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VIBRO-COMPACTION PILES FOR IMPROVEMENT OF LIQUEFIABLE DEPOSITS: CASE HISTORY

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ABSTRACT

Afsoon is a 13-storey residential building complex with 625 square meters in plan area and was built in Babolsar, which is located in the northern coastal area of Iran. The results of the site investigations and in-situ testing indicated the existence of relatively loose and saturated soil to a depth of 10 m, and very soft silts at depths between 6.5 and 8 m. Based on the preliminary analysis, the bearing capacity criteria for a shallow mat foundation was in a reasonable and acceptable range. However, there were problems of uniform and differential settlements under static and dynamic loads, and also instability due to liquefaction potentials. It was decided to choose deep soil stabilization mechanisms by employing compaction piles. The behavior of twelve t test piles were studied after testing procedures, including driven and vibro-replacement piles with tension-compression operations. Results presented downward deformations of soil around piles about 400 mm, i.e. soil densification, where displacements of shallow and deep layers were noticeable. As a final point, for subsoil improvement, 23 driven piles with 300 to 400 mm diameter, and embedment of 12 m, and also 19 vibro replacement piles with H-section and 12 m embedment length were used. A raft foundation with 25×25×0.8m dimensions of reinforcement concrete was constructed to form composite mat (piled-raft) as a foundation system. The data obtained from instrumentation and monitoring at the end of construction demonstrate that the real subsoil displacements and settlements are less than the allowable values regarded in the design procedure and also a good safety factor against liquefaction and unstable conditions.

Introduction

Babolsar is a harbor city, located along the coast line of the Caspian Sea in northern Iran. Construction and marine development is growing in this area. The subsoil of this region consists of loose sandy deposits with high potential of liquefaction and compressibility with ground water levels close to the ground surface. Due to the khazar and Alborz faults, which surround the site, the risk of seismic activity and the occurrence of severe earthquakes are high. Therefore, for important structures, significant effort must be made to avoid drastic hazards.

Afsoon is a 13-storey residential tower building, consisting of 54 apartment units. Its side view and structural system are illustrated in Fig. 1. The Afsoon building project was constructed in February 2006.

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Regarding the importance of the project, geotechnical investigations and experimental tests were made on disturbed and undisturbed samples. Soil composition in this region is made of poorly graded sand (SP) and some silty sand (SM). Also, the ground water levels fluctuate between depths of 2.5 and 3.5 m. The Standard Penetration Test (SPT) records indicate that the underlying soil of the tower consists of sand with low to medium density up to 12 m, where at lower depths there is a dense sand layer. Evaluations showed that there were very soft silts at depths between 6.5 to 8 m (Sham-e Consulting Engineering 2005). Moreover, in the north of Iran, due to the proximity of active faults such as the Khazar fault, many earthquakes have occurred with various accelerations and magnitudes, and some of them have caused crucial damages and loss of human life. Therefore, the low SPT numbers and high ground water level, in addition to the seismic activity in this area, increases the high risk of liquefaction and compressibility (Safari 2006).

First, because of relatively heavy imposed loads from the superstructure and possibility of differential settlement, a mat foundation system was selected. Following more studies and rigorous evaluations, it was demonstrated that despite having good bearing capacity of the raft, the amount of settlement exceeds allowable values during conditions of static and dynamic loading. Moreover, there is a potential for instability against lateral and uplift loadings. Thus, higher safety levels and structural stability were noted by designers and for solving these problems, some solutions were proposed and considered. Among different ground improvement approaches such as dynamic compaction, Portland cement grouting, removal and replacement of loose strata, vibro-floatation densification, vertical drainage and deep compaction, the designers decided using a deep compaction technique by vibro-compaction piles and the installation of a mat foundation. The soil stabilization practice, foundation construction and their performance within field testing and monitoring will be reviewed in this paper.

a) Facing b) structural system

Figure 1. Facing and structural system of Afsoon building.

Alternatives for Subsurface Improvement

In the design procedure for the Afsoon foundation system, first with regard to project extent, relatively heavy superstructure loads and probability of large differential settlements, the mat foundation was selected. However, additional studies and investigations showed that underneath settlements would be outsized and exceed the upper limit. Also, because of the large height to width ratio of the building, there was a concern for instability and overturning due to earthquake lateral loading. Thus, the choice of a suitable way for decreasing the liquefaction risk was regarded as a main requirement. In the end, several alternatives and approaches were supposed:

a-Remove of subsoil and replacement with suitable soil mixtures
b-Vertical drainage systems
c-Semi-deep foundation
d-Improving soil with grouting technique

e-Deep compaction and shallow foundation
f-Dynamic compaction (Hausmann 1990)

Among the different options, with regard to the available equipment, soil conditions, liquefaction existence, high water level, performance period, economical and environmental considerations, the alternative of deep compaction piling combined with mat foundation was selected. Vibro-compaction piles were considerably less hazardous from a personnel and structural safety point of view and the magnitude of vibrations are significantly less than heavy tamping (Hausmann 1990). Also, the nearby structures surrounding the site and granular characteristics of the subsoil meant that the vibro-compaction method was preferable to others. In the initial stage of construction, twelve tests were completed on 8 piles for the study of compaction operation's adequacy and the determination of optimum depth for the vibration process (Sham-e Consulting Engineering 2005). The piling installation and procedure results are summarized in Table 1.

Table 1. Records from twelve tests on vibro-compaction piles in the Afsoon building.

Test NO.	**Pile length (m)**	**Pile geometry**	**Pile type**	**Remarks**
1	12	H pile -30*30	vibro pile	soil subsidence around pile almost 400mm, hard penetration in depths of 8 to 10m
2	6.5	Pipe Steel 30cm diameter	vibro pile	Crippling of pile head in depth 5 m.
3	6.5	Pipe Steel 30cm diameter	vibro pile	Crippling of pile head in depth of 5m.
4	6	Concrete pile 30*30	compaction pile	pile head Breaking in depth less than 1m.
5	12	H pile -30*30	vibro piles	Soil subsidence around pile equal to 45cm, 2cm crack and break, hard penetration in depth 8 to 10 m and stop in 10 m.
6	6.5	Pipe Steel 30 cm diameter	tension test No. 2	High resistance against pullout
7	6.5	Pipe Steel 30cm diameter	tension test No. 3	High resistance against pullout
8	6	Pipe Steel 40cm diameter	compaction pile	Stop in depth 5m and 360 blows for 1.6m penetration after 24 hours
9	10	Pipe Steel 40cm diameter	compaction pile	Stop in depth 8.5 m and 340 blows for 1.6m penetration after 24 hours
10	12	Pipe Steel 30cm diameter	compaction pile	Stop in depth 10m and 330 blows for 1m penetration after 24 hours.
11	12	H pile -30*30	compaction pile	Stop in depth of 10m and 330 blows for 1m penetration after 24 hours
12	10	Pipe Steel 40cm diameter	compaction piles test No. 9	200 blows for 1m penetration after 24 hours

The following major points were deduced from piling operations:

1- Remarkable subsidence of soil around piles in shallow depth that shows exceeding settlements.
2- Exist of weak layers in depth up to 8 m, and dense layers after that.
3- Improper function of concrete piles because of breakage under hammer strike.
4- Find out suitable depth of vibro piles (approximately 8m).
5- Discovering suitable depth of compaction piles (approximately 6 to 10m).
6- Possibility of utilizing vibro-compaction piles, due to minimum damage on nearby structures.

Soil subsidence around pile number 1 and the relationship between pile penetration versus blow is shown in Figs. 2 and 3 below.

Figure 2. Soil subsidence around pile number 1.

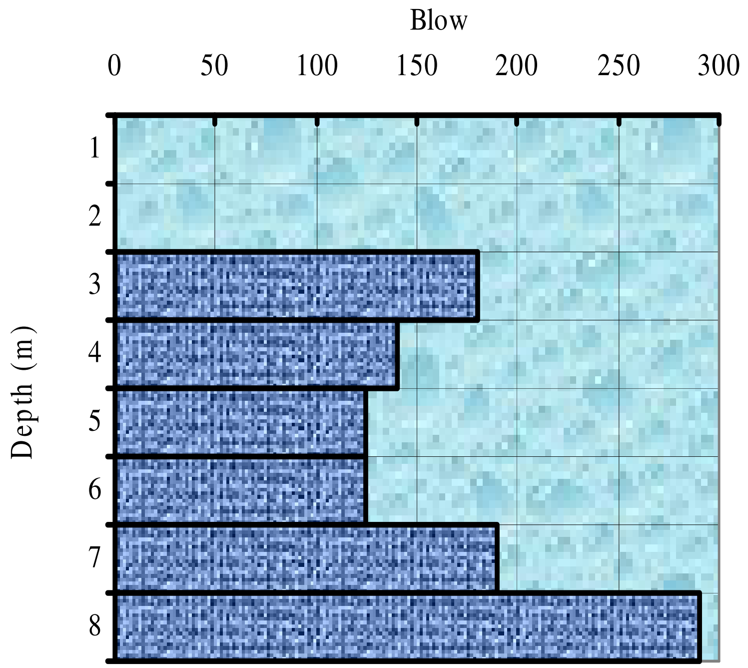

Figure 3. Bearing graph for pile penetration for Test Pile No.12.

Consequently, it was proposed that compaction piles remain in soils as permanent foundation members. These piles could be considered as connected or disconnected piles, such that in the latter case, the piles can act as stiffeners for the base soil. In this project, piles are anchored into the raft to form a rigid connection (Hasanzadeh 2006 and Hemsley 2000). This method has various advantages, such as, reducing the maximum and differential settlements, improving the shallow foundation's serviceability, decreasing the probability of tilting and instability in the structure and adjoining raft to layers that were passed through liquefiable deposits by piles (Poulos 1980 and Hasanzadeh 2006). After these studies and observations, a step by step procedure of foundation construction was introduced:

1- Use of diesel pile hammer and suitable vibration system for compaction.
2- Limiting operation of foundation construction to a depth up to 10m.
3- Utilizing 23 pipe compaction piles of diameters between 30 and 40cm in middle zone of raft as steady members for resistance front uplift, tension, dishing, and also increasing of bed stiffness and well transition of column load in the center.
4- Utilizing 19 temporary H-shape vibro piles, which were used around a mat plan in three reciprocating cycles for soil improvement, soil anchor and reduction of liquefaction potential.
5- Installation of vibro piles to a depth of 8m and compaction piles to depths of 6.5 to 10m.
6- Anchor of piles head in raft.
7- Pouring pipe piles with concrete.
8- Mat construction on piles.

The position of vibro and compaction piles is demonstrated in Fig 4 (Sham-e Consulting Engineering 2005).

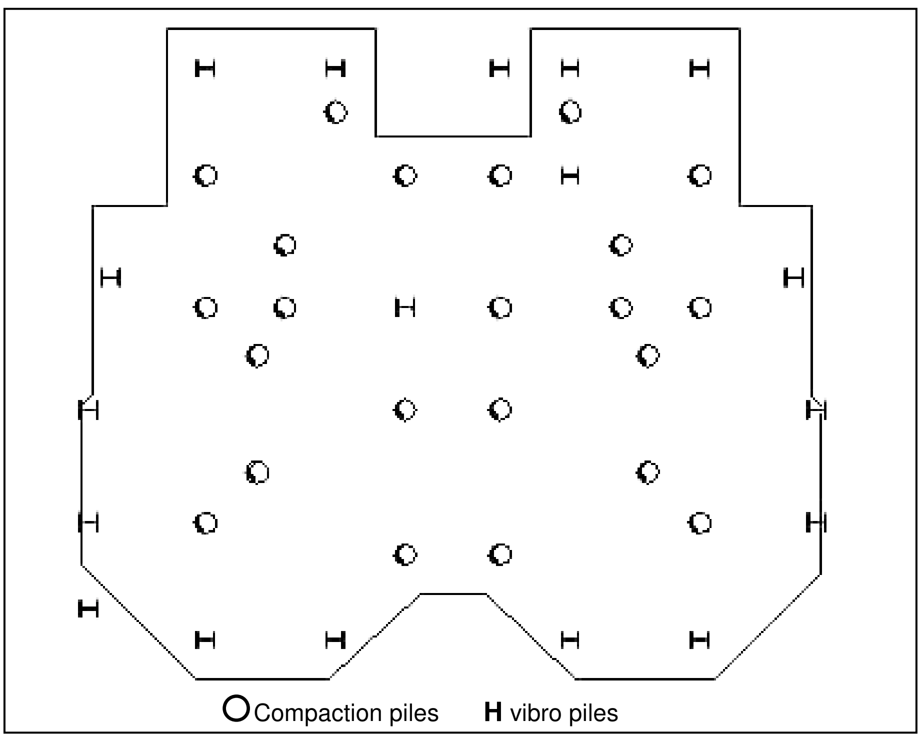

Figure 4. Plan of vibro and compaction piles locations for Afsoon building project.

Instrumentation and Monitoring

For the study of foundation behavior and settlement monitoring during the construction period and after completion, several surveying points and settlement gages were installed on fixed posts and ground movement values recorded. The settlement curve versus time in center of the raft is shown in Fig 5. As it demonstrates, the average settlement was measured to be 18 mm after the 16 months after the end of construction.

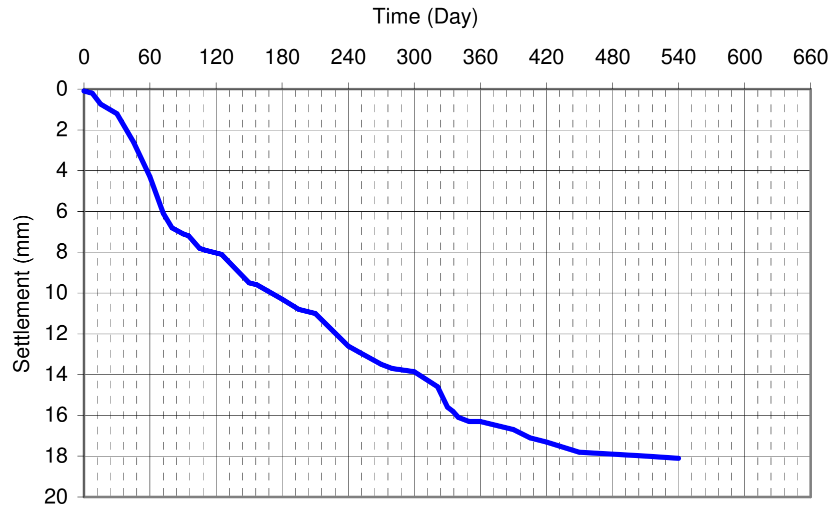

Figure 5. Curve of settlement changes versus time in center of the raft for the Afsoon building project.

It is clear that due to the granular characteristics of the soil and thus the occurrence of immediate settlement, the recorded settlements have reached their maximum value. Inspections of different parts the mat foundations showed no evidence of cracks or non uniform settlement. Also, for the validation of foundation response against dynamic loading (i.e., earthquake) SPT records measured before and after improvement operation are illustrated in Fig 6.

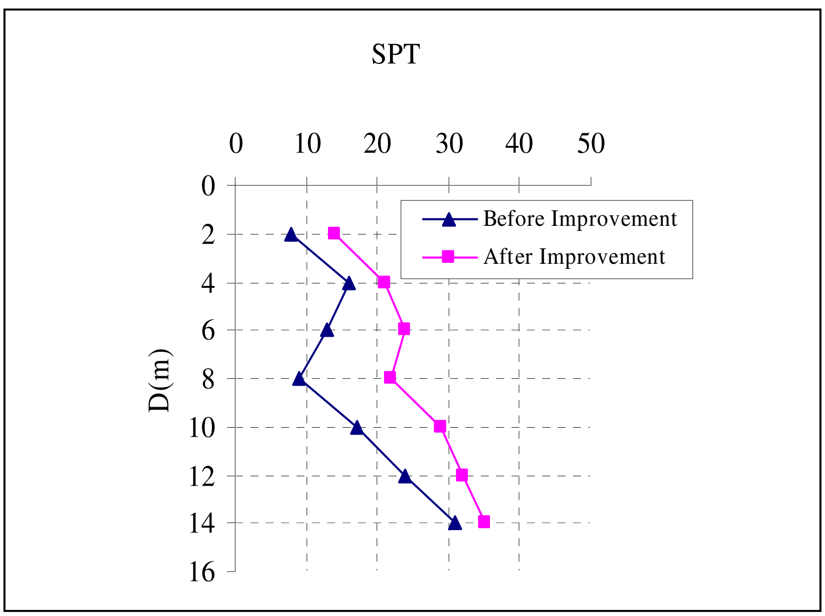

Figure 6. Curve of SPT values at depth of subsoil before and after of improvement.

Liquefaction analysis has been performed using a_{max} =0.3g, earthquake magnitude of 6.5 and cyclic stress ratio approach (Seed 1991) as follows:

$$CSR = \frac{\tau_{avg}}{\sigma'_{\circ}} = 0.65\, a_{max}\, \frac{\sigma_v}{\sigma'_{\circ}} . r_d$$

where, a_{max} = maximum horizontal acceleration at ground surface that is induced by the earthquake.

g = acceleration of gravity

σ_{vo} =total vertical stress at a particular depth where the liquefaction analysis is being performed

σ'_{vo} =vertical effective stress at that same depth in soil deposit where σ_{vo} was calculated

r_d =depth reduction factor.

The CRS were compared to CRR, which is derived from Seed's (1991) chart regarding SPT data. Calculations for determining FSL (Factor of Safety against liquefaction), in which FSL=CRR/CSR, indicate that this factor was less than 1 prior to subsoil stabilization, but increased to 1.3 after improvement. Moreover, considering the factor of safety against liquefaction, settlement due to design based earthquake was calculated according to the Ishihara & Yoshimine method (Ishihara 1992), by a chart as illustrated in Fig 7.

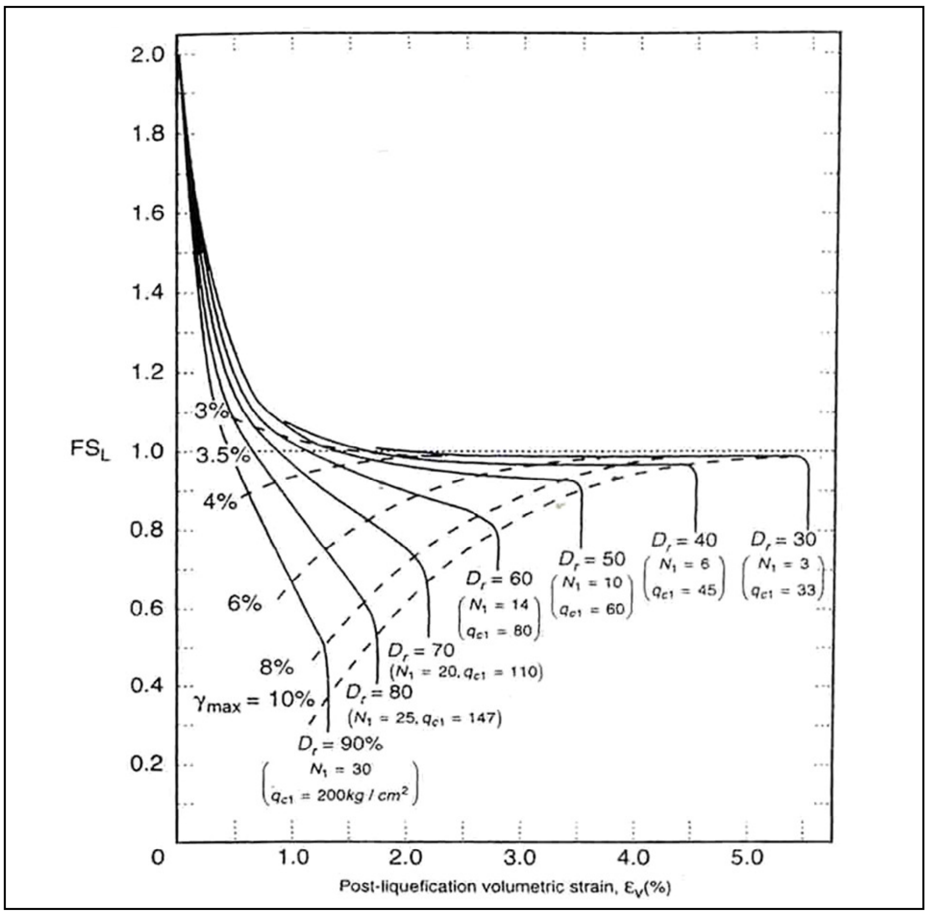

Figure 7. Chart for estimating the ground surface settlement of clean sand as a function of the Factor of Safety against liquefaction (FS_L).

Based on FSL and subsoil properties (N-value), the volumetric strain (ε_v) can be calculated. Finally, using the compressible layers thickness within influence zone, the settlement due to an earthquake is equal to 6mm. Therefore, this system provides suitable performance and design, where the settlement in static and dynamic conditions is in an acceptable range. Although, a few minor earthquakes happened during the construction and after, it was confirmed that the selected foundation system has shown suitable performance.

Conclusions

Afsoon is a coastal tower was built in Babolsar, in northern Iran, where the subsoil of this region consists of saturated loose sandy deposits. Due to the active faults that surround the site, the risk of seismic activity and therefore, the potential of liquefaction and compressibility, are high. Based on preliminary studies, the bearing capacity criteria for a shallow mat foundation was in an acceptable range. However, there were problems of uniform and differential settlements under static and dynamic loads, and also instability due to liquefaction potentials. To overcome these problems, various solutions were proposed, such as; replacing the soil with a suitable mixture, vertical drainage systems, a semi-deep foundation, dynamic compaction, Portland cement grouting technique and Deep compaction. Finally, through these approaches, with regard to available equipment, soil conditions, liquefaction existence, high ground water level, performance period, and also economical and environmental considerations, the alternative of deep compaction combined with mat foundation was preferred. Thus, 23 driven piles and also 19 vibro replacement piles were used. A raft foundation was constructed to form composite mat as a foundation system. The driven piles remained in the ground as permanent member and the vibro piles were pulled out.

Analysis indicates that the combined system of vibro and compaction piles accompanying the raft foundation increased the bearing capacity by up to 60% (Eslami and Fellenius 1997), controlled the soil volume changes, mitigated liquefaction hazard and resisted against lateral loading. The data obtained from instrumentation and monitoring, and from the standard penetration tests at the end of construction and after, demonstrated that the real subsoil settlements in dynamic and static conditions are less than the allowable values considered in the design procedure and also the suitable safety factor against the possibility of liquefaction.

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