoring settlement, shear-strain curves, and maximum soil accelerations and displacements at different depth points. The obtained results showed that the configuration of the rigid inclusions significantly influences the dynamic response of the model. For instance, the settlement at 0.9m is 16% higher than at 0.2m from rigid inclusion.

Keywords-inclusions; dynamic response; flac; settlement; shear strain curve

I. INTRODUCTION

Several studies have been carried out to better understand the behavior of soft soils, due to the spread of soft soils, which cover several areas in Algeria, and develop disaster prevention measures, estimate their parameters, and study the effect of some materials such as rubber concrete and lime on the behavior of composite clayey soils [1-5]. Structures such as highway or railway embankments, tanks, walls, or slopes face several problems with such soft foundations. These problems relate to bearing capacity failures, intolerable total and differential settlements, large lateral pressures, and slope instabilities. Several studies showed that the principal cause of several landslides, which affected the East-West highway in Algeria, is the presence of clayey formations [6-7]. A variety of ground improvement techniques have been used to address the concerns on soft soil foundations, such as geosynthetic [8-11], geogrid [12-14], pile [15-16], PVD [17], soil nail [18-19], chemical injection and grouting [20], stone column [21-24], and rigid inclusions [25-27]. However, the suitable solution depends on several parameters, such as the thickness of the soft soil, the nature of the project to build, the requirements of the client, etc.

Rigid inclusions are a ground improvement technique that has a significant advantage over deep foundations, as they can provide the needed settlement control and retain the shallow foundation support of the structure. Rigid inclusions, known by different names such as Controlled Modulus Columns (CMC), pile-supported earth platforms, jet grouting columns, or soil column reinforcement, are vertical elements across soil layers with low bearing capacity and/or high compressibility, extending down to a more resistant layer. Due to their higher stiffness compared to surrounding soil, they support a portion of the loads applied at the ground's surface. Therefore, the loads taken by the soft soil can be reduced to an acceptable level of soil-bearing capacity and settlement. Several studies investigated the effect of rigid inclusions to improve soft soils. Some studies used the Stress Reduction Ratio (SRR) to find the optimal design [28-29]. However, they did not consider several factors that can potentially influence the SRR, such as the characteristics of the subgrade soils and the influence of dynamic loadings. Other approaches adopted rigid inclusions techniques to improve soft soil intended to support a railroad embankment. The rigid inclusions reduced the ground settlements by 15-20%, depending on the subgrade plasticity index [30]. Several numerical studies investigated the seismic behavior of highway embankments in improved soft soils. These studies used the linear elastic-perfectly plastic constitutive model with a Mohr-Coulomb failure criterion to represent the behavior of the soil and LTP [31-36]. Some studies used the constitutive models UBCYST and PM4silt to take into account the nonlinear behavior of soils during seismic motions [37-40].

This paper presents a fully dynamic analysis and evaluation of the seismic response of highway embankments over rigid inclusions to improve soft soil. The UBCHYST model [41] was adopted to consider the dynamic characteristics of the soil during seismic movements. The effect of ground motions of the CHI-CHI earthquake and two types of rigid inclusion configurations, floating and placed in hard clay, were studied.

II. NUMERICAL MODELING

A. The Geometry of the Numerical Model

A 3-layer soil model was considered, where 10m thick soft soil was built over a 5m thick hard soil layer. The highway was constructed on an embankment with an 11.75m width and a slope angle of approximately 18°. The toe of the embankment was at an elevation of 15m. The embankment includes a load transfer platform 0.6m thick as part of the embankment materials. To simplify the problem, the soil layers were supposed to be horizontal, as shown in Figure 1. The water table was not set up in the model and drained conditions were considered. A finite difference mesh with a size of 0.25cm for each element was chosen to avoid wave distortion during seismic wave transmission through the soil [42]. The constitutive model UBCHYST can be used with low and high-permeability soils, such as clayey, silty, and granular. In this hysteretic model, the shear modulus is a function of the stress ratio and varies throughout the loading cycle to give hysteretic stress-strain loops of varying amplitude and area damping throughout the earthquake excitation. A detailed description of all UBCHYST model parameters was given in [41].

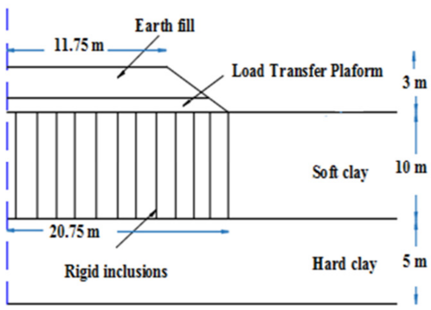

Fig. 1. Geometry of the numerical model

TABLE I. RIGID INCLUSION PARAMETERS

Density (kg/m³)	**Shear modulus *G* (MPa)**	**Young modulus *E* (MPa)**
25000	12.5	30

Tables I and II present the parameters of the soil and structural elements. Soil characteristics were taken from [31, 39, 43]. The calibration parameters of the constitutive UBCHYST model were determined based on laboratory experiments [39, 43]. Since the soft soil used in [31] was modeled as the Mhor-Coulomb constitutive model, a cyclic shear test was conducted to determine the calibration parameters of the UBCHYST model using the modulus reduction curves from [44].

TABLE II. SOIL PARAMETERS OF THE UBCHYST MODEL

Soil parameters	**Stiff clay**	**Soft clay**	**LTP**	**Earth fill**
Bulk modulus *K* (MPa)	76	8.33	41.66	76
Shear modulus *G* (MPa)	38	3.8	19	38
Density (kg/m³),	2000	1600	2000	2000
Friction angle *Φ* (deg)	30	25	25	35
Cohesion *C* (kPa)	15.2	5	50	0
Tensile *T*	0	0	0	0
Dilation angle *dil*	0	0	0	0
Stress rate factor *Rf*	1	0.8	0.98	1
Stress rate exponent *n*	2	2	2.5	2
First cycle factor *Mod1*	0.75	0.75	1	0.75
Large strains exponent *Rm*	0.5	0.5	0.5	0.5
Large strains factor *dfac*	0	0	0	0

B. Rigid Vertical Elements

Numerical analysis was conducted using 12 rigid inclusions per row in the soft soil, with 10m length and 0.6m diameter. The separation between elements in both directions was equal to 1.8m. The rigid inclusion characteristics were taken from [31].

C. Boundary Conditions and Interfaces

Artificial boundaries were used in the static analysis to depict the semi-infinite nature of the soil. The side boundaries were fixed in the horizontal direction while the bottom part was fixed in all directions. However, these boundary conditions were replaced in the dynamic analysis by quiet boundaries along the bottom of the model to minimize the effects of reflected waves at the bottom and free-field boundaries on the sides to avoid wave reflections[45]. To apply quiet boundary conditions along the same boundary as the dynamic input, the dynamic input must be applied as a shear stress boundary, because the effect of the quiet boundary will be nullified if the input is applied as an acceleration or velocity wave. To do this, the velocity record was converted into a shear stress boundary condition using

$$\sigma_s = factor \times (\rho \times C_s) \times v_s \quad (1)$$

where σ_s is the applied shear stress, ρ is the mass density of the material at the boundary, C_s is the speed of s-wave propagation through the medium at the boundary, v_s is the input shear particle velocity, and the *factor* is generally equal to 2.

Figures 2 and 3 show the time history acceleration and velocity of the CHI-CHI earthquake. Regarding soil-rigid inclusion interfaces, since the soil foundations of this study were clayey soils, the interfaces were assumed to have a zero-friction angle and the same cohesive strength as the surrounding soil [46]. The shear and normal stiffness values were determined using (2), based on the FLAC manual [45].

$$K_n = K_s = 10\left(\frac{K + 1.3\,G}{\Delta Z_{min}}\right) \tag{2}$$

where K and G are the bulk and shear modulus of the adjacent soil, respectively, and ΔZ_{min} is the smallest edge of the adjacent soil element.

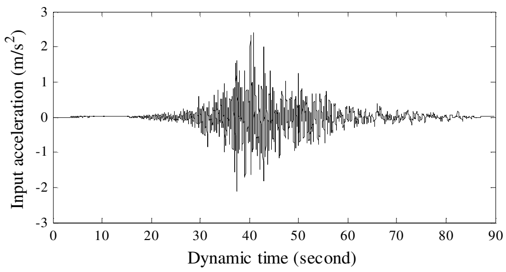

Fig. 2. Input acceleration time history of the CHI-CHI earthquake in 1999.

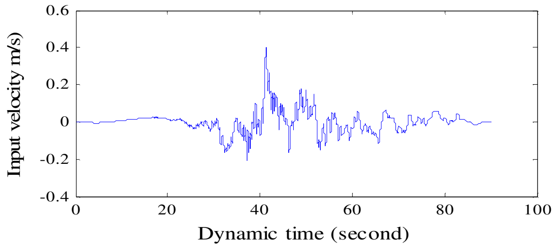

Fig. 3. Input velocity time history of the CHI-CHI earthquake in 1999.

III. RESULTS AND DISCUSSION

The soil response in terms of settlements at the bottom of the embankment and along the depth, and shear stresses and strains were evaluated for both cases of Rigid Inclusions (RI), placed on hard clay and floating. All these results took into account only the influence of the dynamic loading on the soft soils improved with rigid inclusions. In the first step, an initial stress state was generated. Then, the vertical reinforcements were installed, and the last static calculation step considered the activation of the earth platform and the highway embankment. The required seismic boundary conditions, free field boundaries, and quiet boundaries were added for the dynamic analysis, and the dynamic analysis was executed by applying the corresponding horizontal wave using shear stress (2) at the base of the models.

A. Settlements at the Bottom of the Embankment

Figure 4 shows the histories of soil settlements at the base of LTP for different points relative to the RI. It is noticeable that the settlement at 0.9m from RI is greater than at 0.2m. For example, the settlement of the point at 0.9m is 16% higher than at 0.2m from RI. The settlement decreases the closer the point is to the rigid inclusion. This can be explained by the effect of shear stiffness provided via the interaction of the rigid elements with the surrounding soil, which leads to reduce the settlement of the surrounding soil.

B. Settlements along the Depth

Figure 5 shows the histories of soil settlements at different depths along the centreline axis. It is clear that the maximum settlements (6.4cm) occur at the top of the LTP layer and are reduced with depth. The maximum settlement in the middle of soft clay (3.3cm) is 23.6% greater compared to those in its base (0.78cm).

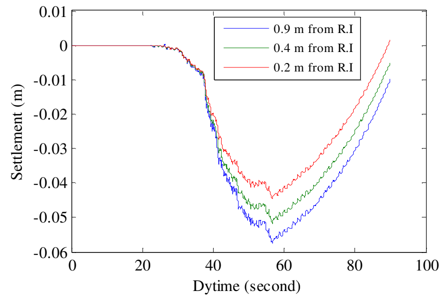

Fig. 4. Settlement at the bottom of the embankment.

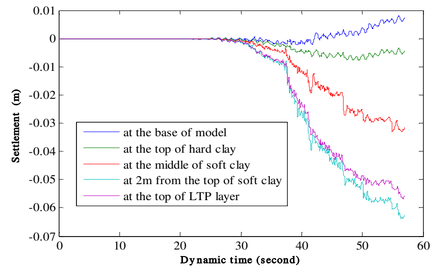

Fig. 5. Settlements along the depth.

C. Shear Strains and stress curves

Figures 6-8 show the hysteresis curve that relates shear stresses and shear strains obtained after dynamic loading in the soil.

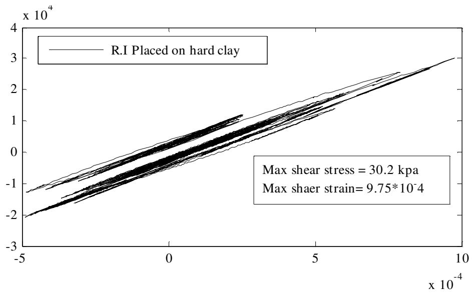

Fig. 6. Shear stress and strain curve at the middle of hard clay.

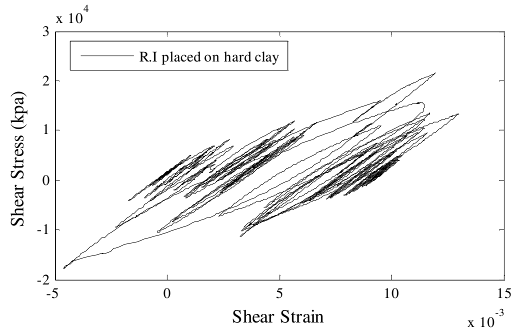

Fig. 7. Shear stress and strain curve at the middle of soft clay.

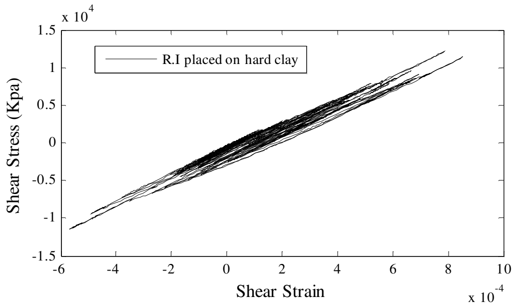

Fig. 8. Shear stress and strain curve at the middle of LTP.

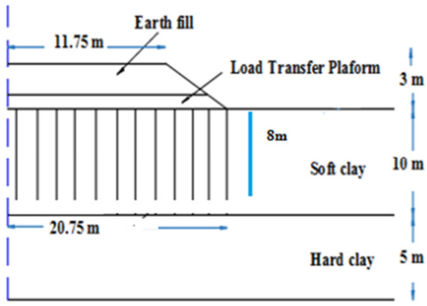

Fig. 9. Floating rigid inclusions.

The values obtained were recorded in the middle of the soft clay and the LTP layer. Figures 3-5 show maximum shear strain at 9.75×10^{-4}, 13×10^{-3}, and 8.55×10^{-4}, respectively. The distribution of the maximum shear strain is higher in the middle of the soft clay. At the LTP layer and the middle hard clay, the maximum shear strains are very close, but the shear stresses differ. These results are due to the higher value of shear stiffness of the hard clay and the LTP layer compared to the soft clay. Figure 9 shows 8m long floating rigid inclusions embedded in the soft soil. Shear stresses and strains at the same points were estimated to show the efficiency of rigid inclusions. Figures 10 and 11 show the hysteresis curve that relates shear stresses and strains obtained after dynamic loading in the soil for floating rigid inclusions. The obtained values were recorded at the same points for rigid inclusions placed on hard clay. The maximum shear strain value in the middle of soft clay was 15.2×10^{-3}, having an increase of 2.2×10^{-3}. Also, the maximum value of shear strain in the LTP layer reached 9.63×10^{-4}, having an increase of 1.08×10^{-4}.

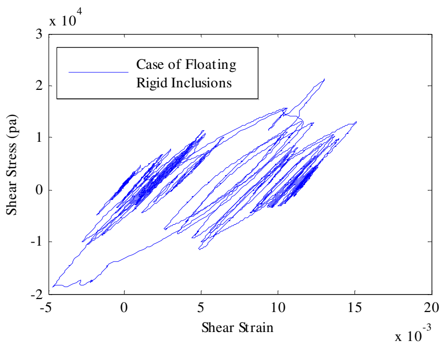

Fig. 10. Shear stress and strain curve at the middle of soft clay.

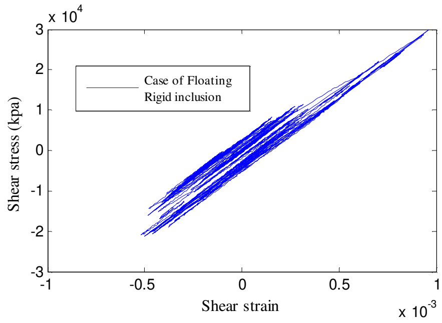

Fig. 11. Shear stress and strain curve at the middle of LTP.

IV. CONCLUSION

A fully dynamic numerical modeling analysis was conducted to evaluate the seismic response of a highway embankment constructed over reinforced soft soil. Two configuration types were considered to study the effect of rigid inclusions, placed on hard soil and floating. The numerical modeling results of all configurations were compared in terms of settlement, shear stress, and shear strain. Settlements at the base of the embankment were evaluated in three different positions relative to the position of the rigid inclusion. The settlement was important at 0.9m from the rigid inclusions while the minimum settlement was recorded at 0.2m. This can be explained by the shear stiffness provided via the interaction of the rigid elements with the surrounding soil, which reduces the settlement of the surrounding soil.The maximum value of shear strains was recorded in the middle of the soft clay compared to the LTP layer and the middle of the hard clay for all cases. The cohesion of the LTP layer and the hard clay increases the strength of the soil and reduces shear strain. In floating rigid inclusions, the maximum shear strain in the middle of soft clay was 15.2×10^{-3}, which is an increase of 2.2×10^{-3}. The maximum value of shear strain in the LTP layer reached 9.63×10^{-4}, which is an increase of 1.08×10^{-4}. These results are due to the shear force that can develop along the rigid inclusion/soil interface, which is a function of the cohesive strength of the interface. Several studies investigated the effect of various parameters such as rigid inclusion diameter, spacing, seismic force intensity, etc. However, few studies investigated the influence of rigid inclusions using a fully dynamic analysis. This paper presented a dynamic study using the UBCHYST model to highlight the nonlinear dynamic behavior of soft soils.

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