Ground responses induced by pile driving

Réaction du sol sur l'enfoncement des pieux

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ABSTRACT: A full-scale pile driving test had been performed at a reclaimed land in central Taiwan. This paper introduces the test program and a small part of the responses measured in the test. During the penetration process of the pile, the maximum accelerations measured at the ground surface and at depth, and the excess pore water pressure in soil induced by each blow of the pile are presented. Besides, the ground deformations and the strains of a concrete pipe resulted from the penetration of test piles are also presented.

1 INTRODUCTION

To accommodate the increasing need of land for industrial use, many large scale reclamation works are undergoing along the west shoreline of the Taiwan Island. The Chang-Hua Coastal Industrial Park, located south to the Taichung Harbor, is a newly reclaimed land with an area of 3643 hectares. The original ground is just below the sea water level. It is filled hydraulically with sands dredged from sea bed to an elevation of 4 meters above sea level, then covered with compacted gravelly materials for wind erosion protection. Since the newly filled sands are in relatively loose state, it is expected that large amounts of driving piles will be used in future constructions to support the heavy industrial facilities. Therefore, the disturbance of pile driving is of concern from the environmental point of view. In order to realize the effects of ground shaking induced by pile driving on the existing pipelines in the park, a pilot pile driving test with comprehensive instrumentations was performed at a planned tank site in the industrial park.

2 TEST PROGRAM

The site selected for test is a free-field without any structure in the nearby. The geological profile explored by cone penetration tests is shown in Figure 1 (Sinotech 1995). From the ground surface to the depth of 30 meters, it is composed of mainly sandy soils, with very few interbedded thin layers of silts. The layers at depth of 3m, 8m and 19 to 21m show relatively larger resistance to cone penetration. The ground water table is essentially same as the sea water level and fluctuates between 2.5m and 5m below the ground surface. The layout of the first stage test is shown in Figure 2. A total of 5 precast concrete piles, each of diameter 80 centimeters and length 2×12 meters, were driven into the ground by using a diesel hammer (KOBELO 80). The number affixed to the pile as shown in the figure indicates the sequence of driving in the test program. For reference, the direction along the P1, P2, and P3 piles will be called the X-direction, thereafter, and the one along the P4, P2, and P5 piles is the Y-direction. To the right of the driving test piles, a trapezoidal trench of depth 1 meter and length 8 meters was excavated to investigate the effects of vibration isolation. To the left, a 30-meter long concrete pipe of diameter 40 centimeters was buried at a depth of 3 meters to investigate the pipe responses during the pile driving.

To fully monitor the environmental responses induced by pile driving, several types of instrumentation were adopted in this test. Figure 2 shows the layout and profile of the P1 pile driving test. To record the driving energy transmitted to the pile, 4 strain gauges and 2 accelerometers were mounted on the shaft near the pile head. To monitor the ground vibrations induced by pile driving, 5 sets of 3-directional accelerometer A1-1 ~ A1-5 were placed on the ground surface, and 3 sets of 3-directional accelerometer D1 ~ D3 were buried at depths of 3.1m, 5.6m and 10.6m, respectively. Beside the downhole accelerometers D1 ~ D3, 3 piezometers U1 ~ U3 were installed to monitor the dynamic response of pore water pressure in soil. Between the pipeline and the driving piles, an inclinometer I1 was installed to the depth of 30m to record the ground deformations produced by pile driving. On the center segment of the pipeline, a downhole accelerometer D4 was placed to monitor the motion of the pipe and 12 strain gauges were glued to the inner side of the pipe to measure the pipe strains. Besides, 15 settlement posts were installed in the test area, as shown in Figure 3, to measure the ground settlement induced by pile driving. After the driving test, the pipeline was excavated to examine the degree of damage.

Figure 2 shows the layout of the surface accelerometers, the downhole accelerometers and the piezometers for the driving test of P1 pile. For the tests of P2 and P3 piles, some of the surface accelerometers are rearranged to other locations (not shown in this paper). Due to the limitation of page numbers allowed, only part of the recordings of the P1 pile driving test will be shown herein.

3 GROUND VIBRATION

During the driving of the first half (0m ~ 12m) of the P1 pile, all the responses were recorded continuously using a sampling rate of 100 Hz. To illustrate the spreading of the driving disturbance, a segment of time-history responses when P1 pile has been penetrated to the depth of 8m below the ground surface is shown in Figure 4. The top figure shows the axial strain of pile head which can be integrated, along with the acceleration measured, to estimate the driving force exerted on the pile. The other three show the variations of the radial accelerations (X-direction) of A1-1, A1-2 and A1-3 accelerometers which are 3.2m, 6.4m and 10.4m, respectively, away from the center of the driving P1 pile. From this figure, it can be seen that the shock waves propagate outward without significant dispersion. During each blow of the pile, the ground vibrates as the wave passes. Its amplitude decays very rapidly without significant free vibrations. From the time delay of the peak responses of each blow, it can be estimated that the propagation velocity of the compressional wave along the ground surface is around 240 m/sec. The peak accelerations of A1-1-X, A1-2-X and A1-3-X in each blow are plotted with

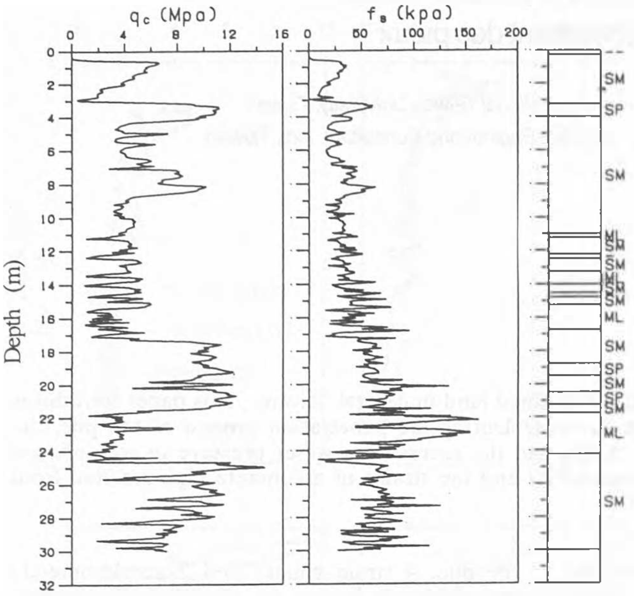

Figure 1. Results of cone penetration test

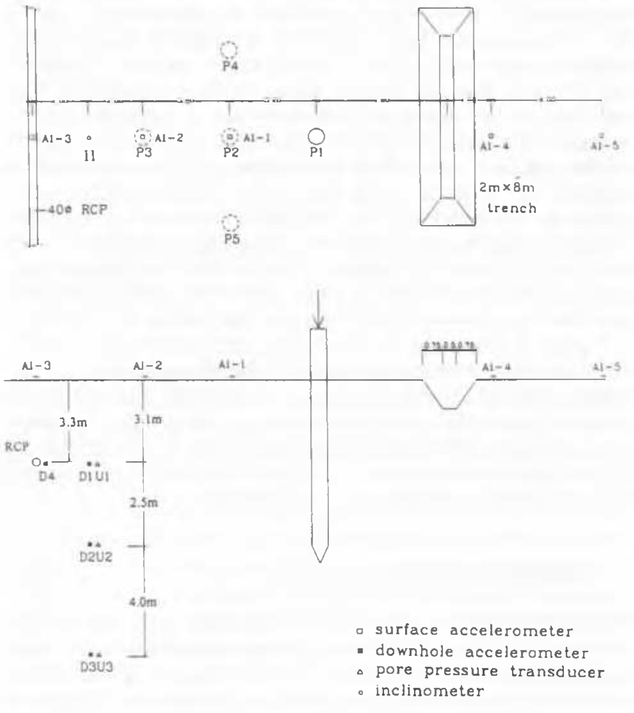

Figure 2. The layout of the *P*1 pile driving test

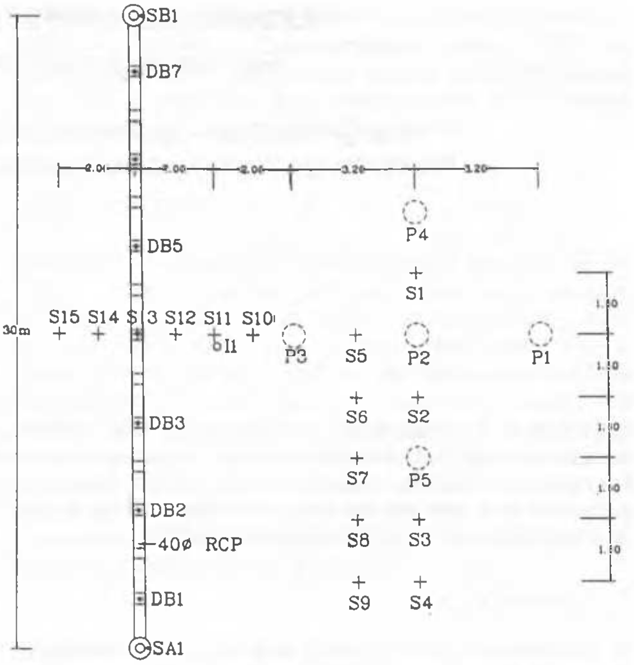

Figure 3. Layout of segmental pipes and settlement posts

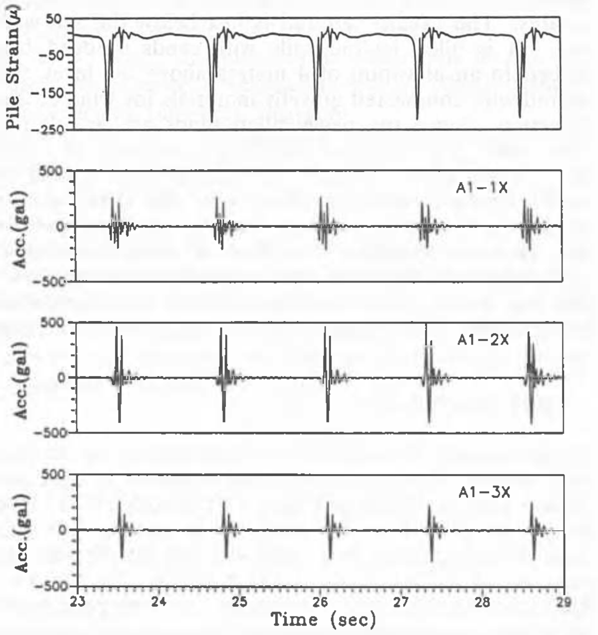

Figure 4. Time-history responses of pile and ground during *P*1 driving

the number of blow as shown in Figure 5. Based on that, it can be seen that the peak acceleration at A1-1-X has a value close to 1000 gals at a penetration depth of 3m and decreases very rapidly as the penetration depth increases; however, the A1-2-X and A1-3-X increase gradually with the increasing of the penetration depth. Comparing the responses recorded at opposite side of the trench, it has been found that the trench excavated has no effect on vibration isolation except for the locations very close to the trench. The peak ground acceleration measured at A1-4 is about half of that measured at A1-2.

Figure 6 shows the peak accelerations of D1-Z, D2-Z and D3-Z accelerometers with the number of blow. Each accelerometer experiences larger vertical acceleration when the pile penetrates to the same depth approximately. The maximum vertical acceleration induced is around 100 ~ 250 gals. The radial acceleration at D1 station has the same magnitude as its vertical acceleration; however, the radial accelerations at both D2 and D3 stations are much smaller than their vertical components.

4 BUILD-UP OF PORE WATER PRESSURE

The excess pore water pressures at depth of 3.1m, 5.6m and 10.6m (U1, U2 and U3 piezometers) are plotted with the number of blow as shown in Figure 7. They are the residual excess pore water pressure deduced between every two consecutive blows. With the increasing of the pene-

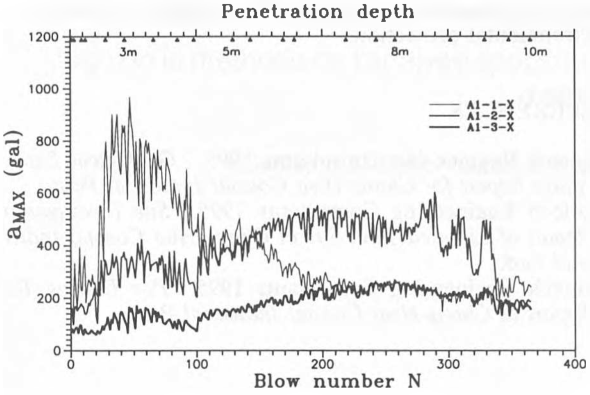

Figure 5. Peak surface ground acceleration due to $P1$ driving

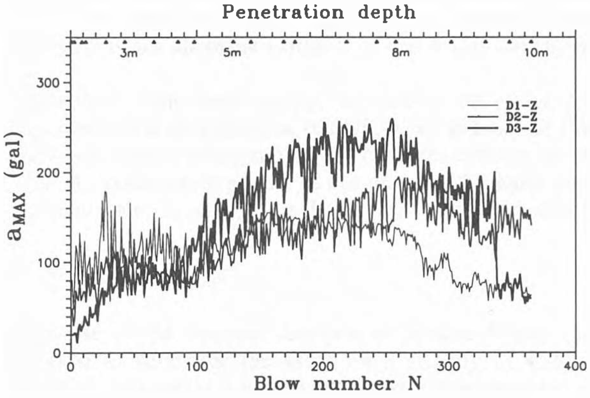

Figure 6. Peak ground acceleration at depth due to $P1$ driving

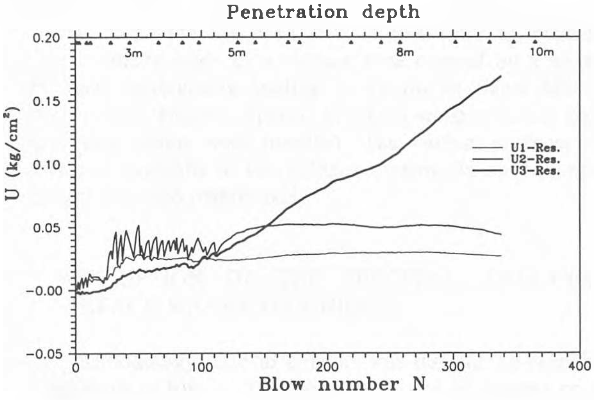

Figure 7. Residual excess pore water pressure due to $P1$ driving

tration depth, the residual excess pore water pressures at shallower depths (U1 and U2) increase gradually at the beginning stage and remain at constant values thereafter. However, the excess pore water pressure at U3 increases continuously with the increasing of the penetration depth. Checking the records of U1, U2 and U3 during the drivings of P1, P2 and P3 piles, the pore water pressures induced are far below the critical values to liquefaction.

5 GROUND DEFORMATION

After the driving of each segment of the P1, P2 and P3 piles (2 segments for each pile), the ground deformation is measured from the inclinometer and the settlement posts installed. The horizontal displacements (X and Y-directions) measured from the I1 inclinometer are shown in Figure 8 and the surface settlements along the X-direction (S10 ~ S15) and the Y-direction (S5 ~ S9) measured are shown in Figures 9 and 10, respectively. It can be seen that both the horizontal and vertical deformation at the measured points are very small due to the driving of the P1 pile and occurred primarily during the driving of the P3 pile. The distribution of significant settlement is very localized, about 5m from the driving pile.

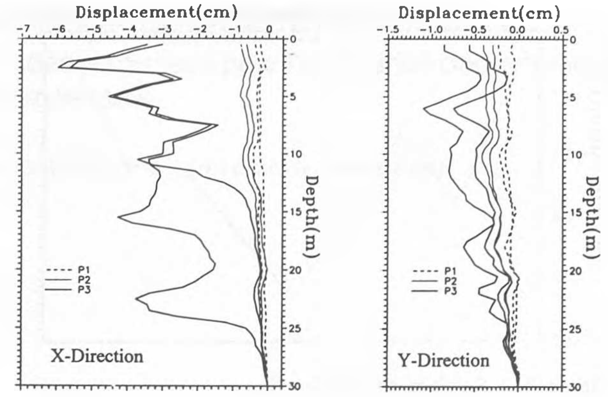

Figure 8. Horizontal displacement at $I1$ due to $P1$, $P2$ and $P3$ drivings

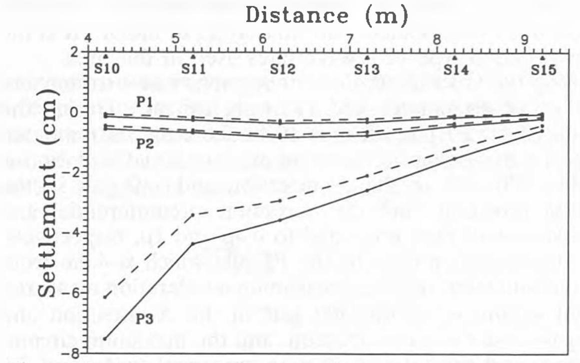

Figure 9. Ground settlement along X-direction due to $P1$, $P2$ and $P3$ drivings

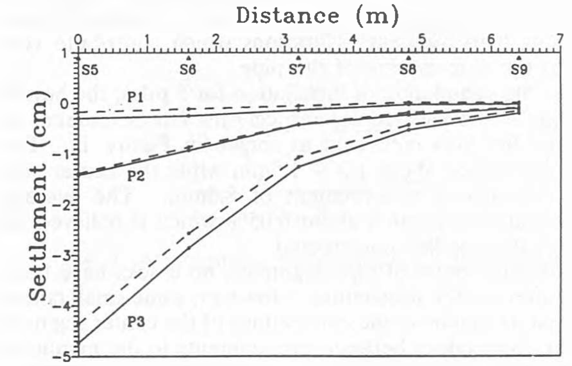

Figure 10. Ground settlement along Y-direction due to $P1$, $P2$ and $P3$ drivings

6 PIPE RESPONSES

The pipe line constructed for test is a segmental concrete pipe of diameter 40cm. Each segment has a length of 2m

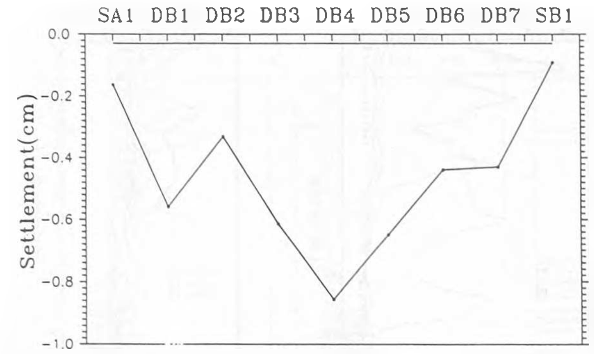

Figure 11. Settlement of pipe line

and an enlarged end for connection. As shown in Figure 2, the test pipeline consists 14 segments with manholes at both ends. It rests on a layer of plain concrete and the connections were sealed with thin layers of motar. It is the most common type of sewage lines used in this area.

Along the pipeline, the center segment was instrumented with an accelerometer and 12 strain gauges. During the driving of the P1 pile which is 10.4m from the instrumented pipe, the maximum acceleration measured at D4 station is around 200 gals in the X direction and 140 gals in the vertical direction, and the maximum circumferential and axial strains of pipe are equal to 0.4μ and 1μ, respectively. During the penetration of the P3 pile which is 4.0m from the instrumented pipe, the maximum acceleration measured at D4 station is around 500 gals in the X direction and 300 gals in the vertical direction, and the maximum circumferential and axial strains of pipe are equal to 4μ and 3μ, respectively.

Based on the results obtained, it can be found that the peak acceleration of pipe resulted from the driving of piles is quite high, however, the maximum strains of pipe are still very low because the ground motion is essentially dominated by high frequency vibrations which contribute very little to the deformation of the pipe.

After the completion of installation for 5 piles, the buried pipe line was excavated for inspection. The settlement of the pipe line was measured as shown in Figure 11. The manholes settled about 1.0 ~ 1.5mm while the center segment experienced a settlement of 8.6mm. The average differential settlement is about 0.05% which is believed no harm to the pipeline constructed.

As for the bodies of pipe segments, no cracks have been found after careful inspections. However, some small cracks occurred on motars at the connections of the center segment and the connections between the segments to the manholes at both ends. The former is due to relatively large deformation resulted and the latter is due to the abrupt change of rigidity between the manhole and the pipe. Those cracks are found to be very minor and will not cause leakage problem of the pipeline. Based on the results observed, it can be concluded that the pipelines so constructed will remain functional even the piles are driven at a quite close distance.

7 GENERAL REMARKS

The pile driving test performed at the Chang-Hua Coastal Industrial Park is aimed at investigating the disturbance produced by the drivings of piles. A complete record of the ground vibration, ground deformation, pore water pressure response and the pipe strain resulting from the driving of P1, P2 and P3 piles had been successfully obtained. This paper just demonstrates part of the results of measurement. Those data will be analyzed analytically in the future and used to assess the degree of environmental impact resulting from the pile driving and, hopefully, set up a criteria for environmental protection.

REFERENCES

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