

A CASE STUDY ON IMPROVEMENT OF  
A VIBRATING FOUNDATION

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## A CASE STUDY ON IMPROVEMENT OF A VIBRATING FOUNDATION

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**SUMMARY** Three oxygen compressors supported on piles were found suffering too severe vibration amplitudes that improvement of the foundation is required. This paper describes a complete case study of analysis and improvement. The original design of the foundation and the soil properties at site are reviewed. Based on a soil-pile interaction analysis, the computed vertical, sliding and rocking mode of vibration were compatible with the actual measured amplitudes. The method of improvement for the foundation is designed according to the required criteria. Improvement of foundation involves installation of additional piles with an enlarged footing. Comparison of the predicted results with the measured vibrating amplitude after improvement is made.

### INTRODUCTION

The Kaohsiung Steel Mill of the China Steel Corporation has been in operation since late 1977. It was found that the three compressors in the Oxygen Plant, each supported by an independent pile foundation created severe vibration problems in both the compressor machine and the foundation. To avoid any potential breakdown of the oxygen supply system, remedial measures had to be taken to improve the situation. Consequently, the original design of foundations were reviewed and analyses. Method of improvement were suggested according to results of prediction. Measurement of vibration was made for evaluation after the foundation had been improved. The purpose of this paper is to provide a detailed case record on the study and evaluation of improvement.

The compressor-and-motor unit concerned was built by a foreign supplier. The original design and construction of the machine foundation were done by a local contractor. Since all the three compressors

in the Oxygen Plant were in a similar situation, the analysis work in the paper does not necessary refer to any particular one of the three compressors. The results of analysis could be applied to any of the three compressors in the Oxygen Plant.

## SUBSOIL CONDITIONS AND FOUNDATION LAYOUT

### Subsoil Conditions

The subsoil conditions as revealed from soil borings are shown in Table 1. The subsurface strata at the site consist of intermixed silty sand layers and silty clay layers. The topsoil is mainly a layer of stiff, possibly compacted silty clay of medium plasticity. Underlying the 2.5 m thick topsoil layer is a layer of 5 m thick, soft gray silty clay of medium plasticity. The average natural moisture content of this layer is 34.2% which is very close to its liquid limit. Beneath the soft clay layer is a thick layer of medium dense gray silty fine sand or sandy silt. The standard penetration resistance, N blows is around 20. This layer extends to a depth of 20 m, and the sandy soil becomes dense to very dense at further below. Groundwater level is around 3.5 m below ground surface.

TABLE 1 CHARACTERISTICS OF SUBSOILS

Layer of Soil	Depth, m	Thick-ness, m	Description of Soils	SPT, N Blows	w <sub>n</sub> , %	w <sub>L</sub> , %	I <sub>p</sub> , %
1	0-2.5	2.5	Topsoil, backfilled, yellowish brown silty clay, stiff, medium plasticity	13	27.0	37	16
2	2.5-7.5	5.0	Gray silty clay or clayey silt, medium plasticity	4	34.2	35	12
3	7.5-20	12.5	Gray silty fine sand and sandy silt, medium dense	20	25.0	-	-
4	>20	>20	Intermixed layers of silty sand and sandy silt dense to very dense	>30	<25	-	-

## Original Design of Foundation

The machine foundation is supported by 12 prestressed concrete pile of 40 cm diameter and 15 m long with a center to center distance of 1.2 m in one direction. The piling plan of the foundation is shown in Fig. 1. The original design considers only the dead weight of machine together with 1.25 times of the dynamic loads. The dynamic behavior of the foundation system was not considered. The foundation for the compressor and the motor were designed as two separate units, but the two foundations were tied together by reinforcement during construction. It should be noted that the connection between the pile and the foundation was relatively weak. The pile head inserted less than 10 cm into the foundation cap and connected by four 1.6 cm  $\phi$  steel reinforcement at a total length of 35 cm bent into the cap.

### PROBLEMS AND CRITERIA

#### Excitation Forces and Moments

According to the design data of the compressor, the dead weight of the compressor and the motor is 32 tons and 15 tons respectively. The operational speed is 590 r.p.m. which is equivalent to angular velocity  $w = 61.36$  rad/sec. The maximum unbalanced forces and unbalanced couples induced by the compressor in each direction are shown in Fig. 2. The magnitudes shown are actually a combination of primary and secondary unbalanced forces and couples.

#### Measured Amplitudes of Vibration

Thorough measurements on the vibrating amplitudes of the machine foundation during normal operation of a compressor were carried out. Vibrating amplitudes in three directions, namely, vertical direction (y axis) horizontal vibration (z axis) and axial vibration (x axis) were measured. It was found that the foundation oscillates in three directions and maximum vertical oscillation occurred at the foundation corners of the compressor side. Smaller amplitudes were measured on the motor side of the foundation. Maximum peak to peak amplitudes as measured on foundation surface and on the machine are listed in Table 2. It is interesting to note that the maximum amplitudes on machine in all three directions occurred at the top of the compressor. This indicates that the modes of vibration of the machine-foundation system might include vertical, sliding and rocking motions. Larger oscillations were observed in axial direction as compared to horizontal direction. Besides the vibration at the foundation system, certain vibrations were also induced in the floor area adjacent to the foundation. Figure 3 shows the measured peak-to-peak amplitude on the floor. It can be seen that larger amplitudes were resulted on the compressor side of the floor and particularly at the vicinity of the foundation corners.

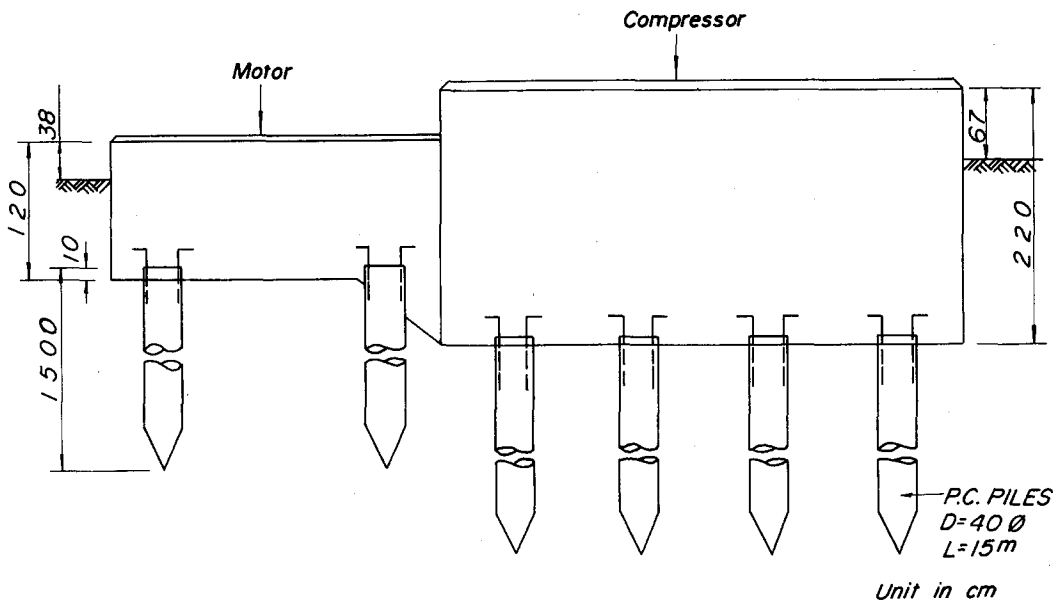
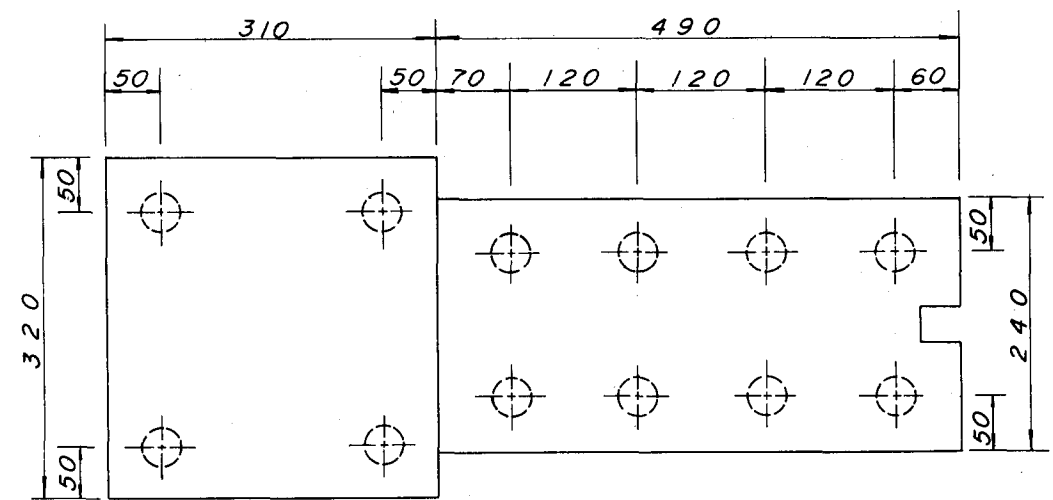


Fig. 1 Original Design of Foundation

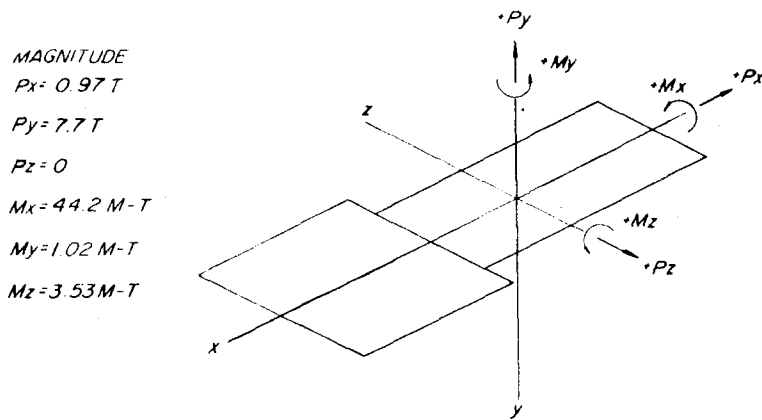


Fig. 2 Unbalanced Forces and Couples

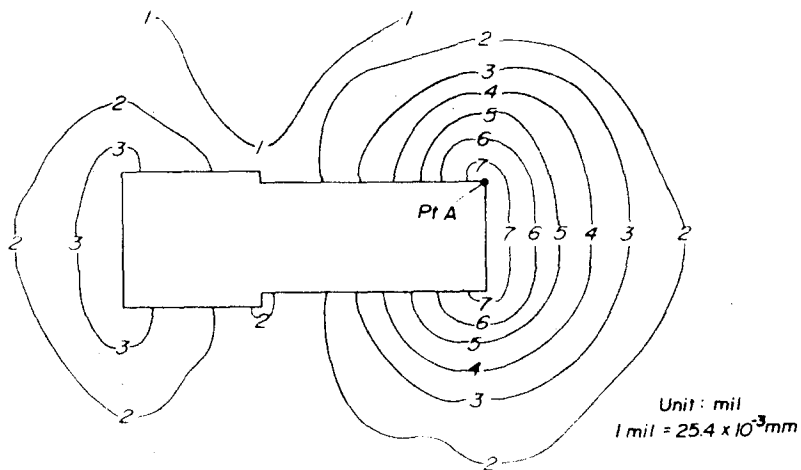


Fig. 3 Measured Peak-to-Peak Amplitudes Around Foundation

## Improvement Criteria and Limitations

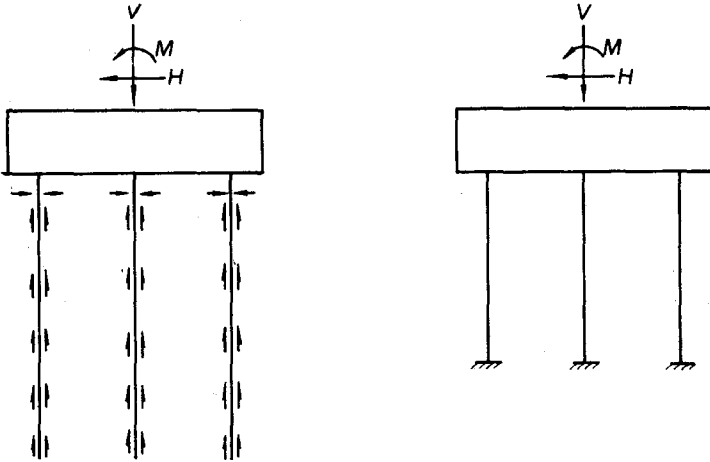
In order to set up a criterion for improvement, a maximum allowable peak-to-peak amplitude on foundation surface  $2A = 3$  mils was followed. This criterion is recommended by HARRIS and CREDE (1976) for reciprocal machine. There were also some limitations for improvement. Firstly, any improvement for one foundation should not hinder the operation of the other two compressors. Secondly, changes or disassembles of all pipings connecting to a compressor should be avoided. Thirdly, the compressors could not be relocated.

## METHODS OF ANALYSIS

### Vertical Vibrations

For a pile foundation which is acted upon by a vertical dynamic force, it will oscillate as if the foundation were supported by an elastic spring. The elastic resistance of the pile depends upon soil properties and pile characteristics, e.g. shape, length and material etc. BARKAN (1962) has established a method for evaluating the elastic resistance of the pile from a static pile load test. SINGH et al (1977) presents an approximate analytical procedure for analyzing dynamically loaded pile-supported foundations. The pile group is simplified as an "equivalent cantilever" in Fig. 4. The length of cantilever is evaluated by the supporting strength of soil upon pile. The equivalent spring constants for vertical, horizontal and rocking motion of the cantilever can be evaluated in accordance to the material and geometric arrangement of piles.

In this study, the equivalent cantilever method was followed. The vibration amplitudes of the foundation were analysed as a forced vibration with no damping. A single-degree-of freedom mass-spring model was assumed in vertical vibration. Sliding and rocking motions were analysed according to BARKAN (1962). For simplicity, torsion motion was neglected in the analysis. It has been known that the damping properties of the foundation soil cause great influence on the vibrating amplitude of a foundation. However the damping effect is greatest in the zone of resonance. When the applied frequency is either below 50% or above 150% of the natural frequency, the influence of damping becomes negligible (BARKAN, 1962). For the present foundation, the applied frequency is about 22% of the natural frequency, therefore the effect of damping can be considered as insignificant. The foundation mass used in the analysis is the combined mass of foundation and machine. Some authors, such as BARKAN (1962) reported that for pile foundation in water - saturated fine dense sand, the vibrating mass was about 30% larger than the mass restricted to the foundation because some enclosed foundation soil oscillating in phase with the foundation. The assumption is not applicable in this study because the soils enclosed in the pile group have remote possibility to oscillate in phase with the foundation.



(a) Foundation - Pile System      (b) Equivalent Cantilever  
after SINGH et al (1977)

Fig. 4 Equivalent Cantilever Analog

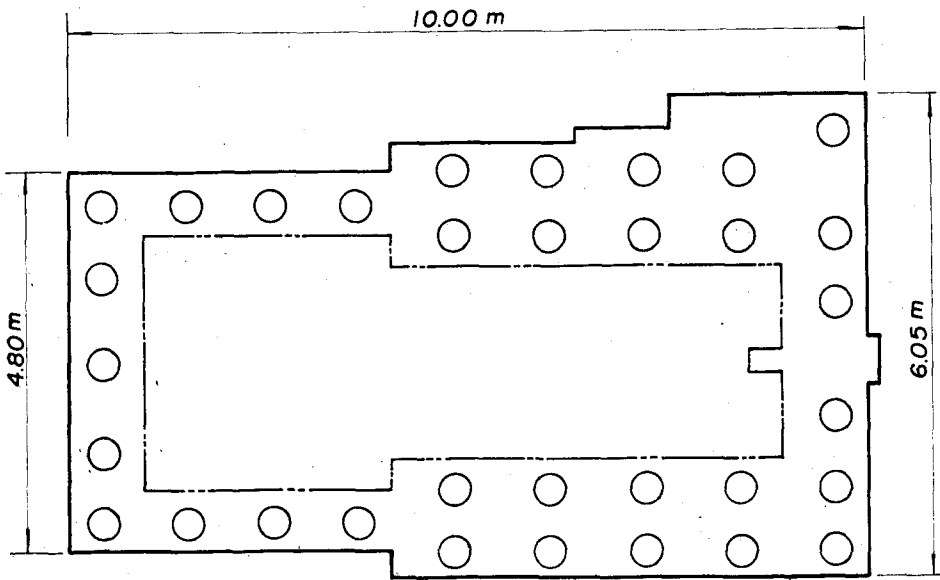


Fig. 5 Foundation Layout after Improvement