

## SEISMIC SOIL-PILE GROUP INTERACTION ANALYSIS OF A BATTERED PILE GROUP

Nan DENG<sup>1</sup>, Richard KULESZA<sup>2</sup> and Farhang OSTADAN<sup>3</sup>

### ABSTRACT

Based on observations from numerous case studies, it is generally accepted that a battered pile group, if not analyzed by appropriate methods and suitably designed, is likely to experience overstressing at the battered portion and at pile head connections. However, there are very few published quantitative assessments on the magnitude of the effect of seismic soil-pile interaction in the literature, partly due to the difficulties in carrying out the analysis for battered piles including the pile-soil-pile interaction effects.

This paper presents the results of a 3-D seismic analysis of a battered pile group design for a heavy machine foundation located in a seismically active region. In addition to seismic analysis of the battered pile foundation, parametric studies are performed for several controlling parameters and comparisons are made between the responses of the battered and vertical piles in the group.

Results of the analysis show that the battered piles tend to attract significantly larger seismic loads in terms of the axial loads when compared with the vertical piles and require careful attention for design of the pile connection to the pile caps. This result is a quantitative confirmation of the commonly known field performance problem. Further study of the results indicates that the main cause of the increase in axial loads in battered piles is the kinematic interaction between the soil layers and the of the pile group.

The latest enhanced version of the computer program SASSI2000 is utilized in the analysis. This enhancement involves implementation of specially developed inter-pile soil elements to model pile foundations including battered piles.

**Keywords:** Soil-Pile Group Interaction, Kinematic Interaction, Seismic Analysis, Battered Pile Foundation, SASSI2000

### INTRODUCTION

A heavy machine foundation is designed for a mining processing plant. The processing plant is located on stiff to very stiff but highly sensitive silty clay/clayey silt deposit overlaying bedrock. The clayey layers are about 30 m in thickness. In consideration of the heavy weight of the machinery and its supporting structure, which have a total weight of 8382 KN, and the potential of excessive lateral deflection due to off-center ore charge during normal operation, the design of the foundation combined battered piles and vertical piles with total of 47 steel pipe piles connected at grade with an 11 m x 17 m x 2.4 m concrete pile cap and driven to the bedrock. All steel pipe piles have an O.D. of 0.273 m, and wall thickness of 12.7 mm. Pipes are filled with concrete. The piles in the perimeter of the foundation are battered at 1H:6V angle and the rest are vertical. Figure 1 shows the plan and vertical layouts of the pile group foundation.

<sup>1</sup> Engineering Supervisor, Bechtel National, Inc., San Francisco, CA. Email: [ndeng@bechtel.com](mailto:ndeng@bechtel.com)

<sup>2</sup> Principal Engineer, Bechtel National, Inc., San Francisco, CA.

<sup>3</sup> Chief Soils Engineer, Bechtel National, Inc., San Francisco, CA.

While the battered piles provided additional lateral stiffness for the operation of the machinery, concerns were raised about seismic performance of the piles since the processing plant is located in a seismically active region. Observations of past case histories of seismic damage to pile foundations clearly show battered piles tend to attract large seismic loads causing overstresses in the battered piles and pile-cap connections. However, very few, if any, documented cases of earthquake-induced battered pile foundation damage give quantitative assessment on the magnitude and distribution of the overstress in the battered piles, and there is no clear answer on whether an alternative design would prevent excessive deflection during normal operation. It was determined, therefore, that a 3-D seismic soil-pile interaction analysis be performed to evaluate these concerns.

## **SOIL PROFILE AND GROUND MOTION**

The soil strata at the site of the foundation consist of layers of silty clay and clayey silt with traces of sand, with a stiff to very stiff consistency. The soil layers are classified as CL-ML, occasional CH. The low strain shear wave velocity profile, as determined from seismic cone (CPT) soundings, is shown in Figure 2. Ground water level is about 2 m below the ground surface.

Using the relevant building code provisions, design rock response spectra were developed for the site. A set of 3-component acceleration time histories compatible with the design spectra were generated utilizing the adjacent earthquake records as seed motions. Site response analysis was performed using the computer program SHAKE2000 (Bechtel, 2004). The shear modulus degradation and damping relationships published by Sun, et al (1988) were utilized in the analysis to represent the dynamic characteristics of the soil layers. Figure 2 also shows the profiles of strain-compatible shear wave velocities and damping ratios. The acceleration time histories at ground surface obtained from the site response analysis are shown on Figure 3.

## **SOIL-PILE GROUP INTERACTION ANALYSIS**

The latest enhanced version of the computer program SASSI2000 (Bechtel, 2005) is utilized to perform the soil-pile group interaction analysis. This later enhancement includes implementation of the inter-pile element (Ostadan, 1983), which is capable of modeling the pile-soil-pile interaction. This enhancement makes the program particularly suitable for pile foundations with vertical and battered piles.

A complete SASSI model for the pile group includes the following components: the layered halfspace with prescribed earthquake motion, excavated soil volume, inter-pile soil volume, beam element assembly representing the stiffness characteristics of the piles, concrete volume for the pile cap, and beam-lumped mass assembly representing the machinery and support structure. The strain compatible soil properties, as shown in Figure 2, are used in the model. The Poisson's ratio of soil is 0.35 above groundwater level, and is 0.48 below.

### **Analysis of Battered Pile Group**

Figures 4(a) and 4(b) show the complete model for the pile group consisting of battered and vertical piles. Figure 4(a) shows the assembled model, and Figure 4(b) is a cut-off view for the internal details. The machinery and its supporting structure are represented by 9 lumped mass points at the centroids of respective components. The lumped mass points are connected to the pile cap with rigid beams. The figure shows only the discretized components. The layered halfspace, which defines the seismic environment with the earthquake motions specified at the ground surface, is implied. As shown in the figure, X-axis is defined in the transverse direction of the pile cap, Y-axis is in the longitudinal direction, and Z-axis is vertical.

Figures 5(a), (b) and (c) show the distribution of maximum axial forces in the piles beneath the pile cap due to X-, Y-, and Z-direction earthquake shaking, respectively. Axial force distributions at other

depths are showing similar patterns but are not presented here due to space limitations. Maximum shear forces and bending moments in the piles are also calculated and are summarized in Figures 10 and 11. In general, the dynamic stresses induced in piles due to shear and bending in this study are less critical than those due to axial forces for structural design purposes and are not discussed hereafter.

The results clearly show that for the combined battered and vertical pile group, the seismically induced axial forces in the piles are highly non-uniform among the piles, especially for the loads caused by horizontal shakings, and the largest values are always in the battered piles. In addition, the distribution pattern of the axial forces appears to resist a large moment in the direction of earthquake shaking, since the maximum pile axial forces in the battered piles are always in tension at one side, and in compression at the other side. Simple hand calculations confirm that this moment is much greater than the moment that the inertia of the machinery and the supporting upper structure were able to generate during the design earthquake. Thus, this moment must come from elsewhere, most likely from the kinematic interaction between the soil and the battered piles.

### **Kinematic Interaction Analysis**

In order to understand better the distribution patterns of the axial forces and the potential origin of this large moment, a kinematic interaction analysis is performed to evaluate the impact of kinematic interaction between the soil and the pile foundation. The kinematic analysis is identical to the first one except all masses in the original battered pile group model are reset to zero, so that the model does not have any inertial loading from the structures during an earthquake shaking, while all stiffness and geometric distributions of the structure remain intact. Therefore, results from a kinematic analysis will reveal the impact of geometric distribution of the stiffness components of the structure.

Figures 6(a), (b) and (c) show the distribution of maximum axial forces in the piles beneath the pile cap due to X-, Y- and Z-direction earthquake shakings, respectively, from the kinematic analysis. Comparing these results with those shown on Figures 5(a), (b) and (c), it can be observed that these figures have all similar patterns and the values from the kinematic interaction account for almost 80 percent of the total axial forces in the battered portions at the pile cap level. It is obvious that the kinematic interaction does have a major impact on the magnitude of the maximum seismic load of the battered piles. Since for battered piles, the horizontal motion of soil layers causes both the transverse and axial motion of the piles, and piles are generally much stiffer in axial direction, this axial motion is the main cause of increase of axial loads in the battered piles.

### **Responses of Vertical Pile Foundation**

The above results indicate that, for a foundation consisting of a combination of battered and vertical piles, a major portion of the seismic axial loads is caused by kinematic interaction effect between soil and the piles. It is then natural to expect that this effect shall be reduced for a foundation with vertical piles only. Therefore, a further study was performed to evaluate the seismic responses of an all-vertical pile foundation. This vertical pile foundation model has all components the same as the battered pile foundation model, except that all the battered piles are replaced by vertical piles. All excavated soil volume and inter-pile soil volume in the SASSI model are changed accordingly. Figures 7(a) and 7(b) show the all-vertical pile foundation model.

Results of analysis for the all-vertical pile foundation are shown in Figures 8(a), (b) and (c) in terms of the maximum seismic axial forces in the piles beneath the pile cap due to X-, Y-, and Z-direction earthquake shakings, respectively. Not surprisingly, the axial forces are much smaller and more uniform for all the piles, and, while the moment in the shaking direction of the earthquake still exists, the magnitude is greatly reduced. At the pile cap level, the axial forces are reduced by more than 80% compared with the battered piles. This result confirms the generally accepted design practice that foundations using only vertical piles generally perform better than foundations with battered piles when subjected to severe seismic shaking.

### **Distribution of Axial Forces with Depth**

It is of interest to study the axial force distribution with the depth to understand better the effect of kinematic interaction. Results from the battered pile foundation analysis indicate that at the depth of 20 m, the X-shaking induced seismic axial force at pile P37 (See Figure 1(a), near the bottom left corner of the foundation) reaches a global maximum of 1,112 KN. The distribution of axial forces at P37 with depth is plotted in Figure 9. The axial force results for P37 from the kinematic interaction analysis and vertical pile foundation analysis are also plotted in the same figure for comparison.

It can be observed from the figure that the proportion of axial force due to kinematic interaction over the total axial force increases steadily with depth to a maximum of 1,056 KN at 20 m depth, as the soil tends to become less stiff with depth (See Figure 2). This value is almost 95 percent of the original global maximum. At the deeper soft layer at 27 m, the axial force induced by kinematic interaction even exceeds slightly the axial force in the full model case. It appears that the kinematic interaction causes the pile to bend in the soil deposit. In the softer layer, the pile segment would endure larger deformation with less lateral support, thus larger forces in the pile. The axial forces of P37 for the vertical pile foundation, on the other hand, remain much smaller throughout the depth. Though these also increase with depth, the maximum value is only 145 KN at the depth of 20 m, which is only about 13 percent of the global maximum for the battered piles.

### **Deflection Characteristics of Pile Groups**

Two types of deflections are computed in the analyses for both battered and vertical pile foundations. The first is the lateral deflections of the pile foundations during earthquake shakings and the second is the lateral and differential deflections during normal operations due to machine vibrations.

The deflections of the pile foundation are calculated as the relative displacements of the pile cap to the pile tip on the bedrock. For comparison purposes, the relative displacement of ground surface to the bedrock is also calculated. Table 1 summarizes the displacement values. It is clear from the calculated values that both pile groups essentially move together with the ground, and their displacement behaviors are almost identical.

**Table 1 Summary of Seismic Horizontal Relative Displacement at Grade (mm)**

	Free Field	Battered Pile Fdn	Vertical Pile Fdn
X-Dir Shaking	53.9	54.3	55.1
Y-Dir Shaking	45.6	44.5	46.2

It can also be observed from Figures 10 and 11 that the enveloped shear and bending distribution vs. depth for either battered or vertical pile foundations are very similar, indicating that the piles are essentially moving together with the ground.

The displacements of the pile foundations due to machine vibration during normal operation are calculated in a foundation vibration analysis for both battered and vertical pile foundations. The maximum lateral load from the off-center ore charge is determined by the manufacturer to be 275.5 KN at 13.3 rpm. This load is applied at the centroid of the machinery. For vertical pile foundation, the maximum lateral displacement at the machinery support is 0.25 mm, the maximum vertical differential displacement between the corners of the pile cap is 0.16 mm. These values are about 10 percent higher than the corresponding values of the battered pile foundation, but are well below the manufacturer-specified operation limits.

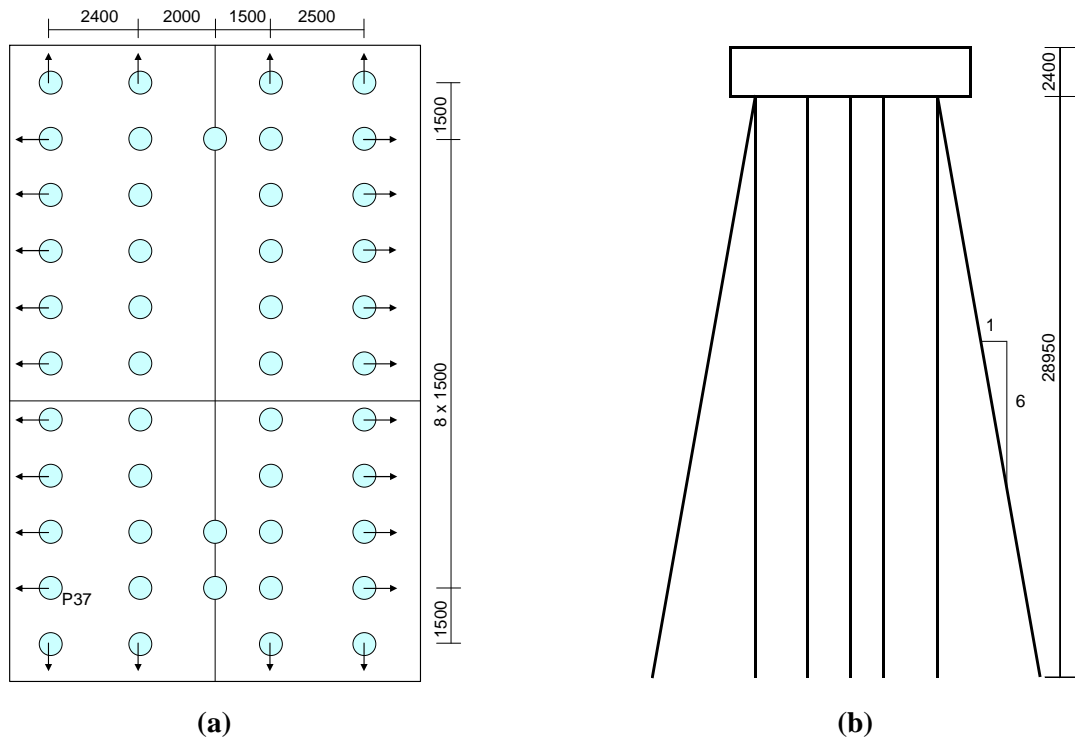
## **CONCLUSIONS**

This paper presents the results of a 3-D seismic soil-pile group interaction analysis for a foundation consisting of battered and vertical piles. As a parametric study to provide an alternative design, a foundation consisting of only vertical piles is also considered. Results of the analysis indicate that the battered piles attract high axial loads due to horizontal earthquake shaking mainly caused by the

effects of kinematic interaction. The axial loads can reach magnitudes of 5 to 8 times greater than the loads in vertical piles for the soil conditions and seismic parameters considered in the study. Furthermore, the calculated displacement results show that the displacement behaviors of both battered and the corresponding vertical pile foundation are very similar. Based on the above results, it is concluded that a pile foundation with only vertical piles should be the preferred choice for the particular set of conditions analyzed herein, as opposed to a design that includes battered piles. The results of the analyses are consistent with the general experience and practice for pile foundations in the geotechnical communities, such as the conclusions reached by Poulos (2006) and Fellenius (2006). In the event that battered piles are used, it is suggested that a kinematic analysis of the pile foundation be performed to obtain the total seismic axial loads for design in addition to the inertia load of the structure. The pile-cap connection for battered piles may require detailed design with careful consideration of appropriate load combinations.

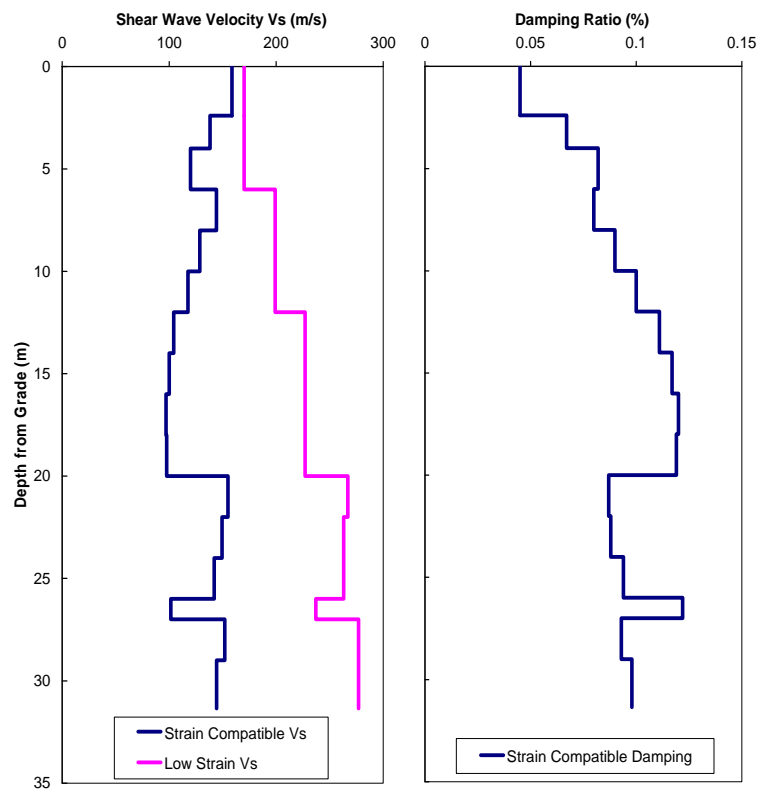
## REFERENCES

- Bechtel National Inc. (2004) "SHAKE2000 – A Computer Program for Conducting Equivalent Linear Seismic Response Analyses of Horizontally Layered Soil Deposits," Version 1.0, December
- Bechtel National Inc. (2005) "SASSI2000 – A System of Analyses of Soil Structure Interaction," Version 3.0, December
- Fellenius, B. H. (2006) Private Communication with the authors, May
- Ostadan, F (1983) "Dynamic Analysis of Soil-Pile-Structure Systems," Ph.D. Dissertation, University of California, Berkeley
- Poulos, H. G. (2006) "Raked Piles – Virtues and Drawbacks" ASCE Journal of Geotechnical and Geoenvironmental Engineering, Vol. 132, No. 6, pp 795-803, June
- Sun, J. I., Goleorkhi, R. and Seed, H. B. (1988) "Dynamic Moduli and Damping Ratios for Cohesive Soils," Report No. UCB/EERC-88/15, Earthquake Engineering Research Center, University of California, Berkeley, 42pp

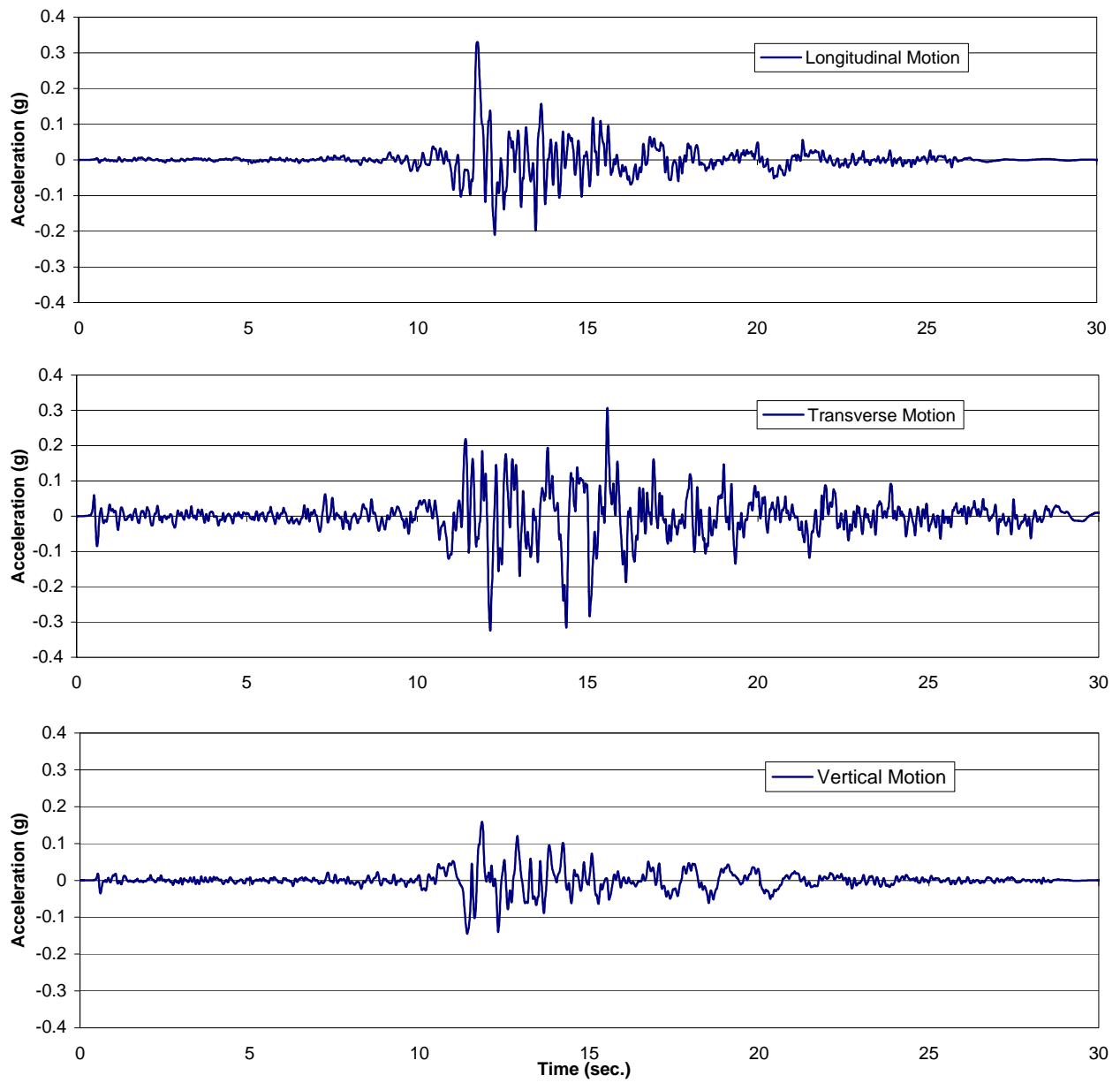


**Figure 1 Plan and Vertical Layout of a Battered Pile Foundation**

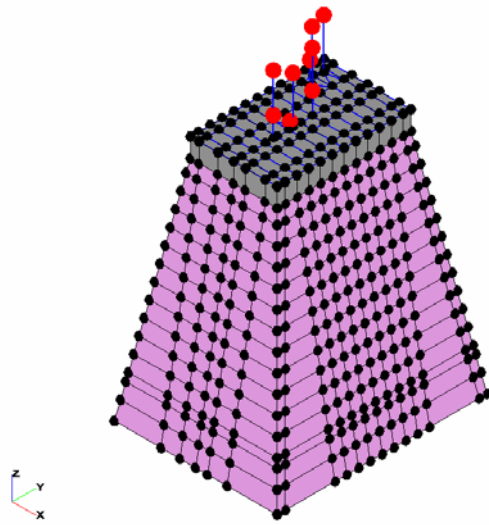
(Note: Unit in mm)



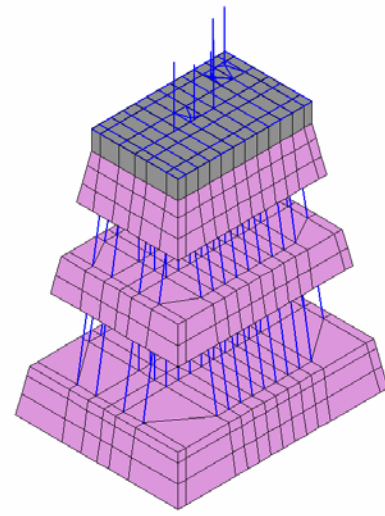
**Figure2 Shear Wave Velocity and Damping Profiles**



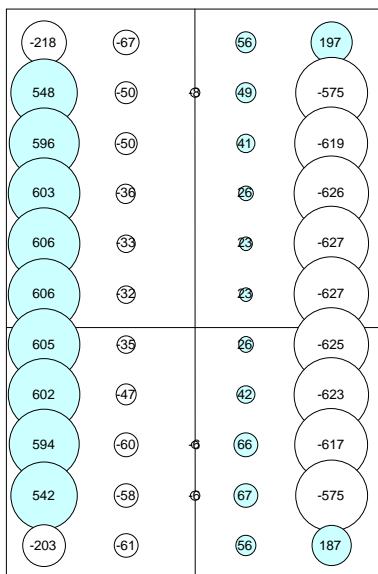
**Figure 3 Acceleration Time Histories at Ground Surface**



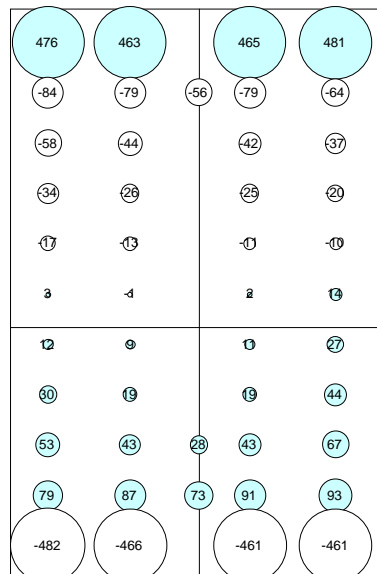
(a) Complete Model



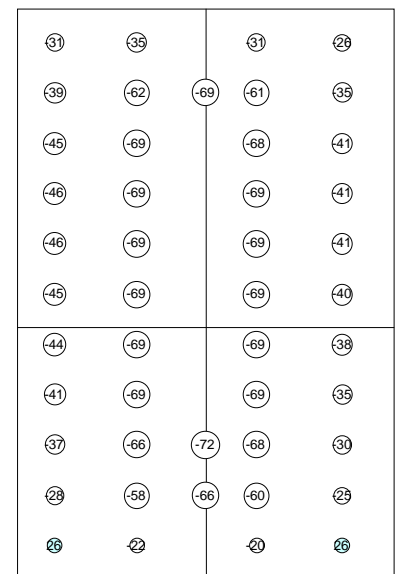
(b) A Cut-off View

**Figure 4 SASSI Finite Element Model for the Battered Pile Foundation**

(a) X-Shaking



(b) Y-Shaking

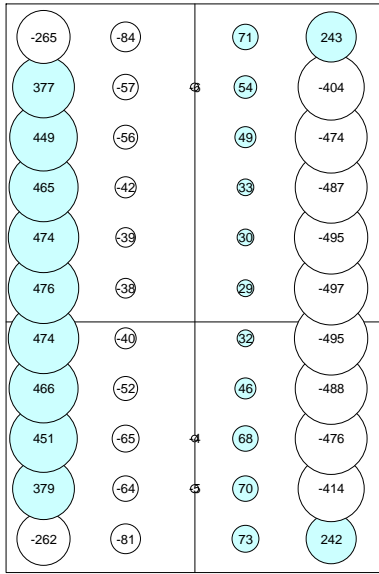


(c) Z-Shaking

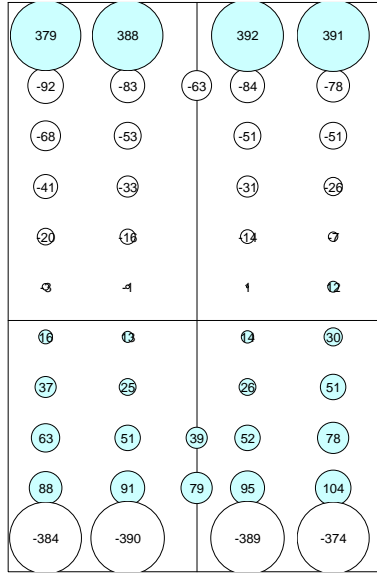
**Figure 5 Maximum Seismic Axial Forces in Piles Beneath Pile Cap. Battered Pile Foundation**

Note: Numbers in the bubbles are the axial force values in KN while bubble areas are proportional to the values. Positive values are pile in tension

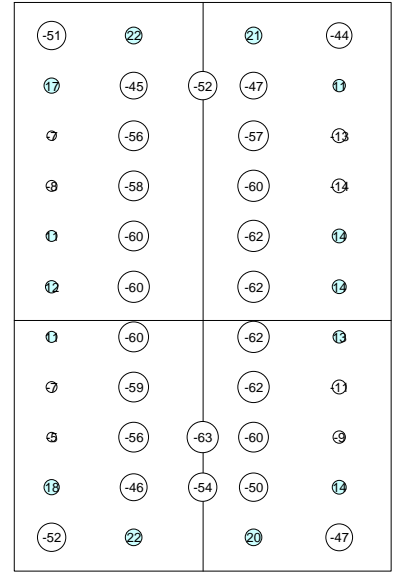




(a) X-Shaking



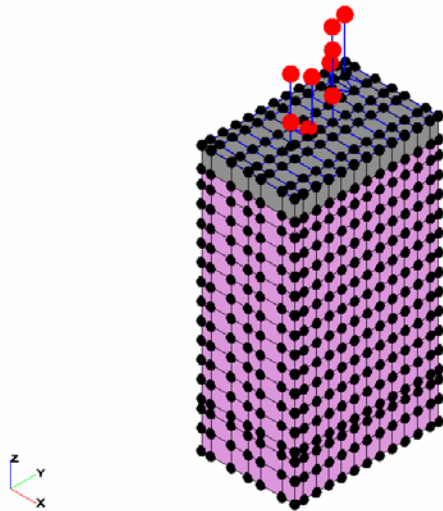
(b) Y-Shaking



(c) Z-Shaking

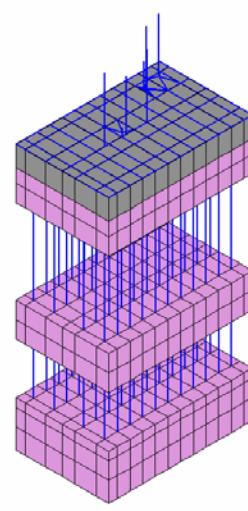
**Figure 6 Maximum Seismic Axial Forces in Piles Beneath Pile Cap. Kinematic Analysis**

SASSI PLOT Version 1.0



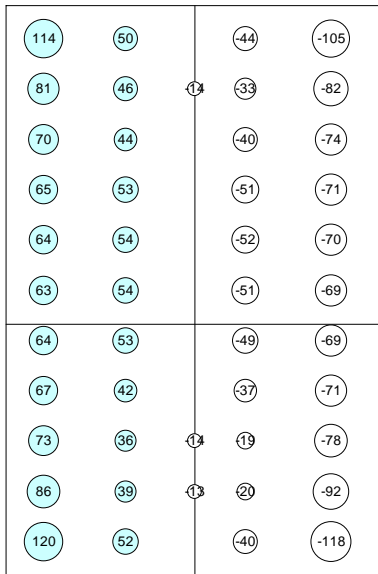
(a) Complete Model

SASSI PLOT Version 1.0

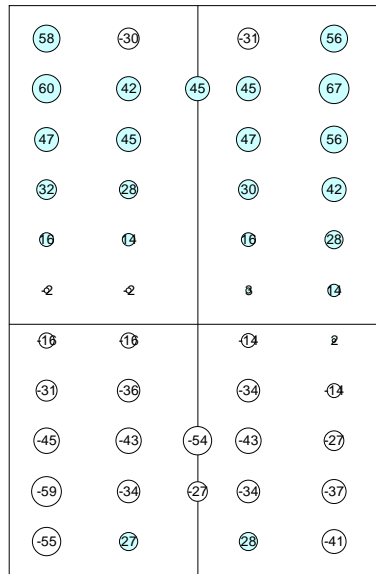


(b) A Cut-off View

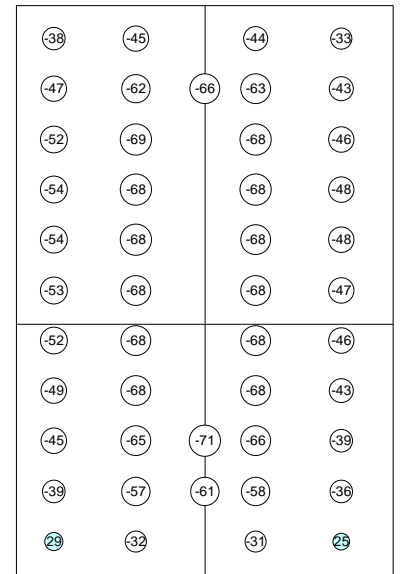
**Figure 7 SASSI Finite Element Model for the Vertical Pile Foundation**



(a) X-Shaking

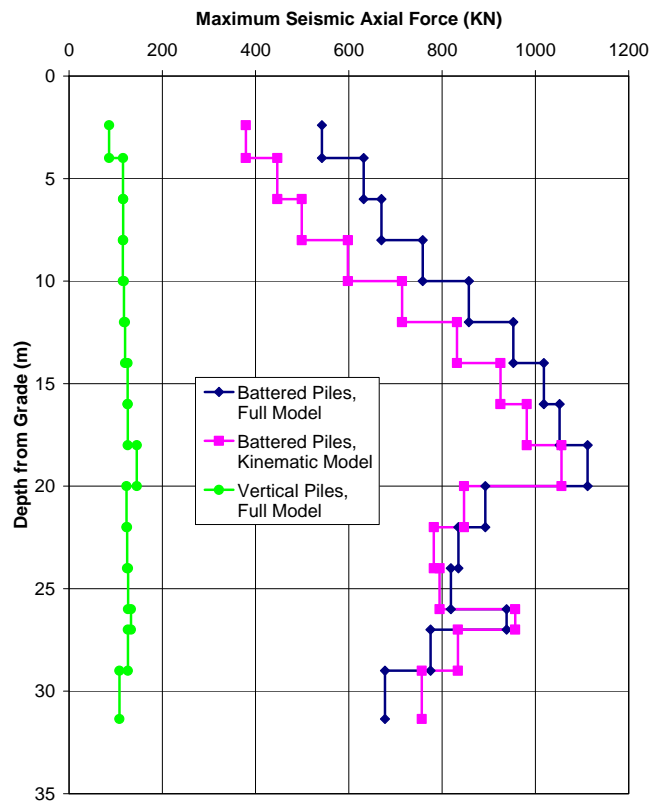


(b) Y-Shaking

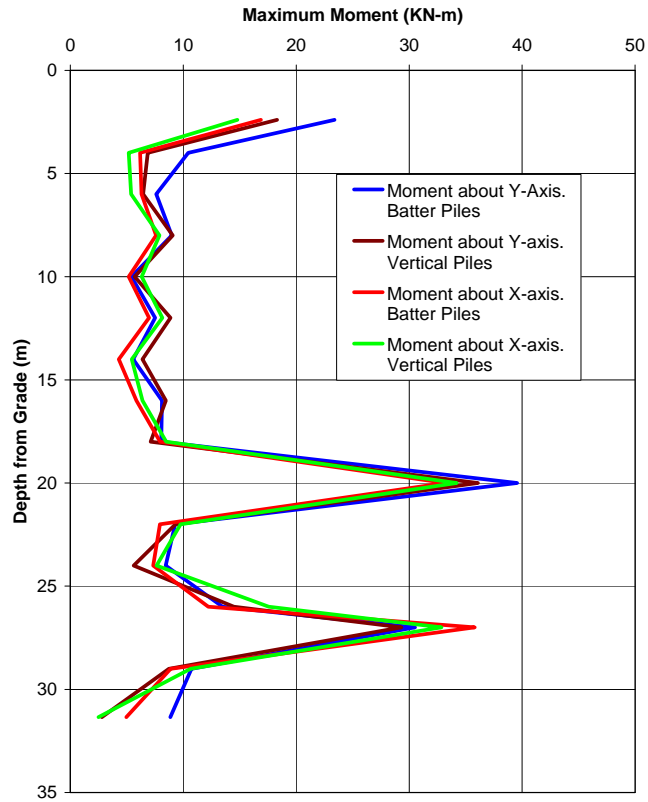


(c) Z-Shaking

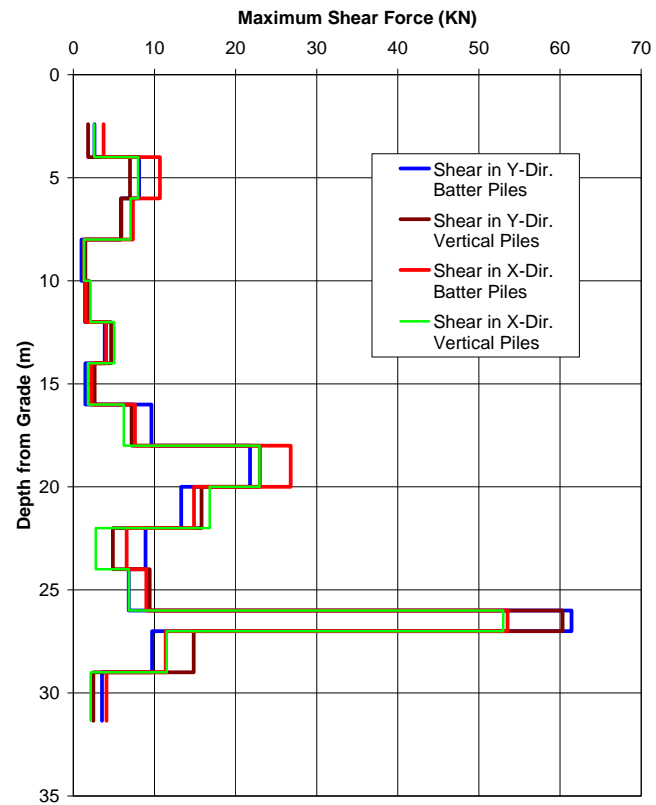
**Figure 8 Maximum Seismic Axial Forces in Piles Beneath Pile Cap. Vertical Pile Foundation**



**Figure 9 Maximum Seismic Axial Forces vs. Depth at P37 due to X-Shaking**



**Figure 10** Maximum Seismic Bending Moments vs. Depth. Envelope of all Piles



**Figure 11** Maximum Seismic Shear Forces vs. Depth. Envelope of all Piles