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ABSTRACT

In this paper, the dynamic behavior and foundation improvement of a K10-type compressor with maximum horizontal load of 1800 KN, operating at 3.3 Hz (200 rpm) located at top of a concrete foundation is studied. The vibration measurements (acceleration, velocity, and displacement) of the compressor and its foundation have been recorded before and after cement pressure grouting. In brief, the maximum displacement before cement injection exceeded the specified values by the manufacturer. Therefore, the existing pile-soil-foundation system needed to be improved. As the result, a retrofit scheme using cement pressure grouting by injection was recommended. In order to predict the dynamic behavior of the foundation after cement pressure grouting, a finite element model was constructed and then calibrated with the measurements that were taken before cement injection. Second set of measurements for compressor were carried out and results were compared with the model results after cement injection and curing procedure. It was concluded that the model has the ability to simulate and predict the behavior of the compressor accurately. The results show that the cement injection technique can be a reasonable and cost- effective remedial alternative to reduce the dynamic vibrations of the compressor. Moreover, the dynamic behavior of the compressor can be modeled using FEM.

INTRODUCTION

The compressor type of K10 has been utilized in a petrochemical complex in Iran. The compressor's foundation consists of a $20\times20\times4.5$ meters mat foundation supported with $0.4\times0.4\times23$ meters vertical and inclined concrete piles spaced at 2 meters (center to center). The maximum force generated by the compressor's cylinders is 1800KN horizontal load applied at the top of the concrete foundation operating at the frequency of 3.3 Hz. In addition, another vertical harmonic load with maximum amplitude of 450 KN and 45 degrees phase difference exists which was considered in the analyses correspondingly. The allowable horizontal displacement specified by the manufacturer of the compressor is 105 micrometers; however, after vibration measurements on March 14, 2006, it was observed that the horizontal displacement of the compressor has reached 219 micrometers. Therefore, it was concluded that the pile-foundation system should be improved to reduce the compressor's vibrations to the level recommended by the manufacturer. In order to enhance the dynamic behavior of the compressor's foundation a cement pressure grouting procedure was designed which resulted in acceptable displacements after modeling, implementation and final measurements. Figure 1 illustrates the compressor used in this study.

The design methodology using dynamic finite element analyses and geotechnical investigations used in the implemented retrofit procedure is discussed herein.

Figure.1. The view of the compressor's concrete foundation

PILOT GEOTECHNICAL INVESTIGATION

The pilot study has been conducted to estimate soil parameters before and after cement injection. Figure 2 shows the schematics of the foundation and piles as well as the position of the pilot bore holes before and after the cement injection.

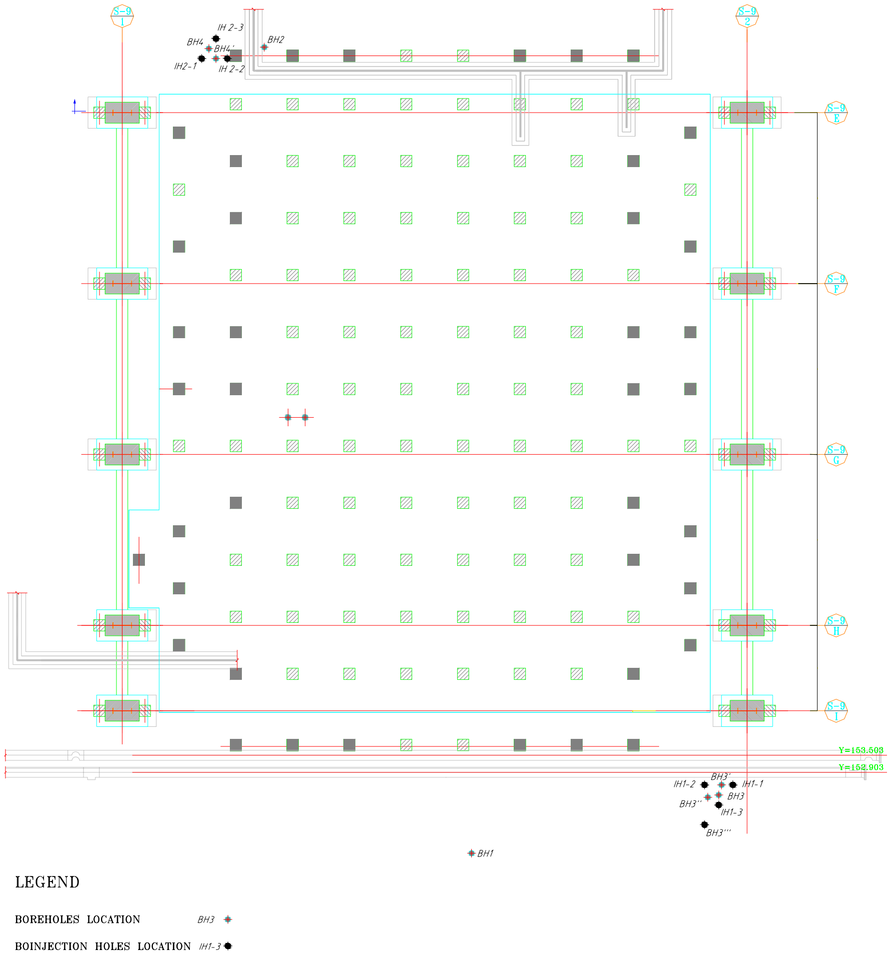

Figure 2. The sketch of the foundation and position of the geotechnical boreholes (The blacked squares are inclined piles)

BH1 and BH2 are drilled before the cement injection and BH3 and BH4 are drilled after the cement injection. Standard Penetration Tests (SPT's), undisturbed sampling for triaxial test, consolidation and unconfined compression tests have been performed for the pilot bore holes. During the pilot study it was observed that the cement grout penetrates through the loose strata, layer by layer, and therefore; causes soil compaction between cement grout layers. The increase in the values of the SPT after cement injection for pilot bore holes is shown in detail in Table 1.

Continuous coring from pilot bore holes showed that about 40 to 45 percent of the bore holes were consisted of hard cement grout layers with a high elastic module (1000-10000 MPa). To estimate the elastic module for the mass of the improved layered-soil, elastic theorem has been used. In this case different probable states of cement grout penetration have been analyzed. These analyses showed that the minimum increase in the elastic module was about 5 times of before cement injection. After this conclusion, numerical studies have been carried out to calculate and predict displacements of the foundation after the cement injection.

Table 1. The result of SPT values before and after cement injection

Depth	BH1	BH3	BH2	BH4
	Before injection	After injection	Before injection	After injection
	N_{SPT1}	N_{SPT2}	N_{SPT1}	N_{SPT2}
4.5	2	12	4	12
5	2	13	9	13
6	1	13	5	14
7	1	26	4	14
8	2	12	12	28
9	3	20	23	22
10	4	12	13	22
11	4	23	25	28
13	10	34	8	
14	10	29	27	
15	4	34	11	
16	9	34	12	
17	15	41	9	
18	17	24	17	
19	15	27	14	
20	9	28	11	

THE FINITE ELEMENT STUDY OF THE FOUNDATION

Verification Of The Model Before Cement Injection

In this part of the study the foundation was modeled by PLAXIS. A two dimensional plane-strain elastic model with absorbent boundaries was used to analyze the problem. The triangular 3 node elements were used in the finite element model. Figure 3 shows the model of the secondary compressor foundation.

The Poisson ratio and dynamic elastic modules of the soil layers before cement injection are shown in Table 2. These values have been chosen based on the results of previous geotechnical investigations and calibration parametric study, in order to have the nearest value of displacements to the measured values in the first phase of the measurements on March 14, 2006.

Table 2. Poisson ratio & soil dynamic elastic modules in the model before cement injection

Soil layer depth (m)	E_{dyn} (Mpa)	Poisson ratio (ν)
0-4	300	0.35
6-12	600	0.35
12-16	600	0.3
16-25	1500	0.3
25-60	2000	0.3
60-130	3000	0.3

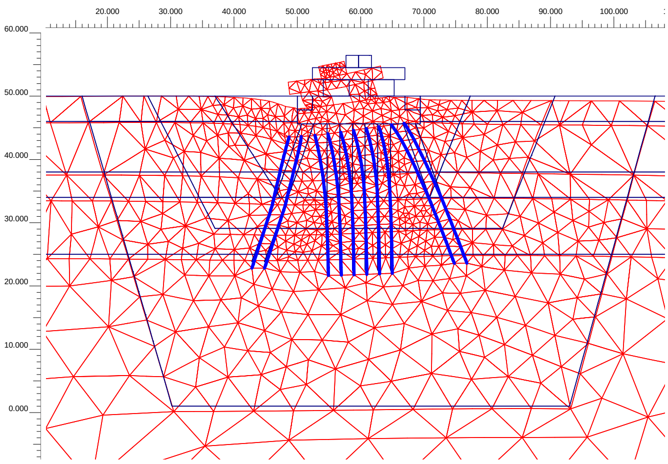

Figure3. The deformation and the behavior of the compressor foundation before cement injection

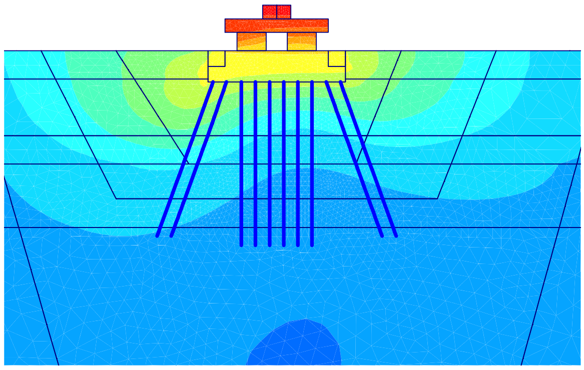

Figure4. Horizontal displacements of the soil layers before cement injection

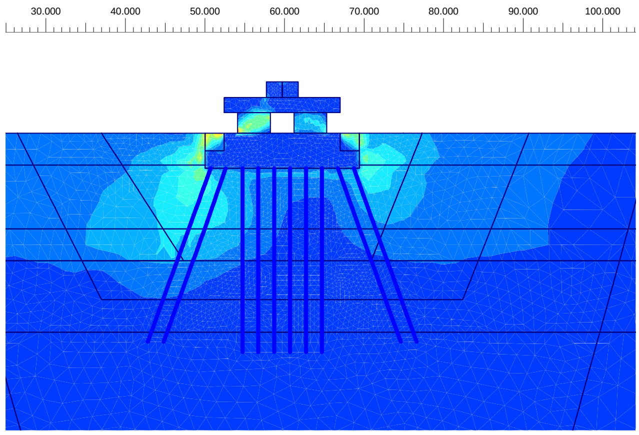

Figure5. Shear strain in the soil layers before cement injection

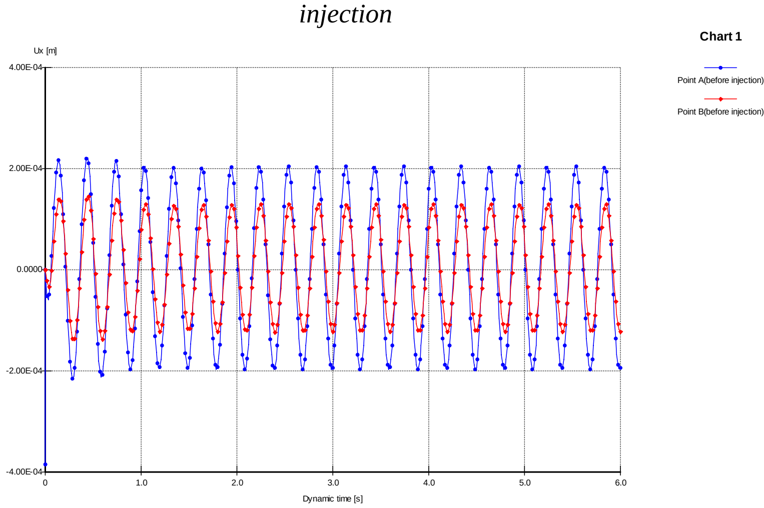

Figure6. Horizontal displacements of points A (top of the deck), B (top of pile cap) before cement injection

Prediction Of The Vibrations After Cement Injection

In this phase of the study, based on the results of different analyses and pilot bore holes, it is assumed that the elastic modules of soil layers have become 5 (Case A) and 7 (Case B) times of those before injection on assuming a good performance by the contractor. It was observed that by increasing the modulus of elasticity to 5 and 7 times of the before injection states, horizontal displacement of point A (top of the compressor deck is decreased from 219 to 125 and 117μm, respectively. Moreover, the horizontal displacements of point B (on the pile cap) are decreased from 96 to 69 and 64μm, respectively.

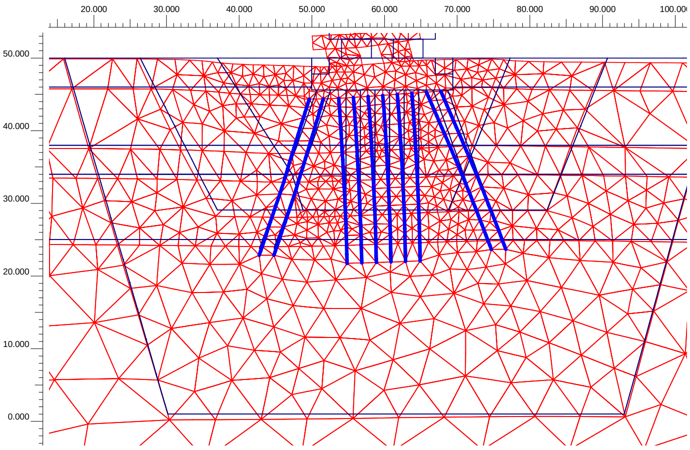

Figure7. The deformation and the behavior of the compressor foundation after injection (case A)

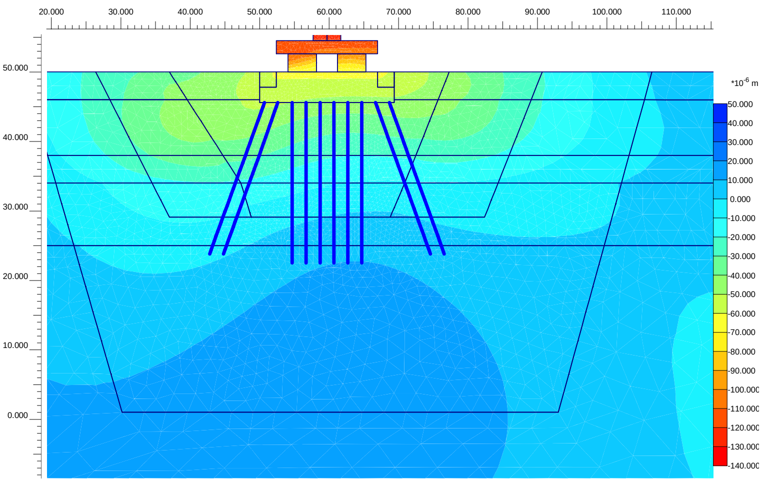

Figure8. Horizontal displacements of the soil layers after cement injection (case A)

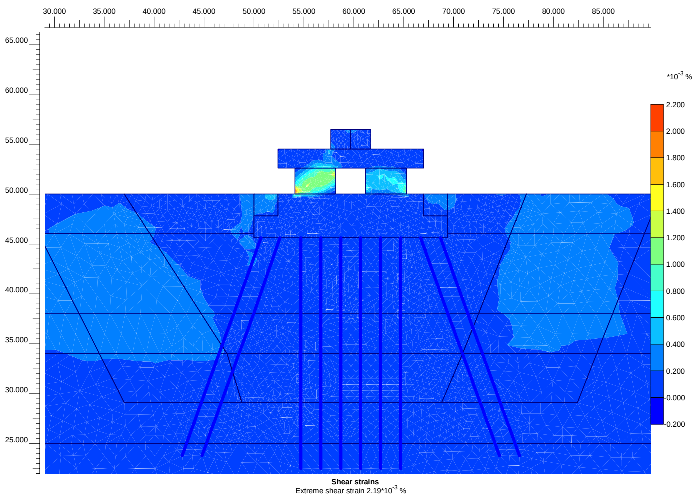

Figure9. Shear strain in the soil layers after cement injection (case A)

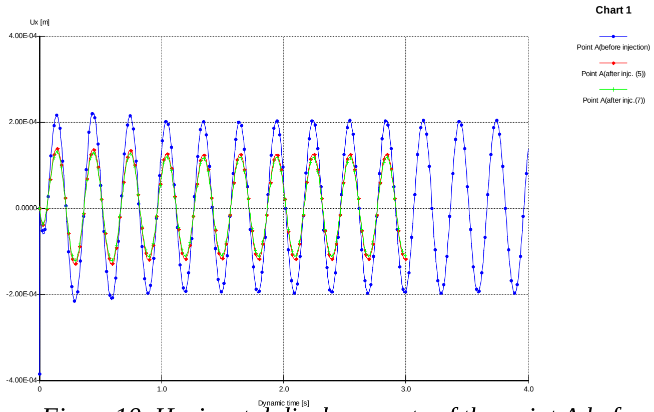

Figure10. Horizontal displacements of the point A before and after cement injection (case A & B)

GROUND MODIFICATION BY CEMENT INJECTION

Finally, it was concluded that in order to decrease the foundation's vibrations, cement pressure grouting to the depth of about 30 meters should be performed. Owing to the fact that the mechanical facilities and the piping systems were impeded the access way to inject cement grout, it was decided to perform cement injection around the foundation by vertical and inclined bore holes. Therefore, about 2000 tons of cement with pressure of 4-12 *bar* was injected around and beneath the compressor's foundation. During the operation the ground heaving was measured to minimize any damage to the surrounding facilities.

FINAL MEASUREMENT RESULTS

Following the second set of measurement performed on January 29, 2007, and comparing the resulted values with the numerical model's outcomes (Table 3), it was concluded that the model has the ability to simulate the behavior of the compressor accurately. Also it was concluded that the application of the model can be extended further to predict other attributes of the foundation. As the result, the present state of the foundation after the retrofit process was accepted and the excessive vibration problem has been resolved. It should also be noted that in the third set of vibration measurements done after preparation of the compressor for Nitrogen run, the horizontal vibration was decreased from 150 μm to 140 μm.

Table3. The measured and predicted values of the amplitude of the displacements in y direction (μm)

Position	Measured values before injection	Prediction of the FEM model after injection (case A)	Measured values after injection
On the deck (A)	219	125	150
On the pile cap (B)	96	54	65

CONCLUSIONS

The following conclusions can be made from this foundation retrofitting project:

- Injection of the cement grout can be an expeditious and low cost measure to modify the ground and reduce the vibration of the foundations.
- A simultaneous survey measurement should be performed during the cement injection, in order to check the ground heaving. It should be noted that cement grouting can cause ground heaving even up to 0.5 meters which can cause costly damages to mechanical facilities.
- Finite element method is a capable tool to predict the vibration of the compressors in modification issues but it is necessary to verify and calibrate the model with reliable insitu measurements.

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